

## Article

# Reliability and Performance Evaluation of IoT-Based Gas Leakage Detection Systems for Residential Environments

Elia Landi , Lorenzo Parri, David Baldo, Stefano Parrino, Tunahan Vatansever, Ada Fort , Marco Mugnaini and Valerio Vignoli \* 

Department of Information Engineering, University of Siena, Via Roma 56, 53100 Siena, Italy; elia.land@unisi.it (E.L.); lorenzo.parri@unisi.it (L.P.); david.baldo@unisi.it (D.B.); stefano.parrino@unisi.it (S.P.); t.vatansever@student.unisi.it (T.V.); ada.fort@unisi.it (A.F.); marco.mugnaini@unisi.it (M.M.)

\* Correspondence: valerio.vignoli@unisi.it

## Abstract

This paper presents the reliability assessment of an IoT-based sensor node designed for detecting combustible gas leaks in residential environments. Building on a previously published design that integrates low-power micromachined (Micro-Electro-Mechanical Systems, MEMS) pellistors and electrochemical Volatile Organic Compounds (VOC) sensors, this study evaluates the node's long-term robustness and stability under both realistic and accelerated operating conditions. The system employs a dual-sensor strategy in which the VOC sensor acts as a sentinel, activating the pellistor only when necessary, thereby optimizing power consumption and extending battery life. BLE and LoRa communication capabilities support flexible deployment and real-time data transmission. To ensure suitability for safety-critical applications, we conducted comprehensive reliability testing, including accelerated life tests and environmental stress testing in compliance with IEC 60068 standards. The results confirm the system's ability to maintain consistent performance and data integrity under thermal, mechanical, and chemical stress, demonstrating its robustness for prolonged operation in demanding environments. Overall, this work underscores the importance of rigorous reliability validation for IoT-based safety devices and positions the proposed solution as a significant step toward enhancing residential gas safety, with potential applications in broader industrial monitoring scenarios.

**Keywords:** gas monitoring; IoT systems; gas leakage; LoRa connectivity; BLE; IoT; reliability assessment



Academic Editor: Bo Zhang

Received: 30 July 2025

Revised: 19 September 2025

Accepted: 22 September 2025

Published: 25 September 2025

**Citation:** Landi, E.; Parri, L.; Baldo, D.; Parrino, S.; Vatansever, T.; Fort, A.; Mugnaini, M.; Vignoli, V. Reliability and Performance Evaluation of IoT-Based Gas Leakage Detection Systems for Residential Environments. *Electronics* **2025**, *14*, 3798. <https://doi.org/10.3390/electronics14193798>

**Copyright:** © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Combustible gases are not only prevalent in industrial environments but are also widely used in residential settings, where they serve as fuel for essential household appliances such as stoves, water heaters, and furnaces. Natural gas, propane, and methane are among the most commonly utilized gases for domestic heating, cooking, and lighting applications worldwide. While these gases offer considerable advantages in terms of energy efficiency and convenience, their presence introduces significant safety hazards if not adequately monitored and controlled. A primary concern associated with the residential use of combustible gases is the risk of leakage. Gas leaks may result from defective appliances, aging infrastructure, improper installation, or accidental damage to gas lines. Unlike many other environmental pollutants, gas leaks are often odorless and invisible, rendering them difficult to detect without the use of specialized sensors or monitoring systems.

Undetected leaks can lead to severe consequences, including structural damage, fires, and explosions. In enclosed spaces, the accumulation of combustible gases creates a highly flammable atmosphere in which even a minor ignition source can trigger catastrophic events. Additionally, prolonged exposure to elevated concentrations of these gases can cause asphyxiation or toxic effects, posing serious health risks and potentially leading to fatalities among residents [1,2]. Finally, the risks associated with gas leaks extend beyond individual households to the broader community and environment. Escaping gases contribute to air pollution and greenhouse gas emissions, exacerbating climate change and environmental degradation [3]. In densely populated urban environments, the potential for widespread harm and disruption resulting from gas-related incidents highlights the urgent need for robust monitoring and mitigation strategies. The severity of these risks necessitates a comprehensive approach to residential gas safety, integrating preventive maintenance, strict adherence to regulatory standards, and the adoption of advanced monitoring technologies.

In this context, Internet of Things (IoT) devices play a critical role by enabling real-time detection, alerting, and remote surveillance of gas systems. These capabilities allow both homeowners and relevant authorities to respond rapidly and effectively to emerging hazards. The deployment of IoT-based gas detection systems within residential settings significantly enhances safety, reduces the likelihood of accidents, and protects both human lives and physical assets from the dangers associated with combustible gas leaks. To achieve meaningful risk reduction, it is essential to combine technological innovation with public awareness initiatives and regulatory enforcement. Promoting the widespread implementation of effective, IoT-driven safety solutions is imperative for mitigating the risks linked to residential gas usage and fostering a safer, more resilient, and sustainable living environment.

Domestic fuel gases, including methane, natural gas, and liquefied petroleum gas (LPG), lack any inherent odor, making unintentional leaks potentially hazardous. To enhance safety and facilitate leak detection, gas providers deliberately introduce odorants, typically volatile organosulfur compounds such as tert-butyl mercaptan (TBM), ethanethiol, or tetrahydrothiophene (THT). These substances produce a strong, distinctive smell that serves as an early warning indicator, allowing users to recognize the presence of leaked gas before dangerous concentrations are reached [3–6].

While this odorization strategy provides a basic layer of safety, it does not ensure comprehensive protection within residential environments. To substantially elevate safety standards, the deployment of reliable and automated Gas Leakage Detection (GLD) systems is essential. Fixed GLD units, commonly installed in LPG and methane facilities, are capable of detecting gas concentrations in the range of 10–20% of the Lower Explosive Limit (LEL) [7–11]. These systems can rapidly notify users or centralized monitoring infrastructures upon leak detection. However, such systems typically rely on pellistor-based sensors, which are power-intensive and therefore unsuitable for integration into domestic appliances without targeted technological adaptations [12,13].

In addition to effective sensing, GLD systems deployed in residential settings must also exhibit high reliability and operate continuously without fault under real-world conditions [8,14]. For this reason, it is essential to plan a series of life tests to verify design compliance with the product intrinsic specifications. Product lifespan is often not evaluated in the actual operating environment, which can lead to a high number of failures once deployed. To avoid this scenario, which can be very damaging to the image of a manufacturer of widely distributed technological goods, it is possible to plan a series of environmental tests on prototype versions of the product that adhere closely to the operational scenario. Such tests for electronic devices are regulated by the IEC 60068 standard

and its various appendices related to different types of thermal and environmental tests. The purpose of these tests is to verify that the preliminary reliability study, which relies on purely statistical means, can, in some way, be validated with predictions confirmed on a limited set of products. However, these tests, if conducted in the operational environment of the design, are unlikely to detect long-term defects and therefore may not provide a meaningful reliability assessment. To address this, a series of tests with acceleration factors that account for the equivalent test hours the product is exposed to can be performed. This methodology allows components, subsystems, and systems to be stressed to gather information about the actual malfunction statistics of the product. The main challenge in this context is designing acceleration factors that do not trigger failure modes dependent on other operating parameters. These test sessions follow standard product reliability evaluation techniques [15–18] and aim to correct the statistics that an analysis, generally based on databases, might present as credible data for a product or class of products whose application field differs significantly from what is observed in reality.

Recent contributions further highlight this need by surveying advances in gas-sensor technologies and IoT-based detection systems. A 2024 comprehensive review provides an overview of catalytic, electrochemical, Metal Oxide sensors (MOX), and Non Dispersive Infra-Red (NDIR) devices, with emphasis on power consumption, selectivity, and long-term stability [19]. At the same time, IoT-oriented studies have explored low-power architectures and novel sensing solutions, including light-powered NDIR detectors [20], multi-hop LoRaWAN networks for distributed monitoring [21], and industrial deployments of MOX-based methane sensing [22]. Recent industrial efforts have also produced ultra-low-power MEMS-type MOX sensors such as the Figaro TGS8410 [23], showing that hybrid strategies for balancing energy efficiency and reliability are becoming increasingly viable.

In this work, we build on these advances by presenting a hybrid IoT-based sensing node for domestic combustible gas leak monitoring that integrates a low-power electrochemical VOC sentinel with an on-demand MEMS pellistor channel [24]. Our perspective differs from most prior studies in that we complement system design with a structured reliability assessment, combining accelerated testing and failure-rate modeling to evaluate robustness under realistic stress conditions.

To the best of the authors' knowledge, none of the recent works on the same topic adopt this reliability-driven viewpoint. IoT gas-leak detection systems are rarely accompanied by reliability studies that validate the suitability of the chosen sensors and technologies for long-term operation. By contrast, our results demonstrate that the selected components are not only functional but also appropriate for safety-critical deployment.

The proposed sensor nodes integrate advanced technologies, including commercial pellistor sensors fabricated on micromachined membranes, which offer reduced power consumption and rapid activation times [25,26]. In addition, each node incorporates a commercial low-power sensor for VOCs, capable of detecting odorant substances commonly added to domestic gases. This configuration enables continuous environmental monitoring through the VOC sensor. When the concentration of odorizing agents exceeds a predefined threshold, the system activates the pellistor sensor to perform a targeted combustible gas measurement. Notably, the pellistor requires only 300 milliseconds to power up and deliver a reliable detection result [27]. This dual-sensing strategy ensures continuous surveillance of residential gas environments while optimizing power efficiency and maintaining high responsiveness to potential leaks. The Internet of Things (IoT)-enabled sensor node is equipped with both LoRa (Long Range) and Bluetooth Low Energy (BLE) communication interfaces, supporting deployment in scalable monitoring networks—such as those spanning entire buildings—as well as enabling direct, localized data access via devices such as smartphones [27,28]. The system also integrates environmental sensors for temperature

and humidity monitoring, further enhancing contextual awareness. A reliability model for the sensor node is proposed in this work and can be extended to other sensing systems having the same operational structure. Experimental validation for the proposed model has been performed by exploiting different node samples under accelerated life cycles tests.

Beyond the hardware aspects, the novelty of this study lies in the methodological approach: we emphasize that IoT-based devices for domestic gas safety must not only demonstrate functionality but also undergo structured testing and reliability evaluation as part of their qualification. Accordingly, we combine system-level reliability modeling (MIL-HDBK-217F N2 and ANSI/VITA 51.1), accelerated environmental testing with controlled RH, and comparative analysis against alternative sensing stacks. This framework represents a reproducible path for qualifying safety-critical IoT nodes, complementing the growing focus on sensor innovation with an equally important emphasis on robustness and long-term reliability.

The paper is organized as follows. Section 2 reviews related work, highlighting recent research trends on combustible gas detection that go beyond individual sensor technologies and increasingly focus on IoT-based architectures. In Section 3 the sensor node is briefly described showing the architecture and the sensors used. Section 4 reports the characterization of the sensor node in terms of power consumption and gas measurement performances. In Section 5 the reliability model of the node together with simulation results is reported and in Section 6 experimental results assessing the node reliability are shown. Finally, Section 7 presents the conclusions.

## 2. Related Work

Recent studies have increasingly focused not only on individual gas-sensor technologies but on architectures for combustible gas leak monitoring in residential and industrial environments. Panda et al. [19] provide a comprehensive review of catalytic, electrochemical, MOX, and NDIR sensors, framing their suitability for safety applications where energy efficiency and long-term stability are critical. While this survey spans multiple sensing principles, its discussion highlights the constraints faced when embedding sensors into IoT nodes intended for domestic gas safety.

Several 2024–2025 works [20–22,29] propose IoT-based system architectures for leak detection. Babu and Nair [29] designed an IoT-enabled gas-leak detection framework combining low-power embedded devices with cloud integration, targeting residential safety. Alhomyani et al. [21] analyzed LoRaWAN-based multi-hop topologies for pipeline monitoring, showing how network-level design directly impacts energy consumption and reliability—an issue equally relevant for scalable deployments in homes or apartment buildings.

At the sensing node level, Rivera-Martinez et al. [22] demonstrated methane quantification using MOX sensors in controlled industrial leak scenarios, discussing the challenges of humidity sensitivity and heater power demand that limit their domestic applicability. In parallel, Fleming et al. [20] introduced a light-powered, battery-less NDIR methane detector, which, while technologically advanced, illustrates the difficulty of reconciling optical specificity with strict domestic energy budgets. From the industrial side, manufacturers have begun offering pulsed MEMS-based MOX sensors, such as the Figaro TGS8410 [23], which achieve sub-0.1 mW average consumption and therefore open new design opportunities for battery-operated combustible gas detectors.

Together, these contributions show that the current research trend is moving beyond single-sensor development toward integrated IoT architectures for leak detection, balancing sensing accuracy, network efficiency, and energy constraints. However, despite these

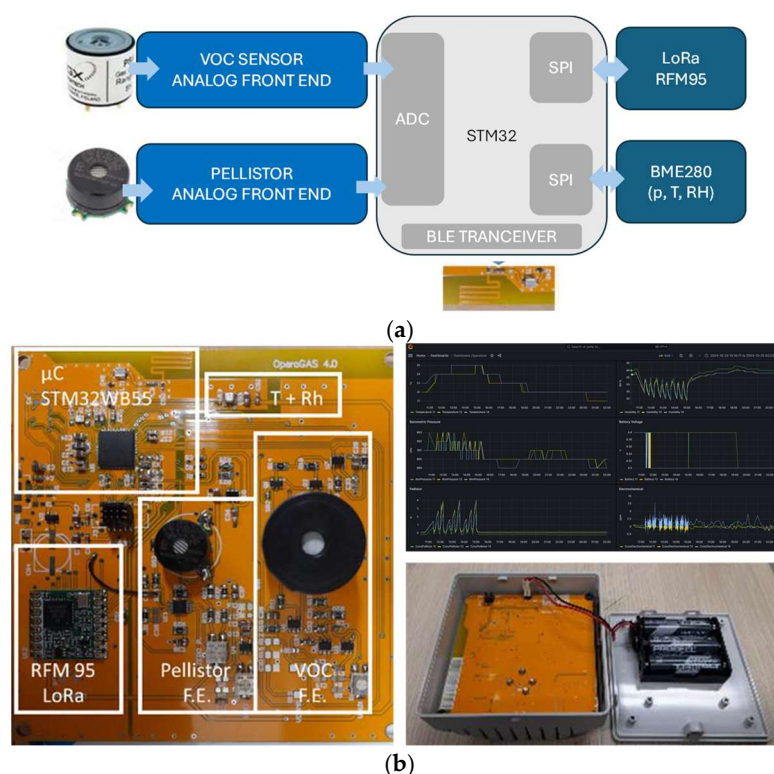
advances, few works explicitly address long-term reliability and robustness validation of such nodes in realistic conditions, an aspect that is central to the present study.

### 3. Sensing System Description

The developed sensor node, shown in Figure 1, is an in-house solution for monitoring methane (or other combustible gases) and VOC concentrations [27], designed to operate within IoT networks. The node integrates two complementary sensing channels: a duty-cycled MEMS pellistor for confirmatory detection of combustible gases and an electrochemical VOC sensor that acts as a sentinel for the odorants typically added to domestic methane or LPG. The integration choices were driven by power consumption, time-to-decision, and field robustness. The node sensor-integration design considered all the aspects summarized in Table 1.

As summarized in Table 1 and to the best of our knowledge, there are currently no commercial electrochemical sensors specifically designed for methane ( $\text{CH}_4$ ). This is the reason why the designed node needs to host also a more power-hungry sensor to confirm methane presence.

The table summarizes why we adopted a hybrid strategy: a low-power VOC sentinel that runs continuously and an on-demand MEMS pellistor that provides a safety-grade combustible-gas confirmation with  $<0.5$  s warm-up. NDIR remains the best performer in terms of chemical specificity, but the energy and cost envelopes are less favorable for battery nodes unless transmissions are very sparse and the optical train is highly optimized. MOX is attractive for very low Bill of Materials (BOM) systems, yet its continuous heater makes it less battery-friendly unless heavily duty-cycled, and baseline drift in humid conditions raises maintenance overhead. In contrast, the VOC-plus-pellistor split keeps average current low and reserves high power consumptions (also in terms of transmissions) for exceptional events, which is aligned with multi-month battery targets as reported in Section 4.



**Figure 1.** (a) Schematic and (b) photo of the developed sensor node and dashboard.

**Table 1.** Comparative view of methane-detection options for battery IoT nodes comprising a VOC sentinel. In the table AFE stands for Analog Front End.

| Aspect                         | MEMS Pellistor (Catalytic)                                          | MOX (Metal-Oxide)                                                                                            | NDIR (Infrared Absorption)                                                                                         | Electrochemical “VOC Sentinel”                               |
|--------------------------------|---------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------|
| Primary role in our node       | Safety-grade confirmation of combustible gas (CH <sub>4</sub> /LPG) | Alternative low-cost CH <sub>4</sub> detection (pulsed/continuous heater)                                    | High-specificity CH <sub>4</sub> channel (if power budget allows)                                                  | Early warning on odorants; triggers confirmation             |
| Sensing principle              | Catalytic oxidation heats active bead; $\Delta R \propto$ gas       | Surface chemisorption modifies conductivity                                                                  | Optical absorption @ CH <sub>4</sub> bands (e.g., 3.3–3.4 $\mu$ m or 4.26 $\mu$ m CO <sub>2</sub> line management) | Amperometric redox (odorant VOCs, e.g., mercaptans)          |
| Warm-up                        | Fast on MEMS: $\approx$ 0.3–0.4 s to stable read                    | heater stabilization seconds to minutes for traditional, tens of ms for those deposited over micromembranes. | Essentially none for detector, source warm-up tens to hundreds ms                                                  | None (always on)                                             |
| Typical power                  | Hundreds of mW continuous, tens of mW pulsed                        | Hundreds of mW continuous, tens of mW pulsed                                                                 | Tens–hundreds mW (source + detector)                                                                               | Very low ( $\mu$ W–mW)                                       |
| Selectivity to CH <sub>4</sub> | Good for LEL-grading, non-specific chemically                       | Moderate; cross-sensitive to humidity and other gases                                                        | High with proper filters/path length                                                                               | Targets odorants, not CH <sub>4</sub> itself                 |
| Cross-sensitivities            | Other combustibles; O <sub>2</sub> dependence                       | Humidity/temperature; other VOCs                                                                             | Window contamination; H <sub>2</sub> O/CO <sub>2</sub> spectral overlaps manageable                                | Broad VOCs (mercaptans/alcohols); design threshold carefully |
| Dynamic range                  | Wide (sub-% LEL to >100% LEL)                                       | Wide but prone to baseline drift                                                                             | Wide; linear by Beer–Lambert                                                                                       | Suited to ppb–ppm odorants                                   |
| Response (T90)                 | Seconds (chemical response)                                         | Minutes (chemical response)                                                                                  | Sub-second to seconds (optics/averaging)                                                                           | Seconds (electrochem/conditioning)                           |
| Calibration and stability      | Needs bench calibration; periodic span check                        | Drift over time; periodic re-zeroing                                                                         | Stable; occasional optical zero/span                                                                               | Factory cal usable; baseline adapt + hygiene rules           |
| Bill of Materials              | Low; simple AFE + heater drive                                      | Very low; single AFE, but heater power                                                                       | Higher (optics, filters, enclosure)                                                                                | Low; low-power AFE                                           |
| Battery suitability            | Excellent with duty-cycle (as in this work)                         | Fair to good (depends on duty-cycle/heater)                                                                  | Challenging unless extremely sparse duty-cycle                                                                     | Excellent (continuous sentinel)                              |
| Best use                       | Confirmatory safety measurement and LEL logic                       | Low-cost continuous presence sensing                                                                         | High-specificity CH <sub>4</sub> quantification                                                                    | Trigger for on-demand confirmation                           |

In our deployment model the sentinel-then-confirm policy reduces false positives and avoids running the catalytic channel continuously, which would dominate the energy budget. The decision thresholds derive from the VOC statistics and a conservative mapping between odorant levels and sub-LEL gas mixtures. When a trigger occurs, the node performs a short catalytic check and, if 10% LEL is reached, start to transmits LoRa packets; otherwise it logs the event and returns to idle BLE advertising. This staged logic matches the physical behavior of domestic leaks (slow accumulation, intermittency) while keeping the node responsive and battery-efficient.

The VOC sensor used is a three-electrode electrochemical amperometric device (PS4-VOC series, SGX Sensortech, Corcelles-Cormondreche 1, Switzerland), available in 10 ppm and 200 ppm full-scale variants. It operates via redox reactions at the working electrode, with a counter electrode completing the electrochemical circuit and a reference electrode ensuring stable operation. This technology is particularly well-suited for low-power applications, as its current consumption is minimal and continuous monitoring is feasible.

For methane detection, a MEMS-based pellistor (MP7227-DA, SGX Sensortech) is adopted. This device employs micromachined diaphragms with integrated catalytic and inert resistive elements. Compared to conventional pellistors, it offers faster warm-up times (~300 ms vs. 15 s) and reduced energy consumption. The node supports data transmission via both BLE and LoRa, enabling integration into distributed monitoring systems. At its core is the STM32WB55 microcontroller (STMicroelectronics, Plan-les-Ouates, Switzerland), a low-power unit with embedded BLE capabilities. The board integrates analog front-end circuits for both the VOC and methane sensors, alongside peripherals for humidity and temperature sensing (BME280, Bosch, Gerlingen, Germany) and LoRa communication through an RFM95 transceiver. Data can be transmitted via BLE advertising packets or LoRa messages to a remote gateway.

The node electronics are optimized for pulsed operation: a low-dropout regulator (ADP3331) enables quick activation, and a low-power instrumentation amplifier (AD8553) conditions the sensor output. Power management is designed to accommodate various battery types (rechargeable lithium, lithium-thionyl chloride, or AA alkaline cells), with regulated voltage supplies for both analog and digital sections. Battery health is monitored continuously for diagnostics.

As already mentioned, the system implements an energy-saving strategy by using the VOC sensor as a sentinel: if VOC levels exceed a preset threshold, the pellistor is activated to verify the presence of combustible gases. The node supports three operation modes:

- Idle mode: continuous VOC monitoring and BLE data transmission.
- Explosive gas monitoring: periodic pellistor activation (once per minute) and VOC sensing at 1 Hz.
- LoRa transmission mode: averaged sensor data and environmental parameters sent via LoRa.

Transitions between modes are automatic. The node remains in idle mode until VOC concentrations rise above threshold; it then activates the pellistor. If gas levels reach 10% of the Lower Explosive Limit (LEL), LoRa transmission is triggered for alerting. Independently, diagnostic data are sent over LoRa every 12 h.

The MEMS pellistor is operated in short bursts to minimize energy consumption: a programmable pre-heat (set to 400 ms in the deployed nodes) is followed by a 100 ms measurement window. During heating the sensor draws  $\approx 45$  mA @ 3 V, which is acceptable because the duty cycle in “explosive-gas monitoring” is low (e.g., one activation per minute unless the VOC sentinel requests immediate confirmation). The electrochemical VOC channel runs continuously at very low current. Its role is to detect odorized mixtures early and call the pellistor only when warranted. We implemented a baseline-adaptive

threshold: the firmware estimates a running baseline over clean-air segments and triggers when the signal exceeds  $\mu_0 + k \cdot \sigma_0$  ( $\mu_0$  average,  $\sigma_0$  standard deviation) with  $k \approx 3$  or when a sustained slope persists for more than 2–3 s. This policy was tuned using the repeatability data in Table 4 (VOC responses at 0.47–1.41% LPG) to ensure triggering well below LEL while minimizing false activations from short VOC bursts (e.g., kitchen aerosols). Because the pellistor readout is referenced to a short, fixed window after thermal equilibrium, the combined decision is robust to slow ambient drifts.

The overall monitoring architecture consists of several nodes communicating with a LoRa gateway connected to a cloud server. The nodes can also be read using BLE by local readers, e.g., smartphones. In detail, the nodes periodically transmitted the sampled data, together with diagnostic information (e.g., battery voltage level), with LoRaWAN network protocol. Afterwards, the gateway forwarded the packets to the remote LoRaWAN server hosted on a cloud, using an UDP protocol (Semtech UDP Packet Forwarder). The LoRaWAN server was in charge of decoding and decrypting the packets to retrieve the transmitted information and of sending it to a JavaScriptbased back-end for processing. The LoRaWAN server used in this project was the open source Chirpstack server. Data are stored on a SQL database implemented with PostgreSQL, together with some radio channel indicators (e.g., RSSI, SNR). The data were finally available for user visualization and exporting on a dashboard realized on the Grafana environment (see Figure 1b).

#### 4. Sensor Node Characterization

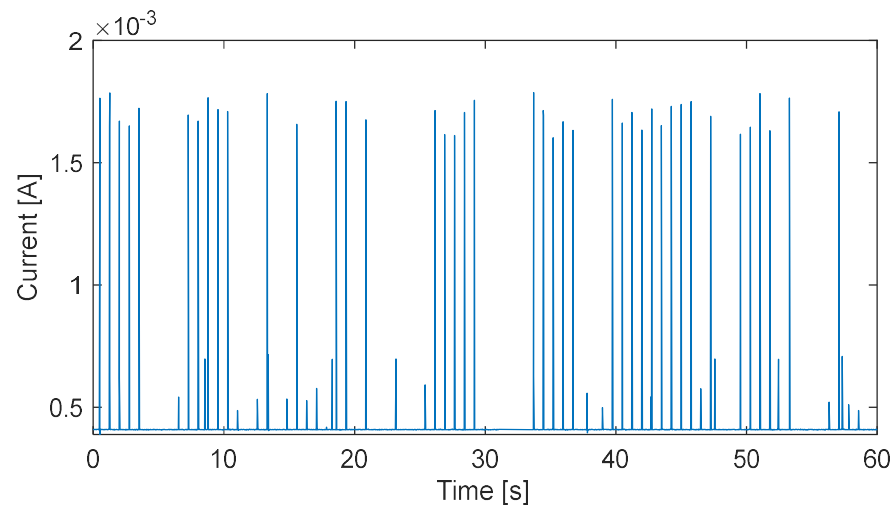
The proposed sensor node was characterized through analysis and experiments, in terms of power consumption in the three operation modes, in terms of gas sensing performance (results are reported in this section) and finally in terms of reliability (results are described in the following section). The experimental characterization was performed on three different sensor nodes.

##### 4.1. Power Consumption Analysis

As already mentioned, the power consumption analysis was conducted by considering the three possible operating modes: idle, explosive gas monitoring and LoRa transmission modes. Measurements have been taken to assess the current drawn by the node when supplied with 4.5 V, simulating the conditions of alkaline battery power. The current consumption of the node was measured using a Keithley (Cleveland, OH, USA) DMM7510 digital multimeter connected in series between the laboratory power supply emulating the battery (TTi EL302T, Huntingdon, UK) and the power input of the sensor node, i.e., before the linear regulator that powers the board. This configuration allows accurate monitoring of the total current profile of the device. The DMM7510 was selected because it supports acquisition up to 1 MS/s at 18-bit resolution and is specifically designed for low-power device characterization, including accurate measurement of sleep-mode consumption through its lower range of 10  $\mu$ A and its autoranging capability.

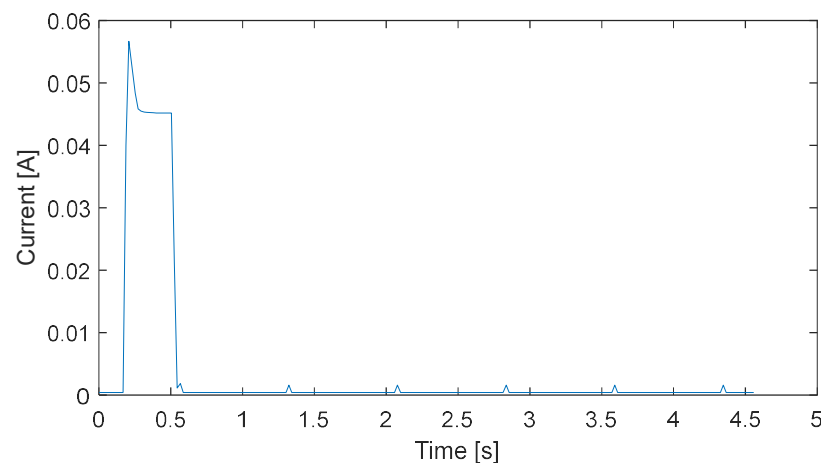
In our configuration, BLE transmission is handled by the embedded radio of the STM32WB55 (STMicroelectronics) microcontroller, which periodically sends an advertising packet every 1.28 s. Under these conditions, the BLE peripheral consumes only about 13  $\mu$ A on average.

Figure 2 shows the sensor node current consumption in idle mode. The spikes are due to BLE data transmission (different heights are due to the sampling used in the figure). The average power consumption in idle mode is 437  $\mu$ A with a standard deviation of 183  $\mu$ A. This includes also the consumption of the VOC electronic front end and the signal acquisition.



**Figure 2.** Current consumption in idle mode (4.5 V supply voltage).

In explosive gas monitoring mode, whose current consumption behavior is reported in Figure 3, the average current drawn by the node is 707  $\mu\text{A}$  (500  $\mu\text{s}$  pellistor ON each 1 min, pre-heat 400 ms, measurement 100 ms). This is given by the reading phase of the pellistor, highlighted by the current peak represented in Figure 3.



**Figure 3.** Current consumption in explosive gas monitoring mode (4.5 V supply voltage). Test performed with VOC threshold set to zero, so that the pellistor was activated at every acquisition cycle.

LoRa communication is managed by the external RFM95 module, which remains in sleep mode (0.2  $\mu\text{A}$ ) when idle. Each active transmission, including wake-up and packet transfer, lasts about 4 s with an average current of 14 mA. Since LoRa messages are transmitted only once every 12 h, provided that the pellistor measurement remains below the preset threshold, the impact of LoRa on the overall energy budget is negligible compared to the continuous but ultra-low-power BLE operation. Regarding the LoRa transmission frequency in emergency mode, when the pellistor measurement exceeds the preset threshold (gas leakage event), a LoRa packet is transmitted every minute (or faster) to ensure timely reporting of the alarm condition.

Table 2 reports the battery life in the different operating scenario. It can be seen that the nodes life in idle mode can extend to 22 months while it is 14 months when used in explosive gas monitoring mode (1 measurement per minute), thus proving as the VOC ‘sentinel’ strategy can effectively extend the node battery life. When used in data transmission mode continuously, with high transmission rates, obviously, the node life is

extremely reduced. However, the node operates continuously in LoRa data transmission only in case of emergency situations, which require immediate intervention.

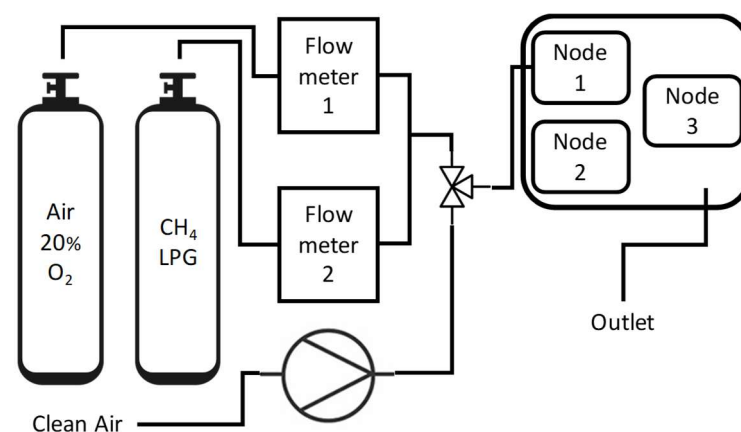
**Table 2.** Battery life comparison in different operating scenario.

| Battery                 | Nominal Voltage and Capacity | Idle Mode (h) | Explosive Gas Monitoring (Continuous: One Measurement per Minute) (h) | LoRa Data Transmission (Continuous: One Transmission per Minute) (h) |
|-------------------------|------------------------------|---------------|-----------------------------------------------------------------------|----------------------------------------------------------------------|
| 3S Alkaline             | 4.5 V,<br>2412 mAh           | 5500          | 3400                                                                  | 172                                                                  |
| 3P Li-SOCl <sub>2</sub> | 3.6 V,<br>7200 mAh           | 16,400        | 10,100                                                                | 514                                                                  |

#### 4.2. Gas Sensing Performance

The gas sensing performance of the nodes were assessed by using an ad hoc automated test bench, in which gas flows from certified gas cylinders were mixed with precision flow meters to create specific gas mixtures. These mixtures were used both to calibrate the pellistor sensor and to evaluate the effectiveness of the VOC sensor as a sentinel for the presence of odorized combustible gases.

The block diagram of the test bench is reported in Figure 4. A diaphragm pump is used to clean the measurement chamber after each gas measurement phase. Data from the sensor node was acquired on a PC via BLE communication. The three sensor nodes were tested simultaneously in a dedicated chamber. A certified cylinder of methane (80% *v/v* in nitrogen) and a commercial cylinder of liquefied petroleum gas (LPG), composed of propane and butane and odorized with mercaptans were used to obtain the test gas mixtures. The gases from the cylinders were diluted with synthetic air using precision flow meters to obtain various concentrations of methane and LPG below their LELs, with a maximum value of 1.8% *v/v* injecting in the test chamber a constant flow (500 mL/min).



**Figure 4.** Gas mixing test bench block diagram.

As far as the methane mixtures used for calibration are concerned, these were obtained using certified cylinders of methane in synthetic air, combined with precision, validated flow meters to ensure accuracy and reproducibility of the injected concentrations, with uncertainty below 5%. Calibration of pellistor sensors was therefore validated against traceable reference standards.

The cross-sensitivity was evaluated using the specifications provided by the sensor manufacturers for the main interfering gases. In practice, cross-sensitivity is considered a secondary concern in this application, since the priority is to avoid false negative alarms.

The catalytic methane sensor is intrinsically selective toward combustible gases, thereby providing a high degree of specificity. Conversely, the electrochemical VOC sensor has a broad response spectrum by design, but this is not a limitation in our framework: it only serves as a sentinel trigger to wake the catalytic channel, which then performs a selective confirmation. This two-stage strategy minimizes the likelihood of false negatives while making cross-sensitivity effects negligible for the system intended use.

The test bench was designed not only to deliver traceable concentrations of methane and LPG but also to allow the simultaneous evaluation of three nodes. To this end, a large-volume chamber was used, in which gas was purged by a diaphragm pump and uniformly distributed by an internal ventilation system. This configuration reduced stabilization times and ensured homogeneous exposure conditions, improving reproducibility across repeated measurements.

Tests were performed on three identical sensor nodes ( $n = 3$ ). For each concentration step, 10 repeated measurement cycles were carried out. The test chamber had a volume of 10 L, with gas flows of 500 mL/min for mixing and over 2 L/min during purge phases using the diaphragm pump. For data analysis, we report mean values  $\pm$  standard deviation. Given the limited sample size ( $n = 3$  devices), descriptive statistics and raw data summaries are provided to avoid over-interpretation of statistical significance.

Calibration has been performed as described in [24] using a second order polynomial function:

$$c_t = f(c_m) = a_1 c_m^2 + a_2 c_m + a_3 \quad (1)$$

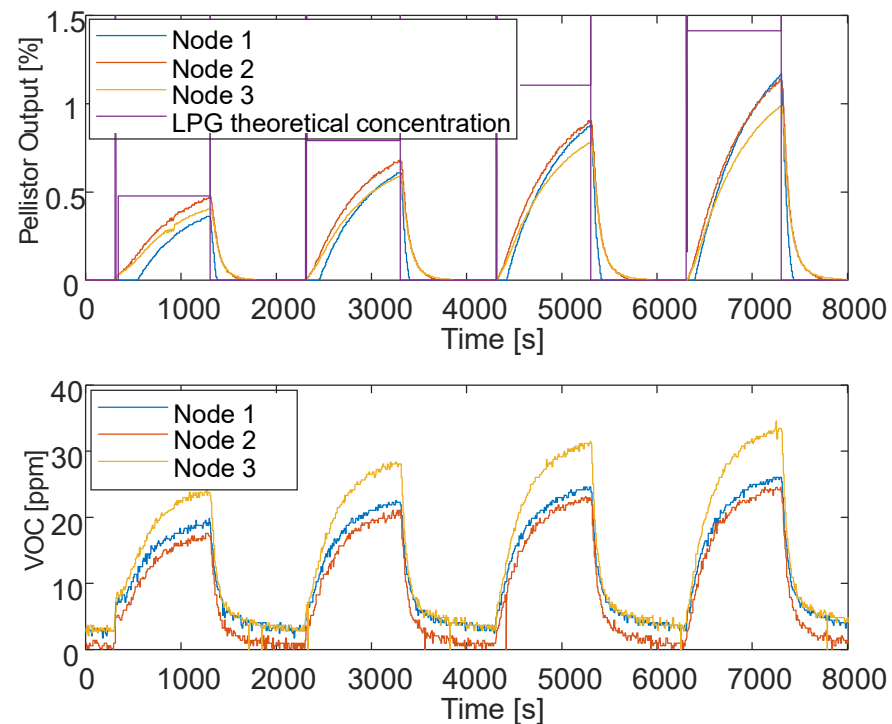
where  $c_m$  represents the measured value of methane concentration expressed in % vol/vol obtained exploiting the nominal sensitivity given by the manufacturer for continuous operation, whereas  $c_t$  represents the calibrated concentration measurement.

Subsequently, the response to LPG mixtures was analyzed to characterize the efficacy of the VOC “sentinel” strategy. Three nodes were tested by injecting into the measurement chamber a flow of synthetic air (500 mL/min) with four different percentages of gas from the LPG cylinder. Specifically, the tests involved a cycle of four phases with increasing LPG concentrations (0.47%, 0.79%, 1.10%, 1.41%), each followed by a chamber cleaning phase. While the calibration curves described in Equation (1) and Table 3 were used for the pellistor outputs, the electrochemical VOC sensors were evaluated using the factory calibration coefficients.

**Table 3.** Calibration coefficients for the three sensor nodes when the concentrations are expressed in % vol/vol.

| Sensor Node | $a_1$ | $a_2$ | $a_3$  |
|-------------|-------|-------|--------|
| 1           | 0.031 | 0.496 | −0.062 |
| 2           | 0.025 | 0.449 | −0.029 |
| 3           | 0.069 | 1.464 | 0.252  |

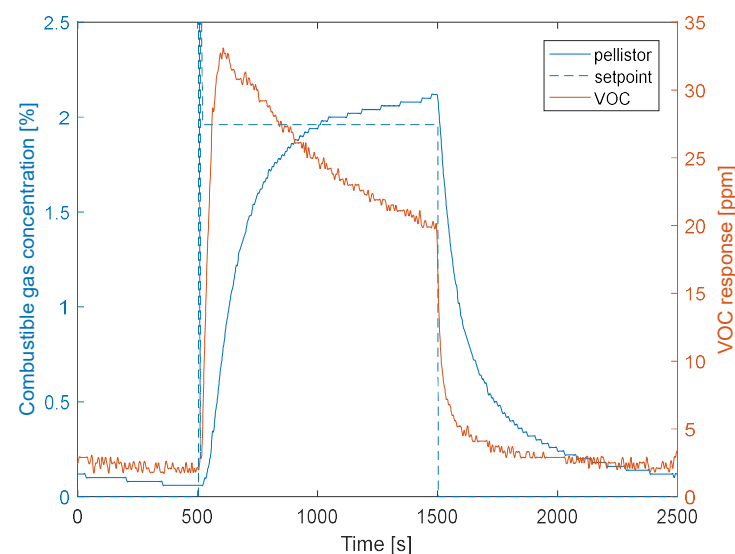
Figure 5 shows the sensor responses during a measurement cycle. For the VOC sensors, the responses at different LPG concentrations are prompt and clearly distinguishable from noise, even during the gas pulse with the lowest concentration, which corresponds to a combustible gas concentration well below the LEL. Based on the observed signal-to-noise ratio, the limit of detection (LOD) of the VOC channel was estimated at about 3 ppm on the sensor’s scale. In the present experiments this corresponds to a combustible gas concentration below 0.1% v/v, i.e., less than 10% of the LEL.



**Figure 5.** Pellistor and electrochemical VOC sensor outputs during one measurement cycle.

It can also be observed that the signals do not reach the steady state; this is due to the relatively large size of the measurement chamber (used to test three systems simultaneously), which is not completely filled during each measurement phase. The chamber volume is 10 L and the gas flow rate is 500 mL/min, as limited by the available flow meters. Faster recovery phases are observed because, during the purge, the flow is driven by the diaphragm pump, which provides much higher flow rates.

The dynamic behavior of the sensors in a smaller, faster chamber is shown in Figure 6, where it can be seen that the response time of the VOC sensor is actually much shorter than that of the pellistor (less than one minute for a 10–90% step). Therefore, the dynamics of the VOC sensor are not the limiting factor for the promptness of the alarm system.



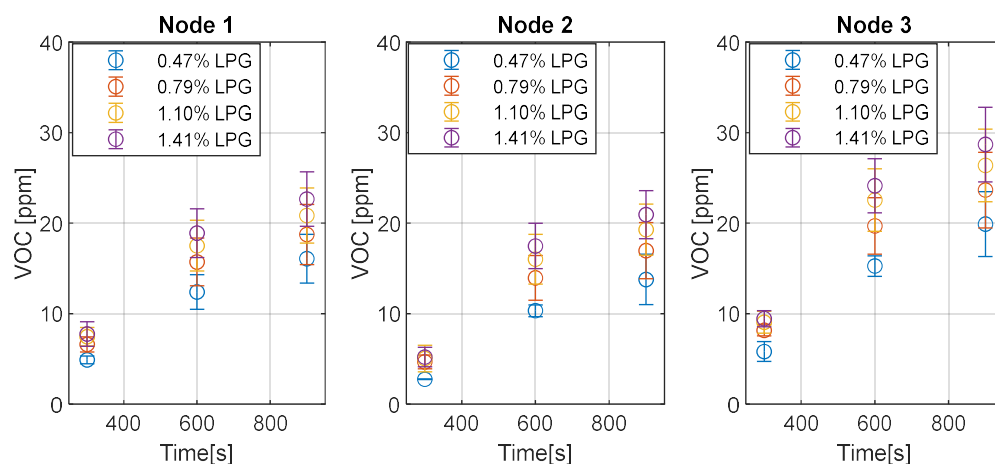
**Figure 6.** Transient responses to gas concentration pulses in a small chamber (the chamber filling time is less than 20 s).

The pellistor response time (10–90%) in the used operational conditions is about 3 min, which is much slower than the value declared by the manufacturer (12 s). Nevertheless, the alarm threshold was set a priori by considering a fraction of the LEL (Lower Explosive Limit), i.e., the minimum concentration at which there is a risk of explosion. Therefore, the reliability of the threshold setting is not affected by the transient behavior of the VOC signal.

The variability observed among the VOC sensor responses mainly reflects the use of factory-provided calibration coefficients without additional in-house calibration. However, these fluctuations are mitigated by the conservative threshold selection: the alarm is triggered at a level well below the VOC concentration corresponding to a few tenths of the LEL, ensuring that the variability does not compromise system safety. In fact, as can be seen from measurements,  $\mu_0 < 3$  ppm,  $\sigma_0 < 1$  ppm and thus alarm corresponds to 6 ppm corresponding to 0.4% *v/v* of combustible gas concentration.

To evaluate robustness of the measurement strategy, a repeatability analysis was performed. The measurement cycle was repeated 10 times, and the mean values ( $\mu$ ) and standard deviations ( $\sigma$ ) of the sensor outputs were calculated at three different times during each measurement phase (for each concentration). The repeatability found with the pellistors is satisfactory, for these sensors the standard deviation is lower than 0.04%.

Figure 7 shows the measurements obtained with the VOC sensor, for each gas phase, 300 s, 600 s, and 900 s after the beginning of the LPG injection, reported as mean  $\pm$  standard deviation. Table 4 shows the repeatability analysis for the VOC sensors output at the end of each gas injection; it can be seen that the behavior of the three sensors is very similar, and the relative standard deviation is lower than 5 ppm.



**Figure 7.** VOC sensor measurement results. LPG injections with concentrations reported in the legends, sensor output measured 300, 600, and 900 s after the start of gas injection (mean  $\pm$  SD over 10 cycles).

**Table 4.** VOC measurement results, different LPG concentrations.

| Sensor Node | 0.47% LPG   |                | 0.79% LPG   |                | 1.10% LPG   |                | 1.41% LPG   |                |
|-------------|-------------|----------------|-------------|----------------|-------------|----------------|-------------|----------------|
|             | $\mu$ [ppm] | $\sigma$ [ppm] | $\mu$ [ppm] | $\sigma$ [ppm] | $\mu$ [ppm] | $\sigma$ [ppm] | $\mu$ [ppm] | $\sigma$ [ppm] |
| 1           | 16.1        | 2.7            | 18.7        | 3.3            | 20.8        | 3.0            | 22.6        | 3.1            |
| 2           | 13.7        | 2.8            | 17.0        | 3.1            | 19.3        | 2.8            | 20.1        | 2.6            |
| 3           | 19.9        | 3.6            | 23.7        | 4.1            | 26.4        | 3.9            | 28.7        | 4.1            |

## 5. Reliability Model and Analysis

The sensor node is a purely electronic system without moving parts, comprising several measurement points, a central processing unit, a central memory, and a communication system for data transmission and lacks any functional redundancy. The Functional Block Diagram (FBD) is therefore not provided due to the simplicity of the interconnection. The reliability block diagram (RBD) can be represented as a simple series connection of the main subsystems of the node: the sensing front-end, the microcontroller unit, the wireless communication module, the power supply stage, and the connectors. The sensing front-end includes the pellistor sensor, the electrochemical VOC sensor, and the associated signal-conditioning electronics, which contribute to the overall failure rate due to exposure to gas, temperature, and humidity variations. Connectors are modeled as a separate category, since mechanical interconnections are a known source of degradation and intermittent failures in long-term operation.

In this series representation, the total failure rate is the sum of the contributions of all subsystems, since the failure of any block leads to the failure of the device. Failure-rate data from established databases highlight that, in addition to the sensing elements, the microcontroller and other complex ICs often dominate the system-level reliability figures, due to their intrinsic complexity and sensitivity to electrical and thermal stress. Furthermore, passive components such as capacitors can be a significant source of failures, particularly electrolytic and multilayer ceramic capacitors (both technologies are used), which are prone to dielectric breakdown, cracking, and humidity-induced degradation. Similarly, oscillators and quartz resonators (two are mounted on the board, crystal #1 and crystal #2) represent critical points, as they are sensitive to thermal cycling, mechanical vibration, and long-term drift. While power regulators and simpler passive components generally show lower intrinsic failure rates, the combined contributions of sensors, microcontrollers, capacitors, oscillators, wireless modules, and connectors determine the effective reliability of the node. This analysis underlines the importance of considering the full component mix in the reliability model, rather than focusing only on the primary sensing devices.

For modeling the critical node, very conservative assumptions were adopted. First, the system operating temperature was set at 25 °C, and the operational environment in terms of humidity and temperature was defined as Ground Fixed (GF) according to the MIL-HDBK-217F Notice 2 standard. Although this standard is widely used in the industrial field, it often provides overly conservative results, with mean lifespan estimates significantly lower than those observed in practice. Therefore, in this study a revised version of the standard was also employed, specifically the ANSI/VITA 51.1 database.

In the reliability calculation, two indicators have been evaluated with a 95% confidence level: the failure rate, expressed as the ratio between the expected number of failures over a given time period and per  $10^6$  operating hours, and the mean time between failures (MTBF), as shown in Table 5. For completeness, MTBF is computed as  $MTBF = 10^6 \text{ h/FPMH}$ .

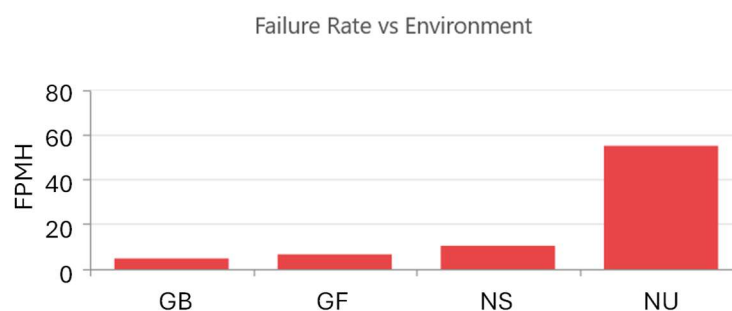
**Table 5.** Prediction Results according to different standards.

| Standard        | Failure Rate [ $f/10^6 \text{ h}$ ] | MTBF [h] |
|-----------------|-------------------------------------|----------|
| MIL-HDBK-217FN2 | 2.910338                            | 343,602  |
| ANSI VITA51.1   | 1.361447                            | 734,512  |

It can be seen that by computing the failure rate with the two databases under the same assumptions (Ground Fixed environment at 25 °C, 100% duty cycle, single-series RBD, no redundancy), different results are found. As expected, MIL-HDBK-217F Notice 2 assigns higher base failure rates and penalizes several modern Component on the Shelf (COTS) families via its quality ( $\pi_Q$ ) and environment ( $\pi_E$ ) factors. This systematically yields

higher FPMH and lower Mean Time Between Failures (MTBF). In contrast, ANSI/VITA 51.1 harmonizes MIL-217 style predictions with updated component families and field-return-informed factors, which better reflect contemporary technologies; consequently, it predicts lower FPMH and higher MTBF for the same architecture and stress conditions. In our case this produces 2.910338 FPMH (MTBF = 343,602 h) with MIL-217F-N2 versus 1.361447 FPMH (MTBF = 734,512 h) with ANSI/VITA 51.1 (see Table 5). We therefore report both figures to bracket a realistic range: MIL-217F-N2 as a conservative bound for screening and ANSI/VITA 51.1 as a more representative estimate for present-day COTS implementations. In both cases, the predicted lifetime, approximately 39 years with MIL-217F-N2 and 84 years with ANSI/VITA 51.1, is fully adequate for the intended residential gas safety application.

Although the proposed sensor node has been designed to operate in GF environments, the reliability study was also extended to Ground Benign (GB), Naval Sheltered (NS), and Naval Unsheltered (NU) environments. This was done because the metrological characteristics of the proposed sensor node are also suitable for monitoring gas leaks in industrial contexts, where it is not always possible to install measurement systems in GF conditions. The outcomes, expressed in failures per million hours (FPMH), are presented in Figure 8. This behavior is not affected by the choice of database and is therefore valid for both datasets considered.



**Figure 8.** FPMH in different operating environments according to both reliability databases.

To evaluate the performance with respect to temperature dependence, Figure 9a shows the FPMH predicted using the MIL-HDBK-217F Notice 2 standard. It can be observed that the process rate (PR) governing component aging follows Equation (2) where A is a geometric constant,  $E_a$  is the average system activation energy, k is the Boltzmann constant, and T is the temperature expressed in Kelvin.

$$PR = Ae^{-\frac{E_a}{kT}} \quad (2)$$

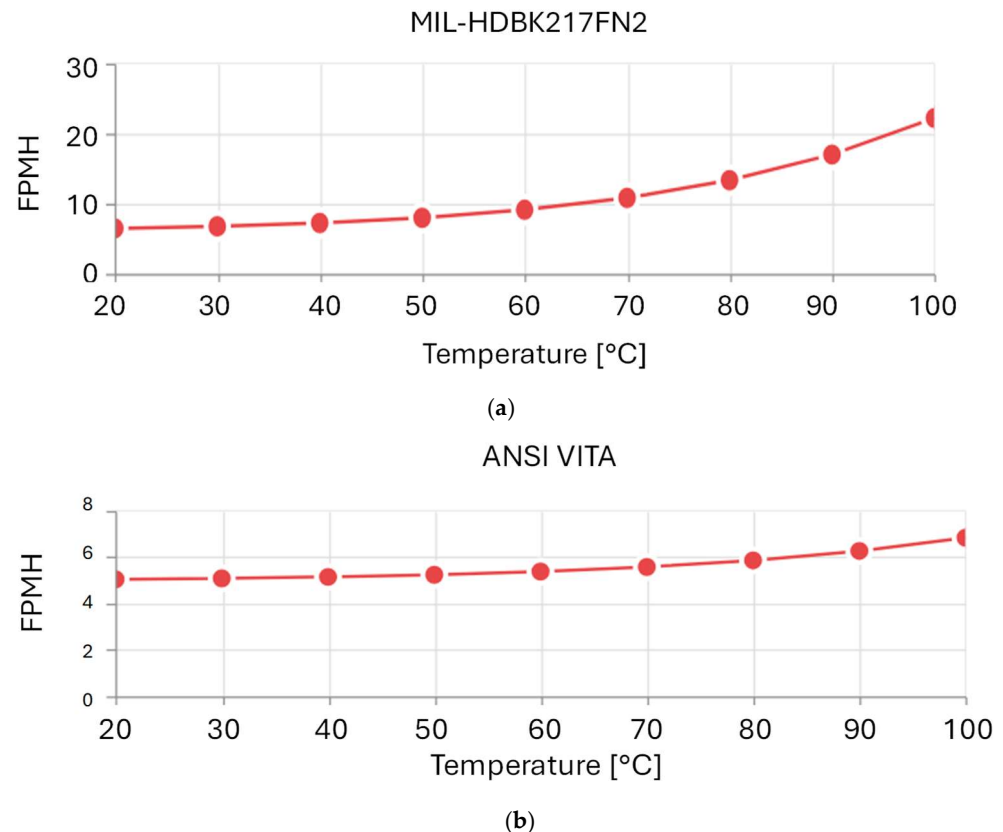
As far as  $E_a$  is concerned, for an unknown failure mechanism, in electronic components, a value of 0.7 eV is assumed.

Moreover, Figure 9b shows also the FPMH predicted using the ANSI VITA standard up to a maximum temperature of 100 °C. As expected from Equation (2), the process rate governing component aging follows an Arrhenius-type behavior: as the temperature increases, the number of activated defects rises, leading to higher FPMHs more than doubled for the more pessimistic standard.

Even when accounting for different operating environments and elevated temperatures, the increase in failure rate only results in a reduction in the useful lifetime that remains compatible with safety-critical applications. Starting from the baseline scenario (GF, 25 °C, 100% duty cycle) with our reference MTBF values—343,602 h (MIL-HDBK-217F Notice 2) and 734,512 h (ANSI/VITA 51.1)—and applying an Arrhenius-type acceleration

factor with  $E_a \approx 0.70$  eV (reproducing the factors 1.5/10/50 at 29.5/52.5/74.9 °C), the following estimates are obtained:

- 29.5 °C ( $AF \approx 1.5$ ) → MTBF  $\approx$  26.1 years (MIL)/55.9 years (VITA).
- 52.5 °C ( $AF \approx 10$ ) → MTBF  $\approx$  3.9 years (MIL)/8.4 years (VITA).
- 74.9 °C ( $AF \approx 50$ ) → MTBF  $\approx$  0.79 years ( $\sim$ 9.4 months) (MIL)/1.68 years ( $\sim$ 20 months) (VITA).



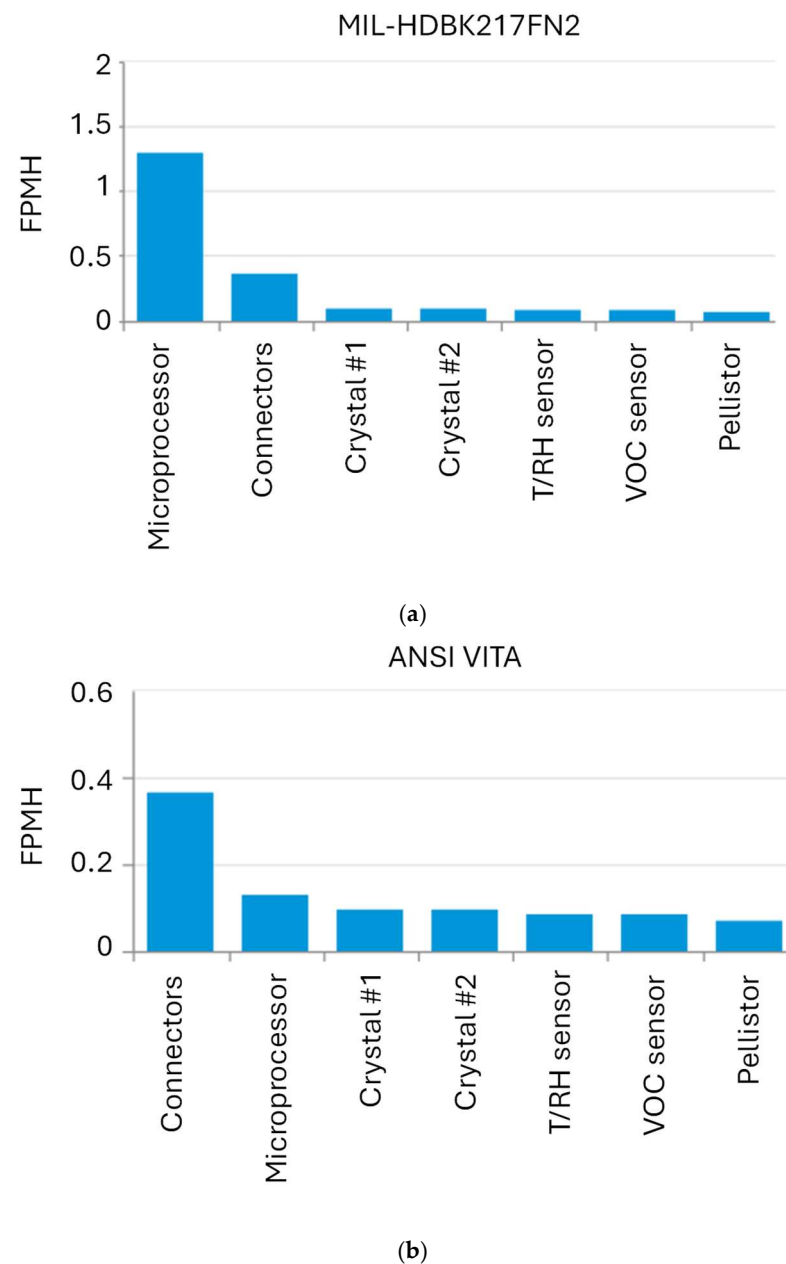
**Figure 9.** FPMH over temperature. (a) For MIL-HDBK217FN2 standard. (b) For ANSI VITA standard.

These values must be interpreted as stress scenarios: under realistic GF/GB conditions, where the average operating temperature is much lower, the expected lifetime remains in the order of several decades. Moreover, the distribution of contributions among component categories (microcontroller, crystal, capacitors, sensors, and connectors) remains consistent across environments: while the relative weights may change, the dominant elements are preserved, and the overall predictions remain adequate for residential safety-critical deployment.

It is interesting to observe how the two standards classify components in terms of criticality. The difference between the two models is presented in the following figures, which show the distribution of FPMH (for the GF simulation environment) by component category and technology according to the MIL-HDBK-217F Notice 2 database (Figure 10a) and ANSI VITA (Figure 10b).

The comparison between MIL-HDBK-217F Notice 2 and ANSI/VITA 51.1 highlights how the two standards classify critical components differently. In the conservative MIL-217F-N2 model the microprocessor dominates the overall failure rate, while in the ANSI/VITA 51.1 database the connectors emerge as the primary contributors. This shift reflects the fact that MIL-217F penalizes modern integrated devices such as microcontrollers, whereas ANSI/VITA 51.1 incorporates updated reliability data and field-return statistics, yielding more realistic estimates. In our case, given the adoption of state-of-the-art micro-

controllers with integrated wireless functionality, the ANSI/VITA 51.1 results are likely more representative of actual field performance.



**Figure 10.** FPMH for the GF simulation environment by component category and technology (a) per MIL-HDBK-217F Notice 2, and (b) per ANSI-VITA.

For this reason, both standards are reported in our analysis: MIL-HDBK-217F Notice 2 as a conservative bound and ANSI/VITA 51.1 as a more representative estimate for present-day COTS implementations, providing a bounded range for reliability assessment.

The ANSI/VITA 51.1 results clearly emphasize that, beyond the microcontroller, passive and electromechanical elements such as connectors, crystals, and capacitors often dominate the long-term reliability profile of IoT nodes. These components are particularly sensitive to mechanical stress, thermal cycling, and environmental exposure, and therefore represent the real weak links in field deployments.

It should also be noted that, in the proposed sensor node, electrochemical sensors are connected to the board via connectors. Although this category of components may at first appear secondary, it is in fact crucial in this context: the VOC sensor, in particular,

plays an essential role in the proper functioning of the node, as it directly affects the management of the pellistor and, consequently, the triggering of alarms in case of gas leakage. For this reason, connectors must be carefully considered in the reliability analysis, since their degradation could compromise not only data integrity but also the overall safety function of the system. As a consequence, careful component selection and the adoption of protective measures, such as conformal coatings or resin encapsulation, become crucial to ensure durability. In many cases, avoiding certain technologies altogether, or substituting them with more robust alternatives, is the most effective strategy. This highlights that reliability in practice is not only a matter of sensor or microcontroller design but critically depends on how supporting components are chosen and protected for long-term operation in harsh conditions.

## 6. Reliability Assessment and Experimental Results

The issue of infant mortality in industrial products is crucial due to its potentially high costs. To address or reduce this problem, the first step is diagnosis, followed by determining the duration of this phase in order to perform “burn-in” tests and eliminate prematurely weak devices. Given the limited number of samples available, the purpose of the reliability tests is to determine whether an infant mortality trend exists. Infant mortality is commonly described by the well-known bathtub curve and can be approximated by a Weibull probability density function (pdf) with a  $\beta$  (shape factor) coefficient smaller than 1 as in (3).

$$f(t) = \frac{\beta}{\mu} \left( \frac{t - t_0}{\mu} \right)^{\beta-1} e^{-\left( \frac{t-t_0}{\mu} \right)^\beta} \quad (3)$$

where  $\mu$  is the component/subsystem/system characteristic life,  $t$  is the random variable, and  $t_0$  is a time displacement factor. Exploiting the well-known relationship between the hazard function ( $h(t)$ ), the Weibull probability density function (pdf) and the corresponding reliability function, it is possible to derive the expression of the hazard function ( $h(t)$ ) as in (4).

$$h(t) = \frac{\beta}{\mu} \left( \frac{t - t_0}{\mu} \right)^{\beta-1} \quad (4)$$

The expression in (4) is representative of a decreasing failure rate if the shape factor is comprised between 0 and 1. To prove design robustness with a reduced sample size, acceleration factors can be applied to determine whether the system exhibits infant weaknesses. If infant mortality occurs, one would expect to observe an increased deviation in the expected sensor and system responses when subjected to short-term accelerated temperature testing. Considering different operating environments, the effect of temperature-induced aging was analyzed. In particular, the acceleration factor (AF) was used in the calculation of the failure rate for each component. AF is a parameter that derates the failure rate due to temperature effects and is described by the Arrhenius equation:

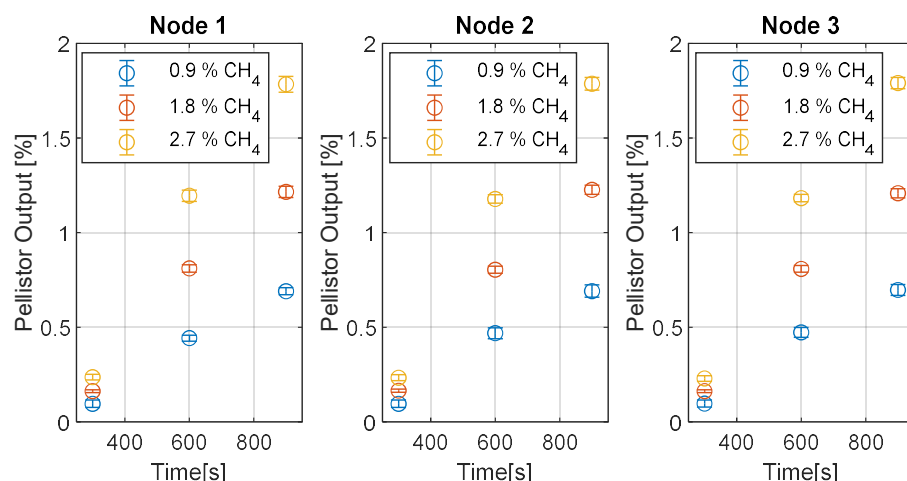
$$AF = e^{\left( \frac{E_a}{k} \left( \frac{1}{T_{use}} - \frac{1}{T_{stress}} \right) \right)} \quad (5)$$

Here,  $E_a$  defines the thermal activation energy,  $k$  the Boltzmann constant,  $T_{use}$  the operational temperature and  $T_{stress}$  the stress temperature, both expressed in Kelvin. Tests were conducted considering different AFs, with three sensor node samples subjected to accelerated life tests. The operating conditions of the nodes were assessed by evaluating gas sensing performance after each stress cycle. Accelerated life tests were performed according to IEC 60068 standards in a controlled climatic chamber (ACS DY200).

Since the device is designed for 25 °C operation, its MTBF is on the order of several hundred thousand hours. It is not feasible to validate this by direct endurance testing, so it is

more effective to identify potential failure factors in the first hours of operation. By applying (5) while keeping activation energy constant for components most susceptible to early damage, the most suitable operating temperatures for accelerated testing can be estimated. Specifically, three acceleration factors of 1.5, 10, and 50 were selected, corresponding to operating temperatures of 29.5 °C, 52.5 °C, and 74.9 °C, respectively. The acceleration factor implies that one hour of operation at 25 °C is equivalent to 1.5, 10, or 50 h at these elevated stress temperatures. An additional test in a cold, dry environment (−25 °C) was included to verify that no failure mechanisms arise from solder joint fragility caused by thermal expansion mismatches. Accordingly, the nodes were exposed to temperatures of 30 °C, 50 °C, 75 °C and −25 °C at controlled humidity (20% RH) for 2 h at each step. Environmental reliability tests were carried out in the ACS DY200 climatic chamber (206 L internal volume) under controlled humidity (20% RH). Starting from 25 °C, the chamber was ramped to the target temperatures (−25 °C, 29.5 °C, 52.5 °C, 74.9 °C) at  $\pm 3$  °C/min. Once the setpoint was reached, the nodes were held at steady state for 2 h before post-treatment measurements were taken. The −25 °C cold test was reached by cooling from 25 °C at  $-3$  °C/min, followed by 2 h steady state. These test conditions correspond to AFs of 1.5, 10, and 50 in the Arrhenius model, ensuring meaningful stress without introducing unrealistic failure mechanisms. After thermal treatments, gas sensing performance was assessed using the experimental setup described in Section 4, with all samples tested simultaneously. The pellistor responses after each stress cycle were compared to baseline measurements obtained in pristine conditions. For the pellistor, mixtures of CH<sub>4</sub> and synthetic air at different CH<sub>4</sub> concentrations were used.

Figure 11 shows the baseline methane measurement results, recorded prior to any temperature treatment and after pellistor calibration. Cycles with increasing methane concentrations were repeated 10 times. Each cycle consisted of three phases with methane concentrations of 0.9%, 1.8%, and 2.7%, each lasting 1000 s and separated by chamber cleaning phases. For each phase, the concentration values measured 300 s, 600 s, and 900 s after the beginning of the methane injection are reported as mean  $\pm$  standard deviation.

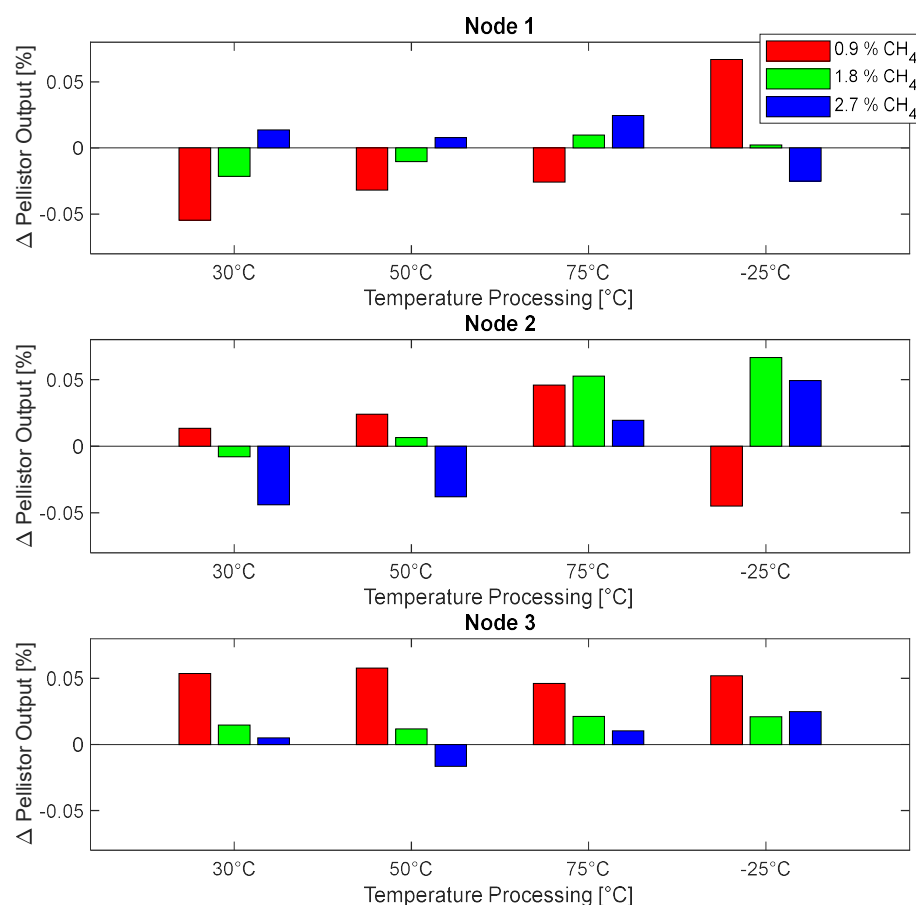


**Figure 11.** Baseline methane measurement results (before temperature treatments). Measurement during gas pulses with the CH<sub>4</sub> concentrations reported in the legends (1000 s each), measurements are taken 300, 600, and 900 s after the start of injection (mean  $\pm$  SD over 10 cycles).

The same cycles were repeated after each temperature treatment, and the deviations between the post-treatment results (averaged over 10 cycles) and the baseline values were evaluated.

Figure 12 shows the deviations in methane concentration measured after the different temperature treatments, expressed with respect to the baseline values. In particular, each

deviation was calculated as the difference between the concentration measured by the nodes 900 s after the start of gas injection and the corresponding baseline measurement. It can be observed that these deviations remain within the range of the standard deviations of the baseline measurements.



**Figure 12.** Deviations in methane concentrations after temperature treatments with respect to baseline values. Each deviation represents the difference between the concentration measured by the nodes 900 s after the start of gas injection (CH<sub>4</sub> concentration shown the legend) and the corresponding baseline measurement.

This result demonstrates the intrinsic robustness of the device against potential malfunctions associated with the infant mortality phase, which is typically modeled by the initial portion of the bathtub curve in reliability analysis. The total equivalent operating time of the accelerated tests corresponds to approximately 125 h at 25 °C, considering the selected acceleration factors. Such testing durations are consistent with typical product screening procedures performed prior to commercialization, aimed at detecting design or manufacturing defects. The fact that no significant deviations were detected even under accelerated stress confirms that the proposed system does not exhibit early-life failures attributable to infant mortality. This is an important outcome, as it shows that the combined use of accelerated life tests and reliability modeling provides effective evidence of design robustness. In practice, this means that the device can be expected to operate reliably beyond the initial high-risk phase without requiring extensive burn-in, while still complying with best practices for safety-critical applications. These findings support the suitability of the proposed node for deployment in real residential and industrial environments, where premature failures could otherwise compromise both safety and trust in IoT-based gas monitoring solutions.

## 7. Conclusions

This work presents the architecture, implementation, and reliability analysis of an IoT-based measurement system designed for monitoring volatile organic compounds (VOCs) and combustible gases in both residential and industrial environments. The system integrates advanced sensor technologies, including low-power MEMS pellistors and electrochemical VOC sensors, to ensure continuous and efficient gas leak detection. The dual-sensor approach, where the VOC sensor acts as a sentinel to activate the pellistor when necessary only, significantly optimizes power consumption and extends battery life. The experimental characterization demonstrated that the sensor node operates effectively in three modes: idle, explosive gas monitoring, and LoRa transmission. The VOC sentinel strategy proved to be effective, extending the node operational life to up to 22 months. The gas sensing performance was validated using an automatic test bench, confirming the system accuracy and reliability in detecting various gas concentrations. Reliability assessments, conducted through accelerated life tests and environmental stress testing in accordance with IEC 60068 standards, showed that the sensor nodes maintained consistent performance under different temperature conditions. The failure rate predictions, based on both MIL-HDBK-217FN2 and ANSI VITA51.1 standards, indicated a robust design with a mean time between failures (MTBF) of up to 734,512 h in ground fixed environments. The results highlight the system potentiality for enhancing safety in residential gas systems by providing real-time detection and notification of gas leaks. The integration of IoT technologies in this context not only improves safety standards but also offers a scalable solution for broader applications in industrial settings. The proposed testing plan, involving mild acceleration factors, as a screening approach, ensures the system reliability and robustness against potential infant mortality issues.

In summary, the main novelty of this work does not lie only in the specific sensor node architecture, but in the methodological approach adopted for its qualification. We have shown that IoT-based devices for residential combustible gas safety should be assessed with the same rigor as safety-critical systems, through a combination of system-level reliability modeling, accelerated environmental testing, and post-stress functional validation. By providing a reproducible framework that links laboratory characterization with reliability analysis, this study contributes to bridging the gap between rapid IoT prototyping and the long-term robustness validation required for real-world deployment. This methodological perspective complements ongoing technological advances and underlines the importance of reliability testing as a fundamental component of innovation in safety-related IoT applications.

This study highlights the importance of integrating reliability engineering into IoT safety devices and proposes a generalizable methodology for ensuring long-term performance in distributed sensing systems. Further tests, beyond those presented in this paper, on larger samples and in field environments will be useful to strengthen the generalization of the results. Moreover, aspects such as long-term calibration stability and operation under varying humidity conditions deserve additional investigation. These points represent natural extensions of the present work and will guide future developments.

**Author Contributions:** Conceptualization, E.L., T.V., A.F. and V.V.; Methodology, E.L., T.V. and V.V.; Software, L.P. and S.P.; Validation, E.L., L.P. and A.F.; Formal analysis, E.L., M.M. and V.V.; Investigation, L.P. and T.V.; Resources, D.B.; Data curation, E.L., S.P., T.V., A.F. and M.M.; Writing—original draft, E.L., T.V., A.F. and M.M.; Writing—review & editing, A.F. and V.V.; Visualization, D.B. and S.P.; Supervision, V.V.; Project administration, V.V.; Funding acquisition, D.B. All authors have read and agreed to the published version of the manuscript.

**Funding:** This study was co-funded by the ConTrack Project, in the context of “Accordi per l’Innovazione” program by the Ministero delle Imprese e del Made in Italy (MIMIT).

**Data Availability Statement:** The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Vardoulakis, S.; Giagloglou, E.; Steinle, S.; Davis, A.; Sleuwenhoek, A.; Galea, K.S.; Crawford, J.O. Indoor Exposure to Selected Air Pollutants in the Home Environment: A Systematic Review. *Int. J. Environ. Res. Public Health* **2020**, *17*, 8972. [\[CrossRef\]](#)
2. Mannan, M.; Al-Ghamdi, S.G. Indoor Air Quality in Buildings: A Comprehensive Review on the Factors Influencing Air Pollution in Residential and Commercial Structures. *Int. J. Environ. Res. Public Health* **2021**, *18*, 3276. [\[CrossRef\]](#)
3. Michanowicz, D.R.; Leventhal, O.M.; Domen, J.K.; Williams, S.R.; Lebel, E.D.; Hill, L.A.L.; Shonkoff, S.B. Natural Gas Odorants: A Scoping Review of Health Effects. *Curr. Environ. Health Rep.* **2023**, *10*, 337–352. [\[CrossRef\]](#)
4. Achaw, O.-W.; Danso-Boateng, E. Industrial Gases. In *Chemical and Process Industries: With Examples of Industries in Ghana*; Springer: Cham, Switzerland, 2021; pp. 213–233.
5. Safari, A.; Vesali-Naseh, M. Design and Optimization of Hydrodesulfurization Process for Liquefied Petroleum Gases. *J. Clean. Prod.* **2019**, *220*, 1255–1264. [\[CrossRef\]](#)
6. Ghazi, M.; Tasnim, N.; Hoorfar, M. Selective Monitoring of Natural Gas Sulfur-Based Odorant Mixture of t-Butyl Mercaptan and Methyl Ethyl Sulfide Using an Array of Microfluidic Gas Sensors. *J. Hazard. Mater.* **2022**, *438*, 129548. [\[CrossRef\]](#)
7. Log, T.; Pedersen, W.B. A Common Risk Classification Concept for Safety Related Gas Leaks and Fugitive Emissions? *Energies* **2019**, *12*, 4063. [\[CrossRef\]](#)
8. Wang, D.; Qian, X.; Ji, T.; Jing, Q.; Zhang, Q.; Yuan, M. Flammability Limit and Explosion Energy of Methane in Enclosed Pipeline under Multi-Phase Conditions. *Energy* **2021**, *217*, 119355. [\[CrossRef\]](#)
9. Wang, K.; Hu, Q.; Qian, X.; Li, M.; Shi, T. Cause Analysis and Damage Mechanism of Explosive Destruction with Case Investigation Involving LPG Tank Trailer. *Eng. Fail. Anal.* **2022**, *133*, 106002. [\[CrossRef\]](#)
10. Kundu, S.; Zanganeh, J.; Moghtaderi, B. A Review on Understanding Explosions from Methane–Air Mixtures. *J. Loss Prev. Process Ind.* **2016**, *40*, 507–523. [\[CrossRef\]](#)
11. Li, Z.; Chen, L.; Yan, H.; Fang, Q.; Zhang, Y.; Xiang, H.; Liu, Y.; Wang, S. Gas Explosions of Methane–Air Mixtures in a Large-Scale Tube. *Fuel* **2021**, *285*, 119239. [\[CrossRef\]](#)
12. Kamieniak, J.; Randviir, E.P.; Banks, C.E. The Latest Developments in the Analytical Sensing of Methane. *TrAC Trends Anal. Chem.* **2015**, *73*, 146–157. [\[CrossRef\]](#)
13. Wiegand, G. Physical-Chemical Gas Sensors. In *Gas Measurement Technology in Theory and Practice: Measuring Instruments, Sensors, Applications*; Springer Fachmedien: Wiesbaden, Germany, 2023; pp. 215–285.
14. Rajbanshi, A.; Das, D.; Udutalapally, V.; Mahapatra, R. DLeak: An IoT-Based Gas Leak Detection Framework for Smart Factory. *SN Comput. Sci.* **2022**, *3*, 273. [\[CrossRef\]](#)
15. Fort, A.; Bertocci, F.; Mugnaini, M.; Vignoli, V.; Gaggii, V.; Galasso, A.; Pieralli, M. Availability Modeling of a Safe Communication System for Rolling Stock Applications. In Proceedings of the 2013 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Minneapolis, MN, USA, 6–9 May 2013; pp. 427–430. [\[CrossRef\]](#)
16. Mugnaini, M.; Catelani, M.; Ceschini, G.F.; Masi, A.; Nocentini, F. Pseudo Time-Variant Parameters in Centrifugal Compressor Availability Studies by Means of Markov Models. *Microelectron. Reliab.* **2002**, *42*, 1373–1376. [\[CrossRef\]](#)
17. Ceschini, G.; Mugnaini, M.; Masi, A. A Reliability Study for a Submarine Compression Application. *Microelectron. Reliab.* **2002**, *42*, 1377–1380. [\[CrossRef\]](#)
18. Addabbo, T.; Fort, A.; Mugnaini, M.; Vignoli, V.; Simoni, E.; Mancini, M. Availability and Reliability Modeling of Multicore Controlled UPS for Datacenter Applications. *Reliab. Eng. Syst. Saf.* **2016**, *149*, 56–62. [\[CrossRef\]](#)
19. Panda, S.; Mehlaawat, S.; Dhariwal, N.; Kumar, A.; Sanger, A. Comprehensive review on gas sensors: Unveiling recent developments and addressing challenges. *Mater. Sci. Eng. B* **2024**, *308*, 117616. [\[CrossRef\]](#)
20. Fleming, L.; Ahmadzadeh, S.; Pomfret, J.; Waddell, E.; McGann, G.; Hutson, D.; Keel, E.; Kauer, M.; Bellanger, M.; Brinkley, I.; et al. Light powered battery-less non-dispersive infrared sensor for methane gas detection. In Proceedings of the Optical Sensing and Detection VIII, Strasbourg, France, 7–12 April 2024; SPIE: Cergy Pontoise, France, 2024; Volume 12999, pp. 92–99. [\[CrossRef\]](#)
21. Alhomyani, H.; Fadel, M.; Dimitriou, N.; Bakhsh, H.; Aldabbagh, G. Modeling the Performance of a Multi-Hop LoRaWAN Linear Sensor Network for Energy-Efficient Pipeline Monitoring Systems. *Appl. Sci.* **2024**, *14*, 9391. [\[CrossRef\]](#)
22. Rivera-Martinez, R.; Kumar, P.; Laurent, O.; Broquet, G.; Caldow, C.; Cropley, F.; Santaren, D.; Shah, A.; Mallet, C.; Ramonet, M.; et al. Using metal oxide gas sensors to estimate the emission rates and locations of methane leaks in an industrial site: Assessment with controlled methane releases. *Atmos. Meas. Tech.* **2024**, *17*, 4257–4290. [\[CrossRef\]](#)

23. Figaro Engineering Inc. Low Power Consumption MEMS Methane Gas Sensor TGS8410. Product Information Page. Available online: <https://www.figarosensor.com/product/feature/tgs8410.html> (accessed on 11 September 2025).
24. Landi, E.; Parri, L.; Baldo, D.; Parrino, S.; Fort, A.; Mugnaini, M. Accurate Battery-Operated IoT Sensor for Detecting Combustible Gas Leaks in Homes. In Proceedings of the 2024 IEEE Sensors Applications Symposium (SAS), Naples, Italy, 23–25 April 2024; pp. 1–6. [\[CrossRef\]](#)
25. Bierer, B.; Grgić, D.; Yurchenko, O.; Engel, L.; Pernau, H.-F.; Jägle, M.; Reindl, L.; Wöllenstein, J. Low-Power Sensor Node for the Detection of Methane and Propane. *J. Sens. Sens. Syst.* **2021**, *10*, 185–191. [\[CrossRef\]](#)
26. Samotaev, N.; Dzhumaev, P.; Oblov, K.; Pislakov, A.; Obratsov, I.; Ducso, C.; Biro, F. Silicon MEMS Thermocatalytic Gas Sensor in Miniature Surface Mounted Device Form. *Chemosensors* **2021**, *9*, 340. [\[CrossRef\]](#)
27. Fort, A.; Landi, E.; Mugnaini, M.; Parri, L.; Pozzebon, A.; Vignoli, V. A LoRaWAN Carbon Monoxide Measurement System with Low-Power Sensor Triggering for the Monitoring of Domestic and Industrial Boilers. *IEEE Trans. Instrum. Meas.* **2020**, *70*, 5500609. [\[CrossRef\]](#)
28. Di Renzone, G.; Landi, E.; Mugnaini, M.; Parri, L.; Peruzzi, G.; Pozzebon, A. Assessment of LoRaWAN Transmission Systems under Temperature and Humidity, Gas, and Vibration Aging Effects within IIoT Contexts. *IEEE Trans. Instrum. Meas.* **2021**, *71*, 5500311. [\[CrossRef\]](#)
29. Babu, T.; Nair, R.R. Enhancing gas leak detection with IoT technology: An innovative approach. *Procedia Comput. Sci.* **2024**, *235*, 961–969. [\[CrossRef\]](#)

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.