HYDROGEN INDUSTRY-RELATED ACCIDENTS AND FUNCTIONAL SAFETY

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Abstract
Hydrogen is being touted as the fuel of the future and will play a key role in the transition to sustainable energy supply. This alternative energy source is gaining increasing attention due to its high energy content, zero-emission usability, and almost unlimited production potential. The widespread adoption of the hydrogen economy on a societal scale requires safe and reliable operation. In Hungary, expanding hydrogen mobility necessitates building a new refueling network, which poses safety challenges due to direct consumer interaction. Currently, accident statistics indicate approximately 10 hydrogen-related incidents annually worldwide, with significant regional variations in severity. The main obstacle to the technology's adoption is the number and severity of these accidents, as hydrogen is a flammable gas and its use involves numerous risks. Safety is the most crucial factor for the smooth development and social acceptance of new technologies. In this article, safety solutions and risk management measures for hydrogen technologies will be discussed, with particular focus on simulation-based approaches to mitigate risks at hydrogen refueling stations.

Keywords: *hydrogen science, safety engineering, accidents, gas mapping, simulation*

1. Introduction

The transition to sustainable energy systems has positioned hydrogen as a promising alternative fuel for the future. With its high energy content, zero-emission usability, and extensive production possibilities, hydrogen has attracted significant attention from both industry and policymakers (Staffell et al., 2019). However, the widespread adoption of hydrogen technology faces challenges related to safety concerns that must be addressed through comprehensive risk management strategies.

This article aims to analyze hydrogen-related accidents, identify their causes and consequences, and propose safety measures based on simulation results and established safety standards. The research utilizes event tree analysis and computational fluid dynamics simulations to develop practical recommendations for hydrogen refueling stations.

Accident figures based on databases that record hydrogen industry-related accidents reveal concerning patterns. Data from the French ARIA, BARPI, Japanese RISCAD, American CSB, NETL, HTP, and HySafe databases (accessed January 2023) indicate a total of 626 recorded hydrogen industry-related accidents in the last 60 years, which translates into an accident rate of 10.43 accidents per year. *Figure 1* shows the distribution of the number of hydrogen technology related accidents in Europe, NA, Asia, Africa. It can be deduced, that Europe accounts for about 60% of these accidents, because Europe has the most hydrogen filling facilities in the world and every accident is documented here.

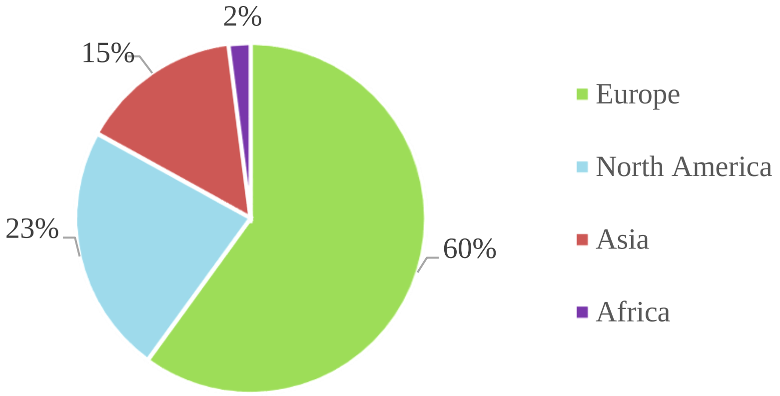

Figure 1. *Geographical distribution of hydrogen industry-related accidents*

The specific injury rate was highest in North America with 547 people injured in 170 incidents, while in Europe 451 people were injured in 357 incidents. Africa has the lowest number of hydrogen industry-related accidents (4), but with 9 injuries and 7 deaths, it has the highest number of deaths per accident event *(Figure 2)*.

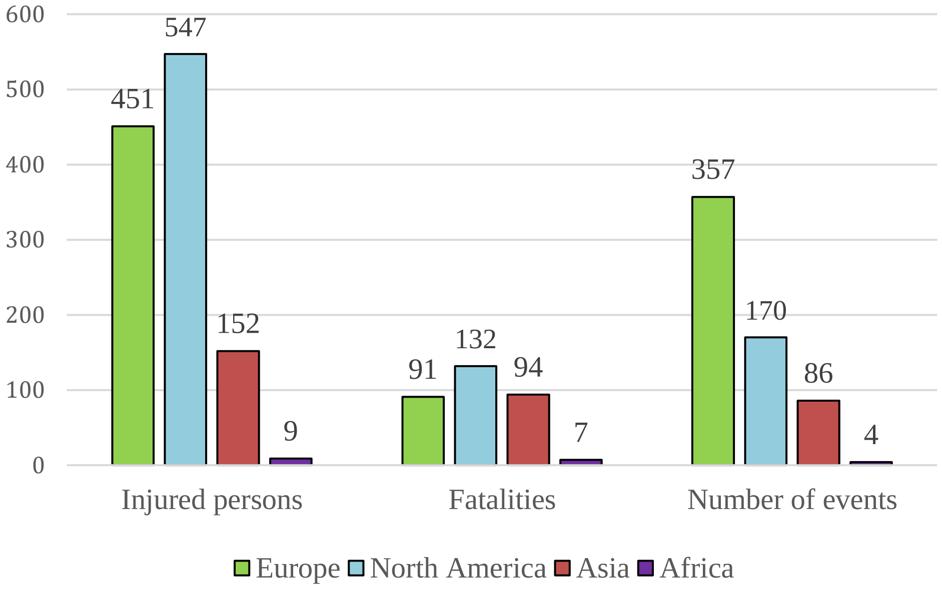

Figure 2. *Distribution of injuries and deaths*

The type and distribution of accidents *(Figure 3)* in descending order are: explosion (48%), fire (31%), and leakage without ignition (21%). István (2023) found that the accidents causing the highest number of deaths (59) and injuries (231) were primarily the result of design deficiencies, improper installation, inadequate supervision, and poor maintenance.

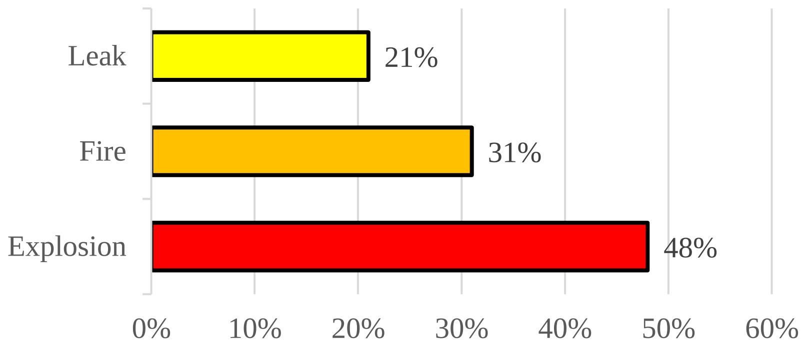

Figure 3. *Type and distribution of hydrogen industry-related accidents*

2. Causes and consequences

The root causes of incidents in hydrogen installations vary. They may be due to inadequate valve seals, connection failures, or installation deficiencies due to human error. Because hydrogen is stored under high pressure, accidents may occur more frequently compared to other fuel sources, with potentially more serious consequences. Hydrogen refueling station explosion accidents are typically preceded by hydrogen leaking from a connection or flange at high pressure. The hazards associated with an accident without an ignition source (e.g., lack of oxygen) are considered less critical than a fire or explosion caused by an ignition source. An event tree is defined as the set of event chains associated with a given initial event. The event tree consists of a network of lines representing the initial event, nodes, end events, and links. The branch points represent the criteria for the fulfillment of safety functions. *Figure 4* presents an event tree analysis for hydrogen refueling station accidents, where the most likely escalation sequence of gas explosion accidents is highlighted. In this analysis, different line types are used to distinguish between incident pathways: thin lines represent low probability paths, thick lines indicate high probability paths, and dashed lines show conditional paths dependent on external factors.

A comprehensive operational safety system is needed to mitigate hydrogen risks, as recommended by standards such as EIGA IGC Doc 224/20, NFPA 2, and ISO 19880-1:2020 (International Organization for Standardization, 2020). The possible consequences of a hydrogen leak are detailed in the event tree shown in *Figure 4*. Ignition sources are critical from a safety perspective because they determine the severity of potential consequences. A small unignited release or a jet fire, for example, will not generate an explosive load but will pose significant physical hazards or thermal loads. Unlike conventional explosives, pure hydrogen cannot explode in either pure or highly diluted form. An explosion can only occur when a mixture of hydrogen and air is present at a volume fraction of 4 to 77%, where even a static spark from clothing is sufficient to cause ignition (Molkov, 2012). The energy required to ignite hydrogen (0.02 mJ) is lower than that of other common fuels such as methane (0.29 mJ) or gasoline (0.24 mJ) (Rigas and Amyotte, 2013). The detonation pressure typically ranges between 15 and 20 bar, as documented in industry standards (EIGA, 2018). Loss investigation statistics from the industry show that approximately 25% of hydrogen fires are attributed to leakage, and about 40% of these leaks are not detected before the loss occurs (Kikukawa, 2007). If undetected, gas leaks can cause catastrophic fires and explosions. Because hydrogen is stored at extremely high pressures at refueling stations and leaks can occur relatively easily due to the small molecular size of hydrogen, leaks must be detected extremely quickly to ensure an adequate safety response. Next to the stages of the incident tree in *Figure 4*, appropriate sensors and detectors are listed that can detect risks (leakage, ignition source, combustion) at each stage, enabling early intervention. Hydrogen fires do not produce smoke, but the heat transmitted by radiation and convection can cause the burning of nearby combustible materials to produce smoke. Therefore, a hydrogen fire can only be detected with specialized flame detectors, as the flame length can exceed 100 meters (Kun et al., 2022).

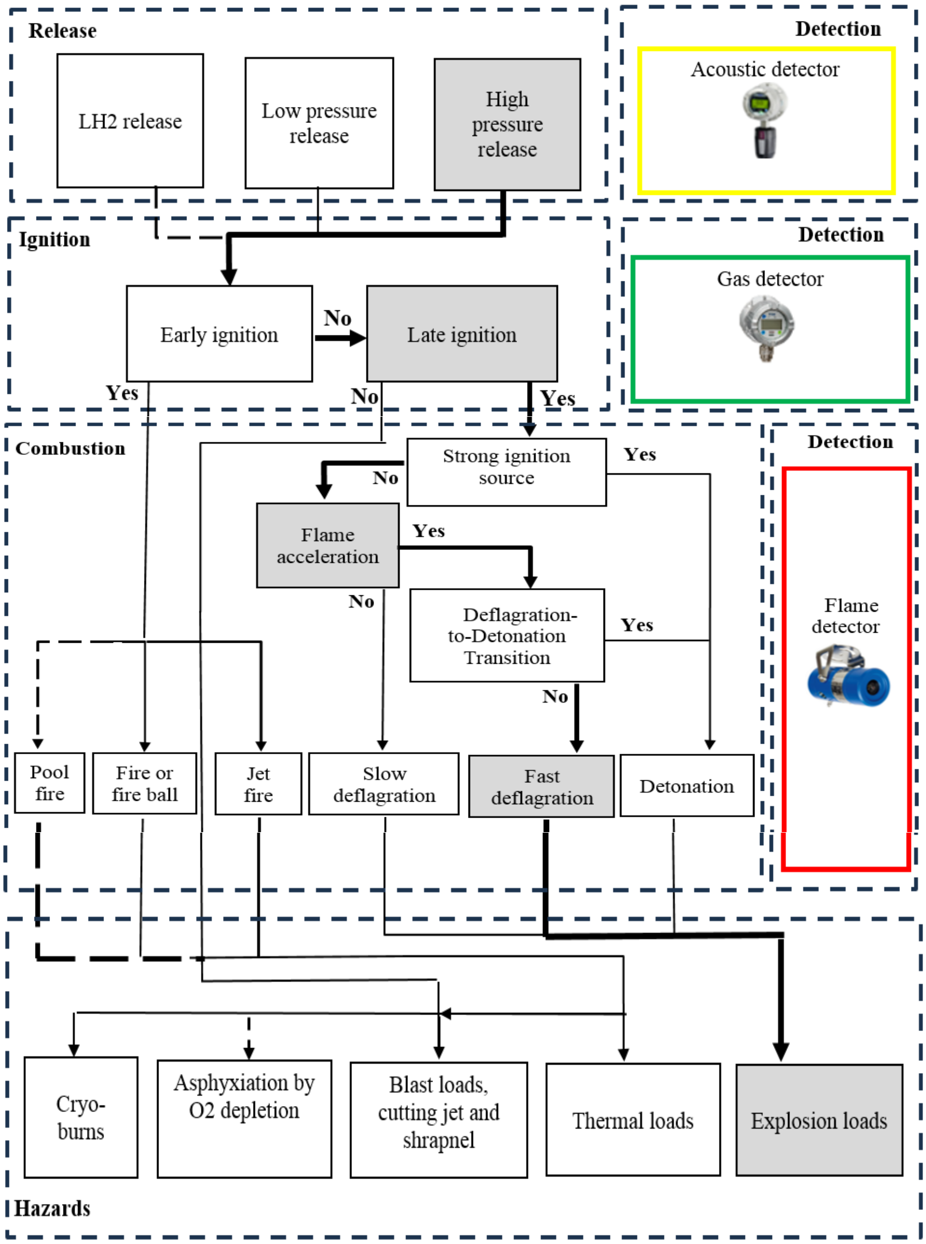

Figure 4. *Event tree analysis of a hydrogen refueling station explosion, showing detection equipment types at each stage*

3. Simulation results

The placement and coverage of sensors is key to effective detection and can be optimized through gas dispersion modelling. Using the process safety software PHAST Standalone 9.1, three-dimensional models of a hydrogen refuelling station were created, including essential elements such as compressor, cooling system, firewall, hydrogen storage tank, and hydrogen refuelling point. Simulations were conducted to model hydrogen leaks with an emission rate of 1 kg per second under varying wind conditions. These specific parameters were selected based on typical leak scenarios documented in hydrogen safety literature (Matteo et al., 2024) and represent a conservative approach to safety planning. The wind speeds chosen (1 m/s, 2 m/s, and 5 m/s) represent common environmental conditions that might be encountered at refueling stations, allowing for comprehensive risk assessment across different scenarios. *Figure 5* shows the results of a simulation with a north-westerly wind speed of 1 m/s (wind direction indicated by arrow). The firewall provides significant protection not only in case of fire but also in limiting the spread of hydrogen gas. The flammable gas cloud (yellow) disperses rapidly around the equipment due to the combination of light winds and hydrogen buoyancy.

Figure 5. *Hydrogen gas cloud propagation at 1 m/s wind speed (north-westerly direction)*

At wind speeds of 2 m/s *(Figure 6)*, it can be observed that the equipment becomes enveloped in a cloud of flammable hydrogen gas. The gas cloud extends up to the roof above the hydrogen refueling point, where it accumulates. This simulation clearly demonstrates how increased wind speed affects gas dispersion patterns.

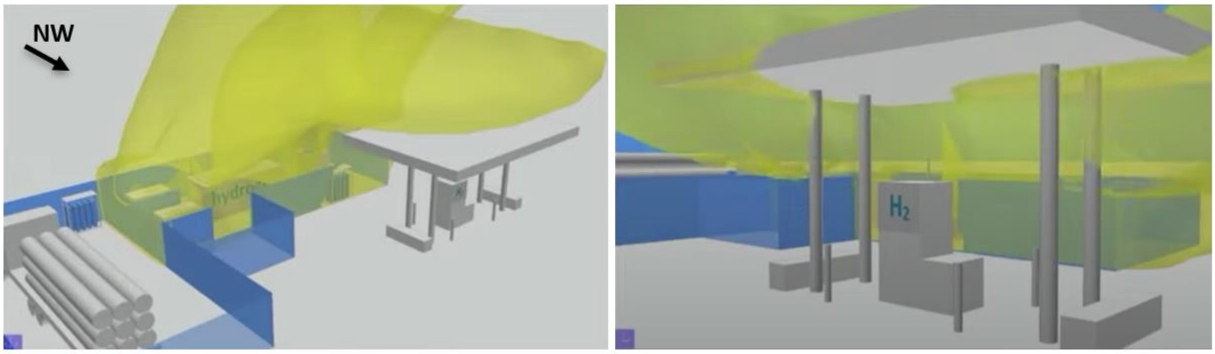

Figure 6. *Hydrogen gas cloud propagation at 2 m/s wind speed (north-westerly direction)*

With wind speed increased to 5 m/s *(Figure 7)*, the hydrogen gas cloud flows less vertically and more horizontally. The gas spread becomes flatter, and the cloud disperses at a lower level, reaching ground level in flammable concentrations. This simulation allows for the determination of appropriate safety distances between system components.

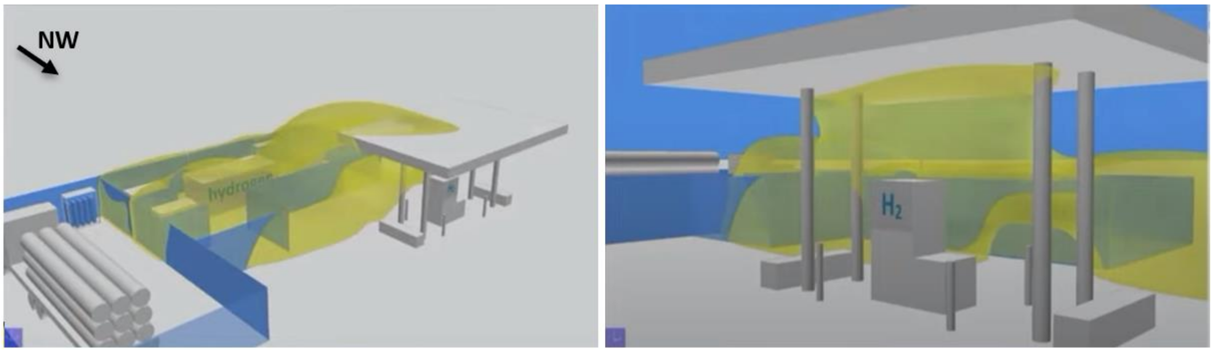

Figure 7. *Hydrogen gas cloud propagation at 5 m/s wind speed (north-westerly direction)*

Higher wind speeds allow for accumulation under the closed roof of the refuelling station. Based on these simulation results, it is recommended to maintain a minimum separation distance of 8 meters between the hydrogen refuelling point and storage facilities, which can significantly reduce risk during high wind conditions. This recommendation aligns with NFPA 2 guidelines, which specify minimum separation distances between hydrogen systems and various exposures (NFPA, 2020). Based on the model results, it is reasonable to prohibit the use of a roof over a hydrogen refuelling station, or to build a roof that is equipped with a ventilation chimney.

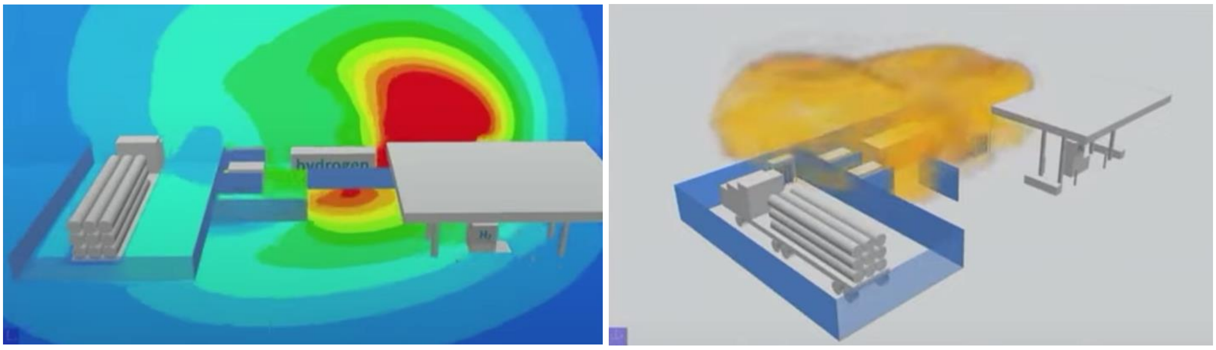

Figure 8. *Explosion analysis showing pressure contours and affected areas*

An explosion simulation was also conducted *(Figure 8)*, which helps to understand the potential effects of gas cloud propagation and accumulation. The simulation predicts that an explosion could generate pressures of up to 20 bar for a gas cloud of 2240 m^3, consistent with values reported in literature (Rigas and Amyotte, 2013). A flammable hydrogen-air mixture formed by hydrogen leakage will trigger sudden combustion and explosive loading when exposed to an ignition source. Safety inspection of hydrogen stations requires comprehensive data on hydrogen explosion characteristics, flame behaviour, and leak propagation patterns. If a fire occurs, appropriate suppression methods must be employed. These include chemical suppression systems such as sodium bicarbonate injection, which prevents combustion by chemical reaction; gas extinguishing systems like carbon dioxide, which reduce oxygen concentration; and specialized extinguishing agents such as FM-200, which eliminate fire through a combination of chemical and physical mechanisms (Matteo et al., 2024).

4. Sensor coverage and functional safety system

Based on the simulation results and manufacturer specifications, optimal placement of gas detectors and flame detectors for a hydrogen refueling station was determined *(Figure 9)*. The detection equipment selection was based on the following performance characteristics:

- Flame detectors with detection range up to 30 m and response time of 5 seconds
- Gas detectors with detection range of 5 m and response time of 5 seconds
- Ultrasonic acoustic leak detectors with detection range up to 20 m (Michael, 2019)

The sensor placement strategy aims to achieve maximum coverage with minimal equipment while ensuring redundancy for critical areas. Particular attention was paid to areas where hydrogen might accumulate, such as beneath canopies or near potential leak points, as identified in the simulations.

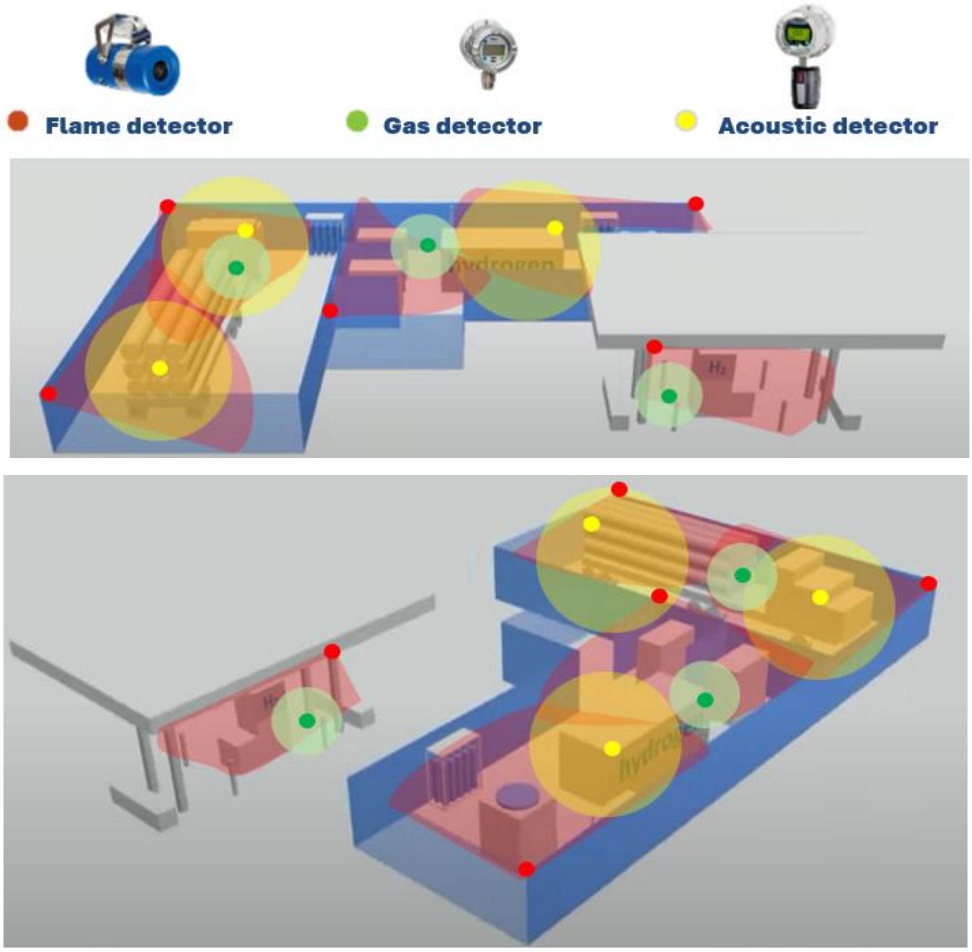

Figure 9. *Location and coverage of gas detectors and flame detectors at the hydrogen refueling station*

For hydrogen refueling stations, specific sensors must be integrated into a reliable safety network *(Figure 10)*. Functional safety is defined as a system in which, in response to a signal from a sensor or an alarm button, the logic system (PLC) activates a device to manage the hazard, such as ventilation or a magnetic switch/contactor, and operates an alarm at the charging station. The term "functional safety" applies when safety depends on the proper operation of a control system. However, functional safety encompasses more than just the current state of the charging station — life-cycle aspects are also considered in the assessment. Functional safety must distinguish between random and systematic failures. Systematic failures are those that are not statistically quantifiable and result from specific causes such as design, manufacturing, or maintenance failures.

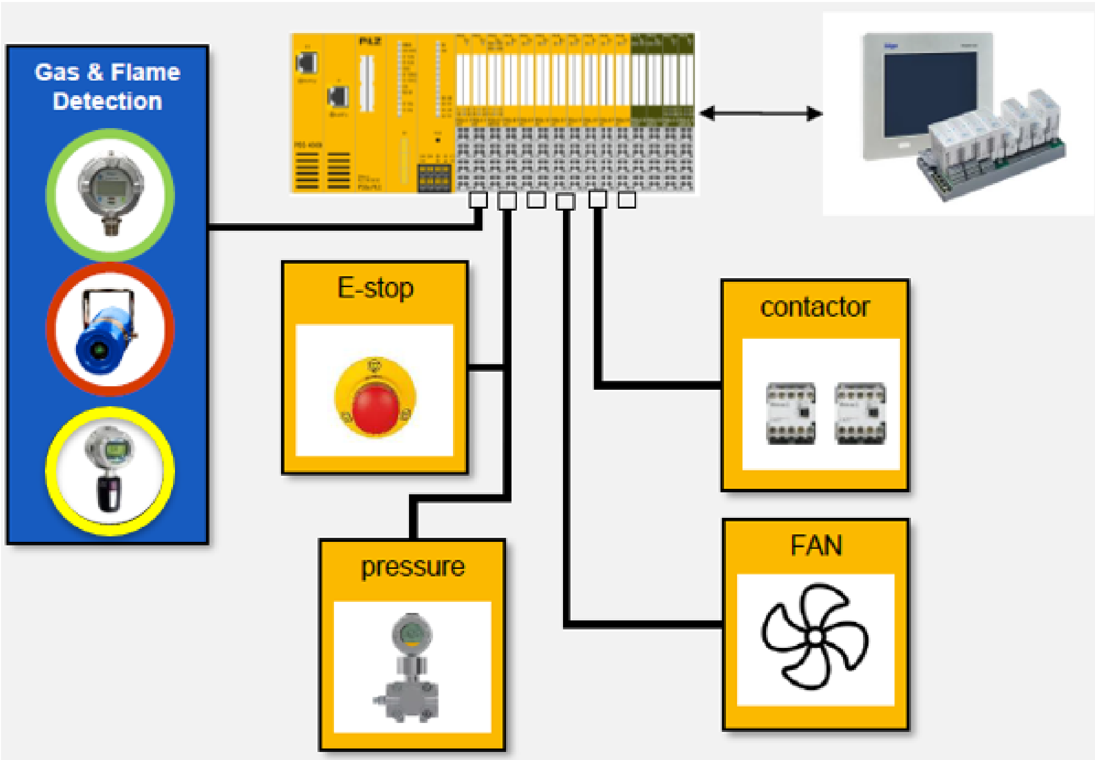

Figure 10. *Functional safety infrastructure architecture*

Figure 11 illustrates signal transmission and logic control in a single-channel security component. Proven solutions in automation technology complement classical security functions by ensuring that safety is considered as an integral function within the plant, machine, and process context. For hydrogen applications specifically, all electrical equipment in potentially explosive atmospheres must comply with appropriate standards such as IEC 60079 series or ATEX directives. Cables, contactors, and other components must be explosion-proof certified to prevent them from becoming ignition sources. The automation system should continuously monitor pressure, temperature, and gas concentration, maintaining safe operating parameters as specified in ISO 19880-1:2020 and EIGA guidelines.

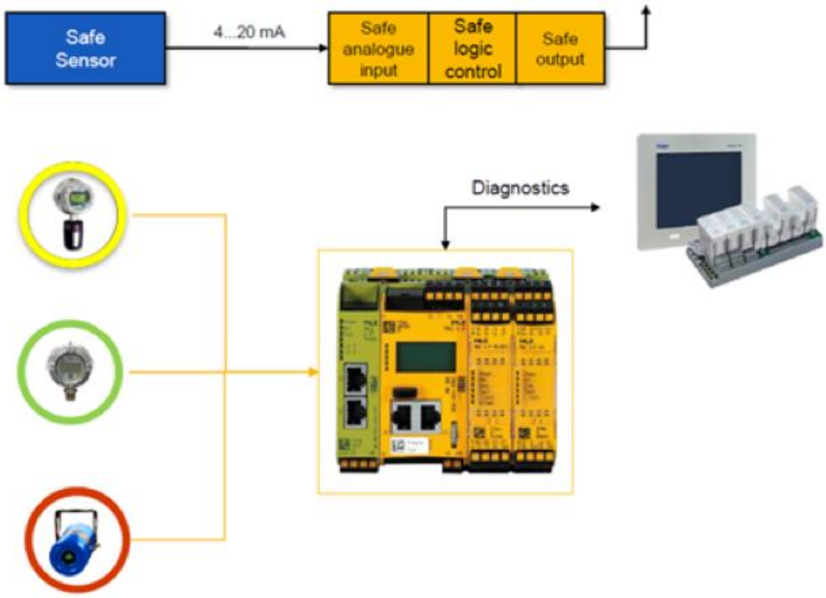

Figure 11. *Signal transmission concept for safety monitoring*

5. Conclusion

Hydrogen technology represents a promising component in the future renewable energy landscape. The analysis of accident statistics and simulation results presented in this article demonstrates both the challenges and potential solutions for enhancing hydrogen safety, particularly at refueling stations.
The simulation results reveal that wind speed and direction significantly influence hydrogen gas dispersion patterns, with higher wind speeds causing more horizontal spread and potentially bringing flammable concentrations to ground level. Based on these findings, specific safety measures are recommended, including:

1. Maintaining minimum separation distances of 8 meters between refueling points and storage facilities
2. Avoiding enclosed overhead structures where hydrogen could accumulate
3. Implementing strategic sensor placement based on gas dispersion modeling
4. Integrating sensors into a comprehensive functional safety system

These recommendations align with established standards such as NFPA 2, ISO 19880-1:2020, and EIGA guidelines, which provide frameworks for the safe design and operation of hydrogen facilities.

The event tree analysis presented demonstrates how early detection can prevent the escalation of incidents, highlighting the importance of appropriate sensor selection and placement. The integration of these sensors into a functional safety system provides a robust approach to risk management.

For hydrogen technology to achieve widespread adoption, its safety record must be comparable to or better than established energy technologies. The simulation-based approach described in this article contributes to this goal by enabling evidence-based safety design and risk mitigation strategies for hydrogen refueling infrastructure.

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