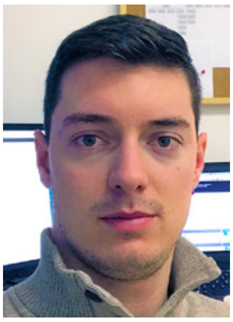
Energy consumption and Indoor Environmental Quality of a residential building before and after refurbishment



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The study was performed in one residential building before and after its renovation. Energy auditing and classification of the selected building into energy classes were carried out. This study investigates the impact of energy renovation on the indoor environmental quality of apartment building during heating season. Evaluation of indoor air quality was performed using objective measurements and subjective survey. Concentration of CO_2 was measured in bedrooms, and sampling of total volatile compounds was performed in the living rooms of the selected apartments. Higher concentrations of CO_2 and TVOC were observed in the residential building after its renovation. The concentrations of CO_2, and TVOC in some of the cases exceeded the recommended maximum limits, especially after implementing of energy saving measures on the building. The average air exchange rate was visible higher before renovation of the building. The current study indicates that large-scale of renovations may reduce the quality of the indoor environment in many apartments, especially in the winter season.

Keywords: Carbon dioxide concentration; Energy renovation; Indoor environment quality; Volatile organic commands concentration

Most of the residential buildings in Slovakia that were built in the 20th century do not satisfy the current requirements for energy efficiency presented in the national building code. Nationwide remedial measures have been taken to improve the energy efficiency of these buildings and reduce their energy use (Földváry V., Bekö G., Petráš D. (2014)). However, since the impact of these measures on indoor air quality is rarely considered, they often compromise indoor air quality due to the decreased ventilation and infiltration rate.

The highest development in the housing stock, as a result of economic changes and population growth, has been recognized as taking place during the second half of the 20th century (Jurelionis A., Seduikyte L. (2010)). The majority of housing in Central and Eastern Europe was constructed from panel technology. The degradation of its quality, which has led to its renovation, has become one of the most important measures from an energy-saving point of view.

The aim of the study was to evaluate the impact of basic energy-saving measures on indoor air quality in a typical high-rise residential building built in the 1960s in Slovakia.

Building description and building energy

The residential building investigated (**Figure 1**) is located in Šamorín, Slovakia. It was built in 1964 from lightweight concrete panels. The building was naturally ventilated. Exhaust ventilation was only used in sanitary rooms, such as the bathrooms and toilets. Renovation of the building was carried out in 2015 and included the following measures: insulation of the building envelope using polyethylene (80 mm), insulation of the roof using mineral wool (120 mm) and hydraulic balancing of the heating system. New plastic frame windows had already been installed over the last years in most of the apartments in the building. (Földváry V., Bekö G., Petráš D. (2015)).

Figure 1. The evaluated dwelling before and after refurbishment.

The heat demand was calculated for the non-renovated and renovated condition. The highest energy-saving is provided by the thermal insulation of the external walls. This can be explained with the large heat exchange surface of the walls. On the **Figure 2**, is clearly indicated the heat demand for the structures for square meter and the solar and heat gains for both types of residential building. The figure shows that the heat demand for the insulated part of the building significantly decreased and for the calculated air exchange rate (AER) and gains remained the same.

Table 1. Heat transfer coefficients of the structures.

Structure	Heat transfer coefficient – Non renovated building Ui [W/(m²K)]	Heat transfer coefficient – Renovated building Ui [W/(m²K)]	Area SUM Ai [m²]	Average heat transfer coefficient – Non renovated building Ui [W/(m²K)]	Average heat transfer coefficient – Renovated building Ui [W/(m²K)]	Improvement of the heat transfer coefficient [%]
External wall 1	1,6	**0,37**	1766,85	1,49	**0,35**	76,50
External wall 2	1,59	**0,36**				
External wall 3	0,49	**0,23**				
External wall 4	0,44	**0,23**				
Wall of the machine room	1,69	**0,38**				
Flat roof	0,8	**0,22**	328,77	1,23	**0,23**	81,30
Flat roof of the machine room	1,93	**0,27**				
Ceiling above the basement	0,88	**0,33**	338,77	0,88	**0,34**	61,40
Transparent structures	1,56	**1,3**	569,43	1,56	**1,3**	16,70
			3013,82	1,439	0,544	

The renovated and non-renovated residential building were classified into energy classes by the valid Slovak legislation: Decree of the Ministry of Transport, Construction and Regional Development No:300/2012.

The energy-saving measures mentioned above decreased the energy consumption by 55%. In accordance to our law on energy efficiency of buildings, the original dwelling belonged to the 'E' category (159 kWh/m²a), after refurbishment to the 'B' category (74 kWh/m²a).

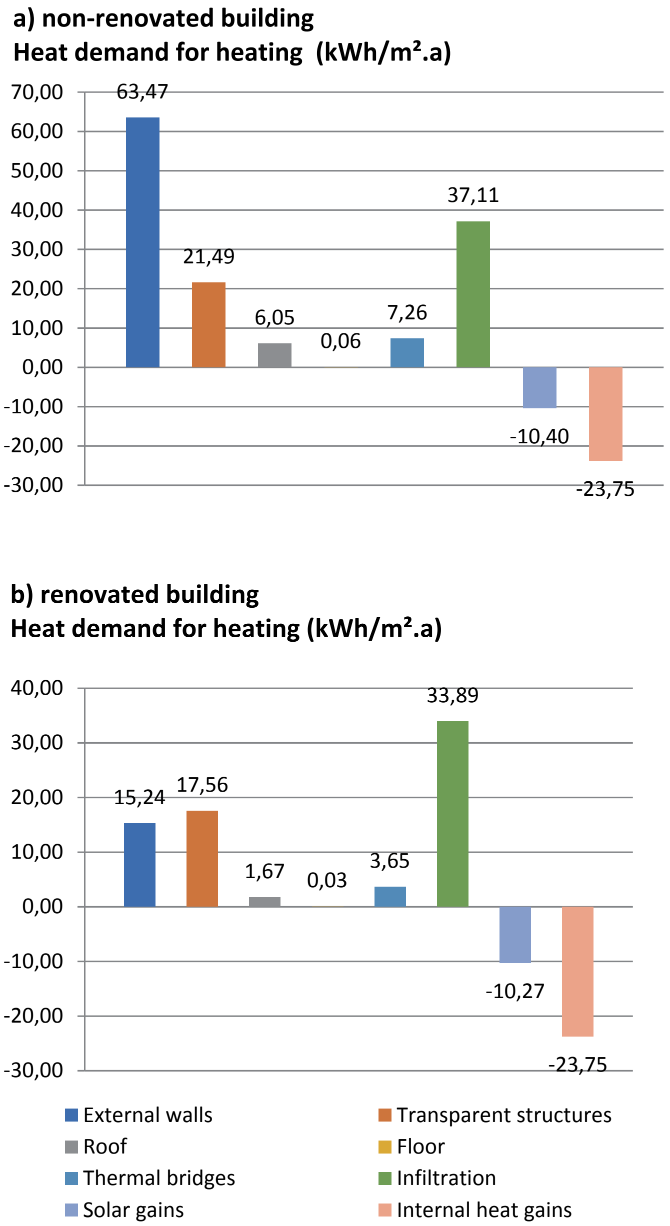
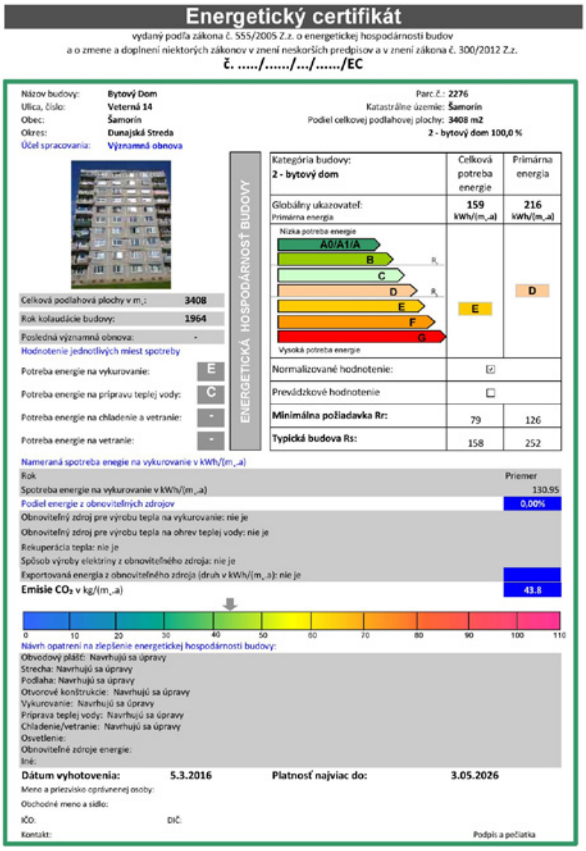


Figure 2. Heat demand of the building.



Energetický certifikát

vydaný podľa zákona č. 555/2005 Z.z. o energetickej hospodárnosti budov a o zmene a doplnení niektorých zákonov v znení neskorších predpisov a v znení zákona č. 300/2012 Z.z.

č. ...../......./.../....../EC

Názov budovy: Bytový Dom
Ulica, číslo: Veterná 14
Obec: Šamorín
Okres: Dunajská Streda
Účel spracovania: Významná obnova

Parc.č.: 2276
Katastrálne územie: Šamorín
Podiel celkovej podlahovej plochy: 3408 m2
2 - bytový dom 100,0 %

Celková podlahová plochy v m2: 3408
Rok kolaudácie budovy: 1964
Posledná významná obnova: -

Kategória budovy: 2 - bytový dom	Celková potreba energie	Primárna energia
Globálny ukazovateľ:	159 kWh/(m2.a)	216 kWh/(m2.a)
	E	D
Normalizované hodnotenie:	☑	
Prevádzkové hodnotenie	☐	
Minimálna požiadavka Rr:	79	126
Typická budova Rs:	158	252

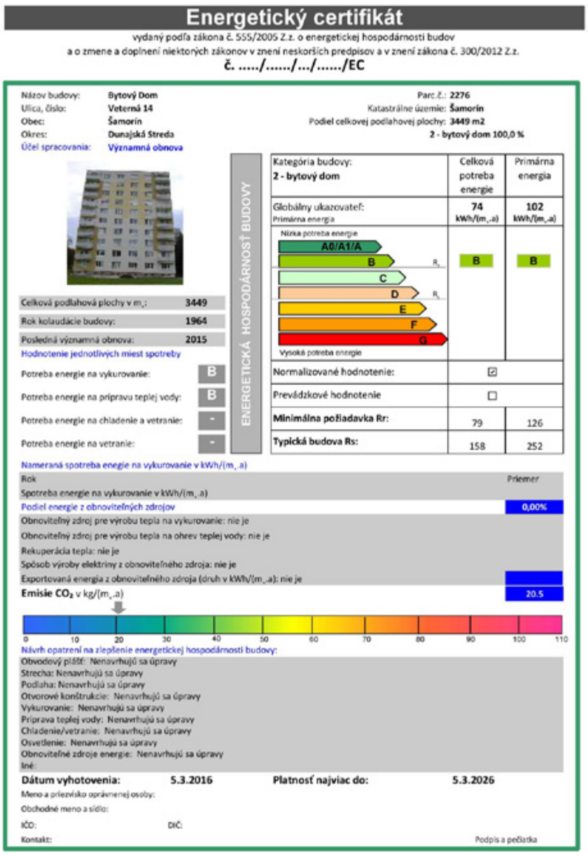
Hodnotenie jednotlivých miest spotreby
Potreba energie na vykurovanie: E
Potreba energie na prípravu teplej vody: C
Potreba energie na chladenie a vetranie: -
Potreba energie na vetranie: -

Nameraná spotreba energie na vykurovanie v kWh/(m2.a)
Rok — Priemer
Spotreba energie na vykurovanie v kWh/(m2.a): 130.95
Podiel energie z obnoviteľných zdrojov: 0,00%
Obnoviteľný zdroj pre výrobu tepla na vykurovanie: nie je
Obnoviteľný zdroj pre výrobu tepla na ohrev teplej vody: nie je
Rekuperácia tepla: nie je
Spôsob výroby elektriny z obnoviteľného zdroja: nie je
Exportovaná energia z obnoviteľného zdroja (druh v kWh/(m2.a)): nie je
Emisie CO_2 v kg/(m2.a): 43.8

Návrh opatrení na zlepšenie energetickej hospodárnosti budovy:
Obvodový plášť: Navrhujú sa úpravy
Strecha: Navrhujú sa úpravy
Podlaha: Navrhujú sa úpravy
Otvorové konštrukcie: Navrhujú sa úpravy
Vykurovanie: Navrhujú sa úpravy
Príprava teplej vody: Navrhujú sa úpravy
Chladenie/vetranie: Navrhujú sa úpravy
Osvetlenie:
Obnoviteľné zdroje energie:
Iné:

Dátum vyhotovenia: 5.3.2016 Platnosť najviac do: 3.05.2026
Meno a priezvisko oprávnenej osoby:
Obchodné meno a sídlo:
IČO: DIČ:
Kontakt: Podpis a pečiatka

Figure 3. Energy certificate of the non-renovated building.



Energetický certifikát

vydaný podľa zákona č. 555/2005 Z.z. o energetickej hospodárnosti budov a o zmene a doplnení niektorých zákonov v znení neskorších predpisov a v znení zákona č. 300/2012 Z.z.

č. ...../......./.../....../EC

Názov budovy: Bytový Dom
Ulica, číslo: Veterná 14
Obec: Šamorín
Okres: Dunajská Streda
Účel spracovania: Významná obnova

Parc.č.: 2276
Katastrálne územie: Šamorín
Podiel celkovej podlahovej plochy: 3449 m2
2 - bytový dom 100,0 %

Celková podlahová plochy v m2: 3449
Rok kolaudácie budovy: 1964
Posledná významná obnova: 2015

Kategória budovy: 2 - bytový dom	Celková potreba energie	Primárna energia
Globálny ukazovateľ:	74 kWh/(m2.a)	102 kWh/(m2.a)
	B	B
Normalizované hodnotenie:	☑	
Prevádzkové hodnotenie	☐	
Minimálna požiadavka Rr:	79	126
Typická budova Rs:	158	252

Hodnotenie jednotlivých miest spotreby
Potreba energie na vykurovanie: B
Potreba energie na prípravu teplej vody: B
Potreba energie na chladenie a vetranie: -
Potreba energie na vetranie: -

Nameraná spotreba energie na vykurovanie v kWh/(m2.a)
Rok — Priemer
Spotreba energie na vykurovanie v kWh/(m2.a)
Podiel energie z obnoviteľných zdrojov: 0,00%
Obnoviteľný zdroj pre výrobu tepla na vykurovanie: nie je
Obnoviteľný zdroj pre výrobu tepla na ohrev teplej vody: nie je
Rekuperácia tepla: nie je
Spôsob výroby elektriny z obnoviteľného zdroja: nie je
Exportovaná energia z obnoviteľného zdroja (druh v kWh/(m2.a)): nie je
Emisie CO_2 v kg/(m2.a): 20.5

Návrh opatrení na zlepšenie energetickej hospodárnosti budovy:
Obvodový plášť: Nenavrhujú sa úpravy
Strecha: Nenavrhujú sa úpravy
Podlaha: Nenavrhujú sa úpravy
Otvorové konštrukcie: Nenavrhujú sa úpravy
Vykurovanie: Nenavrhujú sa úpravy
Príprava teplej vody: Nenavrhujú sa úpravy
Chladenie/vetranie: Nenavrhujú sa úpravy
Osvetlenie: Nenavrhujú sa úpravy
Obnoviteľné zdroje energie: Nenavrhujú sa úpravy
Iné:

Dátum vyhotovenia: 5.3.2016 Platnosť najviac do: 5.3.2026
Meno a priezvisko oprávnenej osoby:
Obchodné meno a sídlo:
IČO: DIČ:
Kontakt: Podpis a pečiatka

Figure 4. Energy certificate of the renovated building.

Methodology

The first round of the measurements was performed in January 2015 when the building was still in its original condition, and the second round was performed in January 2016 after energy saving-measures had been implemented. Twenty apartments were selected across the residential building; they were equally distributed on the lower, middle and highest storeys of the building. The same apartments were investigated in both winter seasons over a period of eight days (Földváry V. (2016); Bekö G., Földváry V., Langer S., Arrhenius K. (2016)). The temperature, relative humidity, CO_2 concentration, and volatile organic compound concentration (TVOC) were measured in the bedrooms (the TVOC concentration in the living rooms) of the apartments. HOBO U12-012 data loggers and CARBOCAP CO_2 monitors (**Figure 5**) were used for recording the temperature and CO_2 concentration data.

For the TVOC concentration Perkin-Elmer adsorption tubes (**Figure 6**) with 200 mg Tenax TA were used. The measurements were performed according to ISO 16017-2. All the devices were calibrated before the measurement campaign began. The data were recorded at 5-minute intervals for eight days in each apartment. The locations of the instruments were selected with respect to the limitations of the carbon dioxide method (Földváry V., Bekö G., Petráš D. (2015))

Each unit was placed at a sufficient distance from the windows and beds to minimize the effect of the incoming fresh air or the effect of the sleeping occupants. The space between the furniture and the room corners was avoided. The CO_2 concentration was used to calculate the air exchange rate over eight nights in each bedroom. The occupants CO_2 emission rate was determined from their weight and height as set out in questionnaires (Földváry V., Bekö G., Petráš D. (2015); Földváry V. (2016)).

Figure 6. Perkin-Elmer adsorption tube.

The calculation of the air exchange rates was performed using the following mass balance (Persily A. K. (1997)):

$$C_i(t) = (C_o - C_a) \cdot e(-\lambda \cdot t_i) + C_a + (E \cdot 103\,\lambda \cdot VR \cdot (1 - e - \lambda \cdot t_i))$$

$C_i(t)$ = concentration at time t, ppm(V)
C_o = concentration in the beginning (at time t=0), ppm
C_a = outdoor concentration, ppm
λ = air exchange rate, 1/h
E = estimated metabolic CO_2 generation rate per person in the zone, 1/h
VR = volume of the room, m³
t_i = time, h

Figure 5. Hobo data logger and Carbocap CO_2 monitor (Sánka I., Földváry V., Petráš D. (2016); Sánka I., Földváry V., Petráš D. (2017))

A questionnaire survey was used to determine the subjective evaluations of the quality of the indoor environments. The questionnaire survey was carried out along with the objective measurements. Two types of documents were prepared (for the unrenovated and renovated building).

The questionnaire contained 6 main parts:

1. Basic information about the occupants
2. The state of the building
3. The ventilation habits of the occupants
4. Sick building syndrome symptoms
5. Perceived air quality
6. Thermal comfort

Results

The results of thermal comfort, the measured values of CO_2, AER, and the TVOC parameters and the questionnaire survey are as follows:

A. Thermal comfort

The measured values of temperature and relative humidity are presented in the following text.

From the measured data is obvious that day and night average temperature was higher in the renovated building than in the non-renovated (**Figure 7**, **Table 2**).

The relative humidity was very similar in both types of residential building (**Figure 8**, **Table 3**).

Table 2. Indoor air temperature before and after.

1) Before renovation (N=20)

Time period	T [°C]		
	Average	Minimum	Maximum
Day	20,7	20,1	23,6
Night	21,2	18,8	24,2
Whole period	20,9	18,7	23,9

2) After renovation (N=20)

Time period	T [°C]		
	Average	Minimum	Average
Day	22,1	20,1	23,9
Night	22,4	20,8	24,0
Whole period	22,2	20,6	24,0

Table 3. Relative humidity before and after.

1) Before renovation (N=20)

Time period	RH [%]		
	Average	Minimum	Maximum
Day	46,1	34,8	59,1
Night	47,1	34,8	63,0
Whole period	46,2	34,5	60,8

2) After renovation (N=20)

Time period	RH [%]		
	Average	Minimum	Average
Day	47,3	38,3	58,4
Night	48,8	38,9	59,9
Whole period	47,9	38,6	59,1

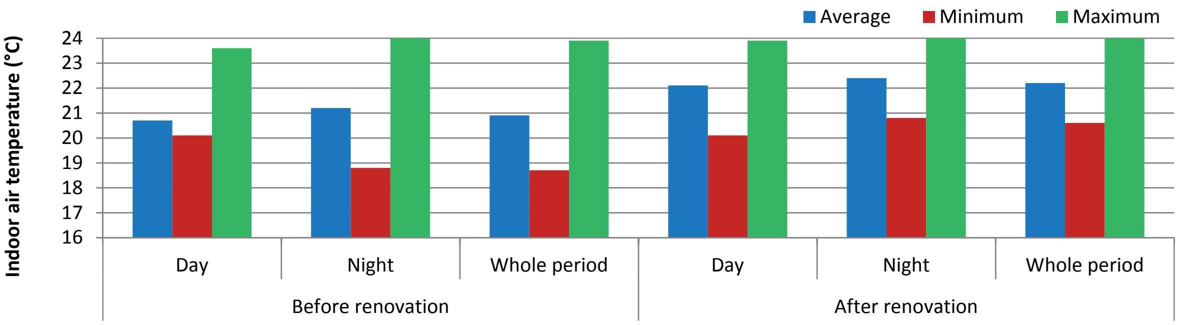


Figure 7. Average temperatures in the apartments before and after complex renovation.

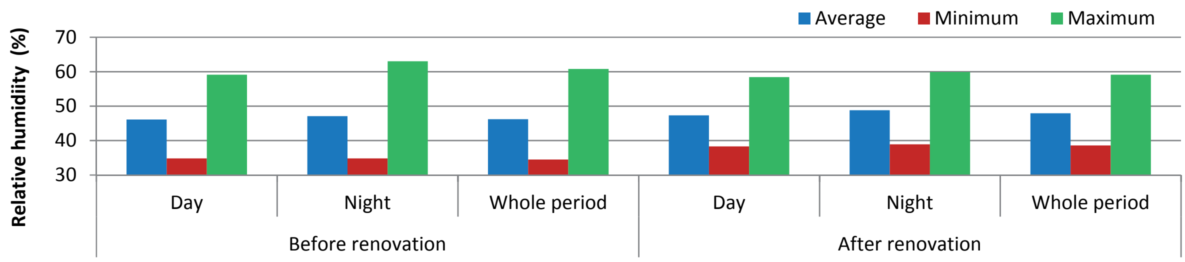


Figure 8. Average relative humidity in the apartments before and after renovation.

Both measured values fulfils the requirement of the Slovak standard STN EN 15 251(T: T>20°C; T<24°C; RH: RH>30%; RH<70%).

B. Carbon-dioxide concentration and Air exchange rate

The CO_2 concentrations before and after the renovation of the building are shown in **Figure 9**. Most of the CO_2 concentration data points were within the acceptable limit (green line) before the renovation (blue line), while significantly higher concentrations were measured after the renovation (red line). **Table 4** and **Figure 10** present the descriptive statistics of the day and night-time CO_2 concentrations before and after the renovation of the residential building. The grand average was 1205 ppm, and the median was 1190 ppm before the renovation.

After implementing the energy-saving measures, the CO_2 concentration visibly increased. The mean was 1570 ppm, and the median was 1510 ppm. **Table 5** shows the percentages of the average day and night-time CO_2 concentrations above four cut-off values in the residential building before and after its renovation. A higher number of the apartments exceeded 1500 ppm and the upper concentrations during both the day and night-time after the renovation than before the renovation.

Table 4. Day- and night-time CO_2 concentrations before and after renovation of the residential building. (Sánka I., Földváry V., Petráš D. (2016); Sánka I., Földváry V., Petráš D. (2017))

1) Before renovation (N=20)

Time period	CO_2 (ppm)			
	avg.	min	max	median
Day	1040	595	1550	1030
Night	1400	740	2665	1300
Whole period	1205	660	2050	1190

2) After renovation (N=20)

Time period	CO_2 (ppm)			
	avg.	min	max	median
Day	1320	790	2210	1265
Night	1925	865	3575	1825
Whole period	1570	870	2770	1510

Table 5. The fractions of the apartments where the average CO_2 concentration exceeded 1000, 1500, 2000 and 2500 ppm during the day- and night-time. (Sánka I., Földváry V., Petráš D. (2016); Sánka I., Földváry V., Petráš D. (2017))

1) Before renovation (N=20)

Time period	Cut-off values [%]			
	CO_2>1000 (ppm)	CO_2>1500 (ppm)	CO_2>2000 (ppm)	CO_2>2500 (ppm)
Day	60	10	0	0
Night	75	40	10	5

2) After renovation (N=20)

Time period	Cut-off values [%]			
	CO_2>1000 (ppm)	CO_2>1500 (ppm)	CO_2>2000 (ppm)	CO_2>2500 (ppm)
Day	75	30	10	0
Night	95	70	40	15

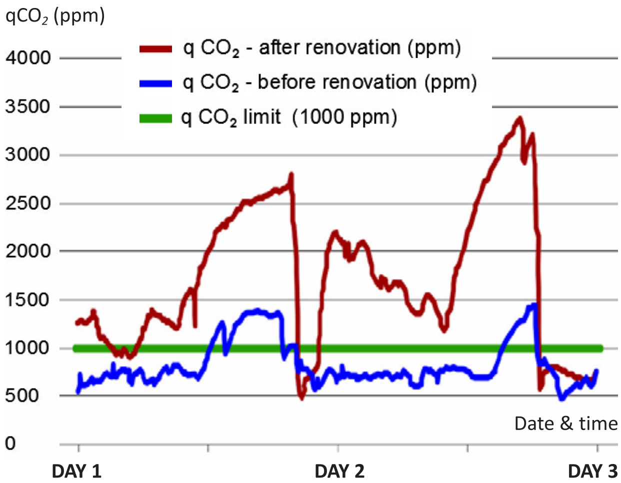


Figure 9. Example of CO_2 concentration in one selected apartment during two days out of the whole measurement period before and after the renovation. (Sánka I., Földváry V., Petráš D. (2016); Sánka I., Földváry V., Petráš D. (2017))

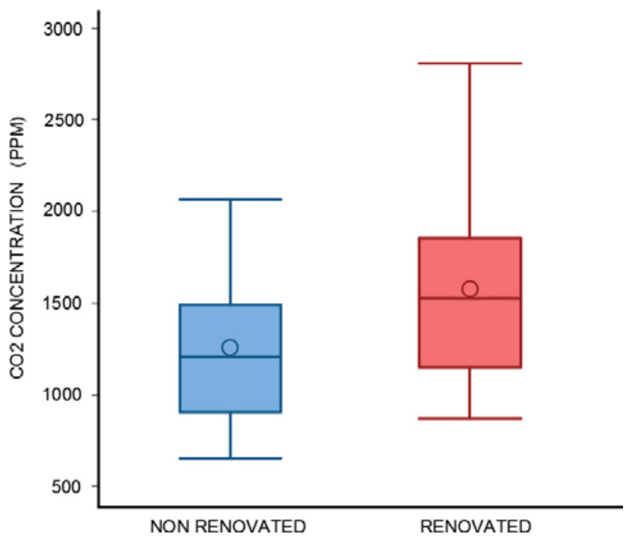


Figure 10. CO_2 concentration before and after renovation as a statistical output (Sánka I., Földváry V., Petráš D. (2016); Sánka I., Földváry V., Petráš D. (2017))

The lower CO_2 concentration before the renovation resulted in higher AERs in the apartments (average 0.61 1/h). After the renovation, the mean air exchange rate (0.44 1/h) dropped below the recommended minimum (0.5 1/h) (**Table 6** and **Figure 11**).

C. Concentration of volatile organic compounds

In both cases (before and after the renovation) the volatile organic compound (TVOC) concentrations were above the maximum limit value (300 µg/m³) Even higher concentrations were measured in the apartments after refurbishment (**Table** 7). In some cases, concentrations of TVOC were measured as very high (>1000 µg/m³), which are illustrated by the green dots on **Figure 12**. **Table 8** contains the percentages of the measured values exceeding the threshold values.

D. Results of the subjective measurements

The results of the questionnaire survey are based on the responses of the occupants of the evaluated residential building. The results below characterize the ventilation habits of the occupants, the perceived air quality, and the acceptability of the indoor air quality.

The residents labelled the acceptability of the indoor air on a scale from –1 to +1. The following figure shows the acceptability of the indoor air quality in the bedrooms and living rooms of the unrenovated and renovated building. The boxplot value of -1 represents poor air quality, and the value 1 represents good air quality.

The changes in the ventilation habits of the inhabitants before and after the renovation are presented in **Table 9**. The first part of the table shows the percentage

Table 6. AER before and after. (Sánka I., Földváry V., Petráš D. (2016); Sánka I., Földváry V., Petráš D. (2017))

AER	avg.	min	max	median
Before renovation (N=20)	0.61	0.32	1.15	0.59
After renovation (N=20)	0.44	0.21	0.76	0.45

Table 7. TVOC concentration before and after.

TVOC concentration, µg/m³	avg.	min	max
Before renovation (N=20)	569	179	1805
After renovation (N=20)	773	185	2362

Table 8. TVOC concentration before and after. (Sánka I., Földváry V., (2017))

Limit values of TVOC concentration	Before renovation (N=20)	After renovation (N=20)
TVOC > 300 µg/m³	80%	85%
TVOC > 500 µg/m³	50%	60%
TVOC > 1000 µg/m³	5%	25%
TVOC > 2000 µg/m³	0%	5%

Table 9. Ventilation habits of the inhabitants.

Ventilation	Before renovation (N=20)		After renovation (N=20)	
	Whole apartment	Bedroom	Living room	Bedroom
Frequency of ventilation [%]				
More than once a day	70	40	60	30
Daily or almost daily	30	60	40	70
The average duration of ventilation [%]				
3.5 min	25	15	15	15
7.5 min	35	20	40	20
20 min	15	30	20	40
30 min	25	35	25	25

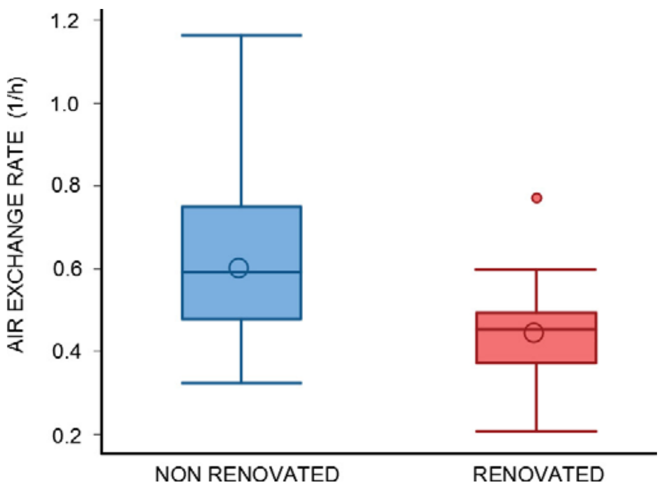


Figure 11. Air exchange rate before and after renovation as a statistical output (Sánka I., Földváry V., Petráš D. (2016); Sánka I., Földváry V., Petráš D. (2017))

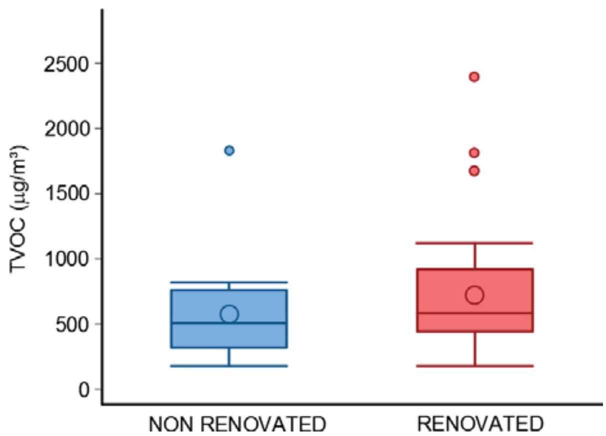


Figure 12. TVOC concentration before and after as a statistical output (Sánka I., Földváry V., (2017))

characterizing the frequency, while the second part contains the duration of the ventilation.

The results indicate that the inhabitants did not change their ventilation habits after the renovation. Most of them ventilated the living room once a day, and the ventilation time was 7.5 min. The occupants ventilated bedrooms daily or almost daily but not every day. After the renovation, the ventilation time slightly increased but not significantly.

The boxplots in **Figure 14** shows the relationship between the duration of the ventilation and the air exchange rate, as well as the relationship between the duration of the ventilation and the acceptability of the indoor air.

The results clearly show a linear relationship between the duration of the ventilation (AER) and the acceptability of the indoor air.

Discussion

Indoor air quality is a dominant contributor to total personal exposure because most people spend a majority of their time indoors (N. Klepeis, W. C. Nelson, W. R. Ott el al. (2001). The findings presented in this measurement campaign support the conclusions of previous studies in Slovakia (Földváry V., Bekö G., Petráš D. (2014)) in which deterioration of indoor air quality follows energy renovations. In this study, the implementation of the energy-saving measures was not combined with measures to improve the indoor environmental quality, which explains the lower AERs and higher CO_2 and TVOC concentrations in the renovated buildings in the winter.

Many international studies have also attributed this phenomenon to the fact that older buildings are leakier and newer ones are more air-tight as a result of improved construction techniques and stricter regulations (Kotol M., Rode C., Clausen G., Nielsen T. R. (2014); Bekö G., Toftum J., Clausen G. (2011)). The limitation of the study is its small sample size. The validation of the results on a larger sample size is warranted. The study is ongoing, and additional results will be available in the near future.

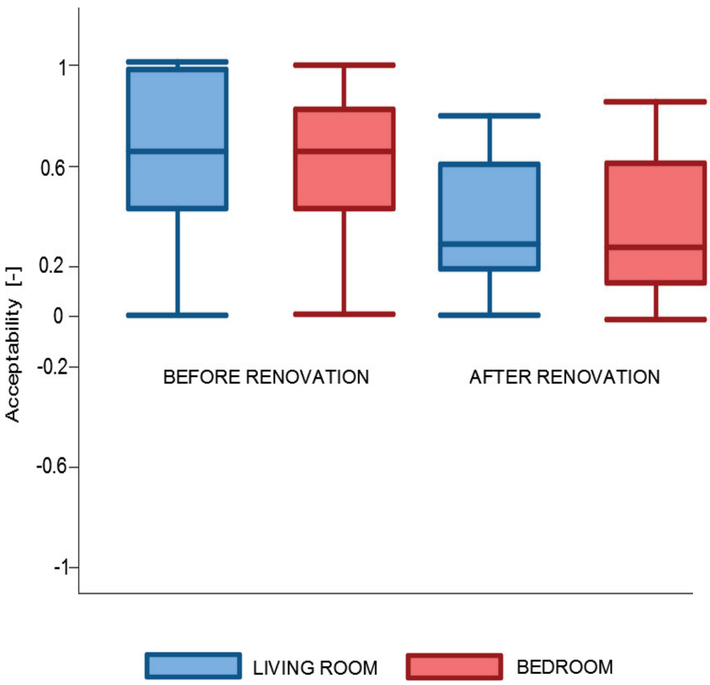


Figure 13. Acceptability of the indoor air as statistical output.

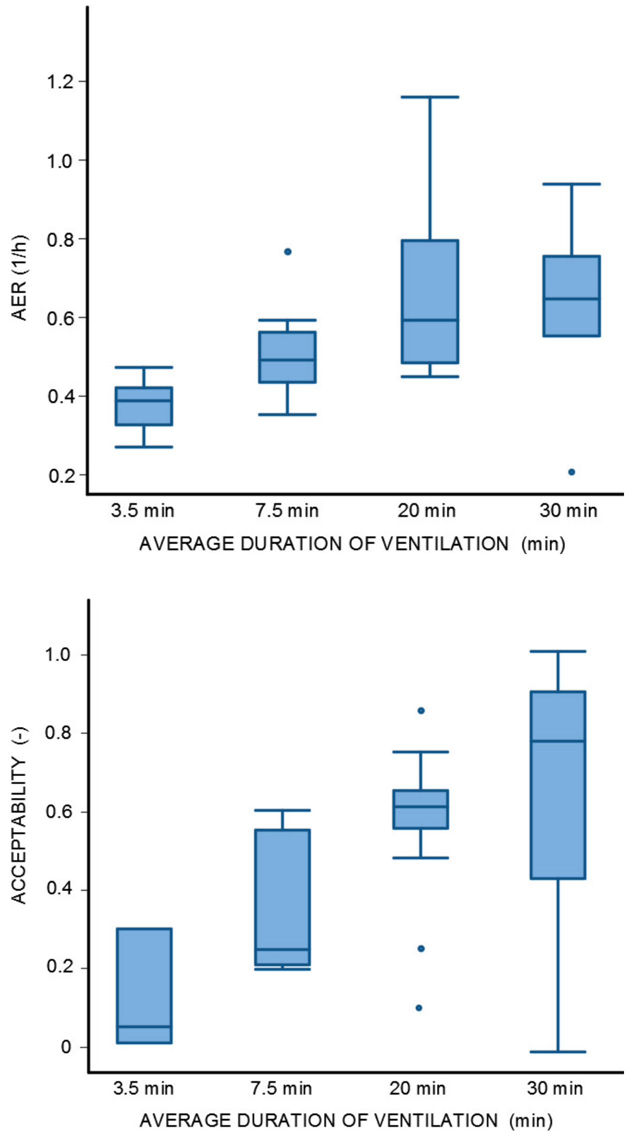


Figure 14. Relation between AER and acceptability.

Conclusion

A key goal of the implementation of an energy renovation strategy is to achieve the improved energy efficiency of buildings. However, the effect of these programs has not been systematically assessed. The effects on indoor air quality and well-being of the occupants is often ignored. There is an urgent need to assess the impact of the currently applied building renovation practices on the residential indoor air quality on a nationwide scale. ■

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