Ultra-low-energy house and indoor environmental quality: a case study

S. Vilčeková, A. Sedláková, P. Turcsányi, L. Mečiarová, E. Krídlová Burdová, J. Varga, P. Rošková

***Abstract*—**In times of minimizing energy performance of buildings to save as much energy as possible while producing minimum harmful greenhouse gas emissions is more than ever essential to understand the concept of "low-energy" design. Design of transparent and non transparent building constructions, application of passive and active systems for using of renewable energy sources and energy demand as well as their balance are the most important to achieve both the goal of the low energy buildings with a healthy indoor environment. This statement led us to investigate an ultra-low-energy house from energy and social aspects. Thermo-physical properties of external wall, roof and floor as well as openings are presented in terms of requirements for ultra-low-energy houses. There is illustrated an importance of house orientation in order to maximize solar gains as well as showed course of isotherms in the details of constructions. The quality of indoor environment directly affects the healthy and comfortable wellbeing of occupants, thus it is important fact that we cannot forget during designing process. Therefore, measurements of indoor environmental quality factors were carried out in selected family house in pre-occupation stage. Correlation analysis was used for finding the relationship between measured factors.

***Keywords*—**energy performance, ultra-low-energy house, thermo-physical parameters, indoor environmental quality, case study, Slovakia

This work was supported by the Grant Agency of the Slovak republic under Grant No. 1/0307/16.

Silvia Vilčeková is with the Department of Environmental Engineering, Institute of Environmental Engineering, Faculty of Civil Engineering, Technical University of Košice, Vysokoškolská 4, 04200 Košice, Slovakia, e-mail: silvia.vilcekova@tuke.sk.

Anna Sedláková is with Institute of Structural Engineering, Faculty of Civil Engineering, Technical University of Košice, Vysokoškolská 4, e-mail: anna.sedlakova@tuke.sk.

Peter Turcsányi is with Institute of Structural Engineering, Faculty of Civil Engineering, Technical University of Košice, Vysokoškolská 4, e-mail: peter.turcsanyi@tuke.sk.

Ľudmila Mečiarová is with the Department of Environmental Engineering, Institute of Environmental Engineering, Faculty of Civil Engineering, Technical University of Košice, Vysokoškolská 4, 04200 Košice, Slovakia, e-mail: ludmila.meciarova@tuke.sk.

Eva Krídlová Burdová is with the Department of Environmental Engineering, Institute of Environmental Engineering, Faculty of Civil Engineering, Technical University of Košice, Vysokoškolská 4, 04200 Košice, Slovakia, e-mail: eva.kridlova.burdova@tuke.sk.

Jaroslav Varga is with IZOLA, s.r.o., Textilná 8, 04012 Košice, Slovakia, e-mail: jaroslavvarga@izola.sk.

Patrícia Rošková is with IZOLA, s.r.o., Textilná 8, 04012 Košice, Slovakia, e-mail: roskova@izola.sk

I. INTRODUCTION

Over the past few years, energy is among the principal factors of the social and economic development of our society, dealing with important issues, such as politics and the environment [1]. An increasing interest in many aspects related to buildings energy efficiency has led to a growing amount of research and studies. Some of these aim at investigating the economic and financial feasibility of energy efficiency measures currently applied in the building sector, as well as deepening to what extent the energy performance of buildings could be able to affect the market price or the rent of real estate units [2]. A growing European literature examining the price-premium for energy efficient durables that can assist the design of EU energy and climate policies is presented in work [3]. This study shows that Europe moves towards nearly zero energy buildings and energy performance certificate ratings. It can play a relevant role in encouraging property developers and the rest of the market to move in this direction. Other study [4] examines what nearly zero-energy terms can be expected to be adopted in Belgium and the Netherlands. In search of defining nearly zero-energy dwellings, international researchers are currently proposing prominence of the terms "net zero energy" in addition to "low energy" and "passive house". Study shows that although definitions can have a different meaning in different regions and are integrated internationally, a few countries have already adopted definitions in their building or policies. Study [5] deals with correlations between the actual energy consumption for water and space heating and the thermal properties of the building. In this study the statistically significant differences were found for different types of ventilation systems. The differences in energy consumption for different ventilation types were very small. These results indicate that thermal characteristics have a greater effect than the type of ventilation system efficiency on energy consumption. Another study [6] calculates energy performance of different cases of activated heated area for the sample building and reflects importance of various design measures, mainly surface to volume ratio and ratio of thermal envelope area to external conditions. There is emphasized that inclusion of attic space in scenarios which is being resulted in lowering surface to volume ratio, and improving energy performance, but had greater effect on overall energy savings in the case with a more balanced ratio between area of thermal envelope to external conditions. According to study [7] an individual home orientation has minimal cost implications, where as the aggregated suburban community house orientation has more significant total annual energy costs. Results show that many existing homes in the analysis oriented east and west (75–90°C) have a negative impact on their energy performance. The number of houses oriented towards south represents the largest percentage of the total; however the majority of homes fall outside of optimal orientation. Therefore the planning and design of a community should benefit from understanding the whole picture of energy performance and costs through the optimal orientation of homes. A study [8] reveals the relationship between size, orientation and glazing properties of façade windows for different side-lit room geometries in Danish "nearly zero-energy" houses. As a result, glazing-to-floor ratios for providing enough day-lighting were found to be the same for both north and south-oriented rooms. However, due to prevention of overheating in south-oriented rooms, more flexibility with regard to the choice of window size and geometries was found for north-oriented rooms than for south-oriented rooms. According to study [9] air conditioning is one of the main energy consumers and developing ways to reduce dependence on air conditioning is of utmost importance to achieve low-energy architecture. Paper [10] demonstrates that a combination of active cooling systems and natural passive ventilation solutions has the potential to deliver an improved result in terms of reducing temperature levels as well as cooling loads. Another study [11] deals with the optimum thickness of adding insulation. Results indicate that adding insulation is not always beneficial, and thus in particular in the regions of Mediterranean climate as susceptible to anti-insulation behavior, an analysis and exploration of the optimum insulation level for the particular building and use is recommended. Results reveals that buildings in a predominantly cooling environment but within a certain range of heating degree days (HDD) will display this behavior: with very few to no HDD, the building's energy consumption becomes insensitive to insulation increase (Dubai case); with a low number of HDDs the building becomes sensitive to anti-insulation (Malaga), and once a threshold is passed (El Dorado), the building's energy consumption decreases with increased insulation. Study [12] addresses not only the primary energy of houses but also the indoor environmental quality. Primary energy demand and primary energy use was determined in five low-energy houses and five older conventional houses. Concurrently researchers interviewed the occupants and evaluated their perceived environment quality with a questionnaire survey. Results show that the perceived indoor environment quality was slightly better in the low-energy houses than in the conventional houses. Another questionnaire survey focused on satisfaction with indoor climate parameters (temperature, draught, air quality, noise, daylight, technical installations) conducted in 2013 among owner of new Danish low-energy houses showed satisfaction with living in this type of house [13]. Previous study conducted in 2011 was not as optimistic. Occupants experienced noise from the technical installations and that it was too cold in winter and too hot in summer. This implies that indoor environmental quality was improved in this type of households in view of its users due to the fact that methods of design as well as construction technology of low-energy houses have moved forward in recent years [14]. The study of Wallner et al. showed that indoor air quality in energy-efficient new houses was better than in conventional new buildings. Investigated parameters were TVOC, aldehydes, CO_2, radon and mould spores in the living rooms and bedrooms in 62 highly energy-efficient (with mechanical ventilation) and 61 conventional buildings (without mechanical ventilation) in Austria [15]. Research performed in 10 Danish Passive Houses also showed good results in relation to relative humidity and CO_2 levels [16]. Study [17] indicates that energy efficiency measures resulted in improved thermal comfort, enhanced health and safety and reduced energy costs. However, study [18] states that zero energy house would require an additional 8.9% of the construction cost and the payback period is approximately 10 years. Another study [19] deals with economic viability of the refurbishment on an old single family house towards a nearly zero energy building. The results indicate that it is financially viable, with a payback period of 8 years. A plus-energy, single family house was under the investigation in study [20]. There was observed that the operation of the heating and cooling system during the transition periods was problematic and it affected the thermal comfort significantly. This study also show that cooling demand of the house was high due to the large glazing façades and the lack of thermal mass in order to buffer the sudden thermal loads.

This paper evaluates ultra-low-energy house designed and built in Košice, Slovakia. Significance of the case study has been discussed from energy performance and indoor environmental quality.

II. MATERIALS AND METHODS

The research object is the family house situated in the town of Košice, Slovakia. The aim of the research is investigation of energy aspects for building constructions in terms of 2010/31/EU on energy efficiency known as “20-20-20” as well as indoor environmental quality.

When designing the house, great importance on constructions of building envelope and critical details was attributed. The whole concept of this family house was done according to requirements for energy efficient buildings. During the construction process, detailed supervision focused on constructions and building physics was conducted with emphasis on eliminating linear thermal bridges and minimizing future energy performance of house. To achieve status of the ultra-low-energy house, many factors have to be implemented such as: maximum solar gains, “great” insulation, thermal mass (with good thermal capacity, air tightness and mechanical ventilation with heat recovery systems. Description of investigated family house, its site and methods of research works are presented in the following subchapters.

A. Locality and climate

House that is being evaluated is located in Košice, Slovak Republic. City of Košice lies at an altitude of 206 meters above sea level and covers an area of 242.77 square kilometers. It is located in eastern Slovakia, about 20 kilometers from the Hungarian borders, 80 kilometers from the Ukrainian borders, and 90 kilometers from the Polish borders (Fig. 1). It is about 400 kilometers east of Slovakia's capital Bratislava. Košice city is situated on the Hornád River in the Košice Basin, at the easternmost reaches of the Slovak Ore Mountains. More precisely it is a subdivision of the Čierna hora Mountains in the northwest and Volovské vrchy Mountains in the southwest. The basin is met on the east by the Slanské vrchy Mountains [21].

Fig. 1. Location of Kosice [22]

Košice lies in the North Temperate Zone and has a borderline continental and marine climate with four distinct seasons. If defined as marine due to the winters just above −3°C (27°F), it would be one of the farthest inland areas with this climate type. It is characterized by a significant variation between hot summers and cold, snowy winters [21]. Weather data for years of 2013 and 2014 are introduced in Fig. 2.

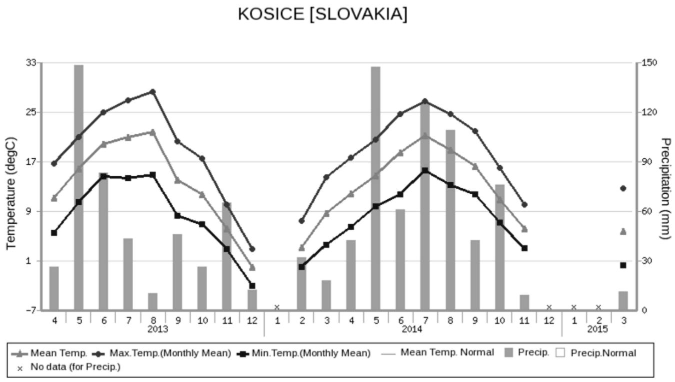


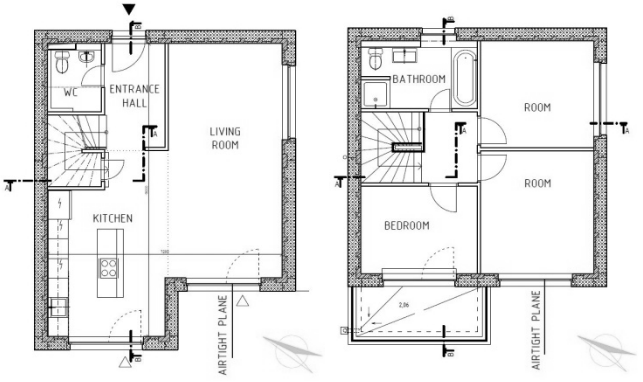
Fig. 2. Weather data in 2013 and 2014 [23]

B. Family house introduction

Family house, constructed in Košice, part of Košice - Krásna (Fig. 3) is placed by the Hornád River (approximately 30 meters), in the flood zone of this river. The risk of flood at this side of the river is minimal since the other side´s altitude is lower, thus in case of water level rise, naturally, Hornár River would flood the other side.

Fig. 3. House location – satellite view (Google Earth)

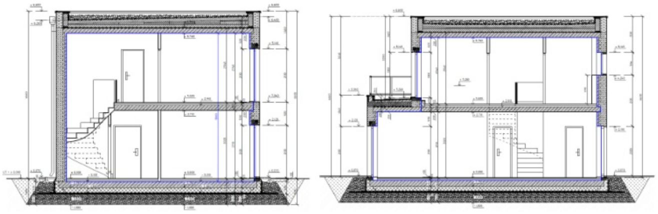
Fig. 4 illustrates ground and first floor disposition.



a) Ground floor b) First floor

Fig. 4. Floor plan

Ground floor consists of entrance hall, toilet with heat recovery compact unit, staircase, and kitchen, visually integrated to living room. Both kitchen and living room have access to summer terrace and to the rest of estate. First floor consists of three rooms out of which one is bedroom (with possibility to step out on the terrace) and two rooms for children. There is also bathroom and small staircase space used for entering individual rooms or bathroom.
Cross sections are illustrated in Fig. 5.



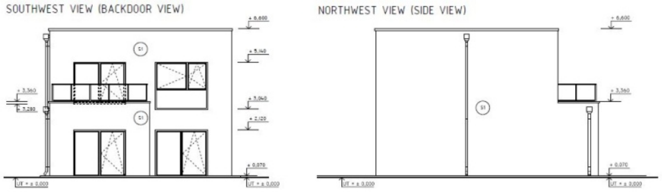
a) A-A b) B-B

Fig. 5. Cross-section

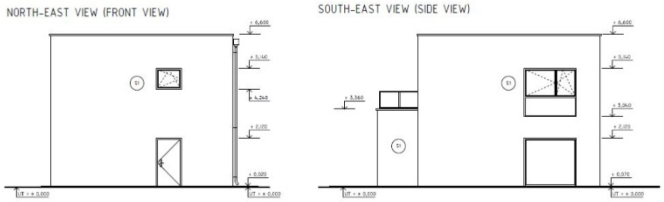
Cross-section of A-A cuts through staircase on the left and "zig-zag" runs through children room oriented south-east with large triple glazed window do maximize solar gains. At the same time, external blinds are installed to protect the indoor environment against overheating in summer time.

Cross-section B-B is a direct cut through entrance hall staircase space and kitchen on the ground floor and bathroom, staircase hall and bedroom with terrace view on the backyard.

Solar gain is the most fundamental factor of the ultra-low-energy building principle. Rightly oriented exterior walls with triple-glazed windows are essential to maximize winter solar gains. On the other hand, proper shading elements should be used to regulate overheating of indoor environment. The biggest part of façade should be oriented south with generous glazing. On contrary, north side should have “minimalistic” design with as many glazed areas as possible. In Fig. 6 can be seen schematic illustration of views of evaluated family house. As shown in Fig. 6 the house was designed to maximize solar gains through southwest and southeast façade. No, or very little glazed areas can be observed on "cold" parts of exterior walls facing northeast and northwest.



a) Southwest façade b) Northwest façade



c) Northeast façade d) Southeast façade

Fig. 6 Views

Equal in importance to solar gains of building is proper insulation. Whether thermal insulations is sufficient or not, can be calculated using heat transfer coefficient "U" (W/m^2.K).

Composition of external wall

Evaluated ultra-low-energy house has its building envelope constructed using ECOB panels with flat roof system. In cross-section the panels are “puzzle-like” to achieve better connection between individual panels. Fig. 7 shows schematic illustration of external wall composition and Fig. 8 shows scheme of cut A and B assigned in Fig. 7.

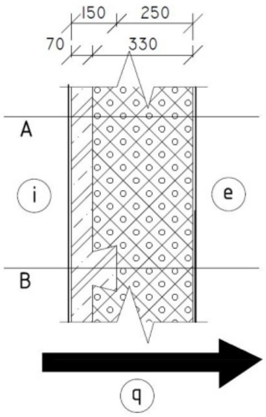
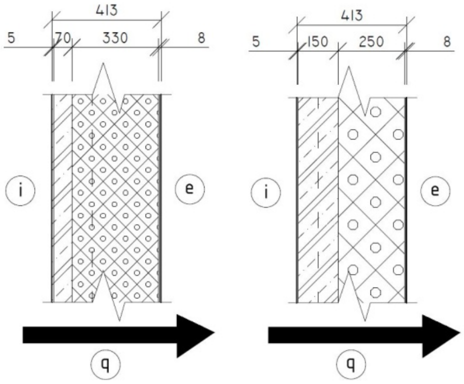


Fig. 7 External wall scheme made of ECOB panels



a) cut A b) cut B

Fig. 8 Schemes of cut A and B of external wall composition

Tables I and II describe thermo-physical parameters for external wall compositions:

d thickness [m]

λ thermal conductivity coefficient [W/(m.K)]

c specific heat capacity [J/(kg.K)]

ρ density [kg/m^3]

m area weight [kg/m^2]

Table I. Thermo-physical parameters for material composition of external wall - cut A

	d [m]	**λ [W/m.K]**	**c [J/kg.K]**	**ρ [kg/m^3]**	**m [kg/m^2]**
Gypsum plaster	0.005	0.570	1000.0	1300.0	10.0
RFC	0.070	1.580	1020.0	2400.0	29.0
Neopor insulation	0.330	0.031	1250.0	18.0	45.0
Adhesive mortar	0.005	0.800	920.0	1300.0	18.0
Silicon render	0.003	0.700	920.0	1700.0	37.0

Table II. Thermo-physical parameters for material composition of external wall - cut B

	d [m]	**λ [W/m.K]**	**c [J/kg.K]**	**ρ [kg/m^3]**	**m [kg/m^2]**
Gypsum plaster	0.005	0.570	1000.0	1300.0	10.0
RFC	0.150	1.580	1020.0	2400.0	29.0
Neopor insulation	0.250	0.031	1250.0	18.0	45.0
Adhesive mortar	0.005	0.800	920.0	1300.0	18.0
Silicon render	0.003	0.700	920.0	1700.0	37.0

Composition of floor on the ground and roof construction

Fig. 9 and 10 show schematic illustration of floor on the ground composition and roof composition.

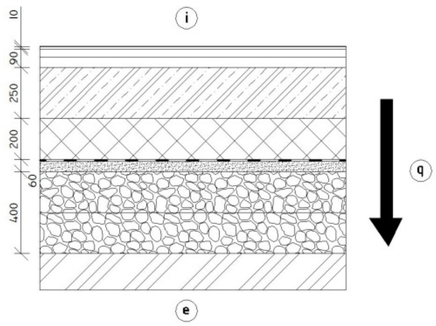


Fig. 9. Floor on the ground

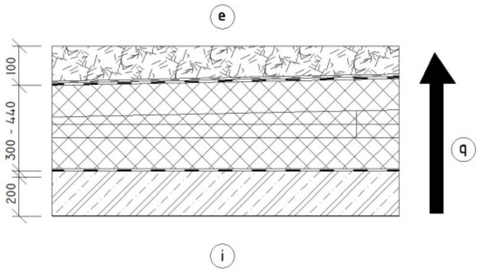


Fig. 10. Roof composition

Tables III and IV describe thermo-physical parameters for floor on the ground composition and roof composition.

Table III. Thermo-physical parameters for material composition of floor on the ground

	d [m]	**λ [W/m.K]**	**c [J/kg.K]**	**ρ [kg/m^3]**	**m [kg/m^2]**
Ceramic tiles	0.010	1.010	840.0	2000.0	200.0
Concrete	0.090	1.300	1020.0	2200.0	20.0
RFC slab	0.250	1.580	1020.0	2400.0	27.0
EPS NEO	0.200	0.031	1250.0	18.0	45.0
Stud membrane	0.0005	0.140	1100.0	1200.0	50000
Sand layer	0.050	0.950	960.0	1750.0	4
Gravel	0.400	0.650	800.0	1650.0	15

*RFC - reinforced concrete slab

Table IV. Thermo-physical parameters for material composition of roof construction

	d [m]	**λ [W/m.K]**	**c [J/kg.K]**	**ρ [kg/m^3]**	**m [kg/m^2]**
Gypsum plaster	0.005	0.570	1000	1300	10.0
RFC	0.200	1.580	1020	2400	29.0
Vapor barrier	0.004	0.170	1470	1300	375000
EPS Stabil150	0.300	0.039	1250	19.0	40.0
Water-proofing	0.0015	0.350	1470	1313	24000
Gravel	0.100	0.650	800	1650	15.0

*RFC - reinforced concrete slab

All family house openings such as windows, entrance door and doors to backyard at ground floor with “balcony door” at the first floor, were designed according to STN EN 73 0540 – 2:2012. Windows are used as triple-glazed window with 7-chambers frame SCHÜCO ALU INSIDE. Entrance door is used as SCHÜCO ADS 112.IC.

HVAC systems

All HVAC systems are being secured by one compact unit NILAN Compact K. Heating is provided by floor heating system. First floor is being heated by ceiling infrared panels. These panels are made from matt white carbon fiber with an aluminum frame, the simple design blends well on most ceilings or can also be fitted high on the wall like a picture. Panels have a long 3 meters flex which we recommend is wired to a programmer or thermostat by an electrician [24]. Ground and first floor are being air-cooled by ventilation system connected to heat recovery unit of energy source NILAN Compact K. Heat pump based on air-water principle, part of NILAN Compact K. Forced ventilation in installed to the whole house securing optimum and healthy indoor environment connected on heat recovery unit.

C. Methods of determination of energy aspects

Thermo-physical parameters were calculated according to STN EN 730540: 2012 for following climatic conditions [25]:
outdoor air temperature θe = -13°C;
indoor air temperature θi = 21°C;
relative humidity outdoors Rhe = 84%;
relative humidity indoors Rhi = 55%.
For determination of heat transfer coefficient and temperature distribution were used software AREA 2010 and TEPLO 2010 from the Svoboda Software package.

D. Methods of measurement the indoor environmental factors

Indoor air temperature (θ_a), relative humidity (RH) and carbon dioxide concentrations were measured using a multifunctional measuring instrument TESTO 435-4 with the IAQ probe. Measuring range and accuracy for temperature is from 0 to 50°C, ±0.3°C; for relative humidity from 0 to 100% RH, ±2% RH; and for carbon dioxide concentrations from 0 to 10,000 ppm, ± (75 ppm ±3 % of remaining measurement value) (+1 to +5000 ppm), ±(150 ppm ±5 % of remaining measurement value) (+5001 to +10000 ppm). The concentrations of particulate matter ($PM_{0.5}$-$PM_{10.0}$ as well as total PM) were determined continuously at five places in the room (in the middle of the room and in the four corners) using HANDHELD 3016 IAQ. The concentrations of TVOC were measured with ppbRAE 3000 – photoionization detector with UV lamp. Measuring range for this device is from 1 ppb to 10,000 ppm and specified accuracy is ±3% (from 10 to 2000 ppm). The Vernon-Jokl globe thermometer was used for measurement of mean radiant temperature. Measuring devices (except HANDHELD 3016 IAQ) were placed approximately in the center of the studied room in the height of 1.1 m above the floor. Measurement lasted 1 hour and 30 minutes and three persons were present in the studied room during it. Doors and windows were closed throughout measurement, but air handling unit was turned on.

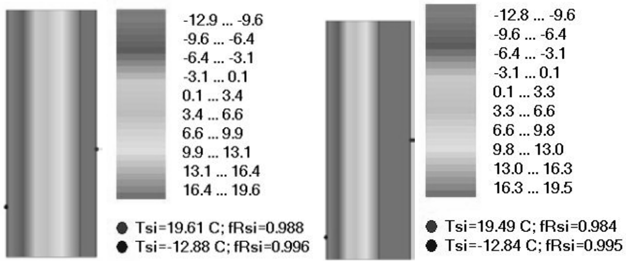
III. RESULTS AND DISCUSSION

In Table V are presented values of heat transfer coefficient U for all constructions of building envelope and compared with recommended values for ultra-low energy buildings according to STN EN 730540: 2012.

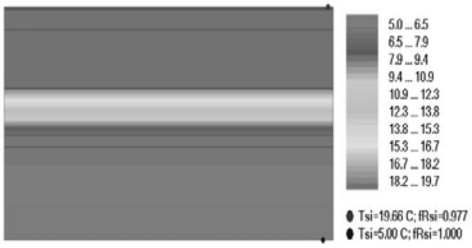
Table V. Heat transfer coefficient Thermo-physical parameters for material composition of roof construction

	Calculated U [W/m^2.K]	**Recommended U** [W/m^2.K] valid	
		31.12.2020	01.01.2021
External wall - cut A	0.089	0.22	0.15
External wall - cut B	0.12	0.22	0.15
Roof	0.123	0.10	0.10
Window	0.66	1.00	0.60
Door	0.1	0.1	
	Calculated R [m^2.K/W]	**Recommended R** [m^2.K/W]	
Floor on the ground	7.98	2.50	2.50

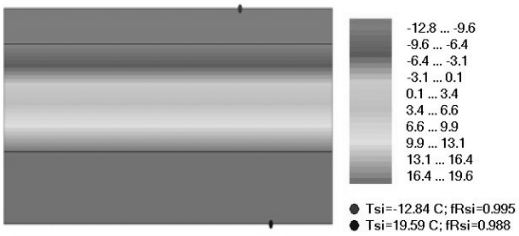
Fig. 11 illustrates temperature distribution in constructions of building envelope.



a) external wall - cut A b) external wall - cut B



c) Floor on the ground



d) Roof construction

Fig. 11. Temperature distribution

As it can be observed from Fig. 11, temperature distribution shows correctness in design of external wall and floor on the ground. But temperature distribution shows some incorrectness in design of roof construction. It can be explained by the fact that the family house was designed and built before 1st of January 2016, by the time of design, mentioned standard was strictly followed.

Primary energy demand in assessed family house according to PHPP software calculations is 53 kWh/m^2.a. Regulation No. 364/2012 sets criteria on building energy ratings constructed in nowadays standards as "A1" category for primary energy use. Evaluated family house fulfills "A0" category, thus this house can be considered as ultra-low-energy house. Study [12] shows primary energy demand determined in five low-energy houses (built 2009-2012) and five older conventional houses (1974-2011). In this study the average calculated primary energy demand was 120 kWh/m^2.a (85-136 kWh/m^2.a) in the low-energy houses and 323 kWh/m^2.a (203-577 kWh/m^2.a) in the conventional houses. The average purchased primary energy use was 125 kWh/m^2.a (88-177 kWh/m^2.a) in the low energy houses and 220 kWh/m^2.a (155-277 kWh/m^2.a) in the conventional houses. In comparison to our research, study [12] shows considerably higher demand for primary energy. It is possible to say that key differences are in architectural design (A/V ratio, proper insulated building envelope, proper openings) as well as used renewable energy sources (heat pump and heat recovery system).

Results from measurement of indoor environmental quality factors are shown in Table VI.

Table VI. Measured indoor environmental quality factors

	Mean	**Min.**	**Max.**	**S.D.**
θ_a [°C]	18.77	18.30	19.30	0.29
RH [%]	43.72	42.5	44.4	0.48
CO_2 [ppm]	576.54	506.00	643.00	42.41
TVOC [µg/m^3]	214.36	97.00	277.00	54.50
$PM_{0.5}$ [µg/m^3]	9.35	7.78	11.02	0.89
$PM_{1.0}$ [µg/m^3]	12.77	10.42	15.20	1.31
$PM_{2.5}$ [µg/m^3]	13.58	11.18	16.09	1.30
$PM_{5.0}$ [µg/m^3]	17.37	15.72	19.34	0.92
$PM_{10.0}$ [µg/m^3]	26.30	19.75	41.50	3.93
Total PM [µg/m^3]	33.29	23.39	70.60	7.85

Operative temperature was calculated according to EN ISO 7726 and this value was 18.4°C. Optimum level of operative temperature for cold part of year is in the range from 22 to 26°C and permissible level from 20 to 27°C according to Decree of the Ministry of Health of the Slovak Republic No. 259/2008 Coll. Therefore, determined operative temperature in the house was about 8% lower than permissible operative temperature for this type of room but this can be explained by that the house was not occupied during measurement. Study [12] in which performed subjective perception of indoor air quality shows that occupants perceived less high room temperature, as well as insufficient ventilation and dim light in the low-energy houses compared with the conventional houses in the winter and summer. Too high and varying room temperature were the most commonly reported unsatisfactory indoor environment factors in both the low-energy and conventional houses in the winter and summer.

The concentrations of CO_2 ranged from 506 to 643 ppm, but as was mentioned above the house was not occupied. Therefore the levels of CO_2 concentrations depended on the presence of three persons. Measurement of CO_2 concentrations were also performed in study [15]. In this study were confirmed higher concentrations, i.e. median of CO_2 concentrations was 1360 ppm in energy-efficient houses and 1830 ppm in conventional houses. Another research carried out in 10 Danish Passive Houses showed good results in relation to CO_2 levels and relative humidity [16].

Mean concentration of TVOC was 214.36 µg/m^3. Recommended value for TVOC concentrations is 200 µg/m^3 according to Mølhave. Measured concentration was about 6.7% higher than this recommended value but selected house is new-built. Generally it is well known that concentrations of organic compounds in new-built houses are usually much higher. In the study of Hodgson et al., the GM concentrations of TVOC in the new manufactured and site-built conventional houses were 1.5 and 2.7 mg/m^3, respectively [26]. In another study median of TVOC concentration was 300 µg/m^3 in energy-efficient houses and 560 µg/m^3 in conventional houses.

Fig. 12 shows the dynamic changes of PM concentrations during measurement. As can be seen, concentrations fluctuated throughout measurement. Fig. 13 and 14 show the dynamic changes of temperature and RH, as well as concentrations of CO_2 and TVOC. Temperature had increasing tendency with the time in contrast with decreasing tendency of relative humidity. Concentrations of CO_2 and TVOC also had increasing tendency with time.

Correlation analysis performed using STATISTICA software (Table VII) revealed that according to Cohen almost perfect negative correlations were between concentrations of TVOC and $PM_{0.5}$, $PM_{1.0}$, $PM_{2.5;}$ between concentrations of CO_2 and $PM_{0.5}$, $PM_{1.0}$, $PM_{2.5;}$ and between concentrations of $PM_{0.5}$, $PM_{1.0}$, $PM_{2.5}$ and temperature. Very large negative correlations were between concentrations of $PM_{5.0}$ and TVOC, CO_2 and temperature. On the other hand concentrations of TVOC almost perfect positively correlated with CO_2 and temperature, as well as concentrations of CO_2 with temperature. High positive correlation was revealed between RH and concentrations of $PM_{0.5}$, $PM_{1.0}$, $PM_{2.5}$, and high negative correlation was found between RH and CO_2. The most interesting relationships are shown in Fig. 15 - 25.

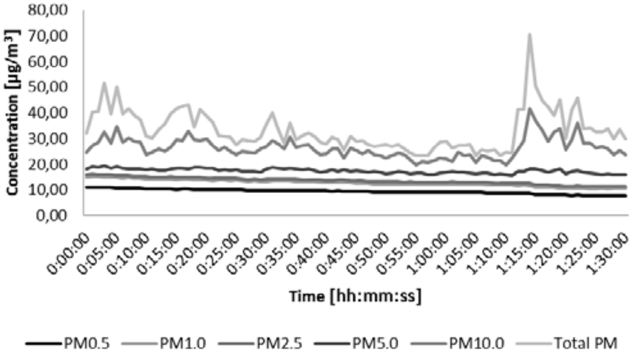


Fig. 12 PM concentrations for measured fractions

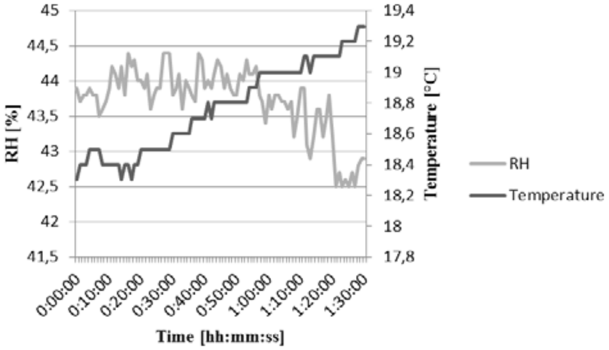


Fig. 13 Indoor air temperature and relative humidity

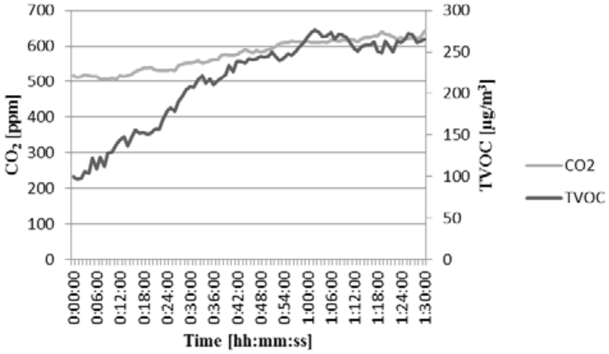


Fig. 14 Concentrations of carbon dioxide and total volatile organic compounds

Table. VII Correlation matrix – level of significance $p<0.05000$

	$PM_{0.5}$	$PM_{1.0}$	$PM_{2.5}$	$PM_{5.0}$	$PM_{10.0}$	TVOC	CO_2	T	RH
$PM_{0.5}$	1,00	**1,00**	**1,00**	**0,72**	0,08	**-0,89**	**-0,95**	**-0,95**	**0,65**
$PM_{1.0}$	**1,00**	1,00	**1,00**	**0,72**	0,07	**-0,89**	**-0,94**	**-0,95**	**0,65**
$PM_{2.5}$	**1,00**	**1,00**	1,00	**0,74**	0,10	**-0,90**	**-0,95**	**-0,95**	**0,64**
$PM_{5.0}$	**0,72**	**0,72**	**0,74**	1,00	**0,64**	**-0,77**	**-0,74**	**-0,73**	**0,33**
$PM_{10.0}$	0,08	0,07	0,10	**0,64**	1,00	**-0,30**	-0,17	-0,13	-0,19
TVOC	**-0,89**	**-0,89**	**-0,90**	**-0,77**	**-0,30**	1,00	**0,94**	**0,89**	**-0,39**
CO_2	**-0,95**	**-0,94**	**-0,95**	**-0,74**	-0,17	**0,94**	1,00	**0,96**	**-0,51**
T	**-0,95**	**-0,95**	**-0,95**	**-0,73**	-0,13	**0,89**	**0,96**	1,00	**-0,66**
RH	**0,65**	**0,65**	**0,64**	**0,33**	-0,19	**-0,39**	**-0,51**	**-0,66**	1,00

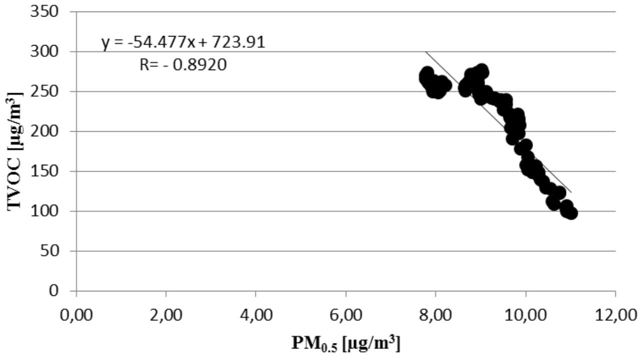


Fig. 15 Corelation between $PM_{0.5}$ and TVOC

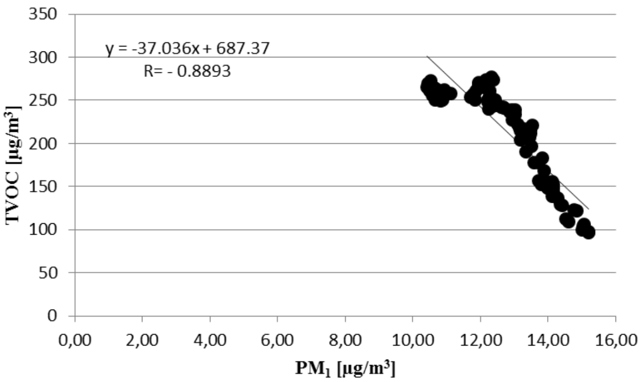


Fig. 16 Corelation between $PM_{1.0}$ and TVOC

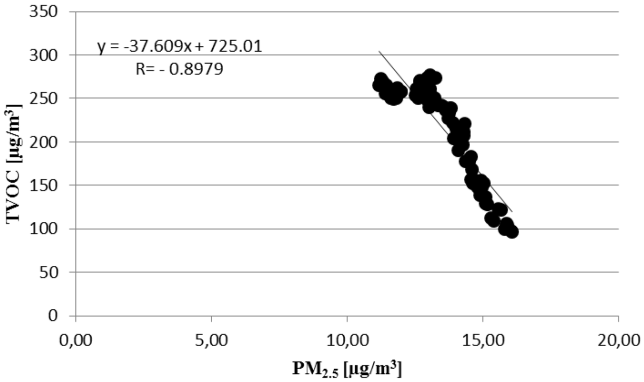


Fig. 17 Corelation between $PM_{2.5}$ and TVOC

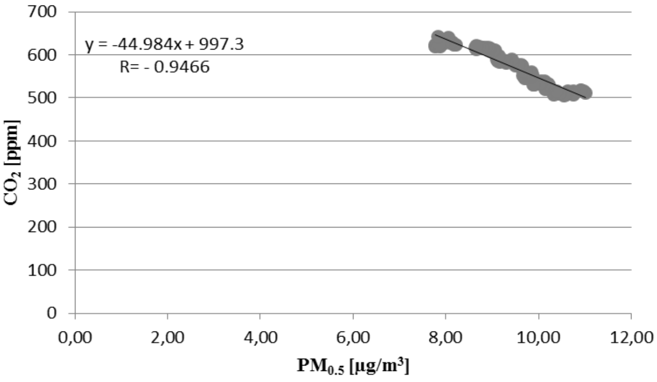


Fig. 18 Corelation between $PM_{0.5}$ and CO_2

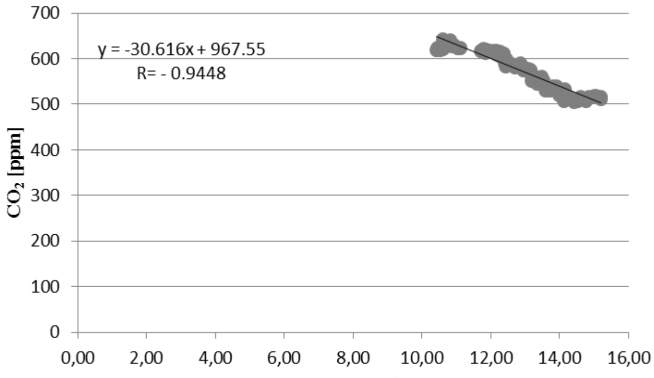


Fig. 19 Corelation between $PM_{1.0}$ and CO_2

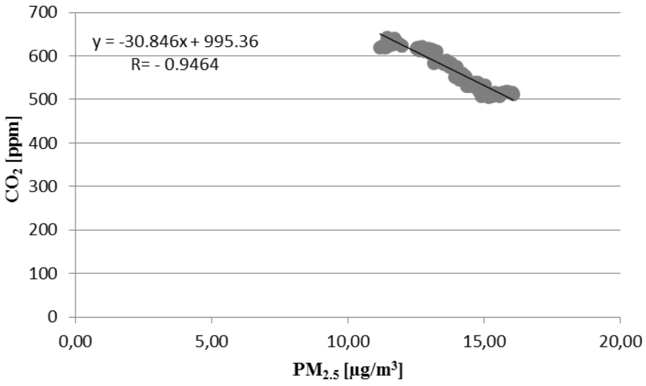


Fig. 20 Corelation between $PM_{2.5}$ and CO_2

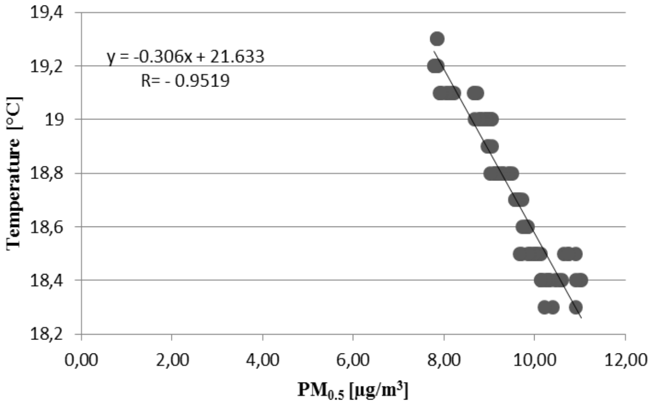


Fig. 21 Corelation between $PM_{0.5}$ and temperature

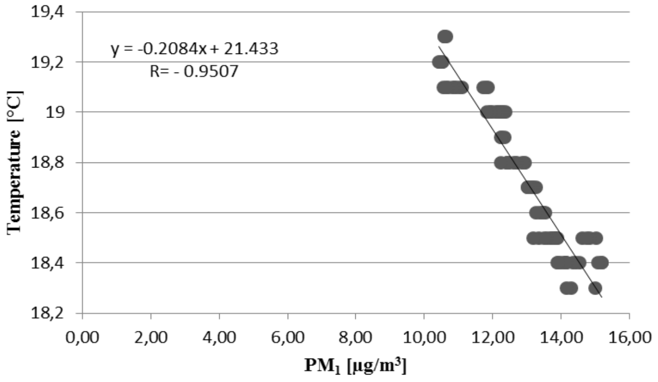


Fig. 22 Corelation between $PM_{1.5}$ and temperature

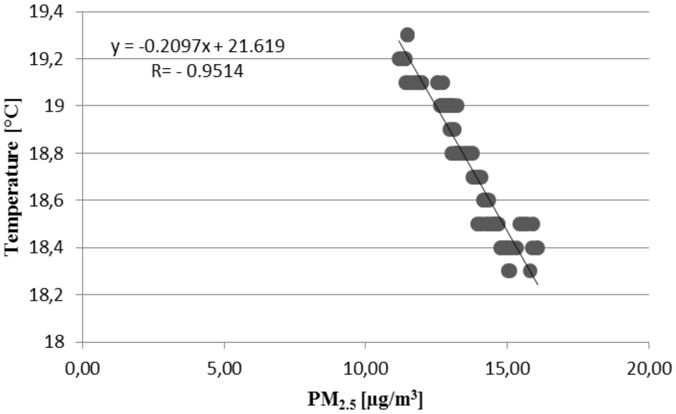


Fig. 23 Corelation between $PM_{2.5}$ and temperature

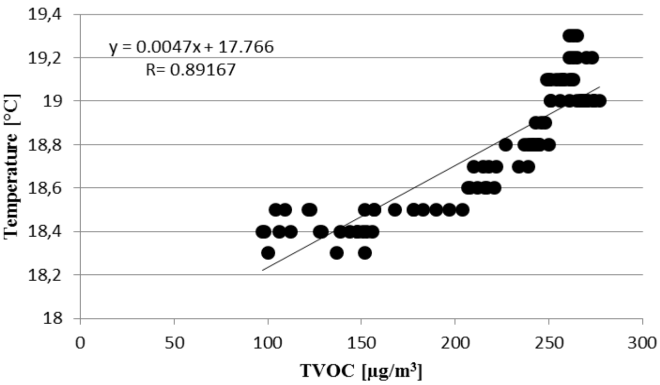


Fig. 24 Corelation between TVOC and temperature

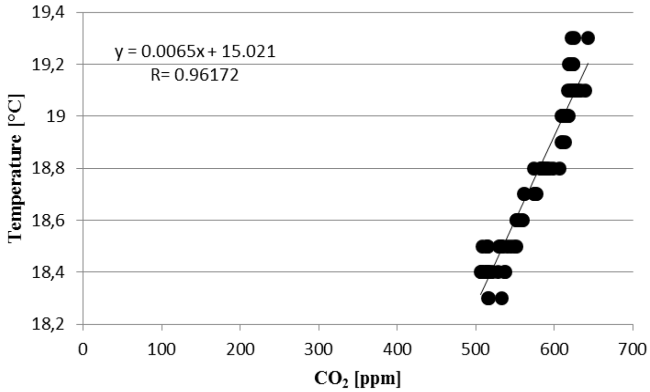


Fig. 25 Corelation between CO_2 and temperature

High correlations between the CO_2 concentrations and $PM_{2.5}$ and PM_{10} were detected in two schools in non-heating period in the study of Lazović et al. [27]. The team of these authors also revealed correlation between CO_2 concentrations with relative humidity and indoor air temperature in their another study [28]. A significant negative correlation between humidity and $PM_{2.5}$ concentration in winter and significant positive correlation in summer was found in research performed in 64 schools in Germany [29]. As was mentioned above we also revealed high positive correlation between these parameters in our study. A significant positive correlation between indoor temperature and PM_{10} together with correlation of CO_2 and PM_{10} was also found in the study of Alshitawi et al. [30]. It is well known that VOC emissions from building materials are effected by humidity, temperature, air change rate or surface air velocity [31]. In our study the correlation between TVOC and temperature was also confirmed. Further the relationship between concentrations of TVOC and CO_2 was also found in nail salons in Boston [32].

IV. CONCLUSION

Family house, designed and constructed in Košice, Slovakia was studied from energy performance and indoor environmental quality. The objective of this case study was to analyze whether the criteria for ultra-low-energy class were fulfilled. Concurrently the quality of indoor environment was investigated by measuring the physical and chemical factors often occurred in indoor air as well as the relationship between them. According to PHPP software the primary energy demand in evaluated family house achieved value of 53 kWh/m^2.a. Thus this house fulfills "A0" category and can be considered as ultra-low-energy house. Results from measuring the physical and chemical factors were compared with permissible values given by Decree of the Ministry of Health of the Slovak Republic No. 259/2008 Coll. Results show that:

- operative temperature of 18.4°C was about 8% under permissible range of values (20 - 27°C for cold period);
- mean relative humidity of 43.72% was in optimum range (40% - 60%);
- mean CO_2 concentration of 1037.77 mg/m^3 is under the recommended value of 1370 mg/m^3 according to WHO;
- mean TVOC concentration of 214.36 $µg/m^3$ is above the recommended value of 200 $µg/m^3$ according to Mølhave;
- mean PM_{10} concentration of 26.30 $µg/m^3$ is under the limit value of 50 $µg/m^3$.

Correlation analysis performed using Statistica software revealed relationship between measured factors.

I can be say that all the issues evaluated in this study are necessary to implement in daily building design in order to provide sustainability of construction process at high level with minimum emissions and low energy consumption.

Our future work will be aimed at the investigation of significant set of low energy buildings to point out the level of indoor environmental quality by objective monitoring as well as sensational perception of occupants.

REFERENCES

[1] V. Belpoliti, G. Bizzarri, “A parametric method to assess the energy performance of the social housing stock and simulate suitable retrofit scenarios: An Italian case study, ” *Energ. Buildings*, vol. 96, pp. 261–271, 2015

[2] S. Copiello, “Achieving affordable housing through energy efficiency strategy, ” *Energ. Policy*, vol. 85, pp. 288–298, 2015

[3] A. de Ayala, I. Galarraga, J. V. Spadaro, “The price of energy efficiency in the Spanish housing market, ” *Energ. Policy*, vol. 94, pp. 16–24, 2016

[4] E. Mlecnik, “Defining nearly zero-energy housing in Belgium and the Netherlands, ” *Energ Effic*, vol. 5, pp. 411–431, DOI 10.1007/s12053-011-9138-2, 2012

[5] O. Guerra-Santin, L. Itard, “The effect of energy performance regulations on energy consumption, ” *Energ. Effic*, vol. 5, pp. 269–282, February 2012

[6] N. Cukovic Ignjatovic, D. Ignjatovic, B. Stankovic, “Possibilities for energy rehabilitation of typical single family house in Belgrade - Case study,” *Energ. Buildings*, vol. 115, pp. 154–162, 2016

[7] T. L. Hemsath, “Housing orientation’s effect on energy use in suburban developments, ” *Energ. Buildings*, vol. 122, pp. 98–106, 2016

[8] L. Vanhoutteghem, G. C. Jensen Skarning, C. A. Hviid, S. Svendsen, “Impact of fac¸ade window design on energy, daylighting and thermal comfort in nearly zero-energy houses, ” *Energy and Buildings*, vol. 102, pp. 149–156, 2015

[9] H. M. Taleb, “Natural ventilation as energy efficient solution for achieving low-energy houses in Dubai,” *Energ. Buildings*, vol. 99, pp. 284–291, 2015

[10] H. M. Taleb, “Natural ventilation as energy efficient solution for achieving low-energy houses in Dubai,” *Energ. Buildings*, vol. 99, pp. 284–291, April 2015

[11] W. A. Friess, K. Rakhshan, M. P. Davis, “A global survey of adverse energetic effects of increased wall insulation in office buildings: degree day and climate zone indicators, ” *Energ. Effic.*, April 2016

[12] R. Holopainen, K. Salmi, E. Kähkönen, P. Pasanen, K. Reijula, “Primary energy performance and perceived indoor environment quality in Finnish low-energy and conventional houses,” *Build. Environ.*, vol. 87, pp. 92-101, 2015

[13] H. N. Knudsen, L.H. Mortensen, and J. Kragh, "Satisfaction with indoor climate in new Danish low-energy houses," in *Proc. 7. Passivhus Norden, Sustainable Cities and Buildings*, Copenhagen, 20-21 August, 2015, pp. 1–10.

[14] H. N. Knudsen, K.E. Thomsen, and O. Mørck, "Occupant Experiences and Satisfaction with New Low-Energy Houses" in *Proc. CLIMA 2013*, Prague, 16-19 Jun, 2013, pp. 1-11.

[15] P. Wallner, U. Munoz, P. Tappler, A. Wanka, M. Kundi, J.F. Shelton, and H.P. Hutter, "Indoor Environmental Quality in Mechanically Ventilated Energy-Efficient Buildings vs. Conventional Buildings," *Int. J. Environ. Res. Public Health*, vol. 12, pp. 14132-14147, Nov. 2015.

[16] T. S. Larsen, and R. L. Jensen, "Measurements of Energy Performance and Indoor Environmental Quality in 10 Danish Passive Houses: a case study," in *Proc. Healthy Buildings 2009: 9th International Conference & Exhibition*, Syracuse, NY USA, 13-17 September, 2009, pp. 1-4.

[17] D. Hernández, D. Phillips, "Benefit or burden? Perceptions of energy efficiency efforts among low-income housing residents in New York City," *Energy Research & Social Science*, vol. 8, pp. 52–59, May 2015

[18] Y. Kwan, L. Guana, "Design a Zero Energy House in Brisbane, Australia," *Procedia Engineering*, vol. 121, pp. 604 – 611, 2015

[19] D. K. Serghides, S. Dimitriou, M. C. Katafygiotou & M. Michaelidou, "Energy efficient refurbishment towards nearly zero energy houses, for the mediterranean region," *Energy Procedia*, vol. 83, pp. 533 – 543, 2015

[20] O. B. Kazanci, B. W. Olesen, "Thermal indoor environment and energy consumption in a plus-energy house: cooling season measurements," *Energy Procedia*, vol. 78, pp. 2965 – 2970, 2015

[21] Available: https://en.wikipedia.org/wiki/Ko%C5%A1ice

[22] Available: http://vignette2.wikia.nocookie.net/ovsc/images/c/c3/Map-slovakia-kosice.gif/revision/latest?cb=20121006082147

[23] Available: http://ds.data.jma.go.jp/gmd/tcc/tcc/products/climate/climatview/graph_mkimg.php?n=11968&y=2015&m=3&p=24

[24] Available: http://www.multiheat-energysystems.co.uk/infrared-heating-panels/standard-white-panels

[25] STN EN 730540, Thermal performance of buildings and components, Thermal protection of buildings.

[26] A. Rudd, A.T. Hodgson, D. Beal, and S. Chandra. (2008). Volatile Organic Compound Concentrations and Emission Rates in New Manufactured and Site-Built Houses. [Research Report]. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/voc_emissions_new_houses.pdf

[27] I. Lazović, M. Jovašević-Stojanović, M. Živković, V. Tasić, and Ž. Stevanović, "PM and CO_2 variability and relationship in different school environments," *Chem. Ind. Chem. Eng*. Q., vol. 21, pp. 179-187, 2015.

[28] I.M. Lazović, Ž.M. Sevanović, M.V. Jovašević-Stojanović, M.M. Živković, and M.J. Banjac, "Impact of CO_2 concentration on indoor air quality and correlation with relative humidity and indoor air temperature in school buildings, Serbia," *Thermal Science*, vol. 0, pp. 173-173, 2015.

[29] H. Fromme, D. Twardella, S. Dietrich, D. Heitmann, R. Schierl, B. Liebl, and H. Rüden, "Particulate matter in the indoor air of classrooms – exploratory results from Munich and surrounding area," *Atmos Environ*, vol. 41, pp. 854-866, 2007.

[30] M. Alshitawi, H. Awbi, and N. Mahyuddin, "Particulate Matter Mass Concentration (PM10) under Different Ventilation Methods in Classrooms," *Int. J. Vent.*, vol. 8, pp. 93-108, 2009.

[31] Y S. S. Kim, D.H. Kang, D.H. Choi, M.S. Yeo, and K.W. Kim, "VOC Emission from Building Materials in Residential Buildings with Radiant Floor Heating Systems," *Aerosol. Air. Qual. Res.*, vol. 12, pp. 1398-1408, 2012.

[32] L.J. Golding, L. Ansher, A. Berlin, J. Cheng, D. Kanopkin et al., "Indoor air quality of nail salons in Boston," *J. Immigr. Minor. Health*, vol. 16, pp. 508-514, 2014.