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Article

Analysis of Hydrogen Value Chain Events: Implications for Hydrogen Refueling Stations' Safety

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Abstract: Renewable hydrogen is emerging as the key to a sustainable energy transition with multiple applications and uses. In the field of transport, in addition to fuel cell vehicles, it is necessary to develop an extensive network of hydrogen refueling stations (hereafter HRSs). The characteristics and properties of hydrogen make ensuring the safe operation of these facilities a crucial element for their successful deployment and implementation. This paper shows the outcomes of an analysis of hydrogen incidents and accidents considering their potential application to HRSs. For this purpose, the HIAD 2.0 was reviewed and a total of 224 events that could be repeated in any of the major industrial processes related to hydrogen refueling stations were analyzed. This analysis was carried out using a mixed methodology of quantitative and qualitative techniques, considering the following hydrogen value chain: production, storage, delivery and industrial use. The results provide general information segmented by event frequency, damage classes and failure typology. The analysis shows the main processes of the value chain allow the identification of key aspects for the safety management of refueling facilities.

Keywords: hydrogen refueling stations; hydrogen value chain; incident analysis; safety management

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1. Introduction

The reduction in carbon dioxide emissions to combat the consequences of climate change is a global imperative that was emphasized in the Paris Agreement [1]. In this context, hydrogen is likely to play a role in our future society, especially as we move towards a low-carbon strategy. This potential for hydrogen-based energy systems identified early this century is now a reality rather than a vision of the future. In fact, hydrogen technologies are being implemented in many end-use applications. In particular, in the transport sector, the introduction of fuel cell vehicles will require the development of an extensive network of Hydrogen Refueling Stations (hereinafter referred to as HRSs), which will need to have ensured operational safety in order to gain public acceptance. Therefore, the successful integration of hydrogen into industries like mobility and transportation hinges on establishing safety and efficiency throughout its entire value chain.

Some of these fundamental challenges are being tackled by the international SUSHy project [2], which seeks to face the challenges associated with the widespread deployment of emerging hydrogen technologies. These challenges arise not only from the complex technical processes involved in hydrogen production and distribution but also from the socioeconomic uncertainties affecting its safe and sustainable deployment. Given the limited availability of data and the multifaceted nature of these barriers, addressing and overcoming them demands crucial international and interdisciplinary cooperation.

Safety is emerging as a crucial element in achieving a profitable, sustainable and green hydrogen economy. Some of the challenges involved are technological, but others are linked to regulations and the precise development of safety systems linked to the entire hydrogen value chain [3]. In-depth analysis of hydrogen-related events can play a pivotal role in addressing this challenges. Fuyuan Yang et al. [4], in a review of 120 hydrogen safety incidents, studied precise aspects of leakage and diffusion ignition and explosion. They concluded that failures of pipes, valves, and filters within the hydrogen system accounted for the majority of abnormal process occurrences. Their statistical approach can be complemented by a more qualitative approach, such as that of Youhyun Lee [5], which addresses safety based on lessons learned from three relevant events in South Korea. Both approaches can provide relevant information for HRSs. As noted by Yuxuan Xing [6] (p. 415), "a comprehensive risk identification of multiple typical accident including hydrogen and non-hydrogen accidents at HRSs is necessary". From this wide perspective, it is worth emphasizing the significance of conducting analyses considering the comparison between the different components of the hydrogen value chain.

Before presenting the methodology and the results of the study, two aspects considered within the hydrogen value chain and the importance of the events analysis are defined. Firstly, the term "hydrogen value chain" is often used to refer to broad categories that can range from hydrogen plant design to end-user applications. In this research, four categories have been considered: production, storage, delivery, and applications (Table 1).

Table 1. Hydrogen value chain description [7–10].

Hydrogen Value Chain Stage		Definition
Production [11]		Free hydrogen is not available on Earth. It is typically attached to molecules such as water and hydrocarbons from which it can be separated by using energy from renewable or non-renewable sources.
Storage [12]		Hydrogen can be stored either by physical methods (compressed gas, cold/cryo-compressed and liquid) or material-based methods (hydrides, chemical carriers and adsorbers).
Delivery [13]		Hydrogen can be delivered as high-pressure gas (through compressed H_2 pressure vessels arranged in tube trailers or via gas pipelines) as low-temperature liquid (via road, railway, or ocean and through cryogenic tankers) and in solid state (with metal hydride-based containers in a truck or railcar).
Applications [14]		Hydrogen has many different end uses: transport, power systems and industry (mainly in the petrochemical sector to produce chemicals and in refineries to process crude oil).

These value chain categories can be clearly extrapolated to HRSs. Thus, an HRS requires a process of hydrogen production (on-site or off-site), storage (tanks or cylinders), delivery (when hydrogen is produced off-site) and hydrogen handling (during refueling activities).

Secondly, this study is based on the information available in the Hydrogen Incidents and Accidents Database (HIAD) 2.0. The database was requested on the 15 June 2022 via the Odin portal (https://odin.jrc.nl, accessed on 15 June 2022). This database is a repository of systematic data describing hydrogen-related accidents, incidents or near misses. HIAD 2.0 was developed by the Joint Research Centre (JRC) of the European Commission as part of the Hydrogen Safety Network of Excellence (HySafe) during 2004–2009 with the aim of learning lessons and preventing future events. The richness of its information has allowed general descriptive studies in the field of safety [15]. Its information also permits targeted analyses, such as the Campari study [16], which, with the aim to prevent hydrogen-related material failures, uses business analytics to identify lessons learned related to inspection and maintenance processes. Therefore, valuable knowledge for the improvement of the safety of HRSs can be generated from the exploitation of HIAD 2.0 information.

In line with these research approaches, the present study analyzes hydrogen-related events compiled in the HIAD 2.0 (considering the hydrogen value chain, the core event, the type of failure and the damage) with the goal of providing reliable and useful insights into critical processes for safety that can be extrapolated to hydrogen refueling stations.

2. Materials and Methods

The HIAD was firstly developed within the HySAFE Network of Excellence by the JRC in 2006 [15]. Subsequently, it was updated to HIAD 2.0 in 2017, with the latest version, HIAD 2.1, being released in 2023. This database was created to store valuable information about accidents and incidents associated with the production, transportation (by road, rail, or pipeline), supply, and commercial utilization of hydrogen. It is regularly updated with the latest details about each event to incorporate the most recent findings from accident investigations [17]. At the time of the study, HIAD 2.0 was only available by requesting access rights via the Odin portal [18]. For this research, the database was requested and received on June 2022. The dataset has been used in accordance with the conditions and statements of the European Commission JRC.

The current study's sample has been obtained from the events collected in the HIAD 2.0, specifically incidents and accidents across the entire hydrogen value chain, excluding HRSs. These events (registered until 31 December 2022, with references ranging from ID 10 to ID 1036) were selected and analyzed based on their potential extrapolation to HRSs processes.

The following two phases were involved in the development of this research.

2.1. Review and Selection of Events from HIAD 2.0

This task was carried out in an identification-review process by the researchers' project, as follows.

(a) Individual review of the database to classify the events considering the stages of the value chain.
(b) Cross-checking of the events selected by the other members of the research team.
(c) Joint review (between the researchers) of unclear events as to their position within the value chain or their potential impact on HRSs. Consensus was essential for the event inclusion.

The review process allowed the classification of the events into three categories, as follows.

- Hydrogen value chain events: Those events that, despite not taking place in HRSs, could potentially take place in these facilities. They constitute the study sample. Table 2 shows some of the kinds of events included in each value chain phase.
- HRS events: Events that took place specifically in HRSs. Their analysis is part of another study of the SUSHy research project that aims to identify incident contributing factors.
- Excluded events: Events that were difficult to extrapolate to the HRSs' value chain because of its specificity and events with scarce information or historical events were excluded from the sample. Further details on the exclusion criteria are shown in Table 3.

Table 2. Typology of events by value chain.

Hydrogen Value Chain Stage	Typology of Events
Production	Problems related to electrolysis process, gas processing systems, gas conversion systems, etc.
Storage	Problems in tanks (bottom rupture), cylinders (leaks, leakage during refueling), etc.
Delivery	Problems in road transport vehicles, road accidents, large hydrogen distribution pipelines, etc.
Industrial uses	Problems with the compressors, failures in the welding of hydrogen pipes, etc.

Table 3. Type of hydrogen events excluded from the collection process.

Typology of Excluded Events
Unintentional generation of hydrogen as consequence of other processes (i.e., ID 886. Paper pulp stored fermented and produced hydrogen)
Accidents derived from experimentation (i.e., ID 862. Incident in a science-class experiment)
Traffic accidents of hydrogen powered vehicles (i.e., ID 406. Fuel cell bus collision)
Incidents in specific hydrogen chemical and refinery processes (i.e., ID 614. Hydrocracking process, ID 227. Catalytic reforming unit)
Hydrogen historical events (i.e., ID 534. Royal Prussian Air Ship Division 1894)
Events without analyzable information. Identified in the database as: "Low quality: the majority of quantitative descriptors missing" (i.e., ID 968. Syngas fire in an ammonia plant)

2.2. Analysis of Events

The database review permitted the identification of a total of 224 events. A mixed-methods approach was employed in analyzing selected events to provide "completeness" to the study, considering that the database contains both quantitative and qualitative information [19].

The quantitative analysis exploited data on the number of injured people and number of fatalities. Additionally, a quantitative variable was generated in order to generate a severity indicator.

- Fatality rate: Multiple metrics exist to express the mortality risk of hydrogen systems [20]. The current research refers to "fatality rate" as the proportion of fatalities relative to the total number of events occurring within a defined time frame. The "fatality rate" concept serves as a valuable and straightforward metric to understand the potential fatalities associated with abnormal events in hydrogen chain value.

For the qualitative analysis, two variables were generated from the information available as "full description".

- Core event: The most significant aspects of the incident, considering, as far as possible, its main adverse manifestation. This variable provides a synthetic view of the extended event (i.e., ID. 707. Leak on a hydrogen tank caused an explosion and subsequent fire).
- Type of failure: The defects or flaws that seem to be associated with the occurrence of the event. Accurate identification of the knowledge associated with the failure of a given event is essential for learning from the event and preventing similar incidents from happening in the future (i.e., ID. 707. Tank material with fatigue corrosion).

Accordingly, the analysis sought to identify the failures, processes and nature of the consequences associated, considering the hydrogen value chain, enabling the extrapolation of this knowledge to hydrogen refueling stations.

3. Results

The results of the event analysis from the HIAD 2.0 encompassing the entire hydrogen value chain are presented below. For each stage of the value chain, frequencies, injuries and fatalities are shown. A qualitative analysis of these events is also undertaken, allowing categories and subcategories to be established based on the inherent nature of each incident.

3.1. Event Distribution by Value Chain

In accordance with the event selection criteria outlined in the methodology section, it is revealed that incidents and accidents with hydrogen involved are most frequent in the context of both industrial uses (34.82%) and delivery processes (33.93%) (Table 4, Figure 1).

Table 4. Hydrogen event description and damage.

Value Chain		Injured	Fatalities	Fatality Rate
Production processes	20	16	6	30.00%
Delivery	76	129	20	26.32%
Storage	50	65	45	90.00%
Industrial applications	78	53	29	37.18%
Total	224	263	100	44.64%

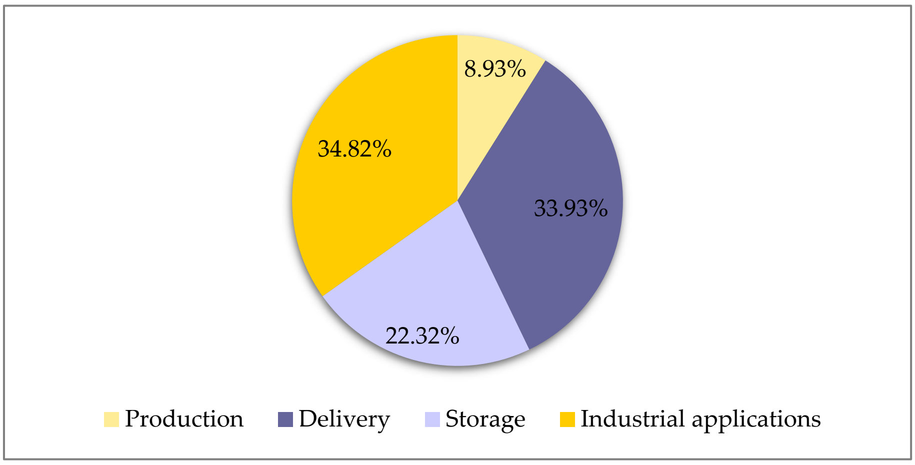

Figure 1. Hydrogen events distribution by value chain.

When focusing on the damage, the analysis shows that the delivery phase of the hydrogen value chain accounts for the most injuries (129 from 263, 49.05%), while the storage phase bears the brunt of fatalities (45 from 100, 45.00%) (Table 4, Figure 2).

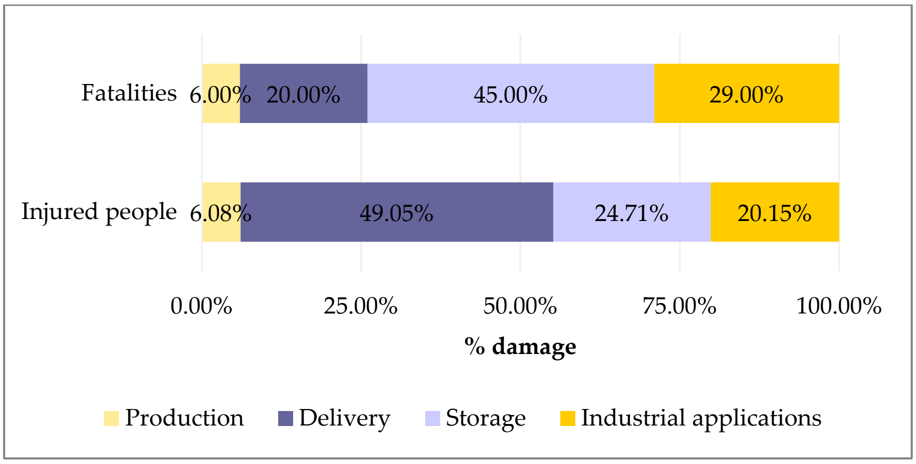

Figure 2. Damage by value chain.

Moreover, when the number of deaths is calculated as a proportion of the total number of events for each value chain phase (fatality rate), it appears that 90% of incidents in the hydrogen storage phase result in fatalities compared to a lower rate of 26.32% during hydrogen delivery (Table 4).

3.2. In-Depth Analysis of Events

Following are the results of the event analysis for each of the four stages of the hydrogen value chain.

3.2.1. Production

Regarding the production phase of the hydrogen value chain, the analysis allows events to be grouped into six types of categories, taking into account the systems/equipment affected (Table 5).

Table 5. Production process/equipment categories.

Process/Equipment	Description	Events	Fatality Rate
Electrolyzer cells and hydrogen generators	Events originating in devices that split water into hydrogen and oxygen by means of electricity	7	57.14%
Gas conversion systems	Events related to problems on the steam reformer and liquefaction system	2	0.00%
Gas processing systems	Events related to problems in the compressor system, separation column preheater system, and separation column	3	0.00%
Gasometers and hydrogen tanks	Events originating in devices that store hydrogen	3	66.67%
Pipes	Event initiated in a cylindrical conduit used for transporting hydrogen within the facility	1	0.00%
Natural causes	Event caused by an earthquake	1	0.00%

The analysis shows that incidents related to hydrogen production are mainly caused by failures in electrolyzer cells and hydrogen generators, often stemming from equipment malfunctions, overheating, and corrosion (Table 6), though these failures have not occurred since 2010 or with fatal consequences since 2006.

Table 6. Core event, failure and consequences in electrolyzer cells and hydrogen generators (production).

Core event in Electrolyzer Cells	Failure	Injured	Fatalities
ID 108 Fire on installation producing hydrogen (2004)	Malfunctioning of the electrolyzer	0	0
ID 166. Hydrogen generator overheated during testing and started a small fire in a power plant (2006)	Hydrogen generator overheat	0	3
ID 180 Fires occur within a few minutes in 4 cells of an electrolyzer (2003)	Failure or malfunction of the electrolyzer	0	0
ID 664 Diaphragm leak in the hydrogen–oxygen electrolytic cell (1968)	Unspecified	0	0
ID 778 Explosion when hydrogen entered in an oxygen drum being part of an electrolytic process (1975)	Corrosion/erosion in the electrolysis cells	0	1
ID 950. Hydrogen leak on the nozzle of a cell collector that had just been repaired and large explosion in the electrolysis room (2010)	Unspecified	2	0
ID 1002 Hydrogen electrolyzer explosion (2005)	Oxygen exposure of the titanium electrode in the electrolysis cell	0	0

Considering the overall events during this phase, electrolyzer cells and hydrogen generator malfunctions contribute to the most fatalities (66.67%), followed by faults in gasometers and hydrogen tanks (33.33%) (Figure 3). When looking at the fatalities per event for each type of failure, it is important to note that gasometers and hydrogen tanks stand out with a fatality rate of 66.67% (Table 5).

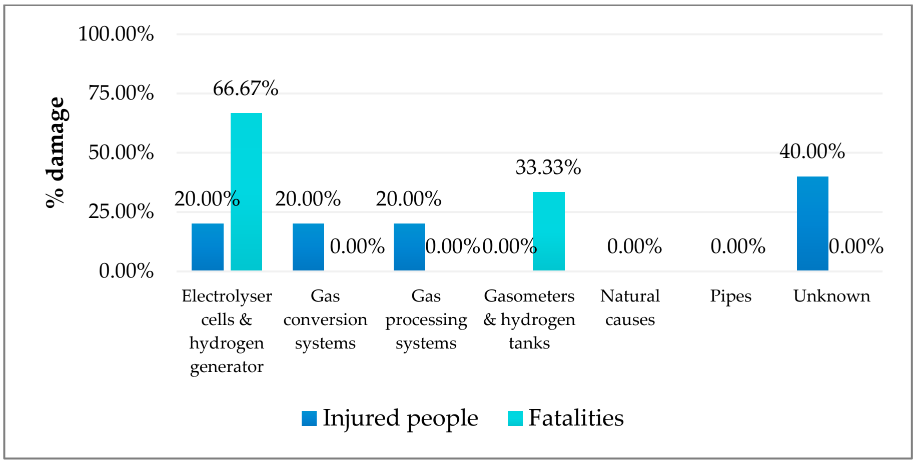

Figure 3. Production damage.

3.2.2. Storage

Regarding storage processes, the analysis allows the establishment of three distinct categories based on the types of processes/equipment involved (Table 7).

Table 7. Storage process/equipment categories.

Process/Equipment	Description	Events	Fatality Rate
Storage tanks	Events initiated in large, stationary vessels used to store large amounts of hydrogen gas at high pressures	19	173.68%
Storage cylinders	Events started in small, portable vessels designed to store small amounts of hydrogen gas at moderate pressures	21	57.14%
Others	Events related to other devices related to hydrogen storage	10	0.00%

As seen in the previous table, events are related to cylinders and tanks, with a nearly equal occurrence. It is worth noting that problems in tanks are the ones that result in more fatalities (73.33%) (Figure 4), with a fatality rate of 173.68% (Table 7) if we consider the fatalities per number of events in each category. This rate over 100% is an indicator of the risk severity of this type of processes.

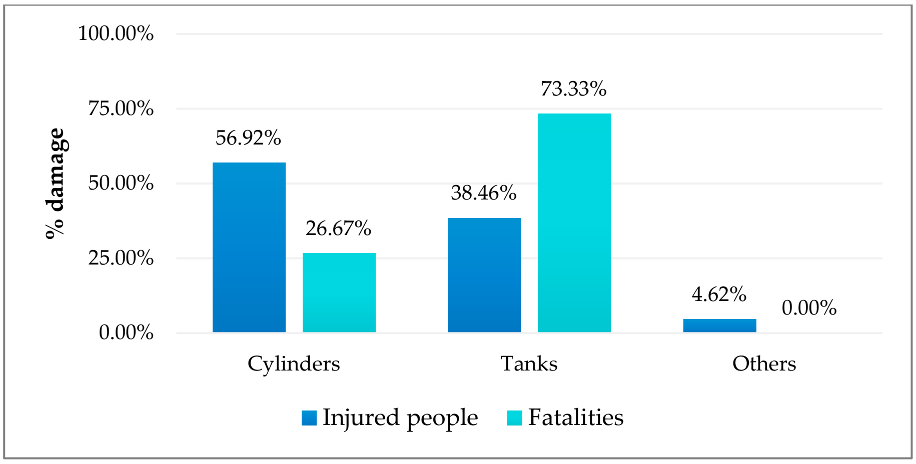

Figure 4. Storage damage.

The analysis has permitted the establishment of cylinder- and tank-related incidents into five distinct subcategories, each based on the type of failure (Table 8). Cylinder-related incidents are primarily attributed to filling processes and mechanical/technical malfunctions, while tank-related incidents are predominantly caused by mechanical/technical failures. Notably, filling activities account for the most fatalities in cylinder-related incidents (six fatalities) due to the mixture of air and hydrogen inside the cylinders (Table 9). Conversely, although mechanical/technical failures (cracks, ruptures and corrosion) are prevalent in tank-related incidents, they do not result in fatalities, while events related to works inside the tanks and degasification activities resulted in seven fatalities (Tables 10–12).

Table 8. Failures, descriptive and damage in cylinders (a), tanks (b) and others (c) (storage).

a. Failures in Cylinders		**Injured**	**Fatalities**
Connection	2	3	0
Filling	5	11	6
Mechanical/technical	4	0	0
Operation/works	3	2	1
Replacement	3	2	0
Unspecified	4	19	5
Total	21	37	12
b. Failures in Tanks		**Injured**	**Fatalities**
Degasification	1	3	4
Hydrogen–oxygen mixture	2	0	0
Mechanical/technical	5	1	0
Relief valves	1	0	0
Works inside the tank	2	3	3
Unspecified	8	18	26
Total	19	25	33
c. Other Failures		**Injured**	**Fatalities**
Backup battery	1	0	0
Gasholder	1	0	0
Hydrogen filling unit	1	1	0
Natural cause	1	0	0
Pressure relief valve	2	0	0
Skid	2	1	0
Unspecified	2	1	0
Total	10	3	0

Table 9. Core event, failure and consequences in cylinder-filling process events (storage).

Core Event in Cylinders	**Failure**	**Injured**	**Fatalities**
ID 179 Release of hydrogen during the filling of rack's bottles causing a fire (2003)	Bracket rupture when a worker moved the rack from one station to another	0	0
ID 641. Leakage of gas from blow-off pipe for depressurization while filling hydrogen in cylinder (1984)	Unspecified	0	0
ID 748 Hydrogen leak and ignition when replacing a pallet of empty hydrogen cylinders with a new full one (1988)	Unspecified	0	0

Table 9. *Cont.*

Core Event in Cylinders	Failure	Injured	Fatalities
ID 1023 Hydrogen cylinders exploded in three industrial locations, when opening valve during the filling process (2004)	Air entered inside the cylinders and mixed with hydrogen (operation mistake, environmental and technical causes, design failure)	10	6
ID 1036 Fire when refilling a cylinder at a hydrogen storage facility (2022)	Malfunction of the pressure regulator mounted on the gas cylinder	1	0

Table 10. Core event, failure and consequences in tank events with mechanical/technical failures (storage).

Core Event in Tanks	Failure	Injured	Fatalities
ID 16 Leak from a high-pressure hydrogen gas system (two tanks and connecting pipes) and subsequent explosion (1980)	Failure of a high-pressure valve from a low-pressure pipe system with corroded wall	0	0
ID 33 Compressed hydrogen release from a storage system (1977)	Rupture of a Bourdon-type pressure gauge	1	0
ID 342 Hydrogen leak at the hydrogen plant (2004)	Rupture at the bottom of the tank from the reformer	0	0
ID 615 Release of gaseous hydrogen that exploded (1975)	Crack in a storage tank	0	0
ID 707 Leak on a hydrogen tank caused an explosion and subsequent fire (1991)	Tank material with fatigue corrosion	0	0

Table 11. Core event, failure and consequences in tank events with failures related to factors inside the tank (storage).

Core Event in Tanks	Failure	Injured	Fatalities
ID 710 A tank filled with low-pressure hydrogen exploded at a food manufacturing plant (2004)	Welding inside the tank	0	3
ID 978 Explosion in a tank that had been drained three days before (2015)	Using an electric rotary in the tank	3	0

Table 12. Core event, failure and consequences in tank events with failure related to degasification (storage).

Core Event in Tanks	Failure	Injured	Fatalities
ID 531 Hydrogen escaped when a venting valve in the tank was opened for the inspection of a cap causing a fire (1984)	Incomplete degasification	3	4

It should be highlighted that some events involving deaths could not be categorized because the database does not provide detailed information (four cylinder events and eight tank events). Particularly noteworthy is the incident with ID 695 in 1990, when a high-pressure hydrogen storage tank leaked and exploded during the plant's initial commissioning, killing 26 people.

3.2.3. Delivery

With regard to the hydrogen delivery value chain, the analysis shows two distinct types of events, described in Table 13.

Table 13. Delivery process/equipment categories.

Process/Equipment	Description	Events	Fatality Rate
Distribution	Events occurred in huge pipelines used to move large volumes of hydrogen over long distances	8	0.00%
Transport	Events occurred during hydrogen movement over shorter distances using trucks, trains, or ships	68	29.41%

In depth analysis of transport events reveals that they relate to hydrogen loading and unloading activities, traffic accidents and incidences with transported cargo (Table 14).

Table 14. Transport process/equipment categories.

Process/Equipment	Description	Events	Fatality Rate
Hydrogen loading and unloading activities	Events during hydrogen transfer from stationary storage systems to transportation vehicles or vice versa	17	5.88%
Traffic accidents	Events in vehicles carrying hydrogen (collisions, rollovers, going off-road and truck breakdowns)	25	76.00%
Transported cargo incidents	Events that involve the transported cargo while in transit or at storage facilities	26	0.00%

While distribution events are relatively less frequent and have no reported fatalities, road, rail, and ocean transport events account for a significant majority and exhibit a fatality rate of 29.41% (Table 13).

Distribution events are primarily linked to welding failures, ruptures in pipelines, or activities in close proximity to pipelines. However, no personal injuries or fatalities have been associated with these events (Table 15, Figure 5).

Table 15. Core event, failure and consequences in distribution events.

Core event in Distribution	Failure	Injured	Fatalities
ID 142 Explosion on a hydrogen pipeline followed a hydrogen leak on a unit conditioning hydrogen (2004)	Mechanical rupture of the membrane of a pressure release device	0	0
ID 478 Hydrogen release from a hydrogen pipeline under the Beaumont Bridge (2019)	Unspecified	0	0
ID 539 A small quantity of hydrogen gas leaked out of a pipe and caught fire (1977)	Unspecified	0	0
ID 549 Fire involving a hydrogen pipe at a fertilizer ammonia plant (1979)	Welding failure from a pipeline	0	0
ID 759 Fire on a "transition corridor" with underground pipelines transporting hazardous substances, including hydrogen (2007)	Differential ground settlement with local deformation of the pipeline and welding works performed nearby	0	0
ID 891 Under-expanded jet fire in a hydrogen pipeline (2019)	Excavation works performed nearby a buried pipeline	0	0
ID 933 During maintenance work on a gas pipeline carrying hydrogen, a worker heard a leak (2013)	Unspecified	0	0
ID 1027 Explosion on a hydrogen pipeline located in a field (2021)	Agricultural drainage works carried out by a farmer	0	0

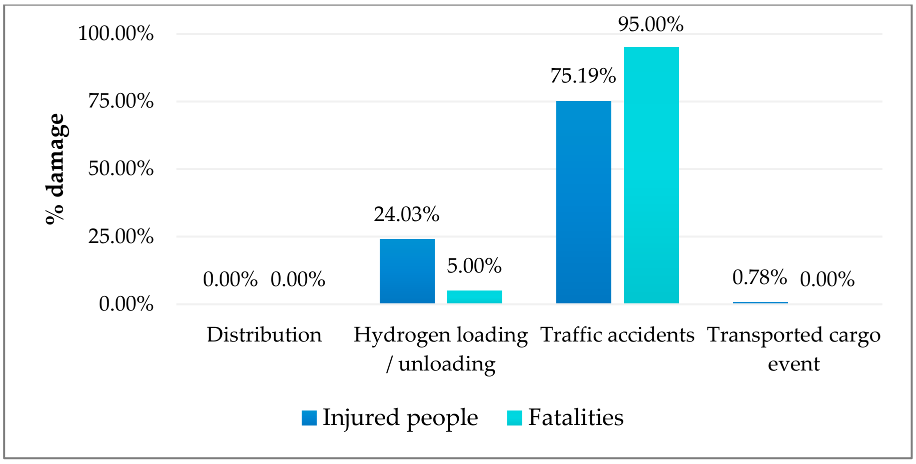

Figure 5. Delivery damage.

Regarding transport accidents, it is crucial to emphasize that traffic accidents are the primary cause of harm during the transportation of hydrogen, accounting for 75.19% of all injuries and 95.00% of fatalities (Figure 5). Furthermore, traffic accidents stand out with a particularly high fatality rate of 76.00% compared to other transport events, as evidenced by the incident with ID 72, which resulted in 15 fatalities (Table 16).

Table 16. Core event, failure and consequences in traffic accidents (transport).

Core Event in Traffic Accidents	Failure	Injured	Fatalities
ID 23 Transport accident of a hydrogen trailer (1973)	Collision with vehicle	1	0
ID 72 A truck with hydrogen cylinders was involved in a road accident causing fire, hydrogen release and ignition (2003)	Collision with vehicle	90	15
ID100 Collision between a truck containing liquid hydrogen and a truck containing manganese dioxide on a highway caused hydrogen release (2006)	Collision with vehicle	0	0
ID109 A tractor–trailer carrying canisters of volatile hydrogen gas crashed on a highway and compressed hydrogen gas leaked from some of the containers (2008)	Collision with vehicle	1	0
ID141 A rollover accident involving a tanker truck carrying liquid hydrogen (1999)	Collision with vehicle	0	0
ID144 Overturning (without rupture) of tanker carrying liquid hydrogen (1998)	Vehicle overturning	0	0
ID171 Road accident of a truck hauling liquid hydrogen (2007)	Collision with vehicle	0	0
ID257 Road accident of a tube trailer caused a formation of a hydrogen jet-fire from one cylinder of the tube trailer (2016)	Collision with vehicle	0	0
ID 336 Road accident involving tube trailer that transported cylinders with pressurized hydrogen gas caused hydrogen release and jet fire. Some cars burned under the back part of the gaseous tube trailer (2003)	Collision with vehicle	0	0
ID 337 Gaseous tube trailer gone off-road. The impact with the ground caused the rupture of a high-pressure valve of one of the cylinders causing a considerable loss of hydrogen (2004)	Vehicle gone off-road	0	0
ID 338 Drive off of a truck transporting hydrogen cylinders caused the break of fixing straps and cylinder packages fell on the middle of the road. Damage caused a gas release and deflagration (2003)	Collision with vehicle	0	0
ID 586 A road tanker of hydrogen overturned and caught fire (1976)	Vehicle overturning	0	0

Table 16. *Cont.*

Core Event in Traffic Accidents	Failure	Injured	Fatalities
ID 755 A truck with hydrogen cylinders crashed and caused a gas leak from hydrogen cylinders and fire (2005)	Collision with vehicle	0	0
ID 769 Semitrailer collision caused release and ignition of hydrogen contained in cylinders (2001)	Collision with vehicle	1	1
ID 795 Frontal road collision between a truck transporting pressurized hydrogen gas and a car (2013)	Collision with vehicle	2	0
ID 847 A tanker lorry carrying liquid hydrogen tipped over into a ditch on a curve caused hydrogen release (2008)	Vehicle tripped over when unauthorized access and incorrect maneuver by the tanker truck driver	0	0
ID 850 Driver of a battery-vehicle carrying cylinders with compressed hydrogen, lost control of his vehicle, crossed the traffic lanes and stopped against the median barriers of the motorway (2010)	Vehicle gone off-road	1	0
ID 852 Road accident with a heavy-duty vehicle transporting compressed gases (2011)	Vehicle gone off-road/overturning	1	0
ID 870 A lorry crashed into a hydrogen tube trailer with considerable speed. The lorry driver was killed. Gas escaped from tanks and ignited (2001)	Collision with vehicle	0	1
ID 910 Fire on the brakes of a truck carrying hydrogen (1993)	Truck breakdown (brakes)	0	0
ID 948 Fire on a truck transporting various flammable compressed gases including hydrogen Truck tire burst and caught fire (2010)	Truck breakdown (pneumatic)	0	0
ID 996 A hydrogen tanker crashed into the guardrail on a ring ramp leading to a highway causing multiple explosions (2020)	Vehicle gone off-road	0	1
ID1001 Hydrogen trailer crash on a highway. Cylinders damage caused hydrogen leak and fire (2013)	Collision with vehicle	0	1
ID1008 Road incident of a liquid hydrogen truck (hydrogen boiled and vented, but there was no ignition) (1987)	Vehicle gone off-road/overturning	0	0
ID1011 Leakage of liquid hydrogen from a tanker truck causing damage to a valve (2017)	Collision with vehicle caused by driver's maneuver in a car park	0	0

It is also worth mentioning that cargo-related events and loading–unloading events, in general, have low levels of associated damage (Tables 17 and 18).

Table 17. Core event, failure and consequences in transported cargo events (transport).

Core Event in Cargo Events	Failure	Injured	Fatalities
ID 43 Continuous hydrogen release from a road truck transporting liquid hydrogen (2001)	Faulty connections	0	0
ID 58 Liquid hydrogen in a cryogenic tank was entirely lost over a period of seven hours via the venting line of a rail tank (1991)	Microcrack in the outer wall of the tank	0	0
ID 139 Explosion at a semiconductor plant caused by hydrogen leak from tanker truck (2004)	Unspecified	0	0
ID 156 Fire in a road tanker carrying 125,000 cubic feet of liquid hydrogen (2000)	Tanker vent stack malfunctioning	0	0
ID 170 A truckload of hydrogen cylinders caught fire at plant producing artificial sweetener (2007)	Unspecified	0	0

Table 17. *Cont.*

Core Event in Cargo Events	Failure	Injured	Fatalities
ID 262 Leak on the safety valve of a liquid hydrogen wagon transporting liquid hydrogen (1992)	Unspecified	0	0
ID 487 Compressed hydrogen gas inside a tanker truck caught fire sending a hissing flame as high as 60 feet (2003)	Unspecified	0	0
ID 596 Fire due to hydrogen gas leakage from a cadre falling in transportation (1995)	Unspecified	0	0
ID 607 Gas leakage from a hydrogen gas cadre in transit (1990)	Unspecified	1	0
ID 754 Bottles with compressed hydrogen fell from a truck at a junction, because of speeding (2004)	Falling bottles due to speeding	0	0
ID 763 Ignition of a hydrogen leak occurred at a semitrailer connected to a pressure reducing station, while waiting a transfer (1988)	Lightning (natural causes)	0	0
ID 794 The fall of a pallet containing gas cylinders from a truck caused a leak in the hydrogen cylinder (2013)	Unspecified	0	0
ID 822 Leak in a vehicle carrying 218 cylinders of hydrogen. The content of 28 cylinders escaped (1989)	Unspecified	0	0
ID 824 Leak on a hydrogen gas transport at a flange of 9 cylinders of 80 m^3 (1990)	Unspecified	0	0
ID 836 A six-cylinder rack containing an argon/hydrogen mixture dropped from a truck on a national highway, causing a gas leak (2003)	Unspecified	0	0
ID 853 Fire at a truck transporting cylinders with compressed flammable gases (2011)	Unspecified	0	0
ID 885 Release of compressed hydrogen and subsequent fire occurred during the transportation of truck tractor chassis with a mounted trailer module (2018)	Improperly secured and incorrectly installed pressure relief devices on cylinders	0	0
ID 908 Liquid hydrogen leak occurs on one of the cylinders that a truck was carrying (1990)	Unspecified	0	0
ID 932 Leak of gaseous hydrogen detected around on a connection of a rack of cylinders on a trailer truck, in aircraft plant (2013)	Unspecified	0	0
ID 956 Leak from a liquid hydrogen truck that escaped through the safety devices of the tank and then dispersed (2008)	Unspecified	0	0
ID 977–ID 993 Hydrogen leak from a compressed hydrogen trailer (2020)	Crack in a valve of one cylinder	0	0
ID 997 Hydrogen release from a liquid hydrogen tanker (2021)	Unspecified	0	0
ID 998 Release of hydrogen from tank (2021)	Rupture of the hose mounted on the hydrogen trailer	0	0
ID 1010 Hydrogen fire in gaseous hydrogen cylinders from a tube trailer. Motorway shutdown (2021)	Unspecified	0	0
ID 1015 Hydrogen release and ignition on hydrogen sea-vessel (2022)	Malfunctioning of a gas pressure control equipment on board of the ship	0	0
ID 1025 Fire on a hydrogen tube trailer truck with compressed hydrogen (2021)	Abnormality in the vehicle's brake system	0	0

Table 18. Core event, failure and consequences in loading/unloading events (transport).

Core Event in Loading/Unloading Events	Failure	Injured	Fatalities
ID 17 Hydrogen explosion from a truck when gas cylinders were being unloaded (1983)	Broken connections and inoperable shut-off valves.	16	0
ID 57 A small amount of hydrogen gas continued to escape from the trailer tank and burn for almost eight hours (2004)	Driver failed to follow standard safety procedures correctly	1	0
ID 174 Hydrogen explosion while truck driver was delivering hydrogen gas to fill storage cylinders at the plant (2007)	Hydrogen relief device failure	9	1
ID 384 A pressure relief device on one of a hydrogen delivery tube trailer's tubes failed and released hydrogen while filling a hydrogen storage tank at a government facility (2008)	Pressure relief valve failure	0	0
ID 382 A safety rupture disc ruptured during filling a tube trailer, causing the tubes to burst and release hydrogen gas. The released gas ignited, creating a large vertical flame (2009)	Rupture of the disc on one of the trailers' tubes	1	0
ID 541 A road tanker was being loaded with liquid hydrogen from a 15,000-gallon storage tank, when fire broke out after (1977)	Rupture disk failure and loose connection in downstream piping	0	0
ID 559 Explosion on a tank truck whilst unloading hydrogen into a storage tank, injuring two people and starting a fire (1983)	Unspecified	2	0
ID 590 Explosions on an industrial estate when hydrogen being piped from a road tanker leaked (1975)	Unspecified	1	0
ID 812 During a delivery a hydrogen leak occurred at an automotive supplier (2012)	Failure in the connection between the delivery truck and a stationary tank	0	0
ID 907 A pallet with hydrogen cylinders is damaged during the operation of unloading the cylinders trailer (1989)	Forklift	0	0
ID 930 Leak on a hydrogen cylinder rack delivered by a lorry inside the fenced storage area of a bulb manufacturing plant (2013)	A lifting chain accidentally opened a gate valve	0	0
ID 941 Hydrogen leak on the hose connection of a tank truck being loaded into an industrial gas company (2012)	Unspecified	0	0
ID 943 Liquid hydrogen release from a truck during a delivery to the unloading station of a steel plant (2011)	Unspecified	0	0
ID 974 Fire after hydrogen vapor from a liquid hydrogen truck ignited. The hydrogen was being pumped from the truck's tank to a tank alongside the business (2018)	Unspecified	0	0
ID 986 Hydrogen leak led to the formation of a fireball at the end of a hose at the conditioning station while tank truck was being loaded (2020)	Unspecified	0	0
ID 989 Leak while loading a semitrailer carrying hydrogen gas cylinders. The vehicle caught fire (2020)	Unspecified	0	0
ID 992 A tanker carrying liquid hydrogen struck an industrial building while backing up, causing a hole in the tank and a subsequent leak and ignition (2004)	Hole in the tank after a struck	1	0

3.2.4. Industrial Uses

Finally, the analysis of events during the industrial uses permits the classification of the events into two categories described in Table 19.

As per the previous table, events related to failures in piping and hydrogen lines are the most prevalent. A majority of the damage is attributed to these events, accounting for 54.72% of injuries and 68.97% of fatalities (Figure 6). However, events associated with compressors, though less frequent, stand out with a higher fatality rate (47.37%) (Table 19).

Table 19. Industrial use process/equipment categories.

Process/Equipment	Description	Events	Fatality Rate
Compressors	Events related to devices used to pressurize hydrogen to the required pressure	19	47.37%
Pipes and hydrogen lines	Events initiating in conduits that distribute hydrogen within industrial facilities	55	36.36%
Others	Events initiating in other equipment (oil pump, hose, valve, analyzer)	4	0.00%

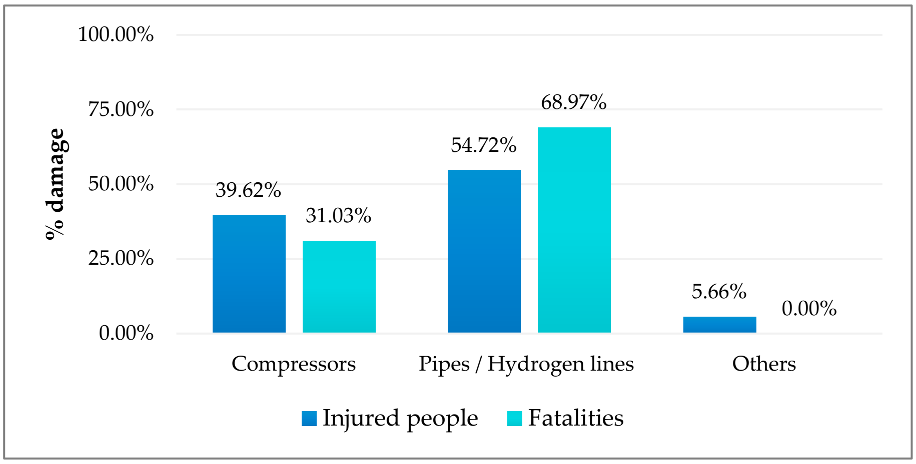

Figure 6. Industrial application damage.

The database allows the categorization of incidents according to the type of failure. Incidents involving compressors can be classified into six distinct categories, while incidents involving pipes/hydrogen lines can be categorized into ten distinct categories (Table 20).

Compressor-related incidents are primarily attributed to cylinder failures mainly caused by overpressure (Table 21), but with no fatalities involved. Looking at the total number of fatalities by category, an incident related to suction pipe rupture is shown as the most significant contributor to fatalities (Table 22).

Pipe/hydrogen line-related incidents are predominantly caused by flange/connection failures, corrosion and performance (Tables 23–25). Remarkably, problems as common as connection failures and corrosion do not lead to fatalities. Events related to performance and welding failures emerge as the most severe incidents, accounting for the most fatalities, each responsible for seven fatalities (Tables 25 and 26).

Table 20. Failures, descriptive and damage in compressors (a), pipes and hydrogen lines (b) and other failures (c) (industrial applications).

a. Failures in Compressors		Injured	Fatalities
Connection failure	2	5	2
Cylinder failure	5	2	0
Operator-induced event during performing works	1	3	2
Suction pipe rupture	1	2	3
Temperature probe failure	1	0	0
Valve failure	1	9	2
Unspecified	8	0	0
Total	19	21	9

Table 20. *Cont.*

a. Failures in Compressors		**Injured**	**Fatalities**
b. Failures in Pipes and Hydrogen Lines		**Injured**	**Fatalities**
Corrosion	8	1	0
Flange/connection failure	13	5	0
Hydrogen attack	3	1	0
Natural causes	1	0	0
Operator-induced leak during performing works	7	7	7
Pipe support failures	2	0	0
Purge/depressurize failure	2	1	0
Seal failure	2	0	0
Valve failure	5	3	0
Welding failure	2	8	7
Unspecified	10	3	6
Total	55	29	20
c. Other Failures		**Injured**	**Fatalities**
Analyzer	1	0	0
Flexible hose	1	1	0
Oil pump	1	2	0
Safety relief valves	1	0	0
Total	4	3	0

Table 21. Core event, failure and consequences in compressors with cylinder failure (industrial applications).

Core Event in Compressors Events	Failure	Injured	Fatalities
ID 110. Release of hydrogen and subsequent fire when a cylinder head of a gas compressor failed during its start-up after maintenance (1995)	Failure of the compressor cylinder head with overpressure	0	0
ID 548. Discharge pressure of a hydrogen compressor and three bumps were heard (1979)	Compressor overheating and cylinder failure caused pressure discharge	0	0
ID 552. Hydrogen release into the confined compressor building and ignition (1980)	Compressor cylinder with over-pressure in the piston	0	0
ID 613. While making preparation for operation of a compressor supplying hydrogen an operator got injured as the checking cover of a crank room came off, emitting a hot wind (1988)	Hydrogen leaking from the shaft of a cylinder at the compressor caused ignition	2	0
ID 675. Explosion and fire at a reciprocating recycle hydrogen compressor during commissioning of a new diesel (1993)	Unspecified	0	0

Table 22. Core event, failure and consequences in compressors with suction pipe failure (industrial applications).

Core Event in Compressor Events	Failure	Injured	Fatalities
ID 582. An explosion occurred in a hydrogen compressor (1985)	Rupture of 4-inch suction pipeline to the compressor	2	3

Table 23. Core event, failure and consequences in pipes/hydrogen lines with flange/connection failure (industrial applications).

Core Event in Pipe/Hydrogen-Line Events	Failure	Injured	Fatalities
ID 98. A hydrogen leak occurred on a flange located on a pipe coming from the hydrogen storage tank (2006)	Flange failure	0	0
ID 201. Hydrogen fire due to unsealing of flange connection in exchanger (2000)	Unsealing of flange connection	0	0
ID 252. Continuous release of hydrogen in hydrogenation reactor through faulty connections causes explosion (1995)	Connection failure	5	0
ID 255. Leak on a hydrogen pipe feeding a reactor and ignition (1993)	Flange/connection failure	0	0
ID 270. Fire sparked by a hydrogen leak in a pipe that brings hydrogen to the oven (2008)	Flange/connection failure	0	0
ID 334. Continuous release of hydrogen through faulty connections caused explosion (2001)	Faulty connections of a valve	0	0
ID 622. Hydrogen escaped from leak in pipeline connection to cylinder (1974)	Connection failure	0	0
ID 633. Fire due to hydrogen gas leakage from a reactor in a high-pressure gas plant (1986)	Flange failure	0	0
ID 825. Hydrogen leakage on a pipe flange in an ammonia synthesis unit started a fire (1990)	Flange failure	0	0
ID 829. Hydrogen release by the failure of a flange caused a fire (1992)	Flange failure	0	0
ID 839. Fire at a flange of a heat exchanger (2005)	Flange failure	0	0
ID 892. Hydrogen leak at a flange of an exchanger (2019)	Flange failure	0	0
ID 923. Fire in a refinery on a flange of a hydrogen supply line that leaked and ignited (2016)	Flange failure	0	0

Table 24. Core event, failure and consequences in pipes/hydrogen lines with corrosion (industrial applications).

Core Event in Pipe/Hydrogen Line Events	Failure	Injured	Fatalities
ID 131. A hydrogen pipe burst (2005)	Pipe corrosion	1	0
ID 341. Self-sustained ignition in the hydrogen pipes (2004)	Pipe corrosion	0	0
ID 527. Piping failed causing a release of hydrogen and a subsequent explosion (1996)	Pipe corrosion	0	0
ID 783. Leak from a thermally insulated pipe (the unit was depressurized, but 15 min later the hydrogen ignited generating a jet fire) (2001)	Pipe corrosion and erosion	0	0
ID 807. Hydrogen leakage occurred in hydrogen pipeline (2018)	Pipe corrosion	0	0
ID 840. Failure occurred on a hydrogen line between a hydrogen compressor and its overpressure protection valve (2006)	Hydrogen line corrosion	0	0
ID 952. Hydrogen leak on a pipeline inside a steam cracking unit located between two hydrogenation units (2010)	Pipe external corrosion by water drop	0	0
ID 958. Hydrogen leak occurred on the hydrogen line of a hydro-desulfurization unit, followed by ignition (2007)	Hydrogen line corrosion	0	0

It is relevant to note that events associated with human performance, such as the events with ID 503 and ID 905, can have a very damaging impact.

As with the storage events, it should be pointed out that some incidents resulting in deaths could not be categorized because the database does not provide detailed information (nine fatalities for compressors and six for pipes/hydrogen lines).

Table 25. Core event, failure and consequences in pipes/hydrogen lines with operator failure (industrial applications).

Core Event in Pipe/Hydrogen Line Events	Failure	Injured	Fatalities
ID 546. Leak in a hydrogen main that had an elliptical hole. The source of ignition was hot welding sparks arising from work being carried out (1979)	Leak in a hydrogen main and sparks during works	0	0
ID 560. Argon and hydrogen gas leaked from pipes they were installing (2000)	Operators performing works	0	3
ID 804. Hydrogen explosion (2017)	Operator opened a valve on the hydrogen network of the plant	3	0
ID 854. Ignition of a hydrogen leak when two employees were performing works on hydrogen piping (2011)	Operators performing works	0	0
ID 905. Hydrogen released from a venting valve opened for inspection and ignited spontaneously (1989)	Inspection works	3	4
ID 922. Hydrogen fire caused by a leak on a pipe system of the distribution circuit (2017)	Operators repairing intervention on a cupboard nearby	0	0
ID 935. A through-cut caused an explosion inside the hydrogen manifold that blew apart the rubber sleeves connecting the manifold to the electrolysis cells (2013)	Operators cutting a purge pipe on a hydrogen manifold	1	0

Table 26. Core event, failure and consequences in pipes/hydrogen lines with welding failure (industrial applications).

Core Event in Pipe/Hydrogen Line Events	Failure	Injured	Fatalities
ID 11. Hydrogen leak resulted from an elbow on the pipeline body carrying gaseous hydrogen (1989)	Welding failure	8	7
ID 196. Explosion in the compressor unit (2000)	Welding of the hydrogen pipe	0	0

4. Discussion

This study has systematically reviewed, selected, and categorized the events collected in the HIAD 2.0, considering the different stages of the hydrogen value chain and its possible extrapolation to hydrogen refueling stations. The damage was quantified in terms of both injuries and fatalities. Simultaneously, the core event of each incident and accident, serving as the focal points leading to abnormal situations, was scrutinized, generating categories and typologies of events.

In this section, three central aspects are emphasized: (1) main findings comparing events by hydrogen value chain; (2) lessons derived from the characterization of events (processes and activities) across the different stages of the hydrogen value chain; (3) key concepts in terms of HRS safety. Additionally, the research limitations and potential avenues for further research are outlined.

Firstly, the study reveals varying levels of risk associated with the different stages of the hydrogen value chain. A significant finding is the disparity between event frequency and severity. The nonlinear relationship between prevalence (number of events) and damage is noteworthy. Consequently, certain stages of the hydrogen value chain experience a higher frequency of abnormal situations, while others, with fewer incidents, pose a potentially higher severity of consequences.

Specifically, hydrogen industrial uses and delivery correspond to the majority of incidents in terms of frequency, a closer examination shows that a higher number of events is not necessarily associated with more significant human damage. Fatality rate emerges as a crucial indicator of the potential severity of events within the hydrogen storage value chain. Simply put, any abnormal event in the storage process substantially increases the risk of fatalities with a 90% fatality rate (45 fatalities in 50 accidents). Paradoxically, the delivery process, despite having the highest absolute number of events together with industrial events, boasts the lowest fatality rate among the categories, standing at 26.32% (20 fatalities in 76 events).

Secondly, the study has enabled the characterization of types of abnormal events within each stage of the hydrogen value chain with a significant level of detail. This thorough analysis reveals relevant aspects for the safety of both the different activities/processes within the hydrogen value chain and refueling facilities.

In the context of the hydrogen production, 50% of the events are associated with two types of components, electrolyzers and gas holders/tanks, which are the factors leading to 100% of the mortality. It could be inferred that the greatest danger during production is related to electrolyzers and their associated gas storage. However, it is crucial to note that in the case of electrolyzers, the last fatal event recorded in HIAD 2.0 was in 2006, and hydrogen production technology has also evolved significantly in recent decades [21].

As regards hydrogen storage, which has the most severe consequences in terms of fatalities, a detailed analysis can pinpoint the activities that pose the greatest safety concerns. The initial conclusion is intuitive: the potential for serious consequences increases proportionally with the amount of hydrogen stored. Therefore, the fatality rate for incidents involving storage tanks is 4.68 times higher than the fatality rate for those involving issues with storage cylinders (despite a similar frequency of events recorded in the database). Additionally, the analysis provides a more nuanced understanding of critical activities/processes for these two storage modes.

For tank storage, two high-risk activities/processes are identified: works inside the tank and degassing. Conversely, for cylinder storage, critical activities/processes are associated with filling hydrogen containers and operation/works with hydrogen cylinders. It is also noteworthy that for both types of storage, human activities (operations conducted by people in the storage area) present a high-risk factor. It is also important to highlight the considerable number of storage events in the data (28%) with limited information, which impedes the identification of the processes/activities involved.

Concerning the delivery stage of the hydrogen value chain, events can be broadly categorized into two types: those related to distribution (large pipelines) and those related to transport (mostly road transport by trucks). Notably, the most prominent and significant risk associated with hydrogen delivery lies in the transportation phase, which is related to cargo incidents, hydrogen charge incidents, and traffic accidents. Even though they occur with nearly equal frequency, the fatality rate indicates that traffic accidents have the most significant safety risk (76% of all hydrogen delivery fatalities), especially in the case of collisions with other vehicles, which have been identified as the leading cause of fatalities in hydrogen delivery.

Finally, examining incidents related to hydrogen industrial uses, two primary event types can be extrapolated to hydrogen refueling stations. These are incidents involving compressors (with a fatality rate of 47.37%) and incidents in hydrogen pipes inside industrial installations (fatality rate of 36.36%). As to compressors, the critical and hazardous process is linked to the pipe compressor connection. This connection can fail (two events, two fatalities) or experience a suction pipe rupture (two events, three fatalities). Conversely, fatalities resulting from failures in hydrogen pipes and lines are primarily associated with leaks caused by human activities (seven events, seven fatalities) and welding failures (two events, seven fatalities).

Thirdly, this study provides insights highly relevant to the safety of hydrogen refueling stations. The knowledge provided by the dissection of the events carried out in this research makes it possible to establish a hierarchy of the potential risk entailed by the different processes and activities that take place in HRSs. This extrapolation of risks can be carried out both by the results of the macro-vision of the hydrogen value chain events and by the findings obtained in the microanalysis of specific HRS events (research in progress in another study) [22].

The findings of the study bear noteworthy implications for the safety of hydrogen refueling stations. Specifically, those gleaned from the storage, delivery, and industrial utilization of hydrogen should be carefully accounted for, owing to its nearly seamless translation from procedural contexts to HRSs. The extrapolation of these findings must consider that hydrogen refueling stations can be either on-site or off-site, depending on whether they incorporate hydrogen production or not. Both primarily operate on processes encompassing hydrogen storage and delivery, which manifest as having the highest potential for fatal accidents. Consequently, enhanced safety protocols are crucial during these stages. For storage, activities within tanks and during offloading hydrogen for subsequent storage at refueling facilities should be prioritized, while in delivery-hase road transport, which emerges as a critical aspect, demands attention. Additionally, heightened vigilance is essential for tasks involving hydrogen compressors and piping. Such undertakings play a pivotal role in industrial hydrogen uses and are susceptible to generating leaks, thereby posing a significant risk.

On-site hydrogen refueling stations, while not the most common type, must also address the inherent challenges of hydrogen production. Stringent safety measures are paramount, especially when dealing with electrolyzers and gasometers/tanks, critical components for hydrogen production. Mishandling these components could result in explosion hazards caused by equipment malfunctions, overheating, and corrosion, amongst others. Hence, adherence to strict safety protocols is imperative in such scenarios.

It should also be underlined that the analysis of events underscores the substantial role of human actions in contributing to incidents and accidents. Specifically, in processes with direct applicability to hydrogen refueling stations, operator-induced failures can have severe repercussions, including equipment damage, fires, explosions, and even personal injuries.

In sum, the findings emphasize the importance of implementing rigorous safety measures, technological advancements, and improved incident reporting and data collection to mitigate risks and improve the safety of hydrogen-related activities. The main findings are shown in Table 27.

Table 27. Summary of the main findings of the event analysis.

Central Idea	Finding
Risk varies depending on the stage of the value chain.	- Disparity between event frequency and severity (in terms of fatalities and injured people). - Storage processes have the highest potential severity.
The in-depth analysis reveals different types of events (in terms of systems, equipment and contributing factors) at each stage of the value chain.	- Production: Electrolyzers and storage devices emerge as critical equipment for safety. - Storage: Tanks (works inside the tanks) and cylinders (filling hydrogen containers and operation/works with cylinders) are the primary components that cause storage events. - Delivery: Hydrogen distribution with large pipelines does not involve personal damage. The riskiest activity is related to road transport (collisions between vehicles). - Industrial uses: Compressors (pipe–compressor connections) and pipes inside installations (leaks caused by human activities and welding failures) show as the most critical elements for safety.
Safety implications for hydrogen refueling stations.	- Enforce rigorous safety protocols for critical components in hydrogen production systems (electrolyzers and gasometers/tanks) to safeguard against equipment failures, overheating, corrosion, and also for hazardous activities involving storage equipment. - Prioritize the criticality of human factors during maintenance works, operation, etc. to prevent human-related accidents.

Lastly, some relevant limitations of the study must be acknowledged. The quality and consistency of the information contained in the database (gathered by third parties) has conditioned the breadth of the analysis. As West et al. [23] pointed out, the lack of consistent data reporting poses a challenge to exploit this database. Thus, some of the events do not have sufficient information to identify the critical activities/processes that contributed to the development of the incident. Also, the analysis is based on data collected up to 2022, which would need to be extended with the most recent incidents. To finish, as mentioned before, the analysis does yet not include knowledge from the events occurring in HRSs, which is part of another study.

Further research and collaborative efforts in the hydrogen industry are necessary to continually improve safety protocols and minimize the impact of incidents and accidents.

5. Conclusions

This review and analysis of the events recorded in the HIAD 2.0 has enabled the identification of risks and hazards associated with each stage of the hydrogen value chain (production, storage, distribution and industrial applications). These insights, related to frequency, severity, activities/processes and types of failures, provide valuable knowledge for enhancing the safety of HRSs.

One of the main findings of the study is related to the binomial frequency–severity, revealing that the event frequency does not necessarily translate into greater severity. In this sense, incidents and accidents occurring during storage operations, while constituting 22.32% of the total, bear an alarming 90% fatality rate. This high severity is linked to critical practices such as performing work activities inside the tanks and degassing processes.

The analysis also identifies critical equipment/systems in the different stages of the hydrogen value chain. This is the case of electrolyzers and storage devices in events during hydrogen production or compressors and hydrogen pipes inside the installations where hydrogen is being used. Additionally, loading and unloading hydrogen for transfer or receipt and transporting hydrogen by road are crucial processes/activities during hydrogen delivery.

These findings can be instrumental in improving the safety of hydrogen refueling stations. HRSs also face the challenges of storage, delivery, use, and production (for on-site installations). This knowledge can help stakeholders in the hydrogen industry, including operators of refueling stations, regulatory bodies, and technology developers, take specific actions that foster safer environments for both workers and the public. This proactive approach to safety is essential for the successful growth of the hydrogen economy and the widespread adoption of hydrogen as an energy carrier.

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Informed Consent Statement: Not applicable.

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