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Citation
Leivo, V., Prasauskas, T., Du, L., Turunen, M., Kiviste, M., Aaltonen, A., ... Haverinen-Shaughnessy, U. (2018). Indoor thermal environment, air exchange rates, and carbon dioxide concentrations before and after energy retro fits in Finnish and Lithuanian multi-family buildings. *Science of the Total Environment*, *621*, 398-406. https://doi.org/10.1016/j.scitotenv.2017.11.227

Year
2018

Version
Peer reviewed version (post-print)

Link to publication
TUTCRIS Portal (http://www.tut.fi/tutcris)

Published in
Science of the Total Environment

DOI
10.1016/j.scitotenv.2017.11.227

Indoor thermal environment, air exchange rates, and carbon dioxide concentrations before and after energy retrofits in Finnish and Lithuanian multi-family buildings

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Abstract

Impacts of energy retrofits on indoor thermal environment, i.e. temperature (T) and relative humidity (RH), as well as ventilation rates and carbon dioxide (CO_2) concentrations, were assessed in 46 Finnish and 20 Lithuanian multi-family buildings, including 39 retrofitted case buildings in Finland and 15 in Lithuania (the remaining buildings were control buildings with no retrofits). In the Finnish buildings, high indoor T along with low RH levels were commonly observed both before and after the retrofits. Ventilation rates (l/s per person) were higher after the retrofits in buildings with mechanical exhaust ventilation than the corresponding values before the retrofits. Measured CO_2 levels were low in vast majority of buildings. In Lithuania, average indoor T levels were low before the retrofits and there was a significant increase in the average T after the retrofits. In addition, average ventilation rate was lower and CO_2 levels were higher after the retrofits in the case buildings (N=15), both in apartments with natural and mixed ventilation. Based on the results, assessment of thermal conditions and ventilation rates after energy retrofits is crucial for optimal indoor environmental quality and energy use.

Highlights

- In Finnish buildings
    - Overheating was common both before and after retrofits.
    - Ventilation rates increased after retrofits.
- In Lithuanian buildings
    - Indoor temperatures improved after retrofits.
    - Ventilation rates decreased while RH increased after retrofits.
- Assessing thermal conditions and ventilation crucial for optimal IEQ and energy use

Keywords

Energy retrofit, thermal environment, air exchange rate, CO_2 concentration, multi-family buildings

1 Introduction

European Commission has adopted the recast 2010 Energy Performance of Buildings Directive (EPBD), aiming to reduce the building energy consumption and strengthen the energy performance requirements. By the end of 2020, all new buildings have to be so-called nearly zero-energy buildings (nZEBs), and also existing buildings subjected to major retrofits must meet minimum energy performance requirements adapted to the local climate [1]. The total residential floor area in the EU-27 member states is approximately 17.6 billion m^2, of which 15.1 billion m^2 is estimated to be heated [2]. Most of the residential buildings (about 70% of the building area) in the EU-27 countries have been constructed before 1980. There is an important energy saving potential in the old multi-family buildings, which are also in need of renovation as many construction parts have reached their expected service life. Energy performance is closely related to both ventilation and heating of buildings.

Main purpose of outdoor air ventilation is controlling exposures, and it is one of the methods for preventing health problems caused by poor indoor air quality (IAQ). Well-functioning ventilation removes air pollutants from indoor sources, and replaces polluted air with fresh (cleaner) outdoor air. In the winter, ventilation also results in heat loss by removing heated indoor air and replacing with the colder outdoor air. In addition, mechanical ventilation systems naturally consume energy. Therefore, a compromise is often sought between satisfactory IAQ and energy needed for the ventilation. Ventilation may also decrease indoor air humidity during the heating season. That could be desirable in humid climate and when the indoor moisture regain is high due to indoor activities (e.g. perspiration, cooking, washing). However, too low RH can cause comfort complaints related to dry nose, throat, eyes, and skin [3].

Total ventilation rate (including intentional air exchange and unintentional infiltration) is difficult to measure exactly mainly due to constantly changing infiltration parameters (such as buoyancy effect due to temperature difference and wind pressure effect). In many instances, measurement of CO_2 concentration (as a tracer gas) is used to assess ventilation adequacy with respect to IAQ.

ASHRAE Standard 62 [4] is one of the oldest standard series (first version in 1973, newest in 2013) for acceptable ventilation and IAQ. There has been two minimum ventilation requirements for living areas since

1989: 0.35 1/h and 7.5 l/s per person [5]. EN 13779:2007 standard [6] does not set strict ventilation requirements but defines a framework for developing national standards, which employ four IAQ classes (IDA1....IDA4). In an informative annex, outdoor air ventilation rates related to CO_2 concentrations or per person are presented. For the lowest IAQ class (IDA4) the default rate is 5 l/s per person or CO_2 concentration less than 1200 ppm above outdoor air, whereas for the highest IAQ class default rate is 20 l/s per person or CO_2 concentration less than 350 ppm above outdoor air. Currently, new minimum values for adequate ventilation are under development and they focus on defining health-based ventilation (with respect to occupants), not to room volume (such as 0.5 1/h).

Ventilation rate is called health-based, when World Health Organization's Air Quality guidelines regarding both the pollutants in the (outdoor) air used for ventilation and in the indoor air have been met [7]. If the guidelines are met through source control, then the health-based ventilation rate is equal to the base ventilation rate. The base ventilation rate is a minimum requirement that should always be fulfilled when people are present indoors. This is the rate required to handle primarily human bioeffluents (e.g. moisture and CO_2). Based on the literature review of the epidemiological studies and other considerations, a base ventilation rate of 4 l/s per person for typical buildings and activities has been proposed [8]. Based on some reviews concerning correlation between health outcomes and ventilation rates, there exists limited data for determining specific outdoor ventilation rates that are applicable to protect against health risks in different buildings [10, 11]. A recent review [10] concluded that the available data do not provide a sound basis for determining specific ventilation rates (variation between 6 to 40 l/s) that can be universally applicable in different public and residential buildings to protect against health risks.

Indoor CO_2 concentrations in residential buildings are typically well below values of health based limits. Concentration of about 1000 ppm has become more or less "a de facto standard" for the maximum recommended value indoors [11], above which occupant perceived air stuffiness and related discomfort may increase. Although several studies have reported associations between higher CO_2 concentrations and occupants' health symptoms, it is commonly assumed that these effects are caused by elevated concentrations of other contaminants or decreased thermal comfort associated with low ventilation, and not directly by exposure to CO_2 [11]. However, a recent experimental study [12] of healthy individuals performing computer-based tests indicated a significant decrease in decision-making performance at 1800 mg/m^3 (approx. 1000 ppm) CO_2 concentration, while other contaminants were controlled. Nevertheless, since high CO_2 concentrations are associated with low ventilation rate and subsequently with other indoor contaminants, it can be used as an indicator of inadequate ventilation or poor IAQ in occupied rooms.

In addition to ventilation, space heating requires energy, more so in poorly insulated buildings. Some studies have assessed impacts of improving energy efficiency on thermal environment, ventilation and IAQ by measurements or occupant surveys [21-23], by simulation of the effects [24-25], or by a combination of measurements, occupant surveys, or simulation [16]. Howden-Chapman reported effects of insulating low-income houses (1350 households and 4407 occupants) in New Zealand where the mean bedroom temperature in winter increased in the insulated houses from 13.6°C to 14.2°C and mean RH decreased from 68.6% to 64.8% [13]. These changes were associated with reduced odds ratios for fair or poor self-rated health in the insulated homes. A study on the effects of England's Warm Front programme on winter thermal comfort in low-income dwellings reported improved thermal comfort [17]: after the new insulation and heating system were installed, mean indoor T increased from 17.1°C to 19.0°C, and the proportion of households feeling thermally 'comfortable' or warmer increased from 36.4% to 78.7%.

Two similar Swedish apartment buildings (retrofitted and non-retrofitted) were studied using measurements, simulation, and occupant surveys [16]. The results indicated 39% reduction potential in space heating demand. In addition, occupants in the retrofitted building reported increased satisfaction with indoor climate, and the simulation results also concluded improved indoor environment both during winter and summer. Short measurements, (maximum of two weeks in May, June or September), were conducted for validation of simulation model. According to the simulation results of thermal comfort (PMV and PPD values, according to ISO 7730), there were no major differences in wintertime thermal comfort between the retrofitted and non-retrofitted buildings, but summertime thermal comfort was substantially improved in the retrofitted buildings.

In Danish study [18], an apartment building underwent a comprehensive energy retrofit including new facade and windows, additional insulation, mechanical ventilation with heat recovery, and a photovoltaic installation on the roof, resulting about 30% energy savings. Based on thermal, CO_2 and ventilation rate measurements after retrofits, which were performed in three apartment for one week in December, the ventilation rates were roughly twice the required rate (0.3 l/s per m^2) after retrofits, CO_2-concentrations were just above typical outdoor level, indoor temperatures were generally above +20–21 °C, and RH levels were about 30%.

Based on previously described studies, there seems to be potential for energy retrofits to have a positive influence on thermal comfort, especially in previously low-insulated buildings, such as in Lithuania. However, this potential is less prominent in already well-insulated buildings, such as in Finland. These two countries located in Northern Europe has somewhat distinct starting points when considering the potential for improving energy efficiency of the existing housing stock. Until 1992, the Lithuanian U-value requirements followed regulations adopted from former Soviet Union. Since 1992, The Lithuanian National Building Code was introduced and U-value requirements are approaching the ones applied in Scandinavian countries. The total heated residential floor area in Finland is about 198 million m2 and in Lithuania about 103 million m2. Some 64% of the multi-family buildings in Finland and 76% in Lithuania are constructed before 1980.

This study focuses on assessing impacts of energy retrofits on indoor thermal environment, ventilation rates, and CO_2 concentrations. Measurements following the same protocol were performed before and after retrofits of Finnish and Lithuanian multifamily buildings. The purpose of the whole project (INSULAtE) was to demonstrate impacts of energy retrofits on indoor environmental quality (IEQ), occupant health and wellbeing, and to develop a common assessment protocol of these impacts on building and national levels [19]. Interpretation of the results were based on national guideline values, as shown in Table 1.

Table 1. National guideline values of measured parameters.

Parameter	Unit	Finland [20][21][22]	Lithuania [23][24]
T	°C	18-26 [1]	18-22 [2]
RH	%	20-60	35-60 [2]
CO_2	Ppm	<1150 + outdoor [3]	<1200
Ventilation, air flow	$(dm^3/s) / m^2$	≥0.5	≥0.5

[1] "Good level" for room temperature is +21 °C. During heating season, indoor temperature should not exceed +23...+24 °C.

[2] Values for T and RH refers only to heating season.

[3] "Adequate level" of CO_2 is 1200 ppm.

[4] 0.7 $(dm^3/s) / m^2$ for bedrooms.

2 Materials and Methods

2.1 Case study buildings

Case study buildings were selected from volunteering multi-family buildings that were planned to be retrofitted during the project, and where approximately five apartments per building were willing to participate in the measurements. Also some buildings, which were not retrofitted during the project, were included as control buildings. The case study buildings were chosen from several regions in Finland (Tampere, Hämeenlinna, Imatra, Helsinki, Porvoo, Kuopio), and Kaunas region in Lithuania. The case study buildings in both countries are comparable their construction type and common building materials (external walls made of prefabricated concrete elements with thermal insulation in the middle). It was also noticed that the average size of the apartments was almost the same in both countries, and the majority of the buildings were built in 1960-1980 (Table 2). For a reference, most of the existing apartment buildings in the Finnish housing stock have been constructed in 1960-1980 [25]. In Lithuania, about 66% of the population lives in multifamily houses built before 1993 and 65 % in houses built in 1960–1990 [26].

Table 2. Case study buildings by year of construction, size and type of ventilation.

	Year of construction						Number of apartments (pre/post)	Average size of apartment (m^2)	Ventilation type	
	before 1960	1960-1970	1971-1980	1981-1990	1991-2000	after 2000			Natural	Mechanical
			FI							
Control	0	1	4	0	0	1	30/21	78	0	10
FER	2	11	13	4	0	0	147/103	64	4	147
DER	3	1	3	0	0	0	23/21	56	11	12
			LT							
Control	0	0	1	1	3	0	24/7	58	11	12
FER	1	1	0	0	0	0	9/5	77	9	0
DER	1	4	3	5	0	0	57/50	58	31	30

Retrofitted buildings were divided into two groups: focused energy retrofit buildings (FER), where only one retrofit action was performed, and deep energy retrofit buildings (DER), where several retrofit actions addressing multiple building components were performed. In Finland, a total of 46 multi-family buildings were included: 39 retrofitted (30 FER and 9 DER) cases and seven control buildings. Average size of the apartments in the control buildings was slightly larger than in the case buildings (Table 2). Majority of the apartments had glazed balconies. Typical U-values of the structures before retrofits were: outer walls U= 0.40 … 0.28 W (m-2 K-1), roof 0.40 … 0.36 W (m-2 K-1), floors 0.40 … 0.29 W (m-2 K-1), windows 2.1 W (m-2 K-1) [28]. The most common retrofit action was replacing windows (new U-value 1.0 W (m^{-2} K^{-1})) and/or installing heat recovery to the existing exhaust ventilation system, which then became mechanical ventilation with heat recovery (MVHR). Distribution of the performed retrofits in Finland is presented in Figure 1a.

In Lithuania, a total of 20 multi-family buildings were included: 15 retrofitted (2 FER and 13 DER) cases and five control buildings. Average size of the apartments in the FER buildings was slightly larger than in the other case buildings (Table 1). Typical U-values before retrofits were: outer walls U=1.27…0.88 (m-2 K-1), roof 0.85 (m-2 K-1), floors 0.71 (m-2 K-1). The retrofits most commonly involved adding thermal insulation to the wall (new U-value 0.20 W (m^{-2} K^{-1})) and roof (new U-value 0.16 W (m^{-2} K^{-1})), replacing windows (new U-value 1.4 W (m^{-2} K^{-1})) and glazing of balconies, but did not typically include changes in the ventilation systems. Distribution of the performed retrofit actions in the case buildings is presented in Figure 1b.

a. b.

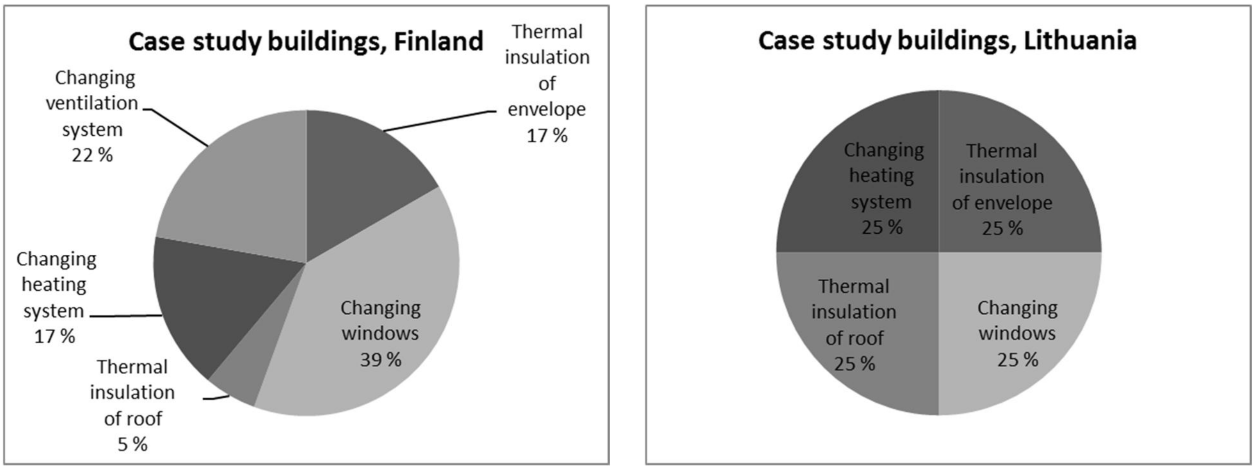

Figure 1. Performed energy retrofits in the case buildings in Finland (a) and Lithuania (b).

Majority of the measured buildings (about 92% of apartments) in Finland had mechanical exhaust ventilation system (with or without heat recovery units), where more efficient exhaust is typically turned on for two hours once or twice a day, in the morning (between 10 am to 2 pm) and in the afternoon (between 4 pm to 6 pm). In Lithuania, the majority of the buildings had natural ventilation, which in some apartments had been improved with occupant-controlled fan driven exhaust in kitchen and natural or mechanical exhaust in bathroom. This kind of mixed ventilation system had been installed afterwards by the occupants into 44% of the apartments. The ventilation systems of the case buildings are common in each country since in Northern Europe (especially in Scandinavian countries), the most common ventilation system is mechanical exhaust ventilation, whereas in other parts of the Europe, natural ventilation is more common [25].

2.2 Measurement and analysis methods

Two rounds of measurements were performed: before and after retrofits in the case buildings and two measurements in consecutive years in the control buildings. Both rounds were performed in the same season, usually during heating season (between November and April). Some apartments were measured only once (e.g. if the occupant could not be reached for the second measurement).

The measurements have been described more detailed elsewhere [19]. Briefly, two months continuous monitoring of temperature (T) and relative humidity (RH) was initially planned, which in some case buildings was extended for over one year in order to study seasonal variations (data not shown). Two, new factory-proofed, loggers (CEM DT-172 logger, Shenzhen Everbest Machinery Industry Co., Ltd, China. T range -40 -+ 70 °C, accuracy ± 1 °C; RH range 3 - 100%, accuracy ± 3%) per apartment were placed. One logger was placed in the occupied zone, e.g., middle of the living room (height of 1.2-1.5 m above ground, i.e. human breathing zone as seated), presented as T_w and RH_w. The other logger was placed to the coldest spot, i.e. place where coldest inner surface temperature was detected by thermographic camera or IR-thermometer (usually by the balcony door), presented as T_c and RH_c. All logger units used in the study were new and recently calibrated by the manufacturer. Outdoor T and RH data during the measurement period were obtained from local monitoring stations, i.e. Kaunas region in Lithuania (by Lithuanian Hydrometeorological Service under the Ministry of Environment), and closest weather stations nearby case buildings (Tampere, Hämeenlinna, Lappeenranta, Helsinki, Porvoo, Kuopio regions) in Finland (by Finnish Meteorological Institute under the Ministry of Transport and Communications). Other meteorological data (e.g. wind speed and direction) were not collected.

Ventilation rate [$(dm^3/s)/m^2$] was calculated based on measured air flows from ventilation outlets and information on the apartment floor area. A new rotating vane anemometer with a built-in 100 mm vane and temperature probe (Testo 417, +0.3 to +20 m/s measurement range, ± (0.1 m/s +1.5% of mv) accuracy and 0.01 m/s resolution) was used to measure air flows. Each ventilation outlet was measured, but the measured values were found unreliable if the outlet was irregular or the air flow was too small. Also ventilation rates based on occupancy [(l/s)/person] were calculated.

Carbon dioxide (CO_2) and carbon monoxide (CO) concentrations were measured every minute during a 24-hour period using new, factory calibrated sensors (HD21AB/HD21AB17, Delta OHM, Italy. Range 0 - 5000 ppm, accuracy ±50 ppm or ± 3%). Side-by-side simultaneous tests before and after the baseline measurements were conducted, based on which replicate precision ranged from 5% to 11%. Sensors were sent to the manufacturer for calibration if needed.

In addition, the associations between retrofitting and IEQ (including average T and RH in warm and cold areas, ventilation rates, and maximum night time concentration of CO_2) were analyzed by linear mixed modelling (LMM) using IBM SPSS Statistics (version 22.0). The estimation was based on the Restricted Maximum Likelihood (REML) method and the Expected Maximum (EM) algorithm. The building and apartment codes were used as subject variables, and the covariance type was identity (covariance structure for a random effect with only one level). Only main effects were studied, while the factorial design with interaction effects were not used.

First we studied a null model, which included only the subject and outcome variables without any predictors, in order to examine the variance between country, building and apartment levels, and to calculate the intra class correlation (ICC) (i.e. proportion of the total variance accounted for by the clustering). Secondly we included the selected independent variables in the models. Retrofit status was based on case/control and pre/post variables. The reference group was case buildings at first measurement (pre-retrofit), and the other groups included case buildings at second (post-retrofit) measurement as well as control buildings at first and second measurements. The fixed effects included country (Finland/Lithuania), as well as outdoor T (models for T, RH, ventilation rate, and CO_2), outdoor RH (models for RH), indoor T_w (models for RH_w), Indoor T_c (models for RH_c), type of ventilation system (models for ventilation rate and CO_2), and number of occupants (model for CO_2). In addition to studying the models among the whole population sample, the models were also run for both Finnish and Lithuanian buildings separately. Finally, the models were used to study effects of level of retrofitting (DER / FER) among the case buildings.

3 Results and discussion

3.1 Thermal environment

Figures 2 and 3 present results of indoor T and RH. In Finland, average indoor T_w during heating season was relatively high in all measurements among both case and control groups, whereas RH_w was low.

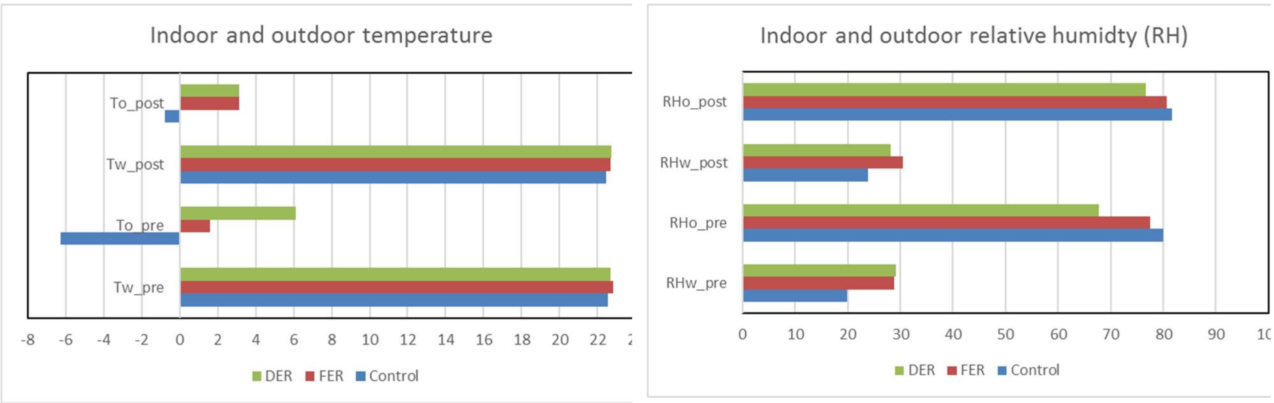

Figure 2. Average indoor and outdoor T (ºC) and RH (%) in Finnish buildings.

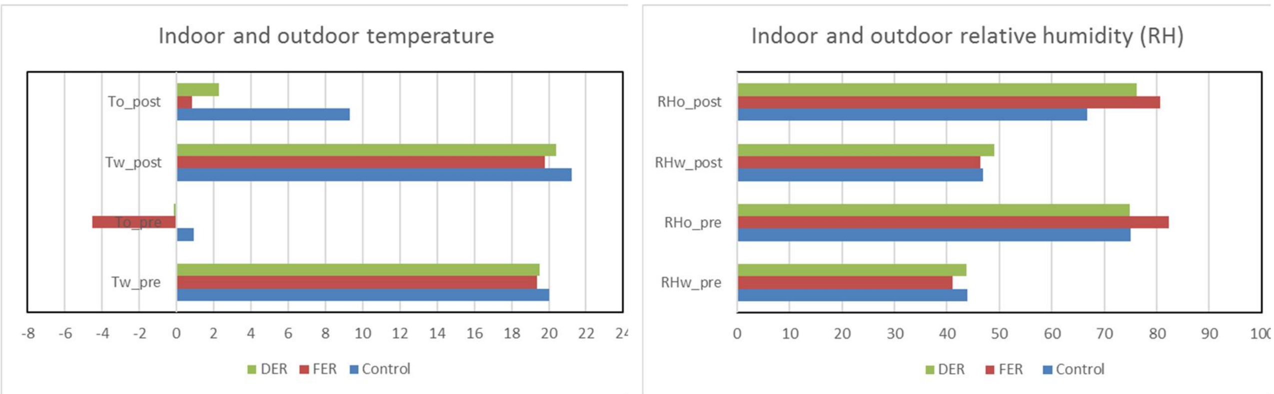

Figure 3. Average indoor and outdoor temperature (ºC) and relative humidity (%) in Lithuanian buildings.

Average T_w in Lithuania were lower than in Finland and there was a significant increase (crude $p<0.05$) after the retrofits in DER buildings. Similarly, there was a significant increase in temperature near the coldest spot (T_c). The level of thermal resistance of the envelope was substantially increased in the retrofitted buildings in Lithuania by added insulation, which could explain the increased temperatures.

Some differences observed between first and second measurements could be related to outdoor conditions (for example, indoor RH is dependent on outdoor T and RH). Therefore, further modelling taking into account outdoor T and RH (as applicable) was conducted. LMM models for average indoor T_w is presented in supplementary material, Table S1. Based on the results, outdoor T is significantly associated with T_w: followed by each 1 ºC increase in outdoor T, average T_w is increased by approximately 0.1 ºC. In addition, Finnish apartments have 2.8 ºC higher average T_w as compared to Lithuanian apartments. Moreover, T_w is slightly lower (-0.2ºC) in Finnish case buildings after the retrofits, whereas T_w is 0.6 ºC higher in Lithuanian case buildings, respectively.

The results are similar for indoor T_c (Table S2). However, the difference between countries is not as large, whereas the association between T_c and outdoor T is stronger. No significant difference in T_c is observed among the Finnish case study buildings after retrofits, whereas among Lithuanian case buildings the difference is 0.7 °C and statistically significant. This finding could be related to that most Lithuanian case buildings added insulation to external walls, which was not so commonly done in Finnish case buildings.

Tables S3 and S4 are presenting results related to relative humidity (RH_w and RH_c). As expected, both outdoor T and RH are significantly associated with indoor RH. In Finland, largest differences in RH_w are seen in the control buildings, which makes the interpretation challenging. In Lithuania, RH_w is significantly increased in the case buildings after retrofits. With respect to RH_c, neither one of the associations are statistically significant.

Indoor RH could be also affected by ventilation rate, which was checked by adding ventilation rate in the model for RH_w. In Finnish buildings, ventilation rate is associated with RH_w: by each 1 l/s per person increase, RH_w was decreased by 0.1 %, ($p <0.000$). At the same time, the association with the retrofit status diminished. In Lithuanian buildings, there is no statistically significant association between ventilation rate and RH (data not shown).

The measurement period for T and RH was quite long (about two months). Therefore, we tested influence of measurement period on the average T and RH values. The calculated minimum and maximum average values for one day, one week, one month and two months are presented in Figure 4. For temperature, the difference between 1-week, 1-month and 2-month average values was less than 0.5 °C in Finland. For RH, the difference was less than 2.7 %. In Lithuania, the difference for T values was less than 0.6 °C, and for RH values it was less than 7.2 %. Influence of measurement period was slightly larger in Lithuania most likely due to the higher influence of outdoor conditions on indoor conditions.

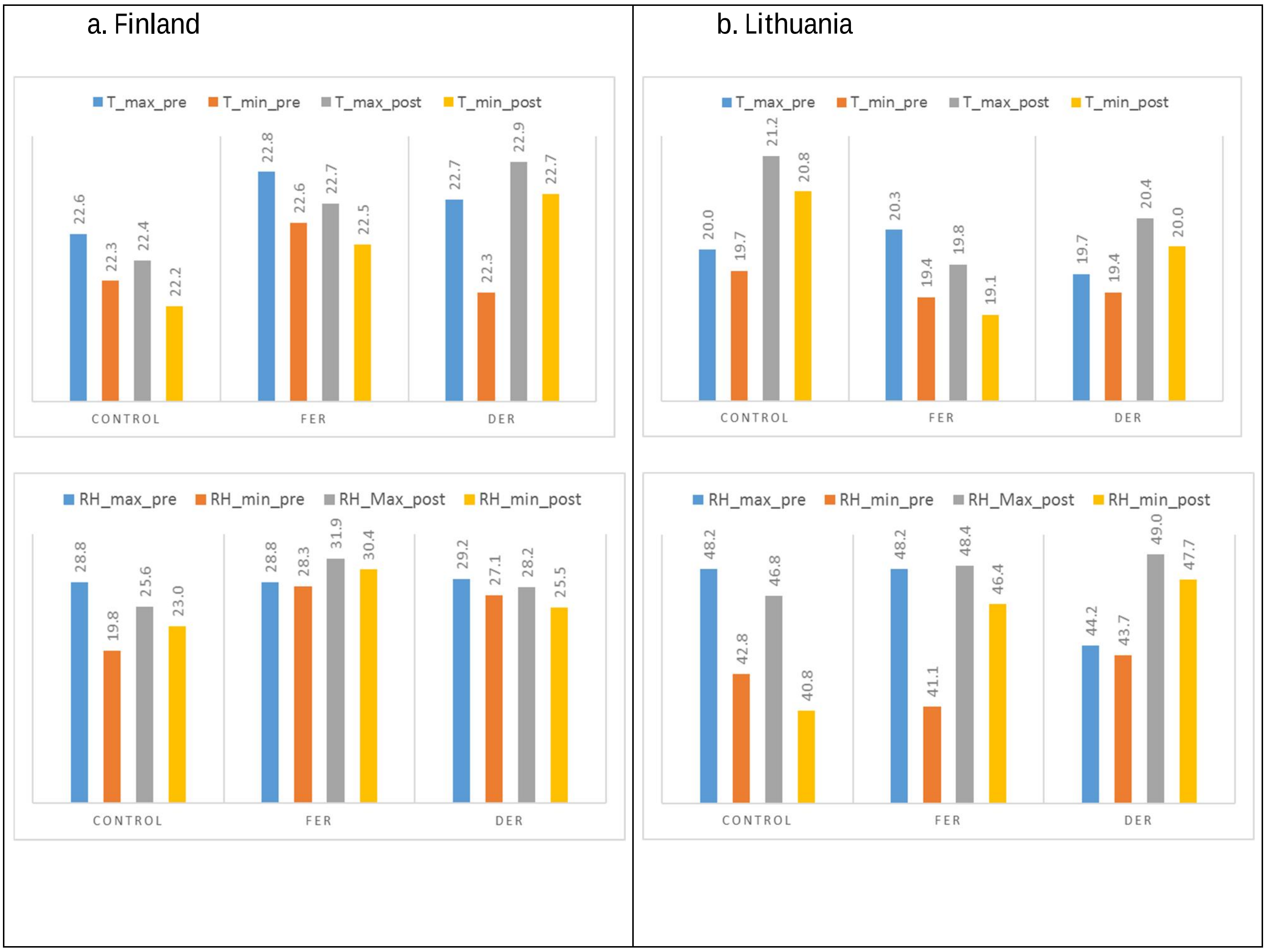

Figure 4. Calculated max/min average values of different measurement period.

3.2 Air flows and ventilation rates

Information on calculated ventilation rates [(dm^3/s)/m^2] based on the measured air flows from ventilation outlets and floor areas are shown in Table 3. For basic analyses, Finnish buildings were divided into three groups: cases (retrofitted) with mechanical exhaust ventilation, cases with natural ventilation, and controls with mechanical exhaust ventilation (there were no control buildings with natural ventilation). The air flow was higher in all buildings with mechanical exhaust ventilation than in the buildings with natural ventilation. No statistically significant difference was observed between measurements before and after the retrofits (crude $p > 0.05$). However, the average air flow was slightly higher after the retrofits in the case building with mechanical exhaust ventilation. On the contrary, the average air flow was slightly lower after the retrofits in the case buildings with natural ventilation, as well as in the second measurement of the control buildings.

Table 3. Air flows in Finnish (FI) and Lithuanian (LT) buildings.

FI	Air flow (dm³/s)/m²	CASE_Mechanical		CASE_Natural		CONTROL_Mechanical	
		1st	2nd	1st	2nd	1st	2nd
	N	114	72	11	9	10	8
	Average	0.32	0.35	0.17	0.15	0.41	0.31
	SD	0.18	0.20	0.09	0.09	0.19	0.11
	Median	0.29	0.30	0.17	0.13	0.41	0.28
	5th	0.07	0.13	0.06	0.04	0.17	0.18
	95th	0.61	0.62	0.31	0.27	0.67	0.44

LT	Air flow (dm³/s)/m²	CASE_Natural		CASE_mixed		CONTROL_Natural		CONTROL_Mixed	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd
	N	41	29	30	26	11	4	12	4
	Average	0.19	0.18	0.40	0.30	0.19	0.20	0.36	0.18
	SD	0.12	0.16	0.24	0.20	0.11	0.07	0.16	0.12
	Median	0.18	0.11	0.37	0.27	0.18	0.17	0.35	0.19
	5th	0.04	0.04	0.11	0.04	0.04	0.16	0.18	0.05
	95th	0.38	0.53	0.84	0.62	0.36	0.29	0.63	0.30

Lithuanian buildings were divided into four groups: cases with natural ventilation, cases with mixed ventilation (natural + exhaust), controls with natural ventilation, and controls with mixed ventilation. The average air flow through ventilation outlets was lower after the retrofits in the case (retrofitted) buildings and also in the second measurement in the control buildings. Similarly, in both case and control buildings with mixed ventilation, the average air flow was lower after the retrofits or in the second measurement.

Calculated ventilation rates (l/s per person) based on measured air flows from ventilation outlets and number of occupants are presented in Figure 5. The trends were similar in both countries. In Finland, ventilation rates were slightly higher after the retrofits in the case buildings with mechanical exhaust (especially in DER buildings), whereas ventilation rates were lower after the retrofits in the case buildings with natural ventilation (especially in FER buildings). Also in the control buildings, ventilation rates were lower based on the second measurement. In Lithuanian buildings, ventilation rates per person were lower than in Finnish buildings. Average ventilation rates were lower after the retrofits (cases) or in the second measurements (controls), especially in the buildings with mixed ventilation.

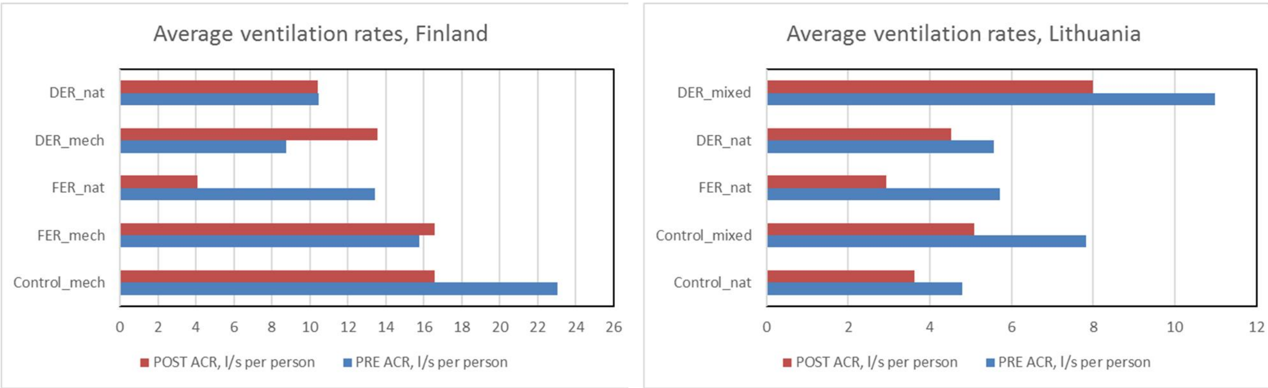

Figure 5. Average ventilation rates in Finnish and Lithuanian buildings.

Table 4 shows percentages of the apartments fulfilling lowest ventilation rate category (IDA4, 5 l/s per person) and highest category (IDA1, 20 l/s per person) of standard EN 13779 [6].

Table 4. Percentages of apartments in Finland fulfilling ventilation rate categories of standard EN 13779.

% of apartments	PRE/1st	POST/2nd	PRE/1st	POST/2nd
	Ventilation rate >5 l/s per person		Ventilation rate >20 l/s per person	
Finland				
CASE_Mechanical (N=114 pre/83 post)	89	90	28	28
Case_Natural (N=12 pre/8 post)	75	63	8	0
CONTROL_Mechanical (N=10 1st/8 2nd)	100	100	50	25
Lithuania	49	30	0	4
Case_Natural (N=39pre/27 post)	85	68	15	4
CASE_Mixed (N=27 pre/25 post)	36	25	0	0
CONTROL_Natural (N=11 1st/4 2nd)	92	67	0	0
CONTROL_Mixed (N=12 1st/3 2nd)	49	30	0	4

In Finnish case buildings, ventilation rate was over 5 l/s per person both before and after the retrofits in about 90% of the apartments with mechanical exhaust, and it was over 20 l/s per person in 28% of the apartments. In the case buildings with natural ventilation, ventilation rate was over 5 l/s per person before the retrofits in 75% and after the retrofits in 63% of the apartments, respectively. In Lithuanian case buildings, ventilation rate was over 5 l/s per person before the retrofits in 49% and after the retrofits in 30% of the apartments with natural ventilation, and before the retrofits in 85% and after the retrofits in 68% of the apartments with mixed ventilation. Ventilation rate was over 20 l/s per person in 15% before and 4% after the retrofits in the case apartments with mixed ventilation.

In Finland, the number of the measured apartments with natural ventilation was small, and air flow measurements were usually conducted during the time when the mechanical exhaust systems were set to the more efficient mode. That may explain why measured ventilation rates appeared to be quite appropriate. In Lithuanian buildings, the occupant operated exhaust fans were usually on during the measurement.

It is noteworthy that ventilation rates of the apartments with natural ventilation depend on the existing outdoor conditions: short term measurements are not necessary representative of a long term situation. In addition to air exchange through ventilation outlets, there is always some air infiltration due to air leakages through the building envelope [29][30]. Other parameters such as wind speed and direction, in conjunction with buoyancy or stack effect (temperature difference between indoor and outdoor air) impacts on air flows and ventilation rates, especially in naturally ventilated buildings, where ventilation largely depends on these forces. Whereas not measured in this study, we did measure pressure differences between indoor and outdoor, which are due to wind, stack effect and mechanical ventilation. These results, including correlations between pressure difference, air flows and CO2 concentrations are reported elsewhere (ref).

3.3 Carbon dioxide concentrations

Carbon dioxide (CO_2) concentrations may give a better indication of the effectiveness of the ventilation in diluting air pollutant concentrations from indoor sources. Calculated 95th percentile values in the evening and night-time (17-08 in Finland, 19-08 in Lithuania) are presented in Table 5. During these times, researchers were not present (therefore not influencing the concentrations) and the apartments were most likely fully occupied.

Concentrations of CO_2 in both case and control buildings were quite low in Finland, especially in the buildings with mechanical ventilation. In the case buildings with mechanical exhaust, and the concentration levels were about the same before and after the retrofits, and the concentration was 1150 ppm above outdoor concentration (about 400 ppm) in 1% of the buildings before the retrofits and in 2% after the retrofits. In the case buildings with natural ventilation, the concentration levels were lower after the retrofits and the concentration was 1150 ppm above outdoor concentration in 17% of the buildings before and 6% after the retrofits, respectively. In the control buildings, the concentration levels stayed about the same between measurements, and the limit concentration was not exceeded in any building.

Table 5. Descriptive statistics for night-time 95th percentile CO_2 concentrations [ppm] in Finland (FI) and in Lithuania (LT).

FI	CO_2	Case_Mechanical		Case_Natural		Control_Mechanical	
	(17-08)	1st	2nd	1st	2nd	1st	2nd
	N	135	91	29	18	22	15
	Average	820	803	1128	943	737	714
	SD	258	323	432	350	135	148
	Median	775	730	965	840	718	682
	5th	518	518	689	548	550	559
	95th	1267	1290	1866	1518	984	952

LT	CO_2	Case_Natural		Case_Mixed		Control_Natural		Control_Mixed	
	(19-08)	1st	2nd	1st	2nd	1st	2nd	1st	2nd
	N	37	31	28	26	10	4	12	4
	Average	1354	1445	1442	1562	1497	1532	1409	973
	SD	658	715	612	659	601	369	423	610
	Median	1254	1320	1372	1384	1420	1594	1279	807
	5th	614	612	742	742	646	1106	894	480
	95th	2670	2763	2456	2721	2316	1870	2072	1698

In Lithuanian case buildings, CO_2 concentrations were higher after the retrofits, both in the apartments with natural and mixed ventilation. Based on these measurements, mixed ventilation, installed afterwards by occupants, does not seem to result in a clear improvement in CO_2 concentrations. The concentration was above 1200 ppm before the retrofits in 51% and after the retrofits in 58% of the case buildings with natural ventilation, and in 64% before and 73% after in the case buildings with mixed ventilation. The concentration levels were lower in control buildings during the second measurement, and the concentration was above 1200 ppm in 70% (first measurement) and in 75% (second measurement) of the control buildings with natural ventilation and in 58% (first) and in 25% (second) in the control buildings with mixed ventilation, respectively.

All measured CO_2 concentrations were lower in Finland than in Lithuania. It was noticed that occupancy rate of the studied apartment was quite low in Finland: one occupant had about 43 m^2 living space on average in Finland, whereas in Lithuania, one occupant had an average of 23 m^2 (before the retrofits one occupant per 26 m^2). Higher occupancy can at least partly explain higher CO_2 concentrations in Lithuania. Therefore, also the ventilation rates per person could be lower in Lithuania. Controversially, there were no clear differences in air flows, especially in the apartments with natural ventilation. Air flows were even higher in Lithuania.

Tables S6 and S7 presents results from LMM analyses related to ventilation rate and maximum night time CO_2 concentrations, also taking into account the number of occupants. The model predicted average ventilation rate of about 2.6 l/s per person higher in Finnish buildings as compared to Lithuanian buildings, whereas maximum CO_2 level was significantly ($p<0.05$) lower (about 358 ppm) in Finland than in Lithuania, correspondingly. There was also a significant association between CO_2 concentration and number of occupants; the association was stronger in Lithuania where occupant density was higher and mechanical ventilation systems were not frequently used. Outdoor temperature was not associated with either ventilation rate or CO_2 concentration in Finnish buildings; however, there was a negative association between CO_2 concentration and outdoor T in Lithuanian buildings, possibly due to reduced opening of windows during cold weather.

It appears that in Finnish buildings, mechanical ventilation resulted considerably higher ventilation rates as compared to natural ventilation, also corresponding to lower maximum CO_2 concentration. Further on, there was a positive association between retrofit status and ventilation rates: average ventilation rate was about 2.1 l/s-person higher in retrofitted buildings than before the retrofits. On the other hand, there was a reverse association between retrofit status and ventilation rate in Lithuanian case building: average ventilation rate was about 2.2 l/s-person lower in the case buildings after the retrofits than before the retrofits. Retrofit status was not significantly associated with maximum night time CO_2 concentration in either countries (or the effect is too small with the current sample size).

3.4 Effects of the level of retrofits

Further analyses were conducted among case buildings in order to evaluate the effects of level of retrofit on T_w, RH_w, and ventilation rate. These analyses were restricted due to small number of buildings undergoing deep energy retrofits (DER) in Finland, and focused energy retrofits (FER) in Lithuania.

With respect to indoor T_w (Table S8), there was no difference between Finnish DER and FER buildings, although only the decrease in T_w in FER buildings after retrofits was statistically significant. In Lithuanian buildings, a larger increase was seen in DER buildings, although non-significant due to a small sample size.

In Finnish buildings, RH_w was slightly decreased, more prominently in DER buildings, which could be related to improved ventilation (Table S9). In Lithuanian buildings, RH_w was increased by 3% in FER and by 7% in DER buildings after the retrofits, indicating that the level of retrofit may have an effect on $RH_{w.}$ However, the p-value of 0.09 does not reach the level of statistical significance, possibly due to the limited sample size.

With respect to ventilation rate (Table S10), once again, there was no difference between FER and DER buildings in Finland: average ventilation rates were increased after retrofits. In Lithuania, the small sample size limits any conclusions, however, the reference group being FER buildings before retrofits, both FER and DER buildings have a relative decrease in ventilation rates after retrofits.

4 Conclusions

Based on the results, overheating was common both before and after the energy retrofits in Finnish buildings. Ventilation rates (l/s per person) were significantly higher after the retrofits in Finnish case buildings with mechanical exhaust ventilation. In Lithuanian case buildings, indoor temperatures increased significantly, whereas relative humidity increased, and ventilation rates were significantly lower after the retrofits. Assessment of thermal conditions and ventilation, and adjusting heating and ventilation systems accordingly, should help to maximize positive effects of energy retrofits.

Acknowledgements

This study is part of the INSULAtE project, funded by EU Life+ programme (ENV/FI/000573) and Finnish Energy Industry. The authors wish to thank the INSULAtE project group, Steering Board members, as well as building owners and occupants who participated in the study.

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Supplementary data. Result tables of LMM analyses.

Table S1. Linear mixed model for average indoor T [ºC] in the warm area during 2-month monitoring.

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	19.81	19.56	20.07	***	22.66	22.49	22.83	***	19.59	19.21	19.96	***
Country												
Finland	2.76	2.48	3.04	***								
Lithuania	0[b]	.	.									
Retrofit status												
Control; 2nd measurement	.18	-.26	.61		-.03	-.50	.43		1.08	-.07	2.23	†
Case; 2nd measurement	.02	-.15	.18		-.19	-.35	-.03	*	.57	.17	.98	**
Control; 1st measurement	.31	-.07	.68		.35	-.12	.81		.37	-.35	1.08	
Case; 1st measurement	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Outdoor T	.08	.05	.10	***	.07	.05	.10	***	0.05	-.00	.11	†

[b] This parameter is set to zero because it is redundant. *p<0.05 **p<0.01 ***p<0.001 †p<0.1

Table S2. Linear mixed model for average indoor T [ºC] in the cold area during 2-month monitoring.

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	18.18	17.80	18.55	***	20.12	19.85	20.38	***	17.9	17.46	18.43	***
Country												
Finland	1.75	1.33	2.17	***								
Lithuania	0[b]	.	.									
Retrofit status												
Control; 2nd measurement	.14	-.60	.88		-.05	-.91	.82		.15	-1.37	1.67	
Case; 2nd measurement	.17	-.08	.42		-.11	-.36	.15		.74	.20	1.29	**
Control; 1st measurement	.36	-.24	.96		.29	-.55	1.13		.40	-.53	1.33	
Case; 1st measurement	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Outdoor T	.16	.13	.20	***	.13	.08	.17	***	0.20	.13	.28	***

[b] This parameter is set to zero because it is redundant. *p<0.05 **p<0.01 ***p<0.001 †p<0.1

Table S3. Linear mixed model for average indoor RH [%] in the warm area during 2-month monitoring.

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	23.94	16.80	31.09	***	6.09	-.65	12.82	†	18.93	-2.37	40.22	†
Country												
Finland	-18.96	-20.60	-17.33	***								
Lithuania	0[b]	.	.									
Retrofit status												
Control; 2nd measurement	-3.59	-6.11	-1.07	**	-3.97	-6.48	-1.46	**	-.95	-8.13	6.24	
Case; 2nd measurement	.33	-.70	1.36		-.65	-1.67	.38		3.04	.35	5.73	*
Control; 1st measurement	-2.62	-4.78	-.46	*	-3.37	-5.81	-.94	**	-.45	-4.97	4.06	
Case; 1st measurement	0[b]	.	.		0	.	.		0	.	.	
Outdoor T	.75	.61	.90	***	.77	.63	.91	***	.64	.19	1.10	**
Outdoor RH	.28	.19	.38	***	.27	.19	.36	***	.33	.05	.61	*

[b] This parameter is set to zero because it is redundant. *p<0.05 **p<0.01 ***p<0.001 †p<0.1

Table S4. Linear mixed model for average indoor RH [%] in the cold area during 2-month monitoring.

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	13.81	5.01	22.61	**	-6.78	-4.45	.89	†	22.02	-2.30	46.34	†
Country												
Finland	-19.29	-21.23	-17.34	***								
Lithuania	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Retrofit status												
Control; 2nd measurement	-2.35	-5.66	.95		-2.37	-5.69	.94		2.97	-5.07	11.02	
Case; 2nd measurement	-.22	-1.40	.96		-.93	-1.90	.03	†	2.40	-.71	5.51	
Control; 1st measurement	-2.14	-4.88	.60		-1.82	-5.12	1.48		-.27	-5.19	4.66	
Case; 1st measurement	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Outdoor T	.75	.56	.94	***	.97	.79	1.15	***	.16	-.35	.68	
Outdoor RH	.47	.36	.59	***	.49	.39	.59	***	.35	.03	.67	*

[b] This parameter is set to zero because it is redundant. *p<0.05 **p<0.01 ***p<0.001 †p<0.1

Table S5. Linear mixed model for ventilation rate [l/s-person].

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	5.60	4.10	7.82	***	7.59	2.57	12.6	**	7.74	-19.99	-.64	***
Country												
Finland	2.60	-1.83	7.04									
Lithuania	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Retrofit status												
Control; 2nd measurement	-.23	-4.41	3.94		3.27	-3.38	9.93		-3.70	-8.50	1.10	
Case; 2nd measurement	.65	-.70	2.01		2.10	.24	3.96	*	-2.17	-3.86	-.49	*
Control; 1st measurement	2.19	-1.00	5.38		7.24	.91	13.57	*	-1.43	-4.19	1.34	
Case; 1st measurement	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Type of ventilation												
Mechanical	8.33	4.08	12.57	***	8.45	3.13	13.37	**				
Natural	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Tout	-0.5	-.25	.14		0.02	-.29	.32		0.00	-.23	.23	

[b] This parameter is set to zero because it is redundant. *p<0.05 **p<0.01 ***p<0.001 †p<0.1

Table S6. Linear mixed model for maximum night time CO_2 concentration [ppm].

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	996	791	1202	***	727	511	943	***	749	409	1090	***
Country												
Finland	-358	-636	-80	*								
Lithuania	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Retrofit status												
Control; 2nd measurement	9	-2401	257		120	-95	336		50	-560	659	
Case; 2nd measurement	58	-48	164		18	-71	108		115	-136	366	
Control; 1st measurement	-135	-343	73		-76	-311	159		-165	-530	199	
Case; 1st measurement	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Type of ventilation												
Mechanical	-112	-369	146		-63	-242	116					
Natural	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Tout	-13	-27	-0	*	-4	-14	10		-37	-69	-5	*
Number of occupants	256	185	328	***	140	63	217	***	360	234	486	***

b This parameter is set to zero because it is redundant. *p<0.05 **p<0.01 ***p<0.001 †p<0.1

Table S7. Linear mixed model for average indoor T [ºC] in the warm area in the case buildings during 2-month monitoring.

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	20.04	19.58	20.49	***	22.7	22.51	22.88	***	19.63	18.56	20.70	***
Country												
Finland	2.60	2.20	3.08	***								
Lithuania	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Retrofit status												
DER; 2nd measurement	.01	-.43	.45		-.26	-.73	.21		.55	-.64	1.75	
FER; 2nd measurement	-.23	-.43	-.03	*	-.24	-.41	-.08	**	.14	-1.11	1.38	
DER; 1st measurement	-.42	-.85	.01	†	-.35	-.81	.12		-.05	-1.18	1.08	
FER; 1st measurement	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Outdoor T	0.08	.05	.10	***	0.08	.05	.11		0.06	-.01	.13	†

[b] This parameter is set to zero because it is redundant. *p<0.05 **p<0.01 ***p<0.001 †p<0.1

Table S8. Linear mixed model for average indoor RH [%] in the warm area in the case buildings during 2-month monitoring.

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	24.59	15.94	33.25	***	6.28	-1.63	14.19	**	18.55	-4.50	41.61	***
Country												
Finland	-18.63	-21.25	-16.02	***								
Lithuania	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Retrofit status												
DER; 2nd measurement	.96	-1.65	3.57		-1.44	-4.08	1.18		6.58	-.94	14.11	†
FER; 2nd measurement	-.45	-1.72	.82		-.61	-1.781	.56		3.03	-4.24	10.30	
DER; 1st measurement	-1.212	-3.80	1.39		-1.075	-3.763	1.62		3.03	-4.20	10.25	
FER; 1st measurement	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Outdoor T	.68	.51	.84	***	.74	.58	.89	***	.47	-.03	.98	†
Outdoor RH	.28	.17	.38	***	.27	.17	.37	***	.30	.01	.58	*

[b] This parameter is set to zero because it is redundant. *p<0.05 **p<0.01 ***p<0.001 †p<0.1

Table S9. Linear mixed model for ventilation rate [l/s-person] in the case buildings.

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	5.77	1.81	9.73	**	8.18	1.54	14.81	*	5.71	1.62	9.8	**
Country												
Finland	1.65	-2.96	6.27									
Lithuania	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Retrofit status												
DER; 2nd measurement	.60	-3.65	4.86		1.88	-5.19	8.96		.17	-4.44	4.78	
FER; 2nd measurement	1.70	-.10	3.50	†	1.89	-.15	3.93	†	-3.45	-9.66	2.76	
DER; 1st measurement	1.56	-2.47	5.60		-1.11	-7.57	5.35		2.37	-2.01	6.74	
FER; 1st measurement												
Type of ventilation												
Mechanical	8.6	3.57	13.61	**	7.77	1.25	14.29	*				
Natural	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Tout	-0.01	-.24	.21		0.02	-.29	.33		-0.00	-.28	.28	

[b] This parameter is set to zero because it is redundant. *p<0.05 **p<0.01 ***p<0.001 †p<0.1

Graphical abstract