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D3.1 – Sensor Requirements

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1 Executive Summary

The HYDRA project aims to develop a monitoring tool to detect and quantify hydrogen leakages along the value chain. To scale the TRL of the sensor, after development and lab tests at AUT premises to validate the correct functioning of the tool, two different types of tests are envisioned:

1- Controlled tests in a hydrogen tunnel (Environment Park in Turin, Italy), where different leakages will be simulated;

2- Tests in real environment, where leakages will be monitored in a storage facility at CERTH (Thessaloniki, Greece).

In this document, areas of interest for the detection and quantification of any hydrogen leakage within the CERTH case study are identified and analyzed. This process included a thorough assessment of risk zones and operating conditions that could affect leak detection. Specifically, to assess the types of potential release, a HAZOP (Hazard and Operability Study) study was conducted in collaboration with CERTH. This study considered the impact of potential deviations using design information and was developed to identify both hazards and operational issues at the hydrogen (H2) storage facility. This study is reported in Deliverable 3.2.

In addition, the regulatory constraints to which the sensor must comply are reported and described. These constraints include safety and environmental regulations which are specific to hazardous gas detection, as well as the technical standards that the sensor must meet to ensure effective and safe operation. Compliance with these regulations is essential to ensure that the sensor operates reliably and that hydrogen leak measurements are accurate and timely.

The deliverable is structured in 6 chapters:

- **Chapter 2** gives an overview of the hydrogen tunnel;
- **Chapter 3** presents the CERTH test site;
- **Chapter 4** lists the sensor requirements;
- **Chapter 5** provides a description of the SAT (Site Acceptance Test) for the system validation process;
- **Chapter 6** draws the conclusions and plans the work ahead.

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2 Validation tests in a hydrogen tunnel

The HYDRA monitoring system will be tested at the Environment Park in Turin (geolocation shown in Figure 1), a technology park that houses a wind tunnel, where the monitoring system will be installed to validate the sensors' performance. The wind tunnel provides a controlled environment that is ideal for simulating different wind conditions and hydrogen leakages and evaluating system performance accurately and reliably. The partner Politecnico di Torino (POLITO) will be responsible for managing the tests and simulating the different wind conditions, as well as conducting various simulations of H2 leaks via H2 releases. Results of these tests will be presented in D3.4.

Figure 1 Geolocation of Turin with detail of the Environment Park

2.1 The hydrogen tunnel and HYDRA tests

The wind tunnel, denominated "hydrogen tunnel" for the tests related to hydrogen that are there performed, is an open-flow, subsonic structure which is 6 meters long, 5 meters wide, and 2 meters high. To ensure safety, the tunnel is equipped with barriers that prevent the release of gases if the doors are not completely closed or if the fans are not in operation. The wind speed can be adjusted in a range from 0 to 8 m/s, with a maximum available power absorption of up to 100 kW.

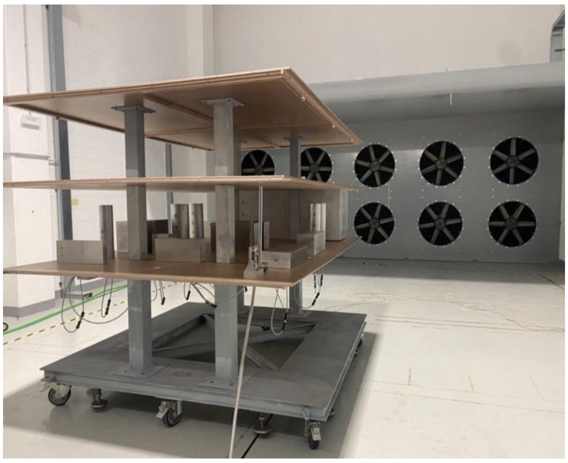
a)  b) 

Figure 2 Wind tunnel (a) and offshore mock-up platform (b)

Currently, tests are conducted on an offshore mock-up platform (as shown in Figure 2), equipped with hydrogen sensors to monitor dispersion concentration. The wind tunnel is equipped with a sophisticated

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supply line that allows the supply of gas at different pressures. Hydrogen, carbon dioxide (CO_2) and other gas mixtures can be supplied, providing the versatility needed for a wide range of experiments and simulations.

The wind tunnel test area (which is identified by means of floor markings) is classified as ATEX ZONE 1. This classification indicates that the area is subject to a risk of explosion due to the presence of explosive atmospheres, such as mixtures of flammable gases, vapors, or dusts.

To perform validation tests for the HYDRA sensor, a point hydrogen emission source is available as shown in Figure 3. The emission takes place with a nominal pressure of 5-10 bar. The scale of the experiment, to be determined at the beginning of the tests, will provide the real scale value of this range of pressures. For example, a release at 10 bars on the 1:10 scaled mockup offshore platform corresponds to 50 bars of pressure at real scale. This means that, although releasing gas at relatively low pressures, the test will be representative of a wide range of real case scenarios.

Figure 3 Hydrogen emission source

All tests will be scheduled through a test matrix that will be shared among the partners directly involved with the laboratory/real tests.

This matrix is being scheduled according to the characteristics of the wind tunnel and specifically, for experimentation with pure hydrogen, some constraints need to be addressed:

- **Physical constraints:** The wind tunnel is capable of generating atmospheric wind with speeds in the range of 0-8 m/s with non-ATEX fans. The wind tunnel has been characterized without obstacles and is able to generate a uniform speed model through transverse planes (parallel to the plane of the fans). Once the mock-up is installed in the tunnel, the flow is perturbed and it is therefore complicated to classify it as laminar or turbulent, especially within the mock-up where the test will take place. Deliverable 3.2 reports an average of the wind speeds measured in 2023 and the range goes from 2.5 m/s to 3.2 m/s, for this reason HYDRA tests will be carried out with a range from 1 m/s to 5 m/s.

- **Security constraints:** The current configuration has been certified to be safe in use when a minimum wind speed of 1 m/s is present and a minimum of 5 bar of release pressure is

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achieved This is due to the need to avoid the formation of gas pockets in the ceiling. For security reasons, tests without wind are thus not possible.

2.2 Compliance to regulations

To comply with ATEX regulations, all equipment and operating procedures within the test zone must ensure safety and prevent accidents. The regulations related to an ATEX ZONE 1 configuration are:

- **ATEX 2014/34/EU [1]:** Regulates requirements for products intended for use in explosive atmospheres;
- **ATEX 1999/92/EC [2]:** Defines the minimum health and safety requirements in workplaces with explosive atmospheres.

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3 Test in real environment

After the hydrogen tunnel campaign, the HYDRA monitoring system will then be installed at CERTH (Thessaloniki, see Figure 4), in a hydrogen cylinder storage site. The partner CERTH will be responsible for managing the tests with AUT support. Results of these tests will be presented in D3.6.

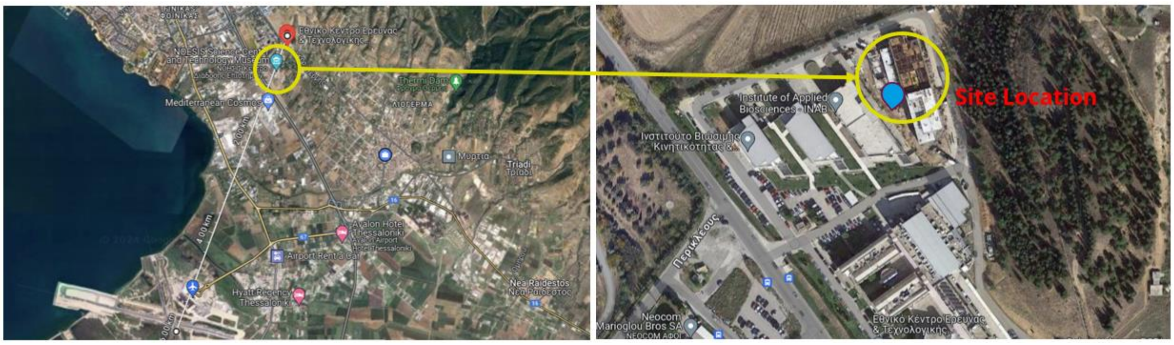

Figure 4 Detail of the CERTH geolocation

3.1 The storage site and HYDRA tests

Currently, the storage site has two areas of interest for monitoring H2 leaks:

- Cylinder Hydrogen Storage Area;
- Control panel.

The storage area consists of 33 high-pressure storage bundle, which operates at a pressure of 35bar. The cylinders formation in the bundle follows the Pressure Equipment Directive (PED) (2014/68/EU) and can be easily considered as fixed installation. In fact, the bundle can be i) refilled in situ, ii) expanded by adding more bundles in stacked design, and ii) transported to another place in case of another future project. The bundle is not fixed to the ground and can be moved with a forklift or a crane

The control panel acts as a real hydrogen distributor, taking H_2 from the cylinder system and distributing it to the CERTH work areas. According to studies conducted by CERTH, micro-hydrogen leaks could occur in this area, probably caused by the presence of different components working together (e.g. control valves, shut-off valves, safety valves, regulators) to ensure safe and efficient distribution of hydrogen in work areas. Based on CERTH preliminary evaluation, the control panel could be a relevant monitoring point and will thus be included in the monitoring area during the tests.

3.2 Compliance to regulations

The peculiarity of the installation site lies in the classification of the different areas according to ATEX regulations. The control panel area is designated as ATEX ZONE 1, indicating an environment where explosive atmospheres are likely to occur during normal operations. In contrast, the cylinder storage area is not classified as an ATEX zone, suggesting a lower risk of explosive atmospheres. The area set up by CERTH for the installation of the monitoring system is instead classified as ATEX ZONE 2, where the presence of explosive atmospheres is less frequent and only in the event of failures or abnormal conditions. Sampling is carried out through a tubing system through which the sample is taken from the critical areas and conveyed into the analysis system, which is located in ATEX ZONE 2.

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Figure 5 shows the area of the CERTH case study.

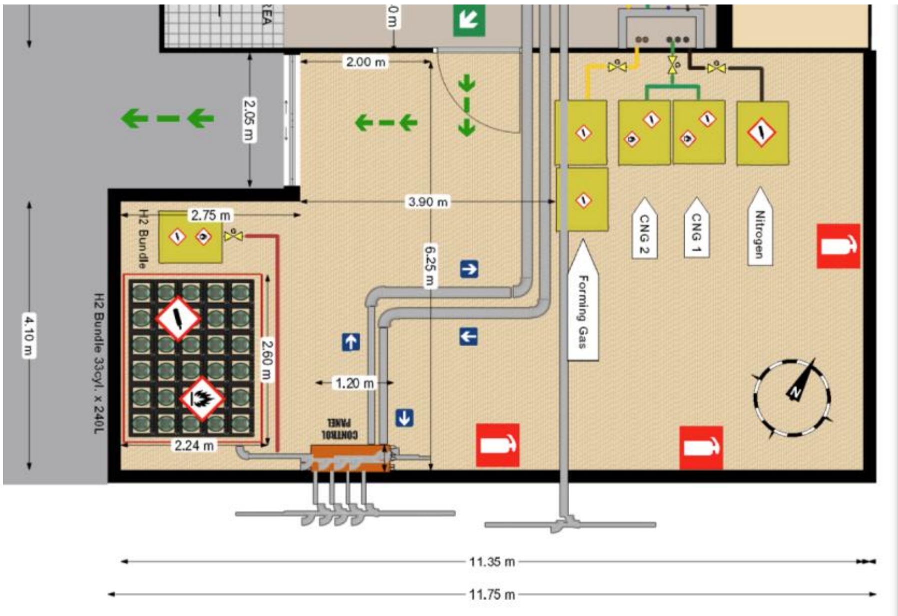

Figure 5 Area of the CERTH case study

Considering the different aspects of the installation and the mitigation measurements that have been considered during the design phase, it was decided to classify the entire area as ATEX ZONE 2.

As for the POLITO tests, during the execution of the tests, a matrix will be created to guide the testing activities.

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4 HYDRA technology and requirements

The technology AUT used to develop the sensor is based on Raman spectroscopy, which can detect multiple gases at the same time, excluding noble gases, and works quickly without the need to prepare the sample.

AUT monitoring system consists of three macro blocks:

- **The sampling unit**, which consists of a tubing system (designed to reduce the risk of sparks and ensure uniform sample collection) and a pump (ATEX classified).
- **The optical drive**, well protected inside an ATEX-certified box. The unit consists of a spectrometer, a laser source, and other equipment necessary for sample analysis.
- **The control system**. A PC connected to the optical unit allows the acquisition, analysis and storage of sensor data. Measurements can be accessed in tabular format, data can be filtered and graphically shown in real time. The data can also be printed. An alert mechanism is included that allows for alarm management and provides specific thresholds for hydrogen values (alarm threshold >1%).

All design specifications and technical characteristics of the individual components are reported in D3.3.

4.1 Technical requirements

The HYDRA monitoring system has set KPI targets to reach, as reported in Table1.

Table 1 Key Performance Indicators

Description	Value
Detection limit	0,1 – 100%
Response time	< 60 sec
Accuracy	> +- 0.1%
Lifetime	> 2 years
Working temperature	-15 to 50°C
Working humidity	0 to 95%

AUT has developed a system that meets the KPIs.

At the moment, the only tricky KPI is the system lifespan, which is mainly related to the laser source used. The more measurements are taken, the shorter the laser lifespan. Assuming continuous sampling and uninterrupted use of the laser, the laser source lifespan is estimated at approximately 1 year (up to 10,000 hours).

Currently, alternatives are being studied to decrease the laser usage time so that the lifespan increases (e.g., sampling for 30 seconds every minute, the system lifespan reaches approximately 2,28 years).

Furthermore, correct maintenance and correct use are essential to maximize the system lifespan. AUTOMA has already proposed to draw up a maintenance plan for the system once the project is completed.

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4.2 Safety requiriments

As previously explained in paragrphs 3.2 and 4.2, the sensor must comply to the ATEX regulations related to the different case studies.

4.2.1 Hydrogen tunnel

In November 2024, AUTOMA and POLITO carried out an inspection at the hydrogen tunnel, veryfing that the testing area is classified as ATEX ZONE 1 due to a situation of forced loss simulated during the tests. In addition, within the controlled area, there are dispensers of hydrogen and other gaseous mixtures. Everything that is installed within this area must guarantee safety standards that comply with current regulations. AUTOMA has thus developed a system compliant with the ATEX ZONE 1 classification.

4.2.2 Storage site

Initially, as described in deliverable 3.2, only the cylinder storage area was defined as a monitoring area which, according to the assessments carried out by CERTH, is not to be considered as an explosive risk area.

Greek and European legislation stipulates that the maximum hydrogen concentration limit in an area must not exceed 25% of the LEL (equivalent to 1% of H2 in the air) to trigger the emergency alarm. If the hydrogen concentration reaches 40% LEL (equivalent to 1.5% H2 in air), an automatic emergency shut-off valve must be activated and the filling process must stop.

Considering the worst-case scenario according to the CERTH risk assessment of the storage area (such as accidental pipe rupture or an unattended major release), with a maximum flow rate of 500 l/min, an emergency response time of approximately 120 seconds, and no air velocity, the release of H2 will be 1% into the air in the area. Therefore, this area is not considered an ATEX zone.

However, following internal analyses conducted by CERTH and thanks to the inspection carried out in October 2024 by AUT at the installation site, it emerged that the control panel is an area with a potential risk of explosion, so it was necessary to incorporate it into the monitored area.

According to the data that CERTH has provided to AUT at a later stage, the hydrogen sensor that AUT has developed will be systematically positioned above the area of greatest potential leakage, i.e. the storage area, in particular between the control panel and the stationery package.

The panel is classified ATEX ZONE 1 while the area where the monitoring system will be installed is classified as ATEX ZONE 2. For development convenience, AUT decided to develop the prototype directly conforming to ATEX ZONE 1 (given the same applies to the hydrogen tunnel).

This specificity caused several problems during the design phase, as some non-ATEX components were initially planned. The problem was solved by placing all these components inside a box which, thanks to its technical characteristics, guarantees compliance with ATEX ZONE 1 regulations.

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4.3 Environmental requirements

In addition to safety regulations, the sensor must comply with certain environmental regulations that ensure that it does not contribute to environmental contamination and is able to operate in specific environmental conditions without degrading or losing accuracy.

The relevant regulations are:

- **UNI CEI EN 45544-4:2016 [3]:** Guidelines on the selection, installation, use and maintenance of electrical instrumentation for the detection and direct measurement of the concentration of toxic gases and vapours in working atmospheres;
- **CEI EN 50402 (2017-11) [4]:** requirements for the functional safety of fixed gas detection systems;
- **UNI 10752:1999 [5]:** general requirements and criteria for gas detection systems, including details of how the sensors are to be designed and maintained.

These regulations were thus considered in the set up of the tool, as well as in the selection of its components.

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5 SAT Analysis

The Site Acceptance Test (SAT) is a crucial step in the system validation process, where it is verified that the installation and operation of the system at the customer site meet the specified requirements. Typically the SAT is performed after the system has been installed and configured in its final operating environment.

In this specific case, the SAT will be performed for both the tests that will be performed at the Turin wind tunnel and at the final installation site at CERTH.

5.1 Objectives of the SAT

- **Installation Verification:** Ensure that the system is installed correctly according to the technical specifications and technical drawings;
- **Compliance with Requirements:** Verify that the system meets all design requirements;
- **Operational Safety:** Ensure that the system operates safely, without risk to operators or the environment;
- **Documentation:** Confirm that all necessary documentation, including operation and maintenance manuals, is complete and accurate.

5.2 SAT Procedures

1- Preparation

- Define a plan of activities to be carried out, the times and resources needed;
- Prepare a test matrix for system validation.

2- Execution

- Visually check that the system installation has been done according to the technical drawings, ensuring that all components are installed correctly. This procedure will be carried out entirely by AUT personnel who hold this information. This activity requires at least a couple of people and 2 days of work;
- Measure the system performance to ensure that it meets the specified requirements. These measurements will be reported for each test performed.
- Verify that the system operates safely. This point will be fulfilled once the system is certified ATEX ZONE 1, so no further supplementary tests will be necessary.

3- Documentation of Results

- ATest Report will document all tests performed, the results obtained, and any anomalies found. The report must also include the corrective actions taken to resolve any problems. For these tests, the presence of 2 people is required (both for the tests that will be performed at POLITO and for the tests at CERTH) and the duration of these tests will depend on the various situations hypothesized in advance and the results obtained. In this

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case, AUT will play a secondary role as it will be a support in the event that technical problems occur.

- Each report must be confirmed by the personnel employed to perform the tests.

4- SAT Acceptance Criteria

- The system must satisfy all project requirements.
- There must be no anomalies or defects that could compromise the functioning or safety of the system. Only any system bugs that will not affect the system itself will be accepted.
- All required documentation must be complete, accurate and shared with partners in order to evaluate actual performance in different environments and serve as a point for reflection and improvement.

In this regard, AUT is proceeding to complete the test matrix that will be shared among the partners in order to refine it as much as possible and make it more accurate and realistic for the tests that can be carried out.

For this reason, the partners, first POLITO and then CERTH, will be actively involved in this activity in order to arrive at the day of installation with the documentation ready to be used.

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6 Cocnlusions

AUT has developed an innovative monitoring system for hydrogen leak detection, seamlessly integrating hardware and software components. This state-of-the-art system guarantees continuous and accurate surveillance, combining advanced sensors with intelligent algorithms to offer a complete and reliable solution.

The monitoring system has been meticulously designed to ensure compliance with current safety and environmental regulations. This compliance is crucial to ensure that the sensor operates reliably, providing accurate and timely measurements of hydrogen leakage. The system design took into account all technical and legislative requirements, integrating advanced technologies and safety protocols to prevent any environmental or health risks.

Currently, AUT is engaged in optimising the design of the prototype with the aim of improving space efficiency and making the solution easier to integrate in different installation areas. This optimisation process involves an in-depth review of the size and arrangement of components to ensure that the system can be adapted to various operating contexts without compromising its performance. The focus is on making the prototype not only more compact, but also more versatile, to meet the specific needs of each operating environment.

In order to significantly improve the functionality and reliability of the monitoring system, making it more efficient and safer, AUT is also making improvements in terms of software and firmware. More specifically:

- For the software, the detection algorithms are being optimised in order to increase accuracy and reduce false positives. Machine learning techniques are being implemented to adapt the system to environmental variations. In addition, AUT is working on the development of a more intuitive and user-friendly User Interface to facilitate interaction and management of the system, which will allow the integration of real-time data visualisation functions for better analysis and monitoring. Finally, given the extreme interest in the subject at a global level, AUT plans to strengthen its IT security systems in order to protect sensitive data and prevent unauthorised access, implementing any advanced cryptography protocols for data transmission;

- For the firmware, bugs are being fixed to improve and optimise performance. This includes the release of regular updates, as well as the implementation of an automatic update system to ensure that the firmware is always up-to-date. Performance optimisation includes improving the firmware's energy efficiency and reducing the system's response time to ensure faster detection. In addition, extensive tests will be conducted to verify the stability and reliability of the firmware under different operating conditions, and a continuous monitoring system will be implemented to detect and resolve any problems in real time.

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