Spatiotemporal humidity variation in student housing

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Abstract. Modern, urban apartments are space-efficient, have bathrooms with no windows, and require energy-efficient ventilation with heat recovery. The requirements for exhaust ventilation rates for the kitchen and bathrooms are independent of dwelling size. In some countries, it is required that the extract air can be increased on demand. There is a need for more knowledge on the effects of these requirements on the resulting moisture level in apartments, and whether these recommendations should be modified. Measurements were done in eight student apartments. Temperature and humidity were measured with 1-minute time resolution at 5 locations in each of the apartments. Median moisture excess was 0.9-1.4 g/m^3, indicating a small risk of interstitial condensation. 90th percentiles of relative humidity were 30-35 %, indicating an elevated risk of eye and airway symptoms due to low humidity. The moisture excess was lower in apartments with heat-recovery ventilation than mechanical extract ventilation. The median moisture excess was higher in the living rooms than in bathrooms, indicating that moisture from showering and personal hygiene had little impact on the overall indoor moisture conditions in the dwellings. The average number of showers per day per apartment varied between 0.6 and 3.1. High peak moisture excess values up to 20 g/m^3 were recorded in bathrooms, but for brief periods only. Consistently higher moisture peaks in extract vents than in bathroom air demonstrated that ventilation extract above the shower is effective in removing moist air from showering. Calculated moisture load in the extract air from a single shower was estimated to be 0.86 kg. Outdoor temperatures were negatively correlated with moisture excess, as predicted by EN -ISO 13788.

Keywords. Moisture excess, ventilation, dwellings
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1. Introduction

Recommendations and regulations for residential ventilation aim at maintaining good indoor air quality by removing pollutants and moisture. In different countries, this may be reflected in requirements for overall air change rate, fresh supply airflow rate per floor area, as well as required extract flow rates from kitchens and bathrooms and supply rates for bedrooms. Important requirements in current Nordic regulations are summarized in Tab. 1.

Increasing ventilation rates beyond what is needed to avoid moisture damage risk and dilute pollutants to healthy and comfortable levels may contribute to uncomfortably or unhealthy low humidity levels. It also increases energy demand for fans, heating, and cooling, as well as space demand due to larger duct dimensions. The forced extract rates required in Norway and Finland also complicate the control of the ventilation system. Earlier studies from Nordic climates have indicated that the moisture excess generally is quite low in newer dwellings [1-4], also lower compared to older buildings[5]. An analysis of data from the Swedish building stock pointed out that smaller dwelling volumes, more recent construction, and higher ventilation rates were among factors associated with low indoor relative humidity [6]. Other countries with similar climatic conditions do not have this requirement. Since the motivation for the extract rates is moisture removal and not general air quality, it is of interest to examine if the extract rates are higher than needed for the removal of actual moisture sources. Most of the previous studies are done with limited temporal and spatial resolution, and mostly in somewhat larger dwellings.

Estimates of moisture loads from individual sources are available in the literature [7-9], but some of this information is relatively old, and may not reflect the current building usage. Short-term events like cooking or showering will typically cause highly variable moisture loads, and measurements with high time resolutioin at different locations within the dwelling would enable more precise risk evaluation than average values in one or two locations. Such datasets are scarce. As the discrepancy between requirements due to extract air and general ventilation are most prominent in small dwellings, the present study examined student accommodation intended for couples or small families.

Tab. 1. Ventilation requirements in four Nordic countries. (Extract values are formally "pre-accepted suggestions" in Norwegian legislation)

		Denmark	Sweden	Finland	Norway
General ventilation requirement (m^3/h per m^2)		1.08	1.24	1.24	1.2
Supply rate bedroom (m^3/h)			14.4 / bed	29-43 / room	26 / bed
Extract bathroom	-normal (m^3/h)	-	54	36	54
	-forced (m^3/h)	54		40	108
Extract kitchen	-normal (m^3/h)	-	36	29	36
	-forced (m^3/h)	72	100-140	25	108

2. Methods

2.1 Apartments

Eight apartments in two student housing buildings were monitored for 14 days, either (I) February 25th – March 10th or (II) March 11th -24th, 2021.

The buildings are situated less than 100 m apart in the municipality of Ås, Norway. Characteristics of the buildings and their apartments are given in Tab. 2. Typical floorplans are shown in Appendix A.

Tab.2 Properties of the monitored apartments

	Palisaden	Pentagon
Construction year	2014, passive house standard	1975
Ventilation system	Balanced mechanical ventilation, supply and extract, heat recovery	Mechanical extract
Floor area per apartment (m^2)	28.0 -30.7	37.8 – 41.6
Extract airflow rates (m^3/h)	Bathroom: 50-59 Kitchen: 0 m^3/h (recycling hood, only)	Bathroom: 58-65 Kitchen: 0-37 Rangehood on: 83-85 m^3/h
Supply airflow rates (m^3/h)	48-53	Passive supply only

2.2 Measurement

Relative humidity (RH), CO_2, and temperature were measured in the kitchen/living rooms and the bedrooms using a Rotronics CP11 handheld instrument. The loggers were placed about 1.1 m above the floor (see Appendix A). RH and temperature were measured in the bathroom, the extract, and supply air ducts using smaller data loggers (EL-USB-2+ and Tinytag ULTRA 2-TGU-4500). All measurements were logged at 1-minute intervals. Measurements of outdoor temperature and relative humidity with 10 minute intervals from the meteorological station at Ås (NMBU) were downloaded and used for calculating moisture excess and assessing the outdoor dependency of indoor conditions. Parameters logged at the different locations in each apartment are summarized in Tab. 3. Airflow rates in air extract vents in bathrooms and kitchens were measured with a Swemaflow 125 air capture anemometer (Swema AB, Sweden) using the back-pressure method.

The inhabitants were asked to log a number of activities, including showers and window airing within each hour of the measurement period.

Tab.3 Monitored indoor parameters.

	Palisaden	Pentagon
Bedroom	T, RH, CO_2	T, RH, CO_2
Cooking/ living area	T, RH, CO_2	T, RH, CO_2
Bathroom	T, RH	T, RH
Extract hood (cooking area)	-	T, RH
Extract duct	T, RH	T, RH
Supply duct	T, RH	-

2.3 Analysis

Moisture excess Δv (g/m^3) was calculated for each time i from indoor and outdoor absolute moisture content v_{ind} and v_{out} by:

$$\Delta v_i = v_{ind,i} - v_{out,i} \quad (1)$$

Where moisture content v is defined by

$$v = \phi_r \cdot \frac{\rho_{sat}}{461.4 \cdot \theta} \quad (2)$$

where ϕ_r = RH (%), ρ_{sat}= water saturation pressure (Pa) and θ is the temperature (K).

ρ_{sat} was calculated for different temperature intervals t as follows:

-30 °C ≤ t ≤ 0 °C: (3a)

$$p_{sat} = 611 \cdot \exp\big((82.9 \cdot 10^{-3} \cdot t) - (288.1 \cdot 10^{-6} \cdot t^2) + (4.403 \cdot 10^{-6} \cdot t^3)\big)$$

0 °C < t ≤ 40 °C: (3b)

$$p_{sat} = 611 \cdot \exp\big((72.5 \cdot 10^{-3} \cdot t) - (288.1 \cdot 10^{-6} \cdot t^2) + (0.79 \cdot 10^{-6} \cdot t^3)\big)$$

To identify the short-term events that generate moisture, we defined Δv(change) as the deviation from the 5-minute running mean of Δv as

$$\Delta v(change) = \Delta v_i - (\sum_{i-6}^{i-1} \Delta v_i)/5 \quad (4)$$

The starting point a of a short term event was determined by analyzing where the moisture excess Δv begins to rise above the humidity that already exists in the room. Pragmatically, $\Delta v(change) >$ 1,5 g/m ^{3}was selected as a criterion.

The endpoint b of an event was determined by analyzing where the moisture supplement again reaches the original moisture level, defined as $v_b < v_a + 0{,}2$ g/m^3.

The total moistuire production G (g) was then estimating by summing 1 minute values according t eq. (5)

$$G = \dot{V} \cdot \sum_{i=a}^{b} (v_i - v_a) \quad (5)$$

where $\dot{V}$ is the measured extract airflow rate (m^3/min)

3. Results and discussion

3.1 Temperature, RH and moisture excess

Tab. 4 shows the outdoor conditions and Tab. 5 the indoor climatic parameters for all apartments in the two buildings. The median temperatures measured in all rooms in the apartments at Palisaden were generally slightly higher than Pentagon. Compared to a survey of 3195 Norwegian family dwellings from 2012 [10], the indoor temperatures in the student apartments in our study were notably higher, however, they were comparable to measured indoor temperature from high-performance residential buildings [11].

Tab. 4 Outdoor conditions during monitoring

Period	**Air temperature** (°C)	**Relative humidity** (%)
	median [min;max]	
I	*1.5* [-7.4;12.1]	*72.6* [28.1;100]
II	*2.5* [-4.6;11.6]	*75.6* [34.3;100]

Compared to previous studies on measurements of RH in dwellings [3, 4, 12], the RH measured in the apartments in our study is low (<30%) in both buildings. 90th percentiles of relative humidity for all rooms were between 30-35 %, indicating an elevated risk of eye and airway symptoms. Although humidification is generally not recommended, for buildings where humidification is installed, EN 16798-1:2019 [13] suggests the design relative humidity in category II for residential buildings to be set at 25 % RH, which is close to the median RH values in our study.

Tab. 5 Indoor parameters. Median [10th;90th percentile] of all measured values.

	Palisaden	**Pentagon**
	Kitchen/living rooms	
RH [%]	24.4 [19.8:29.9]	26.8 [20.9:34.7]
T [°C]	24.1 [23:25.4]	22.3 [21.3:24.2]
$\Delta \boldsymbol{v}$ [g/m^3]	1.3 [0.4:2.5]	1.4 [0.3:2.7]
	Bedrooms	
RH [%]	24.6 [18.5:31.3]	27.3 [20.5:35.4]
T [°C]	22.6 [20.4:24.6]	21.9 [20.6:23.7]
$\Delta \boldsymbol{v}$ [g/m^3]	0.9 [0:2]	1.2 [0.1:2.9]
	Bathrooms	
RH [%]	22 [17.1:29.5]	21.6 [16.9:28.8]
T [°C]	25.1 [23.6:25.8]	24.8 [23.7:25.7]
$\Delta \boldsymbol{v}$ [g/m^3]	1.1 [0.1:2.6]	1.0 [-0.1:2.3]

As shown in fig. 1-3, the moisture excess was also modest (<2 g/m^3) compared to previous studies [3, 5, 14, 15]. The highest median internal moisture excess was found in the kitchen/living rooms indicating that moisture from showering and personal hygiene had little impact on the overall indoor moisture conditions in the dwellings.

The moisture excess was generally lower in apartments with heat-recovery ventilation at Palisaden than at Pentagon (mechanical extract ventilation).

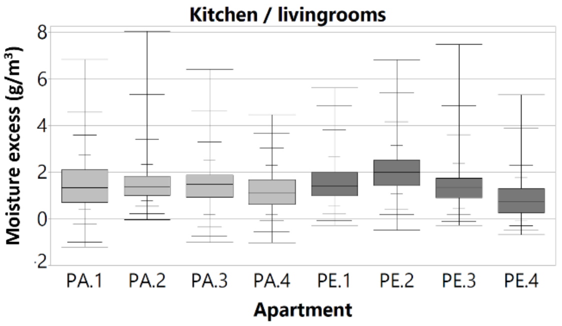

Fig. 1 Internal moisture excess in kitchen/living rooms measured during 14 days for each apartment at Palisaden (PA) and Pentagon (PE).

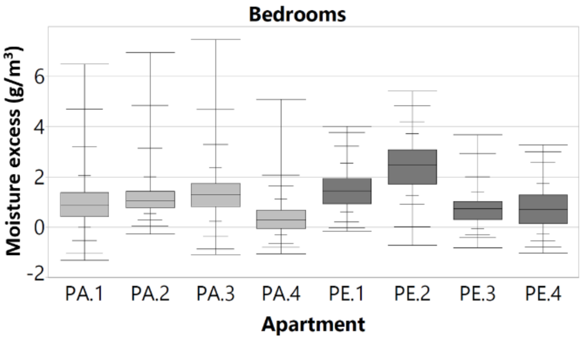

Fig. 2 Internal moisture excess in bedrooms measured during 14 days for each apartment at Palisaden (PA) and Pentagon (PE).

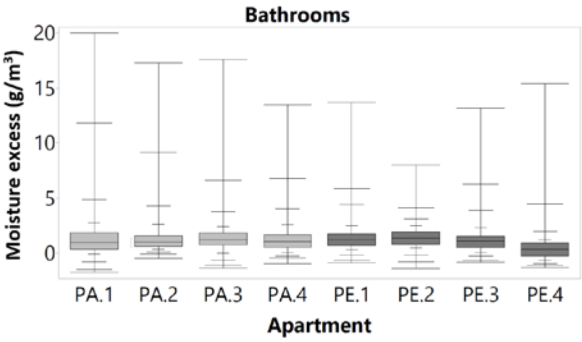

Fig. 3 Internal moisture excess in bathrooms measured during 14 days for each apartment at Palisaden (PA) and Pentagon (PE).

3.2 Outdoor temperature dependency

Previous studies have uncovered that the mean moisture excess levels tend to be higher with lower daily mean outdoor temperatures, an effect ascribed to more frequent opening of windows and doors at higher outdoor temperatures [16]. A common assumption is that this effect is present above a certain outdoor temperature, below which windows are kept closed and moisture excess is constant.

According to EN 13788, the moisture excess is reduced as outdoor temperature increases from 0 to 20°C. Based on the analysis of Finnish and Estonian dwellings, Ilomets et al. [12] suggested +5°C as a more suitable deflection point for an indoor humidity model.

Measurements for individual rooms and apartments were fitted to a linear model using the least sum of squares. The temperature coefficients are summarized in **Tab. *6***.

Tab. 6. Temperature coefficients of moisture excess (g/m^3 per °C). *Media*n [minimum: maximum]

	Palisaden	Pentagon
Bedroom	*-0.04* [-0.08:0.08]	*-0.03* [-0.07:0.12]
Living room	*-0.05* [-0.19:0.03]	*-0.02* [-0.13:0.07]
Bathroom	*-0.14* [-0.70:0.95]	*-0.10* [-0.40:0.15]

In our study, we found an overall reduction of moisture excess with increasing temperatures. The strongest correlation between temperature and moisture excess was found for the bathrooms, and the temperature dependency was generally stronger at Palisaden than at Pentagon.

The daily mean outdoor temperatures during the study were below 0 °C for four days only, all occurring during the first monitoring period. Temperature coefficients for days where the outdoor mean temperature was < 0° C are given in **Tab. *7***. Any inferences from this small data set are highly uncertain, but it can be noted that the two apartments at Palisaden still show a negative correlation between moisture excess and outdoor temperature below 0°, while this is the case only for the bedrooms at Pentagon.

Tab. 7. Temperature coefficients of moisture excess (g/m^3 per °C) when daily outdoor temperatures were < 0°C. Values for individual apartments (N=4).

	Palisaden	Pentagon
Bedroom	-0.23/ -0.12	-0.18/ -0.26
Living room	-0.26/ -0.29	0.25/ 0.35
Bathroom	-0.48/ -0.15	0.26/ 0.24

According to the user logs, the inhabitants ventilate through windows even at the lowest temperatures, presumably to improve thermal comfort. The inhabitants are not billed for their individual heating costs and have little motivatation to reduce heat loss.

3.3 Moisture in bathrooms

Median relative humidity and moisture excess in the bathrooms were low, but with short periods of high humidity, as clearly visible in Fig. 3.

Moisture excess above running mean of previous 5 minutes ($\Delta v(change)$) higher that 1.5 g/m^3 effectively identified shower events reported by inhabitants, se example in Fig. 4, with a notable exception being one inhabitant reporting 2-3 repeated showers within one hour. These were not readily identified as separate events. In addition to 145 showers reported in the user logs, 8 further events with similar pattern were identified from measurement data. These were assumed to be showers as well. Average number of showers per day per apartment in the 14-day period ranged from 0.6 to 3.1.

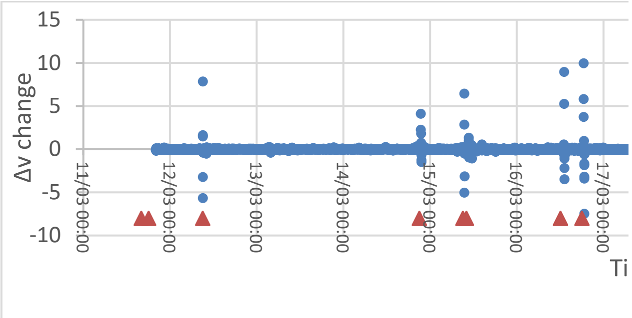

Fig. 4 Moisture excess change from 5-minute running mean (dots) and showers from user diaries (triangles)

3.4 Moisture loads

Moisture loads calculated from two representative shower events based on the ventilation rate and moisture excess above baseline were 0.75 and 0.86 kg when using data from the extract air duct, and 0.47 and 0.58 when using data from the room sensor. This is notably higher than values suggested by Johansson et al. [17] which were in the range of 0.20-0.38 kg per event.

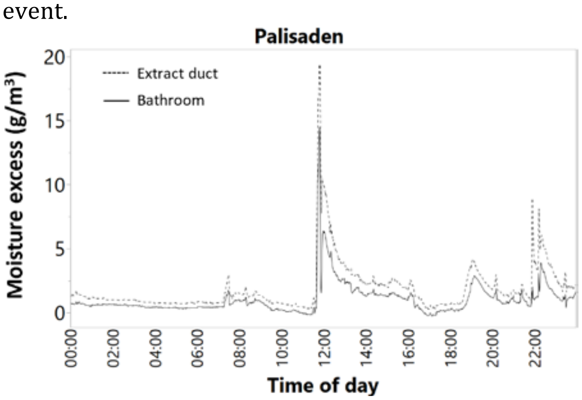

Fig. 5 One representative shower event in Palisaden showing the difference between moisture excess when using data from the extract duct and data from the room sensor.

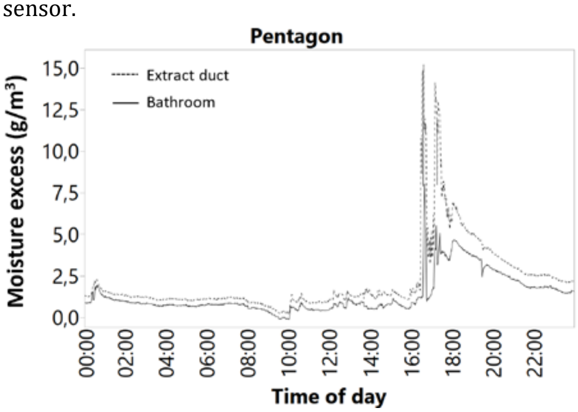

Fig. 6 Representative shower events in Pentagon (two showers during two hours) showing the difference between moisture excess when using data from the extract duct and data from the room sensor.

Fig. 7 shows the comparison of the time of day when showers are taken from our study with data from literature [17]. The data of showering is based on a survey of activity patterns for Californian residents in the period of 1987-1988.

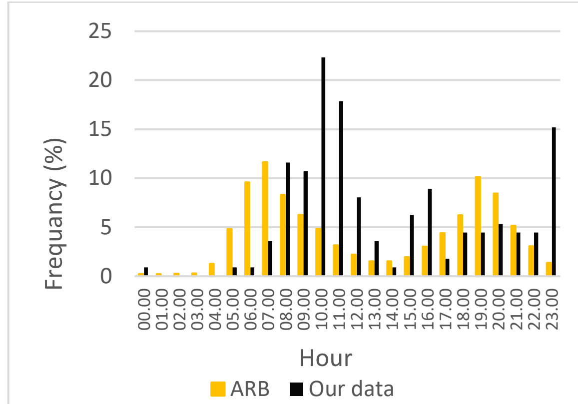

Fig.7 Relative frequency of showering in 1h intervals in our data, compared with data from California Air Research Board (ARB) *[17].*

The showering habits are likely affected by the monitoring taking place in a period of lockdown due to Covid-19 but are still plausible according to assumed student activities. Our findings support the results from analysis of domestic hot water loads that the diurnal patterns of showering in buildings may vary substantially between households [18]. The likelihood of several simultaneous showers may influence the function of the heat recovery units as well as the energy demand. Monitoring of humidity in dwellings can potentially add further insights into these patterns.

3.6 Risks

Indoor humidity can affect building users in several ways. In Nordic climate, the main concerns are possible negative effects on eyes, airways and skin due to low relative humidity [19, 20]. Risk of microbial growth due to condensation on surfaces or within the construction may be among consequences of high relative humidity. The mean relative humidities well below 30 % observed in this study are sufficiently low to cause some concern about possible negative effects of low humidity, in particular because the mean outdoor temperatures in the studied periods were higher than the local monthly normal mean temperature for January and February of -2.9 °C and -2.5 °C. Thus, even lower indoor humidity is probably common. The mean moisture excess, on the other hand, was well below the suggested design moisture excess [12]. Thus we regard that the low relative humidity as more likely to cause negative effects than any condensation due to indoor moisture excess.

4. Conclusion

The conditions in the apartments, and the bathromms in particular were mostly dry. The highest 90th percentile value for moisture excess and relative humidity in bathrooms in either of the eight apartments was 2.6 g/m^3 and 28.8 %, respectively. These low values, even in a period with low outdoor temperatures, and in apartments with up to 3 daily showers on average, indicate that the actual extract rates of 50-65 m^3/h may be sufficient to prevent moisture problems related to sources in the bathrooms, with no need for additional forced ventilation. However, the substantially higher moisture load estimated from showers when using measurements in the extract duct than in the room may not be representative for all ventilation configurations. Furthermore, moisture capture will be less efficient in situations where the supply air contains more moisture.

We recommend further studies of the factors affecting the efficacy of ventilation to remove moisture from sources, these include the location of air supply and extract relative to main moistur source (shower), the moisture content of supplied air, the moisture buffering and the effect of floor heating in bathrooms before making specific recommendations on extract ventilation rates in bathrooms.

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6. Appendix A Floorplans

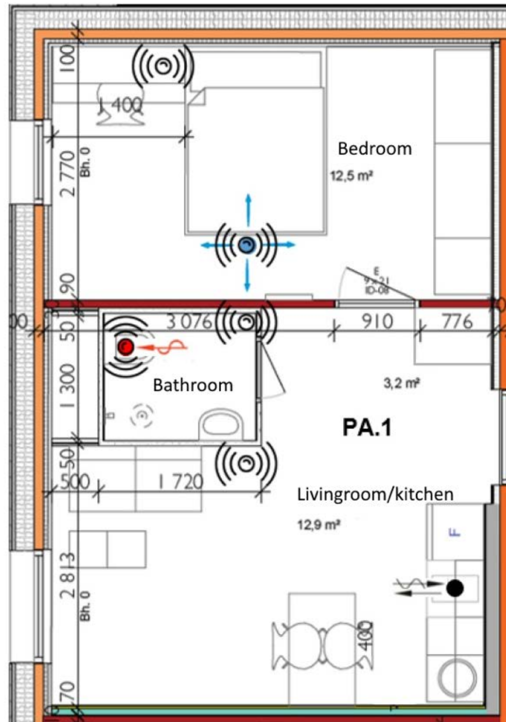


Fig. 8 Representative floorplan for apartment in Palisaden.

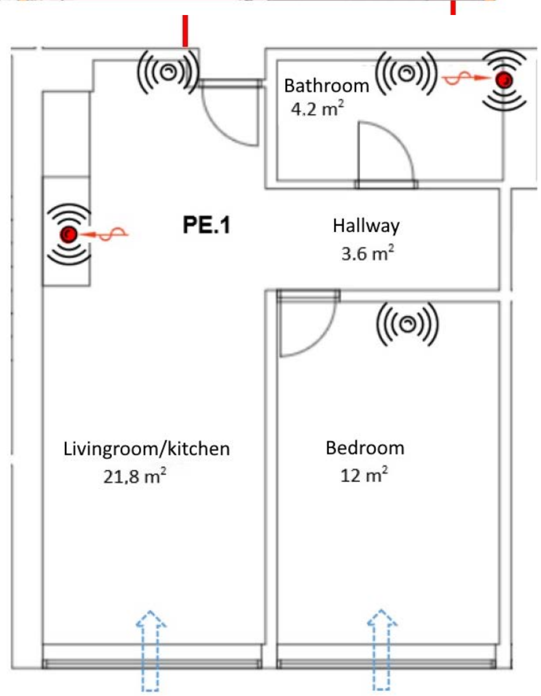
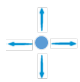
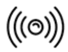


Fig. *9* Representative floorplan for apartments in Pentagon.

Tab. 8 Explanation of the symbols used in floor plans (Fig. 8 and Fig. 9)

Symbol	Explanation
	Extract valve
	Recycling kitchen hood
	Mechanical supply air
	Passive supply air
	Sensor

7. References

1. Kalamees T, Korpi M, Vinha J, Kurnitski J. The effects of ventilation systems and building fabric on the stability of indoor temperature and humidity in Finnish detached houses. Building and Environment. 2009:1643-50.
2. de Place Hansen EJ, Møller EB. Moisture supply in Danish single-family houses – the influence of building style. Energy Procedia. 2017;132:147-52.
3. Møller EB, de Place Hansen EJ. Moisture supply in Danish single-family houses – the influence of occupant behavior and type of room. Energy Procedia. 2017;132:141-6.
4. Vinha J, Salminen M, Salminen K, Kalamees T, Kurnitski J, Kiviste M. Internal moisture excess of residential buildings in Finland. J Build Phys. 2018;0(0):1744259117750369.
5. Geving S, Holme J. Mean and diurnal indoor air humidity loads in residential buildings. J Build Phys. 2012;35(4):392-421.
6. Psomas T, Teli D, Langer S, Wahlgren P, Wargocki P. Indoor humidity of dwellings and association with building characteristics, behaviors and health in a northern climate. Building and Environment. 2021;198:107885.
7. Rousseau MZ. Sources of moisture and its migration through the building enclosure. Standardization News. 1984;12(11):35-7.
8. IEA IEA. IEA Annex 14, Condensation and Energy: Volume 1, Sourcebook1991.
9. Yik FWH, Sat PSK, Niu JL. Moisture Generation through Chinese Household Activities. Indoor and Built Environment. 2004;13(2):115-31.
10. Halvorsen B, Dalen HM. Ta hjemmetempen. Oslo: Statistics Norway; 2013.
11. Berge M, Mathisen HM. Perceived and measured indoor climate conditions in high-performance residential buildings. Energy and Buildings. 2016;127:1057-73.
12. Ilomets S, Kalamees T, Vinha J. Indoor hygrothermal loads for the deterministic and stochastic design of the building envelope for dwellings in cold climates. J Build Phys. 2018;41(6):547-77.
13. STANDARDIZATION ECF. Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (Module M1-6). 2019.
14. Geving S, Holme J, editors. Diurnal variations of indoor air humidity in Norwegian houses. Energy Efficiency and New Approaches - Proceedings of the 4th International Building Physics Conference; 2009: Istanbul Technical University.
15. Wang J, Engvall K, Smedje G, Nilsson H, Norbäck D. Current wheeze, asthma, respiratory infections, and rhinitis among adults in relation to inspection data and indoor measurements in single-family houses in Sweden—The BETSI study. Indoor Air. 2017;27(4):725-36.
16. Kalamees T, Vinha J, Kurnitski J. Indoor humidity loads and moisture production in lightweight timber-frame detached houses. J Build Phys. 2006;29(3):219-46.
17. Johansson P, Pallin S, Shahriari PDM. Risk Assessment Model Applied on Building Physics: Statistical Data Acquisition and Stochastic Modeling of Indoor Moisture Supply in Swedish Multi-family Dwellings2015.
18. Ivanko D, Taxt Walnum H, Lekang Sørensen Å, Nord N. Analysis of monthly and daily profiles of DHW use in apartment blocks in Norway. E3S Web Conf. 2020;172:12002.
19. Derby MM, Hamehkasi M, Eckels S, Hwang GM, Jones B, Maghirang R, et al. Update of the scientific evidence for specifying lower limit relative humidity levels for comfort, health, and indoor environmental quality in occupied spaces (RP-1630). Science and Technology for the Built Environment. 2017;23(1):30-45.
20. Wolkoff P. Indoor air humidity, air quality, and health - An overview. Int J Hyg Envir Heal. 2018.