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Risk Management at various stages of project management of a hydrogen facility

Sharmin Sultana
DynSoL AS , Email: ss@dynsolonline.com

Abstract

Hydrogen is regarded as a potential future energy source. Various hydrogen facilities are being constructed worldwide, and research is advancing fast. Proper and systematic risk management procedures should be prioritized during project development to avoid future mishaps. The present study identifies risk management procedures at various project stages of a hydrogen facility. Risk management problems should be considered at various levels of project management. Risk management entails determining the scope, risk assessment, communication, risk treatment, monitoring, and review. Specific risk management strategies are identified during distinct engineering stages of hydrogen facilities, from conceptual to operational. The usefulness of various methodologies at various project stages is described. Areas and procedures that require further investigation are also highlighted. This study examines existing methodological flaws and current advancements in establishing risk-informed decision-making and highlights the hurdles to initiating hydrogen-related activities. Work has progressed in several areas, including the examination of the consequences of an unintentional incident, the identification of risks, and the comparative investigation of several hydrogen concepts, such as grey, blue, and green. Future research should examine other green hydrogen approaches, such as solar or wind power, to determine their potential regarding safety, resilience, and sustainability. Inherent safety is regarded as the most proactive risk mitigation option. However, this method has received much too little attention on hydrogen safety. The application of various methodologies at various engineering phases should also be investigated. Even though significant work has been done on quantitative risk assessments of hydrogen plants, several specific elements should be investigated further. The information gained from the oil, gas, and LNG (liquified natural gas) sectors can be helpful in this prospect. However, specialized research should be conducted to gather specific knowledge to aid decision-making.

Keywords: Risk management, hydrogen safety, risk assessment, risk analysis, inherent safety.

1 Introduction

Hydrogen (hydrogen) is considered a future energy source since it can be made from renewable sources and is virtually non-polluting. Due to its potential for zero emissivity and sustainability, it has been thought of as a primary energy source by scientists and policy maker. The significant advantage of green hydrogen is that it does not emit polluting gases during combustion or production.

Hydrogen can be grey, blue, or green based on its production process. It is called grey if it is produced from natural gas in the methane reformation process. When it is produced from coal gasification, it is called brown. Blue hydrogen is produced using fossil fuels (Liu, Song, and Subramani 2010). It is termed green when it is produced using renewable sources such as solar and wind via water electrolysis (Fig. 1). The process is clean but currently expensive (SolarEdition 2022).

Produced hydrogen need to be stored before distribution to industrial sectors. The selection of a storage concept for a particular application depends on the technical constraints and the priorities set in a project. In some projects, minimizing technical risk or budget constraints may be more critical than thermodynamic efficiency (Steinmann 2022). Although hydrogen has the highest energy per mass of any fuel, it has lower energy per unit volume. Advanced storage methods should be developed to have the potential for higher energy density (EERE 2022).

Eight types of storage methods are widely used for hydrogen: storage as compressed gas, as liquid, as gel storage, as a metal hydride (Fig. 1), in alienates, in carbon nanotubes, storage with glass microspheres, using $NaBH_4$ (Sodium Borohydride) in vehicles. A significant advantage of hydrogen is that it can be stored without losses for long periods as gas. However, it has a low volumetric energy density at atmospheric pressure compared to other energy carriers like natural gas or oil (Sharma 2022). Underground hydrogen storage is possible in large caverns built into salt domes up to 1000 meters deep, close to more significant hydrogen production sites.

Hydrogen can be stored in compressed form in specially designed light, small and cylindrical tanks due to its low density compared to other gases. It can also be stored as a cryogenic (low-temperature) liquid. The storage method, called gel hydrogen, is realized by transforming the gallant substance into liquid hydrogen. The gel reduces the likelihood of hydrogen spillage, the potential for leakage, motion instabilities, and the level of agitation in the storage tank and increases hydrogen permeability. Hydrogen can also be stored by combining adsorption or absorption on the surfaces of solids or within solids. The hydrogen molecules are chemically bonded within the metal compound structure and remain stable and non-hazardous at atmospheric pressure in these low-pressure systems.

After being produced and processed, hydrogen needs to be safely transported and stored. The distribution of gaseous hydrogen can be via high-pressure containers or pipelines. Transport in high-pressure tanks faces similar challenges as the storage in high-pressure vessels and can be enabled using road, rail, or maritime transportation. This makes this solution flexible and suited to reach any destination. Hydrogen pipeline transmission is a good solution if large quantities must be distributed. The existing gas pipeline infrastructure in countries like Germany can transport hydrogen with few adaptations. However, transportation via natural gas pipelines depends on the integrity of the pipeline components like fittings and joints. It is possible that hydrogen embrittlement accelerates the formation of cracks and thus shortens the pipeline's service life significantly. Other factors like dynamic stress and existing fractures also need to be considered. Mixing hydrogen with natural gas to mitigate these risks and decrease the required adaptions to the pipeline is also possible.

Project management involves planning tasks and resources to achieve the organization's goal. It can be a one-time project or ongoing activity for several years. Resources management includes properly utilizing personnel, finances, technology, and intellectual property to achieve the goal. Project management for engineering design projects includes adopting tools and technologies for project initiation and implementation. Engineering design project management goes through several phases: concept selection, basic engineering design, detailed engineering design, and operational stage. each stage has its importance and sets the basis for the following steps.

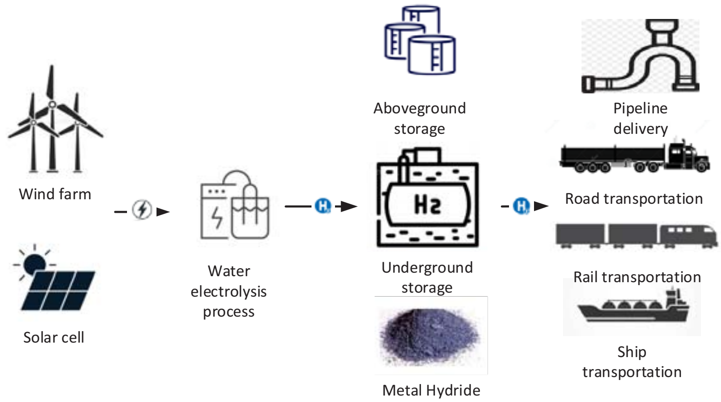

Fig. 1: Various alternatives for hydrogen production, storage, and transportation

This paper discusses the current state-of-the-art methods relevant to hydrogen safety that can be utilized at various project stages. It adopts a general risk management model described by ISO 31000. Different project stages it describes are relevant for small-scale projects. Other pertinent stages to the big-scale project are out of the scope of the work. Section 2 discusses various components of risk management. Section 3 discusses risk management processes at different project stages. Only technical and accidental risks are considered in the study. Financial and strategic risks are kept out of the scope. Section 4 discusses the issues that should be explored in the future. Section 4 proposes the problems in general, not in detail. Section 5 concludes the findings in short.

2 Risk Management

Risk management involves identifying the scope, risk assessment, communication, treatment, monitoring, and review. In a technical sense, 'safety' is a yes/no state which describes the absence of danger. The state of safety means the risk associated with using technology is lower than the accepted risk threshold. In contrast to 'safety', 'risk' is quantifiable and combines the probability of an event with the consequence of the event. Risk is a combination of an event's probability and consequences. Risk management involves all the steps to understand, mitigate, manage, and proactively control risk.

The first initiating step of risk management is defining the scope and corporate risk management strategy (Fig. 2). The scope includes defining external and internal environments, generating context, and formulating risk criteria. Risk assessment consists of three tasks: identification, analysis of relevant risk, and evaluation. Risk identification is identifying the risk that can affect an organization in achieving its objective. Risk can be unwanted events for the chemical industry that hamper production or delivery. Identified risks are quantified by combining the probability of events and the consequence of the occurrence. In the risk evaluation process, the quantified risk is compared with risk acceptance criteria, which shows the acceptability of the projects or process. In the risk treatment process, various risk control options are identified, and action lists are made that should be implemented in the project. Residual risks are identified and compared with risk acceptance criteria. Risks identified, treated, and residual are communicated with relevant authorities and stakeholders to take further action. Risk management procedures are monitored, reviewed, and updated throughout the project.

3 Risk Management at Various Project Stages

3.1 Conceptual Stage

At the conceptual stage of the engineering project, the complexity of innovative technology, feasibility, expected output, throughput time, availability of project resources, dependency on deliverables, and implementation of new methodology, commercial success is assessed. Risk management at this stage consists of three steps: identification of risk, evaluation of risk, and risk management opportunities. During risk identification complexity of technology, the feasibility of requirements, the availability of project resources, and dependency on deliverables are found. Risk valuation is performed by determining the impact and likelihood of occurrence. Risk management opportunities include reduction, acceptance, rejection, and risk transfer. During the risk-based concept selection process, several concept designs are generated, the expected performance of developed concepts are evaluated, and the most promising concept design are evaluated based on the involved risk. This stage is reasonable for looking at alternatives and assessing the risks involved. The risk identification method to be utilized at the conceptual stage can be preliminary hazard identification. It is mainly to find out which risks are concerned with the concepts.

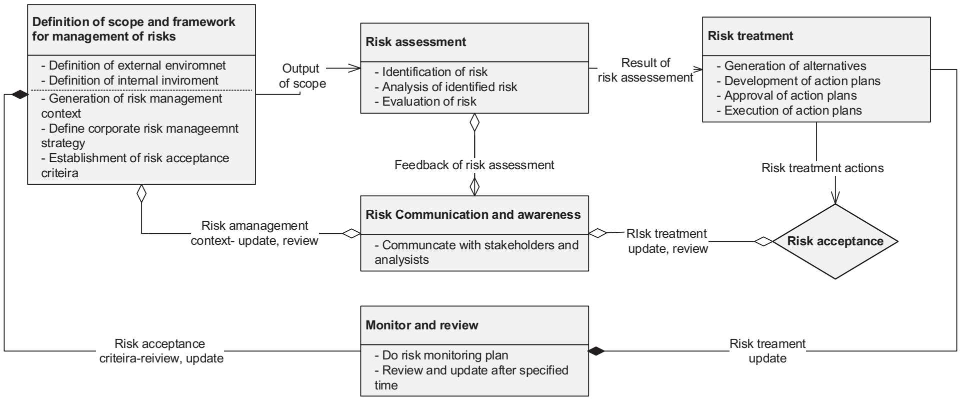

Fig. 2: General risk management framework of a process plant

For hydrogen production, at the conceptual stage, various alternatives can be assessed based on the system's complexity for the selected method, availability of resources for the procedure, profitability of each choice, and risk associated with each option. Various production methods, their economic feasibility, environmental impact, and cost have been discussed in the work of Kothari, Buddhi, and Sawhney (2008); Suleman, Dincer, and Agelin-Chaab (2015); Ji and Wang (2021). Various options for green hydrogen production have been discussed by Nadaleti, Lourenço, and Americo (2021). For hydrogen storage, multiple alternatives can be underground, offshore, or onshore. Each choice should be selected based on each alternative's risk. Since hydrogen is highly flammable, the locality population and distance from the locality will play an important role. Various hydrogen storage alternatives are discussed in the work of Yartys and Lototsky (2005); Ni (2006). For hydrogen distribution, the same conditions should be assessed. The research of Demir and Dincer (2018); Moradi and Groth (2019) discuss state-of-the-art techniques of hydrogen delivery options. The earlier works can give the analysts valuable insights into the pros and cons of multiple methods during new project establishment.

3.2 Basic Design Stage or FEED Engineering Stage

In the basic design or preliminary design phase, the production facility, structural configurations, and dimensions in sufficient detail are prepared to allow the start of further procedures. The FEED (front-end engineering design) stage consists of equipment design, instrument design, purchase of critical equipment, building structural concept design, and feedback to process design. The risk identification scope covers the selection of equipment, instruments, and process design alternatives. One strategy for safe fuel use is preventing situations such as the presence of three combustion factors—ignition source, oxidant, and fuel. Preventing these scenarios should be considered during design. Hydrogen has properties that make it safer to handle and use than other fuels. For example, it is non-toxic and much lighter than air. So, it dissipates rapidly in case of a leak(EERE 2023). During site selection and layout configuration, these properties should be considered.

For risk identification, various methods are HAZOP (hazard and operability study), preliminary hazard identification, and HAZID (hazard identification). The potentiality of HAZOP has been discussed in many works of literature. Alizadeh (2020) has presented the use of HAZOP for hydrogen production at the refinery. An example of HAZID for the hydrogen supply chain is demonstrated by Oyama, Satoh, and Sakanaka (2017). FMECA (failure mode effect and criticality analysis) determines a system's failure mode and effect analysis. FMEA (failure mode and effect analysis) has been used for risk analysis of liquid hydrogen storage systems in the work of Correa-Jullian and Groth (2020) and qualitative risk assessment of generation systems by Kasai et al. (2016).

The risk assessment method at the FEED stage can be qualitative risk analysis, quantitative risk analysis, hazardous area classification drawing, fire water demand calculation, fire, gas detection layout, fire water network layout, and safety philosophy. Defining risk and risk acceptance criteria is crucial before conducting a risk assessment. The selection of a risk assessment technique is the first critical task. The risk assessment method can be qualitative, semi-quantitative, or quantitative. The procedure's choice and level of detail depend on the technology's complexity, novel features, systems, and other influential environmental factors. There are three main steps in the quantitative risk assessment method. They are risk identification, risk analysis, and risk evaluation. Risk analysis consists of three essential steps: frequency assessment, consequence assessment, and risk calculation.

Inherent safety is considered as most prominent risk reduction technique. Inherent safety options should be judged throughout the concept selection stage until the detailed system design stage. Landucci, Tugnoli, and Cozzani (2008) investigate hydrogen storage technologies' expected inherent safety performance. The inherent safety principles "substitution" and "moderation" is applied for the assessment. The findings show that new storage technologies, like metal or complex hydrides, can reduce potential hazards.

Quantitative risk analysis (QRA) has been applied to hydrogen generation units (Jafari, Zarei, and Badri 2012), and refueling stations (Russo et al. 2018). QRA to assess facility risk for a specific country is performed in various literature, for example, for the Netherlands (Honselaar, Pasaoglu, and Martens 2018), for Japan (T. Suzuki, Shiota, et al. 2021) (Tomoya Suzuki, Kawatsu, et al. 2021), Korea (D.-H. Kim et al. 2022) considering the specific geographical situation. Semi-quantitative risk assessment of the hydrogen production unit has been discussed by (Jafari, Lavjevardi, and Mohammadfam 2013).

Consequence analysis has been performed in various earlier works. Different consequences of the uncontrolled release of hydrogen can be the formation of a fireball, explosion, or spill on water (Ruiz-Sanchez et al. 2012; Bauwens and Dorofeev 2014; Kikukawa 2008; Tsunemi et al. 2017; Ustolin, Paltrinieri, and Landucci 2020; Lin et al. 2022; Zarei, Jafari, and Badri 2013). CFD modeling can provide valuable insights into the potential consequences of gas releases, including dispersion, fires, and explosions. Various projects are undergoing worldwide to validate experimental work with such modeling to determine the consequence of hydrogen base release. Examples of such projects are SUSAAN (Baraldi et al. 2017), SH_2IFT (Ødegård et al. 2019), and H_2CS (Campari et al. 2022). the results and findings of the projects are giving insights into risk control and management in real case scenario.

3.3 Detailed engineering stage

Detailed design is the phase of refining the design and planning, specifying the types and pieces of equipment, and estimating the cost and time of the project. Detailed design includes outputs such as 2D and 3D instrumentation models, control systems, P & IDs (process and instrumentation diagrams), cost build-up estimates, procurement plans, management of suppliers, schedule of activities, economic evaluation, and vice versa.

Risk assessment at the detail engineering stage includes barriers identification, safety requirement specification for SIL (safety integrity level), SIL determination, verification, validation, and emergency preparedness analysis. Identifying, establishing, and assuring proper and effective barriers is crucial for adequate risk control. The bow tie method is used for preliminary hazard identification to identify the related risk control barriers and possible consequences of barrier failure (Yazdi 2017). Safety barriers analysis has been performed by Tsunemi et al. (2019); Duijm and Markert (2009). LOPA (layer of protection analysis) can be used to find independent protection layers of the system.

Safety integrity level is determined for the hydrogen unit using the LOPA method (Alimohamdadi, Jalilian, and Nadi 2014; Delavar, Tehrani, and Alizadeh 2016; Hosseini and Nemati 2015; Sh S and MJ 2014; Lajevardi, Jafari, and Mohammadfam 2014; J.H. Lee and Lim 2020). In the work of Lajevardi, Jafari, and Mohammadfam (2014), the Layers of protection analysis method is used to assess SIL requirements for the hydrogen production unit. Emergency shutdown systems have been studied by Hosseini and Nemati (2015). Alimohamdadi, Jalilian, and Nadi (2014) identified twenty hazardous scenarios by the HAZOP study, and SIL was determined by applying the LOPA method to the ESD (emergency shutdown system) system.

Optimizing cost and safety in the project is a critical task. The work of Hugo et al. (2005); Li, Manier, and Manier (2019); J. Kim and Moon (2008) discuss optimizing the cost of safety for hydrogen infrastructure and supply chain networks. With the help of the multi-objective optimization model. J. Kim and Moon (2008) develop a generic optimization-based model to support decision-making. The network design problem is formulated as a mixed integer linear programming problem to identify the optimal supply chain configurations from various alternatives. Hugo et al. (2005) also utilize mixed integer linear programming techniques to identify optimal investment strategies and integrated supply chain configurations from many options. The methods shown in this work may help analysts with strategic long-range investment planning and the design of future hydrogen supply chains.

The work of Rajesh et al. (2001); Dufo-Lopez, Bernal-Agustín, and Contreras (2007) shows how optimized operating conditions are to make the plant energy-efficient and cost-effective. This type of analysis may help the analysts to establish optimized process conditions to increase plant energy efficiency and reduce operative costs.

3.4 Operational stage

Managing operational risk is a critical part of the organization. Organizations may face emerging risks that can impact their functional ability correctly. These risks may come from various sources, such as natural disasters, human errors, or technology. All the emerging risks should be considered at the FEED, and detailed engineering stages and steps should be taken accordingly. Two critical steps in the operational stages are risk monitoring, risk review, and update. Safety performance indicators or risk indicators can be developed for risk monitoring of the system.

Resilience engineering is being focused nowadays on managing operational risk in addition to safety and security, which makes an organization capable of being resilient in times of disasters or unwanted events. Theoretically, it is to maintain the system in an intermediate state to run with a minimal function instead of complete collapse. The works of Afgan and Veziroglu (2012) identified resilience indicators that should be given particular focus to ensure resilience in hydrogen facilities. To assure higher resilience, along with reduction of probability of failure, consequence, and recovery time, is also thought.

A challenge at the operating stage of any process plant is to reduce human error and lost time injury rate. Castiglia and Giardina (2013) discuss possible human error in hydrogen refueling stations using first and second-generation Human Rate Assessment (HRA) techniques. Al-Shanini, Ahmad, and Khan (2014) incorporate prevention barriers associated with human factors, management, and organizational failures in a risk assessment framework. These works may provide procedural recommendations and suggestions regarding safety equipment and procedures that can be adopted to reduce the risk of accidents.

4 Discussion

Section 2 of this paper presents risk management procedures in general, and section 3 offers various methods to be carried out across multiple engineering phases of the project. Various earlier researchers' works in academia and industry are discussed in short. Work has been and is being done in diverse areas of hydrogen safety and risk management, including the examination of the consequences of an unintentional incident, the identification of risks, and the comparative investigation of several concepts, such as grey, blue, and green. This section discusses various issues that should be focused on for research in the future. The areas to be focused on in the future include comparing multiple pathways of green hydrogen, plant layout, inherent safety, risk assessment of mixture, cryogenic mixture, leakage detection, and measurement. More areas that should be explored are maritime dispersion, global distribution, SIL determination, safety performance measurement, and human factors. Along with these areas, system and resilience engineering can be utilized more to ensure efficient risk management.

4.1 Techno-economic assessment and comparison of various pathways of green hydrogen

Various works have compared blue, grey, or green hydrogen production processes. Which is most effective in terms of cost and risk needs to be investigated. The effectiveness of each alternative, whether solar or biomass, or wind, also depends on many other factors such as geography, population, socioeconomic condition, and financial capability. A comparison of alternatives for various geographical locations needs to be explored. Wind facilities may not be a good option for highly populated countries where the area is constrained. The safety aspects of fossil-based production are well-known in the process industry, but there is limited experience with large-scale water electrolysis. A better safety approach and increasing safety awareness are needed for large-scale green production through water electrolysis to meet the CO2 emission reduction goals (ISPT 2022).

Today, electrolyze suppliers, operators, and owners have limited operating experience with the safety aspects of large-scale water electrolysis installations. For large-scale installations, the study should objectively assess scenarios with exceptionally low probability and high potential consequences (black swans) and determine cost-effective safety measures to address these. There is a need to develop further joint safety practices and guidelines based on credible scenarios for large-scale plants. It is also essential to communicate safety risks transparently (ISPT 2022).

4.2 Plant design and layout

Preventing fire and explosion hazards requires careful planning and plant design. Even the most minor components should be carefully selected with safe service. Plant design and layout should be focused on at the basic design stage to reduce the risk of hazards. To limit potential leak points, piping, tubing systems, fittings, and connections should be designed with less leak potential through their lifecycle. The layout should be prepared to keep a safe distance so that any unwanted incident does not affect the structures. Ventilation intakes and vehicle routes to minimize the risk of leaks and potential fires inside the plant. A guideline for a layout design for a hydrogen facility should be developed. In particular, developing commercial software, such as Aspen Plus/HYSYS and Matlab and related, should be carried out.

4.3 Assuring inherent safety

In the work of Landucci, Tugnoli, and Cozzani's (2008), inherent safety principles, 'substitution', and 'moderation' were applied to check the hazard potential for various alternative hydrogen storage. Studies show that hazard potential is less for metal or complex hydrides as storage. However, the reliability of the auxiliary equipment is a critical issue and must be addressed. Inherent safety potential for various green production methods and delivery should be explored.

4.4 Risk assessment of the hydrogen mixture

Potential risks of explosions due to mixtures of hydrogen and oxygen in electrolysis equipment should be studied more. Various impurities can be added during hydrogen processing for transport or storage. Hydrogen fuel efficiency requires enough pressure at the right purity level and sufficient quantity. Objective risk assessment methodology should be studied more regarding equipment fire and explosion risks with oxygen and hydrogen mixtures. The development of consistent assessment methods covering data on delayed ignition and detonation, corresponding safeguarding, and appropriate safety distances should also be studied.

4.5 Maritime environment Cryogenic hydrogen research

Due to the deep cryogenic state, liquid hydrogen can condense all gas components in the air. The process involves complex heat and mass transfer coupling, phase change, and turbulent flow. Research should be carried out on multi-dimensional simulation for cryogenics mixtures for use in simulations and validation with experimental results. The safety level of cryogenic tanks has not reached the desired level, and the production costs are too high. Cryogenic hydrogen engines' design, systematic, safety, and maintenance conditions should also be improved.

The properties of the fuel bring many engineering challenges associated with its safe and efficient transport onboard a ship, including loading and unloading procedures, that must be understood to enable the design of safe and reliable systems. Computational fluid dynamics and fire modeling considering turbulent heat and mass transfer in maritime environments should be investigated.

4.6 Detection and measurement

Hydrogen can ignite more easily if leaked, so adequate ventilation and leak detection are essential in safety systems design. Special flame detectors are required due to the invisibility of their flame. An accurate measurement method of concentrations at the parts-per-billion level of leakage must be developed to quantify leakage rates more accurately. Safe pressure relief systems are essential to protect high-pressure storage tanks in emergencies. This fuel has wide flammability limits and low minimum ignition energy; therefore, it could be ignited using traditional pressure systems during the pressure release phase. It poses a significant fire and explosion hazard to the storage tanks surrounding equipment and equipment buildings. Advanced pressure relief systems should be developed incorporating novel safety measures to prevent hydrogen fires and explosions during pressure relief processes. It involves experimental investigation and chemical kinetic modeling of the mixtures.

4.7 Consequence analysis

Various works have been done on the consequence analysis of hydrogen release, including experimental investigations, CFD simulation, and software validation with practical outcomes. Considering the importance of impacts in the decision-making effect of leakage on strategy, local commodities should also be researched. Results should be studied concerning various territories, weather, and climatic situation, for example, in highly populated areas, highly congested areas, and high snowfall areas, and considering extreme weather, e.g., hurricanes and storms.

4.8 Global distribution and shipment of Green hydrogen

With the increase of future demand as an energy source, supply chain alternatives in far distances should be investigated. Regarding the number, size, and speed of suitable vessels, the risk and demand for shipment should be explored. A strategy to meet the challenges which can evolve from cross-country distribution, cross-continent shipment, and multiple stakeholders needs to be developed.

4.9 SIL determination

Presenting existing methods of the layer of protection and LOPA is time-consuming. Combining the technique with a software tool will increase speed and precision. More case studies should be conducted for various hydrogen production, storage, and distribution systems.

4.10 Safety performance determination

Development of safety performance or risk indicators at the operational stage should be explored for hydrogen production, storage, and delivery unit. Key performance indicators for hydrogen storage systems have been developed by Landucci, Tugnoli, and Cozzani (2008); Tugnoli, Landucci, and Cozzani (2009). However, the work focuses on finding a safer alternative for storage. Safety performance or risk indicators focusing on various operational risks, including human factors, organization, and management issues, is scarce.

4.11 Human factor aspects

One of the essential Human Factors activities an organization can undertake to manage its human Factors risk is Safety Critical Task Analysis (SCTA). This is the formal process of identifying the most critical human tasks creating accidents and determining plausible human errors which could lead to or fail to prevent a significant accident hazard. It also validates that reasonable and sufficient controls are in place to avoid or mitigate those errors, for example, the design of the equipment, the job, the working environment, shift design, or the organizational culture. However, equipment is replaced, procedures are adjusted, and job roles change, which can significantly impact the risk and the associated controls. Therefore, SCTA should be a rolling program with triggers to revalidate over time and in the event of some associative change.

Decision support and situation awareness are essential to effective incident response. It is also important to consider the actual plant itself, which is designed around process and structural considerations and often consists of a mass of pipework, valves, instruments, vessels, pumps, and electrical & mechanical equipment. This plant, however, must be installed, inspected, operated, and maintained by people. Therefore, plant design must actively consider access, egress, escape, operability, and maintainability to ensure that workers can easily access & identify the plant they need to work on, have clear space to operate it, and have room to maintain or remove it. Human Factors reviews during

Other critical human factors issues to be addressed by the producer should include safe staffing levels, workload, fatigue, procedure design, safety-critical communication, management of change, and incident investigation. Each of these areas interacts with the controls that prevent a significant accident hazard and could be even more critical with a remote monitoring & control configuration. Operators should be satisfied that they understood any risks affecting their site and managed them appropriately.

4.12 Resilience engineering

As the most potential energy source in the future, assuring resilience of the overall facility should be given importance to provide a minimum level of service in the face of various challenges to regular operation. The comprehensive hydrogen energy system is complex, including its production, utilization, and storage. Further study can be executed to investigate other characteristics to achieve higher resilience.

4.13 System engineering perspective

System engineering models and methods are being adopted to gain in-depth knowledge of the system to aid structured risk management and better control. S.H. Lee (2022) proposes a safety enhancement model based on STPA (system theoretic process analysis) techniques for hydrogen refueling stations. STPA can consider control issues between the entire system and its components. It can help to install improved ESD and safety-related systems to meet international standards. Such a safety enhancement model should be studied more for other transport methods and production and storage systems.

4.14 Multi-objective optimization

For commercial production, issues for any fuel arise, such as energy efficiency, environmentally benign, and cost-effective. to choose from many technological options, consideration of all the problems such as cost, operation, reliability, environmental impacts, safety, and social implication simultaneously is challenging and cumbersome work. Usually, a multi-objective optimization model requires time and extra computation effort. User-friendly software, including all the assessable prospects, should be developed to reduce computation time and effort.

5 Conclusion

Considering the prospect of hydrogen as a future energy source, risk and safety issues should be investigated as described. Various works have compared the techno-economic aspects of hydrogen processes and various consequence investigations. Future work should be carried out on analyzing multiple production processes of green H2s. At the conceptual stage, qualitative risk assessment can provide an overview of potential risks in system concepts. Concepts from numerous alternatives can be carried out based on the assessed risk and mitigation options. Quantitative risk analysis can be performed throughout the preliminary design engineering stages to be aware of the facility's vulnerabilities.

Quantitative risk analysis can be performed throughout the preliminary design engineering stages to understand the facility's risk picture and control methods. At the detailed engineering stage, numerous methodologies can be used to assess safety integrity and emergency preparedness adequacy. It is also necessary to establish risk-based concept selection for diverse distribution networks. More emphasis should be placed on the production, storage, and distribution system's safety barrier analysis. Many studies have been conducted on fire, explosion, and spillage effects. Specific situations, however, should be investigated in the event of an uncontrolled leak, and potential risk mitigation strategies should be devised. The development of safety performance indicators should be studied more, focusing on the features of hydrogen plants. Each facility's emergency response and evacuation procedures should be investigated.

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