UNIVERSITY OF BRESCIA

Smart Pollution Monitoring for Sustainable Mobility: Low-Cost Environmental Sensing for Air Quality Assessment

S. Dello Iacono [1], A. Flammini [1], A. Fort [2], E. Panzardi[2], S. Rinaldi [1]

1. *Università degli Studi di Brescia, Brescia – Italy*
2. *Università degli Studi di Siena, Siena – Italy*

Emerging Opportunities in MOX-Based Air Quality Sensing

- Air pollution is a major environmental risk factor for respiratory and cardiovascular diseases (WHO).
- **Exposure** varies strongly at **street level** and **along commuter routes**, not captured by sparse monitoring networks.
- Rapid progress in MOX, MEMS and low-power electronics enables compact, multi-parameter environmental sensors.
- Mobile sensing platforms enable **exposure-aware mapping** aligned with human activity patterns:
  - supports evidence-based urban planning,
  - sustainable mobility strategies,
  - health-risk assessment.

Indoor Air Quality
- Smart Homes
- HVAC

Smart Mobility
- Sustainable mobility
- Cycling Safety
- Touristic chargin stations in

Behind Mobility
- Distributed Sensing
- Agricolture

Bosch BME688 Development Kit

Operation range

- Pressure: 300 hPa to 1100 hPa
- Humidity: 0% to 100%
- Temperature: -40 °C to 85 °C

Gas sensor

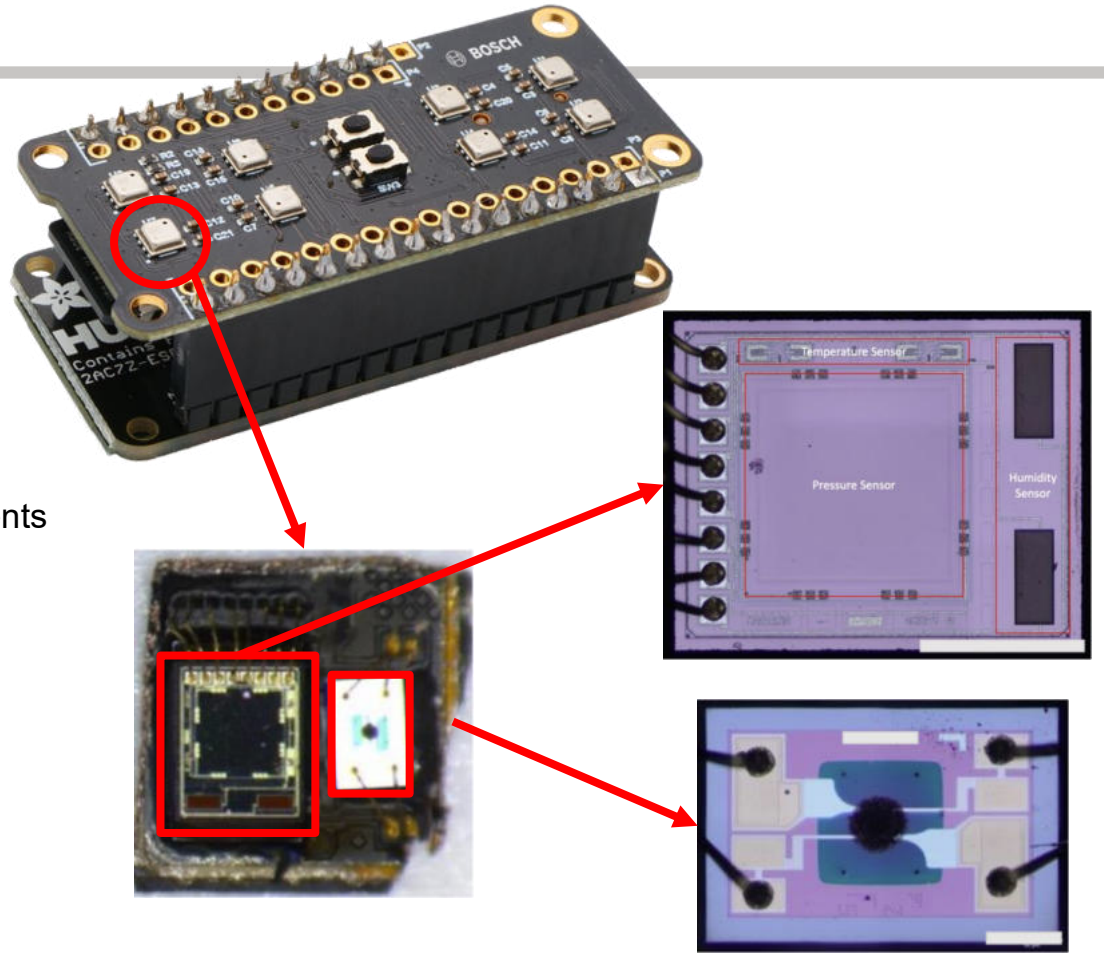
- F1 score for H_2S scanning of 0.92
- Standard scan speed of 10.8 s/scan
- Response time (τ33% to 63%) of <1s
- Sensor-to-sensor deviation of ±15%
- Output data processing: Index for Air Quality (IAQ), bVOC- and CO2-equivalents (ppm), Gas scan result (%)

Humidity sensor

- 8s Response time (0% to 63%)
- Accuracy tolerance of ±3% relative humidity
- Hysteresis of ≤1.5% relative humidity

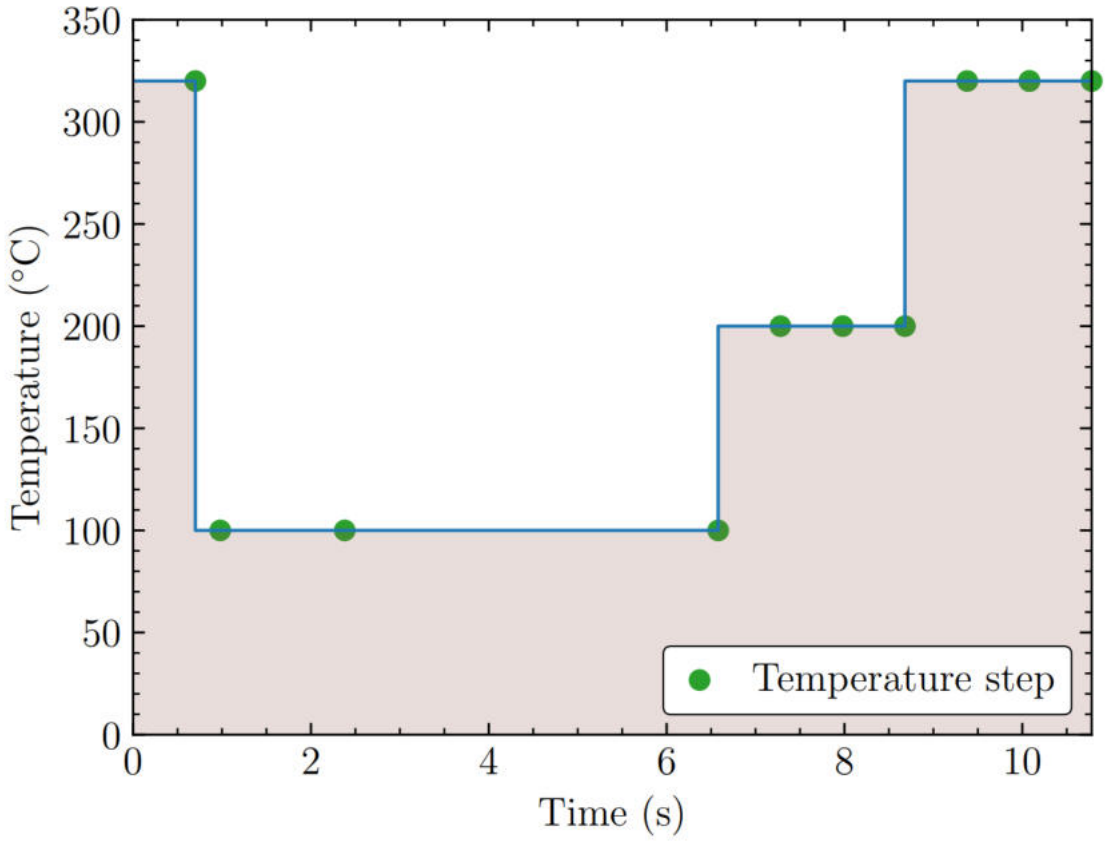
Pressure sensor

- RMS Noise of 0.12 Pa (equivalent to 1.7cm)
- Sensitivity Error of ±0.25% (equivalent to 1m at 400m height change)
- Temperature coefficient offset of ±1.3Pa/K (equivalent to ±10.9cm at 1°C temperature change)



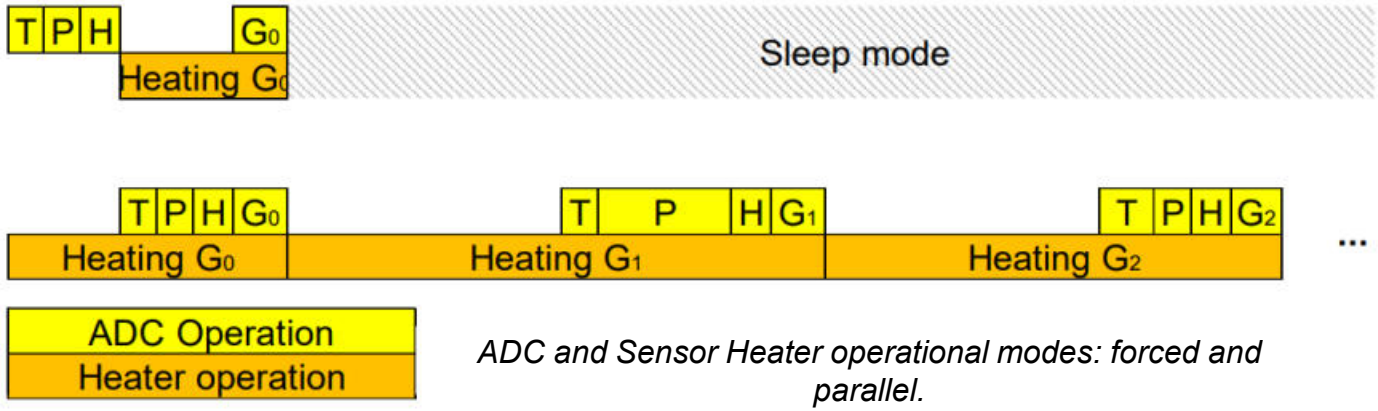
Klibanov, Lev & Boldt, Paul. (2021). «Preliminary analysis of Bosch BME688 4-in-1 environmental sensor with AI»

Bosch BME688 Main Features



Standard Sensor Heater temperature profile.

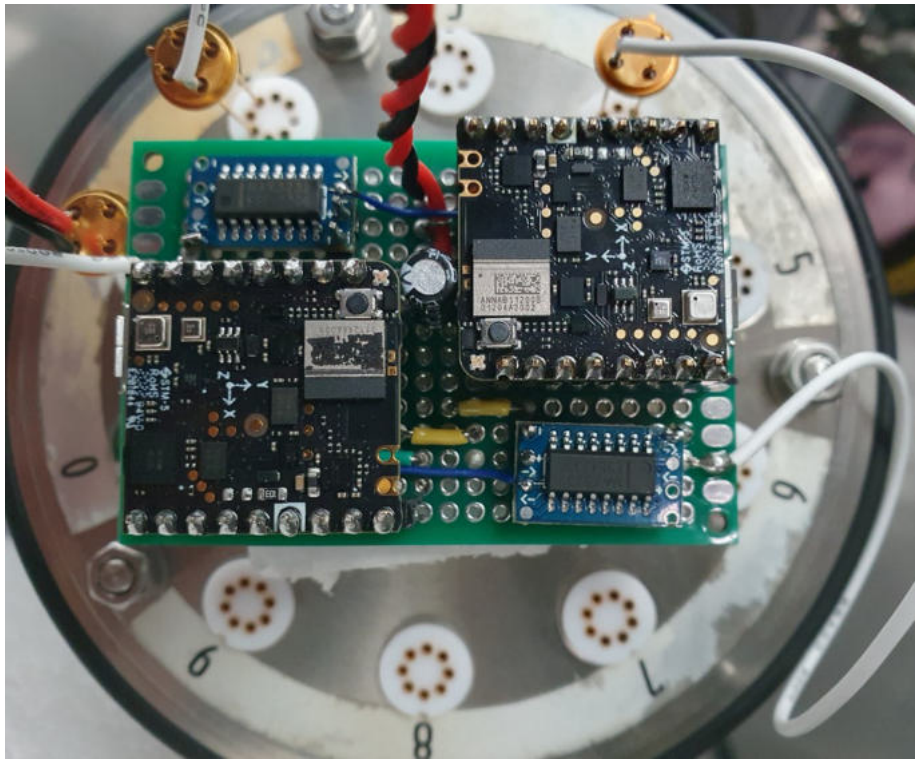
- The BME688 is a **metal oxide sensor** (MOX) that detects gases by absorbtion (and oxidation/reduction reactions) on its sentitive layer.
- **Selectivity** is the ability of a gas sensor to distinguish and classify differnet gas compositions.
- Operating MOX layer at different temperatures changes reaction sensitivity and gives the possibility of **fingerprinting gas compositions**.



ADC and Sensor Heater operational modes: forced and parallel.

Preliminary Tests

ACS DY110 test chamber: 110 liters, temperature control from −40 °C to 180 °C ± 0.3 °C.

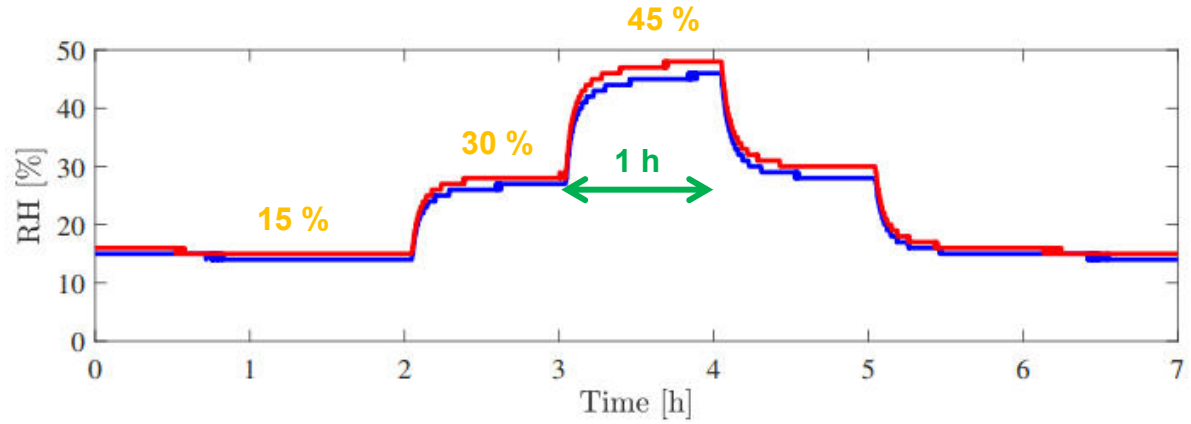


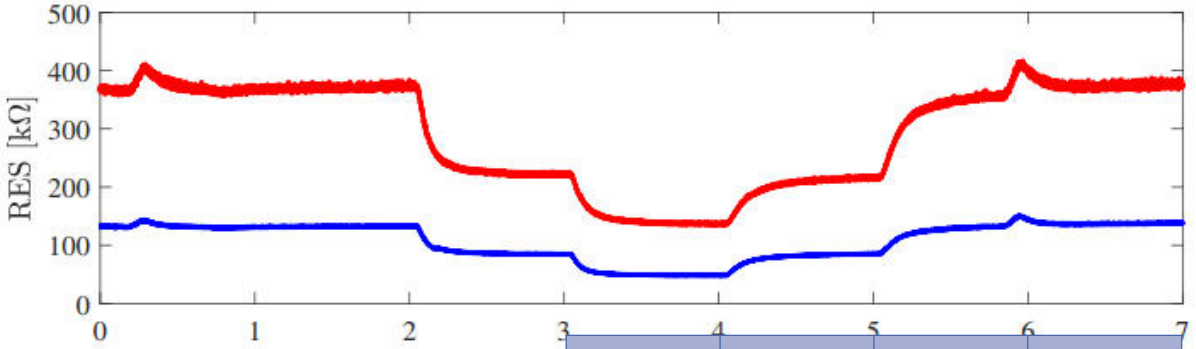
Custom stainless-steel fluxing chamber (1 L) located inside M120-TBR climatic chamber and details of the connection of the Nicla Sense ME to metallic transistor outline.

Temperature, Pressure & Humidity Dependance

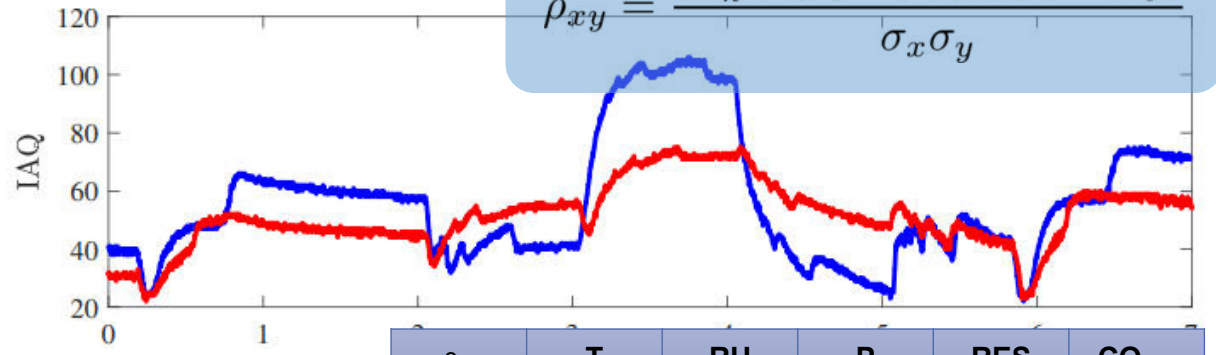
Pearson correlation of RH, IAQ, CO2, RES for two Nicla boards at 20 °C in the thermal chamber; no injected speciem.

$$\rho_{xy} = \frac{\sum_k (x[k] - \mu_x)(y[k] - \mu_y)}{\sigma_x \sigma_y}$$

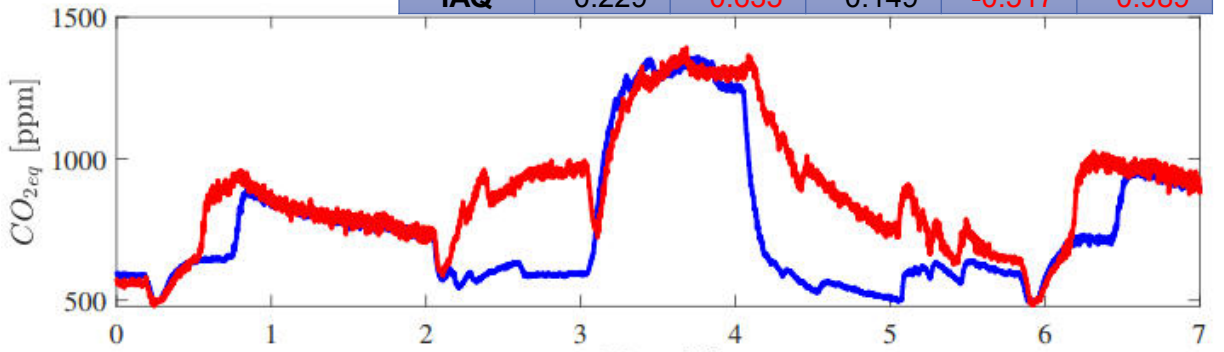




ρ_{xy}	T	RH	P
RES	-0.703	-0.978	0.221

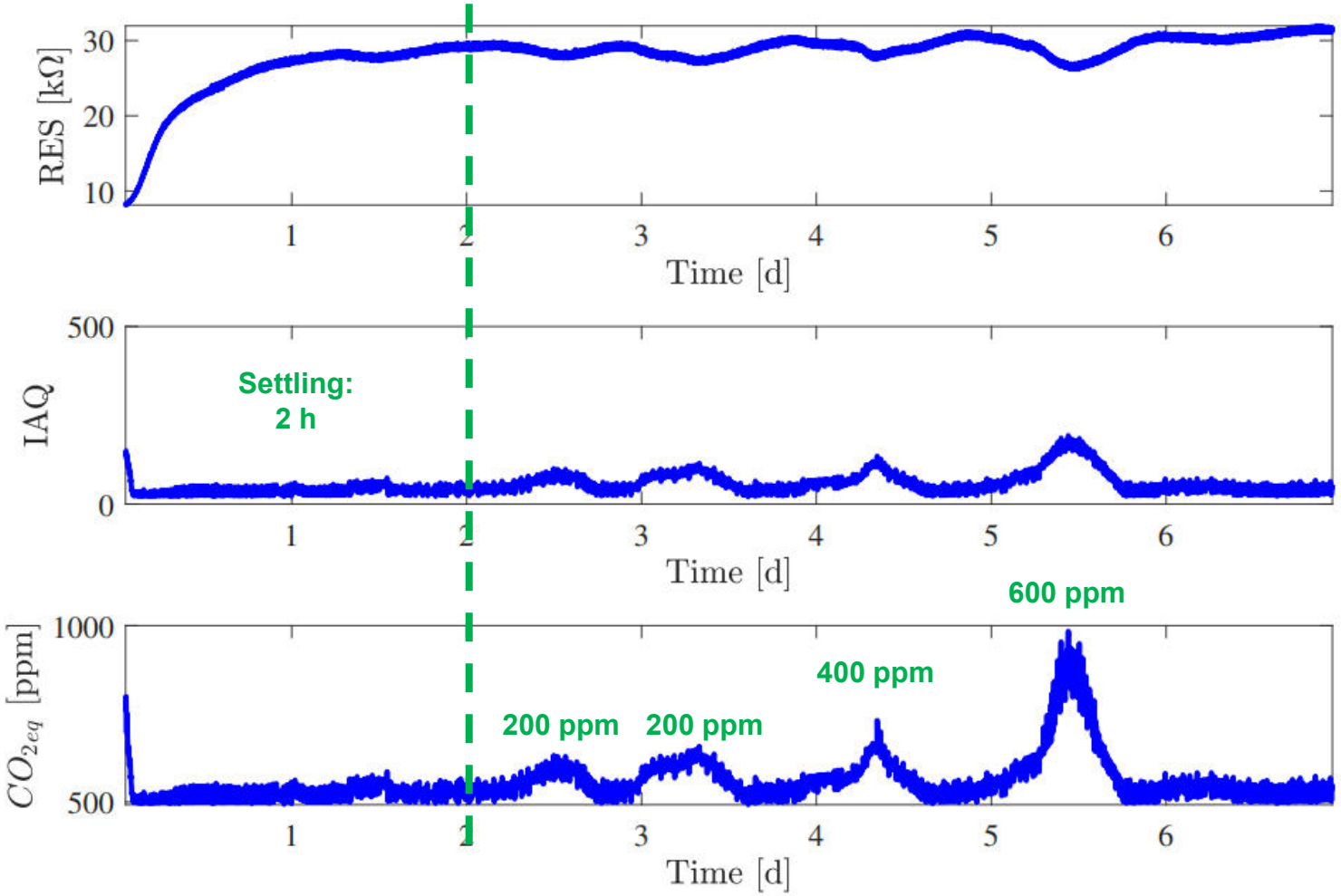


ρ_{xy}	T	RH	P	RES	CO_{2eq}
IAQ	0.229	0.635	0.149	-0.517	0.989



ρ_{xy}	T	RH	P	RES
CO_{2eq}	0.277	0.690	0.113	-0.568

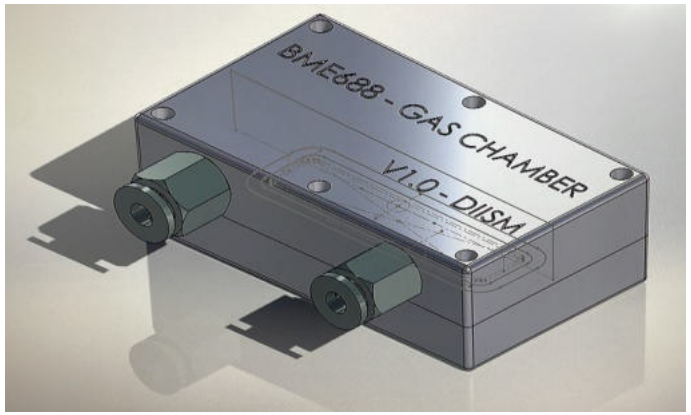
Fluxing Chamber CO_2 Results

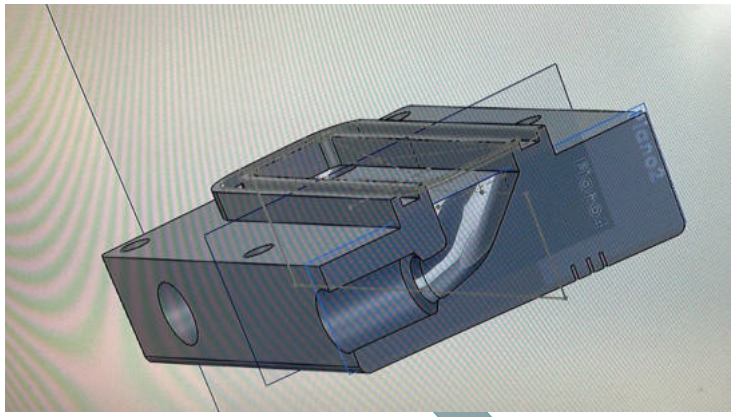


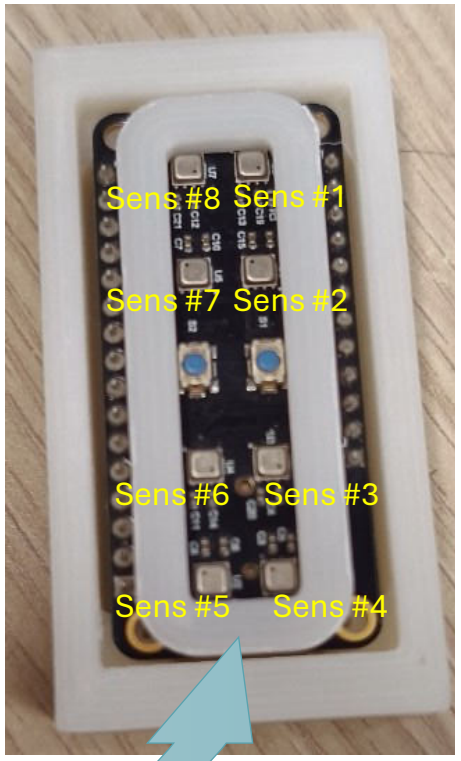
- Temperature: **25 °C**
- Relative Humidity: **40 %**
- CO_2 Injection: **15 min @ 200/400/600 ppm**

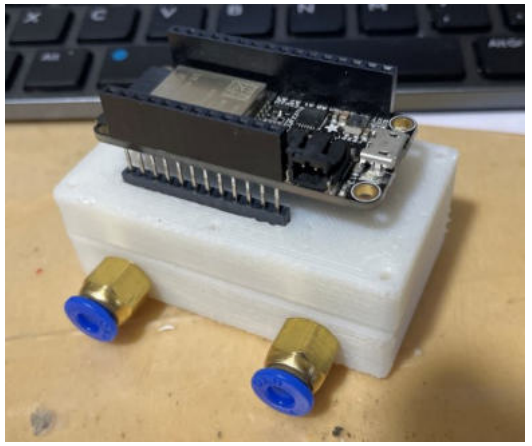
Custom BME688 Gas Chamber

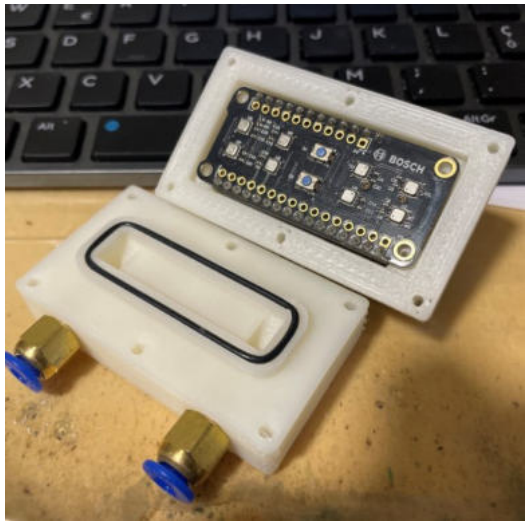
- The Device Under Test was placed in a **custom-designed gas chamber**, fabricated using 3D printing in **ABS material**.
- This chamber enables the delivery of **reference gas mixtures** with a controlled and known flow keeping it sealed by ensuring proper fluid dynamics condition during gas test.







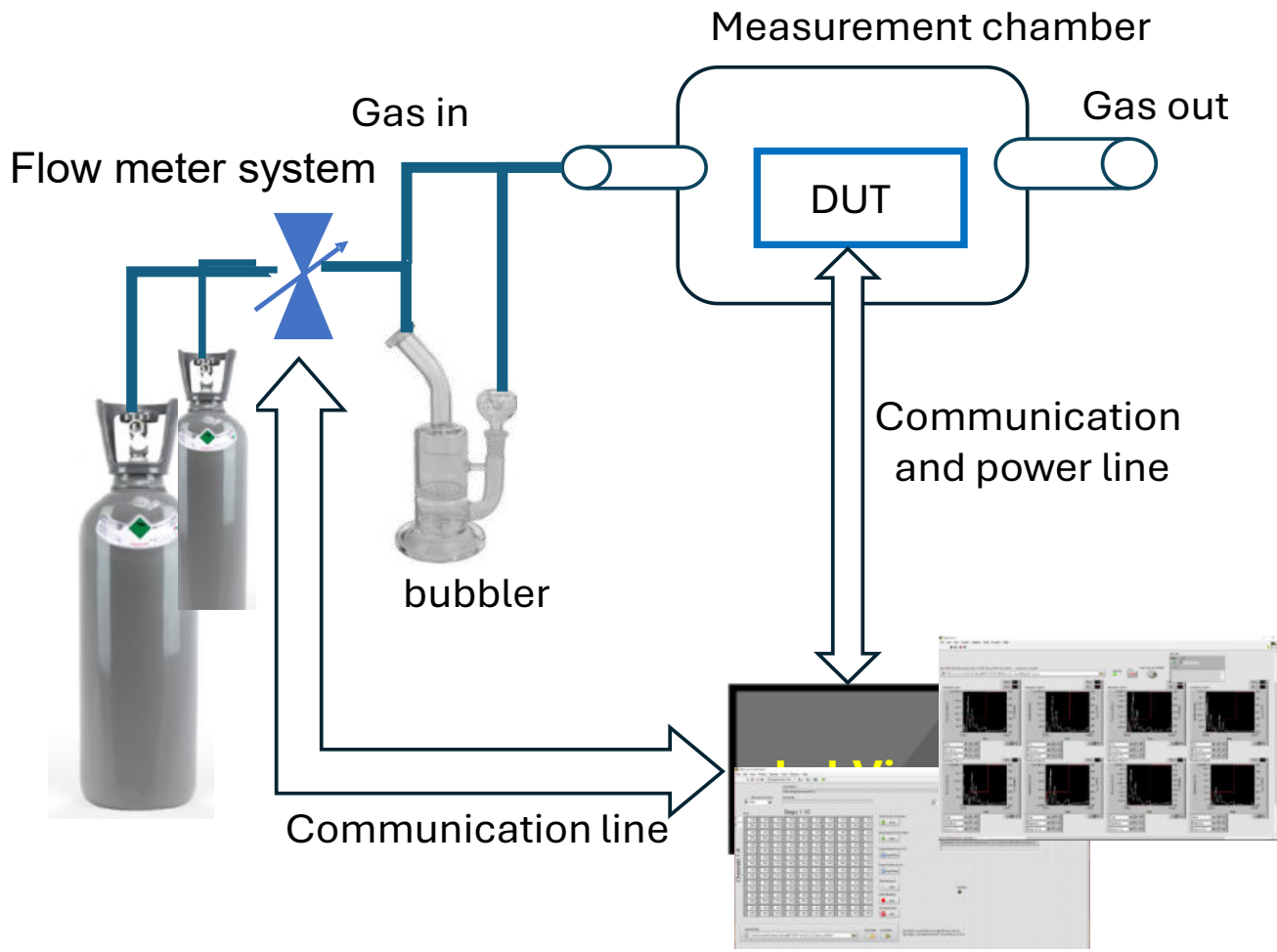




Test chamber housing the BME688 Development Kit

Gas Injection Setup

- Carrier gas: **air**
- The **humidity level** obtained by mixing dry airflow with the dry synthetic airflow saturated in a bubbler containing ultrapure water
- Different gas species with varying concentration:
  - nitrogen dioxide, **NO_2**
  - Isobutylene, **C_4H_8** .
- Sampling interval: **1960 ms**
- Flow meter: **BronkHorst F-201C**
- Total flow kept constant to **100 ml/min**
- Communication with DUT via a USB (virtual serial)
- Dynamic set the 8 BME688 sensors heater profiles profiles, and to read the raw resistance data, save and display measurements



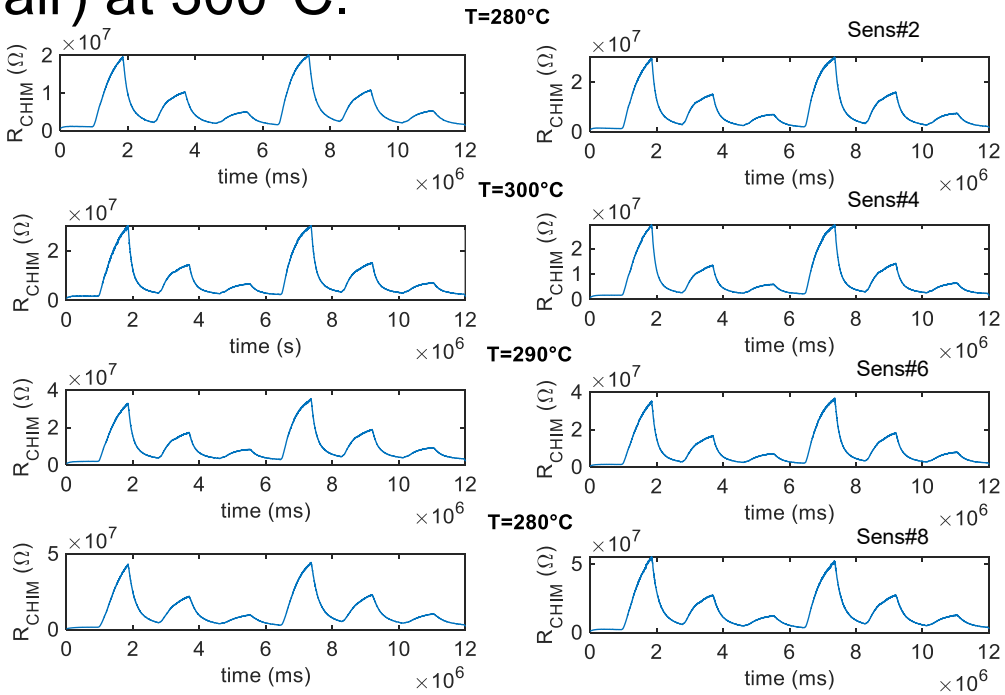
Experimental Gas Sensor Response

Given the manufacturing process of this type of sensor, slightly differences are observed among the evaluated sensors in terms of **baseline resistance R_0** (in dry air), and gas **amplitude response** (% at 2 ppm of NO_2 in dry air) at 300°C.

T \ R_0	Sensor Baseline Resistance [MΩ]							
	#1	#2	#3	#4	#5	#6	#7	#8
300° C	1.22	1.02	0.642	0.576	0.901	0.325	0.997	1.19
380 °C	1.84	1.86	1.35	1.38	1.65	1.02	1.40	1.75

$$Resp = \frac{R_{sens} - R_0}{R_0} \times 100$$

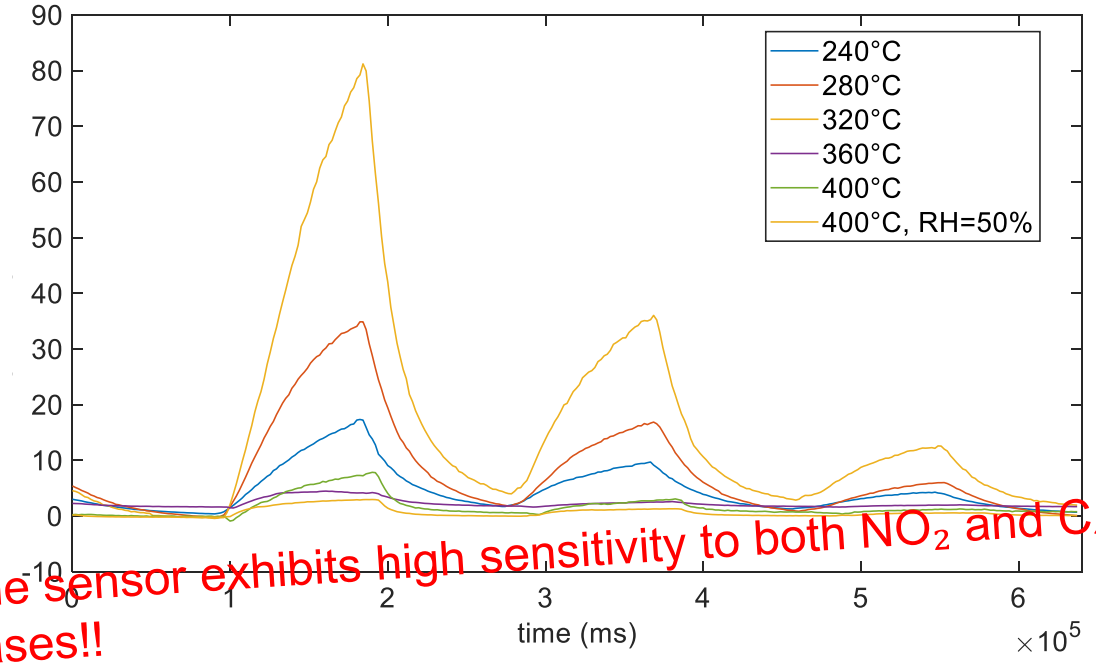
T \Resp	Sensor Response							
	#1	#2	#3	#4	#5	#6	#7	#8
300 ° C	485	387	601	611	488	634	370	311



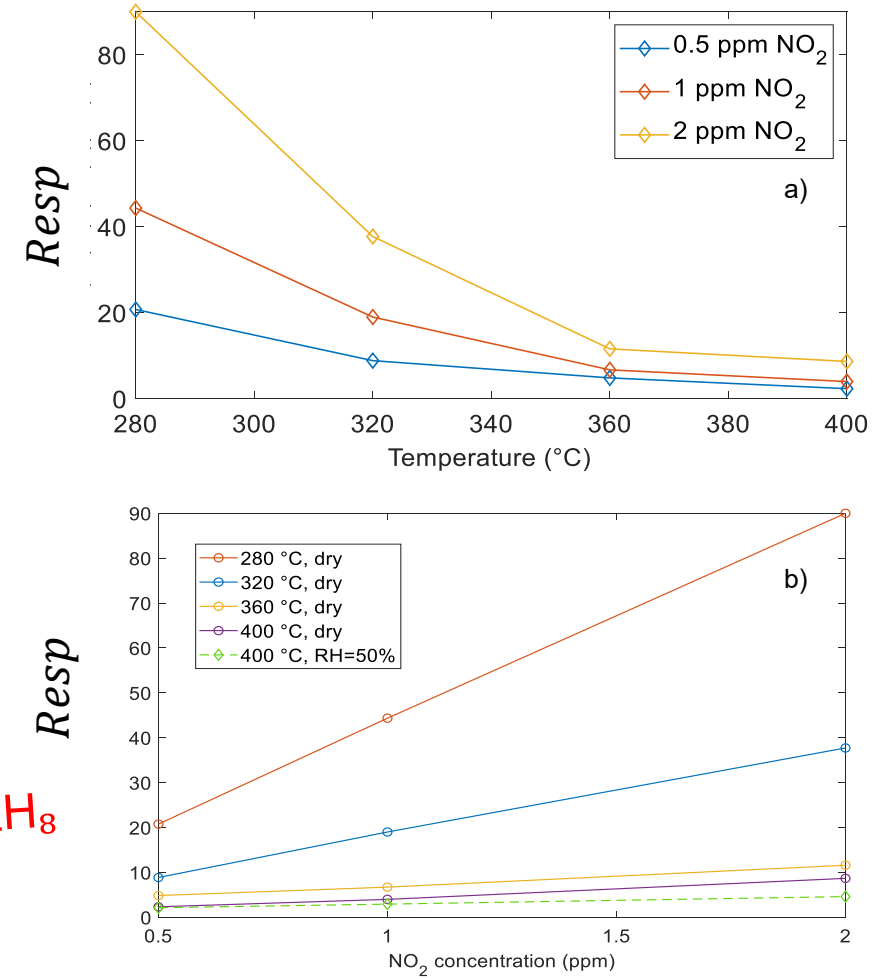
Example of **NO_2 sensor response** in time for the **8 BME688** sensors operating simultaneously in pairs at the same temperature. Gas concentration: **2 ppm , 1 ppm and 0.5 ppm** alternated to pure air gas phases. Gas duration phase: **15 minutes**.

NO_2 Sensor Response

- Gas concentration varies in pulses of **2 ppm**, **1 ppm** and **0.5 ppm** alternated to pure air pulses.
- **Different working temperature** were tested
- Gas phases duration: **15 minutes**



The sensor exhibits high sensitivity to both NO_2 and C_4H_8 gases!!



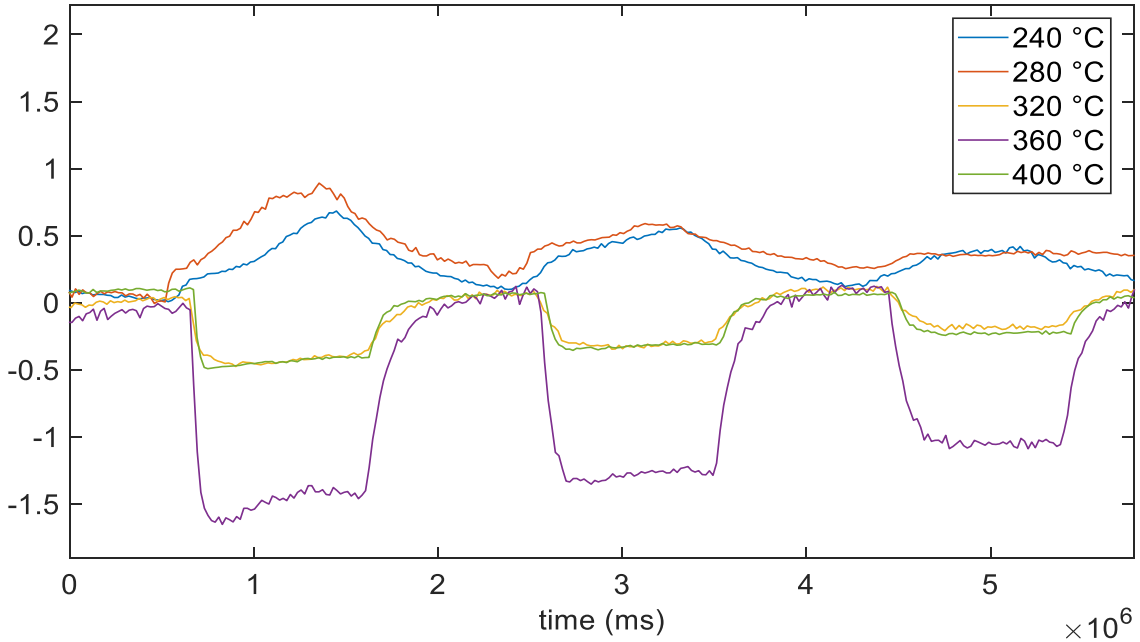
$$Resp = (R_{CHIM_g} - R_0)/R_0$$

value of the chemical resistance at the end of the target gas exposure phase

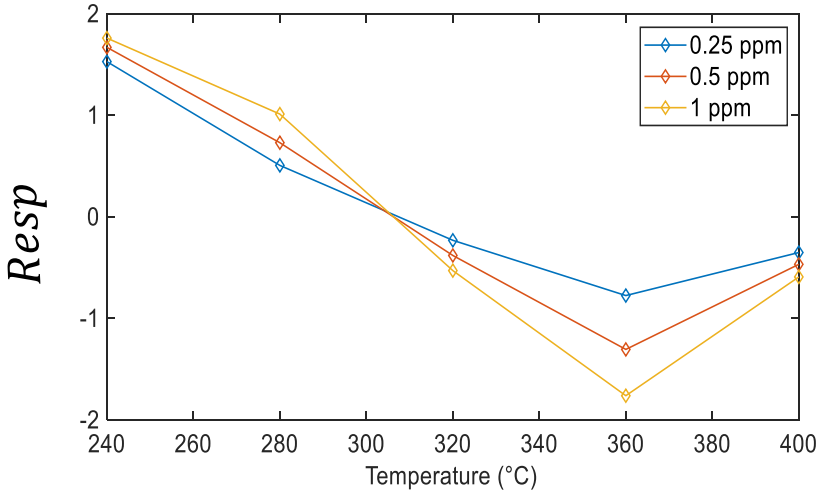
Sensor response with different temperature (a) and NO2 concentration (b)

C_4H_8 Sensor Response

- Gas concentration varies in pulses of **1 ppm, 0.5 ppm and 0.25 ppm** alternated to pure air pulses
- **Different working temperature** were tested
- Gas phases duration: **15 minutes**

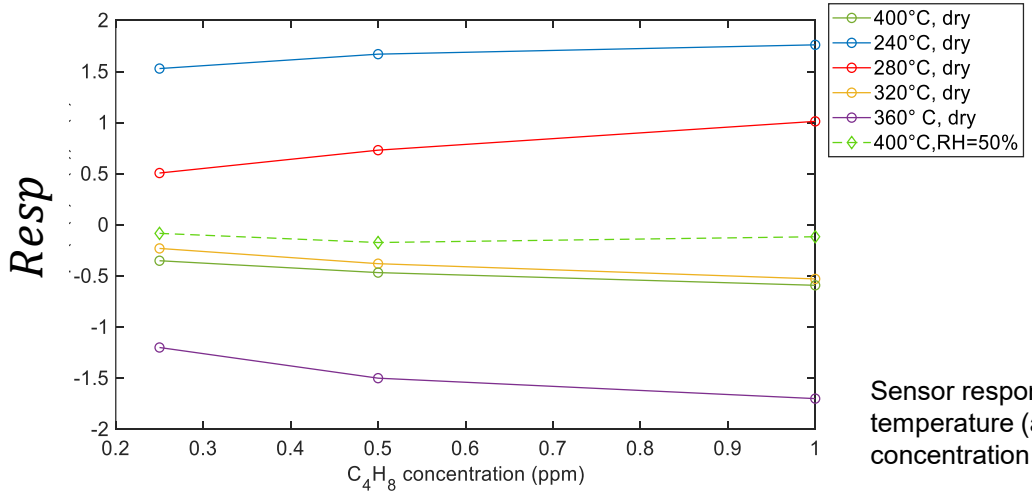


Normalized sensor response with respect to the R0 evaluated in air



$$Resp = (R_{CHIM_g} - R_0)/R_0$$

value of the chemical resistance at the end of the target gas exposure phase



Sensor response with different temperature (a) and C4H8 concentration (b)

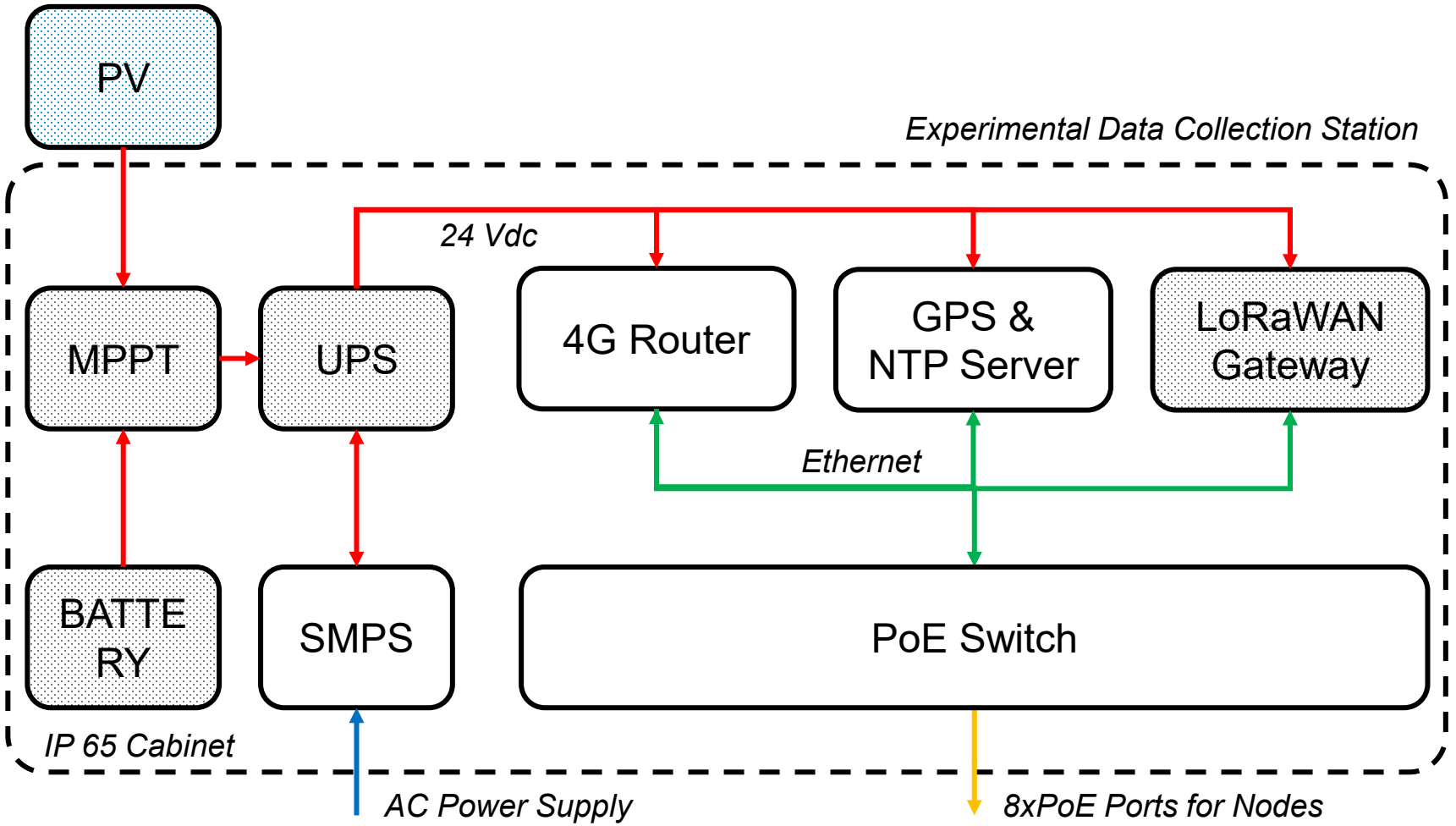
Dynamic Sensor Response

The sensor shows **long response and recovery time** at the considered gas concentrations. In some of the tested conditions, the sensor is unable to fully recover to its baseline state as well as to reach the steady state in target gas.

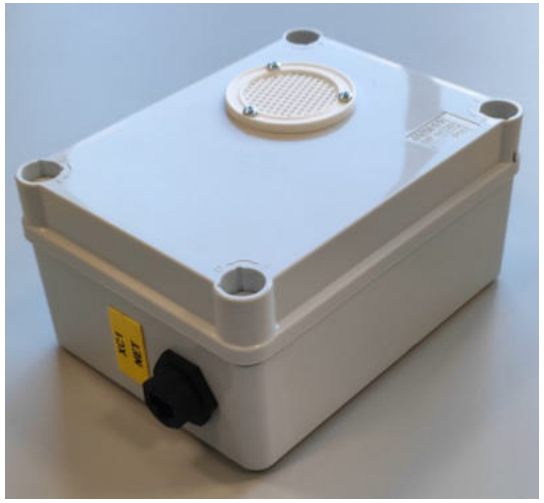
	280 °C	320 °C	360 °C	400 °C
	NO2 (@2 ppm)			
Response time	>15 min	>15 min	>15 min	>15 min
Recovery time	>15 min	>15 min	>15 min	12 min
	NO2 (@1 ppm)			
Response time	>15 min	>15 min	>15 min	>15 min
Recovery time	>15 min	>15 min	10 min	10 min
	NO2 (@0.5 ppm)			
Response time	>15 min	>15 min	>15 min	8 min
Recovery time	>15 min	>15 min	8 min	4 min
	NO2 (@2 ppm) RH=50%			
Response time	not evaluable (n.e.)	n.e.	n.e.	>15 min
Recovery time	n.e.	n.e.	n.e.	3 min
	NO2 (@1 ppm) RH=50%			
Response time	n.e.	n.e.	n.e.	4 min
Recovery time	n.e.	n.e.	n.e.	3 min
	NO2 (@0.5 ppm) RH=50%			
Response time	n.e.	n.e.	n.e.	2 min
Recovery time	n.e.	n.e.	n.e.	3 min

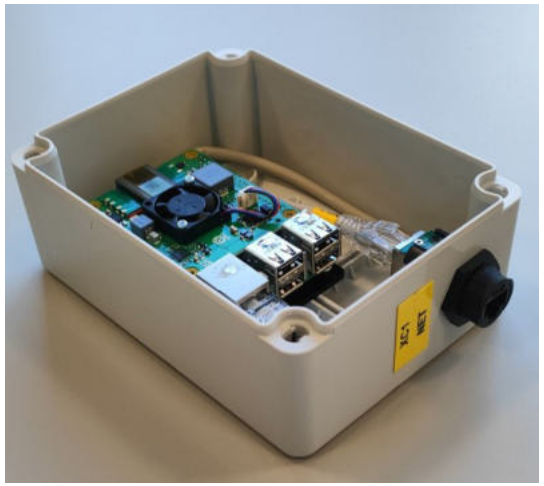
	240 °C	280 °C	320 °C	360 °C	400 °C
	isobutilene (@1 ppm)				
Response time	>15 min	12 min	1.3 min	1 min	0.8 min
Recovery time	>15 min	15 min	9 min	7 min	5 min
	iso (@0.5ppm)				
Response time	>15 min	10 min	2.2 min	1.8 min	1.2 min
Recovery time	>15 min	12 min	9 min	7 min	5 min
	iso (@0.25ppm)				
Response time	>15 min	2 min	3.6 min	2.7 min	2 min
Recovery time	>15 min	10 min	9 min	7 min	5 min
	iso (@1 ppm) RH=50%				
Response time	n.e.	n.e.	n.e.	0.5 min	0.5 min
Recovery time	(n.e)	n.e.	n.e.	3.5 min	3.5 min
	ISO (@0.5 ppm) RH=50%				
Response time	n.e.	n.e.	n.e.	1.7 min	1.7 min
Recovery time	n.e.	n.e.	n.e.	3.5 min	3.5 min
	ISO (@0.25 ppm) RH=50%				
Response time	n.e.	n.e.	n.e.	1.9 min	1.9 min
Recovery time	n.e.	n.e.	n.e.	3.5 min	3.5 min

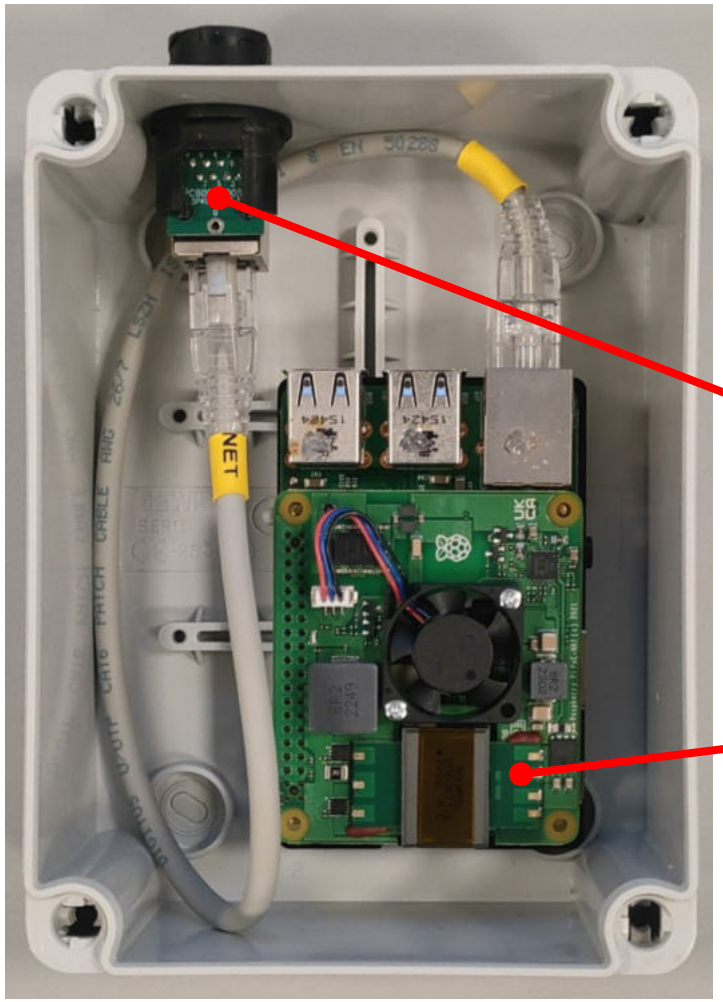
Upcoming Experimentation (1)



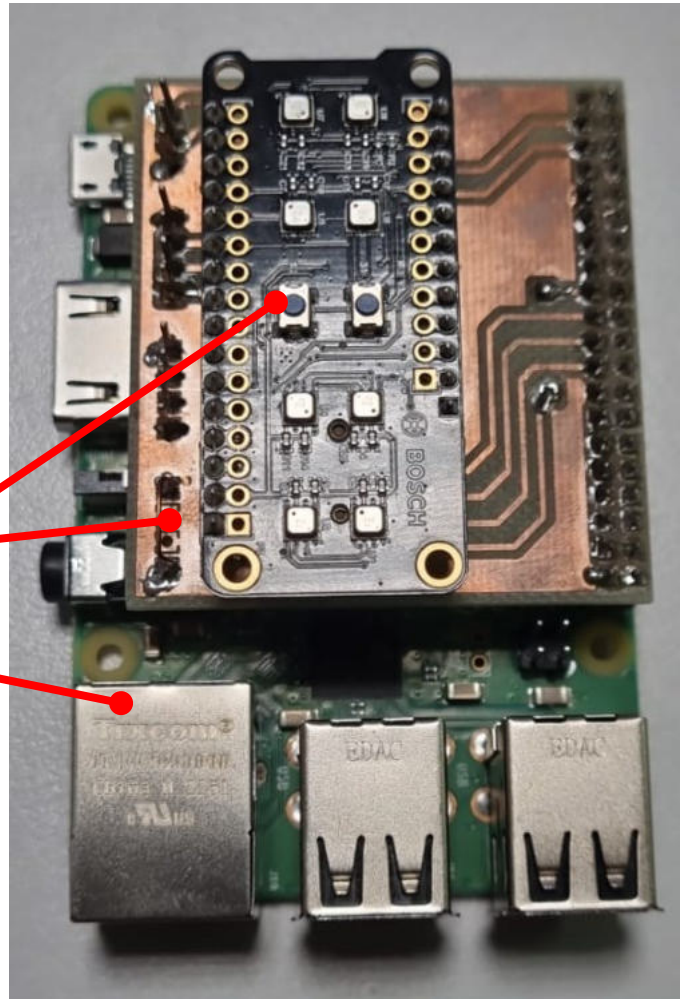
Upcoming Experimentation (2)



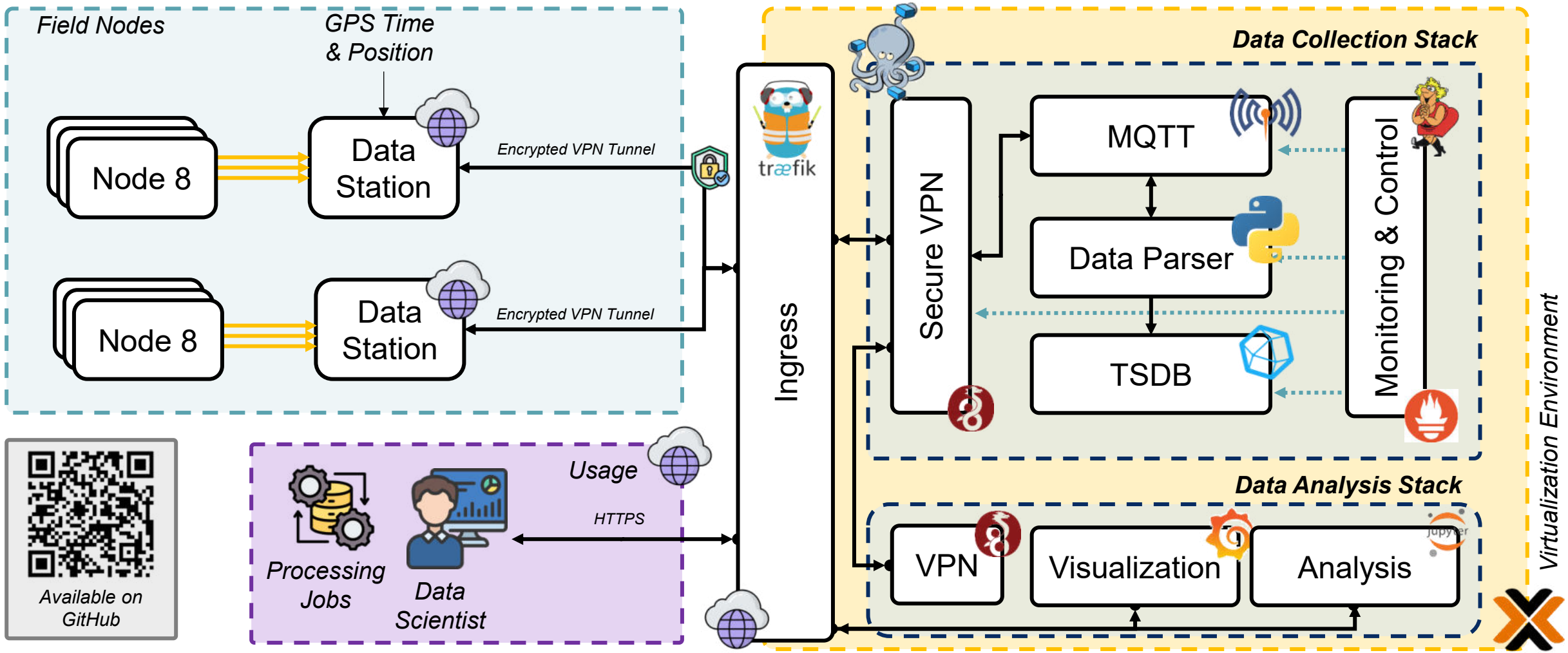




- IP65 RJ45 Ethernet Connector
- Bosch BME688 Development Kit
- Adapter Board
- Raspberry Pi 3 Model B+
- Raspberry Pi PoE HAT



Data Collection Infrastructure



Related Works & Contact

E. Panzardi et Al. «*Assessing BME688 Sensor Performance Under Controlled Outdoor-like Environmental Conditions*» Sensors 2025, 25(23),
doi: 10.3390/s25237102

E. Panzardi et Al. «*Towards Sustainable Mobility Through Smart Pollution Monitoring: The BME Sensor Case Study*», 2025 IEEE International Workshop on Metrology for Automotive (MetroAutomotive),
doi: 10.1109/MetroAutomotive64646.2025.11119271

S. Botticini et Al. «*Index Air Quality Monitoring for Light and Active Mobility*», *Sensors* 2024, *24*(10),
doi: doi.org/10.3390/s24103170

Salvatore Dello Iacono, Ph.D
Department of Information Engineering
Università degli Studi di Bresica, Brescia, Italy