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Reliability considerations in Hydrogen Safety Lifecycle Management

Xueli Gao

Risk and Safety Department, Institute for Energy Technology, Norway. E-mail: xueli.gao@ife.no

Sizarta Sarshar

Risk and Safety Department, Institute for Energy Technology, Norway. E-mail: sizarta.sarshar@ife.no

Hydrogen facilities present safety challenges that differ from those in conventional process industries. Properties such as high leak propensity, low ignition energy, rapid dispersion, and material embrittlement significantly influence how risk and reliability must be managed across the safety lifecycle. This paper outlines an integrated approach to applying IEC 61508 and IEC 61511 within hydrogen systems, focusing on reliability considerations from early concept development through the Safety Requirements Specification (SRS) phase. The paper discusses how reliability must be adapted to address data scarcity, fast event escalation, stringent response-time requirements, and the need for redundancy and diversity in leak detection and shutdown functions.

Keywords: Hydrogen, Reliability, Functional Safety, Safety Lifecycles.

1. Introduction

Hydrogen is expected to play a central role in the energy transition, yet its physical and chemical properties introduce unique safety challenges that differ significantly from those associated with conventional process gases. Hydrogen leaks easily due to its small molecular size, ignites at very low energy levels, and disperses rapidly, forming flammable clouds that are difficult to detect because of its invisible flame. Additionally, hydrogen can cause embrittlement and accelerated degradation of metallic materials, creating reliability concerns throughout production, storage, and distribution systems. These characteristics require a more rigorous and adapted approach to risk and reliability management across the full lifecycle of facilities. Managing these risks requires a structured safety framework that combines:

- Risk identification and reduction (understanding hazards and putting layers of protection in place),
- Reliability assurance (making sure safety functions has sufficient capability), and
- Human and organizational factors (ensuring people, teams, and organizations interact safely).

To ensure sufficient safety integrity for hydrogen plant/facility development and operation, the following two standards are relevant and applied widely. IEC 61508: The global, cross-industry standard for functional safety of electrical, electronic, and programmable electronic systems. It sets the overall framework, including the safety lifecycle, Safety Integrity Levels (SILs), and methods for ensuring safety integrity. IEC 61511: A sector-specific adaptation of IEC 61508 for the processing industries, including hydrogen plants, refineries, and chemical facilities. It translates the generic principles of IEC 61508 into practical requirements for Safety Instrumented Systems (SIS) in continuous processes.

IEC 61511 is often the primary reference for process systems. The SIS components (e.g., sensors, logic solvers, actuators) are often designed and certified under IEC 61508.

A project report (Gao, X, & Massaiu, S., 2025) in HydrogenI project explores how to apply IEC 61508 and IEC 61511 in an integrated way for hydrogen plant, with emphasis consideration on reliability and human factors across the safety lifecycle.

This paper presents selected results from the project, focusing on reliability considerations from early stage to safety requirements specification phase. For details and considerations in other phases, refer to the project report (Gao, X, & Massaiu, S., 2025).

2. Project Lifecycle and Safety Lifecycle of Hydrogen Production Plant

IEC 60300 (Dependability management), ISO 55000 (asset management) and some process industry project governance refer to framework of project lifecycles. A typical hydrogen plant project lifecycle would follow stages such as:

- Feasibility & Concept.
- Front-End Engineering Design (FEED).
- Detailed Engineering & Procurement.
- Construction & Installation.
- Commissioning & Start-up.
- Operation & Maintenance.
- Modification & Expansion.
- Decommissioning.

IEC 61508 and 61511 do not define the project lifecycle but define a safety lifecycle specific to functional safety. IEC 61508 introduces a generic safety lifecycle framework as a structured way of managing functional safety from concept to decommissioning phase. IEC 61511 adapts this lifecycle for process industries, which is highly relevant to hydrogen production plants. The safety lifecycle is important since it ensures that hazards are identified, risks are managed, safety systems are designed in, verified, operated and maintained for a hydrogen production plant, refer to IEC 61511 (Part 1, Clause 5 and Annex A) for a described safety lifecycle. These phases must be embedded within the overall project lifecycle, so that safety is carried along from concept to end.

In a structured and step-by-step SIS lifecycle, reliability engineering plays a key role. It helps make sure that the safety function meets the required Safety Integrity Level targets and the equipment operated and maintained at required reliability capability. In the following chapters, the special challenges and consideration related to hydrogen plant design, consideration about reliability and human factors are introduced for each safety lifecycle phases.

3. Feasibility/ Concept phase, Hazard and Risk Analysis

IEC 61511 emphasizes that safety must be designed in from the beginning of the project, rather than added later as an afterthought. This means that during feasibility and concept studies, initial design discussion, and early risk reviews should already be performed. In this phase of the project, the following need to be considered:

- The overall purpose and scope of the hydrogen facility.
- The major hazards and risks associated with large-scale hydrogen production, storage, and transport.
- The regulatory and organizational framework under which the plant will operate.
- The role of designers, operators, maintainers, and emergency responders in achieving safe operation.
- The risk acceptance criteria need to be defined, which can be based on international and national regulations, industry standards or company risk policies. For hydrogen facilities, tolerability criteria often demand higher levels of protection than conventional gas plants due to the difficulty of detecting leaks and the catastrophic potential of explosions.

Hydrogen introduces several unique failure modes compared to conventional process gases. These must be systematically captured and analysed in hazard studies, some hydrogen specific failure modes can be:

(i) Electrolyzer Hazards:

Overpressure due to cooling system failure: Loss of cooling can lead to uncontrolled temperature rise and rapid pressure buildup in cells, potentially triggering relief activation or containment rupture. Consequences: Stack rupture, hydrogen release, fire/explosion, damage to equipment, and potential injury to personnel.

Hydrogen-oxygen crossover from membrane failure: Defects or degradation in PEM or alkaline membranes may result in explosive H_2/O_2 mixtures forming inside the cell stack or downstream piping. Consequences: Internal detonation, fire/explosion, equipment destruction, and high risk to nearby personnel.

Electrical arc faults in high-voltage power supply: Arc flashes in rectifiers or busbars can ignite local hydrogen releases. Consequences: Fire or explosion, electrical equipment damage, production downtime, and potential injury.

(ii) Pipeline and Distribution Hazards:
Rupture of high-pressure hydrogen pipeline: Full-bore ruptures release large quantities of hydrogen. Consequences: Jet fire or vapor cloud explosion, severe infrastructure damage, and serious risk to personnel or the public.

Leaks leading to jet fire or delayed ignition explosion: Small leaks may form invisible high-velocity jets; if ignition is delayed, a vapor cloud explosion may occur. Consequences: Fire, equipment destruction, and potential injuries.

Material embrittlement causing crack growth and failure: Long-term hydrogen service can accelerate hydrogen-enhanced fatigue (HEF) in susceptible steels and alloys, particularly in pipelines exposed to variable or cyclic loads. HEF may be the dominant degradation mechanism under such conditions, potentially leading to sudden brittle fracture. Consequences: hydrogen release, fire/explosion, structural damage, and unplanned downtime (see API 571:2012. Consequences: Hydrogen release, fire/explosion, structural damage.

(iii) Trailer Loading Hazards:
Overfill of trailer cylinder: Excessive filling during gaseous or cryogenic hydrogen transfer may result in venting, relief valve lift, or vessel rupture. Consequences: Hydrogen release, fire or explosion, mechanical stress on cylinders, and potential operator exposure.

Hose rupture during loading/unloading: Failure of flexible hoses can release large amounts of hydrogen near personnel and ignition sources. Consequences: Jet fire, equipment damage, and risk of injury to operators.

Operator exposure to cryogenic hydrogen (if LH_2): Contact with cryogenic fluids may cause severe cold burns and asphyxiation, as well as secondary brittle failure of nearby materials. Consequences: Personnel injury, material damage, and operational disruption.

(iv) Detection and Alarm Hazards:
Gas detectors failing low (not detecting leaks): Instrument drift or poisoning may result in undetected hydrogen releases. Consequences: Escalation of fire or explosion hazards, delayed emergency response, and increased risk to personnel and assets.

Alarm flooding during small leaks masking critical alerts: Multiple low-level leak alarms may desensitize operators. Consequences: Delayed response to significant hydrogen release, potential escalation to fire/explosion, and compromised safety.

Flame detection failing due to invisible hydrogen flame: Hydrogen burns with a near-invisible flame in daylight, requiring specialized UV/IR detectors. Consequences: Undetected hydrogen fires, delayed shutdown, spread of fire, and increased risk of damage and injury.

Material integrity monitoring revealing Hydrogen-Enhanced Fracture (HEF): Routine inspections or integrity assessments may detect hydrogen-promoted cracks or embrittlement. Consequences: Early identification of HEF can prevent catastrophic failures, allowing maintenance or shutdown before leaks escalate to fire or explosion hazards.

3.1. *Reliability considerations*

The specific hazards need to be considered in the systematic hazard analyses, with specific considerations on reliability, e.g.:

(i) Data Quality and Availability
By integrating reliability analysis at concept and early design stage, reliability input relies heavily on generic failure rate databases (e.g., OREDA, PDS) since vendor and operation reliability data is not yet available. However, for hydrogen systems, this approach presents several challenges: generic databases often lack sufficient hydrogen-specific failure data, and the applicability of generic values must be carefully justified to avoid over- or underestimating actual reliability. If generic data from OREDA, or PDS used for hydrogen component/equipment, different operating profiles, e.g. electrolyzers, compressors, and storage valves may operate in cyclic, dynamic conditions that differ from conventional petrochemical processes, will need to be judged for data application. This highlights the importance of complementing database values with operational feedback, expert judgment, and hydrogen-specific test data as they become available.

(ii) Failure Mode Coverage

Reliability assessment must encompass both random hardware failures and systematic failures, ensuring that all potential failure modes are represented in the risk analysis framework.

Random hardware failures include component malfunctions such as valves sticking, sensors drifting, or compressor seal degradation.

Systematic failures arise from design deficiencies, software logic errors, calibration issues, or inadequate maintenance procedures.

Undetected safety dangerous failures, such as detectors failing low or valves failing to close on demand, must be explicitly analysed, as they can remain undetected until a safety function is required.

4. Allocation Safety Function to protection layers

After hazards are identified and risks are analysed, the next stage of the functional safety lifecycle is the allocation of safety functions across multiple protection layers (IPLs). This ensures that risk reduction is achieved through multiple, independent, and reliable layers. This step is critical to ensure that: "No single protection layer shall be relied upon to provide the required risk reduction factor" (IEC 61511-1:2016, Clause 9.2), and that hydrogen-specific challenges are adequately addressed. According to IEC 61511 and the Layer of Protection Analysis (LOPA) methodology, protection layers must be independent, effective, and auditable. Protection layers for hydrogen installations typically include:

- Inherent safety and design features (material compatibility, segregation, ventilation).
- Basic process control system (BPCS) and alarms for maintaining normal operation.
- Safety Instrumented System (SIS) for automatic isolation, purge, or shutdown.
- Passive and mechanical systems such as pressure relief and venting.
- Human and organizational layers, including operator actions, emergency response, and maintenance procedures.

The following provides some brief introduction of the protection layers, with reference to ASME B31.12; API 571; ISO/TR 15916 IEC 61511, ISO 19880-1, NFPA 2:

Inherent Safety and Design Controls - The first layer removes or reduces hazards at the source through material selection, layout, and segregation. Hydrogen systems depend heavily on embrittlement-resistant materials, pressure-rated equipment, and open layouts that promote ventilation. The reliability of this layer depends on design standards and conservative margins that prevent failure initiation.

Process Control and Alarm Systems - The Basic Process Control System maintains stable operation and provides early warning of abnormal conditions. Because hydrogen leaks and pressure excursions can evolve rapidly, the reliability of these systems depends on fast-acting control loops, hydrogen-compatible sensors, and well-prioritized alarms that prevent operator overload. Independence from the SIS must be demonstrated when control functions are credited as protective layers.

Safety Instrumented System - The SIS provides automatic, fail-safe intervention to prevent escalation of critical hydrogen events. Each Safety Instrumented Function is allocated based on the required risk reduction, and its reliability is quantified by the Probability of Failure on Demand. For hydrogen systems, SIS design must account for rapid event escalation, detector performance at low gas concentrations, redundant architectures (e.g., 2oo3 logic), and fast response times. Electrolyzers add complexity by introducing hydrogen-oxygen co-hazards, requiring interlocked purge and isolation sequences to prevent crossover ignition.

Passive and Mechanical Protection Systems - Relief devices, vent stacks, blast panels, and containment structures act as secondary safeguards. Their reliability depends on robust design, inspection, and environmental resilience. Hydrogen's buoyancy and high flame speed mean vents must remain unobstructed and flame arrestors must be tested for hydrogen-specific conditions. Inspection strategies should consider risk-based approaches adapted for hydrogen technologies (e.g., API 581 Risk-Based Inspection), rather than relying solely on conservative fixed intervals, as overly conservative intervals may increase costs without proportionally improving detection effectiveness.

Operator and Human Response Layers - Human intervention provides a final safeguard, supported by alarms, training, and procedural control. Because hydrogen flames are invisible and leaks odourless, operators rely entirely on instrumentation and automated cues. The reliability of this layer depends on interface clarity, alarm prioritization, alarm response procedures, knowledge of immediate operator actions, and realistic human reliability assumptions. Training must emphasize hydrogen's unique hazards, including fast ignition and oxygen co-existence during electrolysis or purging.

Emergency and External Protection - External response systems provide containment and community protection. Hydrogen-specific emergency response requires adapted firefighting procedures, visual flame detection tools, and rapid isolation mechanisms.

Some examples of specific hydrogen considerations during safety function allocation:

Fast hazard dynamics: Hydrogen releases ignite or disperse in seconds. SIFs must deliver extremely short detection and shutdown response times.

Invisible and odourless hazards: Since hydrogen flames and leaks are undetectable to human senses, detection must rely entirely on instrumentation (e.g., UV/IR, catalytic, or ultrasonic sensors). Alarms should immediately show the relationship of the alarm to related systems, functions, equipment or components.

High diffusivity and low ignition energy: Even small leaks can form flammable clouds quickly, requiring dense detection coverage and rapid isolation functions.

Cryogenic and embrittlement risks: SIFs must address material degradation mechanisms, including valve seat wear, embrittlement, and brittle fracture under cryogenic conditions.

Integration with process dynamics: Transient operations, such as start-up, shutdown, and pressure ramping, can cause false trips or delayed activation, requiring robust logic design and filtering.

Electrolyzer co-hazards with oxygen: Electrolyzers generate both hydrogen and oxygen, creating cross-contamination and explosion risks if gases mix. SIFs must include segregation monitoring, differential pressure controls, and interlocks to prevent H_2/O_2 crossover or simultaneous venting into shared systems.

4.1. *Reliability considerations*

Beyond assigning safety functions to specific layers, several reliability principles must be addressed to ensure that protection layers provide effective and sustainable risk reduction. These principles are particularly important in hydrogen systems, where fast failure progression and data uncertainty amplify the consequences of weak protection design.

(i) Independence and Diversity

- Independence: Each Independent Protection Layer must function without being compromised by the same initiating cause or by other IPLs. For example, if the same pressure transmitter is used both for process control and for initiating shutdown, a single failure could disable both layers.
- Diversity: Using different technologies for risk reduction reduces the likelihood of common-cause failure. For hydrogen systems, redundant and diverse leak detection methods (UV/IR, catalytic, ultrasonic) are critical to detect hydrogen's nearly invisible flames and rapid dispersion.

(ii) Reliability Quantification and SIL Allocation

Reliability of each IPL is expressed through Probability of Failure on Demand (PFD), fault tolerance, etc.

- High-frequency or high-consequence hydrogen events (e.g., electrolyzer rupture, compressor seal leaks) typically require higher SIL targets.
- Hydrogen-specific data scarcity demands conservative reliability assumptions, validated by component testing in hydrogen environments.
- SIFs must deliver fast response times, to manage hydrogen's fast escalation. The required response time is determined by several factors, including the available process safety time, the expected operator response time, the dynamics of the process, and the time needed for protective systems to effectively mitigate hazards. Accurate estimation of these factors is essential to ensure timely intervention and maintain overall system safety.
- Electrolyzer systems require interlinked SIFs (e.g., simultaneous power cut-off,

pressure equalization, and purge initiation) to prevent H_2/O_2 co-release.

(iii) Determination of Safety Integrity Levels

It often uses LOPA or quantitative risk assessments for SIL determination. The required risk reduction is converted into a target probability of failure on demand, which corresponds to a specific SIL for the SIFs. Given the limited reliability data for hydrogen components in existing databases, SIL determination must explicitly account for uncertainty and apply conservative assumptions.

(iv) Reliability Modelling

Quantitative modelling tools support the allocation of safety functions and provide confidence that overall risk targets are achieved.

- Fault Tree Analysis (FTA): Used to model hazardous event likelihoods, identifying single points of failure and dependencies between layers.
- Reliability Block Diagrams (RBD): Useful for visualizing and quantifying system reliability, including redundant architectures (e.g., 2oo3 detectors).
- Common-Cause Failure (CCF): Must be explicitly considered. For example, a site-wide power failure could disable both DCS and SIS unless independent power supplies are provided.
- Bayesian Methods: Support probabilistic modelling of system reliability by incorporating prior knowledge, observed data, and expert judgment. Particularly useful for updating failure probabilities over time and for systems with limited operational data.

5. Safety Requirements Specification

Once hazards are identified and risks are analysed, safety functions are allocated to protection layers, the next step is allocating safety requirements to Safety Instrumented Functions. Safety requirements specification defines how each safety function will respond to hydrogen-specific hazards, the performance level it must achieve, and the environmental and human conditions under which it must operate. The safety requirements specification defined for hydrogen systems must consider reliability from multiple perspectives: SIL determination, hardware and redundancy, proof testing, systematic integrity, availability, human reliability, and lifecycle management.

(i) Functional Requirements

For every defined SIF, the SRS shall specify functional behaviour in normal, demand, and fault conditions. IEC 61511 §10.3.2 requires these to be complete and testable. Typical items include:

- Process variable(s) to be measured: type, range, and measurement location.
- Trip conditions: set points, voting logic (1oo2, 2oo3), and response thresholds.
- Safety actions: required actuator movements, shutdown sequences, venting, isolation, or other protective actions.
- Response time: maximum allowable time from hazard detection to risk-reducing action.
- Reset and restart conditions: how the SIF is restored to normal operation after a trip.
- Modes of operation: startup, shutdown, maintenance, and degraded states. Startup operations should be highlighted as potentially critical for certain systems (e.g., solid oxide electrolyzers), where transient conditions may increase risk.
- Interfaces and dependencies: communication and control relationships with other systems.
- Diagnostics and alarms: required fault detection and alarm generation behaviour.
- Power supply and energy isolation requirements: normal and emergency power sources.
- Failure behaviour: defined fail-safe state (e.g., valve to close on loss of signal or power).

For hydrogen service, these requirements should reflect the system's fast flame propagation and leak dispersion dynamics, for instance, shorter response times and higher diagnostic coverage in gas-detection loops.

(ii) Non-functional and Integrity Requirements

IEC 61511 §11 establishes that each SIF must meet both functional and integrity requirements consistent with its assigned SIL. The SRS must therefore define:

- Target SIL: per LOPA or equivalent analysis.
- Required PFD: numerical target for low-demand SIFs, or PFH for high-demand / continuous SIFs.
- Proof test interval: interval assumed in PFD calculations.
- Safe Failure Fraction (SFF) and Hardware Fault Tolerance (HFT) Criteria: to guide later architectural selection.
- Diagnostic Coverage and Response to detected faults.
- Systematic capability level: minimum capability required of components per IEC 61508 certification or proven-in-use justification.
- Common cause and common mode failure assumptions: including β-factors or equivalent parameters.
- Reliability data sources and assumptions: documented origin of failure rates, uncertainty bounds, and confidence levels.

The integrity section forms the quantitative foundation for the reliability verification in detailed design.

In addition to the functional, non-functional and integrity requirements, additional requirements e.g. environmental, operational, and external requirements, human-machine interface and operator requirements, proof testing, maintenance, and diagnostic requirements need to be specified. For details, refer to the HydrogenI project report.

5.1. *Reliability considerations*

In the SRS, reliability considerations focus on defining what the safety system must achieve rather than how it will be accomplished. At this stage, the goal is to translate hazard analyses into measurable targets for the safety instrumented functions.

(i) SIL target

Each SIF must have a clear SIL target which comes from the SIL determination, refer to the reliability consideration at last phase in this report, and it establishes the required probability that the function will perform correctly when needed. For hydrogen systems, these targets are often conservative due to the fast escalation potential of leaks, the invisibility of flames, and limited data on hydrogen component reliability.

The quantitative reliability parameters include the average probability of failure on demand for low demand functions or probability of dangerous failure per hour (PFH) for high demand functions. These values provide measurable goals for the later design and verification phases.

(ii) Proof Testing and Maintenance

The specification also sets proof test intervals and minimum test coverage assumptions. In hydrogen systems, valves and detectors are prone to degradation through embrittlement, seal permeation, or sensor drift, so the SRS must explicitly define the maximum Proof Test Intervals needed to maintain required reliability and test coverage targets, ensuring hidden failures are revealed. Hydrogen-specific reliability requirements:

- Relief valves: Higher susceptibility to leakage and seat wear in hydrogen service; shorter Proof Test Intervals than in methane systems.
- Gas detectors: Small molecule size increases false negatives; frequent calibration is required to detect drift or poisoning.
- Cryogenic systems (LH_2): Proof testing must verify insulation performance, valve function at low temperatures, and prevention of brittle fracture.

(iii) Maintenance and MTTR

Repair times must be minimized to avoid extended unavailability of safety systems. Availability requirements are another critical element. The SRS defines minimum operational uptime for each SIF, accounting for repair times, maintenance activities, and potential downtime. Hydrogen-specific availability considerations:

- Electrolyzers, compressors, and distribution lines must maintain high availability despite frequent cycling.
- Auxiliary systems (cooling water, high-voltage power supplies) are critical since their failure can rapidly escalate to hazardous events.
- Backup supply or redundancy strategies must be defined to sustain production continuity during outages.

(iv) Systematic Reliability

Unlike random hardware failures, systematic failures arise from design errors, software issues, or procedural weaknesses. Hydrogen safety requirements must explicitly address these risks including the need for design compliance, configuration control, and operational discipline, ensuring that software, procedures, and human interactions do not introduce latent failures.

7. Safety Lifecycle Planning and Management

In accordance with IEC 61511, the management of functional safety establishes the overarching framework that ensures all activities related to Safety Instrumented Systems, from concept design through operation and decommissioning, are performed in a consistent, traceable, and controlled manner. It defines how organizations maintain competence, manage changes, ensure verification and validation, and continuously demonstrate that risk reduction targets are achieved and sustained. More details about safety lifecycle planning and management, refer to project report (Gao, X, & Massaiu, S., 2025).

8. Conclusion

Hydrogen's unique properties require tailored approaches to risk and reliability management across safety lifecycle. This paper highlighted how these hydrogen-specific characteristics influence early hazard analysis, protection layer allocation, and the development of safety requirements. The work provides practical guidance for integrating reliability engineering with functional safety in hydrogen installations, supporting safer design and operation of emerging hydrogen systems. Future efforts should focus on developing hydrogen-specific reliability datasets and improving diagnostic technologies to enhance the accuracy and confidence of safety assessments.

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References

API 571:2012. Damage Mechanisms Affecting Fixed Equipment in the Refining Industry.

ASME B31.12:2019. Hydrogen Piping and Pipelines.

Gao, X, Bucelli, M., Massaiu, S., Liu, Y.L, DRA_2023_[RA4].[WP2].2 (2023): *Assessment of risk and reliability challenges in hydrogen systems.* HydrogenI project report

Gao, X, & Bucelli, M., DRA_2024_[RA4].[WP2].1 (2024): *System Reliability Analysis of Blue Hydrogen Production*. HydrogenI project report.

Gao, X, & Massaiu, S., DRA_2025_[RA4].[WP2].8 (2024): *Integrating Reliability and Human Factors in Hydrogen Safety Lifecycle Management*. HydrogenI project report

NASA, 2003. Guide for Hydrogen Hazards Analysis on Components and Systems.

NFPA 2:2021 – Hydrogen Technologies Code, Guidance on hydrogen-specific firefighting, emergency response, and safety distances.

U.S. Department of Energy (DOE): 2019. Hydrogen Safety Best Practices Handbook (4th Edition). U.S. DOE, Pacific Northwest National Laboratory.

Sakamoto, J., Sato, R., Nakayama, J., Kasai, N., Shibutani, T., & Miyake, A. (2016). *Leakage-type-based analysis of accidents involving hydrogen fuelling stations in Japan and USA*. International Journal of Hydrogen Energy.