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Technological Development and Safety Assessment Criteria in Hydrogen Distribution Sites

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A fully sustainable mobility is one of the main objectives that the Member States of the European Community aim to achieve, in accordance with the Sustainable Development Goals of the United Nations 2030 Agenda and in order to achieve climate neutrality at European level in 2050. Between all the energy sources alternative to the traditional ones, hydrogen appears as one of the most promising energy vectors and that is why - in line with the European strategy - Italy intends to actively engage in production and practical use of hydrogen through the construction of several stations for transport by rail and road (also including trucks and busses) by 2026.

The present study aims to deepen the actual technological development and safety conditions in sites for hydrogen production and distribution in the Italian context, particularly focusing on hydrogen supply systems for automotive applications. The existing technical regulations in relation to safety of these plants are outlined, with particular attention for the European legislation as well as for international codes and standards. Plant and functional data relating to the main operating hydrogen distributors at national level - as well as to new other ones being activated - are presented. At the same time, the recent international scientific literature is analyzed to identify emerging safety-related technical issues and management approaches. The need to define shared approaches in Europe, in order to identify common safety procedures and good practices, emerges.

1. Introduction

In all the European context, it appears essential today to identify energy sources alternative to the traditional ones, by exploiting solutions including “renewable energy sources” (e.g. solar and hydroelectric ones), which are natural primary forms of energy, as well as the so-called "energy vectors", that is compounds capable of conveying energy from one form to another, accumulating it and then being released to the need.

Hydrogen is an alternative energy vector whose applications in Italy are currently mainly limited to industrial use and mobility, while they are not yet significantly extended to residential contexts, e.g. domestic heating (even if in Emilia-Romagna a first Italian trial of hydrogen injection into the residential gas network has been recently carried out). We are also beginning to see its use in the field of agricultural machinery and construction (forklifts, telehandlers) as well as in motorbike races, where the use of liquid hydrogen for refueling is about to be included in international regulations. Hydrogen represents a form of secondary energy, since all its production methods initially require primary energy (e.g. in natural gas reforming), which must be transformed using appropriate technologies and plants. A complete sustainability - also from the social point of view - of such promising solution includes the attention to ensure preservation of the working environment and operators from hydrogen-associated risks (i.e. fires, explosions, material embrittlement) during production, transportation and storage phases, as well as that of users in final applications, because of its high flammability.

This necessarily resulted in a progressive interest in the definition of specific sector regulations. CEN/CENELEC has received a mandate from the EU Commission to draft standards on hydrogen, which will be referenced in legislation. In particular, in August 2024, the CEN-CENELEC Coordination Group on Hydrogen (CEN-CLC/COG H2) was created, in order to coordinate standardization activities related to Hydrogen among their technical bodies, avoiding topic inconsistency and overlap. At the international level, the ISO TC 197 Hydrogen Technologies Committee is in charge of preparing standards dealing with systems and devices for the production, storage, transport, measurement, and use of Hydrogen. In parallel, other groups – as the European Clean Hydrogen Alliance (ECH2A) and its dedicated Working Group (WG) born in 2022 – are trying to bring order to the variety of emerging standards by giving guidance to stakeholders (e.g. industry, public authorities, civil society) (ECH2A, 2023).

Hydrogen potential for producing energy without CO2 emissions is counterbalanced by the fact that its molecule H2 must be produced, with consequent additional costs. To the current state of the art, hydrogen is mainly produced through (i) natural gas steam reforming (e.g. grey, blue hydrogen) and (ii) water electrolysis (e.g. yellow, pink, green hydrogen). The latter methodology is often more expensive and more hardly sustainable.

After production, hydrogen can be stored (i) in gaseous form by compression, (ii) in liquid form (in cryogenic tanks because it must be cooled to a temperature below its boiling point of 20 K (-253 °C)) and (iii) in solid form within the structure or on the surface of certain solid materials. In its use, in certain cases it can be blended with natural gas. It has peculiar physical-chemical characteristics that differ from many other gases and that must therefore be considered in each different application. For example, at high pressures it does not behave as an ideal gas, and the van der Waals state equation for real gas should be used instead of the state equation of an ideal gas. The gas takes up more space than the theoretical ideal gas law predictions, and the introduction of a compressibility factor can allow for compensating for the additional compression (Raj et al., 2024).

In the field of mobility and transport, Hydrogen can be used in two different types of engines: (i) internal combustion engines HICEs (direct combustion with oxygen from the air) and (ii) fuel cells that convert fuel into electricity to drive an electric motor. In this last typology of engine, the fire dangers of electric car batteries are compounded by the dangers of hydrogen cylinders. In both cases, water vapour is the only waste product. However, Italy shows an investment lag if compared to the rest of Europe, since installers are disincentivised by long authorisation procedures and energy availability and costs. Consequently, the scarcity of hydrogen refueling stations (HRS) seems to make them not yet completely attractive to the average road user.

1. Hydrogen supply systems for road transport

The actual number of HRS in many European countries is significantly higher than in Italy. In Germany it stands at almost more than 100 sites, while in Italy there are only two currently active refueling stations. Much further away, in South Korea, there are already nearly 200 filling stations. Almost 1,200 hydrogen refueling stations (HRS) are widespread worldwide, with the highest concentration in Asia Pacific, followed by Europe. Consequently, incidental and near-incidental events in this field are mainly emerging abroad: that is the case of an explosion of a hydrogen filling station in Norway in 2019, probably related to a leak due to untightened bolts, which caused Toyota and Hyundai to suspend sales of some car models. The danger of bursting is generally significant, since the pressures involved are higher than those of natural gas cylinders used in automotive. Badia et al. (2024) reviewed more than 220 accidents occurred worldwide all along the hydrogen value chain (production, storage, delivery, industrial use) and they underlined how much each one of these phases can influence safety of HRS, also depending on the fact that they incorporate hydrogen production or not (electrolysers and gasometers/tanks require rigorous safety protocols). They also showed the possible significant role of human factors, during maintenance and other operations, in causing human-related accidents (e.g. operator-induced leaks, incorrect valve opening). Because of these safety risks, companies in Italy must be particularly careful when proposing new installations, since Italian regulations impose strict limitations.

* 1. Technical features and emerging safety issues

With respect to other countries, the Italian technical regulation for HRS installation is much more restrictive, in terms of safety distances, boxes and fences, with higher costs and longer authorization times, which discourage companies from investing in the sector and realizing such plants. Sometimes, extremely compact solutions are proposed, according to specific “engineering approaches”, but Italian regulations do not accept them by default and the time for their evaluation becomes longer. At local level, the National Fire Corps is responsible for safety and fire prevention evaluations. However, by 2026, almost 40 refueling stations are planned on Italian roads, and by 2030 it is estimated that 5-7% of heavy-duty vehicles will be powered by hydrogen.

At the international level, from the point of view of technical regulations, the ISO 19880-1:2020 “Gaseous hydrogen - Fuelling stations - Part 1: General requirements” is currently in force. The American Codes ASME B31 Pressure Piping Code and ASME Boiler & Pressure Vessel Requirements for high pressure equipment and hydrogen storage tanks, together with NFPA 2 Hydrogen Technologies Code, enrich the de facto internationally recognized regulatory framework. In Europe, the DAFI Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 (Directive Alternative Fuel Initiative) on the establishment of an infrastructure for alternative fuels was decisive in giving real potential for the diffusion of hydrogen-powered vehicles. This Directive has been transposed in Italy through the Legislative Decree 16 December 2016, n. 257, whose article n.5 provided for the establishment of an adequate number of publicly accessible hydrogen refueling points by 31 December 2025, which must comply with specific technical standards.

The relevant technical regulations have been updated in Italy by the Decree 23 October 2018, (Fire prevention technical regulation for the design, construction and operation of hydrogen distribution systems for motor vehicles) which introduced the possibility of applying methodologies of “engineering approach” for fire safety distances as well as applying internationally recognized standards (e.g. ISO 19880-1) (H2IT, 2023). Moreover, the previously imposed limit of 350 bar was definitively raised to 700 bar, so as to allow safe refueling of cars as well as trucks. The scope of the Decree was later extended and updated through the subsequent enactment of Decree 7 July 2023 (Fire prevention technical regulation for the identification of methodologies for risk analysis and fire safety measures to be adopted for the design, construction and operation of hydrogen production plants by electrolysis and their storage systems), which introduced a number of new features, including the dependence of the required safety distances on the operating pressure value of the hazardous elements. Even in the scientific field, research is going on about the topic: for example, Vianello et al. (2020) studied the hydrogen jet fire resulting from rapid fired depressurizations and evaluated safety distances from person and pressurized tanks to avoid domino effects, considering a temperature limit of 309 °C and an exposure of 20 s.

Each HRS has a number of components that require special safety precautions, e.g. compressors (the pressure at which hydrogen is made available is lower than the one required by trucks and vehicles, that is 350 and 700 bar respectively), pumps (if hydrogen is stored at site as a liquid distribution), refueling columns (eventually equipped with a pre-cooling system), hydrogen production units, tankers (if present) and storage units (in gaseous or liquid form). Hydrogen can be produced on site or also be transported there via trailers or pipelines, on whose pressure the compressor power depends (the lower the inlet pressure, the greater the power required from the compressor). The refueling time depends on various factors (e.g. mass flow of the compressor, which affects the filling speed) but it is usually in the order of minutes. The hydrogen flow is regulated by a dispenser control unit, whose working conditions (pressure, temperature, etc.) have to follow specific design parameters according to protocols such as SAE J2601 for regulating and optimizing the fueling process.

Table 1 outlines the most important safety-critical aspects in HRS (mainly related to risk of fire, explosion and domino effect) and some recommended countermeasures. Data include observations from international literature, which has progressively increased its interest for the topic in the last 10 years.

Table 1: Main safety-critical conditions in HRS and recommended countermeasures (Caponi et al., 2021; Veres et al., 2022; Genovese et al., 2023; Genovese et al., 2024; Campari et al., 2024; Chauhan et al., 2024; He et al., 2024; Lu et al., 2024; Xing et al., 2024; Kang et al., 2025)

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| Safety-critical condition | Description | Countermeasures |
| Air (oxygen) being sucked in at its inlet part of the compressor unit. | Risk of internal burn or explosion. | Hydrogen compressors are designed to prevent air intake (temperature/pressure sensors). |
| Hydrogen leak from compressor unit. | Risk of fire or explosion due to high flammability. | Metal seals, fire protection systems. |
| Hydrogen leak from high-pressure storage. | At high-pressure, the amount of hydrogen leakage is much higher than at low-pressure, even in open spaces. If the space is enclosed (e.g. container), hydrogen is trapped inside and internal accumulation of large amounts of flammable gas must be prevented. | Compressor containers must be equipped with automatic ventilation and gas detection systems. |
| Hydrogen leak from safety valves. | Safety valves prevent uncontrolled pressure rise or control depressurization of piping systems during maintenance. Hydrogen is released with high flow velocities and risk of a several meters long flammable cloud. | An exhaust chimney is usually designed to allow controlled combustion of the mixture or it is inertized to prevent combustion. |
| Leak from liquid hydrogen tanks. | As in all cryogenic tanks, a venting valve is present, as heating causes part of the liquid to evaporate (boil-off), increase pressure and pose a danger of explosion (e.g. for static electricity). The fuel is lost to the atmosphere and energy is wasted. | Manage and monitor pressure levels and properly size venting valves. |
| Overpressure in high-pressure storage. | Risk of explosion. | Separate monitoring for each high-pressure gas storage section. Gas management panel able to automatically activate protocols to stop the hydrogen flow if a leak-detection alert occurs. |
| Leak from dispenser and nozzle. | Hydrogen leakage can pose a significant risk during vehicle filling. Moreover, the dispenser produces thermal radiation to adjacent units and the contained hydrogen can help sustain the fire. | Use of certified components (e.g. for environments with flammable gases or dust), regular inspections, detection of sudden pressure drop due to leakage with automatic shutdown of the hydrogen source, optimized design of the dispenser. Effective temperature control.  Starting of the filling procedure with a leak test of the circuit from the high-pressure storage system to the vehicle, to verify the absence of gas leaks and to measure the initial pressure of the vehicle tank to find the corresponding pressure ramp. |
| Refueling parameters. | Refueling performances should aim at both speed and safety, since too fast fueling may cause gas heating and consequent hazards. Hydrogen heats up instead of cooling when it expands (reverse Joule Thompson effect). | Respect of SAE J2601 standard (e.g. maximum instantaneous flow rate limit) and pre-cooling to -40°C. Accurate hydrogen flow measurement. Regular calibration of sensors and measuring instruments. Cleaning. |
| Connection system for tankers. | Risk of explosion (related to leaks). | Stop device to interrupt hydrogen flow in case of emergency system activation. |
| Human error during inspections and maintenance on high-pressure storage. | Inspections and maintenance (e.g. isolating the storage from the supply line) guarantee safety of plants but they can be affected by human error. | Proper training of the operators. |
| Recovery process after experiencing shocks. | After an unexpected problem, spare parts management and timely supply has a central role in system recovery. | Strengthening of daily management and training, regular replacing of worn and aged parts. |
| Failure of hydrogen detection and alarm devices. | Even intelligent systems, eventually with integrated artificial intelligence, for real-time monitoring and rapid location of hydrogen leakage, can have a failure. Or they can have a sub-optimal intervention capacity. | Reinforcement of manual inspection and personnel training for safety awareness. Design of a multi-level alarm system including three phases (initial warning, emergency alarm, accident confirmation) to ensure adequate responses under different risk levels. Emergency shutdown systems. |
| Poor environmental ventilation system. | Sometimes the ventilation system can be not adequate to the actual hydrogen concentration. | Simulation of the hydrogen diffusion path to optimize ventilation openings. Use of IoT to develop intelligent ventilation systems to adjust the ventilation based on real-time hydrogen concentration. |

An example of a complete risk analysis for a petrol station at design stage in the Czech Republic was described by Veres et al. (2022). However, Park et al. (2025) reviewed global risk assessment practices for HRS infrastructures, highlighting the existence of a variety of approaches and underlining the importance of applying comprehensive and integrated methodologies, in order to address complex production systems, also including, for example, additional hazards like chemical toxicity and domino effects. They underlined the need to harmonize risk assessment practices globally, through continuous innovation and international collaboration.

In general, many safety systems (e.g. sensors and alarms to detect leaks, ventilation systems, emergency shutoff systems) have to be incorporated into HRS to guarantee safety during refueling operations (EIGA, 2024).

Cybersecurity risks must be taken into account, especially for automated HRS control, due to the increasing coexistence of Operational Technology and Information Technology. Particular attention must also be paid to the choice of materials, given the high temperatures and pressures involved. In this sense, specialised companies are gradually trying to develop better and safer hoses for high-pressure hydrogen distribution systems, looking for high tightness, flexibility and durability at the same time, even by combinations of different materials. Even the hydrogen embrittlement phenomenon (that is a reduction in the ductility of a metal due to absorbed hydrogen with increased susceptibility to crack) requires new material insights, e.g. in order to obtain hydrogen-tolerant aluminium alloys.

* 1. Italian on-field applications

In Italy, the National Recovery and Resilience Plan envisages 40 truck and car refueling stations, as well as 9 refueling stations on 6 railway lines, by 2026 (approximately one tenth of the Italian railway network is served by old diesel-powered trains that will have to be replaced soon), for a total investment of 530 million euros. Actually, a total of 36 renewable hydrogen refueling station projects have been considered eligible for such support, but many of them are still at an early stage of development. If compared to other countries that can boast an already widespread refueling station network, Italy therefore needs to speed up. Following indications from the European Commission (e.g. "Fit for 55" package and “Alternative fuel infrastructure regulation (AFIR)”), it would be a matter of imagining a station every 100-150 km on the Trans-European Network - Transport (TEN-T) by 2030, possibly favouring multifuel and multipurpose stations.

The only hydrogen filling stations currently operating in Italy (in Mestre and Bolzano) provide a full tank in 4 to 5 minutes to cars at a maximum pressure of 700 bar. In the Bolzano station, hydrogen is produced through renewable energy (hydroelectric), then it is stored and used to supply hydrogen fuel cell vehicles (buses used for urban public transport as well as a fleet of rental cars). The system can refuel up to 15 city buses or up to 700 cars, as well as providing the possibility of refueling groups of hydrogen cylinders or tanker trailers.

The Mestre station has been realized by ENI (even in collaboration with Toyota) and it was opened to the public in 2022. Hydrogen refueling is combined with refueling made by traditional fuels and electricity. Hydrogen is supplied by means of tank cars, in presence of appropriate safety systems, capable of interrupting the flow of hydrogen in case of emergency. The compressor increases the pressure of the hydrogen gas from the pressure present in the cylinder carriage up to the maximum working pressure of the medium pressure and high-pressure hydrogen storage tanks. During cars refueling process, the compressed hydrogen is transferred in sequence from the medium-pressure storage sections to the high-pressure storage section and finally to the vehicle tank, passing through the refrigeration unit (at -40 °C) and the 700 bar dispenser, where the refueling takes place according to protocol SAE J2601. In case of buses, compressed hydrogen is transferred from the medium-pressure storage sections to the vehicle tank via the dispenser at 350 bar.

Other stations are currently being built throughout the country, some of which are in the context of the development of the whole hydrogen production and distribution chain in specific areas (“hydrogen valleys”). For example, the “SerraH2valle” project is expected to include the construction of five hydrogen fueling stations along the Milan-Serravalle motorway for both light and heavy vehicle traffic: hydrogen will be stored at 900 bar and different dispensers will be installed, in order to supply hydrogen at both 350 bar pressure for trucks and 700 bar for cars. An “hydrogen demo valley” in Roma area, aimed at setting technologically advanced infrastructures for research and experimentation along the entire hydrogen chain, is instead the one currently being developed by the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA). The implementation of a hydrogen refueling station distribution network in Italy is underway, but it is still far from matching those already present in other countries; moreover, stations already operational and those in the testing phase are mainly concentrated in Northern Italy. Specialists worldwide are also gradually proposing specific methodologies for optimising the location of refueling stations, starting from some already known methods (e.g. p-median and flow-capture location models), but pointing out that there is a need to incorporate safety elements and risk assessment procedures in order to provide more robust solutions (Isaac and Saha, 2023). The possibility of developing temporary mobile refueling stations could also help boost confidence and interest in the use of hydrogen with reduced costs.

1. Conclusions

In the present study, many crucial safety aspects related to hydrogen refueling stations have been outlined, also taking into account the main international and local regulations currently in force. From the technical point of view, the fundamental role of fire protection and gas detection devices, intelligent shutdown and control systems, but also of taking into account the human factor influencing quality in maintenance and inspection activities, in order to guarantee safety of such plants, has emerged. With regard to the regulatory constraints, given Italy's delay in completing hydrogen refueling plants, it appears important to foster collaboration between those actors who deal with safety in Italy (Fire brigades, research organizations, Institutions, etc.) in order to define common guidelines and good practices while avoiding regulatory and procedural discrepancies between different geographical areas in Italy, as well as - as far as possible - between Italy and the other European countries. At the same time, the world of scientific research signals that, at the international level, there is a specific need to harmonize risk assessment practices, as well as guidelines for inspecting and maintaining hydrogen refueling stations. To meet 2030 targets, inter-institutional task forces may need to prioritize the development of shared solutions in order to guarantee safe management of new rising hydrogen refueling stations.

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