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A review of the indoor air quality in residential Passive House dwellings

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Abstract

The Passive House (PH) Standard is a voluntary building energy performance standard focused upon reducing space heating demand to a very low level and therefore considered a viable climate change mitigation technology. Besides comfort and energy requirements, the PH standard also defines criteria with respect to ventilation. However, the question remains, how well do PH dwellings perform when they are occupied? Does the PH approach provide good indoor air quality (IAQ) for its occupants and how does IAQ compare to non-PH homes, in particular, naturally ventilated homes? Additionally, can PH certification improve the quality of installed ventilation systems? This paper summarizes indoor air quality relevant aspects of the PH standard and presents results from measurements examining in-use IAQ in more than 600 PH or PH-like, newly built or retrofitted dwellings. The results reveal that pollutant and carbon dioxide concentration are generally lower compared to naturally ventilated homes, presumably due to the requirement to install a balanced Mechanical Ventilation with Heat Recovery (MVHR) system. Results also suggest that the quality assurance measures of PH certification are capable of improving ventilation and IAQ performance. However, the lack of cooking fume capture requirements in the PH standard, in combination with efforts to avoid energy losses associated with a possible extraction kitchen hood, may lead to elevated particulate matter concentration in PHs. Future research on cooking induced IAQ impairment is encouraged to assess the effectiveness of recently published PH-specific recommendations. Future efforts in empirical IAQ research should also address the lack of high quality IAQ measurement data and the standardisation of IAQ assessment methods and protocols.

Keywords

Passive House, Passivhaus, indoor air quality, measurement, ventilation, airtightness, quality assurance.

1. Introduction

The oil crises in the 1970's encouraged the development of more energy efficient construction methods (Steinmüller 2008). In response to these crises, the Passive House (PH) concept was first developed by Bo Adamson and Wolfgang Feist in the late 1980's. to drastically reduce the energy demand of buildings. In 1996, the Passive House Institute (PHI) was formed in Germany (PHI 2015b), which not only specified the PH criteria, but developed quality assurance systems and certification schemes for buildings, components, and skills and provided design tools and supportive literature to assist with the implementation of the PH concept (PHI 2015c). The PH standard not only claims to provide a high level of thermal comfort and good indoor air quality (PHI 2015a), but it also considered to be a climate change mitigation technology in IPCC assessment reports (Cabeza et al. 2022).

More than 30 years have now passed since the first PH project was completed and occupied in 1991 (PHI, 2019c). As of 07/2023, it is estimated that around 3,660,000 m² of treated floor area have been built and PH certified worldwide , with the vast majority of these being located in Europe; primarily Germany and Austria (iPHA 2023). In addition, a significant number of non-certified Passive Houses have also been built, which have adopted the PH principles, although it is difficult to quantify approximate numbers.

Although numerous in-use monitoring studies have been undertaken over the years on PHs, the focus of these has been primarily on thermal and energy performance of PHs, for example see (Johnston et al. 2020). In contrast, the subject of indoor air quality (IAQ) has received much less attention. Although it is acknowledged that a previous review of studies investigating IAQ in certified PHs has recently been undertaken, see Moreno-Rangel et al. (2020), the review lacks a substantial number of measurement studies published as “grey literature” (mainly in German language). Therefore, this paper presents a comprehensive ‘state-of the art’ review of the results obtained from in-use measurement studies that incorporate this “grey literature”, while differentiating between certified PHs, declared PHs and homes with a mechanical ventilation system similar to the PH approach. In total the review covers 648 such dwellings.

The following chapters summarise the PH approach and summarize the results of existing measurement studies with the aim to answer the question on how PHs have been performing in practice in terms of IAQ and if certification (and/or PH guidelines) can improve IAQ performance.

2. The Passive House approach to indoor air quality (IAQ)

Looking at how the PH energy criteria has been derived, it is apparent that IAQ was considered from its inception. For instance, the peak load requirement was originally derived from a number of simple assumptions including: 30 m^3/h of fresh air per person to maintain good IAQ, an average floor area of 30 m^2 per person, an indoor air temperature of 20°C and a maximum supply air temperature of 50°C (to avoid pyrolysis of dust particles). When brought together, this results in a maximum heat load requirement of 10 W/m^2, which is roughly equivalent to the more renowned PH space heating demand threshold of 15 $kWh/(m^2a)$ (PHI 2019a). Given this, the supply air flow needed for IAQ can be used to satisfy the space heating demand and, in theory, the requirement for a hydronic heat distribution system becomes redundant.

2.1. Person-related supply air rates

In the Passive House Planning Package (PHPP), the energy calculation tool used for designing a PH, the default fresh air supply rate used is 30 m³/h per person, or 8.3 L/s per person (PHI 2019b). This value corresponds to recommendations provided at that time in the German standard DIN 1946-6 (DIN 1994). By comparison, the often referenced European standard for covering energy performance and ventilation of buildings EN 16798-1 (EN 2019) requires a default design supply air flow rates of 10 L/s per person for indoor environment category I (high) and 7 L/s per person if category II (medium) is targeted. The latter is equivalent to a stationary CO_2 concentration of approximately 800 ppm and 550 ppm above outdoor levels in the living room and bedroom, respectively. EN 16798-1 also provides two alternative design supply air flow rate criteria. The second criterion defines the required total ventilation including air infiltration as total air exchange (0,7 h^{-1} for cat. I and 0.6 h^{-1} for cat. II) and the third criterion combines a per-person and a per-floor-area requirement. It is supposed to fulfil perceived IAQ expectations for adapted persons recommending 3.5 L/s per person plus 0.25 L/(s m²) per floor for category I and 2,5 L/s per person plus 0.15 L/(s m²) for category II. Note that for a bedroom of 20 m² with two adults, this criterion suggests a supply air flow of 4 L/s per person. Furthermore, a minimum of 4 L/s is required in any case due to health reasons, as it corresponds to category III (moderate IEQ) of the first criterion of EN 16798-1. Also, in the EU-project HealthVent, a consortium of renowned European research institutions recommended a 'health-based reference minimum ventilation rate' of 4 L/s per person (14.4 m³/h) if the pollutant exposure is dominated by bio-effluents (Carrer et al. 2018; Remacle et al. 2013). Depending on the metabolic rate (roughly 1.0 to 1.4 met/) and its corresponding CO_2 emission rates (according to EN 16798-1 13.6 L/h to 20 L/h), this is roughly equivalent to a steady-state CO_2 concentration of 1350 to 1800 ppm. (Persily and de Jonge 2017) estimate an average CO_2 generation rate of 14.4 L/h in residential setting (one female, one male adult and child each with 1.4 met) and of 13 L/h in adult bedroom (one female and one male adult with 1.0 met), which corresponds to a steady state concentration of 1300 to 1400 ppm (assuming an outdoor concentration of 400 ppm).

Based on this literature and due to the fact that detailed IAQ measurements are very scarce, CO_2 concentrations of up to 1400 ppm are considered an indicator for acceptable ventilation from a health perspective for the following review. When using CO_2 as a proxy for IAQ, lower concentrations may be desirable when considering olfactory comfort rather than health alone, particularly in non-residential settings (EN 2007). The use of this threshold value of 1400 ppm assumes the use of low or very low emitting products as categorized in EN 16798-1. This review supports that this assumption is reasonable when looking at measured total volatile organic compounds and formaldehyde concentrations (see further below). The use of low-emitting building products has been discussed in PH literature (Gilgen et al. 1997; Gruen 2003); however, it is not a certification criteria.

In contrast, ASHRAE 62.2 (ASHRAE 2016) prescribes 3.5 L/s per bedroom (a minimum of two bedrooms are always considered), plus 0.15 $L/(s \cdot m^2)$ for residential applications. Assuming the same occupant density as above, i.e. 30 m^2 per person, this results in a supply air rate requirement of 11.5 L/s per person or 41.4 m^3/h per person.

2.2. MVHR with supply air filtration and the cascade ventilation principle

Except for a limited number of climates, adoption of the PH standard implies the installation of mechanical ventilation with heat recovery (MVHR). Historically, to reduce the amount of particulates introduced to habitable spaces, and avoid fouling of the heat exchanger, the intake filter must be F7 (EN 779, 2012) or better, however, as for November 2018 (PHI, 2018b) this was changed to ePM1(50%) or better (ISO 16890, 2016), which is roughly equivalent to MERV13 (ASHRAE 52.2, 2017). Similarly, the extract filters used should be at least G4 (EN 779, 2012) (PHI 2009) and are now required to be ISO Coarse (60%) or better.

The air from the MVHR system is typically supplied into habitable rooms (bedrooms, living rooms, studies, etc.) and extracted from wet rooms (kitchens, bathrooms, toilets and utility rooms). As air flows between the habitable and the wet rooms, other internal volumes, such as hallways, stairways and landings, act as overflow zones (Feist et al. 2005). This is termed the ‘cascade ventilation principle’.

Air transfer between supply, overflow and extract zones have to be considered at the design stage. Typically, in a domestic environment, a door undercut of 10 mm will be sufficient (Rojas, Rothbacher, and Pfluger 2012). However, provided the floor plan allows, it is possible to use the fresh air supply more effectively, by using the living room as an overflow rather than a supply zone (Rojas, Pfluger, and Feist 2014). Consequently, the supply air volume can be reduced to as little as 20 m^3/h per person without compromising the air flow within critical rooms, i.e. bedrooms. This strategy also reduces capital costs by eliminating the need for supply air terminals and ducting within the living room. Based upon this research, the PHI now recommends that living rooms are treated as an overflow zone whenever possible. This principle is often termed the ’extended cascade ventilation principle’. To help identify eligible floor plans, guidance and tools are available (Sibille, Rojas, and Pfluger 2013).

There is no specific PH requirement addressing cooktop ventilation, in particular the question whether an exhaust or recirculating cooker hood should be installed to supplement the kitchen extract air from the MVHR system. However, in practice most PH projects do not foresee the installation of an exhaust cooktop ventilation device and the use of recirculating devices has been recommended in the past for several reasons, primarily to avoid the associated ventilation heat losses (Werner and Laidig 1999). In a recent project, this topic was addressed providing recommendations on the use of extracting or recirculating cooker hoods (Bräunlich et al. 2019).

Noise from mechanical ventilation can also be a significant cause of occupant dissatisfaction (Harvie-Clark and Siddall 2013, 2014). Research undertaken by (Rasmussen and Machimbarrena 2014) identified a trend in occupant dissatisfaction and proposed comfort classes for limiting noise from building services.

With respect to PH buildings, PHI certified MVHR units must ensure maximum sound pressure levels in the installation room of <35 dB(A) under normal operating and typical boundary conditions. There are stipulated sound pressure levels of <25 dB(A) in living areas, including living rooms, bedrooms, studies, etc. and <30 dB(A) in functional rooms, such as kitchens, bathrooms, WCs, etc. (PHI 2009). When comparing the PH standard to the acoustic discomfort levels described in Rasmussen and Machimbarrena (2014), a dissatisfaction level of <5% can be predicted.

In terms of thermal comfort, PH certified MVHR units need to be able provide a minimum supply air temperature of 16.5°C at an ambient temperature of -10°C, to avoid draft issues (PHI, 2018b).

2.3. Airtightness

An important aspect of PH requirements is airtightness. The n_{50} must be $\leq 0.6\ h^{-1}$ at 50 Pa and verified with a blower door test. As uncontrolled in-/exfiltration is reduced to approximately $0.03\ h^{-1}$ (Liddament 1996), mechanical ventilation becomes essential in order to maintain adequate IAQ. Furthermore, MVHR can only save energy if most of the total air exchange actually runs through the heat exchanger. In (Pfluger 2019), the economic viability of MVHR was calculated as a function of the n_{50} value. Assuming a constant total air exchange rate and other boundary conditions like interest rates, service life, etc. it was found that a MVHR system for the reference dwelling would be profitable if the total investment costs can be held below 4300€ with a $n_{50} <= 0.6\ h^{-1}$. Higher n_{50} values would lead to increased yearly losses.

Based upon similar economic and primary efficiency arguments, PH certification requires a heat recovery efficiency >75% and a specific fan power (including controls) of <0.45 Wh/m³ (Feist 1997; PHI 2009; Werner 1997). In other words, to minimise life cycle costs (LCC) when compared to mechanical extract ventilation (MEV), exemplary airtightness and highly efficient heat recovery is a prerequisite. However, potential LCC savings strongly depend upon many boundary conditions and are considered marginal (Pfluger 2019).

2.4. Quality assurance measures

Various other certification requirements and recommendations are in place with the intention of ensuring the MVHR system performs as expected (Feist (Ed.) 1999; Feist et al. 2005; PHI 2009). Those pertinent to this paper include:

- Each MVHR system must be commissioned to ensure the air flow within each room corresponds to the design and to ensure the intake and exhaust air flows are balanced to within <10%.
- Certified MVHR units must either have self-balancing controls capable of maintaining the balance within <10% or include clear instructions on how balance can be adjusted on-site.
- Frost protection should be achieved without disturbing the balance, i.e. without reducing the supply air flow.
- Preventing cross-contamination between intake and extract air flows i.e. air leakage within the MVHR unit is limited to <3%.
- Air leakage from duct systems should be to Class C according to EN 12237 (EN 2003), or better.

3. Method

The aim of this review was to provide a summary from in-use measurement studies to evaluate the performance of the ventilation approach as applied in PH’s. It intends to answer the following questions: Does the PH approach, as outlined above, provide good IAQ for its occupants and how does IAQ compare to conventional, naturally ventilated, homes? Additionally, since quality issues in the planning, installation and commissioning of MVHR systems have been frequently reported (Zukowska et al. 2021), the question of whether PH certification can improve the quality of installed MVHR systems is investigated. Since many PH monitoring projects where documented exclusively or to a greater extend in German “grey literature”, a preliminary list with potential studies was created based on the authors knowledge. It was amended with journal publications of the years 2000 to 2021 by searching the databases of academic publishers (namely Elsevier, Taylor & Francis and Wiley) with the following search term (in the full text):

("passive house" OR "passivhaus") AND ("indoor air quality" OR "ventilation") AND ("measurement" OR "monitoring").

More recent relevant studies (after 2021 until mid-2023) were added “manually”. This publication list was filtered in a two-stage process, first on basis of title and abstract and second on basis of the full text. The following inclusion criteria was applied for the selection process: measurements of indoor air pollutants within occupied residential dwellings, measurement methods reported, quantitative analysis of measurement data and/or raw data provided (or graphical representation of timeseries e.g. of CO_2 concentration), CO_2 measurements for at least three consecutive days. Additionally, the studied dwellings should fulfil the PH standard or apply its ventilation approach. In this context, the dwellings were categorized in the following way:

- Certified PH in which the project has been vetted by PHI or by an independent, PHI approved, third-party. It is assumed that all PHI criteria as outlined above and all quality assurance measures have been applied.
- Declared PH where the design was reportedly completed in accordance to PHI guidelines but certification was not pursued, or certification status is unknown. It is assumed that PHI criteria have been applied and PHI certified components, in particular MVHR units, were installed. However, it has not been independently confirmed that other quality assurance measures, like MVHR flow adjustment, have been performed.

- The third category, MVHR homes, includes all dwellings that were built to some other low energy or passive house standard and therefore do not conform to one or more PHI criteria (as discussed above). These homes are equipped with a balanced MVHR system and have typically an airtightness of 1-2 h^{-1} @ 50 Pa. It is assumed that the cascading ventilation principle is applied and that the general ventilation approach is comparable to the PH approach. However, other design criteria and quality measures as outlined above may not have been applied. Known deviations to the PH approach are noted where applicable.

If the study included other homes without MVHR for direct comparison with the PH ventilation approach, they were also included in this review for comparison.

4. Results from in-use measurement studies

In total 35 studies reporting measurements of 648 dwellings (applying the PH ventilation approach) from around the world were identified for this review. The great majority thereof being from Germany and Austria, where most PH certified buildings have been built. Most studies evaluated temperature, relative humidity (RH) and carbon dioxide (CO_2) concentration. Their results are summarized in Table A.1 (Appendix A). In 13 of the reviewed studies more detailed IAQ measurement results were reported, which are summarized in subsection 4.4.

4.1. CO_2 concentrations

The carbon dioxide (CO_2) concentration of indoor air is often considered a good proxy or marker for exposure to bio-effluents, exposure to occupant induced pollutant concentrations (Persily 2016) and for ventilation requirements (EN 2019). Consequently, this review concentrated on extracting either typical night-time peak CO_2 concentrations in the bedroom, or the fraction of time where the CO_2 concentration was above 1400 ppm. In those instances where either of these metrics could not be extracted, the maximum CO_2 concentration is reported.

An analysis of the CO_2 measurements reveals that in homes which apply the PH ventilation approach, peak concentrations were, on the whole, substantially lower than in conventional homes which only rely upon natural ventilation and/or occupant-controlled window opening and that 74% of those dwellings never measured CO_2 concentrations above 1400 ppm (see Figure 1, left). Two of the studies suggest that mechanical extract ventilation with trickle vents (EV-TR) is less reliable for bedroom ventilation (Laverge, Delghust, and Janssens 2015; McGill, Oyedele, and McAllister 2015). In terms of CO_2 concentrations, the results also confirm that bedrooms are the most critical environment, as observed by (Laverge et al. 2015).

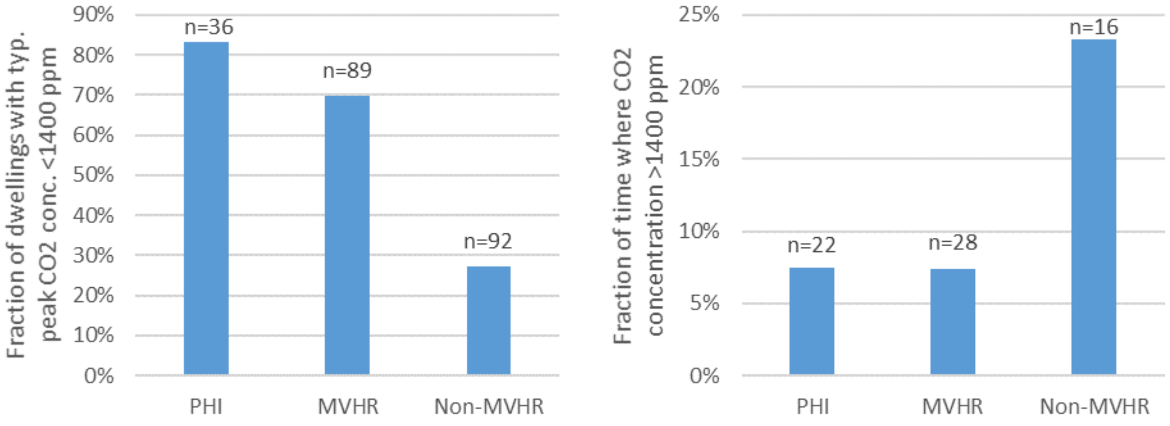

Figure 1: Left: Fraction of dwellings where measured maximum CO_2 concentration was <1400 ppm (and reported dwelling-wise for bedroom or living room). Right: Average fraction of time where CO_2 concentration in bedrooms was >1400 ppm of dwellings where this metric was reported and >0%. PHI: Passive House certified dwellings only, MVHR: dwellings with Passive House ventilation approach excluding PHI certified dwellings, Non-MVHR: all other dwellings (mostly naturally ventilated). Based on data from Table A.1.

In homes with balanced MVHR, typical bedroom peak concentrations of around 800-1500 ppm were observed towards the end of the night. Cases which regularly reach 2000 ppm or more during the night were rare, but were observed in some studies, e.g. (Kaunelienė et al. 2016; Mickaël et al. 2014; Rojas, Wagner, et al. 2016). The fraction of time where the bedroom CO_2 concentration was greater 1400 ppm is around 7-8% for dwellings with MVHR (with or without PHI certification or declaration) compared to 23% for dwellings without MVHR (see Figure 1, right). Note that the average exceedance time for non-

MVHR dwellings is based on a small sample size (n=16) and therefore with a higher uncertainty. The cause of high CO_2 concentrations was usually identified, and could be attributed to high occupant density, misadjusted supply air rates or occupants switching off the ventilation system. Occupant density is an important control variable for CO_2 measurements, but hardly reported. Herein it is assumed that deviations between real occupancy and design occupancy will average out over a larger number of observed dwellings. An example for misadjusted airflows is provided in (O. Kah, Peper, Ebel, Kaufmann, Wolfgang Feist, et al. 2010) which reviewed a PH refurbishment project which almost reached the PH standard for new buildings. On average, for all six dwellings, the CO_2 concentrations exceeded 1400 ppm in the bedrooms for 44% of the night-time hours. Further investigation in three of the six dwellings, determined that the malfunctioning of the MVHR system. It is also important to note that the same building was studied two years earlier by (Feist, Peper, and Feist 2008), which showed lower peak CO_2 concentrations. In MVHR homes, a number of other reasons were identified for high CO_2 concentrations, such as occupants turning off the MVHR system due to noise or other comfort issues. An example of this is in (Kaunelienė et al. 2016), where residents were switching the ventilation off due to uncomfortable airflows in their sleeping areas.

4.2. Relative humidity

Relative humidity is generally lower in PHs or MVHR homes compared to naturally ventilated homes. Although RH values of below 30% have been observed in PH homes in cold, dry climates, the average RH in PH or MVHR homes typically ranged between 30-40%, with hourly averaged peak values rarely surpassing 50% or 55%.

In contrast, a number of naturally ventilated homes had peak RH values greater than 60% for a substantial amount of time (Laverge et al. 2015; Rojas, Wagner, et al. 2016; Tappler et al. 2014). In combination with a lower quality thermal envelope, in particular the existence of thermal bridges, this can lead to conditions favouring mould growth, see(Peper and Feist 2008). In fact, two studies (totalling

80 homes) identified possible mould or moisture problems in roughly 30% of conventional new homes (Langer et al. 2015; Wallner et al. 2015). Compared to declared PH dwellings, abnormal ratios between indoor and outdoor mould spore concentrations were reported in 10% of cases (Wallner et al. 2015). To date, no case of mould growth in PH certified dwellings has been published.

4.3. Air exchange rates

A good portion of the reviewed studies reported ventilation rates that were measured during commissioning or as part of measurement study. Unfortunately, many studies reported only design values or did not report ventilation rate data at all. The available data is summarized in Table A.1. Only a few studies provided ventilation rate per person, which would be most insightful. Most studies did not survey occupancy. In those cases, the whole-dwelling air exchange rate is provided. In some publications, air flows for specific rooms where reported. A comprehensive analysis of measured ventilation rates is hardly possible. Nevertheless, Figure 2 (left) compares the whole-dwelling air exchange rate for PHI-certified homes, with all other MVHR-homes and with naturally ventilated homes. It shows that for multi-family houses the air exchange is highest for certified PH's, somewhat lower for the other MVHR-homes and substantially lower for naturally ventilated dwellings. For building types where one can usually except lower occupancy density, i.e. single-family houses (SFH), semi-detached houses (SDH) or terraced houses (TH), there is no difference between PHI-certified and MVHR-homes and smaller difference with naturally ventilated homes.

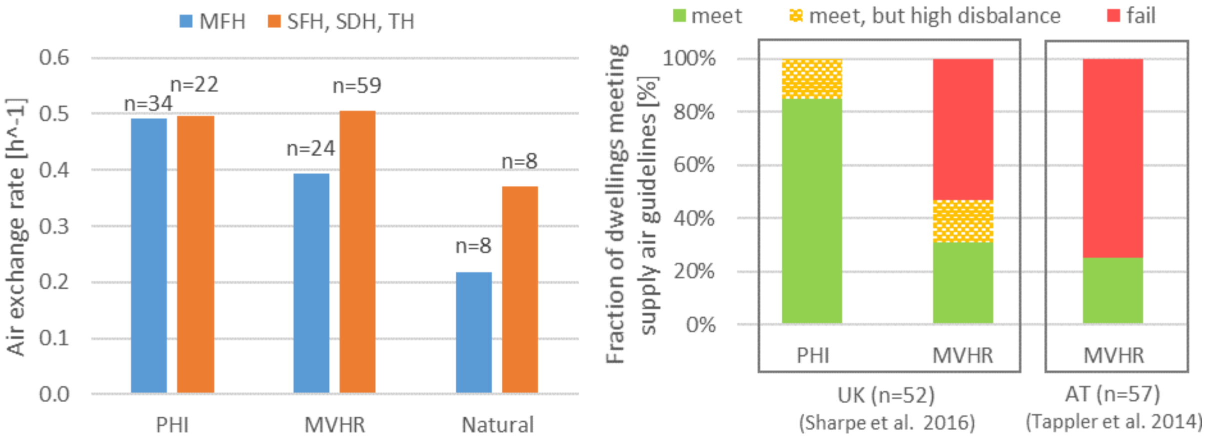

Figure 2: Left: Average air exchange rate in multi-family houses (MFH) and single-family (SFH) / semi-detached (SDH) / terraced houses (TH). See also Table A.1. Right: Fraction of dwellings of selected studies, where measured supply air flow complied with national guidelines. For UK the compliance with total dwelling air flow rate as required in AD:F (HM Government 2013) was evaluated. For Austria compliance with supply air rate requirement for bedrooms as defined in ÖNORM H 6038:2014 was assessed. See also Table A.1. PHI: Passive House certified dwellings only, MVHR: dwellings with PH ventilation approach excluding PHI certified dwellings, Natural: all other dwellings were measurement data was available (all naturally ventilated).

A UK meta-study examining the installation of MVHR systems allows comparison between PH certified homes and regular UK construction practices, see (Sharpe et al. 2016), in particular Figures 3.3a and 3.3b. Whilst all projects are judged in respect to conformance with Building Regulations Approved Document Part F (HM Government 2013), rather than requirements of the PH standard, the benefits of PH quality assurance become evident and quantifiable. The meta-study presents the measured air flow rates for 52 dwellings with MVHR, 20 of which are PH-certified and the other MVHR-homes can be considered standard UK construction practice. As shown in Figure 2 (right), all of PH certified dwellings provided the required supply air flow and only 47% of the other MVHR-homes satisfy the air flow requirements of AD:F. Additionally, unlike the PH standard, AD:F does not impose a requirement for the MVHR system to provide balanced ventilation. If excluding homes with a disbalance between supply and extract air flow of >20%, the compliance rate would sink to 85% for PHI-certified versus 31% for the other MVHR-homes. In an Austrian study the compliance of 57 dwellings, which can be considered declared PHs or other MVHR-homes, is evaluated (Tappler et al. 2014; Wallner et al. 2015). Therein, the measured supply air flow into the main bedroom is compared with national per-person requirements

(> 5.6 l/s, see ÖNORM H 6038:2014) applying actual occupancy information, revealing that about 75% of the bedrooms were under-ventilated.

Contextually it is worthwhile acknowledging another study examining 80 dwellings, 25 with continuous mechanical extract ventilation (MEV) in combination with trickle vents and 55 with intermittent extract fans (also in combination with trickle vents). Here, (MHCLG 2019) established that only 4% of dwellings of either type satisfied the provisions recommended in AD:F.

Noteworthy, is also a study undertaken by (Kah et al. 2005), which investigated the contribution of occupant operated window ventilation in eight PH certified apartments and one PH certified terraced dwelling over a two-week period. The total air exchange (average of 0.8 h^{-1} and 0.3 h^{-1} in apartment and terraced house) was determined via SF_6 tracer gas measurements and segregated into the contribution from mechanical ventilation, natural infiltration and window ventilation. The additional window ventilation correlated with weather conditions and amounted on average to 10% of the total air exchange. Natural infiltration amounted to only 0.01 h^{-1} over the same timeframe. This example indicates that in practice almost 90% of the total air exchange during winter was provided by the MVHR system. However, this is not the case in less airtight buildings. Work undertaken by (Laverge et al. 2015) estimated that infiltration accounted for around 30% of the total air exchange in low-energy homes with an MVHR system and a n_{50} value of around 2 h^{-1}.

4.4. Other indoor air quality parameters

Various IAQ parameters were measured by (Tappler et al. 2014; Wallner et al. 2015) within 62 MVHR homes (including an unknown number of declared PHs) and 61 conventional homes, twice during the first year of occupation (roughly 3 and 12 months after initial occupancy). The conventional homes were naturally ventilated. Total volatile organic compounds (TVOC) and formaldehyde (FA) concentrations were significantly lower in homes with MVHR than those in conventional homes. During both sets of measurements (later measurement value in brackets), the median TVOC concentration was 300

(120) µg/m³ in homes with MVHR and 560 (230) µg/m³ in conventional homes (see (Shrubsole et al. 2019) for a review on health-based guideline values for VOC's and TVOC). The measurement and analysis of aldehydes was undertaken in accordance with ISO 16000-2 (ISO, 2004) and ISO 16000-3 (ISO, 2011a). The median formaldehyde concentrations were 27 (22) µg/m³ and 40 (31) µg/m³, respectively. Differences were similar among other investigated aldehydes. These median values were well below the WHO recommended formaldehyde concentration limit of 100 µg/m³ for a 30 minute exposure (WHO 2010) but still above the chronic limit of 9 µg/m³ defined by the California Office of Environmental Health Hazard Assessment (OEHHA 2015), even in homes with MVHR.

In Sweden (Langer et al. 2015), measurements were performed in 20 new PH and 21 new conventional houses (both having MVHR). Good IAQ was generally observed in both groups. The median TVOC concentration was higher in the PH dwellings compared to conventional new houses, but was below 300 µg/m³. The authors concluded that the differences between PH and conventional houses could be attributed to the higher fraction of single-family homes (SFH) in the PH group. Formaldehyde concentrations measured in accordance with ISO 16000-4 (ISO, 2011b) and were lower in the group of PHs with a median of 11.1 µg/m³. NO_2 concentrations were slightly higher in the PH and conventional houses compared to the rest of the housing stock, but none of the homes exceeded the Swedish limits. The authors concluded, that the good IAQ in the mechanically ventilated homes could be attributed to a higher air exchange rate.

In an earlier study (Schulze Darup 2002), various IAQ parameters were measured in four semi-detached PH homes over the course of two years. Formaldehyde measurements revealed concentrations ranging from 10 to 40 µg/m³ and showed a slight upward trend in the first six months after occupancy. The TVOC concentrations, as well as certain evaluated compounds like pentane, styrene, aromatic hydrocarbons (mostly toluene) and higher aldehydes, showed high values during the construction phase. However, they dropped below the German target or guideline values within one year of occupancy. The authors argue that this is faster than typically observed in homes without continuous mechanical ventilation.

In Lithuania, IAQ measurements undertaken in 11 new LEHs with MVHR showed high VOC concentration after interior decoration, but the concentration fell below national limits within one month (Kaunelienė et al. 2016). The authors attribute the rapid decrease to the air exchange rate of 0.5 h^{-1} in these homes. Formaldehyde concentrations ranged from 3 µg/m³ to 52 µg/m³, with a median of 31 µg/m³. These values are similar to those measured in the other studies, but above the Lithuanian daily average limit level of <10 µg/m³. The SVOC measurements showed that polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyl (PCB) and hexachlorbenzene (HBC) were present at similar concentration levels to those observed in non-PH-certified dwellings (Gale et al. 2009; Strandberg et al. 2006). The concentration of alkylated PAHs was reported to be higher than in (Gale et al. 2009; Strandberg et al. 2006), without providing a possible explanation. Unfortunately, only a limited number of SVOC measurement studies exist, but in general, the reported SVOC concentrations seem to be within typical observed ranges.

In France, the IAQ of seven newly built energy efficient SFH were measured before occupancy and twice during the first year of occupancy (summer and winter) (Mickaël et al. 2014). Although only two of the homes were certified PHs, the results obtained for each dwelling were not substantially different. Compared to concentrations found in typical French houses, median concentrations of $PM_{2.5}$, radon, benzene and toluene were lower, whilst the formaldehyde concentration was similar. With regard to benzene it is recognised that no safe level of exposure can be recommended (Shrubsole et al. 2019). The concentrations of ethylbenzene, m- and p xylene, 1,2,4-trimethylbenzene and acrolein were slightly higher (less than 1.5-fold). In contrast, concentrations of hexaldehyde, acetaldehyde, styrene, o-xylene, n-decane and n-undecane exceeded the levels in typical French dwellings by more than 50%. It is concluded that the concentrations of these compounds appear to be related to new construction. The

IAQ measurements were extended in two of the non-certified PH dwellings for an additional two years to cover three years of occupancy (M. M. Derbez et al. 2014). Across the study period, it was observed that formaldehyde, hexaldehyde, and benzaldehyde concentrations were relatively stable over time. Seasonal variations were also observed for CO_2, $PM_{2.5}$ and acetaldehyde, which appeared to be linked to the different occupant ventilation practices in summer and winter. As a result, the PM concentrations were highly correlated to ambient concentrations in summer, whereas in winter, the indoor PM levels were stronger influenced by indoor sources.

In Colorado, USA the IAQ and its impact from cooking was investigated in one certified PH and nine other MVHR-homes. The latter consisted of five PH's designed and built to a different or unknown PH standard, three (for North American building practice) tightly constructed and one conventionally constructed SFH (Militello-Hourigan and Miller 2018). Only the conventionally constructed home was equipped with an exhausting range hood. All others had either a recirculating or no range hood installed. Measurements undertaken following a prescribed cooking activity resulted in drastically increased $PM_{2.5}$ concentrations in those homes, with short term averages of roughly 100 µg/m³ - 500 µg/m³. In comparison, the only home with an extracting hood showed a short-term average of <100 µg/m³. It is important to note that the absolute PM values measured within this study should be interpreted with care, as PM was determined using an optical particle counter with only two bin sizes and by applying a linear correlation factor. The study also found that PM concentrations remained high for several hours (1 – 10 hrs) after cooking, even when the MVHR boost was active. It is not clear from the documentation if these homes recirculated the air, as often done in US homes (forced air system), or if the cascading ventilation principle, typical for European PH, was applied. Nevertheless, the results indicate that the ventilation strategy typically applied in PH (MVHR extract in combination with a recirculating hood) might not be sufficient to remove cooking pollutants and that this topic needs further attention. Formaldehyde concentrations were also measured and were similar to other studies with a median of 32 µg/m³ for all ten dwellings. Radon concentrations were above the EPA action level of 4 pCi/l (U.S. EPA n.d.) in three of the non-certified PHs and in one of the tight homes. All of these houses had a basement and no active or passive radon mitigation system was installed.

In a separate study of 24 high performance dwellings (seven reported as “passive house-style”) (Less et al. 2015), measurements in the kitchen revealed that homes with filtration via central forced air (n=9) and supply air ventilation (n=7) had average particle count levels (>0.5 µm) that were 67% and 38% lower, than homes without any filtration (n=8). It can be assumed that the higher removal rate of the central recirculating system is due to its ability to also remove indoor generated particles, e.g. from cooking. Six-day formaldehyde concentrations in the bedrooms ranged from 11.7 µg/m³ to 47 µg/m³, with a median of 17.5 µg/m³. Interestingly, the study found little correlation in formaldehyde concentrations with air exchange rate, presence of mechanical ventilation, presence of new materials or cooking fuel. The majority of the homes (n=22) reported using low-emitting materials. The study also found that median NO and NO_2 concentrations were 2 to 3 times lower in homes using electric cooktop appliances (n=9), compared to those homes that had gas-fired cooktops (n=15). Three of the latter exceeded the California EPA annual ambient air quality benchmark of 30 ppb (CCR 2008). When segregating homes with gas-fired cooktops, the NO_2 concentration in PHs (n=4) was elevated with a median of 23 ppb compared to 9 ppb in the other homes (n=11). Due to the small sample size, the difference is not statistically significant. Nevertheless, it points at potential IAQ issues when combining gas-fired cooktops and recirculating range hoods, a seemingly common combination in North American PHs.

IAQ measurements have also been undertaken in the first PH apartment block built in a severe cold climate zone in China (Wang et al. 2018). Amongst others, CO_2, $PM_{2.5}$ and PM_{10} concentrations were measured in eight out of 66 apartments and compared to eight apartments from conventional apartment blocks. In contrast to the low CO_2 concentrations measured in the PH certified dwellings, are the reported indoor PM levels, with an average $PM_{2.5}$ concentration of 92 µg/m³. The authors report that differences between PH and conventional apartments were not obvious under low ambient PM levels. During periods were ambient $PM_{2.5}$ was >200 µg/m³, indoor $PM_{2.5}$ concentrations in PHs were significantly lower (ranging from 60 µg/m³ to 330 µg/m³) than in conventional houses (ranging from 200 µg/m³ to 520 µg/m³). Nevertheless, under those conditions, the average concentration (170 µg/m³) in PH apartments was more than twice the Chinese standard for indoor $PM_{2.5}$. It is important to note that the MVHR was equipped with a M5 quality supply air filter only, not fulfilling the PH criteria (F7). A typical M5 filter has a $PM_{2.5}$ filtration efficiency of only 20-30%.

In another recent Asian study (Lim et al. 2021) the measured IAQ in 25 PH dwellings and the repeatedly self-reported health status of their occupants was compared to an equally sized sample of conventional homes over a period of one year. The mean level on indoor air parameters, including PM, CO_2 and VOC's were lower in PHs. However, statistically significant difference could only be shown for CO_2 in fall, winter and spring and for $PM_{2.5}$ in summer. For both housing types an increase in daily mean level of $PM_{2.5}$ was associated with a significant increased risk of symptoms including eye fatigue (adults) and allergic rhinitis (adults and children).

(McCarron, Meng, and Colclough 2020) present a research on radon levels examining 97 PH's (which includes 5 retrofits to the PHI EnerPHit Standard) and 25 comparison dwellings located in the U.K. and Ireland. The mean radon level in PH dwellings was 36 Bq/m³ as compared to a national average of 77 Bq/m³ and 88 Bq/m³ in comparison dwellings or to the WHO recommended action limit of 2.7 pCi/L or 100 Bq/m³ (WHO 2009). In general, measurements fell below 100 Bq/m³ in 93% of all PH cases compared to 84% in the comparison sample. The researchers concluded that the radon levels in PH dwellings aligned with the "as low as reasonably achievable" principle. Similar results were obtained in a recent study by the German Federal Office for Radiation Protection (Meyer 2019) with 35 declared PH having a mean concentration of 46 Bq/m³ vs. 99 Bq/m³ in 105 energetically refurbished homes without mechanical ventilation. The positive effect of the ventilation system was also observed by (Uhlig 2010) who examined four masonry PH dwellings. When the ventilation system was switched off, the radon concentrations rose from roughly 20 to 60 Bq/m³ (as interpreted from a chart for various measurement locations in one of the four investigated homes) to up to 350 Bq/m³). It is also worth noticing that peak radon concentrations of up to 4000 Bq/m³ were measured in zones not covered by the mechanical ventilation system, like basement and entry area.

In a Swiss study (Yang et al. 2020), radon, TVOC, formaldehyde and fungi concentrations were measured in 650, 169, 169 and 164 dwellings, respectively, using passive sampling methods by instructed occupants. Around 30% of the dwellings were newly built (after 2000) complying to MINERGIE standard (Minergie 2023). This Swiss certification scheme requires the installation of MVHR system similar to the PH standard and 98% of MINERGIE occupants confirmed to have a mechanical ventilation in the survey. The other 70% of dwellings were energy retrofitted dwellings were only 4% of occupants reported to have mechanical ventilation. Mean concentrations of all measured pollutants were significantly lower, radon (48 vs. 91 Bq/m3), TVOC (167 vs. 259 µg/m3), formaldehyde (12 vs. 15 µg/m3) and fungi (33 vs.48 CFUs) in MINERGIE compared to energy retrofitted dwellings, respectively.

(Szabados et al. 2023) performed extensive IAQ measurements in 15 PH dwellings in Hungary revealing high NO_2 and $PM_{2.5}$ concentrations with median values of 34.8 µg/m³ and 21.7 µg/m³ during a one-week period in the heating season, respectively. Unfortunately, the authors do not report on the type and use of cooker and cooker hoods. Indoor/outdoor ratios, the fact that construction works were reported in the surroundings of eight homes and that G4 (EN 779) or lower grade outdoor air filters were used (partly) point to outdoor sources as possible causes. The use of lower grade filters points to the issue that proper operation of MVHR systems by occupants is not ensured through the PH certification process.

5. Summary and discussion

The reviewed IAQ measurement studies indicate that good IAQ can be achieved when the general PH approach is implemented, i.e. airtight construction ($n_{50} \leq 0.6\ h^{-1}$ at 50 Pa) in combination with a balanced mechanical ventilation with high grade filtration, cascading air distribution and a fresh air supply of 20 to 30 m^3/h per person. Nevertheless, some studies also showed shortcomings and point to possible areas of improvement. Here a summary and discussion of positive and negative observations with respect to the PH ventilation approach.

CO_2 peak concentrations in the bedrooms of MVHR homes were generally below 1400 ppm and substantially lower than comparable naturally ventilated homes. A prerequisite is the correct and reliable operation of the MVHR system. The PH certification scheme appears to provide some sort of quality assurance. Various studies have measured supply air flows, or total air exchange rates, that were significantly below design or recommended values, e.g. (Kaunelienė et al. 2016; Militello-Hourigan and Miller 2018; Sharpe et al. 2016; Wallner et al. 2015). PH certified homes, which have to undergo an air flow adjustment during commissioning and a third party review of the measurements, seem to exhibit this problem less often (see Figure 2), although poor air flow provision was also reported in a few early PH certified developments (Mlecnik, Hasselaar, and Van Loon 2008). An estimation of the compliance rate for the PH balance requirements between supply and extract air could only be derived from (Sharpe et al. 2016). Therein, large imbalances were observed in about 15% of the dwellings, also for PH-certified. Where an imbalance in the system does occur, it will not only have an impact on the efficiency of heat recovery, but will also potentially increase condensation risk within the dwelling and its fabric. Progress has been reported with respect to air flow balancing technologies in the last years, see e.g. (Cremers 2023). However, it seems that accuracy and resilience of air flow control in MVHR systems is still a topic that needs further attention. Further technological advancements, introduction of inspection schemes and/or automated fault detection algorithms may increase reliability and should be investigated further.

Issues with high humidity and/or mould growth was not reported for PH type homes, in contrast to naturally ventilated new or existing homes, see e.g. (Langer et al. 2015; Wallner et al. 2015). However, in climates with cold winters, relative humidity levels tend to be on the low side, falling below 30% RH for a substantial amount of time, even when supply air flows are set rather low (~20 m^3/h per person). This can be attributed to higher air exchange rates (AER) and higher temperatures (Peper and Feist 2008; Rojas, Wagner, et al. 2016). In climates with cold, dry winters, as evaluated in (Pfluger 2012) RH values below 30% were observed for substantial periods. In those regions, surveys confirmed that around 30% of the occupants perceived the indoor air to be 'too dry', e.g. (Rojas 2016; Tschui and Emmenegger 2005; Wallner et al. 2015). Extended periods with RH <30% are not recommended for sensitive occupant groups (Pfluger et al. 2013; Wolkoff 2018). Suffice to say, balanced MVHR itself is not the root cause of dry air, rather dry air is a by-product of two conditions which conflict with one another, namely: outdoor environmental conditions (low specific moisture content) and the need to provide good indoor air quality (removing pollutants). One of the reasons why the PHI advocates the use of cascade ventilation, is because this approach permits a reduced ventilation rate, and in turn, allows indoor RH to be higher than would otherwise be the case. Nevertheless, simulation studies show that humidity recovering ventilation units could resolve this "supply air dilemma", in particular for PH dwellings where the risk of condensation on cold surfaces is greatly reduced (Rojas, Pfluger, and Feist 2016). Future investigations should evaluate the risk of condensation and mould when installing enthalpy recovery systems as part of energy-efficiency retrofits.

Many studies report lower concentrations of specific VOC's or TVOC for all MVHR-homes compared to naturally ventilated homes, e.g. (Lim et al. 2021; Wallner et al. 2015; Yang et al. 2020). Longitudinal studies indicate that certain VOC concentrations can be high after construction but target values are reached within the first few months of occupancy and that levels observed in conventional housing stock are met or undercut within the first year.

Formaldehyde concentrations in PH-like ventilated dwellings are similar, sometimes lower compared to values found in buildings without MVHR. These results are probably due to the implementation of continuous mechanical ventilation. However, another contributing factor that cannot be ruled out is that many of the builders and occupants that choose a high-performance building standard, such as the PH standard, are also likely to choose low-emitting building products and/or furniture. Note that the typically observed formaldehyde concentrations are well below the WHO limit of 100 $\mu g/m^3$ (WHO 2010) but often above the California Office of Environmental Health Hazard Assessment (OEHHA) chronic limit of 9 $\mu g/m^3$ (OEHHA 2015).

Average radon levels in homes with a PH ventilation approach were generally lower than comparable homes without MVHR (and higher air leakage). In almost all cases concentrations were well below the WHO recommended action limit of 2.7 pCi/L or 100 Bq/m^3 (WHO 2009) with typical average values between 20 and 50 Bq/m^3. However, various airtight MVHR homes in the USA without an active or passive radon mitigation system, substantially exceeded the EPA action limit of 4 pCi/L. This shows that, depending on the location, additional radon mitigation strategies might be required.

There are only few studies reporting particulate matter exposure in PH or airtight homes with MVHR. Results suggest that the typical PH-ventilation approach (MVHR with high grade supply air filtration in combination with a recirculating cooker hood) is likely to effectively reduce particles originating from the ambient environment, but not necessarily from indoor sources like cooking. It is worth noting, that since the above papers were published, PHI has produced design guidance for kitchen exhaust systems in residential kitchens (Bräunlich et al. 2019). The use of outdoor air filter grades below PH certification requirement, most likely also responsible for elevated PM concentrations in two studies, raises some questions on how compliance with PH requirements can be better ensured during MVHR operation.

6. Conclusions

The authors conclude that energy efficient homes with MVHR can provide healthy IAQ conditions in dwellings if proper design and implementation is ensured. The PH approach with its certification criteria and guidelines does seem to provide better IAQ performance compared to building practises without quality assurance measures. However, as pointed out in (Ortiz, Itard, and Bluyssen 2020) this might not always be true for energy-efficient retrofitting, and needs further investigation. Further research is also needed to examine particulate matter exposure in PH's and energy efficient strategies to reduce PM exposure from cooking. As also concluded in (Moreno-Rangel et al. 2020), this review shows a lack of measurement data and/or standardised IAQ assessment methods. While many studies measure CO_2 concentration over an extended period of time, there is a lack of comparable long-term measurements on actual indoor air pollutants, e.g. formaldehyde, $PM_{2.5}$, ozone, etc. and how the PH approach performs in different climate zones. Unfortunately, the ventilation rate is often not reported, a crucial information for assessing ventilation system and indoor emission sources. An international project is currently addressing these short comings of non-standardized IAQ assessment for residential buildings (IEA 2020). On the engineering side, further research and developments are needed to overcome challenges and barriers such as resilient air flow control, spatial requirements and cost effectiveness in particular for refurbishment projects, to promote wider implementation in the process of building stock decarbonization.

Appendix A: Table A.1 Summary of reviewed IAQ measurement studies

Project (Publications)	Country	Build. type [a]	Declared energy designation (applied standard) [b]	PHI-cert. (Datab.-ID) [c]	# dwellings	Ventilation [d]	Measurement period	Location [e]	CO2-concentration [f]	Humidity	Ventilation rate/ Volume flows for entire home unless otherwise stated	Ventilation rate/ Volume flows determination method and time [ae]	Other IAQ parameters
Nürnberg (Schulze Darup 2002)	GER	SDH	PH (PHI)	C (0248)	1	MVHR	5 days (Feb)	BR	Max~1000ppm	35-45% range no abn. mould spore [u]	Design: 0.4h^{-1}	n/a	VOC, FA, mould sp., radon, ions
Kassel Marbach (Kah et al. 2005)	GER	MFH	PH (PHI)	Y (0164)	8	MVHR	1-2 weeks	BR	Max: 1000ppm (1 BR measured)	mostly 20-50% range	Avg: 0.8h^{-1} (incl. natural vent.)	tracergas (SF6); study (cont.)	-
		TH		Y	1	MVHR		BR	Max: 1400ppm	mostly 30-50% range	Avg: 0.3h^{-1} (incl. natural vent.)	tracergas (SF6); study (cont.)	
(Balvers, Boxem, and Wit 2008)	NL	SFH TH	PH/LEH [s]	C	4	MVHR	2-3 weeks	BR	6% of time >1000ppm	30-60% range	Avg @ min. setting [x]: 25m^3/(h·per) 0.20h^{-1}	flowmeter (pc); study	FA, CO
Ludwigshafen (Peper and Feist 2008)	GER	MFH	PH-refurb (PHI)	C (1450)	3	MVHR	1 winter	BR	10% of time >1400ppm	n/r	Avg (commis.): 0.45h^{-1} Avg (study): 0.37h^{-1}	flowmeter (pc); commissioning + study	-
								LR	9% of time >1400ppm	Avg. abs. hum: 7.2g/kg			
			LEH	N	3	Natural		BR	26% of time >1400ppm	n/r	Avg: 0.15h^{-1}	calc. based on measured window use; study	-
								LR	25% of time >1400ppm	Avg. abs. hum: 7.9g/kg			
Ludwigshafen (Oliver Kah, Peper, Ebel, Kaufmann, Bastian Zeno, et al. 2010)	GER	MFH	PH-refurb (PHI)	C (1450)	6	MVHR	1 winter	BR	44% of night-time >1400ppm	n/r	Avg: 84m^3/h 0.46h^{-1}	flowmeter (pc) +fan control sig.; study	-
								LR	42% of eve. [t] time >1400ppm	n/r			
			LEH	N	5	Natural		BR	81% of night-time >1400ppm	n/r	Avg (+/- meas. uncert.): 46 (+/-13)m^3/h 0.26 (+/-0.06)h^{-1} w/ high daily variability	tracergas (SF6) in 1 apt.+measured window use; study	-
								LR	67% of eve. [t] time >1400ppm	n/r			
Dreherstrasse (Mahdavi and Doppelbauer 2010)	AT	MFH	PH (PHI)	Y (3403)	2	MVHR	1 mo (Feb)	BR	2.5% of time >1400ppm	(mostly 30-50% range; Feb-Jun)	n/r	-	-
			LEH (ÖNORM B 8110-1)	n/a	2	EV-TV			45% of time >1400ppm	(mostly 30-50% range; Feb-Jun)			
(Uhlig 2010)	GER	SFH	PH	n/r	4	MVHR	10 days	n/r	-	-	-	-	Radon
Frankfurt Tevesstrasse (Peper, Schnieders, and Feist 2011)	GER	MFH	PH-refurb (PHI)	C (1211)	15	MVHR	1 winter	LR	5% of time >1400ppm	Nov-Feb: Avg (min-max): 33% (25-40%)	Nov-Feb: Avg (min-max): 62m^3/h (35-102m^3/h) 0.37h^{-1} (0.17-0.59h^{-1})	flowmeter (pc) +fan power cons.; study	-
			(1950's) [g]	n/a	1	Natural			>50% of time >1400ppm	n/r	n/r	-	-

Project (Publications)	Country	Build. type [a]	Declared energy designation (applied standard) [b]	PHI-cert. (Datab.-ID) [c]	# dwellings	Ventilation [d]	Measurement period	Location [e]	CO2-concentration [f]	Humidity	Ventilation rate/ Volume flows for entire home unless otherwise stated	Ventilation rate/ Volume flows determination method and time [ae]	Other IAQ parameters
Enerbuild-Study (Exner and Mahlknecht 2012)	GER AT IT	SFH MFH	PH/LEH [e]	some	8	MVHR	>1yr	BR (3)	3-16% of time >1000ppm	n/r	n/r	-	-
								LR (8)	0-16% of time >1000ppm	n/r	n/r	-	-
Camden (Ridley et al. 2013)	UK	SFH	PH (PHI)	Y (1777)	1	MVHR	1 year	BR	1% of time >1400ppm	Avg: 46% (winter) 52.2% (summer)	@ medium setting: 104m^3/h 0.38h^{-1}	n/r; commissioning	-
Ebbw Vale (Ridley et al. 2014)	UK	SFH	PH (PHI)	Y (1849, 2039)	2	MVHR	2 years	BR (2)	23% of time >1000ppm 6.5% of time >1400ppm	n/r	n/r	-	-
								LR (2)	7.5% of time >1000ppm 0.5% of time >1400ppm	n/r	n/r	-	-
(M. Derbez, Berthineau, Cochet, Murielle, et al. 2014)	FR	SFH	PH (PHI): 4 LEH (BBC [i]): 2	Y: 2 N: 4	6	MVHR	3x 3 weeks (pre-occup, sum, win)	BR	Max <1400ppm (4 of 6) Max <2030ppm (2 of 6)	Avg: 31-35% (2 units only)	Avg (min-max)@ medium/normal setting: 0.52h^{-1} (0.3-0.9h^{-1})	tracergas (SF6) in rooms + estimation for home; study	VOC, FA, noise, radon
(M. Derbez, Berthineau, Cochet, Pignon, et al. 2014)	FR	SFH	PH (PHI): 1 LEH (BBC [i]): 1	N	2	MVHR	7 weeks over 3 yrs	BR	Weekly median in winter: 550-840ppm	n/r	Extract air @ medium kitchen and 2 baths [ad]: 83m^3/h, 61m^3/h	flowmeter (hw)	PM, VOC, FA, noise
(McGill, Qin, and Oyedele 2014)	UK	TH	PH (PHI)	n/r	3	MVHR	1 day in summer & winter	LR	~15% of time >1400ppm	Avg: 45%	n/r	-	-
(Tappler et al. 2014; Wallner et al. 2015, 2017)	AT	SFH MFH	PH / LEH (ÖNORM B 8110-1)	n/r	62	MVHR	1 week (1 yr after move in) (Oct-May)	BR	Max. mov. avg: 1280ppm <1400ppm (41 of 61) [aa]	Median: 41% abn. mould spores [u]: 10 homes	BR: <20m^3/(h*per): 75% 20-25m^3/(h*per): 21% >25m^3/(h*per): 4%	flowmeter (pc); study	VOC, FA, radon, mould sp., dust mite, noise, survey
			Conventional	N	61	Natural			Max. mov. avg: 1740ppm <1400ppm (18 of 59) [aa]	Median: 48% abn. mould spores [u]: 21 homes	n/r	-	
(Langer et al. 2015)	SWE	SFH MFH SDH	PH (Swedish [j])	N	20	MVHR	1 week in winter	BR	6% of time >1000ppm	Avg: 30% ± 7% abn. mould spores [u]: 0 homes	Median: 0.68h^{-1}	CO_2 decay; study	VOC, FA, NO2, O3, mould sp.
			Conventional	n/a	21	MVHR			10% of time >1000ppm	Avg: 38% ± 9% abn mould spores [u]: 6 homes	Median: 0.60h^{-1} (hous.stock: 0.38h^{-1})	CO_2 decay; study (hous. stock: n/r)	

Project (Publications)	Country	Build. type [a]	Declared energy designation (applied standard) [b]	PHI-cert. (Datab.-ID) [c]	# dwellings	Ventilation [d]	Measurement period	Location [e]	CO2-concentration [f]	Humidity	Ventilation rate/ Volume flows for entire home unless otherwise stated	Ventilation rate/ Volume flows determination method and time [ae]	Other IAQ parameters
(Laverge et al. 2015)	BE	TH	PH (k)	some *	16	MVHR	~9 days	BR	Typ. peak: 1250ppm	Avg (bath): 40%	Kitchen: 20-60m^3/h [w] Bath: 10-50m^3/h [w]	flowmeter (pc); study	-
			LEH (l)	n/a	23	MVHR	~9 days		Typ. peak: 1150ppm	Avg (bath): 50%	Avg. AER (incl. infiltr.): 0.38h^{-1} [w]	flowmeter (pc); study +calc. of infiltration	-
			new conventional	n/a	39	EV-TR	~9 days		Typ. peak: 1650ppm	Avg (bath): 47%	Kitchen: 5-45m^3/h [w] Bath: 10-65m^3/h [w]	flowmeter (pc); study	-
			housing stock	n/a	36	Natural	n/a		Typ. peak: 1250ppm	Avg (bath): 70%	n/r	-	-
(Less 2012; Less et al. 2015)	US	SFH	PH [m]	n/r	7	MVHR	6 days (Jan-Apr)		n/r	Avg (7 units): 51%	Avg (min-max)(4 units): 0.31h^{-1} (0.26-0.38h^{-1})	tracergas (passiv C6F6); study	FA, PM, NOx, Acetaldehyde, CO
			other [m]	n/a	11	Natural			n/r	Avg (9 units): 48%	Avg (min-max)(8 units): 0.37h^{-1} (0.14-0.8h^{-1})		
(McGill et al. 2015)	UK	TH	LEH (UK:C4) [n]	N	4	MVHR	24h in winter	BR	Max <1400ppm (2 of 4) Max (all): 1450ppm	Avg: 42%	n/r	-	FA
			LEH (UK:C3) [n]	n/a	3	EV-TV			Max <1400ppm (1 of 4) Max (all): 3430ppm	Avg: 57%	n/r	-	
Lovashagen (Berge and Mathisen 2016)	NOR	MFH	PH / LEH [o]	N	4	MVHR	1 year	BR(7) + LR (3)	2% of time >1200ppm	Avg. mostly 30-55%	BR: 24-50m^3/h	flowmeter (hw)	
Kranichstein (Feist et al. 2016)	GER	Ter	PH (PHI)	Y (0195)	1	MVHR		LR	Max <1400ppm (1 of 1)	n/r	n/r	-	TVOC, FA, mould sp.
Dormont Park + Dunoon (Foster et al. 2016)	UK	SDH TH (Soc.)	PH (PHI)	Y	5	MVHR	1 year	BR (8)	11% of time >1000ppm	mostly 35-55% range ≥10% of time <30% (4 of 8)	BR: 22-54m^3/h	flowmeter (n/r); study	-
(Kaunelienė et al. 2016)	LIT	SFH	LEH (p)	N	11	MVHR	1 week (spring/summer)	LR	Max <1400ppm (9 of 11) Max <2200ppm (2 of 11)	Avg range: 44-58 (summer!)	Med (min-max): 0.2h^{-1} (0.08-0.69h^{-1})	CO_2 decay; study	-
Lodenareal (Rojas, Wagner, et al. 2016)	AT	MFH (Soc.)	PH (PHI)	Y (1225)	18	MVHR	2 winters	BR (6)	15% of night time >1400ppm	Avg: 33% ± 6%	Avg (min-max): 0.41h^{-1} (0.35 - 0.51h^{-1})	flowmeter (pc); study	-
								LR (18)	2% of time >1400ppm				
			LEH (ÖNORM B 8110-1)	n/a	6	Nat + EV-INT		BR	35% of night time >1400ppm		manual window vent.: unknown	-	-
								LR	26% of time >1400ppm				

Project (Publications)	**Country**	**Build. type** [a]	**Declared energy designation (applied standard)** [b]	**PHI-cert. (Datab.-ID)** [c]	**# dwellings**	**Ventilation** [d]	**Measurement period**	**Location** [e]	**CO2-concentration** [f]	**Humidity**	**Ventilation rate/ Volume flows** for entire home unless otherwise stated	**Ventilation rate/ Volume flows** determination method and time [ae]	**Other IAQ parameters**
(Gupta et al. 2017; Sharpe et al. 2016)	UK	n/r	PH (PHI)	Y	20	MVHR	Feb	BR [v]	Max <1400ppm (11 of 14) Max <2000ppm (3 of 14)	LR: 20%< Avg <30% (4 of 14) 30%< Avg <40% (4 of 14) 40%< Avg <50% (6 of 14)	meet AD:F [y] (17 of 20) meet AD:F but high disbalance [y] (3 of 20) fail AD:F [y](0 of 20)	flowmeter (n/r); study	-
			CSH [q] w. MVHR	N	33	MVHR			Max <1400ppm (2 of 2)	LR: 20%< Avg <30% (4 of 17) 30%< Avg <40% (7 of 17) 40%< Avg <50% (4 of 17) 60%< Avg <80% (2 of 17)	Meeting AD:F [y] (6 of 32) Borderline [y] (5 of 32) Fail AD:F [y](21 of 32)		
			CSH [q] w/o MVHR	N	15	Natural or EV			Max <1400ppm (2 of 20) Max <2000ppm (5 of 20) Max <3000ppm (7 of 20) Max >3000ppm (6 of 20)	LR: 20%< Avg <30% (9 of 15) 30%< Avg <40% (5 of 15) 40%< Avg <50% (1 of 15)	n/a		
Kapfenberg (Sibille et al. 2015)	AT	MFH (Soc.)	PH-refurb (PHI)	C	16	MVHR	1 year	BR	4.5% of time >1400ppm	n/r	Total supply (flat): 40-80m^3/h DCV systems 85-100m^3/h with manual control	flowmeter (n/r); commissioning + continuous in-duct measurement	-
								LR	2% of time >1400ppm	mostly 20-55% range			
Chifley PH (Truong and Garvie 2017)	AUS	SFH	PH (PHI)	Y (4438)	1	MVHR	8 days (spring)	LR	Max: 1000ppm	n/r	n/r	-	-
(Colcough et al. 2018)	IRL	SFH TH (Soc.)	PH (PHI)	Y	10	MVHR	3 months (winter)	BR (3)	9% of time>1400ppm	n/r	n/r	-	-
				n/r			1 night (winter)	BR (10)	Max <1400ppm (7 of 10) Max <2000ppm (3 of 10)	n/r	n/r		
			Building Reg.	n/a	9	Natural	1 night (winter)	BR (9)	Max <1400ppm (4 of 9) Max <2000ppm (1 of 9) Max >2000ppm (4 of 9)	n/r	n/r	-	-
(Militello-Hourigan and Miller 2018)	US	SFH	PH (PHI)	Y	1	MVHR	3-5 days (Oct+Mar)	BR	2% of time >1000ppm	n/r	Design: $0.16h^{-1}$	n/a	PM, FA, radon, VOC [z]
			PH & TH [r]	N	8	MVHR			Max <1000ppm (2 of 8)		Design: $0.08\text{-}0.42h^{-1}$	n/a	

Project (Publications)	Country	Build. type [a]	Declared energy designation (applied standard) [b]	PHI-cert. (Datab.-ID) [c]	# dwellings	Ventilation [d]	Measurement period	Location [e]	CO2-concentration [f]	Humidity	Ventilation rate/ Volume flows for entire home unless otherwise stated	Ventilation rate/ Volume flows determination method and time [ae]	Other IAQ parameters
Harbin (Wang et al. 2018)	China	MFH	PH (PHI)	Y	8	MVHR	1 winter	LR	Max <1000ppm (8 of 8) Max (all): 840ppm	Avg: 31%	Avg (min-max): 97m^3/h (76-114m^3/h) Avg: 0.37h^{-1}	flowmeter (hw); study	PM
			Conventional	n/a	8	Natural			Max <1000ppm (4 of 8) Max (all): 1650ppm	Avg: 35%	n/r	-	
(McCarron, Meng, and Colclough 2018; McCarron et al. 2020)	UK	SFH	PH (PHI)	Y (2474, 2856, 4749, 4751)	4	MVHR	3 months (winter)	n/r	Max <1400ppm (3 of 4) Avg: 530ppm (all units)	Avg: 58%	n/r	-	Radon
(Meyer 2019)	GER	SFH MFH SDH TH	PH	n/r	35	MVHR	1 year	various			n/r	-	Radon
			LEH-refurb	n/a	105	Natural					n/r	-	
(Yang et al. 2020)	Swi	n/r	Minergie	n/a	217	MVHR	div. [ac]	BR [ac]			n/r	-	Radon, TVOC, FA, fungi
			Energy-renovation	n/a	433	Nat					n/r	-	
Nowon EZ-House (Lim et al. 2021)	KOR	MFH SDH TH	PH (PHI)	Y (5817)	25	MVHR	1 year	LR	Max: 1550ppm (winter)	Avg (SD): 36.0 (9.1)%	n/r	-	PM, VOC
			Conventional	n/a	25	Natural			Max: 1900ppm (fall)	Avg (SD): 34.1 (8.0)%	n/r	-	PM, VOC, health status (self-reported)
(Szabados et al. 2023)	HUN	SFH	PH (PHI)	Y [ab]	13	MVHR	1 week (winter & summer ea.)	LR	Max: 961ppm (winter)	Avg (SD): 39 (6)% (winter)	Avg (min-max)@winter: 17.3 (7.7-27.5) $m^3/(h*per)$ 0.51 (0.21-1.3)h^{-1}	flowmeter (hw); study	PM, FA, VOC, bacteria, fungi
		MFH			2								

[a] Building type: SFH…single family house, MFH…multi family house, SDH…semi-detached house, TH…terraced house, Soc…social housing

[b] Energy designation as reported and applied standard or guidelines if known. PH…Passive House, PHI: Passive House Institute, LEH…Low Energy House, refurb…energetic refurbishment

[c] certified according to PHI criteria: Y...yes; N…no; C...certified components used; n/r...not reported; If listed in https://passivehouse-database.org/, the ID is provided in ().

[d] Ventilation concept: MVHR…mechanical ventilation with heat recovery; Natural…natural via in-/exfiltration and window opening; EV-TV…extract air fan with trickle vent openings; EV-INT…intermittently operated extract air fan, e.g. in bathroom operated with light switch

[e] Measurement location referring to CO_2-concentration and humidity, unless otherwise stated: BR…bedroom, LR…living room, n/r…not reported

[f] One of the following metrics was extracted if available: % of time >1400 ppm or >1000 ppm; typical peak concentration in bedrooms, e.g. reported as median of maximum hourly average; maximum concentration during the measurement period or number of dwelling with a maximum below certain threshold. Partly extracted with WebPlotDigitizer (https://apps.automeris.io/wpd/)

[g] before refurbishment

[h] designed accord. to "best regional practice"

[i] according to BBC-Effinergie (EFFINERGIE n.d.)

[j] accord. to Swedish PH standard (Forum for Energy Efficient Buildings (FEBY) 2012)

[k] reportedly designed to heat energy demand of 15 kWh/m^2a and a n_{50}~0.5 h^{-1}

[l] reportedly designed to heat energy demand of 30 kWh/m^2a and a n_{50}~2 h^{-1}

[m] high performance new and refurbished homes, with energy designation provided by occupants including PH (7), Net-zero energy (6), Deep energy retrofit (12)
[n] according to UK building code
[o] according to the preliminary version of the Norwegian standard NS 3700
[p] according to Lithuanian standard STR 2.01.09:2002
[q] Code for Sustainable Homes (CSH) level 4, 5 (Department for Communities and Local Government 2010)
[r] included non-certified, PHIUS-certified (PHIUS n.d.) and homes that were considered “tight” (TH) from the original authors.
[s] designed using PHPP; 2 out of 3 are listed in PH database as LEH using PH components (n50=1.2)
[t] evening hours from 4 p.m. until 11 p.m.
[u] abnormal mould spores refers to the ratio of measured indoor vs. outdoor concentrations of colony forming units (CFU/m^3) being greater unity.
[v] CO_2 / RH measurements were not performed in all dwellings, but sometimes in multiple bedrooms.
[w] measured values at reported fan setting (most often at lowest setting)
[x] according to survey: typically operated at lowest setting
[y] Building Regulations Approved Document Part F (AD:F) (HM Government 2013)
[z] measured with photoionization detector (PID)
[aa] This study reported the maximum of moving average of the hourly averaged CO_2 concentration for each home. The median of all homes is interpreted herein as the typical peak concentration.
[ab] PH certification reported, but reference to PH standard unclear, and the use of G4 (EN779) or worse filters for outdoor air reported for the majority of homes in contrast to PH requirements.
[ac] Fungi (12 weeks), TVOC and FA (1 week) measurement in bedroom; radon (3 months) in a heated and regularly occupied room at the lowest floor of the dwelling
[ad] previous study/publication indicates that further extract air locations exist
[ae] air flow measurement methods and time: pc…pressure compensated flowhood/balometer; hw…hotwire anemometer/balometer; study…as part of reported study; commissioning…during system or building commissioning

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