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D6.1 - TwinAIR Pilot Sensor Portfolio

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Abstract

In this deliverable, we compile our analysis for the sensor portfolio proposal in TwinAIR, specifically targeting stationary low-cost sensor solutions. We hereby detail a systematic literature review of both, target pollutants and possible sensing solutions that can best suit the purpose of TwinAIR as a whole, namely, indoor air quality and health impact assessment, building assets management, and digital twins. From this literature review, we conduct a sensor selection that can be integrated in the Smart Citizen project hardware portfolio, that will be part of the available solutions that TwinAIR pilots can use for their interventions.

Keywords

sensors, indoor, IAQ, air quality, health, exposure, low cost, environmental monitoring

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List of abbreviations

Abbreviation	Definition
ADC	Analog to Digital Converter
AQD	Air Quality Directive
BTEX	Benzene, Toluene, Xylene and Ethylbenzene
CO	Carbon Monoxide
CO2	Carbon Dioxide
DCV	Demand Control Ventilation
EC	Electro Chemical
eCO2	equivalent CO2
GBCO	Gate Bias Cycled Operation
GC	Gas Chromatograph
GC x GC	Two-Dimensional Gas Chromatograph
HCHO	Formaldehyde
IAQ	Indoor Air Quality
IoT	Internet of Things
IMS	Ion Mobility Spectrometer
IR	Infra-Red
LCPMS	Low-Cost Particulate Matter Sensor
LDA	Linear Discriminant Analysis
LOD	Limit of Detection
LOQ	Limit of Quantification

MEMS	Micro Electro-Mechanical System
MOx	Metal Oxide Sensor
NDIR	Non-Dispersive InfraRed
NO2	Nitrogen Dioxide
NRND	Not Recommended for New Designs
OPC	Optical Particle Counter
PAH	Polycyclic Aromatic Hydrocarbon
PID	Photo Ionization Detector
PM	Particulate Matter
RMSD	Root Mean Square Deviation
RSD	Relative Standard Deviation
SCK	Smart Citizen Kit
SiC-FeT	Silicon Carbide Field Effect Transistor
TCO	Temperature Cycle Operation
TTL	Transistor-Transistor Level
tVOC	Total Volatile Organic Compound
VOC	Volatile Organic Compound
WHO	World Health Organisation

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1. Introduction

This deliverable compiles an analysis for the sensor portfolio proposal in TwinAIR, specifically targeting low-cost sensor solutions. The deliverable includes a review of the relevant pollutants in the scope of the project, contrasting the literature on the topic of Indoor Air Quality (IAQ), and the expert opinion and requirements from partners and pilots in TwinAIR which was collected through a survey. To complement this analysis, the deliverable includes a market review, based on current state of the art and most recent sensor models available for integration within the sensor system. Finally, an evaluation of the market alternatives in terms of low-cost sensors to enable the measurement of the most relevant pollutants identified from the analysis of the reviews, is conducted, including limitations, and real-world applicability from existing studies and own research. Hardware and software integration is done within the Smart Citizen ecosystem, which already supports a wide range of sensors Potential market solutions need to comply with the ecosystem requirements.

This document does not include the potential harmful effects of the different pollutants mentioned, as there are other very well defined documents that can provide that information at a much better level of detail (see WHO guidelines for indoor air quality: selected pollutants [4]). Furthermore, these effects will be studied in detail in the context of the TwinAIR health WP.

In addition, this document includes a section dedicated to indoor comfort metrics which can potentially extend the sensor portfolio, including physical parameters and others such as noise, or light intensity.

2. Scientific Progress

2.1 Pollutants of interest

This section aims to understand the most critical indoor pollutants to be measured during the TwinAIR project, focusing on their impact on health. The section will also take into account the types of spaces that will be measured during the TwinAIR pilot demonstration sites: schools, hospitals, workplaces, and transportation. To proceed with the selection, there are two main sources of information, namely: a literature review of the most commonly targeted pollutants in recent studies and guidelines, alongside a TwinAIR internal survey (ANNEX I), circulated prior to the preparation of this deliverable. The objective of this survey is twofold - to understand what the current needs for the different uses within the TwinAIR group are, as well as to understand and consolidate the expectations of the different research groups.

2.1.1 Literature Review

Indoor air contains a complex mixture of various pollutants which come from different sources, all of which are not simultaneously traceable. Note that target species and target pollutants are used interchangeably throughout the document. According to the World Health Organisation (WHO) [4], the most critical pollutants and parameters to consider in order to characterise indoor air quality (IAQ) are:

- Volatile Organic Compounds (VOCs)
    - Polycyclic aromatic hydrocarbons (PAHs), especially benzo[a]pyrene
    - Formaldehyde (HCHO)
    - Benzene, naphthalene, trichloroethylene and tetrachloroethylene (BTEX)
- Particulate Matter (PM) (PM1, PM2.5, PM10)
- Carbon monoxide (CO)
- Nitrogen dioxide (NO2)
- Radon
- Bullet Points here

In general, other literature reviewed followed the guidelines indicated above by the World Health Organisation (WHO). However, other authors provided additional possible target pollutants [3]. For instance, O3, which is in general lower in indoor environments in comparison to outdoor ones, and in general much lower than WHO recommended guidelines, could be important to monitor in some particular locations [4], as there is a local concern for the pollutant in question. In addition, CO2, although not a pollutant per se, can also be considered an indicator of ventilation, and several international norms indicate levels of CO2 that are recommended depending on different indoor space categories (EN 15251, EN 16789, EN 13779 and ASHRAE 62.1 standards [5]).

An important group of pollutants to consider is Volatile Organic Compounds (VOCs). VOCs are organic chemicals that have a high vapour pressure at ordinary temperature and pressure. According to WHO, VOCs are one of the most critical pollutants in indoor air, being what is identified as "harmless air" in which VOCs concentration is lower than 100 ug/m^3 [1, 4]. However, there is a wide variety of volatile

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organic compounds identified, only some of which are found to be pathogenic, producing different symptoms: allergies, headaches, loss of concentration, irritation, etc. [1]. These pollutants are varied and complex, and their sources range from construction materials, finish materials (e.g. paints and varnishes), as well as cleaning substances. In addition, an obvious source for this and many other pollutants of interest in indoor environments are combustion processes, including cooking, heating, energy generation, and tobacco smoking. Within VOCs, an interesting group to consider are benzene, toluene, xylene and ethylbenzene (BTEX), alongside aldehydes, such as formaldehyde and acetaldehyde [41], while the monitoring of benzene in ambient air is mandatory as set by the European Air Quality Directive (AQD) [42]. Some of these pollutants overlap with the Indoor Air Quality Guidelines provided by WHO [4]. According to reference studies, target VOCs of high relevance are benzene, naphthalene and formaldehyde [49]. The difficulty of assessing VOCs comes not only from the varied species, but also from the limits of detection needed (guideline values are for benzene 1.5 ppb, for naphthalene 5.6 ppb and formaldehyde 80 ppb) [51].

In addition, particulate matter (PM) is of great importance in indoor environments. Sources include both indoor and outdoor origins, and in both cases, important sources are various types of combustion processes. Indoor sources include cooking, smoking, wood burning, fuel burning for heating, incense burning [15], deodorizers [16] and other human activities. Outdoor infiltration is also an important source of PM in indoor spaces, either by mechanical or natural ventilation, and its origins range from combustion engines in traffic areas, road dust, results of industrial activity, and other natural sources [15]. In most cases, the particle aerodynamic diameter (i.e. the equivalent diameter of a spherical particle with a density of 1 g/cm3 that has the same settling velocity as the irregular particle [7]) of the median mass never exceeds 1 µm [17]. This fact is key for selecting low-cost sensors in the following section. Another factor is the chemical composition of the particles themselves. In many cases, indoor environments can be composed of, or coated with, particular chemical substances that can not only reach the respiratory tracts, but also react in different ways because of their chemical composition. This has been shown by authors [18], in which particles were found with high concentrations of Vanadium (V), Selenium (Se), Zinc (Zn), Chromium (Cr) and Arsenic (As) in PM2.5.

The above-mentioned combustion processes are also responsible for the presence of CO (incomplete combustion) and NOx (NO, NO_2, from high-temperature combustion), which are also present in WHO's recommendation. Carbon monoxide is normally provoked by burning appliances that are poorly maintained, or without properly working safety features that prevent carbon monoxide venting into indoor spaces. In the case of NOx, the most important indoor sources include tobacco smoke and either burning appliances (gas, wood, oil, kerosene and coal) such as stoves, ovens, space and water heaters and fireplaces, particularly unflued gas heaters or poorly maintained appliances. Outdoor NO_2 from natural and anthropogenic sources also influences indoor levels [9].

Finally, WHO recommends the monitoring of Radon as it has shown in epidemiological studies that increases the risk of lung cancer [60]. Radon is a radioactive gas that emanates from rocks and soils and tends to concentrate in enclosed spaces like underground mines or houses. Soil gas infiltration is recognized as the most important source of residential radon. Other sources, including building materials and water extracted from wells, are of less importance in most circumstances. Radon is a major contributor to the ionising radiation dose received by the general population [60].

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2.1.2 Literature Review

An internal survey was conducted during December 2022, prior to the creation of this deliverable, in order to understand the priorities, needs, and expectations of the TwinAIR consortium with regards to the indoor air quality measurements. The survey and its results are detailed in ANNEX I. A total of 9 responses from various participants and fields (health, environmental, technical) were collected. The survey completion was requested to all participants in a voluntary manner. The questions included a list of pollutants based on the abovementioned list, including as well other target pollutants such as SO2.

The questionnaire proposed a preliminary list of pollutants and metrics as follows:

- Particulate Matter
- CO2
- VOCs: tVOCs, HCHO, other
- Chemical composition: CO, NO2, NO, SO2, O3 and H2S
- Other indoor metrics for comfort characterisation: temperature, relative humidity and noise level

The survey results are shown in Figure 1, and highlight the importance of PM, CO2, VOCs and chemical composition, as well as temperature and humidity as comfort metrics. However, there was a lack of clarity in which VOCs species are to be considered, if any, with only two participants indicating the need to monitor formaldehydes (HCHO), with no other particular focus on the target species recommended from the WHO Guidelines. In addition, there was very little specificity regarding the need for measuring chemical compounds, with only one respondent requesting CO, and two requesting NO2 and O3. Other compounds, such as radon, were requested by two participants, whereas one participant requested lead and SO2. Finally, there was a relatively large number of requests for Bioaerosols (a total of 3), which was initially out of the scope of the survey but triggered a further review of potential sensor solutions discussed in the Market review section.

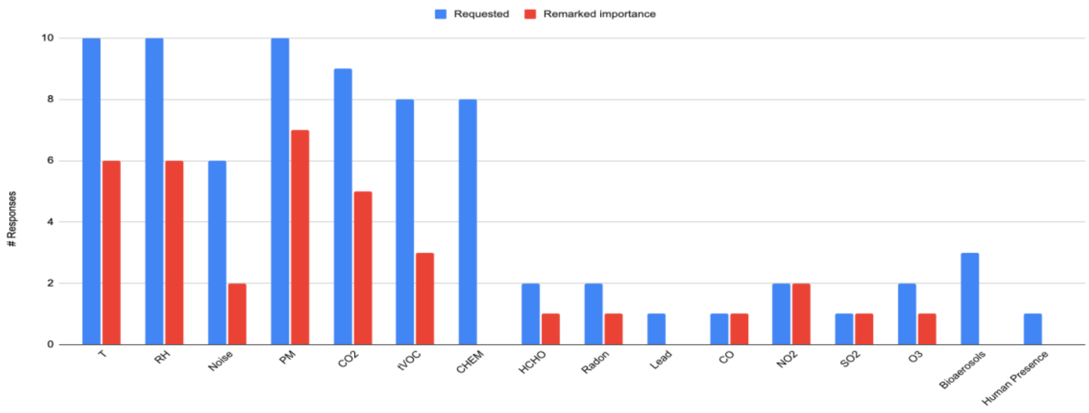

Figure 1. Survey results for TwinAIR Consortium sensor requirements

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As a first step, in order to understand the variety of the responses, an initial filter from the respondents' background perspective is done, considering different groups: health, technical and environmental. Considering the responses from the health category first, overall, there is an interest in basic environmental parameters such as temperature and humidity, and in terms of pollutants, aligned with the general analysis, PM is the target pollutant of most interest. However, CO2 and VOCs are requested by two respondents, whereas chemical composition (NO2 and O3) has been also requested by only one respondent. As we will detail later, it is important to clarify the specificity needed in VOCs (i.e., the need to characterise particular VOCs or a total VOCs), for which this survey reveals only one response from the health category (2 in total) with formaldehydes. Radon and Lead are also variables requested in this particular questionnaire, for which further information is requested to the respondents.

Similar to the health category, but with overall higher numbers, the environmental category follows on the same trend, only including two other pollutants (CO and SO_2), in addition to those already indicated by the health group. Finally, the technical responses will not be discussed, as there is no particular significance on the results to highlight.

Finally, due to the low number of responses (total of 10), further information and analysis is needed, which is being collected at the time of writing this deliverable.

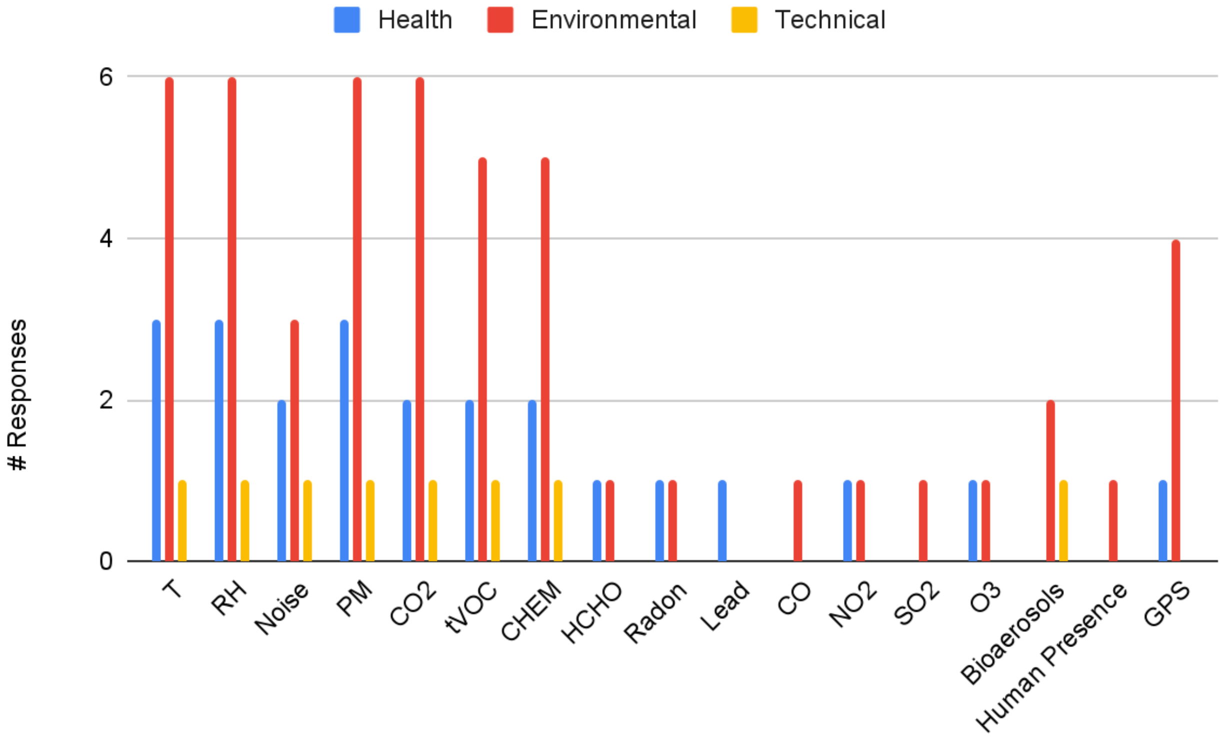

Figure 2. Survey results categorised in respondents background

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2.1.3 Preliminary Selection

Having carried out a literature review on the most important target species, the preliminary list of target pollutants is as follows:

- Volatile Organic Compounds
    - Polycyclic aromatic hydrocarbons, especially benzo[a]pyrene
    - Formaldehyde
    - Benzene, naphthalene, trichloroethylene and tetrachloroethylene
    - Total Volatile Organic Compounds
- Particulate Matter (PM1, PM2.5, PM10)
- Chemical composition:
    - Carbon monoxide
    - Nitrogen dioxide
    - Ozone
    - Sulphur dioxide
- Carbon Dioxide
- Radon

Note that despite the technicality of CO2 and VOCs also being considered chemical composition substances in air, they have been listed as separate categories due to their differentiation in measurement techniques in the low-cost sensor field, as well as the wide variety of VOCs that can be targeted. This list will be now contrasted with a market review, which will lead to the final sensor selection in the following section.

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3. Technical Progress

This section of the deliverable discusses the sensor technologies and models that can be used for measuring the pollutants identified in the previous section. The final sensor selection is detailed in the Conclusions section, and it will be integrated into the Smart Citizen Ecosystem, which is described in the following subsection, and which will be followed by an extensive market and performance review of the different sensors that can measure the identified pollutants.

3.1 Smart Citizen Ecosystem

The Smart Citizen Ecosystem is a flexible, easy-to-use, and fully open-source environmental monitoring solution for environmental monitoring, balancing modularity with integration to fulfil scientific monitoring needs by providing an extendable solution, with different ranges of sensors based on the same core components [61]. The core of the hardware ecosystem is the Smart Citizen Kit (SCK), which refers to the different variants of devices that consist of a datalogger, a set of low-cost MEMS sensors and a PM sensor. In addition to the standard SCK's measurements, additional sensor probes can be added to the system in a modular way. The design is based on the principle of reproducibility, also integrating non-hardware components such as a dedicated storage platform and sensor data tools. The documentation of the project details the different versions of the hardware, as well as the software components [62].

In terms of sensors, the system already supports the following measurements:

- Default configuration (SCK)
    - Air temperature and relative humidity (Sensirion SHT31)
    - Barometric pressure (NXP MPL3115A2) (to be changed for a similar sensor - discontinued)
    - Light (ROHM BH1721FVC)
    - Noise level (in different scales such as dBA, dBC and dBZ – one at a time) (Invensense ICS43432)
    - tVOC (Total volatile organic compounds) and eCO2 (equivalent CO2) (AMS CCS811)(to be changed for a similar sensor - discontinued)
    - PM1, PM2.5 and PM10.0 (Plantower PMS5003)
- Add-ons
    - CO2 via NDIR digital sensor (Sensirion SCD30)
    - High precision analog readings, which are usable for EC, PIDs and MOx sensors. The current supported sensors are those by Alphasense Ltd, A and B series sensors for measuring CO, NO2, NO, H2S, O3 and SO2
    - External temperature probes (Various models. Recommended Sensirion SHT31)
    - GPS (Various models)

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In general, any digital sensor with compatible interfaces, transistor-transistor levels (TTL) in the range of 0-5V, can be integrated and supported. The system also supports other types of sensors, such as physico-chemical sensors for water and soil monitoring, which are not relevant to the TwinAIR project.

A complete description of the device is available in a HardwareX publication listed in the references section [62]. A summary of the device is done here for completeness purposes. The Smart Citizen hardware has at its core the Data Board, a data-logging board which offers Wi-Fi (IEEE 802.11 b/g/n) connectivity and SD card logging capabilities. In terms of power, it offers a USB port for serial data connection and power (with USB power supply or outdoor ones) and has a JST-2 pin battery connector for Lithium Polymer batteries (up to 8Ah, and in default case 2Ah with 2 days battery duration). It also offers user feedback via an on-board LED, and has two input buttons, one for basic user interaction and one for hardware reset. The Data Board is depicted in Figure 3 (left), and it's connected to the sensors via two different connectors: a female 2x8 header pin for the Urban Board, and a 4-pin Grove System compatible auxiliary connector[1]. The Urban Sensor board depicted in Figure 3 (middle) is a custom board designed to hold MEMs digital sensors, and it also exposes a connector for particulate matter sensors, which is shown in Figure 3 (right). The auxiliary connector is a 3.3V digital communication port, which exposes two pins for digital communication with external boards. This connector is used for the integration of custom solutions, such as analog front ends, or more advanced interfaces to external probes. Finally, in terms of enclosure, a normal one (including a PM, temperature, humidity, noise, and CO2 measures roughly 10x10x5cm at approximately 300g of weight.

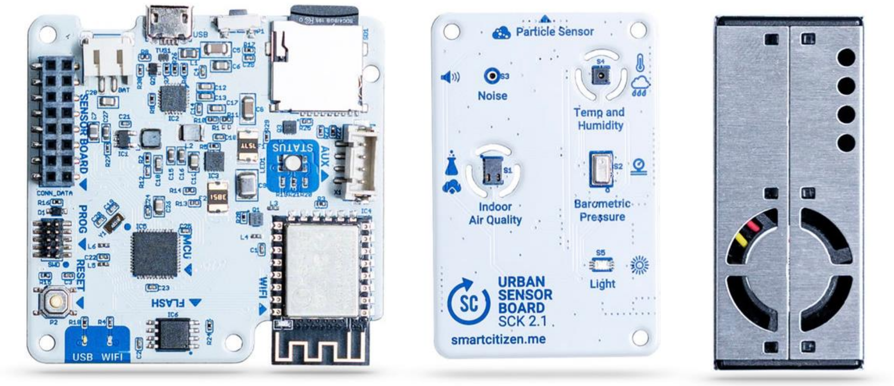

Figure 3. Smart Citizen Kit basic components

For the case of TwinAIR, the system described above allows for a modular and flexible architecture, and will be used with all components shown above, as well as other sensor boards that will add additional features to the basic device configuration. In addition, during TwinAIR, different hardware components will be revisited, and potential improvements in the connectivity features, among others, can be added. The final device implementation is the subject of D6.2 TwinAIR sensor implementation.

3.2 Market Review

In this section, a market review for each of the target pollutants indicated above will be conducted. For each pollutant, the most common and commercially available measurement techniques are listed,

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[1] *Grove system documentation: https://wiki.seeedstudio.com/Grove_System/*

including the manufacturers that provide them. The results of the market review are detailed in the tables found in ANNEX III.

This deliverable will assume the terms “sensor” and “sensor unit” as referring to hardware devices that are able to provide readings of one or several related target metrics. For instance, a PM sensor can provide three or more metrics such as PM1, PM2.5 and PM10; a modern Micro Electro-Mechanical System (MEMS) temperature and humidity sensor is often encapsulated on the same package, being both readings provided to the data-logger through the same digital and hardware interfaces. When talking about different sensor units in the same pack (a group of sensor units that monitor multiple parameters at the same time) the term “device” is used.

3.2.1 Parameters Evaluated

Potential solutions are compared according to the following parameters, factors and performance metrics. These serve as criteria for sensor selection in section 4.1.

3.2.1.1 Performance metrics

- **Accuracy**: the degree of closeness of measurements of a quantity to the true value of that quantity. Air temperature and relative humidity (Sensirion SHT31)
    - **Accuracy versus measured value**: the variation of the sensor accuracy with respect to the absolute measured value. Most sensors show variance differences at different levels of the measurement value. This is particularly relevant for TwinAIR project, as some of the target pollutants are likely to be found at higher levels of concentration indoors compared to outdoors (i.e., PM concentrations can peak to several times the outdoor values). Sensors need to produce appropriate accuracy, at least within the desired range of measurement.
- **Sensitivity:** changes in sensor readings with respect to variations in the true value.
- **Selectivity:** how accurately the sensor is able to detect the target pollutant and to ignore other interferences (environmental or chemical).
- **Limit of quantification (LOQ) and range**: the minimum and maximum concentration the sensor can accurately measure.
- **Type of measurement:** whether the sensor yields a continuous and linear measurement, or not. Some sensor responses are considered to be safety-type (i.e. a response is only seen when reaching a certain concentration).
- **Long term stability:** sensor performance drifts over time.

3.2.1.2 Other Factors

- **Cost**: a low-cost sensor has been defined by the United States EPA, as a sensor unit with a cost less than USD 1000 and equipped with miniaturised electronics. However, this cost is too broad, and, in this document, sensor units are deemed as low-cost when the cost

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is approximately between USD 10 and USD 100, whereas a low-cost multi sensor device can range between USD 100 to USD 1000.

- **Stock availability**: due to the nature of the TwinAIR project, and ensuring the feasibility of the pilot interventions, sufficient stock is needed for numbers ranging from 100 to 1000 units.
- **Long term support:** in order to provide a long-term solution for indoor air quality monitoring, end of life products, or other sensor units that are not recommended for new designs (NRND) will not be used.
- **System integration feasibility:** the feasibility of integration on the existing hardware system. This implies compatibility with low voltage electronics (5V or 3.3V), the availability of digital communication protocols in the sensor unit, in addition to the availability of open-source libraries or documentation that allows the sensor integration either by the sensor manufacturer or contributed by others in online repositories.
- **Documentation, sensor literature, validation and calibration processes:** due to their low-cost nature, a great amount of sensors lack documentation and reference material, even from the manufacturer [2, 7]
- **Size:** in some cases, such as mobile situations, bulky devices can have a potential downside for ease of the deployment

The limitations of this review are three-fold: firstly, there is a wide variety of sensors available in the market (for instance, in the particular case of PM sensors, in ANNEX III, more than 15 commercially available sensors have been reviewed, but other authors in 2020 have reviewed more than 50 sensor units [7]). Secondly, most of the low-cost particulate matter sensors are not well documented in terms of performance by the manufacturers or they lack performance evaluations. Finally, there are different evaluation methods for PM sensors, but the vast literature on the topic differs greatly in the approaches [7]. For instance, authors have conducted several laboratory evaluations, outdoor collocations with reference instruments, and performed calibration on different scenarios that do not necessarily work in all conditions [7]. This poses a challenge for the researchers using the sensors, and for the uptake and trust of the sensor readings. This review aims to identify sensing technologies to measure the target pollutants (see section 2.1.C), focusing on those that have been extensively tested in the literature and the industry. Considering that the evaluation of all the available sensor units is unrealistic within the scope of the TwinAIR project within available time and budget for the task, the review covers the use of most sensing technologies for the target pollutants. In addition, there are several government entities (i.e., South Coast AQMD through AQ-SPEC [10]) and environmental institutions (i.e., Airparif [11]) that have conducted different continuous evaluation campaigns and challenges for low cost sensor units. In ANNEX III, AQ-SPEC sources are included for reference.

The following sections explore the market review conducted for each one of the pollutants of interest categories included in the Preliminary selection Section.

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3.2.2 Particulate Matter

Current technical solutions for measuring for PM using low-cost sensors are mostly performed by using light scattering by particles. These sensors are an evolution of the Optical Particle Counters (OPCs), but with a lower cost, ranging from approximately USD 10 to USD 500 in some cases [7]. The following section focuses on this type of sensors, and will provide an overview of the measurement principles, their limitations, and their potential applications.

3.2.2.1 Light Scattering Sensors

3.2.2.1.1 Measurement principle

This type of sensor measures suspended particles by employing a light beam in the form of laser beams or infrared (IR) LEDs and a light detector. When using laser beams, it is most commonly set to one side (often 90°) of the source beam, to avoid reflections of the light source itself which could induce noise in the readings [7]. The amount of particles per unit of volume is then a function of the light reflected into the detector and the mass is a calculation derived from this density, assuming certain properties of the particles, such as shape, colour and reflectivity, among others [7].

An onboard microcontroller is in charge of taking readings from the sensing element and counts how many particles are passing in front of the light detector. The sensor element can differentiate between different particle sizes, and group them in size bins according to the results of an onboard, proprietary algorithm. In other words, this algorithm will group, for instance, the particles that have a diameter between 1 µm and 2.5 µm in one size bin and provide a particle count for them. Once it has the particle number estimation for all the bins, it will then estimate the mass for each relevant metric. For instance, it will use all the size bins counts below 2.5 µm for estimating PM2.5. The number of size bins is normally higher than the number of actual mass sizes, and the discrimination capacity of the sensor will result in a better quality. For the final conversion, the algorithm has to make some assumptions (and normally the internal calculations are not disclosed), including but not limited to (see [7] for further details):

- Particle shape (normally a sphere, but with some shape factors)
- Particle colour, and hence reflectivity index
- Particle chemical composition (and density), biological composition

3.2.2.1.2 Limitations

Most of the low-cost PM sensors that are currently on the market follow the same principle, and in fact, all of them are in one way or another aggregators of different types of suspended particles due to their inability to distinguish them because of the above mentioned assumptions. Hence data quality comes down to the following factors:

- Number of particle sizes and differentiability between them: depending on the particle selectivity of the sensors, when compared to real monodisperse or polydisperse aerosols, the device will or will not be suitable for corrections [6,7], as there might be bins that are falling in ambiguous size distributions.

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- Theoretical assumptions made by the algorithm designers: this is a consequence of the device's measurement principle, and that the particle count to mass calculations need to assume physical parameters of the particles in question. This leads to over or underestimations of the PM values and will need calibration in the field in almost all cases, since these assumptions are unknown to the end users.
- Quality of the hardware, production deviations: due to their low cost, the manufacturer might not be able to test in house every unit, and inter-device deviations might lead to expensive individual calibrations in the field.

In addition, most sensors tend to only perform well on the low-mid range of the particle size spectrum (approximately 1 to 2um) due to technological limitations [7, 13], which are derived from the principle of measurement based on Mie's Theory, and the relationship of the wavelength of the light source used with respect to the particle's size [7]. This is relevant for two reasons:

- The inability to capture ultrafine particles, since most sensors can count particles which size is larger than 0.3 µm.
- The underestimation/lack of correlation of coarse particles by almost all the devices [11].

These are well known limitations that some manufacturers are tackling at the moment providing new solutions to the market [12]. It is important to consider the impact of relative humidity on the readings, which leads to hygroscopic growth of the particles by absorption [19]. It is generally accepted that this is not the case for temperature, which has been shown to have no effect on the readings [20]. For the purposes of this deliverable, and the TwinAIR project, it is recommended to include a relative humidity sensor that can compensate for the effects on particle sizes. Following the recommendations of [6], the final sensor selection should not only provide particle numbers, in size distribution bins, but also show a proper distinction between different sizes in order to apply these corrections.

Finally, it is very important to remember that low-cost particulate matter sensors are particle counters, which in case of polydisperse aerosols of unknown composition, the conversion between particle number to mass is not always attained properly, especially without other measurement methods in place [7]. No matter which final selected sensor is used, there will always be an assumption made by the manufacturer that will never be fulfilled in every deployment scenario. If not only precision, but also accuracy is needed, then using the particle counts directly can provide one of the necessary pieces to derive the final mass, which will only be determined if the particle composition and density are known by other means (i.e. laboratory analysis of collected samples).

3.2.2.2 Scoped solutions

The scoped solutions are listed in ANNEX III, including the most relevant research articles reviewed for each sensor. Many of the sensors included in the list have not gained enough popularity in the scientific community, probably due to a combination of factors such as the price range, and integration feasibility. The sensors that have the most reviews are:

- Plantower PMSX003 (different versions)
- Alphasense NX and RX (different versions)

- Novasense SDS011
- Shinyei Family
- Sharp GDP2
- Sensirion SPS30 and SEN50

Some of the literature also included a more extensive review of these families [7], but did not include the new Sensirion SPS30 sensor, which was recently introduced. The Sensirion SPS30 has picked up some attention in the market and has been evaluated in various studies providing good results [30, 32, 34]. At the time of writing this deliverable, there are other potential interesting sensors such as the Tera NextPM [30], which also integrates a heater for reducing humidity effects, and that has a good review in AQ-SPEC [31], but that there are no other reviews that justify the choice of implementing such device for TwinAIR demonstrations. This is the case too for some other devices, such as the Piera IPS family [12], that could potentially be integrated into the Smart Citizen portfolio in future developments thanks to its modular and flexible nature. In particular, the IPS family claims to provide ultrafine estimates in the IPS7100 model, at a cost of USD 80 from distributors, however, the literature review conducted did not provide enough results for the implementation as only one article using the device was found [58]. Finally, it is worth mentioning that the Smart Citizen portfolio already supports the Plantower family, and this section will focus on understanding whether there are other options that serve better the requirements of TwinAIR project in terms of PM measurements quality, namely:

- Accuracy, precision and LOQ
- Valid characterisation of particle sizes, in particular in the low end of the spectrum
- Stability over time
- Influence by weather parameters understood or corrected.

Plantower PMS5003 vs. Sensirion SPS30 have been reviewed with good results for the SPS30 in terms of Relative Standard Deviation (RSD) [27]. In the same study, the Plantower measures more accurately some types of aerosols (especially Urban PM), whereas the Sensirion SPS30 always underestimates the readings with respect to the Plantower and with respect to the TEOM equipment. The same study also evaluated the effect of RH and found out that the PMS5003 is more susceptible to changes than the SPS30. When tested in co-location Sensirion SPS30, Alphasense N3 and PMS5003 sensors and concluded that humidity affects the PM readings of the N3 and PMS5003, but not as significantly for the SPS30 [29]. Furthermore, the particle size distribution shifts when using different aerosols were reported. The PMS5003 showed a surprisingly similar size distribution for all types of aerosols tested, while the SPS30 did better represent the real particle distributions. This is aligned with the findings in other studies in laboratory conditions, highlighting the PMS5003 inability to differentiate different particle sizes [6]. With respect to long term stability, the SPS30 showed much better stability after being exposed to intense levels or Arizona road dust, whereas other sensors, including PMS5003 showed deviations in the readings after a few hours of test [27]. This is a feature provided by the SPS30, which uses the highest speed possible by its fan to clean the interior ducts from particle accumulation periodically. Finally, the SPS30 also is able to more accurately allocate the fraction of PM mass to the right bins in the lower end of the particle size spectrum [27]. The SPS30 however, is not able to measure PM10 as seen in laboratory evaluations [6]. In addition to the

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SPS30, the sensor manufacturer Sensirion also provides the SEN50 model. This model is quite recent and has currently not been reviewed by scientific literature. However, in comparison to the SPS30, the sensor is of much lower price and is a potential good candidate for sensor evaluation.

In a very extensive and valuable review of low-cost particulate matter sensors (LCPMS), the Alphasense N series is not considered to provide good quality results, despite its price [7].

Other sensor families such as the Shinyei and Sharp sensors have been also evaluated in laboratory conditions and field conditions [6]. The Shinyei PPD42 sensor has shown to be unusable due to its inter-unit inconsistency in valid detection ranges, and each sensor which would need to be quantified case by case before reliable measurements can be achieved [6]. The Sharp GP2Y1010AU0F has also been tested and its response is aligned with other devices such as the PMS5003, performing well when compared to reference instrumentation in terms of correlation, but grossly underestimating PM10.

Finally, the Novasense SDS011 has been evaluated in few but very consistent studies, and the various tests seems to indicate that this device is one of the best performing options in the laboratory and in field tests [7]. This is reflected in the clearer difference between particle sizes detection ranges, the SDS011 has the potential to measure PM2.5 more accurately than the PMS5003, but not PM10 [6]. Despite this, the size and interface for the SDS011 are potentially downsides for TwinAIR, and other options like the SPS30 are performing potentially in similar ways, but are smaller, and have added features that cope with long term stability [27].

3.2.3 Chemical Composition

Chemical composition sensors are those that are able to measure a specific chemical target species that are present in the air. Current state of the art of these sensors has proven capabilities of measuring CO, NO2, NO, SO2, H2S, O3, among others. For the purpose of this deliverable, note that other target species are not included in this category such as CO2 or VOCs. This is a deliberate decision, since the measurement principles, limitations and technologies available are different for these two target species. These types of sensors will be detailed in their respective sections. Regarding chemical composition, for those components listed above, most of the sensors available in the market are based on two types of technologies: electrochemical sensors, and metal oxides [14].

3.2.3.1 Electrochemical Sensors

3.2.3.1.1 Measurement Principle

In electrochemical (EC) sensors a gaseous pollutant undergoes a chemical reaction that results in a signal – typically manifested as a current – that is related to the concentration of the target gas in the air [14]. This type of sensor is called an amperometric gas sensor. Since the interface to this sensor is normally provided as a current reading, dedicated circuitry is necessary to convert such to a voltage reading, for which an Analog to Digital converter (ADC) will suffice on the data-logger side. Signal processing and calculation of the final concentrations can be done in different ways, some of which rely on physically rooted models or, more commonly, on empirical evaluations (e.g., linear models) or even black-box models shaped by sample-based knowledge (e.g., machine learning models).

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3.2.3.1.2 Limitations

Electrochemical sensors typically show a good sensitivity; however, they can be affected by a series of factors such as temperature, humidity, and the presence of other pollutants. Not only temperature and humidity absolute levels affect the readings, but also the speed at which the changes take place can induce short term instabilities on the readings that provoke noise and some artefacts. These artefacts can provoke two issues: wrong readings, and wrong calibrations, especially if not cleaned and when using machine learning algorithms [21]. In addition, ageing and drift are known problems, which affect the loss of sensitivity and deviations in the baseline response [14]. In general, it is a common practice to include temperature and humidity sensors of the target air, as well as the electrochemical cells used for the measurement. This is particularly relevant in the case of indoor environments, as mentioned above, since the absolute values and the changes can be more abrupt in certain times of the day due to human activity, i.e. opening windows, doors, heating and air conditioning activation, etc. Typically, the approach for the deployment of electrochemical sensors is to provide a factory base calibration, in laboratory conditions, and to correct this in the final deployment conditions, by co-locating the sensors with high-end instruments during a pre-assigned period of time [14]. In most cases, a laboratory evaluation to derive linear models will not be sufficient but will provide good enough information to kick-off the deployment. Specific on-site calibration is needed if accurate readings and other effects, as explained above, are to be compensated. This is a recommendation for the case of the TwinAIR pilots.

3.2.3.2 Metal Oxide Sensors

3.2.3.2.1 Measurement Principle

Metal oxide sensors (MOx) have an exposed surface film that changes its electrical properties (typically resistance) when exposed to the target gas. Small changes in conductivity/resistance are measured and are proportional to the concentration of the adsorbed gas [14]. In very simple terms, chemical reactions take place between the target gas and the exposed surface film, which for oxidising gases such as O3 or NO2 will make the resistance increase; whereas for reducing gases such as CO or VOCs will make the resistance decrease. In general, these reactions occur at elevated temperatures and hence the sensing layer needs to be heated up. There are various sizes and formats for these sensors, sometimes in separate replaceable units, whereas other times are integrated in MEMS solutions.

3.2.3.2.2 Limitations

The value of the resistance of the MOx layer cannot be considered as an absolute measurement of the target pollutant concentration, since the resistance varies from sensor to sensor, and it's affected by several conditions, such as temperature, humidity and other non-target pollutant affectations. To mitigate this problem, the output of the sensor (RS) is normalised using the baseline resistance (RA): RS is divided by RA. This baseline resistance is the resistance that the sensor sees in clean air. Unfortunately, since RA varies with the deployment conditions, RA cannot be determined by a one-time calibration, and depending on the manufacturer and type, is maintained on-the-fly in software. This process is known as baseline correction.

Depending on the sensor type, and specially for MEMS formats, the results are often not valid without careful data analysis. For this reason and based on the fact that electrochemical sensors already provide valid data, for which the Smart Citizen project has proven experience [57], it is then considered that these sensors are best employed for detecting instances or trends of gas presence rather than highly accurate

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readings. For this reason, MOx sensors will not be considered for TwinAIR for the purpose of chemical composition measurements.

3.2.3.3 Scoped Solutions

The electrochemical sensors evaluated as part of this deliverable are mostly from two manufacturers (Alphasense [32] and SPEC Sensors [33]), both of which have similar interfaces and very similar range of target pollutants and are potentially suitable for TwinAIR sensors. However, the performance of SPEC Sensors is not as well documented as the Alphasense ones, and the literature review conducted did not retrieve as much information from the former to be able to justify its implementation for the scope of the TwinAIR project. In addition, the Smart Citizen project has already worked with the various electrochemical sensors provided by Alphasense, which would reduce the potential implementation and testing effort during the project.

In the Alphasense electrochemical sensor portfolio, several versions and sizes are available, with differences that affect the performance of the sensor units and their capacity to accurately represent the target species. In particular, the A-series and B-series are two comparable series with similar target pollutants [35] but different in sizes and interference filtering. The smaller size comes at the expense of lower performance, as indicated by the manufacturer, and reflected in ANNEX III.

Several studies have conducted evaluations on these sensors and have shown that the most important aspect is to understand the environment being measured, with the inclusion of additional sensors to understand the impact of interference [35]. In this regard, the body of knowledge already available, and shown in ANNEX III justifies the continuation of the work on these sensors and to keep the development to gain more experience, especially in indoor environments such as the ones targeted in TwinAIR. It is also important to consider the transients in temperature changes, which can be relevant in indoor spaces with varying conditions [36].

3.2.4 CO2

Most CO2 sensors in the low-cost range are NDIR (NonDispersive InfraRed sensors), a spectroscopic sensor often used as a gas detector that uses infrared absorption to measure CO2 [14]. At the time of writing this deliverable, some manufacturers are exploring the usage of MEMS technologies for CO2 measurements, but there is currently no marketed sensor capable of measuring CO2 [8]. In addition, a new emerging low-cost CO2 sensing technology, building on photoacoustic sensing principle has been developed [34] and is being subject of evaluation in various studies discussed below.

The scoped solutions for TwinAIR are listed in ANNEX III. The most common cost range for these sensors is between approximately USD 50 and USD 100, and they vary in shapes and sizes, some of them being suitable for small sensor systems [34]. Probably, the most important aspect to consider in this particular type of sensor is their embedded signal processing, which in some cases can be beneficial to avoid additional data processing infrastructure (see limitations section below).

3.2.4.1 NDIR Sensors

3.2.4.1.1 Measurement Principle

In NDIR CO2 sensors, a non-dispersive element, is used to filter the light produced by an emitter with a band-pass filter, allowing the infra-red (IR) wavelengths around 4.2 µm to pass through [22]. CO2

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molecules strongly absorb IR light in these wavelengths, so shining these through a gas sample, the CO2 concentration can thus be calculated from the proportion of light that is absorbed. The so-called transmissive NDIR sensors typically feature an IR emitter and an optical detector, such as a photodiode, at opposite ends of a specially designed optical cavity. The optical detector measures the amount of IR light energy that is not absorbed by (i.e., transmitted through) the gas sample. The higher the CO2 concentration, the lower the light detected. A comparison between the measurement and a reference intensity at known CO2 concentration hence provides a direct way to calculate the CO2 concentration. This technique, though, requires careful alignment of the emitter and detector, and the mechanical stresses on the device can provoke wrong readings [37].

In the case of photoacoustic NDIR sensors, the amount of energy absorbed by the CO_2 molecules is measured in terms of molecular vibration and the resulting pressure waves inside a measurement chamber. The higher the CO_2 concentration, the greater the amplitude of the acoustic waves. A microphone can then be employed to measure them and estimate the final gas concentration. Photoacoustic NDIR sensors allow for great miniaturisation and more robustness than transmissive NDIR sensors, because the microphone implemented is omnidirectional [37].

3.2.4.1.2 Limitations

NDIR CO2 sensors tend to show drift in the data signal over time, and have interferences by humidity [14, 23]. This can lead to invalid data, jumps in the signal, and other artefacts that need to be corrected. In the particular case of TwinAIR, these limitations will be addressed by first, including a temperature and humidity sensor that can correct the interference by the latter, and selecting a sensor with baseline correction algorithms implemented or already available. This type of algorithm is commonly used to detect clean instances of air and correct the readings, assuming no sensitivity loss occurs over time [24].

Authors also reported the need to evaluate the baseline value, and that certain transition speeds on the pollutant concentration might affect the sensor outcome [26]. Nevertheless, it is generally agreed that this type of technology is currently providing good results and evolving rapidly [25, 26].

Finally, in case of transmissive NDIR sensors, mechanical stress can make these sensors yield invalid values, due to the misalignment between the emitter and the photodetector. In the case of mobile devices, photoacoustic NDIR sensors would be more suitable, with the further advantage of their smaller size.

3.2.4.2 Scoped Solutions

The scoped solutions in this category are detailed in ANNEX III. The most relevant ones are listed below:

- Sensirion SCDXX (different versions)
- SenseAir family (different versions)
- Winsen family (different versions)

Tests conducted in indoor spaces comparing the Sensirion SCD30, based on transmissive NDIR principle, it's successor, the Sensirion SCD41, based on photoacoustic principle, the SenseAir K30 and LP8 and Winsen MH-Z14 (all NDIR), showed that the SCD30 was one of the best CO2 sensors among the ones tested. Furthermore, the SCD41 performed the best in terms of accuracy, and was the only one that met

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the values stated in the specifications. Another sensor performing well in terms of accuracy was the K30, although not as accurate as the SCD41 [25]. Further studies coincide on the same performance by the SCD41, being the better correlated and accurate of the options tested [26]. Another evaluation of the K30 sensor was conducted and found out that the K30 sensors fell within the manufacturer's stated accuracy range of the reading when compared to a high-accuracy CO2 analyzer [38].

The performance of a wide network of SenseAir LP8 sensors was evaluated and concluded that calibration, drift correction and outlier detection are crucial for these sensors [23]. Drifts are dependent on the sensor operating environment (some are harsher than others), but generally these sensors can show significant drifts in 6-12 months of operation after calibration. The differences in the individual responses need individual characterisation in terms of accuracy and to improve the usability of the measurements. They also noted the influence of environmental parameters such as temperature, humidity and pressure, and the lack of stability of the sensors over time was highlighted, leading to a frequent recalibration.

Very few studies have been found on the Winsen family. In addition to the above-mentioned study, the only other performance study found was conducted with the Winsen MH-Z16, which showed, according to the authors, acceptable performance in comparison to its counterpart, the Winsen MH-Z14B [38]. The Winsen family of NDIR sensors is quite extensive, being the most prominent one the MH-Z16, which has a higher cost than the Sensirion sensors discussed above, as shown in the ANNEX III. In addition, the MH-Z16 sensor has an elongated shape that could be beneficial in some cases, as it can be separated from the interference from the electronics and heat build-up that might affect the readings. However, the lack of performance evaluation literature found on these sensors are an important downside for their consideration within TwinAIR, given there are other more evaluated options in the market.

The Sensirion SCD30 has already been implemented and tested in the Smart Citizen project, aligned with the finding by experimental studies. A logical addition to the portfolio would be its successor, the SCD41, given the smaller size, robustness and its accuracy [25].

3.2.5 VOCs

As mentioned above, Volatile Organic Compounds (VOCs) in indoor environments are a complex mixture of chemical substances that are not simple, quick or cheap to characterise [1]. Contrary to the consolidated knowledge in the gas sensor options from the Chemical composition Section, in the case of VOCs, there are different techniques in the market for measuring for which there are very few performance evaluation studies that have tested systematically whether or not this type of sensor solutions qualify as quantitative Data Quality Objectives (DQO) as indicated by the AQD [41]. It is generally not possible to confirm the sensor performances claimed by the manufacturers for various reasons, which are detailed below, so systematic testing of the devices and particular attention to the field of study at hand is necessary.

A review of the literature available shows that almost all low-cost sensors for measuring VOCs use one of the following techniques [1,41]:

- Photo Ionization Detector (PID)
- Metal Oxide Sensors (MOx)
- Electrochemical sensors

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It is crucial to highlight that almost all the techniques above, except some cases of MOx sensors, only provide measurements of total Volatile Organic Compounds (tVOCs), and in all cases they provide decent readings in the ppb range (see PID section for clarification). It is then important to emphasise the limitations of measuring them for exposure studies. In cases where selectivity (the ability to measure individual VOCs or aggregated tVOCs) and low concentrations are needed, reviewed literature includes the use of gas chromatographs (GC), ion mobility spectrometers (IMS) and portable mass spectrometers, which are more reliable, but not necessarily cheap in cost (price range up to USD 10k) [45, 46]. For simpler, cheaper devices, as mentioned above, tVOCs are generally the metric provided with very low selectivity, and the difficulty comes in when trying to perform sensor quality assessments in relation to reference equipment. This is due to the fact that a low-cost tVOCs sensor will not distinguish between different target species, and the sensitivity to each of them is not generally provided or determined by the manufacturer. This presents a challenge in defining firstly exactly what they are responding to, and in the case of using this data for scientific studies, what practical use this non-specific data has [46]. Reference equipment might show different sensitivities to the same target species, and be more or less selective, so the tVOCs measurement is rendered useless for quantitative measurements and should be used for trend assessment or qualitative analysis, especially at low ppb levels (<50 ppb) [26,28,40,41].

Since existing literature compiles existing measurement principles of each of the above-mentioned techniques [1,41], this section will not detail them in the same manner as the previous sensors and will focus on the potential limitations and usage they have within the TwinAIR project. An extensive literature review has been conducted on the topic for this purpose.

3.2.5.1 PID

PID technology appears to be the primary sensor element of choice for VOCs measurements and is often used for measurement of summary concentration [2, 47]. Substances with ionisation potential below the sensor's lamp specification will be measured as a whole, with very little specificity in the readings [2,26,28].

When testing PID sensors in laboratory conditions, good performance has been achieved, however this has not been later on comparable to field results [28]. Careful treatment of the readings, including electromagnetic noise, compensation for relative humidity changes, and power supply voltage stability, are a must for PID sensors [28,46]. A distributed network of sensors with these characteristics, in combination with a selective and sensitive VOCs observation technique, such as gas chromatography, may enable a better characterisation of the overall temporal and spatial variability [46]. However, the authors in the study suggest that VOCs sensors need to be highly sensitive (a characteristic of PIDs), but also have low limits of detection (LoD), which some solutions claim to have, but not much evaluation is available for them. This might be a limiting factor if accuracy is required at ppb level, where correlation and accuracy are very weak [28]. However, potential usage in alarm systems due to rapid changes could be a feasible solution, alongside with the deployment of multiple devices with high consistency, with potential multiple calibration points at various low ppb levels for different target species, and at different relative humidity values [28].

Other studies have used low-cost PID sensors as sensing elements in more advanced equipment, such as gas chromatographs, and in particular two dimensional GCs (GC x GC) [40,43,44,45]. These solutions are not only field deployable, but also more affordable in relative terms to other benchtop solutions [48]. The

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reported cost of the solution ranges between USD 2500 and USD 10000, which are not necessarily low cost, although provide promising results.

3.2.5.2 Electrochemical Sensors

Electrochemical sensors for VOCs work in similar ways to those used for other target species. In general, these sensors are low cost, low power, and compact, however their response time is higher than other types of sensors (>100s in some cases) [41]. Electrochemical sensors do not have selectivity to certain species unless operated with certain bias voltages (Alphasense Ltd. offers a version in which increments of bias voltages provide a broader response to VOCs), and in general, are less sensitive when compared to PIDs. Some other manufacturers provide selectivity through different materials in both the electrodes or the diffusion barrier. Finally, the calibration is normally linear or logarithmic, but they generally present limits of detection that are too high for indoor applications (>50 ppb) [41].

In some cases, the presence of CO will also affect the measurements of these sensors, and the solution would need to incorporate an additional CO electrochemical sensor to be able to decompose the VOC sensor readings, with the obvious cost increase.

3.2.5.3 Metal Oxide Sensors

These sensors are similar to those discussed in the chemical composition section. As detailed below, MOx sensors are a potential candidate for VOC measurements, with the advantage that the cost saved from the sensor unit itself with respect to other technologies (PIDs for instance) can be compensated with a larger amount of sensors or more advanced and original ways of handling the sensors.

In general, manufacturers do not provide performance assessment of these sensors and the specifications sheets are not generally detailed for this type of sensor. Because of this and other factors detailed below, it is generally recommended to calibrate them on the field [41]. The response time of MOx is much faster than electrochemical sensors, and their selectivity is similar to that of PIDs, although sometimes worse where interfering factors such as CO and NOx presence, or temperature and humidity affect the readings [46]. This can be improved by the sensor construction itself, but it is normally required to include at least temperature and humidity sensors to be able to compensate for these effects. In general, the probability of having a complex gas mixture with interfering gases, the lack of sensitivity, as well as the manufacturing deviations, make this type of sensor not easy to handle for real case scenarios. Drift for these sensors is also a downside. Manufacturers do not provide information about how much sensors drift overtime, and generally the sensor decay is much faster than other types. Calibration frequency is higher than in other cases, and LoD is normally not studied [41]. For these reasons, MOx are only recommended when PIDs are not available or because of budget constraints.

Despite all this, there are potential innovations in the field of MOx sensors that could be further assessed and improved in TwinAIR. In particular, temperature cycle operation (TCO), as well as calibration schemes where linear discriminant analysis (LDA) and other machine learning models are employed to calibrate the sensors against reference equipment, has been proven to provide good results [41, 50, 54]. TCO is particularly relevant for TwinAIR and could provide synergies with other tasks (specially T6.2) because the process can be seen as a virtual sensor array providing multi-channel information [41]. However, despite the promising results of these techniques in scientific literature, there is currently not much information on how to proceed per device, as the manufacturer's information is scarce and not very detailed. Other calibration approaches have been explored by using reference equipment and MOx in co-location for a period of time [52]. The authors highlight the fact that MOx are normally used for higher pollutant concentrations, but that they can be used in air quality monitoring applications when calibrated in the field, and they prove that real-time estimates and possibly benzene, toluene, ethylene, xylene (BTEX) measurements are possible. In addition, the usage of multiple gas sensors can mitigate cross-sensitivities, although they highlight the need to pre-assess the target environment to validate that high above-background concentrations are actually possible. This approach could be very useful in TwinAIR in case other reference equipment is available for intercomparison. However, as highlighted in field studies, the transferability of the models is not guaranteed as the pollution profiles in each location will differ from each other.

Other authors have highlighted the benefits of using MOx sensors, or any broadband VOCs sensor, for the usage of demand control ventilation (DCV), as VOCs changes are more representative of perceived air quality than CO2 measurements [53]. In the same study, the authors indicate that the gas sensors used (own design) did not show long-term drift, and that the calibration would be possible in an empirical way by also offering baseline correction algorithms.

Finally, another type of MOx sensors that could be used for the purpose of VOCs monitoring are the Silicon Carbide Field Effect Transistors (SiC-FET). These sensors provide a good gas-sensitivity because of their construction and materials used. In contrast, selectivity can be improved by dynamic operation, such as TCO or other techniques, such as gate bias cycled operation (GBCO) [51, 55]. These innovative techniques should go along with electronics for sensor operation and signal readings [55]. Sensor readings are to be taken and controlled at a wide dynamic range and very high speeds, which can increase the cost of the solution.

3.2.5.4 Scoped Solutions

As seen by the literature review, and for the purpose of TwinAIR, it is necessary to establish a clear objective that can fulfil the requirements for the measurement campaigns but limiting the cost of the solution. A clear understanding of the target species, LOQ, and usefulness of the selectivity (or lack of it) of the sensor remains unclear at the moment of writing this deliverable.

As detailed above, the integration of VOCs sensors within a more complex system could provide relevant data to explore within TwinAIR. Studies with GC, passive adsorption tubes, pre-concentrators and other setups can provide more innovative solutions, and it would be possible to combine various VOCs sensors to reduce the calibration needs in the field [52]. While there are many challenges associated with the use of VOCs sensors, it has been shown above that there are different explorations possible within the TwinAIR project that could leverage the modularity and flexibility of the Smart Citizen project, and leverage on other task synergies for VOCs measurements.

In this line, and due to the current need for further assessment within TwinAIR, the scoped and proposed solutions are as follows:

- Off-the-shelf MOx sensors with full software support, as part of an integrated commercial solution, which can provide an indicative and aggregated measurement of VOCs with a low budget.
- Advanced solutions that can be integrated with or operated at more advanced and innovative ways, which could provide better selectivity, including PIDs or MOx.

3.2.5.4.1 *Off-the-shelf Sensors*

The sensors in this category are meant to be low-cost, self-managed solutions, commercially available, and as a bonus, with a digital communication interface. State-of-the-art market solutions that provide these listed in ANNEX III table, and the most prominent ones are the following:

- Sciosense ENS160
- Sensirion SGP40

An evaluation of both solutions and integration of the best one will be performed and will be reported in D6.2.

3.2.5.4.2 *Advanced Solutions*

These options include the usage of PIDs and MOx in a more innovative way, which would both be supported by the hardware portfolio in terms of interface electronics at a primary level. Based on the preliminary literature review, electrochemical units are not considered due to their slow response times, and their low selectivity.

In addition, since the decision for integrating this technology goes beyond the purpose of this deliverable, as it has potential budgetary constraints, and additional effort is to be discussed, it is currently only suggested as an option, which can then be evaluated once the discussions evolve within the project. The scoped solutions are:

- Integration of PID sensors within more advanced systems such as gas chromatographs (GC) or 2-dimensional GCs (GC x GC). The system integration and design will be heavily dependent on the budget and the overall capacity for the system integration. Since these sensors only require an ADC for their integration, which is already supported within the Smart Citizen project, and considering that other Alphasense sensors are already part of the sensing portfolio, and that new PID sensor units by the manufacturer are claimed to measure at low ppb levels (Alphasense PID AH2), this is a logical step for further integration. Other options include Baseline piD-TECH eVx and VOC-TRAQ II.
- Commercial MOx sensors with advanced operation modes, including TCO and field calibration. The scoped solutions are:
    - Figaro family (TGS2600 and TGS2602)
    - UST Umweltsensortechnik GmbH GGS family (GGS 1330, GGS 2330, GGS 5330)

Additional sensors are included in ANNEX III.

3.2.6 Radon

Some overall categories of radon measurement devices and characteristics are detailed in the WHO handbook on indoor radon: a public health perspective [60]. According to the handbook, radon measurements are often discussed in either short-term or long-term tests. In general, long-term radon measurements are preferred for assessing the annual radon concentration, especially due to the high temporal variability of indoor radon, which makes short-term measurements generally unreliable, unless

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there is an interest in assessing spikes for a particular purpose. This handbook also explains the different measurement methods and detectors associated with those:

- Alpha-track Detector (ATD)
- Activated Charcoal Detector (ACD)
- Electret Ion Chamber (EIC)
- Electronic Integrating Device (EID)
- Continuous Radon Monitor (CRM)

According to the handbook, ATDs, ACDs and EICs are passive devices that do not require electrical power or a pump to sample air, whereas EIDs and CRMs are active devices, which require electricity to work. In general, passive devices, especially ATDs and ACDs are lower in cost, whereas CRMs are traditionally the most expensive options, although there are some developments in an emerging field of lower cost CRMs [63], which are fundamentally the study of this section. Passive detectors, also include some home kits that are normally the least expensive systems, and consist of short-term radon test kits such as ACDs. In these cases, the collector of the kit has to be placed at the lowest floor of the house to be evaluated for a minimum of one day to up to a week, and the sample to be sent to a laboratory for analysis [64]. This type of detectors will not be explained and considered for the TwinAIR sensor portfolio hereby presented, although they can potentially be used in the pilots if desired. Passive detectors can also be used for long term radon evaluation (3-12 months), and would be the preferred option for long term assessment [60], but it wouldn't provide any insights or continuous feedback that can help the building management aspect part of TwinAIR. For these reasons, CRMs are the only options discussed from now on.

In the case of Continuous Radon Monitors, there are very few commercially available options [63, 66], some of which have been listed in ANNEX III. These are mostly Pulsed Ion Chambers (PIC), Solid-state silicon detectors and Alpha Scintillation Monitors [64]. Another technology is based on photodiodes or phototransistors for alpha particle detection, which is the technology being used in lower cost integrated devices, namely the Safety Siren Pro Series 3 or the Airthings Wave [67], and in more costly units such as the Tesla TSRS [69]. These technologies are described in WHO's manual [60] and in [72] and will not be replicated here.

Besides the detector type, when selecting a radon sensor, accuracy and limits of detection (LoD) are probably the most critical factors, which have an impact on price [64]. In addition, sampling intervals, which can range from continuous sampling to a sample per hour; and more importantly, the time that the sampler needs to show initial measurements are to be considered, which can range from hours to months [64].

For reference, the radon decay speed in the air is measured in becquerels per cubic metre in the International System of Units (Bq/m3) or picocuries per litre (pCi/l). Depending on the country's national law, acceptable radon levels vary. A generally accepted action level, established by the WHO, is 100 Bq/m3, or 2.7 pCi/L. If this level cannot be implemented under the prevailing country-specific conditions, then the upper limit should not exceed 300 Bq/m3, or 8 pCi/L, as required for most European countries. For indoor radon concentrations higher than 300 Bq/m3, it is advised to take remedial action to lower the radon level [63]. These remedial actions are normally ventilation by various means (natural or forced

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ventilation) and are also subject for study for the scope solutions below as some of them can interface with a ventilation system as part of an integrated platform [73].

3.2.6.1 Scoped Solutions

Evaluation of radon monitors is very scarce in literature, and few intercomparison studies have been found. A comparison study was conducted between two CRMs based on Pulsed Ion Chambers (RadonEye both based on FTLab products RD200 and RD200P2 [68]), and a passive diffusion chamber (Airthings Wave). The results in terms of correlation or root-mean square deviation (RMSD) were very promising for both RadonEye in comparison with a reference instrument, but not for the Airthings Wave (although the authors highlight the fact that the warmup requirements for the Wave were not necessarily fulfilled). The cost of both solutions does not differ much, being in the range of USD 200 for the cheaper RadonEye and Airthings Wave. However, none of these can be easily integrated into an existing data platform, as they are stand-alone solutions and do not expose digital communications to which the Smart Citizen Data board can connect to. An integration into the Smart Citizen project would need to be done by potentially tampering with the device, as authors have done in other reviews [64]. The sensing unit for the RadonEye (FTLab RD200 Series), are very promising but are only available for academic prototypes [63, 68], and it hasn't been possible to obtain the cost at the time of writing this deliverable by contacting the manufacturers or the providers. However, this could be the most promising solution as the solutions that integrate the measurement cell range from USD 200 to USD 400 (for the more advanced RadonEye). This option is also the choice by authors in [72], who use the FTLab RD200M and provide a complete implementation in a device with an Internet of Things (IoT) platform.

A system integrating another manufacturer is detailed in another study [65]. This system is based on the Tesla TSRS [69], which features a measuring chamber with a semiconductor photodetector [70]. However, this option's cost is USD 800 for the sensing unit, and no other literature has been found that can justify the selection of this device. Finally, other literature reviewed in the topic includes new designs [71], which are potentially not mature enough for their use in the TwinAIR pilots.

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4. Conclusions

In the Pollutants of interest section this deliverable reviews which options are critical to monitor in indoor environments in general, and highlights those that are of special relevance for the TwinAIR project purpose. In the Market review section, the Smart Citizen Ecosystem is detailed, and the solutions for different sensor technologies and potential development within TwinAIR are detailed. Based on the two previous sections, the final sensor selection is listed and compared against the criteria set for its selection (see section 3.2.A). The integration of the selected sensors is not detailed in this deliverable, as it will be part of D6.2 TwinAIR Sensor implementation. Finally, the sensor performance is detailed in ANNEX II to serve as a summary of the available options for the pilot interventions.

4.1 Sensor Selection

4.1.1 Environmental Metrics

Environmental metrics such as temperature and relative humidity, have been identified throughout the deliverable as they are used to compensate for their effect on some other sensor readings such as PM or chemical composition readings. In the case of PM, a relative humidity sensor is necessary in order to be able to compensate for the hygroscopic growth of the particles. In the case of chemical composition, both in the case of electrochemical (EC) sensors and metal oxide (MOx) sensors, temperature (and in some cases humidity), has been identified as a necessary parameter to be measured. However, in the case of EC sensors the important temperature to measure is that of the sensor itself, whereas in other cases is air temperature. For this reason, temperature and humidity sensors are included in the final sensor selection. In addition to these reasons, air temperature and humidity can be useful for the assessment of comfort metrics.

The Smart Citizen project already includes several probe versions based on Sensirion SHT3X series (a MEMs temperature and humidity sensor), and has experience on its usage [21, 61]. Details about its performance are found in ANNEX II, and even if its cost depends on the packaging, it ranges from USD 6 for basic MEMs packages to USD 20 for more advanced weather-proof probes. Based on the evaluations conducted for the sensor [21], the available support through open-source libraries[2], and the overall market availability of the sensor[3] being in the order of tens of thousands at the time of writing this deliverable, it is considered a good option for the TwinAIR project.

Other environmental metrics are not necessary in the case of the TwinAIR pilots, such as barometric pressure, light intensity or noise levels, but all those are included in the Smart Citizen Kit by default, and are detailed in ANNEX II for reference.

4.1.2 Particulate Matter

As seen in the Market review section, there are plenty of commercially available options for measuring Particulate Matter in the market. The Smart Citizen project already supports the Plantower PMS5003, a very low-cost sensor (USD 15 at the moment of writing this deliverable), which has been reviewed in many

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[2] *Open source libraries available at Github for Sensirion SHT31(Accessed January 2023): https://github.com/search?utf8=%E2%9C%93&q=sht31*

[3] *Availability of Sensirion SHT31-DIS in Octopart (Accessed January 2023): https://octopart.com/search?q=SHT31-DIS&currency=USD&specs=0*

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performance evaluations (see ANNEX III table for a list of those that have been found). As explained above, this sensor has its (well documented) limitations, and a better performing solution that has been found in the market is the Sensirion SPS30, which outperforms the PMS5003 in terms of long-term drift, accuracy in the fine particle range, and particle size distribution. Sensirion SPS30 is steadily available in the market at the moment of writing this deliverable[4] and software support is provided through manufacturer libraries[5]. However, it's cost is significantly higher (USD 55), and other competing options are emerging at similar costs (i.e., Piera IPS Family or Tera NextPM - see ANNEX III for more details), although with no performance reviews available for indoor environments. For these reasons, the PMS5003 will still be supported for TwinAIR, and the Sensirion SPS30 will be implemented as a better performing option.

4.1.3 Chemical Composition

The Market Review section concluded that reliable low-cost sensor options for measuring chemical composition are currently limited to electrochemical sensors. The Smart Citizen project already supports interfacing with those via its analog front-end (a dedicated high precision analog-to-digital converter), and has experience only with Alphasense Ltd. sensors [21, 62]. Additionally, the Market review section included SPEC Sensors as an alternative manufacturer, but no performance review has been found at the moment of writing this deliverable. Despite the cost of Alphasense sensors (between USD 100 to USD150 per cell), other options are not currently explored as there is no experience in using other manufacturers. For these reasons, Alphasense Ltd. sensors will be used, and it is recommended to use the B-series, due to their improved performance (see ANNEX III). It is worth noting that both options are compatible with the Smart Citizen project, so the usage of SPEC sensors is not unfeasible should more performance reviews appear.

4.1.4 CO_2

CO2 is currently mostly measured by the usage of NDIR technology, as detailed in the Market Review. The best performing sensors found are the Sensirion SCD30 and the Sensirion SPS40. Both sensors have ranked as best performing units in the Market review section, and the Smart Citizen project currently supports both. Cost for both options is in the order of USD 50, similar to other market options, and it is currently available in the market[6] [7], with software support through open-source libraries[8].

4.1.5 VOC

Volatile Organic Compounds measurements with low cost sensors is currently a technological challenge. To address this complexity in the scope of TwinAIR, different options are provided, which will be subject to further evaluation during the implementation phase. These options are:

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[4] *Availability of Sensirion SPS30 in Octopart (Accessed January 2023):* *https://octopart.com/search?q=sensirion+SPS30&currency=USD&specs=0*

[5] *Open-source libraries available at Github for Sensirion SPS30 (Accessed January 2023):* *https://github.com/Sensirion/arduino-sps*

[6] *Availability of Sensirion SCD30 in Octopart (Accessed January 2023):* *https://octopart.com/search?q=sensirion+scd30&currency=USD&specs=0*

[7] *Availability of Sensirion SCD41 in Octopart (Accessed January 2023):* *https://octopart.com/search?q=sensirion+scd41&currency=USD&specs=0*

[8] *Open-source libraries available at Github for Sensirion SCD4X (Accessed January 2023):* *https://github.com/Sensirion/arduino-i2c-scd4x*

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- Off-the-shelf low cost sensors: such as the Sciosense ENS160, which provides tVOC index readings and a very low cost (USD 12). These sensors are currently easy to integrate into the Smart Citizen project, as they have software support available, and are currently available in the market . However, there are no performance evaluations available for this sensor (situation similar to other MEMs VOC sensors of similar range)
- Advanced sensors: these options are either more expensive in terms of hardware (PIDs) or require more effort in terms of calibration (MOx), however they present an innovation opportunity for TwinAIR in the field of VOC sensors as seen in the Market review section.
    - PID options: these are most costly (USD 300). None of the sensors has been tested within the Smart Citizen project and evaluations will need to be conducted and agreed with other partners. Scoped solutions are compatible with the current hardware interfaces and can be integrated interchangeably with each other depending on the final decision.
    - MOx options: these are cheaper options (<USD 50) with overall worse performance if not operated in innovative ways (such as those detailed in the Market review section).

4.1.6 Radon

As shown in the Market review section, at the time of writing this deliverable the most promising (and possibly the only feasible solution) is to use a custom solution based on the FTLab RT200M device. However, as indicated in the section above, the device is not openly available for purchase, and it would require integration within the Smart Citizen architecture, similar to the work done in [72]. This device, however, is the most promising in terms of performance and cost. However, there is a discrepancy between the interest of monitoring it within TwinAIR partners, as highlighted by the internal survey (only two responses), and the importance given by WHO's guidelines [60], and this needs to be clarified internally before any integration effort is considered.

4.2 Remarks on Sensor Selection

This section summarises the identified limitations for the sensor selection detailed above that need to be addressed as the TwinAIR project progresses. These limitations are generally related to technology limitations or commercial solutions availability, which are listed below in relation to the TwinAIR objectives. For each case, a brief summary, linked to relevant sections, actions points and potential synergies with other tasks are detailed:

- Ultrafine particles: technology limitations for ultrafine particles monitoring are presented in section 3.2.B.1.2. It is important to address the need for ultrafine and fine particles and their size selectivity. Synergies with TwinAIR Task 3.6 (Ultrafine Particle pollutant sources monitoring & data treatment) are being established at the time of writing this deliverable in order to characterise the performance of the selected low cost particulate matter sensors, as well as to develop an innovative ultrafine particles estimation methods with these.

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- **Need for VOC specificity:** section 3.2.E.4 elaborates on the low-cost technological limitations for monitoring volatile organic compounds, and in particular, the difficulties to assess individual species. Various solutions are proposed in section 3.2.E.4, but at the time of writing this deliverable there is insufficient information about these needs and the particular needs of individual pilots (still to be defined) will be addressed using these solutions. A potential synergy with Task 6.2 (Virtual Sensing Technological Solutions) will be explored in order to develop virtual sensors for the estimation of individual species of volatile organic compound substances from a multisensor array as described in section 3.2.E.4.2.

- **Radon**: current availability of radon monitors is scarce as shown in section 3.2.F.1, although none is openly available with a cost lower than USD 500. An existing option is available for academic prototypes (for indoor dosimetry) at an assumed cost below USD 200. However, given the complexity of the radon sensor integration, the decision of using these sensors will be evaluated based on the pilots' location and its radioactive substance exposure risks.

- **Assessment and calibration methodology:** an integrated performance assessment and calibration methodology needs to be developed in order to provide effective monitoring solutions, as seen in almost every pollutant section. This aspect is highly important, as the performance of the sensor solutions can depend on it, and it is one of the proposed novelties within TwinAIR project (Proposed Novelty 7), and will need to strengthen synergies with the various participants in the TwinAIR consortium. This will be the subject of Deliverable 6.3.

As seen above, the sensor selection identified in this deliverable aims to extend the indoor measurement capabilities for low-cost sensor systems, with a focus on health exposure and digital twins. The selection is done based on a set of criteria that prioritise the availability of the solutions, as well as their potential to extend the overall understanding of low-cost sensors for IAQ monitoring. Deliverable 6.2 will include the technical implementation of the solution, and will serve as an accompanying document for Deliverable 6.1.

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6. ANNEX 1

Survey questions

- Partner ID (Person of Contact / Email)
- Field of application (Air quality sensors or Weather sensors)
- Deployment type (Indoor, Outdoor, Mobile (with GPS))
- Weather and Air Quality Measurements
  - Indicate here the main purpose you will give the data you are collecting (this will help us get the best sensor performances, types, enclosures). For instance: understand spatial air pollution distribution in an indoor space.
  - Indicate here how if you have any requirement about how you need to place the units (indoor, outdoor, heights, orientation...). Detail special details such as potential aggressive or difficult environments such as high/low temperatures, humid conditions, high flows.
- Metrics
  - Choose from:
    - Temperature
    - Relative humidity
    - Noise level
    - Atmospheric Pressure
    - Particulate Matter
    - CO2
    - Chemical composition (CO, NO2, NO, SO2, H2S, O3)
    - VOC (Indicate which one or tVOC)
    - Other
  - Describe below what are the main metrics needed from the device and if any of them require specific attention (i.e. air temperature is important to be accurate and not affected by anything)
  - Indicate here the priority of the metrics you willing to collect and if you can make any compromise regarding them or not
  - Indicate here if you have any requirements in terms of range, and accuracy. If you are doing a literature review, please, include here relevant sources or conclusions.
- Data
  - How often do you need the data to be recorded?
  - Do you need access to real time data? (Yes / No)
- Special needs
  - Do you need geolocated data? (Yes / No)
  - Do you need dynamic measurements? (i.e. to perform measurement while moving on a vehicle) (Yes No)
- Any other requirement

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7. ANNEX 2

Air temperature relative humidity

- **Sensor model:** Sensirion SHT31
- **Probe type:** Digital thermometer in MEMS package or in weatherproof capsule
- **Humidity Detection Range:** 0%RH~100% RH
- **Humidity Accuracy:** ±2% RH@0% RH~100% RH (at 25℃)
- **Temperature Detection Range**: -40℃~125℃
- **Temperature Accuracy:** ±0.2℃@0℃~90℃ (Typical)
- **Cable Length:** about 1m
- **Reaction Time:** not tested.
- **Life expectancy:** not tested.

Barometric pressure

- **Sensor model:** Infineon DPS310XTSA1
- **Sensor type:** Digital piezoresistive absolute pressure sensor in MEMS package
- **Pressure Operating Range:** 30-120 kPa
- **Sensor precision:** 0.002 hPa
- **Relative accuracy:** 0.06 hPa
- **Absolute accuracy:** 1 hPa
- **Reaction Time:** not tested.
- **Life expectancy:** not tested.

Light

- **Sensor model:** ROHM BH1721FVC
- **Sensor type:** digital light sensor in MEMS package
- **Light Detection Range:** 1-65528 lx
- **Measurement variation:** ±15%

Noise

- **Sensor model:** INVENSENSE–TDK ICS43432
- **Sensor type:** digital microphone in MEMS package
- **SNR:** 65 dBA
- **FS Sensitivity:** −26 dB
- **Sensitivity Tolerance:** ±1 dB
- **Frequency Response:** 50 Hz to 20 kHz
- **Acoustic Overload Point:** 116 dB SPL
- **Reaction Time:** <20 ms
- **Life expectancy:** not tested.

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Particulate Matter

Option A

- **Sensor model:** Plantower PMS5003
- **Sensor type:** forced ventilation laser scattering nephelometer
- **Minimal particle diameter:** 0.3 µm
- **PM bins:** PM1, PM2.5, PM10
- **Number of bins:** 6
- **PN Bins:** 0.3 µm, 0.5 µm, 1 µm, 2.5 µm, 5 µm, 10 µm
- **Resolution:** 1 µg/m^3
- **Particle Effective Range:** 0~500 µg/m3
- **Particle Max. Consistency Err:** ±10%@100~500 µg/m^3 and ±10 µg/m^3@0~100 µg/m^3
- **Working Humidity Range:** 0-99% rh
- **Reaction Time:** single <1 s, total 10 s
- **Life expectancy:** > 3Y

Option B

- **Sensor model:** Sensirion SPS30
- **Sensor type:** forced ventilation laser scattering nephelometer
- **Minimal particle diameter:** 0.3 µm
- **PM bins:** PM1, PM2.5, PM4, PM10
- **Number of bins:** 5
- **PN Bins:** 0.5 µm, 1 µm, 2.5 µm, 4 µm, 10 µm
- **Resolution:** 1 µg/m^3
- **Particle Effective Range:** 0~1000 µg/m3
- **Working T/H Range:** 10-40ºC 20-80% rh
- **Reaction Time:** 1s
- **Life expectancy:** > 10Y with 24h/day operation
- **Mass concentration precision for PM1 and PM2.5:**
  - 0 to 100 µg/m^3 ±10 µg/m^3
  - 100 to 1000 µg/m3 ±10 % m.v.
- **Mass concentration precision for PM4, PM10:**
  - 0 to 100 µg/m3 ±25 µg/m3
  - 100 to 1000 µg/m3 ±25 % m.v.
- **Maximum long-term mass concentration precision limit drift:**
  - 0 to 100 µg/m3: ±1.25 µg/m3 / year
  - 100 to 1000 µg/m3: ±1.25 % m.v. / year
- **Number concentration range:** 0 to 3000 #/cm3
- **Number concentration precision for PM0.5, PM1 and PM2.5**
  - 0 to 1000 #/cm3: ±100 #/cm3
  - 1000 to 3000 #/cm3: ±10 % m.v.
- **Number concentration precision for PM4, PM10:**
  - 0 to 1000 #/cm3: ±250 #/cm3
  - 1000 to 3000 #/cm3: ±25 % m.v

Chemical Composition - CO

- **Sensor model:** Alphasense CO-A4 and CO-B4
- **Probe type:** electrochemical cell
- **Range:**
    - A-series: 0-500 ppm
    - B-series: 0-1000 ppm
- **Noise:**
    - A-series: ±2 standard deviations: 20 ppb equivalent
    - B-series: ±2 standard deviations: 4 ppb equivalent
- **Reaction Time:** t90 (s) from zero to 10 ppm CO < 30s
- **Life expectancy:** 2 years warranted, 3 years (50% drift after more than 36 months)

Chemical Composition - NO2

- **Sensor model:** Alphasense NO2-A43F or NO2-B43F
- **Probe type:** electrochemical cell
- **Range:**
    - A-series: 0-20 ppm
    - B-series: 0-20 ppm
- **Noise:**
    - A-series: ±2 standard deviations: 15 ppb equivalent
    - B-series: ±2 standard deviations: 15 ppb equivalent
- **Reaction Time:** t90 (s) from zero to 2 ppm NO2: 80s
- **Life expectancy:** 2 years warranted (50% drift after 24 months)

Chemical Composition - NO

- **Sensor model:** Alphasense NO-A4 or NO-B4
- **Probe type:** electrochemical cell
- **Range:**
    - A-series: 0-20 ppm
    - B-series: 0-20 ppm
- **Noise:**
    - A-series: ±2 standard deviations: 80 ppb equivalent
    - B-series: ±2 standard deviations: 15 ppb equivalent
- **Reaction Time:** t90 (s) from zero to 10 ppm NO < 25s
- **Life expectancy:** 2 years warranted (50% drift after 24 months)

Note: Current experience with this sensor provides only experimental results.

Chemical Composition - O3 + NO2

- **Sensor model:** Alphasense OX-A431 or OX-B431
- **Probe type:** electrochemical cell
- **Range:**
  - A-series: 0-20 ppm (O3)
  - B-series: 0-20 ppm (O3)
- **Noise:**
  - A-series: ±2 standard deviations: 15 ppb equivalent
  - B-series: ±2 standard deviations: 15 ppb equivalent
- **Reaction Time:** t90 (s) from zero to 1 ppm O3 < 80s
- **Life expectancy:** 2 years warranted (50% drift after 24 months)

Note: this sensor needs to be deployed with another NO2 sensor of the same kind to be able to calculate O3.

Chemical Composition - H2S

- **Sensor model:** Alphasense H2S-A4 or H2S-B4
- **Probe type:** electrochemical cell
- **Range:**
  - A-series: 0-50 ppm
  - B-series: 0-100 ppm
- **Noise:**
  - A-series: ±2 standard deviations: 5 ppb equivalent
  - B-series: ±2 standard deviations: 1 ppb equivalent
- **Reaction Time:** t90 (s) from zero to 2 ppm H2S < 60s
- **Life expectancy:** 2 years warranted (50% drift after 24 months)

Note: Current experience with this sensor provides only experimental results.

Chemical Composition - SO2

- **Sensor model:** Alphasense SO2-A4 or SO-B4
- **Probe type:** electrochemical cell
- **Range:**
  - A-series: 0-50 ppm
  - B-series: 0-100 ppm
- **Noise:**
  - A-series: ±2 standard deviations: 15 ppb equivalent
  - B-series: ±2 standard deviations: 5 ppb equivalent
- **Reaction Time:** t90 (s) from zero to 2 ppm SO2 < 20s
- **Life expectancy:** 2 years warranted (50% drift after more than 36 months)

Note: Current experience with this sensor provides only experimental results.

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Chemical Composition - CO2

Option A

- **Sensor model:** Sensirion SCD30
- **Probe type:** NDIR with digital interface. Not waterproof.
- **Measurement range:** 400 ppm – 10000 ppm
- **Accuracy:** ±(30 ppm + 3%)
- **Reaction Time:** 63% in 20 s
- **Life expectancy:** 15 years

Option B

- **Sensor model:** Sensirion SCD40 and SCD41
- **Probe type:** Photoacoustic NDIR with digital interface. Not waterproof.
- **Accuracy:**
    - SCD40: 400 ppm – 2000 ppm ± (50 ppm + 5% of reading)
    - SCD41: 400 ppm – 5000 ppm ± (40 ppm + 5% of reading)
- **Repeatability:** Typical ± 10 ppm
- **Measurement range:** 0 ppm – 40000 ppm
- **Reaction Time:** 63% in 60s
- **Life expectancy:** unknown

VOCs

Off-the-shelf MEMS sensor

- **Sensor model:** Sciosense ENS160
- **Sensor type:** digital metal oxide in MEMS package
- **Output range (tVOC):** 0 to 65000 ppb
- **Resolution tVOC:** 1 ppb
- **Reaction Time:** not tested.
- **Life expectancy:** not tested.

PID

- **Sensor model:** Alphasense PID-AH2
- **Sensor type**: PID
- **Target gases** VOCs with ionisation potentials < 10.6 eV
- **Minimum detection level** 1 ppb isobutylene
- **Linear range** 40 ppm isobutylene 3% deviation
- **Sensitivity** >25 mV /ppb isobutylene
- **Stabilisation time** 5 minutes for 20 ppb
- **Warm-up time** 5s
- **Response Time (t90):** < 3s
- **Life expectancy:** 5Y

MOx

For MOx VOC options, see table in Annex III.

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ANNEX 3

In this annex, various lists for different sensors are provided. The information provided should be read as follows:

- Manufacturers that provide a series of similar sensors (a family) are grouped. Cost is provided on average, except for those that present a significant variability within the prices, for which ranges of prices are provided.
- Cost is provided in USD, for one unit.
- If cost is not found in retail, and is not provided by the manufacturer, na is indicated. If price is found, but differs from previous experience due to unknown reasons, it is marked with (*)
- Reviewed literature evaluating the sensor is included (DOI). Not limited to the table.
- All links in the tables were accessed January 2023

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PM SENSORS

POLLUTANT	TYPE	MANUFACTURER	MODEL	POLLUTANTS	OTHER METRICS	COST	REFERENCE	EVALUATION LITERATURE	AQ SPEC
PM	Laser	Plantower	PMSX003	PM (1, 2.5, 10)	PN Count	$15.00	Plantower PM Sensors Page	10.5194/amt-13-2413-2020 10.1016/j.envint.2022.107372 10.1016/j.jaerosci.2020.105654 10.3390/atmos12080961 10.1016/j.buildenv.2020.107415	PMS5003 (SCK) Summary PMS5003 (Purple Air) Summary
PM	Laser	NovaFitness	SDS01X	PM 2.5, PM10	PN Count	$25 (*)	na	10.5194/amt-13-2413-2020	na
PM	Laser	Sensirion	SPS30	PM (1, 2.5, 4, 10)	PN Count	$55.00	Sensirion SPS30 Page	10.5194/amt-13-2413-202 10.1016/j.jaerosci.2020.105654 10.1016/j.envint.2022.107372 10.3390/atmos12080961 10.1016/j.buildenv.2020.107415	SPS30 Eval Kit Summary
PM	Laser	Sensirion	SEN50	PM (1, 2.5, 4, 10)	PN Count	$23.72	Sensirion SEN50 Page	na	na
PM	Laser	Sciosense	APC1	PM1.0, PM2.5, PM10, tVOC	tVOC, eCO2 , AQI , temperature and relative humidity	$54.57	Sciosense APC1 Page	na	na
PM	Laser	Winsen	ZHXXX	PM (1, 2.5, 10)	na	$18.00	Winsen PM Sensors Page		na
PM	Laser	Wuhan Cubic	PMXXXX	PM (1, 2.5, 10)	na	na	Wuhan Cubic PM Sensors Page	10.1155/2020/8749764	na
PM	IR (Led)	Omron	B5W-LD0101-1	PN 0.5 and PN 2.5	na	na	Omron B5W-LD0101 Sensor Page	10.5194/amt-13-2413-2020	na

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POLLUTANT	TYPE	MANUFACTURER	MODEL	POLLUTANTS	OTHER METRICS	COST	REFERENCE	EVALUATION LITERATURE	AQ SPEC
PM	Laser	Alphasense	OPC-N3	PM (1, 2.5, 10)	PN Count	+$100	Alphasense PM Sensors Page	10.3390/atmos12080961	Alphasense Summary
PM	Laser	Alphasense	OPC-R2	PM (1, 2.5, 10)	PN Count	+$100	Alphasense PM Sensors Page	-	Alphasense Summary
PM	Laser	Tera	NextPM	PM (1, 2.5, 10)	PN Count	$70.00	Tera Next PM Sensor Page	-	Tera NextPM Summary
PM	LED	Panasonic	SN-GCHA1	PM 2.5	na	na	Panasonic PM Sensors Page	-	na
PM	LED	Panasonic	SN-GCJAX	PM 2.5 (some PM10)	na	$30.00	Panasonic PM Sensors Page	-	na
PM	Laser	Honeywell	HPMA115S0-XXX	PM2.5, PM10 output (standard) - PM1.0, PM2.5, PM4.0, PM10 output (compact)	na	$75.00	Honeywell HPMA PM Sensors Page	10.5194/amt-13-2413-2020	na
PM	Laser	Piera	IPSX100	PM (1, 2.5, 10) (ultrafine?)	PN Count +	$50 - $78	Piera IPS Sensor Family Page	10.3390/atmos14020324	Piera Systems IPS7100 (Canaree) Summary
PM	Laser	Amphenol Advanced Sensors	SM-UART-04L	PM (1, 2.5, 10)	na	$30.00	-	10.1016/j.jaerosci.2020.105654	na

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CHEMICAL COMPOSITION

POLLUTANT	TYPE	MANUFACTURER	MODEL	POLLUTANTS	OTHER METRICS	COST	REFERENCE	EVALUATION LITERATURE
CO	MOx	SGX Sensortech	MICS 6814	CO, NO2	-	$6.50	SGX MICS 6814 Product Page	10.1016/j.envint.2022.107372
CO	MOx	Winsen	GM 702B	CO	(2)	na	Winsen GB 702B Product Page	
CO	Electrochemical	Alphasense	CO-B4 and CO-A4	CO	(2)	$60 + $75 (cell + electronics)	Alphasense Carbon Monoxide Sensors	(1)
CO	Electrochemical	SPEC	DGS-CO	CO	(2)	$150.00	SPEC DGS-CO Product Page	
COeq	Electrochemical	SPEC	DGS-IAQ	COeq	IAQ	$150.00	SPEC DGS-IAQ Product Page	
NO2	Electrochemical	Alphasense	NO2B4F and NO2-A4	NO2	(2)	$60 + $75 (cell + electronics)	Alphasense Nitrogen Dioxide Sensors	10.1021/acssensors.0c01129 (1)
NO2	Electrochemical	SPEC	DGS-NO2	NO2	(2)	$150.00	SPEC DGS-NO2 Product Page	
O3	Electrochemical	Alphasense	O3-B431 and O3-A431	NO2	(2)	$60 + $75 (cell + electronics)	Alphasense Nitrogen Dioxide Sensors	(1)
O3	Electrochemical	SPEC	DGS-O3	O3	(2)	$150.00	SPEC DGS-O3 Product Page	
SO2	Electrochemical	Alphasense	SO2-B4 and SO2-A4	SO2	(2)	$60 + $75 (cell + electronics)	Alphasense Sulphur Dioxide Sensors	(1)
SO2	Electrochemical	SPEC	DGS-SO2	SO2	(2)	$150.00	SPEC DGS-SO2 Product Page	
H2S	Electrochemical	Alphasense	H2S-B4 and H2S-A4	H2S	(2)	$60 + $75 (cell + electronics)	Alphasense Sulphur Dioxide Sensors	(1)

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POLLUTANT	TYPE	MANUFACTURER	MODEL	POLLUTANTS	OTHER METRICS	COST	REFERENCE	EVALUATION LITERATURE
H2S	Electrochemical	SPEC	DGS-H2S	H2S	(2)	$150.00	SPEC DGS-H2S Product Page	
Respiratory Irritants	Electrochemical	SPEC	DGS-RESPIRR 968-041	NO2eq	-	$150.00	SPEC DGS-RESPIRR Product Page	
IAQ	Electrochemical	SPEC	DGS-IAQ	Combustion byproducts	-2	$150.00	SPEC DGS-IAQ Product Page	

(1) Relevant evaluation literature is too broad on the topic to be included in the table. See market review section for details.

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CO2 SENSORS

POLLUTANT	TYPE	MANUFACTURER	MODEL	POLLUTANTS	OTHER METRICS	COST	REFERENCE	EVALUATION LITERATURE
CO2	Photoacoustic	Sensirion	SCD41	CO2	-	$50.00	Sensirion SCD41 Product Page	10.1016/j.envint.2022.107372 10.1016/j.buildenv.2020.107415
CO2	NDIR	Sensirion	SCD30	CO2	-	$50.00	Sensirion SCD30 Product Page	10.1016/j.buildenv.2020.107415
CO2	NDIR	Winsen	MH-Z16	CO2	-	$73.00	Winsen MH-Z16 Product Page	
CO2	NDIR	Winsen	MH-Z19X	CO2	-	$17.50	Winsen MH-Z19X Product Page	10.1016/j.envint.2022.107372
CO2	NDIR	SenseAir	Sunlight CO2	CO2		$42.37	SenseAir Sunglight CO2 Product Page	
CO2	NDIR	SenseAir	K30	CO2	-	$61.35	SenseAir K30 Product Page	10.1016/j.buildenv.2020.107415
CO2	NDIR	SenseAir	S8	CO2	-	na	SenseAir S8 Product Page	10.1016/j.envint.2022.107372 10.5194/amt-13-3815-2020
CO2	NDIR	Wuhan Cubic	CM1106SL-N	CO2	-	na	Wuhan Cubic CM1106SL-N	
CO2	MEMS	Invensense	SmartEnviro	CO2	-	na	Invensense SmartEnviro	

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VOCs SENSORS

POLLUTANT	TYPE	MANUFACTURER	MODEL	POLLUTANTS	OTHER METRICS	COST	REFERENCE	EVALUATION LITERATURE
VOC	MOx	Sciosense	ENS160	tVOC, eCO2	(1)	$12.00	Sciosense ENS160 Product Page	
VOC	MOx	Sensirion	SGP40	tVOC, eCO2	(1)	$9.21	Sensirion SGP40 Product Page	
VOC	MOx	Winsen	ZP0X-MP503	TVOC	(1)	$2.50	Winsen ZP0X-MP503 Product Page	
VOC	MOx	Winsen	GM 502B	TVOC	(1)	$3.50	Winsen GM-502B Product Page	
VOC	MOx	Ogam Tech	GSBT1X-P110	TVOC	(1)	na	Ogam Tech GSBT1X Product Page	10.1155/2020/8749764
VOC	MOx	Wuhan Cubic	VM-1001	TVOC	(1)	na	Wuhan Cubic VM-1001 Product Page	
VOC	MOx	Figaro	TGS2602	TVOC	(1)	na	Figaro TGS2602 Product Page	10.5194/amt-12-1441-2019
VOC	MOx	MQ	MQ135	TVOC	(1)	na	na	
VOC	MOx	Fevas	QS-01	TVOC	(1)	na	na	
VOC	MOx	Renesas	ZMOD4410	TVOC	(1)	$5.37	Renesas ZMOD4410 Product Page	10.1016/j.envint.2022.107372
VOC	MOx	Dart	WZ-S	Formaldehyde	-	$13.50	Dart WZ-S Product Page	10.1016/j.buildenv.2022.109380
VOC	MOx	UST Umweltsensortechnik GmbH	GGS and UST	TVOC - Custom	(1)	na	UST GmbH GGS X330 Product Page	
VOC	Electrochemical	Alphasense	VOC-X4	TVOC	(1)	$130.00	Alphasense VOC-B4 Product Page	
VOC	Electrochemical	Winsen	ZE40B-TVOC	TVOC	(1)	na	Winsen ZE40B-TVOC Product Page	

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POLLUTANT	TYPE	MANUFACTURER	MODEL	POLLUTANTS	OTHER METRICS	COST	REFERENCE	EVALUATION LITERATURE
VOC	Electrochemical	Winsen	ZE30-C2H5OH	Alcohol	-	$20.00	Winsen ZE30 Product Page	
VOC	Electrochemical	Sensirion	SFA30	Formaldehyde	-	$52.00	Sensirion SFA30 Product Page	
VOC	Electrochemical	Wuhan Cubic	CB-HCHO-V4	Formaldehyde	-	na	Wuhan Cubic CB-HCHO-V4 Product Page	
VOC	Electrochemical	SGX Sensortech	PS1-HCHO-5	Formaldehyde	-	$56.87	SGX PS1 HCHO5 Product Page	
VOC	PID	Alphasense	PID-AXX	TVOC	(1)	$415.00	Alphasense PID Sensor Product Page	
VOC	PID	Baseline	piD-TECH eVx	TVOC	(1)	na	Baseline piD-TECH Product Page	
VOC	PID	Baseline	VOC-TRAQ II	TVOC	(1)	na	Baseline VOC-TRAQ II Product Page	

(1): All these sensors are, in general, broadband sensors that will be sensitive to VOCs and other non-target pollutants.

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RADON

POLLUTANT	TYPE	MANUFACTURER	MODEL	POLLUTANTS	OTHER METRICS	COST	REFERENCE	EVALUATION LITERATURE
Radon	Photodiode detection for alpha particles	Teviso	RN53	Radon	-	na	Product Datasheet	
Radon	Pulsed Ion chamber	FTLab	RD200M	Radon	-	(1)	FTLab RD200M radon sensor	10.3390/su14031529
Radon	Phototransistor detection of alpha particles	Nuvap	NXRADON	Radon	-	na	Nuvap OEM Radon Sensor	
Radon	Passive Diffusion Chamber	Airthings	Wave Rdon	Radon	-	$200	Airthings Wave Radon	10.3390/su14031529
Radon						$870	Tesla TSRS / TSRS2 Product Page	Tunyagi et al.
Radon	Passive Detectors	Various providers	-	Radon	-	(2)	-	

(1): This sensor is not openly available for commercial purchase, but other options integrating it have costs of $200 and $400.

(2): Potentially lower than $200, although unclear if it includes laboratory analysis.

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