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ABSTRACT

Global climate change, demographic change and advancing mechanization of everyday life will go along with new ways of living. Temperature extremes, an ageing society and higher demands on a comfortable life will lead to the implementation of sensor based networks in order to create acceptable and improved living conditions. Originally, the idea of the smart home served primarily the efficient use of energy and the optimization of ventilation technology connected with new ways of constructing buildings (low-energy and passive houses, respectively). Today the term 'smart home' is also linked with the networking of home automation systems, home appliances and communications and entertainment electronics. Living in a smart home often makes also significant demands on the occupants who are required to drastically change some of their living habits. This review summarizes current findings on the effect of measured environmental parameters on indoor air quality, individual thermal comfort and living behavior in smart homes with focus on central Europe. A critical evaluation of available sensor technologies, their application in homes and data security aspects as well as limits and possibilities of current technologies to control particles and gaseous pollutants indoors is included. The review also considers the acceptance of smart technologies by occupants in terms of living habits, perceived indoor air quality and data security.

1. Introduction

Alongside population growth and increasing environmental pollution, global warming is one of the greatest challenges facing us today and will entail scientific, political and social consequences around the world. The report by the International Panel on Climate Change (IPCC) makes clear that anthropogenic greenhouse gas emissions, which are increasing annually, are primarily responsible for climate change [1]. Taking into account the conservative RCP 2.6 scenario (Representative Concentration Pathways), which is based on carbon dioxide concentrations of 400 ppm and a radiative forcing value of 2.6 W/m^2, the following scenarios are assumed for Germany and Central Europe: more days of sunshine with extreme temperatures and heavy rainfall with a simultaneous decrease in average precipitation volume [2]. Changes in climatic conditions such as temperature, water balance and direct sunshine will also lead to a worsening of air quality [3], which will have a particularly high impact during heat waves [4,5]. In Fig. 1, different scenarios for Germany concerning the change of summer days, average temperature, global irradiation and water balance until 2040 are shown. In many megacities the air is already so heavily polluted with gaseous substances and particles that it is no longer advisable to ventilate interior spaces with unfiltered outside air [6].

In the near future we will therefore need to look intensively at the matter of how we can create healthy living environments in areas with extreme air conditions [7]. In the United States, a group of experts has already dealt extensively with the possible impacts of climate change on living conditions and general health [8]. On the basis of the Institute of Medicine (IOM) report, Fisk [9] sees potential for health risks caused by climate change, in particular for children, older people and people with respiratory and/or cardiac conditions. He identifies intelligently designed and operated buildings as one possibility for reducing climate-based health risks. Nazaroff [10] has also postulated negative impacts of climate change on indoor air quality and names effective ventilation and filter technology as significant factors for the planning of buildings.

People had been used to controlling the indoor climate manually for centuries when automation was first introduced in the early 20th

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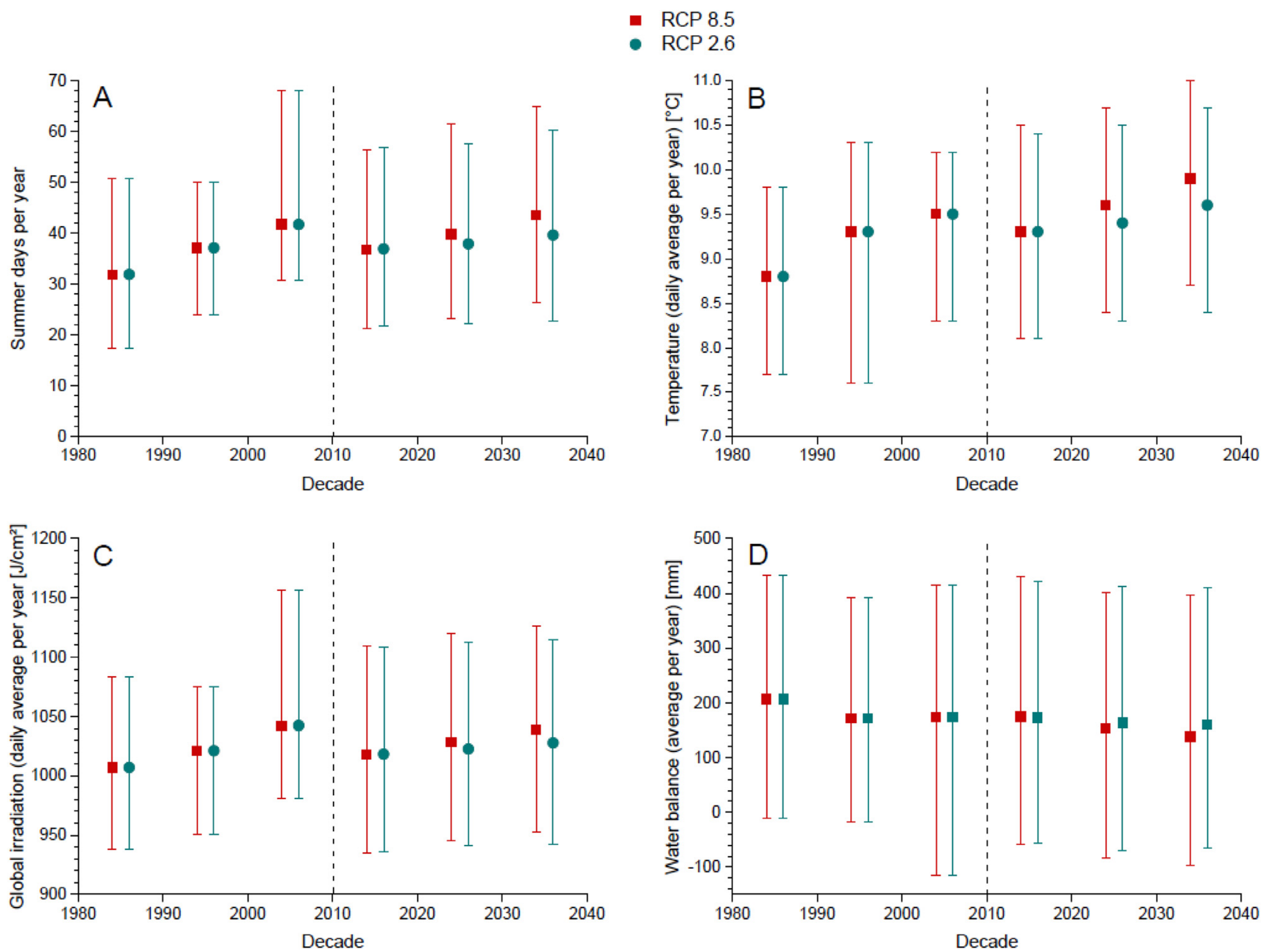

Fig. 1. Climate change scenarios for Germany between 1980 and 2040 in 10 year cycles on the basis of RCP 8.5 (1370 ppm CO_2, 8.5 W/m^2 radiative forcing) and RCP 2.6 (400 ppm CO_2, 2.6 W/m^2 radiative forcing): A: summer days per year; B: daily temperature (daily average over year, °C), C: global irradiation (daily average over year, J/cm^2), water balance (average over year, mm). The water balance is the difference between rainfall and evaporation. The calculation was performed by use of the online portal http://www.klimafolgenonline.com, the models are described in [128]. The model considers experimental data until 2010.

century with the invention of air conditioning. Despite constant improvements in control technology, for almost a hundred years room temperature remained the major manipulated variable in air conditioning technology. Finally, powerful computers and rapid data transmission systems enabled the development of smart grids which include various operational and energy measures (e.g., smart meters, smart appliances). Thus, smart grids enhance the linkage between producers and consumers of energy. Building on this technology, Home Energy Management Systems (HEMS) have been developed which are today the foundation for smart homes [11,12]. Originally, the idea of the smart home served the efficient use of energy [13,14] in times of transition toward sustainable energy [15] and the optimization of ventilation technology connected with it [16]. Today the term 'smart home' is also linked with the networking of home automation systems, home appliances and communications and entertainment electronics.

In general, low-energy houses, which as a rule have a system of artificial ventilation, require special technologies to achieve good indoor air quality [17]. Smart homes in particular offer opportunities with regard to the expected negative impacts of climate change on air quality. Using modern sensor technology [18] it is possible to measure online not only the climatic parameters but also the concentrations of air polluting substances such as carbon dioxide (CO_2), sum parameters for volatile organic compounds (VOCs) and particles and record them in the HEMS (see Fig. 2). 'Indoor air quality and air hygiene' are now being taken ever more seriously as aspects of smart home technology. Nevertheless, living in a smart home often puts significant demands on the occupants who are required to drastically change some of their living habits. In particular, no longer being able to open windows manually, is hard for many people to accept.

The rapid developments in the scientific field of housing technology will significantly impact everyday life in the near future. Consequently, there is a need to summarize the main achievements in order to obtain an overview about the actual state-of-the-art, to discuss advantages and disadvantages of the smart home concept from the technical and social perspective and to give guidance for further research. We report therefore current findings on the effect of measured environmental parameters on indoor air quality, individual thermal comfort and living behavior in smart homes for the temperate climate zone. This includes a review of available sensor technologies, their application in homes and data security aspects as well as limits and possibilities of current technologies to control particles and gaseous pollutants indoors. The results drawn from this publication could be used for future planning, recommendations and guidelines on indoor air quality in automated private homes and residences.

2. Application of sensor technologies in private homes

Smart home technology can be mainly applied in two ways: (i) to ensure the occupants safety, health and comfortability as well as to facilitate household operations, especially in order to reduce energy costs (e.g. automatically controlled blinds, ventilation, appliances) and (ii) to assist elder and disabled people by smart sensor technology to

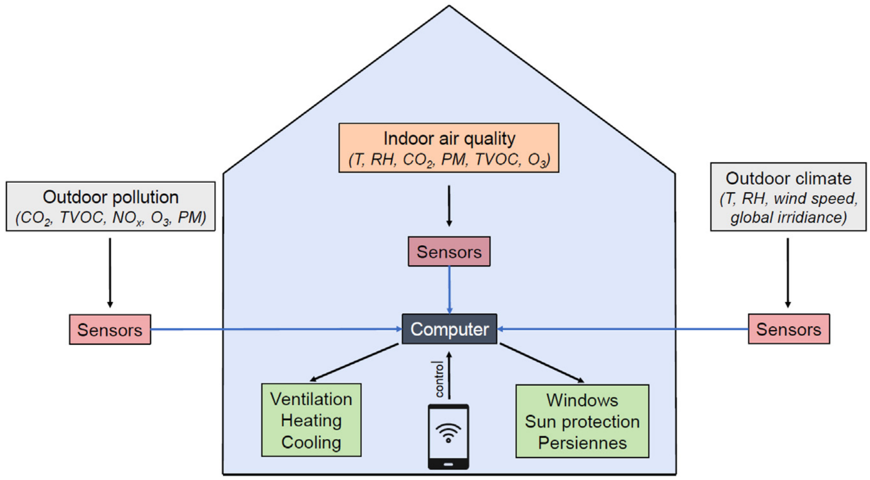

Fig. 2. Possible manipulated variables (indoors and outdoors) for the control of ventilation, indoor climate and indoor pollutants.

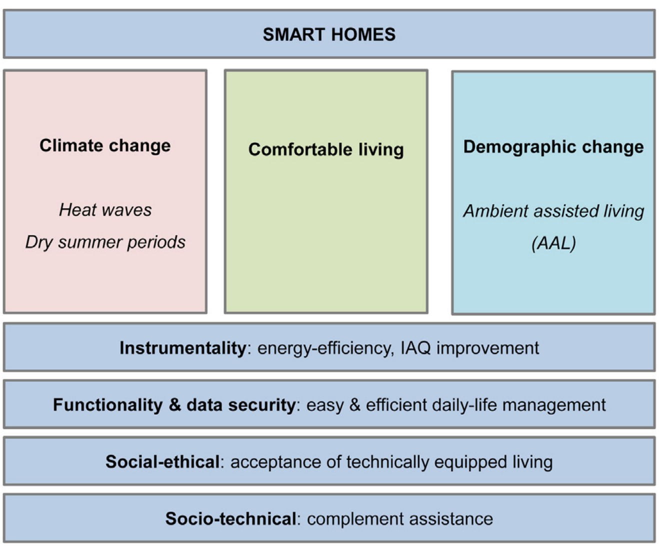

Fig. 3. Application ways of smart homes, their main targets and functionalities as well as important aspects to be considered.

stay independently in their own house or flat as long as possible. These applications, their main targets and functionalities as well as important aspects to be considered are illustrated in Fig. 3.

There is a long list of requirements a home should fulfil to keep their occupants safe, healthy and comfortable. One of its basic functions is to provide the necessary environmental conditions to ensure thermal comfort, but also to protect people against temperature extremes, which are a cause of severe health effects [19]. As a consequence of climate change, heat waves are increasing [20]. Protective measures have to be dynamically, in response to outdoor temperature variations, according to the diurnal and seasonal local climatic patterns. Whereas humans themselves are temperature ‘sensors’, thermometers provide quantitative information of the temperature and its trends. Good indoor air quality is another characteristic expected of home. Unlike temperature, which people sense and can tell whether it is appropriate or not, presence of air pollutants is not always sensed by people, and in fact people cannot smell one of the most common indoor pollutant generated by themselves, carbon dioxide (CO_2). Its concentration can significantly exceed limit values without people knowing it, unless the room is equipped with sensors measuring its concentration.

Using smart technology in a health perspective, a complex network of different sensors, computers, mobile devices and software applications are summarized under the term Ambient Assisted Living (AAL), targeting on personal healthcare monitoring and telehealth systems [21]. The development of AAL systems is mainly driven by the demographic change. The technology might help to minimize increasing costs in the healthcare sector. In general, three broad views concerning AAL are differentiated: (i) functionality: smart homes as help for a more efficient and easy management of the demands of daily living; (ii) instrumentality: possibility of smart home technology to improve energy efficiency and to lower energy costs and negative environmental influences (e.g. outdoor/indoor pollutants); (iii) socio-technical: complement assistance for human healthcare [21,22], as shown in Fig. 3.

Concerning healthcare applications, it is important to consider social and ethical problems, such as the handling and acceptance by older people. An important aspect in this regard is that sensor technologies must not replace human care but that technologically solutions are provided in order to complement and support healthcare treatments and systems without distracting or attracting attention as realized in the Internet of Things [21,23]. Based on this approach, an IAQ sensor system for AAL has been developed incorporating sensors for temperature, relative humidity, light intensity and CO_2 [21].

Even if there are many technologies available for measuring thermal and air quality parameters in homes, there are significant challenges in application of these technologies and in making them useful in controlling the indoor environment. One of the reasons is that the indoor environment is a complex system, with its elements strongly connected and affecting each other. For example, when increasing the ventilation rate by opening the window to allow cooler outdoor air to enter the house interior, some fraction of the pollutants generated indoors is removed, for example CO_2 or combustion products generated during cooking. However, increased ventilation can promote the ingress of pollutants and particles from outside leading to elevated concentrations indoors, especially when the indoor environments are close to busy roadsides [24,25]. Different studies targeting on indoor air quality within low energy buildings and passive houses have shown that air exchange rates are mostly too low ($< 0.2\,h^{-1}$) due to an inadequate setting or missing knowledge in operation and management of occupants leading to increased CO_2 levels indoors [26,27]. Increased CO_2-concentrations were also found during night-times as residents switched off the mechanical ventilation system due to uncomfortable air flows. Otherwise, facing the high area/resident ratio in newly built low-energy houses, CO_2 values can stay unintentionally low because of dilution effects [26]. While sensors would provide information on concentration of particular pollutants, such information on its own would be useless to the occupants. Thus, a smart sensor system would not just monitor, for instance, temperature conditions and pollutant concentrations both indoors and outdoors in the immediate vicinity of the house, but based on all these parameters would in addition determine the necessary actions to be taken. This could include the appropriate ventilation conditions and indoor source operation to remove indoor generated pollutants, to prevent ingress of outdoor pollutants, to ensure the right temperature and to do all this in an energy efficient manner. These challenges as well as the benefits of indoor air quality sensing systems were reviewed by Kumar et al. [18]. There are more stringent requirements for real-time sensors in indoor environments, which are (i) high sensitivity as concentration levels are lower indoors, (ii) long operating life, (iii) miniaturized size and (iv) low operating noise to be used discreetly and to be accepted by the building occupants [18,28,29]. Moreover, the technology has to be applicable in complex wireless sensor networks. Commercial devices are currently ranging from simple and low cost to very sophisticated and expensive. To be suitable for mass application in smart homes, the available technologies and sensors should be sufficiently cheap, but also of good quality to be able to detect specific pollutants in adequately low concentration levels relevant to indoor environments. They should also be robust with good response times, provide reliable data and should not requiring frequent maintenance or replacement. In addition, the sensors should be adaptable to room specific usage habits and, thus, to room specific ventilation strategies [29].

As smartphones are increasingly important and influencing human's life, smart technology can also be based on smartphone applications. These offer already a broad functionality, from e.g. global positioning systems (GPS), camera, microphone, Bluetooth and accelerometer to integrated sensors detecting the owners activity (walking, running) with no additional sensing hardware [21,30]. However, there is no generally accepted definition or set of parameters which the technology has to fulfil to be called a ‘sensor’. In fact, with this being a hot topic at the moment, many instrument manufactures or users call their instruments ‘sensors’. Regarding the price, a review of low cost sensors for respirable particulate matter showed a price range from 10 to 100 Euros [31]. Monitors for accurately measuring particle masses in a wide range of settings were considered as low cost at prices below US$ 500 [31,32].

3. Control of environmental parameters with impact on indoor air quality

Indoor air quality (IAQ) is typically affected by three major groups of pollutants: (i) outdoor air pollutants, such as e.g. carbon monoxide (CO), benzene (C_6H_6), sulfur dioxide (SO_2), ozone (O_3), oxides of nitrogen (NO, NO_2), and particles, which penetrate the building envelope, or enter the building through windows or air handling units (AHU); (ii) those mainly generated in households, namely occupant-related pollutants like CO_2, bio-effluents and particulate matter (PM) in different size ranges, and (iii) building-related pollutants, typically volatile organics (VVOCs, VOCs, SVOCs) originating from e.g. construction material, furnishings and office equipment as well as microbial contaminants such as viruses, fungi and bacteria [33]. The affection of IAQ by the infiltration of outdoor air to indoor environment depends also on the type and operation of the ventilation system of a building, which could be natural or mechanically ventilated.

The spatial distribution of ambient air pollutants might be diverse as shown in Fig. 4 for PM_{10}, $PM_{2.5}$, NO_2 (annual mean) and ozone (number of days (calculated as 8 h averages) exceeding 120 µg/m^3) in the year 2016 in Germany. The dashes represent urban areas with a high density of population. As expected, NO_2 is clearly related to city centres and traffic with annual concentrations sometimes exceeding the WHO guideline value of 40 µg/m^3 [34]. On the other hand, increased annual means of PM_{10} and $PM_{2.5}$ are also found in rural areas in the north east of Germany. Surprisingly, the highest number days exceeding 120 µg/m^3 ozone are located in the south east of Germany where NO_2 concentrations are comparatively low. This is probably due to the warm and sunny climate in this region, which supports photochemical reactions. Stowell et al. [35] consider climate change induced tropospheric ozone as one of major threats to human health. Fig. 4 makes clear that different geographic regions are affected by different types of air pollutants. For example, the WHO guideline for PM_{10} (24 h average) of 50 µg/m^3 was exceeded 63 times in Stuttgart city centre, 120 µg/m^3 ozone (8 h average) was exceeded 46 time in the Freiburg area (source: German Federal Environment Agency (UBA: Umweltbundesamt)). This needs be taken into account in the building design of ventilation systems in modern housings.

Outdoor conditions also may change rapidly, as shown in Fig. 5 for the diurnal variations of global irradiance, ozone and temperature in the Braunschweig area (North Germany) on 19.05.2017. At 2 pm there is a sudden decrease of global irradiance from 415 W/m^2 to 115 W/m^2; at 6 pm the temperature dropped from 20 °C to 13 °C within 2 h. The unusual increase of the ozone concentration after sunset is due to intensive lightning. Modern sensors are able to monitor such changes within milliseconds, but in order to avoid permanent feedback, modern automatic control engineering requires intelligent algorithms for attenuation and hysteresis. As illustrated, IAQ itself impacts the health of human beings residing in indoor environments [36,37]. Published research indicates that an increase in the ventilation rate is associated with improved occupant health and productivity [38,39]. At the same time, it reduces the energy consumption within office buildings if they are equipped with Heating, Ventilation and Air Conditioning (HVAC)-systems. However, negative effects of increased ventilation have to keep in mind, which might be the increased infiltration of outdoor pollutants.

Ozone (O_3) levels indoors are mostly low due to chemical reactions on indoor surfaces. However, nitrogen dioxide (NO_2) concentrations can be increased during warm periods (spring, summer) because of the frequent opening of windows, especially near busy roads. Indoor combustion processes (e.g. gas cooking, decorative fireplaces) result in elevated indoor/outdoor (I/O)-ratios for NO_2 [40]. For this reason, increased NO_2 concentrations can also occur during the cold seasons (autumn, winter) even though air exchange rates (AER) are low, as it was shown for extensive candle burning in Swedish houses [41]. High I/O ratios for formaldehyde (HCHO) and TVOC (total volatile organic compounds) were traced back to consistent indoor emission sources without significant seasonal variations. However, HCHO concentrations in new buildings were higher than in old houses even though the AER was higher in the new buildings, probably due to increased emissions of new building materials and furnishing. Given similar AER in newly built passive and conventional houses, higher HCHO emissions were found in conventional buildings in contrast to increased TVOC levels, lower terpene concentrations and more constant O_3 levels in passive houses, which might indicate ozone initiated reaction processes [27,41,42]. Values of volatile organics might be increased in passive and low-energy houses at different stages of use, mainly after installing building materials, equipment or furnishings. Even though primary emissions decline usually over several months, Kaunelienė et al. [26] encourage not just to focus on low-energy demands in modern building designs, but to extend this approach also to the installation of environmentally friendly and low-emitting materials and furnishings indoors. This is also underlined by a French study conducted in ten low-energy school buildings. Despite new construction techniques, 150 different VOCs were detected with pollution patterns and concentrations similar to those reported for standard buildings [43]. Most abundant substances were aldehydes (formaldehyde, acetaldehyde, hexanal, pentanal), ketones (acetone, 2-butanone) and aromatic hydrocarbons (toluene) which could be attributed to indoor sources with the exception of benzene introduced by outdoor air (I/O ratio ~ 1 or < 1) [43]. Indoor air quality and also room climate parameters can be significantly improved if low-energy buildings are equipped with mechanical ventilation systems. This could be considerably improved by supervision regarding the selection and use of low-emitting construction materials and furnishing [26].

Francisco et al. [44] studied ventilation, indoor air quality and

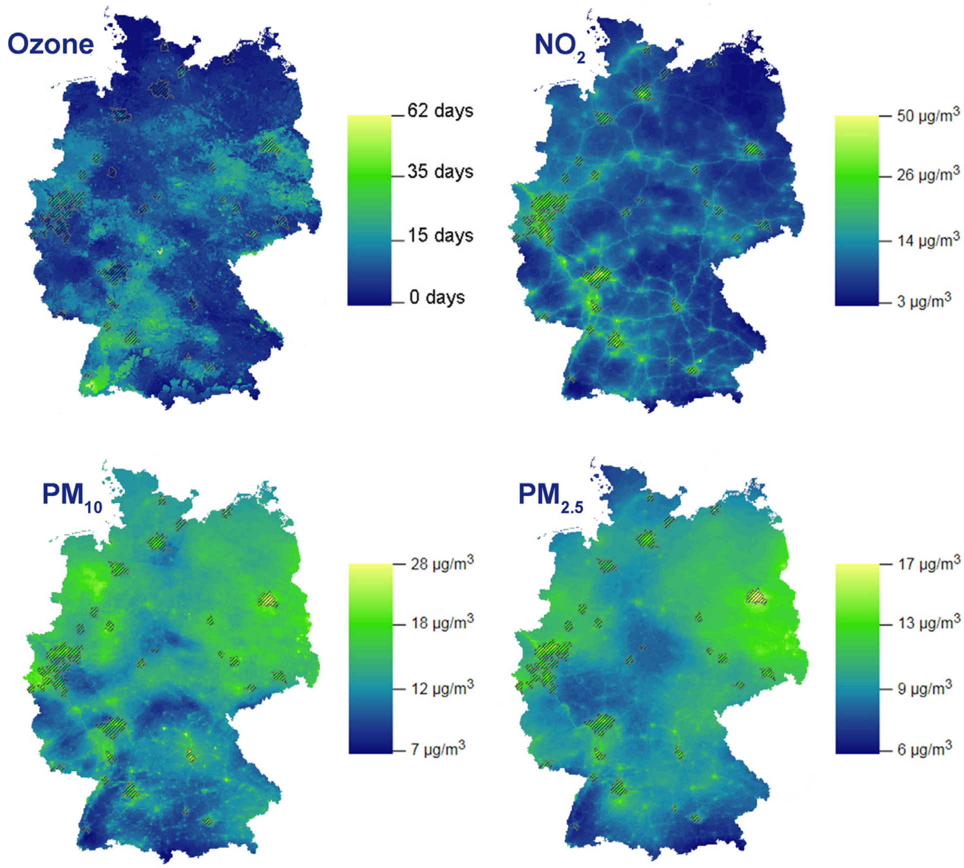

Fig. 4. Spatial distribution of ambient air pollutants in Germany for the year 2016. NO_2, PM_{10} and $PM_{2.5}$ are provided as annual means, for ozone the number of days exceeding 120 µg/m^3 (8 h averages) are presented. The dashed lines indicate urban areas with high population densities. The figures were taken from the Air Monitoring Sites Information System of the Federal Environment Agency (Umweltbundesamt), https://gis.uba.de/Website/luft/index.html (accessed January 25, 2018) and reproduced under non-commercial Creative Commons 4.0 License. Copyright remains with Umweltbundesamt, Germany.

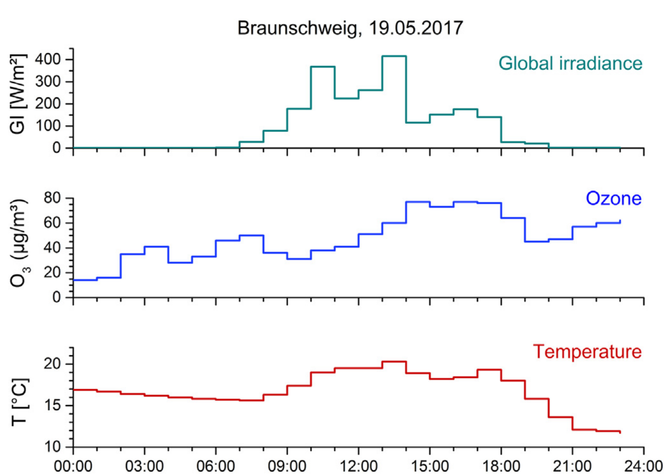

Fig. 5. Diurnal course of outdoor global irradiance (GI), ozone concentration (O_3) and temperature (T) in Braunschweig area (52° 15′ 57″ N; 10° 31′ 36″ E), North Germany. The data represent 1 h averages and were taken from the monitoring station Braunschweig (BGSW) of the Lower Saxony Ministry of the Environment, Energy and Climate Protection (http://www.umwelt.niedersachsen.de).

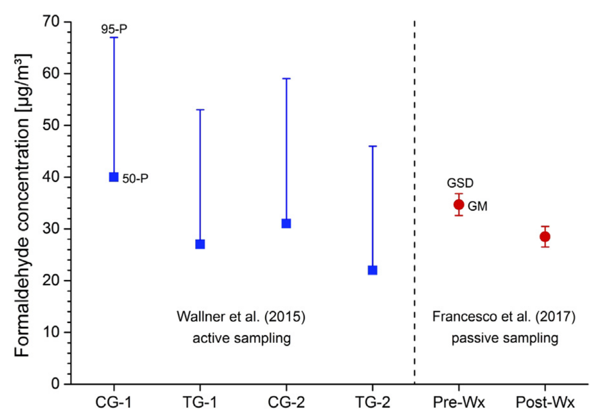

Fig. 6. Comparison of formaldehyde concentrations in energy efficient (retrofitted) and conventional homes from [44] and [46]. CG-1: control group (conventional, manual ventilation), three months after moving in; TG-1 (energy efficient, mechanical ventilation), three months after moving in; CG-2: control group (conventional, manual ventilation), one year later; TG-2 (energy efficient, mechanical ventilation), one year later; Pre-Wx: before weatherization, Post-Wx: after weatherization. 50-P: 50th percentile (median); 95-P: 95th percentile; GM: geometric mean; GSD: geometric standard deviation.

health in homes undergoing weatherization (energy retrofits) and came to the conclusion that life conditions are significantly improved when weatherization is accompanied by an ASHRAE residential ventilation standard [45]. Due to the increased air supply through ventilation systems, indoor concentrations of volatile organic compounds, formaldehyde, saturated acyclic aliphatic aldehydes and CO_2 are typically lower in newly built or retrofitted houses with mechanical ventilation than in conventional buildings. Moreover, concentrations usually decrease during occupancy due to decreasing emissions of newly installed building materials and products. These effects are visualized in Fig. 6 for the indoor pollutant formaldehyde using data from Refs. [46] and [44]. Table 1 summarizes median values of other key parameters in regard to indoor air quality and thermal comfort from different studies, measured in energy-efficient houses.

Table 1
Median values of key parameters in regard to indoor air quality and thermal comfort in retrofitted and energy-efficient homes (N = number of measurements).

N	T [°C]	RH [%]	AER [h^{-1}]	CO_2 [ppm]	NO_2 [µg/m^3]	O_3 [µg/m^3]	Comment	Ref.
11	23.4	51.2	0.2	655	4.0	n.d.	Low energy residential buildings Lithuania	[26]
10	21.5	44.7	2.9	1306[a]	18	3.9	Low energy school buildings France	[43]
20	22.1	30.0	0.6	< 1000	10	9.7	Passive houses Sweden	[41]
6	21.6	45.9	0.5	< 1000	n.d.	n.d.	Energy efficient houses France	[27]
23	n.d.	n.d.	n.d.	587	4.6	n.d.	Retrofitted houses Finland	[92]
13	n.d.	n.d.	n.d.	849	15.3	n.d.	Retrofitted houses Lithuania	[92]
62	22	40	n.d.	1360	n.d.	n.d.	Energy efficient buildings Austria	[46]
24	20.8	47.4	0.304[b]	n.d.	18.6	n.d.	High performance homes California	[122]
66	n.d.	n.d.	n.d.	914	n.d.	n.d.	Retrofitted homes United States	[44]

[a] Median of maximum values.
[b] N = 16.

4. Technical solutions for online measurement of VOC concentrations

Utilization of information on volatile organic compounds, such as their concentration, is considered to be a substantial improvement for demand-controlled ventilation in private rooms and offices. Major benefits to be expected are: (a) more exact occupancy detection in rooms, and (b) a ventilation control more related to health, especially if the sensors are capable of making a distinction between toxic and non-toxic volatiles. In addition, when building ventilation in megacities with poor outdoor air quality is considered, using such a sensor at the air intake may assist in preventing the ventilation with polluted air during rush hours. As many odorous substances are part of the VOC range, improvements in the perceived air quality may also result as the ventilation might be better focused on removing offending odors quickly. So in total, the consideration of VOCs could significantly enhance building ventilation strategies.

The measurement of VOCs with cheap sensors, however, is not simple: the group of VOCs comprises a broad variety of substances with very different physicochemical properties, covering a large boiling point range (50–250 °C [47]). Most sensors provide only a 'TVOC' sum value, which tells very little about the actual concentration levels, and even less about possible health effects. This reduces their applicability, and forces the developer to choose the right type for a certain application. To be easily integrated into ventilation systems, sensors have also to fulfil some important requirements: They need to be stable towards changes in climatic conditions, safe to operate in a ventilation system or in rooms, easily maintainable (if not maintenance-free) with a long lifespan (> 1 year) and, especially for room-level monitoring, have low production costs.

In general, there are conventional instruments available to measure the variability of pollutants listed above. However, when it comes to indoor environments where non-bulky, small, quiet and more sensitive instruments are needed (as indoor concentrations could be quite low at times to go below the threshold levels of many pollutants), available systems may not work well. Such a need points towards the need of IAQ sensors that are miniaturized battery-operated and low-power devices as well as wearable and able to communicate data via Bluetooth or Wi-Fi to a remote platform (e.g. smartphone or a PC) to view, analyze and interpret [28,48,49]. Advances in air sensor technologies have now made it possible to measure numerous pollutants, such as VOCs, CO, O_3, NO_2, SO_2 and PM, through a diverse range of air sensing devices [50,51]. Some of the key requirements for the indoor air sensing is that these sensors have a good response time; they are robust, vandal proof and exhibit high performance [28]. A good number of these sensors are battery operated, mobile, and wearable and have communication protocols incorporated in them that allow data to be transmitted to a remote platform for viewing, with the help of application software [49].

Possible sensor technologies for measuring VOC/TVOC include optical/non-dispersive infrared (NDIR) technology sensors, photoionization detectors (PID), metal-oxide-semiconductor (MOS) sensors, electrochemical (EC) sensors and catalytic sensors [52,53]. Usually, MOS sensors and EC sensors are used to measure gaseous pollutants. While the MOS sensors are low in cost, they generate non-linear output signals with the gas concentration and are easily affected by changes in temperature and relative humidity. Concerning substance quantification, they experience various cross-interferences and have a very limited sensitivity and specificity. Technologies to overcome these drawbacks are still under development [54]. In contrast, EC sensors generate a current proportional to the gas concentration [55,56]. The sensors are less sensitive to climatic changes and usually have lower power consumption than MOS sensors, as they do not require a heater to reach operating conditions [55]. However, MOS sensors are generally cheaper than EC sensors [57]. Even though PID sensors can be used to detect a wide range of substances, a main disadvantage is that the sensitivities of PID sensors differ substantially from one substance group to the next, and substances with high ionization potentials will not be detected at all. Due to the UV light source used, the sensors are comparatively expensive and require more power. However, this may change when UV-LEDs become more readily available.

Within these technical solutions, some MOS sensors are already used for environmental monitoring in relevant concentration ranges: The iAQ-100 TVOC sensor was described in more detail and used by Moltchanov et al. [58] in a study of urban air quality. The TGS2602 VOC MOS sensor was used for monitoring indoor air quality [59]. The device was found to be sensitive to higher concentrations of VOCs such as toluene and other gaseous pollutants, including ammonia and hydrogen sulfide, affording a detection range as low as 1–30 ppm. Leidinger et al. [60] tested an array of MOS VOC sensors (GGS 1330 (SnO_2 based)), GSS2330 (SnO_2 based) and GSS5330 (WO_3 based) with different targeted gases at ppb and even sub-ppb levels. Using linear discriminant analysis, background VOCs could be distinguished from the targeted gases. The results demonstrated that the combination of sensors can improve the reliability of VOC identification and enhances the potential utility of the array in in-field test sensor systems. Penza et al. [61] investigated the application of low-cost solid-state gas micro sensors based on commercial metal-oxides sensors (TGS 2600, SP-AQ2, TGS 2106, TGS 822) for odor control as well as for cost-effective and on-site air-quality monitoring in a landfill in Italy. The study also indicated that the sensors were quite sensitive to methane, a fact that might impact on the reliability of VOC measurements. Some of the requirements for the sensors in terms of measuring range of various pollutants and their detection limits are presented in Table 2.

The sensitivity of common VOC sensors discussed above is a major limitation to their widespread application in air quality assessment. PID sensors may offer a high level of accuracy in VOC monitoring, but the relatively high cost of PID VOC sensors will be the limiting factor. Overall, it appears that currently the low-cost sensors (MOS, EC) seem to be the most promising technologies to facilitate widespread use, although more investigations on their practical uses are warranted to

Table 2
Requirements for smart sensors in terms of measuring range of various pollutants and their detection limits (Source: Kumar et al. [18]).

Pollutants	Measuring range [mg/m^3]	Detection limit [µg/m^3]
Carbon monoxide	0–100	100
Benzene	0–200	0.2
Nitrogen dioxide	0–500	10
Ozone	0–500	20
PM_{10}	0–400	1
$PM_{2.5}$	0–400	1
PM_1	0–400	1

confirm and validate their utility for use in ventilation control systems. The cross-interferences of such sensors towards CO, CO_2, other inorganic gases and sometimes water vapor (relative humidity) are a major problem for their application.

5. Challenges in the field of VOC sensors

Unlike other substances monitored for air quality control, the term ‘VOC’ covers a large group of individual substances. An air sample may easily contain 100–200 single VOCs of different chemical structures. Therefore, a second, equally critical drawback of the available sensors is the varying (and often unknown) response factor to certain substance groups. A sensor may show a good performance for one specific substance, but may fail to detect the same concentration of another substance at all. The response factors may vary considerably for e.g. PID sensors [62] or certain MOS sensors [63]. Especially in complex mixtures of 20 or more substances this may lead to significant inaccuracies. Critical substances may be missed entirely or false-positive may interfere with the evaluation. The same situation was observed for arrays of MOS sensors [64]. MOS sensors are also susceptible to erroneous readings when exposed to high concentrations of certain organic substances, or when coming into contact with gaseous sulfur-containing substances [65].

Earlier studies have shown that simple TVOC sensors can indeed make the occupancy detection in rooms more precise [66]. As occupancy detection is a key step to efficient ventilation, this alone justifies more research in the field of VOC sensors. If, in addition, single substances could be identified and roughly quantified by a sensor system, this would certainly open up new possibilities in target-oriented ventilation, with strategies like in Ye et al. [67] used to minimize energy consumption. It must, however, be noted, that VOC-concentration should not be the primary parameter to determine the required ventilation rate – the CO_2 concentration is more suitable for that purpose. Introducing the VOC concentration into ventilation systems is rather a step towards optimizing the air quality inside a building and having the ventilation system to react correctly in case of sudden activities releasing VOCs (renovation work, new furnishings, other dweller activities). Already established guidelines for indoor air pollutants can serve as basis for correct setting of sensor technology and ventilation systems (Table 3).

6. Control of carbon dioxide and thermal comfort

The personal thermal comfort of occupants is defined as the occupant's satisfaction with the indoor environmental conditions, which is however assessed by subjective evaluation [68]. Thus, the term ‘thermal comfort’ includes a number of environmental parameters which are interrelated with each other and which are directly or indirectly influencing the individual's well-being, namely ambient air temperature, mean radiant temperature, relative humidity, thermal radiation, the speed of air passing through the room as well as human activity, gender, and clothing insulation [69,70]. This also underlines how difficult the task of sensor based online monitoring of thermal comfort within a HEMS is. A wealth of studies has been performed during the last decades in order to clarify thermal comfort of different population groups in various indoor environments and its main influencing factors [70–75]. Ventilation governs the temperature and indoor air pollution. Published research has clearly indicated an inter-relationship between poor IAQ and thermal comfort with a number of factors that include (i) reduced human productivity and dissatisfaction in adults [76], (ii) adverse impacts on the learning ability of school children [38], and (iii) the growth of bacterial and fungal staining (blackening) on the building's interior walls and roofs [77,78]. Most studies have used CO_2, temperature and relative humidity as indicators for thermal comfort [66–73]. As the room temperature is the most important control variable for occupants, the personal well-being is highly dependent on regulatory options for heating and ventilation, respectively. As can be seen in Fig. 7, the ventilation rate again directly influences the CO_2-concentration indoors.

Table 3
Guidelines for indoor air pollutants as defined by the World health organization (WHO) and the German Committee on Indoor Guide Values (AIR), formerly known as ‘Ad hoc AG’.

Pollutant	Guideline value	Remark	Defined by	Ref.
Benzene[a]	n.d.	Unit risk: $6{\cdot}10^{-6}$ at 1 µg/m^3	WHO	[123]
Carbon monoxide	100 mg/m^3	15 min (once per day)	WHO	[123]
	35 mg/m^3	1 h (once per day)		
	10 mg/m^3	8 h		
	7 mg/m^3	24 h		
Carbon dioxide	< 1000 ppm	Hygienically harmless	AIR	[80]
	1000–2000 ppm	Elevated		
	> 2000 ppm	Hygienically unacceptable		
Formaldehyde	0.1 mg/m^3	30 min	WHO	[123]
Nitrogen dioxide	200 µg/m^3	1 h	WHO	[123]
	40 µg/m^3	Annual		
TVOC[b]	< 0.3 mg/m^3	No hygienic objections	AIR	[124]
	> 0.3–1 mg/m^3	No relevant objections		
	> 1–3 mg/m^3	Some objections		
	> 3–10 mg/m^3	Major objections		
	> 10–25 mg/m^3	Not acceptable		
$PM_{2.5}$[c]	25 µg/m^3	Derived from WHO [34]	AIR	[125]
Ozone	100 µg/m^3	8 h (ambient air)	WHO	[126]

[a] Carcinogenic compound. No safe level of exposure can be recommended.
[b] TVOC value as defined by ISO 16000-6 [127].
[c] For orientation only.

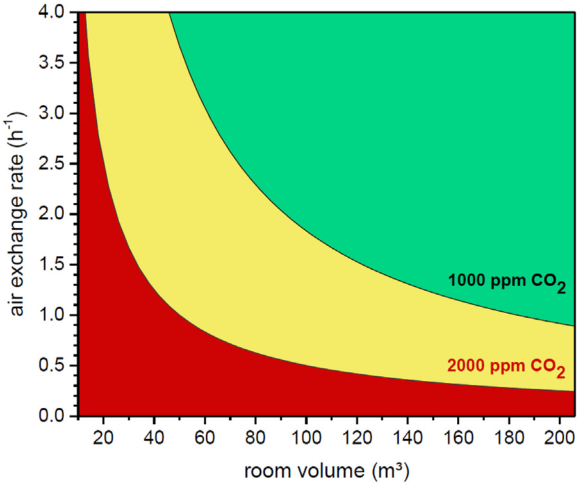

Fig. 7. Air exchange rates (AER) in dependence of the room volume for N = 4, $\dot{Q}_{CO2}$ = 20 l/h and person, $CO_{2(ambient)}(t)$ = 400 ppm and two CO_2 indoor concentrations (1000 ppm and 2000 ppm).

In a Swedish study, mean indoor air temperatures in passive and conventional houses showed no significant differences and were each in the thermal comfort range of 22–24 °C (see Table 1). Despite of mechanical ventilation systems installed, envelops of energy-efficient buildings investigated in Lithuania were not able to prevent indoor air from overheating during warm periods with outdoor temperatures above 30 °C.

Thus, adaptability of low-energy buildings during changing climates might be challenging [26]. In contrast, RH levels in passive houses were lower than in conventional buildings because of the ingress of dry outdoor air through mechanical ventilation systems [41,46]. Wallner et al. [46] therefore recommend moisture recovery strategies to be considered in low-energy buildings. Whereas in 50% of the passive houses the average RH was lower than 30%, which can lead to discomfort, mold problems in some conventional buildings were probable due to higher RH levels [41]. The fact that there were fewer indications of mold problems in mechanically ventilated buildings, than in those naturally ventilated (by opening of windows and doors), was demonstrated by an Austrian study. The authors also pointed out that mold concentrations indoors cannot be evaluated without knowledge of outdoor concentration. A higher I/O ratio of colony forming units (CFU) per m^3 indicates indoor sources. Concerning dust mite allergens, no significant difference between building types could be observed [46].

In low-energy school buildings located in France, temperature, relative humidity and CO_2 concentrations were within the ASHRAE Standard 55 [43,79]. Indoor/outdoor water concentration ratio was in most cases close to 1 which means that the ventilation systems do not influence the humidity conditions of the injected outdoor air. However, in nine of ten investigated low-energy school buildings, CO_2-levels were between 1000 ppm and 2000 ppm during occupancy, regardless of the season. In three buildings, peaks from 2000 ppm up to 5000 ppm were observed due to time schedules, starting the ventilation delayed in order to allow the rooms to warm up in the beginning of the courses. According to the German Committee for Indoor Guide Values (AIR) of the German Federal Environment Agency (UBA: Umweltbundesamt), CO_2 concentrations below 1000 ppm are regarded as harmless, those between 1000 ppm and 2000 ppm as elevated and concentrations above 2000 ppm as unacceptable (see Table 3) [80]. As human attention and performance are decreasing with increasing CO_2 concentrations, the use of a kind of 'CO_2 feedback systems' (e.g. 'ventilation traffic lights') has been tried for improving thermal comfort in schools and educational institutions [81]. It has been shown that in classrooms without mechanical ventilation, a feedback monitor can help by increasing ventilation rates and, thus, by lowering CO_2 concentrations, but its application can result in an increase of energy consumption. However, there was no effect within classrooms with mechanical ventilation, as the CO_2 level never exceeded 1000 ppm anyhow. Therefore, Verriele et al. [43] recommended an operation time slightly larger than the occupancy period in order to achieve the best compromise for air quality and energy consumption provided that classrooms are not occupied all the time. Also a pre-ventilation period before classes was found to be useful during winter time in order to improve both indoor air quality and energy efficiency by providing heated rooms at the same time. Saving energy costs can also be achieved by night ventilation (passive cooling) instead of active cooling during warm periods. Passive cooling provides also indoor air conditions more appropriate for thermal comfort [82].

Apart from this, most public buildings worldwide and up to 83% of all residential buildings in the United States, are equipped with a heating, ventilation and air conditioning (HVAC) system [83]. With the introduction of passive houses and smart homes, technologically supported solutions for regulating indoor climate parameters are increasing. Smart home technologies (SHT) comprise mainly sensors enabling automatic control of appliances and devices, such as lighting, windows, curtains and doors. The applied sensors (and monitors) detect environmental factors such as temperature, light, motion, humidity and CO_2 level. The control functionality is provided by software installed on computing devices including smartphones, tablets, laptops and PCs, or through dedicated hardware interfaces (e.g. wall-mounted controls) [84].

An important question regarding wireless sensors will be which kind of pollutants has to be detected in order to achieve a reliable measurement of 'thermal comfort'. There are currently sensors on the market, which are able to measure a range of common indoor air pollutants, e.g. volatile organic compounds (VOCs), carbon monoxide (CO) and particulate matter (PM). They have good response times, are robust with high sensitivity and selectivity and are vandal proof [18]. Air sensing devices are mainly based on microelectromechanical systems (MEMS). These microscopic devices are transducers consisting of a microprocessor connected to microsensors which are interacting with the surroundings. Reactions between the sensor material and the target gaseous pollutants trigger a signal or an electrical pulse which is correlated to a specific concentration of the target gas [18,85]. Also sensors based on conductivity or optical changes have been introduced [86,87]. Caron et al. [88] have shown that electronic gas sensors are already able to measure simple gas matrices and, therefore, to provide relevant information for air treatment control systems and the detection of indoor air quality events. However, the measurement of complex matrices as in real environments is not possible. In addition, high indoor pollutant concentrations might lead to sensor saturation. Low temperature gas sensors based on titanium dioxide (TiO_2) were able to detect CO_2 at temperatures near to room temperature at low power demand [89].

The individual's thermal comfort is mainly driven by temperature, a key factor to well-being of the indoor inhabitants. Cetin et al. [83] studied buildings operating under time-of-use electricity pricing (TOU) strategies and their relationship to HVAC use focusing on smart thermostats. These are programmable thermostats that communicate with the utility companies' pricing of electricity. The thermostat reduces automatically the electricity consumption during on-peak times. It has been shown that homes equipped with 'enabling technology' or technological solutions which enable an automatically reduction in electricity use have achieved the highest energy savings [90]. It was found that the strongest influencing factor on the long-term thermal comfort is the indoor set point temperature in comparison to other variables, such as thermal mass, setback temperature, and air exchange rate. The air exchange rate and the thermal mass are less influential on thermal comfort. In most cases, an increase in temperature leads to a decrease of the occupants' thermal comfort. This influence is greatest in the hot-dry climate zone. Also Vanus et al. [91] showed that a change in operating temperature in the internal environment leads to a direct influence on thermal sensation of a person. Wang et al. [82] highlighted that both thermal comfort and building energy consumption are depending on the room temperature set-point and occupant behavior. A study conducted in three northern European countries outlined that an adaption of RH values to country-specific guidelines after energy retrofits can improve the thermal comfort [92]. In addition to sensors for thermal comfort, CO_2 sensors are also used for detecting motion inside the house or inside specific rooms and can therefore be used for sensor based control of the environment according to the user preference based on their profiling [93].

7. Online technology for measuring airborne particles indoor

Airborne particulate matter (PM), ubiquitous in indoor and outdoor air, has been shown to be the leading environmental risk factor, ranking 7th and 12th, respectively, as household and ambient air pollution. Airborne particulate matter are measured as $PM_{2.5}$ which is the mass concentration of particles with an aerodynamic diameter < 2.5 µm [94]. Particles in indoor air originate from many different indoor sources and also penetrate from outside. Furthermore, there are a number of other influencing factors, including lifestyle (e.g. operation of natural ventilation or air-conditioning system, use of air fresheners and burning candles), meteorological conditions which affect the air exchange rate and influence the choice of the ventilation method, socioeconomic factors (cooking methods and kitchen facilities, types of stove hoods, etc.), as well as building structures that define the infiltration rate and impact of outdoor air on indoors. During cold and warm seasons windows are mainly closed as air conditioning or heating systems are in use. Thus, infiltration becomes the primary pathway for outdoor pollutants and particles to enter the indoor environment [95]. High indoor particle concentrations are of particular concern for home environments, where people potentially susceptible to air pollution (the very young, old or sick) spend most of their time, and where a number of particle sources may be in operation at the same time. Chen and Zhao [95] have shown high I/O ratios in private homes in which the occupants cooked and smoked without chimneys, whereas in contrast lowest I/O ratios were found in an uninhabited building equipped with air filters. This means that high I/O ratios indoors are mostly caused by indoor combustion processes (e.g. smoking, cooking, fireplaces), while buildings with no, or just few indoor sources, air filtration systems and tight envelopes have low I/O ratios. However, it was found that the I/O ratio is not useful in understanding pathways and distribution processes of, and relationship between indoor and outdoor particles as no reliable and consistent conclusion can be drawn concerning the impact of particle size on I/O ratio. Findings obtained in different studies indicate that measurement results and theoretical assumptions do not fit together so there are still open questions regarding size-dependent particle emission rates, transport mechanisms, penetration factors, deposition rates and distribution ways. These parameters are also strongly connected with the air exchange rate indoors and, again, also in this regard no consistent conclusions could be drawn yet. Further, infiltration processes of outdoor particles are not easy to reflect. It has also to be noted that the ingress of outdoor particles on, and by clothing of the occupants (e.g. woolen garments during winter) is another important pathway [95]. This demonstrates that measuring particle concentrations as helpful tool in the context of indoor air monitoring in a smart sensor network is challenging.

Unlike outdoor air where routine monitoring of PM has already been conducted by networks of monitoring stations for several decades in most countries of the world, there is no routine monitoring of PM in home environments anywhere in the world. The lack of appropriate instrumentation for indoor PM monitoring has been a significant impediment. In addition to all the requirements for low cost sensors for outdoor monitoring [50], PM sensors for indoor applications should be non-intrusive to the occupants, and in particular quiet. A further challenge in PM monitoring is that mass concentration ($PM_{2.5}$ and PM_{10}) provides information on larger airborne particles, typically generated by mechanical processes (e.g. dust resuspension), but not on particles originating from combustion processes, which are very small, with the majority of them of diameters < 0.1 µm (ultrafine particles). Therefore, these particles have to be monitored in terms of number rather than mass concentration.

Review of the sensors for PM measurements reported in peer reviewed literature revealed that the technologies available at present are only suitable for $PM_{2.5}$ and PM_{10} [32,96–99] and include the following sensors: Shinyei PPD42NS (Shinyei Technology, Japan), DSM501A (Samyoung S&C, South Korea), Sharp GP2Y1010AU0F and Sharp DN (Sharp, Philippines). Low-cost PM sensors use light scattering methods and thus optical detection either of individual or assembly of particles. The number concentration of particles is typically larger than at least 0.1 µm (but some of them even > 0.5 µm) being the primary parameter measured, which is then recalculated into $PM_{2.5}$ and PM_{10} based on assumed particle density. The sensors based on this principle are cheap to manufacture, have low power requirements, and quick response times [57,98]. Quality control of the data is an important drawback to deploy these sensors at a large scale in buildings because of several reasons. Firstly, their performance characteristics under the diverse range of indoor conditions are yet not available. Secondly, a variety of experimental set-up and reference equipment under diverse environmental conditions were used by past studies, creating a challenge for their direct inter-comparison [57]. Finally, standards or guidelines for sensor application are currently missing, and the manufacturers do not provide enough calibration information for the sensors. This means that a tedious exercise of their on-site, laboratory and/or via the application of advanced techniques such as neural networks [100–105] based, calibration is needed before their deployment. This is in order to ensure reliable data quality; the quality is hugely impacted by the environmental conditions, as well as by particle characteristics and gaseous cross-sensitivities for PM and gaseous sensors, respectively [57].

Several studies evaluated these sensors through laboratory [32,96,98,99] and field [97] measurements to assess their performance in terms of some of the characteristics including: linearity of response, precision of measurement, limit of detection, particle size, composition, or impact of relative humidity and temperature. While the full review of these assessments is outside the scope of this paper, in general the results showed that the technologies are promising. However, they should be still improved and more comprehensively assessed before they could reliably be applied for outdoor or indoor monitoring. The limitations included not sufficiently low detection limit (and therefore preventing their application at low to moderate to particle concentrations), saturated outputs under high particle concentrations, linearity of response only within a certain concentration as well as output dependence on composition and size of particles.

While the studies above assessed performance of individual sensors, packages of several sensors are becoming commercially available, and enable not only monitoring of a set of specific pollutants, but also are equipped with means to communicate the data, either to a mobile phone or to a database. An example of this is Airbeam (http://aircasting.org), which measures temperature, relative humidity, and $PM_{2.5}$ (using a Shinyei sensor, Shinyei Technology Co., LTD., Japan). In addition, it has the capability of logging the data in real-time to a central database system via Bluetooth connection and to communicate them to the user's (Android-based) smartphone through a free mobile application software ('app'). Although such packages are advantageous and easy to use, their costs are higher since they consist of a number of sensors and often not all the pollutants measured are necessary for a particular application.

Some of the PM sensors mentioned above have already been tested in systems monitoring indoor air quality. In particular the Sharp GP2Y1010AU0F was used within a system to monitor and automatically control building climate including air purifiers, kitchen hoods, bathroom or whole house fans, operable windows, or dampers in the mechanical room. The authors concluded that such systems could now be considered for utilization on a larger scale and provided recommendations for their further improvements [106]. Khadem and Sgârciu [107] included the sensors Sharp GP2Y1010AU0F and Shinyei PPD42NS in a system for monitoring of indoor or outdoor environment. In addition to the sensors, the system consisted of a microprocessor unit interfaced with them, wireless radio devices (IRIS sensor nodes, USB radio base station XM2110) and data acquisition board (MDS 300 board).

In summary, despite the still existing limitations as discussed in the text, the implementation of low-cost sensors for real-time measurements of $PM_{2.5}$ time-series at homes holds a promise of providing most detailed $PM_{2.5}$ concentration profiles. However, the technology has not been applied yet on a larger scale. Moreover, there are no low-cost sensors available at present for ultrafine particle (UFP) monitoring, which is a significant technological deficiency. Especially since UFP sources, in particular combustion processes, have a significant impact on indoor air quality, and should be controlled in future smart homes.

8. Data security

To what extent digital networking increases the energy efficiency of a building is amongst other matters a question of complexity of the system and of the algorithms used [14]. The networking of batteries, system technology and any photovoltaic system which may be present by means of intelligent control technology is often seen as meaningful. The most important thing is the exchange of information with the smart grid. Demand response mechanisms (DRM) can be used to support a reliable and sustainable power supply via the HEMS. The term 'DRM' refers here to the change in households' energy consumption in response to price changes or threats to the system [108]. For example, air conditioning systems can be equipped with a demand response mechanism in order to respond automatically to real-time demands. At the same time, the system can also check the operational condition of the air-conditioning system. Overall the HEMS concept is considered as an appropriate system for managing and controlling the generation, storage and consumption of power within a building [12]. Security technology can also be integrated with ease. The social benefit is also undisputed. Older people in particular can benefit immensely from smart home technology with regard to medical care, emergency calls and help with daily tasks [109]. Lastly, networking also offers outstanding opportunities for an indoor environment survey. Provided that a sample representative of the average population is taken, simple parameters such as temperature, humidity, CO_2, ozone, particle and TVOC concentrations can be anonymized, recorded and analyzed online.

At the same time, digital networking is also susceptible to sabotage and abuse. For example, in November 2016 the control computers for building heating systems in Finland were put out of use by DDoS attacks (Distributed Denial of Service). Jacobsson et al. [110] have undertaken a comprehensive risk analysis of smart home systems taking into account the categories of software, hardware, information (processed data), communication and human actors. The authors come to the conclusion that there are significant threats, due in particular to software and user behavior. Kirkham et al. [111] propose a reduction of risk by means of data management using cloud computing. Other approaches make use of user behavior analyses [112] or malware analyses [113] for the development of digital security concepts.

What is certain is that in the current circumstances, the private lives of smart home occupants are susceptible to threats through the unauthorized access of data or through manipulation. As in all areas of the Internet of Things (IoT), risks can only be minimized, not eliminated. Information on energy consumption, ventilation preferences and indoor climate says much about the living conditions and activities of people, and are thus valuable for market analyses. The same applies to air quality data. Intruders can use temperature readings to tell whether anyone is present in a building. Insurance groups will be principally interested in correlating measured indoor air concentrations with health-related data, e.g. the appearance of respiratory diseases. In extreme cases there is even the possibility of evaluating individual health risks by comparison with health-related guideline values for indoor air [114]. Insurance companies also have the opportunity of offering their members reductions in premiums as motivation to voluntarily provide air quality data. A similar development has been seen for some time in relation to fitness tracking bracelets [115].

Seen as a whole, home networks are clearly more open to digital attacks than professional systems. The required security tools are often absent, in particular for networked household appliances and communications technology. In addition, the automated control of a smart home often needs professional expertise, which may require networking to the provider concerned. Users are often unaware of all the opportunities for abuse which exist when it comes to air quality data so that before reaching a decision about the implementation of sensor networks in homes, it is essential to explain all of the risks.

9. Living behavior

Whether a house or apartment can be considered a smart home depends primarily on the behavior of the occupants. Energy efficiency for example can only follow if the occupants adapt their day-to-day habits accordingly. With this in mind, there is a need to investigate the intentions of occupants with regard to acquiring a smart home or components of a smart home and the influence that smart home services have on how the activities of occupants run on a day-to-day basis.

The continuing development of technologies as part of energy conservation measures is leading to increasing heat insulation, airtightness and heat storage capacity. One of the consequences of this is also an increasing demand for ventilation, and with it, for mechanical ventilation systems.

As part of a thesis on the future development of smart homes in Germany, Salthammer [116] designed a questionnaire using LimeSurvey software, which was sent out online to 300 households. 94 responses were received and evaluated. Excerpts from the survey are summarized in Table 4. Users often have reservations about acquiring a mechanical ventilation system for reasons of habit and personal preference. This is frequently seen not as a necessity for the smart home concept but as a comfort element [116]. The additional costs for maintenance and repair are also factors for deciding against the installation of artificial ventilation. Nevertheless, living space ventilation systems increasingly form part of the basic equipment of smart homes. The survey of house occupants shows that in 60% (56 of 94) of the cases houses possess a ventilation system. 48% of the houses (27 of 56) possess sensors for measuring indoor air components. Artificial ventilation is not necessarily perceived as unpleasant (Question 1 in Table 4), nevertheless the need to open a window still exists (Question 2 in Table 4). In regions with a temperate climate, people are generally used to living with open windows and doors in the warmer seasons. It is therefore reasonable to offer the possibility of separately switching off any ventilation system. Comfort also plays a role in the decision to ventilate living spaces. All of the 31 people who answered said that artificial ventilation increased their living standard at least to some extent (Question 3 in Table 4). Automation is rated particularly highly (Question 4 in Table 4), as is the ability to operate a variety of household components via smartphone or tablet (Question 5 in Table 4). Lastly, increased quality of life also plays an important role in the smart home according to the respondents (Question 6 in Table 4). The results of the survey show that occupants do not focus only on energy efficiency. Comfort is also a significant factor. An important aspect here is thermal comfort. With regard to indoor climate, people are not very adaptable as even minor temperature fluctuations and air movement can cause them to feel uncomfortable.

Table 4
Results of a questionnaire on living behavior in German homes (see [116] for details).

Is your home equipped with a system for artificial ventilation?						
N = 94 (100%)		Yes: 56 (60%)		No: 38 (40%)		
Does your home concept consider indoor air quality?						
N = 56 (100%)		Yes: 27 (48%)		No: 13 (23%)		
Question	N	Fully agree	agree	partly agree	hardly agree	disagree
1	32 (100%)	0 (0%)	0 (0%)	3 (9%)	3 (9%)	26 (82%)
2	32 (100%)	5 (16%)	9 (28%)	12 (38%)	3 (9%)	3 (9%)
3	31 (100%)	7 (23%)	16 (52%)	8 (25%)	0 (0%)	0 (0%)
4	72 (100%)	23 (32%)	37 (51%)	9 (13%)	0 (0%)	3 (4%)
5	74 (100%)	20 (27%)	29 (40%)	24 (32%)	0 (0%)	1 (1%)
6	76 (100%)	25 (33%)	18 (23%)	25 (33%)	6 (8%)	2 (3%)

Question 1: I consider artificial ventilation as unpleasant.
Question 2: My home has artificial ventilation but I feel the desire to open the windows.
Question 3: Artificial ventilation increases my standard of living.
Question 4: A smart home requires automation.
Question 5: I consider remote control by smart phone or tablet as essential for a smart home.
Question 6: A smart home increases the quality of living.

Wallner et al. [117] performed a survey concerning health and well-being of occupants in highly energy efficient buildings equipped with mechanical ventilation in comparison to people living in conventional houses with natural ventilation. Occupants of energy efficient buildings rated the perceived indoor air quality better than inhabitants of conventional buildings which more frequently expressed a negative perception (e.g. stale, stuffy, bad smelling). Inhabitants of mechanically ventilated homes associated the air quality with fresh, clean and pleasant. In addition, these occupants reported more often improvements after living in their new houses for 15 months in comparison to those living in conventional homes. Also the self-reported health improved more frequently in mechanically ventilated homes. In contrast, the occupants also reported dry eyes in comparison to the people living in naturally ventilated houses due to low RH levels in mechanically ventilated interiors.

Paetz et al. [13] investigated the influence of smart homes on their occupants. The study did not look at people who actually lived in smart homes but at people who were testing various smart home functions for the study. The results showed a primarily positive reaction with regard to individual components of a smart home system. In summary, Paetz et al. [13] concluded that it is primarily cost savings on fuel which are of interest when it comes to smart homes. Moreover, it became clear that components of a smart home have a considerable influence on the living habits of the occupants. For example, time-dependent variable electricity tariffs mean that appliances are used at different times of day or night. This may be effective for washing machines and dishwashers but makes little sense when it comes for example to entertainment electronics. Smart homes can however contribute to optimizing work processes within the home through the networking of household appliances. On the other hand, decision-making processes are taken away from the occupants.

The provision of sensor controlled functions to improve the personal comfort can change habits, depending on the attitude of the individual. Missaoui et al. [14] presented an interesting smart home concept based on a Building Energy Management System (BEMS). This rests on the premise that above a certain point additional comfort requires an excessively large proportion of the energy used. The authors present algorithms for an acceptable compromise between comfort and cost based on electricity prices.

The monitoring of air quality in private residences has hardly been commonplace as yet. Accordingly, there are very few investigations into the influence of air quality data on living behavior in smart homes. In outdoor areas on the other hand, inexpensive sensors are increasingly being used [50], often in connection with smartphones, for measuring personal exposure [30]. There have been good experiences with regard to indoor air quality in schools with the introduction of CO_2 traffic light systems. On the other hand, the buildings' energy usage was increased [118]. It is difficult to estimate the level of acceptance of sensors in the private sphere. With normal occupancy levels and the typical household activities, air quality data could certainly be considered as suitable manipulated variables for controlling ventilation systems. However, things look different with high occupancy levels, the presence of combustion processes (smoking, the burning of candles, use of fuels containing ethanol etc.) and other events which lead to spikes in indoor air concentrations of the target pollutants. In this case controlling the ventilation system on the basis of guideline values may even be undesirable. This circumstance requires intelligent algorithms taking current behavior at any moment into account.

10. Conclusions and future trends

Advanced sensor technology opens up great potential to ensure living comfort and health for inhabitants and to assist elder and disabled people with staying in their private homes [19,21]. However, available hardware and software technologies do not yet fulfil all requirements needed to be routinely integrated into daily life [18]. The electronic detection of complex particle dynamics is also challenging, especially, as specific transport mechanisms, penetration factors, deposition rates and distribution ways as well as I/O-relationships are not fully understood so far [95]. Smartphones can already be applied for remote control. However, end users should be aware that the correct setting of smart home technology is a sophisticated task. Inaccuracy might not only lead to discomfort and health impairment, but might also open up security gaps.

The future acceptance of smart home technology, in particular in private households, will depend significantly on the climatic conditions and the pollution level in the respective region, the building type and the personal habits. Moreover, age, gender and socio-ethical background of the specific user group will play an important role. According to a representative survey at UK homeowners, smart homes are predominantly accepted and evaluated as energy management systems to minimize energy costs and time. Secondly, respondents also see the benefit for making life at home more comfortable and perceive the potential advantages in terms of saving energy [79]. Also another study performed in Singapore outlined that smart home appliances are mostly accepted by the occupants for cutting electricity costs. However, even though there were more advantages than disadvantages, people found it difficult to adapt their lifestyle to a smart home environment in order to save money. Thus, the personal comfort has a higher priority. For a successful integration and acceptance of smart home technology in private homes, both current gaps in sensor systems and prejudices and fears towards these new systems have to break down. Bhati et al. [119]

see therefore as the main challenge for smart homes modules that the technology has to seamlessly interact with the consumers behavior. At the current state of the art, the maturity and design of the technology does not consider the occupants behavior and perceptions. There is also seen a great gap between the pure smart home technology and its fit into the residences structure and contents in terms of integration in order to be accepted and used by the occupants. Studies focusing on social barriers for smart homes have highlighted the four main aspects, which are: (i) losing control, (ii) reliability, (iii) exclusive or irrelevant technology, and (iv) high installation costs [120,121]. In this regard, smart home technology should also be an evolvable system.

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