Quantitative Risk Assessment Models for Extinguishing and Controlling Hydrogen Fires and Explosions Across the Hydrogen Energy Cycle

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ABSTRACT

Hydrogen is widely regarded as a clean energy carrier for decarbonising mobility and stationary power, yet its wide flammability range, low ignition energy and high flame speed make fire and explosion the governing hazards across the supply chain. This study develops and applies a quantitative risk assessment (QRA) framework to estimate, evaluate and control fire and explosion risks for seven representative objects spanning the hydrogen energy cycle: a solar hydrogen production plant, a liquid-hydrogen (LH_2) depot, a fuelling station, an on-board vehicle tank, a fuel-cell combined heat and power (CHP) unit, a road tanker and a gaseous-hydrogen (GH_2) pipeline. Accident scenarios were identified using HAZOP and FMEA. Event frequencies were derived from a combined fault-tree and event-tree analysis (FTA/ETA) with lognormal basic-event data propagated through 10,000 Monte-Carlo trials, while road-transport and pipeline frequencies were obtained from historical accident statistics. Physical consequences—dispersion, jet fire, pool fire, fireball, flash fire and vapour-cloud explosion—were simulated with PHAST Professional v6.4 (DNV) and converted to fatality levels using thermal-radiation and overpressure probit relations. Individual and societal (F-N) risks were benchmarked against the ALARP/ALARA acceptance criteria and against an equivalent liquefied-petroleum-gas (LPG) study. Continuous releases dominated loss of containment (~94%), with tank overpressure as the leading initiator (~50%); fires accounted for ~60% of outcomes and explosions ~5%. The overall societal risk of the hydrogen cycle was 8.5×10^{-3}/year, dominated by the fuelling station (39%) and the on-board vehicle tank (35%). Although individual risks for hydrogen storage exceeded those of LPG, the maximum effect distances and societal risks were consistently smaller, indicating that hydrogen poses a lower public risk than LPG of comparable tank size. The framework identifies critical weak points and prioritised risk-reduction measures for the safe deployment of hydrogen infrastructure.

Keywords: Hydrogen safety; Quantitative risk assessment (QRA); Fire and explosion; PHAST consequence modelling; Fault-tree and event-tree analysis; ALARP criteria; Liquefied petroleum gas (LPG) comparison

INTRODUCTION

Hydrogen is increasingly viewed as a cornerstone of a low-carbon energy system because it can be produced from renewable resources, stored, and reconverted to electricity or used directly as a fuel without emitting greenhouse gases at the point of use. Its high gravimetric energy density and versatility make it attractive for both mobile and stationary applications. Realising a large-scale "hydrogen economy", however, requires an integrated infrastructure of production, transportation, storage, refuelling and end-use, every link of which introduces potential failure points where hydrogen may be released to the environment.

The safe handling of hydrogen differs fundamentally from that of conventional fuels because of its distinctive physical behaviour: high buoyancy and diffusivity promote rapid dispersion, but a very wide flammability range (4–75% by volume), a low minimum ignition energy (~0.02 mJ) and a high laminar flame speed make ignition easy and combustion rapid. Consequently, fire and explosion are the dominant flammability hazards in hydrogen systems. When hydrogen has historically been handled within the chemical and process industries by trained personnel, the migration of hydrogen into the public domain—where untrained users interact with the fuel at refuelling stations, in vehicles and in domestic CHP units—raises new and largely unquantified safety questions.

This work addresses that gap by establishing the safety-technological conditions for the public use of hydrogen as an energy carrier. The objective is to quantify the fire and explosion risk associated with hydrogen across its energy cycle, to identify the weak points that contribute most to that risk, and to recommend prioritised risk-reduction measures. The risks are further benchmarked against a comparable LPG system so that hydrogen can be judged relative to an established, publicly accepted technology.

Scope and Contribution

Quantitative risk assessment (QRA) is adopted as the system-analytic method. The contributions of this paper are: (i) a unified QRA of seven study objects that together represent the complete hydrogen energy cycle, rather than a single installation studied in isolation; (ii) an integrated FTA/ETA frequency model with Monte-Carlo uncertainty propagation coupled to PHAST consequence simulation; (iii) a consistent evaluation of both individual and societal risk against the ALARP/ALARA criteria; and (iv) a like-for-like comparison with LPG that places hydrogen risk in a familiar regulatory context. The remainder of the paper is organised as follows. Section 2 reviews related work and the research gap. Section 3 details the QRA methodology and governing models. Section 4 describes the study objects and simulation setup. Section 5 presents and discusses the frequency, consequence and risk results, including the LPG comparison. Sections 6 and 7 give the conclusions and future scope.

LITERATURE REVIEW

Research on hydrogen safety has expanded alongside interest in the hydrogen economy, drawing on the mature body of chemical-process risk-analysis practice consolidated by the AIChE/CCPS guideline series (AIChE/CCPS, 2000). These guidelines codify hazard identification, frequency estimation through fault-tree and event-tree analysis, and consequence modelling for vapour-cloud explosions, flash fires and BLEVEs, and they form the methodological backbone for most subsequent hydrogen QRA studies.

Alcock et al. (2001) compiled the existing safety data on hydrogen and benchmarked it against comparable fuels, establishing that hydrogen's wide flammability range and low ignition energy are partly offset by its rapid buoyant dispersion, which limits the persistence of flammable clouds in open air. Cadwallader and Herring (1999) reviewed the safety issues specific to hydrogen as a vehicle fuel, highlighting embrittlement, permeation and the difficulty of detecting near-invisible hydrogen flames. Cancelli et al. examined release from cryogenic tanks, underlining the additional hazards introduced by liquid hydrogen, including loss of vacuum, cold embrittlement and two-phase discharge.

On the consequence-modelling side, the PHAST technical framework developed by DNV (2002) provides validated source, dispersion, fire and explosion sub-models and has become a de-facto standard for industrial consequence analysis. Vilchez, Carol and Casal (1996) demonstrated the use of major-hazard databases to construct event trees for flammable materials, an approach mirrored in the present study. For societal-risk benchmarking, Ball and Floyd's work on societal risk and the Dutch risk-policy framework (Bottelberghs) supply the F-N curve formalism and the ALARP/ALARA acceptance limits used here.

Although these studies individually address hazard data, cryogenic release, consequence modelling or acceptance criteria, most concentrate on a single installation type—typically a refuelling station or a storage vessel. Comparative QRA studies that span the entire hydrogen cycle and that explicitly benchmark hydrogen against an established public fuel such as LPG remain scarce. The present work addresses this gap by applying a single, internally consistent QRA framework to seven objects covering production, storage, distribution, transport and end-use, and by comparing the resulting individual and societal risks with an equivalent LPG study (Table 6). This breadth allows the relative contribution of each link in the hydrogen cycle to be ranked and the dominant risk drivers to be identified across the system rather than within one component.

METHODOLOGY

The study follows the five-stage QRA process: hazard identification, frequency estimation, consequence modelling, risk estimation and risk evaluation. Figure 1 summarises the workflow, in which probabilistic frequency analysis and physical consequence analysis are developed in parallel and combined to produce individual and societal risk measures that are finally evaluated against acceptance criteria.

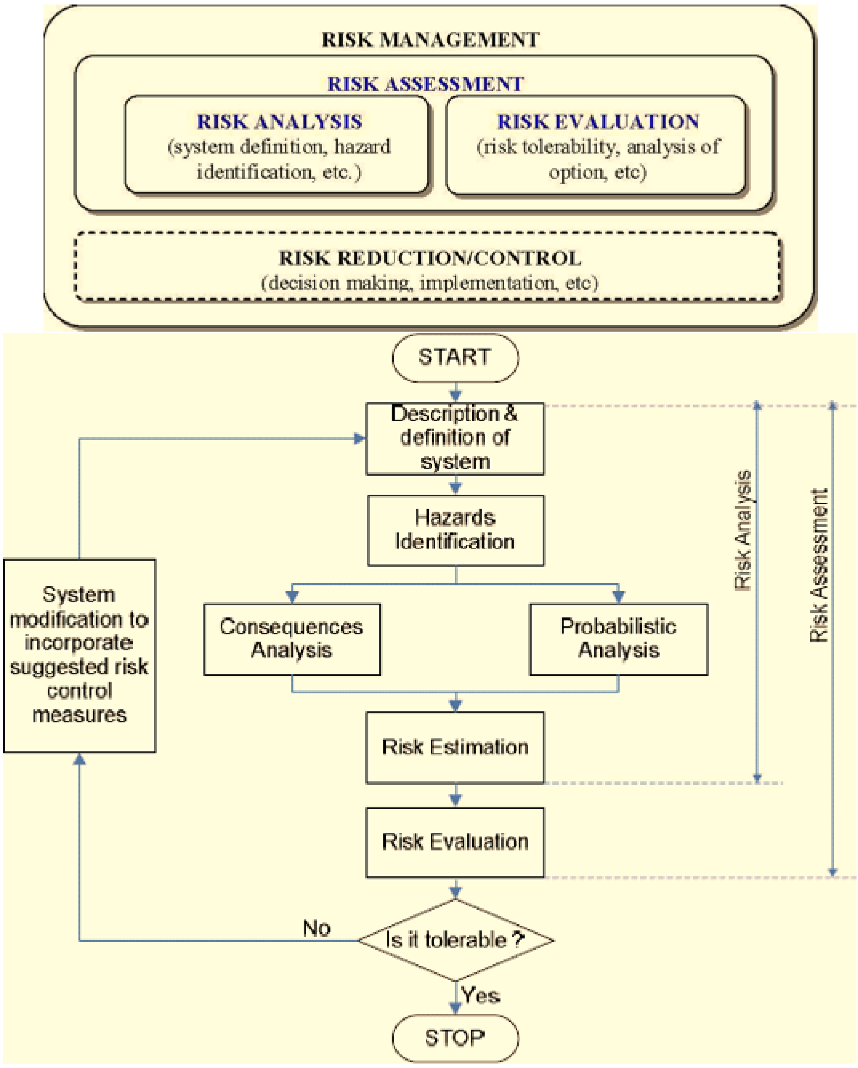

Fig. 1. Quantitative risk assessment (QRA) framework integrating hazard identification, frequency estimation (FTA/ETA), consequence modelling (PHAST) and risk evaluation against acceptance criteria.

Hazard identification

Hazards were identified using a Hazard and Operability (HAZOP) study supported by Failure Modes and Effects Analysis (FMEA) and a Fire & Explosion Index screening. Guide words (no flow, more flow, reverse flow, more pressure, less temperature, etc.) were applied node-by-node to each study object to enumerate deviations, causes, consequences and existing safeguards. The screening confined the detailed QRA to the items holding the largest hydrogen inventory for the longest time—storage vessels, on-board tanks, tankers and pipelines—since these dominate the risk.

Frequency estimation: fault-tree and event-tree analysis

Loss-of-containment (LOC) events were grouped into two top events, instantaneous release (catastrophic tank rupture releasing the full inventory) and continuous release (leak or line rupture). For the four stationary objects (production plant, depot, fuelling station and CHP plant), top-event frequencies were synthesised from component failure-rate data using fault-tree analysis (FTA). Basic-event failure rates were treated as lognormally

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distributed and propagated through 10,000 Monte-Carlo trials, so that each top-event frequency is reported as a mean together with the 5th, 50th and 95th percentiles and the 95% uncertainty factor K_{95}.

For the on-board vehicle tank and the road tanker, release frequencies were obtained from historical road-traffic accident rates r combined with annual travel distance and conditional probabilities of spill and ignition, following Eq. (1):

$$F_{rel} = r \times L_a \times P_{spill} \times P_{ign} \quad (1)$$

where F_{rel} is the expected release frequency, L_a the annual distance travelled, and P_{spill} and P_{ign} the conditional probabilities of spill and ignition. Pipeline failure frequencies were taken from European gas-pipeline base-failure data, disaggregated by cause (external interference, corrosion, construction defect, ground movement) and by hole size, and scaled by reduction factors appropriate to hydrogen service.

The accident-outcome frequencies (early explosion, fireball, pool fire, jet fire, flash fire, late explosion, or no effect) were then obtained by multiplying each top-event frequency by the conditional branch probabilities of the relevant event tree. Separate event trees were used for liquid- and gaseous-hydrogen releases (Figure 2) to reflect their different ignition and phase behaviour.

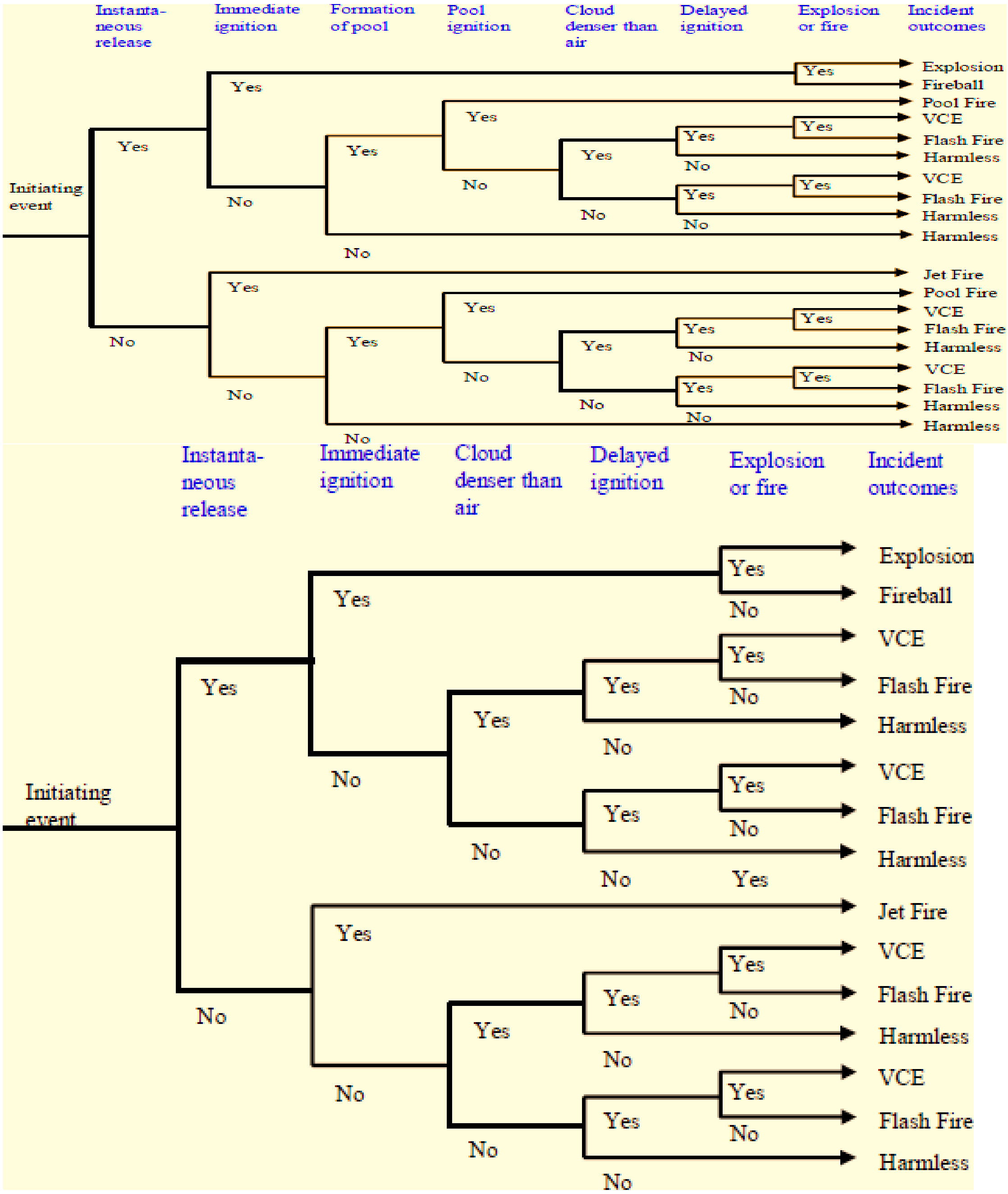

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Fig. 2. Event-tree diagrams mapping continuous and instantaneous releases of liquid and gaseous hydrogen to fire and explosion outcomes with their conditional probabilities.

Consequence modelling

Physical consequences were simulated with PHAST Professional v6.4 (DNV). Source terms for choked and two-phase discharge were computed from the storage pressure P_v, aperture area A and discharge coefficient C_D. For an idealised gas release the mass flow rate follows Eq. (2):

$$Q = C_D A\, P_v \sqrt{\left(\gamma M_w / R T \times (2/(\gamma+1))^{(\gamma+1)/(\gamma-1)} \right)} \qquad (2)$$

where Q is the release rate, γ the specific-heat ratio, M_w the molecular weight, R the universal gas constant and T the storage temperature. Dispersion was modelled with the Unified Dispersion Model; jet fire, pool fire, fireball, flash fire and vapour-cloud explosion were modelled with the corresponding PHAST sub-models, and explosion overpressure was estimated with a TNT-equivalence model. Thermal-radiation fatality was evaluated through a probit relation linking incident radiation q and exposure time t to lethality, while explosion fatality was assigned conservatively from peak-overpressure damage thresholds.

Risk estimation and evaluation

Individual risk and societal risk were obtained by combining consequence effect zones with outcome frequencies on a population grid of 231 inhabitants per km². For each outcome the factored area A_f (effect-zone area weighted by fatality level) was multiplied by frequency F and population density to give the expected number of fatalities N. The contribution of each outcome to risk is expressed as the triplet (scenario, frequency, consequence) of Eq. (3):

$$R = \Sigma F_i \times N_i \qquad (3)$$

Individual risk was plotted as a risk-versus-distance transect, and societal risk as a frequency-number (F-N) curve obtained by ranking outcomes in order of increasing consequence and accumulating their frequencies. Both measures were evaluated against the ALARP (UK Health and Safety Executive) and ALARA (Dutch National Environmental Policy Plan) acceptance criteria proposed for hydrogen by the European Integrated Hydrogen Project (EIHP2).

Experimental Setup and Study Objects

Seven study objects were defined to represent the complete hydrogen energy cycle from production through transport to end-use. Each object was characterised by its storage phase (gaseous GH_2 or liquid LH_2), inventory capacity and operating conditions, and a tailored set of accident scenarios was developed for it. Table 1 summarises the objects and their principal characteristics; these inventories and the associated scenario lists are the inputs to the frequency and consequence models of Section 3.

Table 1. Hydrogen study objects representing the energy cycle and their principal characteristics.

No.	Study object	Storage	Role in cycle	Dominant hazard considered
1	Solar H_2 production plant	GH_2	Production	Gaseous release → jet fire / late explosion
2	H_2 fuelling station	LH_2	Distribution / end-use	Two-phase release → fireball / flash fire
3	H_2 fuel-cell CHP unit	LH_2	Stationary end-use	Domestic release → flash fire / jet fire

4	H_2 depot (liquefaction)	LH_2	Storage	Large LH_2 inventory → pool fire / fireball
5	H_2 private car (on-board)	LH_2	Mobile end-use	Collision release → jet fire / flash fire
6	H_2 road tanker	LH_2	Transport	Traffic accident → fireball / flash fire
7	H_2 pipeline	GH_2	Transport	Line rupture → jet fire / late explosion

Storage phase: GH_2 = compressed gaseous hydrogen; LH_2 = liquid (cryogenic) hydrogen.

The distinctive flammability of hydrogen relative to other fuels governs the severity of these scenarios. Table 2 lists the deflagration and detonation properties used to parameterise the consequence models, including the wide flammability and detonability ranges and low ignition energy that distinguish hydrogen from methane and propane.

Table 2. Deflagration and detonation properties of hydrogen compared with other fuels.

Property	**Hydrogen**	**Methane**	**Propane**	**Gasoline**
Flammability range (vol % in air)	4.0–75.0	5.3–15.0	2.1–9.5	1.0–7.6
Detonability range (vol % in air)	18.3–59.0	6.3–13.5	3.1–7.0	1.1–3.3
Minimum ignition energy (mJ)	0.02	0.29	0.26	0.24
Laminar burning velocity (m/s)	2.65–3.25	0.37–0.45	0.43–0.52	0.37–0.43
Auto-ignition temperature (°C)	585	540	487	228–471

Values are representative literature figures used to configure the PHAST fire and explosion sub-models.

RESULTS AND DISCUSSION

The QRA results are presented in the sequence frequency → consequence → risk, followed by evaluation against acceptance criteria and comparison with LPG.

Frequency estimation results

Table 3 summarises the overall hydrogen-release frequencies of the seven objects. The mean release frequency across the cycle is approximately 1.9×10^{-3}/year (about once in 517 years). Continuous releases dominate loss of containment, accounting for roughly 94% of events, with instantaneous (catastrophic-rupture) releases contributing only about 6%. GH_2 storage exhibits lower release frequency than LH_2 storage because the cryogenic liquid introduces additional failure modes—loss of vacuum, cold embrittlement and tank under-pressure. Tank overpressure is the leading contributor to rupture (>50%), followed by external and spontaneous events; for LH_2 an additional ~30% derives from tank under-pressure.

Table 3. Overall expected hydrogen-release frequencies of the study objects (1/yr).

No.	**Study object**	**Storage**	**5%**	**Mean**	**95%**	**Source**

1	Solar H_2 plant	GH_2	1.8E–06	3.6E–05	1.3E–04	FTA
2	H_2 fuelling station	LH_2	4.7E–05	7.1E–04	2.5E–03	FTA
3	H_2 fuel-cell CHP	LH_2	5.1E–06	1.4E–04	5.4E–04	FTA
4	H_2 depot	LH_2	5.6E–06	1.2E–04	4.6E–04	FTA
5	H_2 private cars	LH_2	—	7.1E–04	—	Data
6	H_2 road tanker	LH_2	—	6.9E–05	—	Data
7	H_2 pipeline	GH_2	7.5E–04	1.5E–04	3.9E–03	Data
—	Overall	—	—	1.9E–03	—	—

FTA = fault-tree analysis with Monte-Carlo propagation; Data = historical accident/base-failure statistics.

Applying the event trees to these top-event frequencies yields the distribution of accident outcomes. Across the cycle, fire outcomes (jet fire, pool fire, fireball, flash fire) dominate at about 60% of events; explosions account for only about 5%, because hydrogen explosions require confinement and high ignition energy; the remaining ~35% of releases have no harmful effect on the population. Table 4 gives a representative outcome breakdown for the gaseous-hydrogen production plant, where jet fire (≈67%) is the dominant fire mode and late explosion contributes ~7%.

Table 4. Representative accident-outcome frequencies for the GH_2 production plant (1/yr).

Accident outcome	Conditional prob.	5%	Mean	95%
Early explosion	0.008	1.4E–08	2.7E–07	9.8E–07
Fireball	0.030	5.4E–08	1.1E–06	3.9E–06
Jet fire	0.475	8.5E–07	1.7E–05	6.2E–05
Late explosion	0.043	7.7E–08	1.5E–06	5.6E–06
Flash fire	0.171	3.1E–07	6.1E–06	2.2E–05
No effect	0.273	4.9E–07	9.8E–06	3.5E–05
Overall	1.000	8.6E–06	3.6E–05	9.0E–05

Conditional probabilities are taken from the GH_2 event tree (Fig. 2).

Consequence modelling results

PHAST simulations show that the buoyant, high-momentum hydrogen jet disperses rapidly: centre-line concentration falls below the lower flammability limit within a short distance of the release point, so flammable clouds are short-lived in open air (Figure 3). Fire and explosion consequences scale with inventory—larger hydrogen mass produces larger effect zones—so the fuelling station and depot generate the most extensive thermal footprints. Figure 4 illustrates the decay of incident thermal radiation with distance for jet fires from different release events, which underpins the 1%-fatality effect zones used in the risk calculation.

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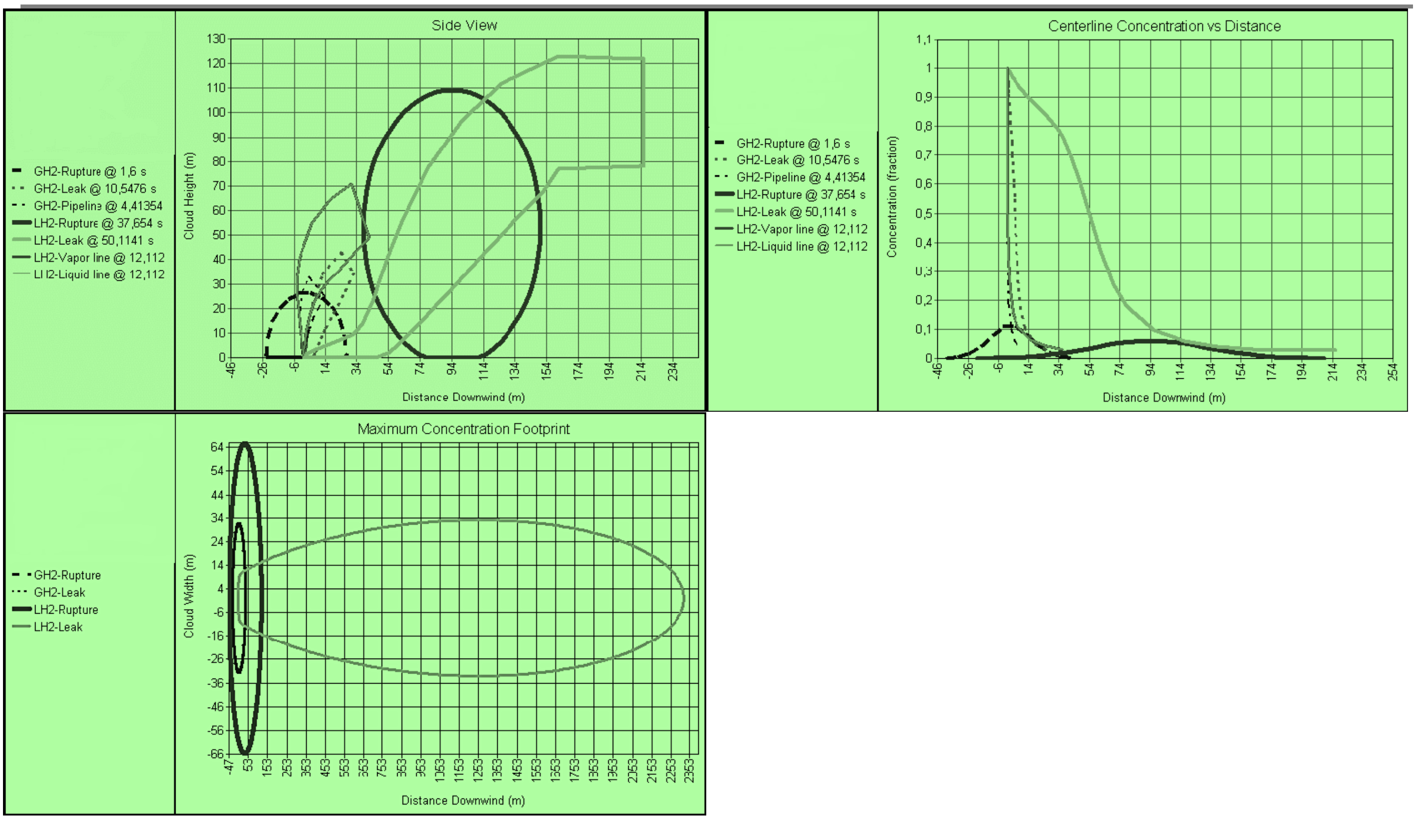

Fig. 3. Centre-line hydrogen concentration versus downwind distance for representative production and end-use releases, showing rapid dilution below the lower flammability limit.

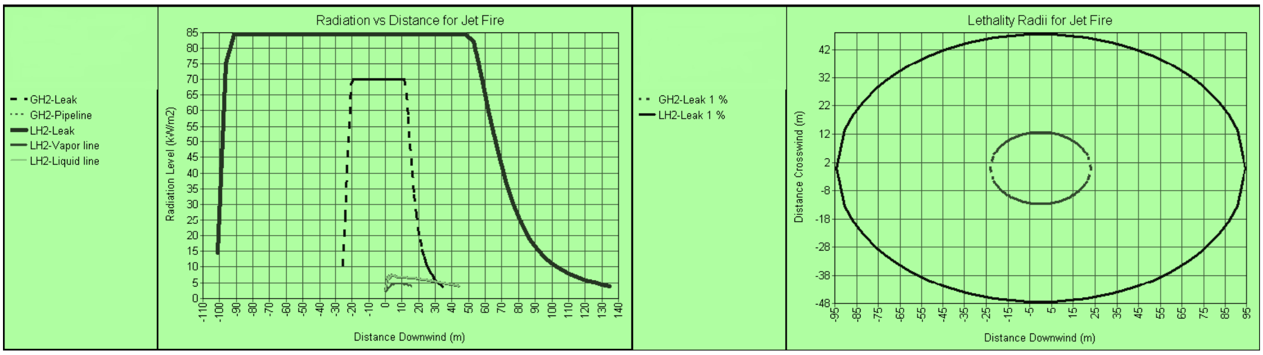

Fig. 4. Incident thermal radiation versus distance for jet fires arising from different release events, used to define 1% fatality effect zones.

Risk estimation results

Combining consequence and frequency results gives the individual and societal risk of each object. The overall societal risk of the hydrogen cycle is 8.5×10^{-3}/year (about once in 118 years). Table 5 ranks the objects by their contribution: the LH_2 fuelling station is the single largest contributor (39%), followed closely by the on-board vehicle tank (35%); together these two end-use/distribution objects account for nearly three-quarters of the total risk, while the production plant contributes least (2.7%). Figures 5 and 6 show the individual-risk transects and the societal F-N curves for the hydrogen cycle.

Table 5. Overall mean individual/societal risk of the hydrogen study objects and their contribution.

Study object	5%	Mean	95%	Share
GH_2 at production plant	1.1E–05	2.3E–04	8.5E–04	2.7%

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VI June 2026

LH_2 at depot	2.3E–05	5.5E–04	2.1E–03	6.5%
LH_2 at fuelling station	2.2E–04	3.3E–03	1.1E–02	39%
LH_2 at CHP plant	2.3E–05	6.5E–04	2.5E–03	7.7%
LH_2 in private car	9.5E–04	3.0E–03	1.3E–02	35%
LH_2 tanker truck	—	3.7E–04	—	4.4%
GH_2 pipeline	—	4.1E–04	—	5.0%
Overall risk	—	8.5E–03	—	100%

Risk values in 1/yr; share is the percentage contribution to the overall cycle risk.

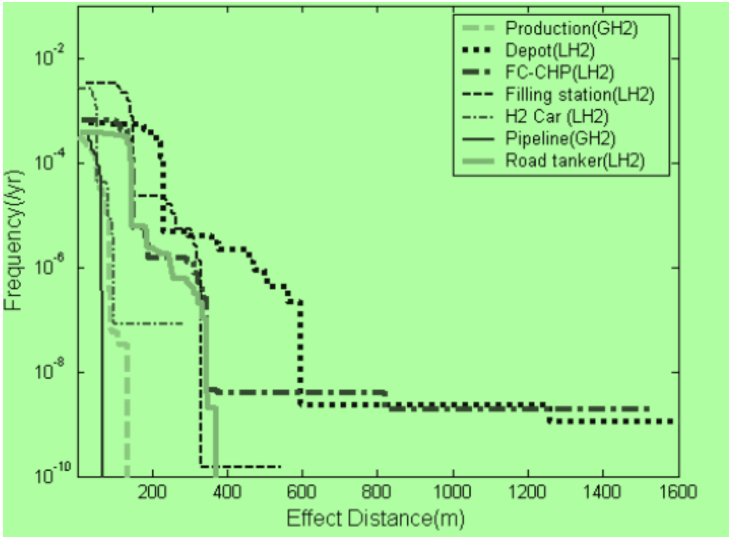

Fig. 5. Individual-risk transects (risk versus distance) for the seven hydrogen study objects.

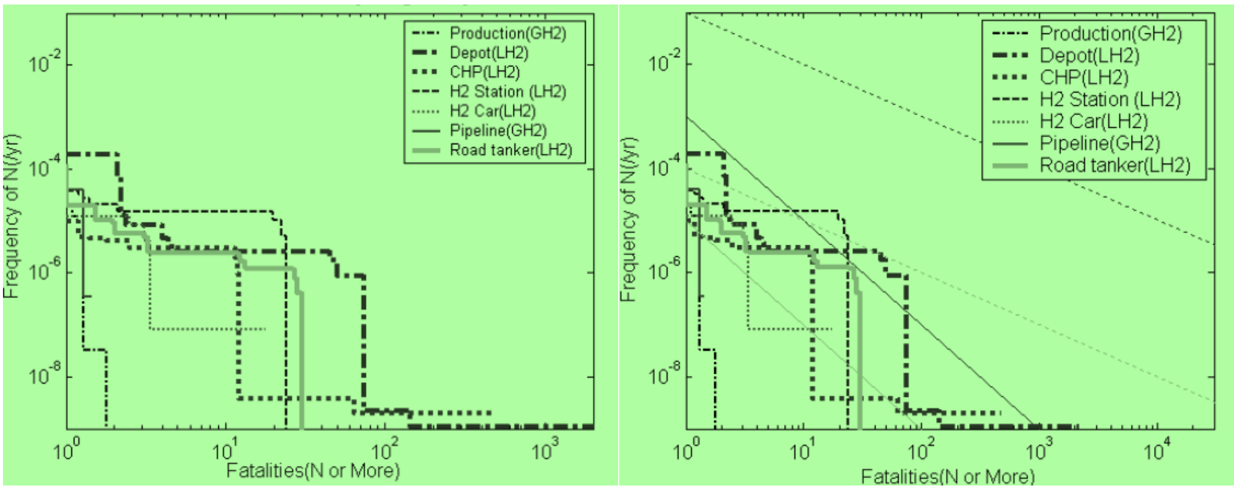

Fig. 6. Societal risk (F-N) curves for the hydrogen energy cycle plotted against the UK ALARP and Dutch ALARA acceptance criteria.

Evaluation against acceptance criteria

Evaluated against the EIHP2/ALARP criteria, the individual risk of the hydrogen objects lies almost entirely above the Dutch acceptability limit of 1×10^{-6}/year and, for the storage objects, above the UK limit of 1 ×

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10^{-4}/year—so risk-reduction measures are required if these plants are operated for the public. The societal risk, however, is globally lower than the individual risk: the transport objects and the GH_2 production plant and pipeline fall within the acceptable region of the UK ALARP envelope, while the LH_2 storage objects fall in the tolerable (reduce-if-practicable) ALARA band. In practice this means hydrogen public facilities are admissible provided risk is reduced as far as reasonably practicable, subject to cost-benefit analysis.

Comparison with LPG

To place these results in a familiar context, the hydrogen objects were compared with equivalent LPG (propane) objects of similar function and size. Although the individual risks of hydrogen storage exceed those of LPG, the maximum effect distances of hydrogen are smaller: hydrogen jet-fire intensity radii are about 60% lower, while LPG flash-fire impact is about 58% lower than hydrogen—reflecting hydrogen's high energy density and very wide flammability range, which lengthen flash-fire reach but shorten radiant-fire reach. Critically, the societal (F-N) risks of every hydrogen object are lower than those of the corresponding LPG object. A qualitative ranking of catastrophic-rupture outcomes (Table 6) confirms that, for comparable tank sizes, hydrogen poses lower overall consequences than LPG.

Table 6. Qualitative ranking of catastrophic-rupture consequences for hydrogen and LPG tanks.

Accident outcome	LH_2 12 m³	LPG 20 m³	LPG 12 m³	LPG 2 m³
Early explosion	3	1	2	4
Late explosion	3	1	2	4
Flash fire	1	2	3	4
Fireball	3	1	2	4
Average rank	2.5	1.25	2.25	4

Severity rank: 1 = highest, 2 = high, 3 = moderate, 4 = low. A higher average indicates lower overall consequence.

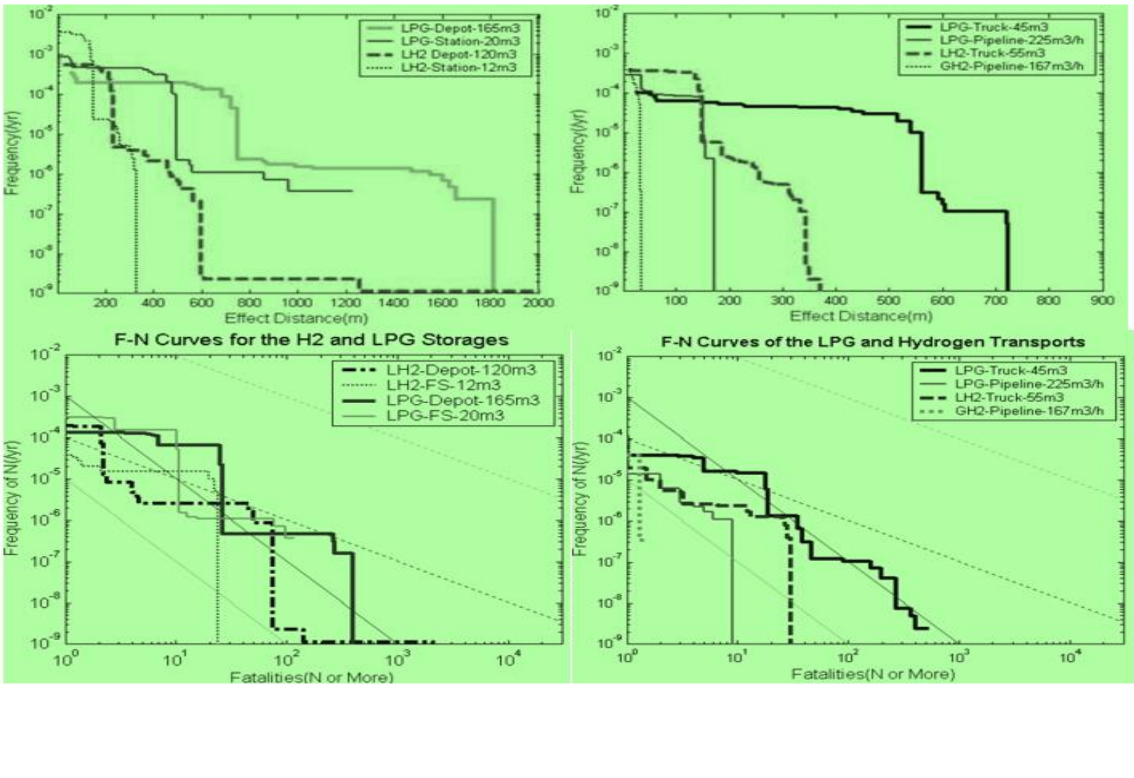

Fig. 7. Comparison of individual risk and societal F-N curves between hydrogen and LPG storage and transport objects.

Practical implications and limitations

The risk ranking points to clear, prioritised mitigations. Because tank overpressure dominates rupture, the highest-value measures are redundant, high-reliability over-pressure protection (relief valves and rupture discs), strict overfill-prevention procedures and operator training, particularly at fuelling stations and on-board vehicle tanks, which together drive ~74% of cycle risk. For LH_2 objects, vacuum-loss protection (e.g., a nitrogen-fed vacuum breaker) and withdrawal/pressure-building safeguards address the additional under-pressure failure mode, while material selection mitigates embrittlement and fatigue. For continuous releases, remotely or automatically actuated emergency shut-off devices limit inventory loss where hand valves cannot. The principal limitations of the study are the reliance on lognormal expert-judgement data for under-developed basic events, simplifications inherent in the PHAST physical models, and the conservative overpressure-fatality assignment adopted in place of probit relations that under-predict explosion lethality; these are the main sources of uncertainty in the reported frequencies and risks.

CONCLUSION

A unified quantitative risk assessment was performed for seven objects spanning the complete hydrogen energy cycle, combining HAZOP/FMEA hazard identification, fault-tree and event-tree frequency analysis with Monte-Carlo uncertainty propagation, and PHAST consequence modelling, with results evaluated against ALARP/ALARA criteria and benchmarked against LPG. Continuous releases dominate loss of containment (~94%), tank overpressure is the leading rupture initiator (~50%, plus ~30% under-pressure for LH_2), and fires account for ~60% of outcomes versus ~5% for explosions. The overall societal risk of the cycle is 8.5×10^{-3}/year, dominated by the fuelling station (39%) and on-board vehicle tank (35%). Although hydrogen storage shows higher individual risk than LPG, its smaller effect distances and consistently lower societal risk indicate that hydrogen poses a lower public risk than LPG of comparable tank size. With redundant over-pressure protection, robust operating procedures, vacuum-loss safeguards for LH_2, and emergency shut-off devices, the residual risk of hydrogen infrastructure can be reduced to a level that is as low as reasonably practicable, supporting the safe public deployment of hydrogen as an energy carrier.

Future Scope

Several extensions would strengthen the present assessment. Coupling experimental release-and-ignition trials with CFD simulation for each object type would improve consequence accuracy and validate the PHAST results. A structured expert-elicitation panel would refine the multiplier and basic-event estimates that currently rely on judgement. Egress-and-evacuation modelling under different fire scenarios would yield more realistic consequence values, and the analysis of complex chained-event scenarios would capture escalation effects not represented by the present event trees. Finally, developing statistical reporting pipelines that allow risk to be computed directly from incident databases, and extending the framework to green-hydrogen production, distribution and end-use, would keep the assessment current as the hydrogen economy matures.

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