

Towards a Safe Hydrogen Economy: Addressing Safety and Siting for Refueling Stations

BY

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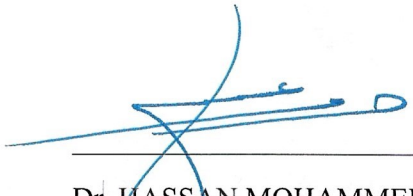
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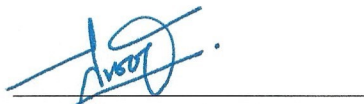

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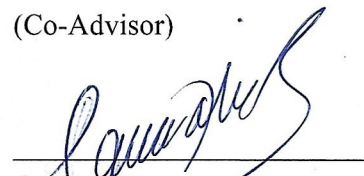
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Dedication

To my family |

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I offer my heartfelt gratitude to the Almighty, whose will made completing this work possible.

Without his blessings, none of this would have been achievable.

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LIST OF ABBREVIATIONS

ALARP	As Low As Reasonably Practicable
BN	Bayesian Network
CFD	Computational Fluid Dynamics
DBN	Dynamic Bayesian Network
ESD	Emergency Shutdown
FCEV	Fuel Cell Electric Vehicle
FLACS	Flame Acceleration Simulator
FTA	Fault Tree Analysis
FMECA	Failure Mode Effect and Criticality Analysis
HAZID	Hazard Identification
HAZOP	Hazard and Operability (HAZOP) studies
HyRAM	Hydrogen Risk Assessment Models
HRS	Hydrogen Refueling Station
HSE	health safety and environment
ICC	International Code Council
IEC	International Electrotechnical Commission
IFC	International Fire Code
IR	Individual Risk
LOHC	Liquid Organic Hydrogen Carrier
MIE	Minimum Ignition Energy
NFPA	National Fire Protection Association
PHAST	Process Hazard Analysis software Tool
P&ID	Piping and Instrumentation Diagram
QRA	Quantitative Risk Assessment
SIL	Safety Integrity Level
SHIPP	System hazard identification and prevention
SR	Societal Risk
TNO	The Netherlands Organization
VCE	Vapor Cloud Explosion

ABSTRACT

Full Name : Bashir Hashim
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As the global community actively seeks alternatives to diminishing fossil fuels and aims to stabilize the variability of renewable energy sources, hydrogen emerges as a key player in transitioning energy systems towards enhanced cleanliness and efficiency. This shift is particularly evident in the commercial advancement of fuel cell vehicles, which rely on an expanding network of hydrogen refueling stations (HRSs). For instance, currently, only one pilot-scale hydrogen station is present in Saudi Arabia. More stations are expected to be installed for public use in the coming years. Despite the promising energy transition plans, potential incidents at HRSs, which negatively impact on HRS operations, station workers, public personnel, properties, and nearby facilities, have affected the rapidly expanding hydrogen energy industry. To avoid or minimize the chance of such potential incidents, proactive safety-related research is crucial. The research path for this thesis is two-fold:

- Part 1 provides a review of the global research efforts for Hydrogen Refueling Stations safety.
- Part 2 conducts a case study on HRS safety using Quantitative Risk Assessment in Saudi Arabia.

This thesis highlights shared methodologies among existing risk assessment tools, identifies regional approaches, and discusses emerging technological innovations critical for hydrogen's

adoption as a sustainable energy source. The role of risk assessment methodologies in ensuring the safety and public acceptance of hydrogen refueling stations (HRSs) is highlighted. By examining global practices across hazard identification (HI), consequence analysis (CA), frequency analysis (FA), and risk analysis (RA), it provides a comprehensive understanding of the tools and approaches used to address hydrogen's unique hazards.

After highlighting the robustness of the risk assessment methodologies, the study evaluates the safety of a hypothetical hydrogen refueling station (HRS) in Saudi Arabia, incorporating region-specific characteristics with consequence-based and risk-based methodologies. Using GEXCON EFFECTS, RISKCURVE, and the US Sandia Lab's HyRAM tools, the analysis focuses on incident probabilities, harm zones, and risk levels. Safe distances for jet fire and vapor cloud explosion (VCE) scenarios were assessed. The dispenser required the greatest safe distance for personnel in jet fire scenarios, while the compressor posed the largest VCE risk. Risk-based analysis identified compressors, intermediate cylinders, and dispensers as contributing over 80% of individual risk. Societal risk, visualized through FN curves, predominantly fell within the As Low As Reasonably Practicable (ALARP) region, indicating tolerable but improvable risks. These findings emphasize the need for targeted mitigation strategies, including advanced leak detection, robust isolation mechanisms, and strategic processing unit placement.

ملخص الرسالة

الاسم الكامل: بشير هاشم

عنوان الرسالة: نحو اقتصاد هيدروجيني آمن: معالجة السلامة وتحديد المواقع لمحطات التزويد بالوقود

التخصص: الهندسة الكيميائية

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بينما يسعى المجتمع العالمي لإيجاد بدائل للوقود الأحفوري المتناقص ويهدف إلى تحقيق استقرار لمصادر الطاقة المتجددة يظهر الهيدروجين كعنصر رئيسي في تحول أنظمة الطاقة نحو مزيد من النظافة والكفاءة. يتجلى هذا التحول بشكل خاص في التقدم فعلى سبيل (HRS) التجاري للمركبات العاملة بخلايا الوقود، والتي تعتمد على شبكة متنامية من محطات التزويد بالهيدروجين المثال، توجد حاليًا محطة واحدة للهيدروجين تعمل على نطاق تجريبي في المملكة العربية السعودية، ومن المتوقع تركيب محطات أخرى للاستخدام العام في السنوات القادمة على الرغم من خطط التحول الواعدة في مجال الطاقة، فإن الحوادث، المحتملة في محطات التزويد بالهيدروجين، والتي تؤثر سلبًا على العمليات، والعاملين في المحطات، والجمهور، والممتلكات، والمنشآت القريبة، قد شكلت تحديًا أمام صناعة الطاقة الهيدروجينية المتنامية بسرعة. لتجنب أو تقليل احتمالية مثل هذه الحوادث يصبح البحث المتعلق بالسلامة استباقيًا وضروريًا. يأخذ البحث في هذه الرسالة مسارين رئيسيين:

الجزء الأول: يقدم مراجعة للجهود البحثية العالمية المتعلقة بسلامة محطات تعبئة الهيدروجين

الجزء الثاني: يجري دراسة حالة حول سلامة محطات تعبئة الهيدروجين باستخدام تقييم المخاطر الكمي في المملكة العربية السعودية

تسلط هذه الرسالة الضوء على المنهجيات المشتركة بين أدوات تقييم المخاطر الحالية، وتحدد النهج الإقليمية، وتناقش الابتكارات التكنولوجية الناشئة ذات الأهمية البالغة لاعتماد الهيدروجين كمصدر طاقة مستدام من خلال دراسة ممارسات عالمية تشمل تقدم الرسالة فهمًا شاملاً، (RA) وتحليل المخاطر، (FA) وتحليل التكرار، (CA) وتحليل العواقب، (HI) تحديد المخاطر للأدوات والأساليب المستخدمة لمعالجة المخاطر الفريدة للهيدروجين

بعد إبراز قوة منهجيات تقييم المخاطر، تقيم الدراسة سلامة محطة تعبئة هيدروجين افتراضية في المملكة العربية السعودية، مع دمج الخصائص الإقليمية باستخدام منهجيات تعتمد على العواقب والمخاطر. باستخدام أدوات مثل GEXCON EFFECTS و

RISKCURVE وأداة **HyRAM** من مختبر ساندايا الأمريكي، ركز التحليل على احتمالية الحوادث، مناطق الخطر، ومستويات المخاطر.

تم تقييم المسافات الآمنة لسيناريوهات الحريق النفاث وانفجار سحب البخار (VCE) وكانت وحدة التوزيع تتطلب أكبر مسافة آمنة للأفراد في سيناريوهات الحريق النفاث، بينما شكل الضاغط أكبر خطر في السيناريوهات VCE. حدد تحليل المخاطر القائم على المخاطر أن الضواغط، والأسطوانات الوسيطة، وأجهزة التوزيع تسهم بأكثر من 80٪ من المخاطر الفردية. أما المخاطر المجتمعية، التي تم تصورها من خلال منحنيات **FN**، فقد وقعت بشكل كبير ضمن منطقة **ALARP** (الحد الأدنى الممكن عملياً)، مما يشير إلى مخاطر مقبولة ولكن قابلة للتحسين. تؤكد هذه النتائج على الحاجة إلى استراتيجيات تخفيف مستهدفة، بما في ذلك تقنيات كشف التسرب المتقدمة، وآليات العزل المثبتة، والتخطيط الاستراتيجي لوحدة المعالجة.

CHAPTER 1 INTRODUCTION

1.1 Background and Motivation

The global energy trend is shifting from conventional energy sources towards renewable alternatives. This shift is driven by the significant environmental challenges posed by traditional energy sources, such as global warming and air pollution, prompting a move from fossil fuels towards cleaner energy solutions [1, 2]. Hydrogen energy, particularly in the transportation sector, has emerged as a promising alternative in the search for environmentally sustainable energy options [1, 2] because it can be sourced from renewables and does not have the ordinary car's dependency on burning fossil fuels. The massive adoption of hydrogen fuel cell vehicles (FCVs) is expected to play a critical role in reducing reliance on oil-based internal combustion engines, necessitating an increased collaboration between governments and industry to provide robust hydrogen infrastructure [3].

Hydrogen can be produced by several methods, such as water electrolysis, gasification, dark fermentation, steam reforming, photocatalytic, and water thermolysis [4, 5]. Industrially, a significant portion (90%) of hydrogen produced is from non-renewable feedstocks through steam methane reforming (SMR), leading to the emission of harmful gases, including carbon dioxide (CO₂) and carbon monoxide (CO). In contrast, hydrogen can be obtained from other sources utilizing only electricity and water, which is called electrolysis. This hydrogen is considered green, provided the electricity source is one of the renewable energies like biomass, wind, and geothermal, which guarantees low carbon emissions [6]. Generation of hydrogen for fueling

purposes can be done right at fueling stations or offsite, where large-scale production is achieved and further taken to the point of use via one of the hydrogen delivery means [3].

Moving hydrogen from the production source to the point of use, including an HRS, requires a robust transportation infrastructure. The significant pathways include pipelines and trucks (tube trailers and cryogenic tankers). Tube trailers and pipelines are utilized for gaseous hydrogen delivery, while cryogenic tankers are employed for liquid hydrogen transport [7]. Also, hydrogen carriers (capable of delivering hydrogen in a moderate environment) are being studied for storing and transporting hydrogen energy-efficiently [8-14].

Governments and industries globally invest heavily in developing a hydrogen economy, aiming to decarbonize the transport sector for sustainable society [6, 15, 16]. For instance, hydrogen vehicle commercialization is advancing in countries like Japan, North America, Europe, and South Korea [6, 17]. Japan, in particular, leads the deployment of hydrogen-powered FCVs and the establishment of hydrogen infrastructures [6]. In Saudi Arabia, a joint effort led by Aramco and Air Products company commissioned a pilot gaseous hydrogen refueling station (HRS) in 2019, located at the latter's premises in Dhahran Techno Valley Science Park, with the capacity to feed 6 Toyota Mirai FCEVs [18]. Additionally, Saudi Arabia is exploring partnerships with companies from Europe and North America to build local manufacturing capabilities of FCEVs [19].

To sustain the continued progress of hydrogen technologies, ensuring the safety of relevant infrastructures remains a key requirement, including developing safe and reliable refueling environment [3, 20]. Furthermore, evolving station operations, such as increased capacity and changing locations, necessitate continual reevaluation of safety measures [21]. Incorporating these

factors is essential to ensure the safe and efficient operation of HRSs within the hydrogen economy.

1.2 Objectives

The main objective of this study is to support the sustainable growth of the hydrogen energy sector in Saudi Arabia, particularly by focusing on the hydrogen refueling stations safety. The objective could be achieved by doing the following:

- Reviewing global research trends regarding hydrogen refueling stations' safety by preparing a comprehensive review paper (Part 2).
- Conducting a Quantitative Risk Assessment (QRA) on a hydrogen refueling station case study in Saudi Arabia (Part 3).

1.3 Thesis Structure

This structure is carefully organized to achieve the work's objective. Each chapter presents specific aspects of this research while ensuring that the general purpose is achieved. The Figure 1-1 illustrates the thesis structure.

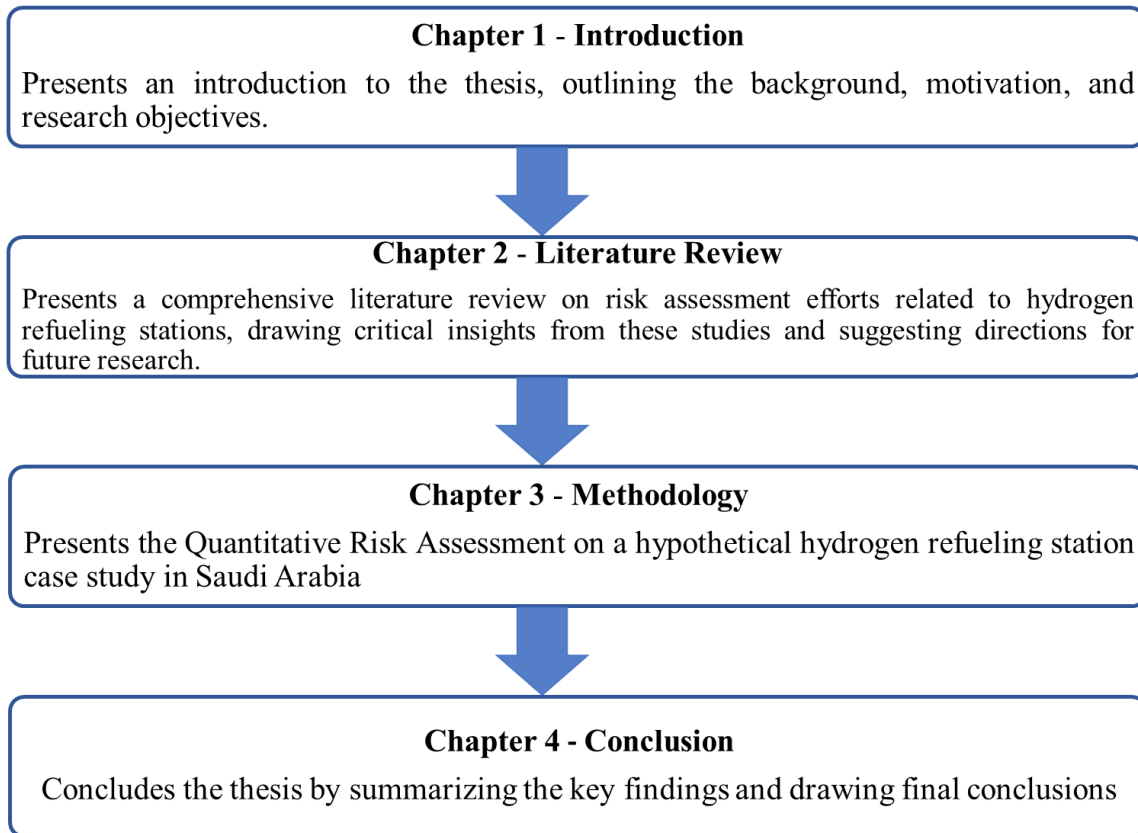


Figure 1-1. Thesis Structure.

CHAPTER 2 Part (1) Towards a Safe Hydrogen Refueling: Reviewing Risk Assessment Measures

2.1 Introduction

The global market for fuel cell vehicles (FCVs) is experiencing significant growth, leading to increased accessibility of HRSs and bridging the gap between hydrogen production and consumption [22-26]. Consequently, HRSs provide high-purity hydrogen at the required pressure primarily to FCVs. These stations are operational and under construction for both heavy and light-duty vehicles, as well as for material handling equipment [27]. The burgeoning number of HRSs built by various countries, especially Japan, China, Korea, and the US, reflects their optimism towards hydrogen energy [28].

Global statistics indicate that by the end of 2023, there were 921 operational HRSs, with plans for an additional 338 locations. 40 countries currently have operational hydrogen refueling facilities or are in the construction phase. In Europe, there are 265 stations, with Germany leading the regional presence with 105 operational stations, followed by France with 51 HRSs. The UK and Switzerland each have 17 operational stations, with the Netherlands adding 22 HRSs [29]. In the Asian region, China, with about 197 HRS, has the highest number, followed by South Korea with 174, and lastly Japan with 166 HRS operational. It should be noted that many completed HRS are in operation waiting for permits from local regulations. Moreover, a total of 92 HRS in the United States of America (USA) are reported, including Canada with 8 HRS. A higher percentage (75%) of the USA's HRS are in California [29].

HRSs are categorized based into four divisions (Figure 2-1): (1) the location of hydrogen production, (2) the storage status, (3) the form of construction, and (4) the content of construction.

Although designs differ, they comprise of they generally have similar major equipment. The major units common to all designs include production, compression, storage, control, and refueling equipment [27]. Moreover, understanding the various HRS designs and categories is fundamental for easy identification and analysis. For Instance, a mobile HRS may present distinct safety concerns compared to a fixed hydrogen station.

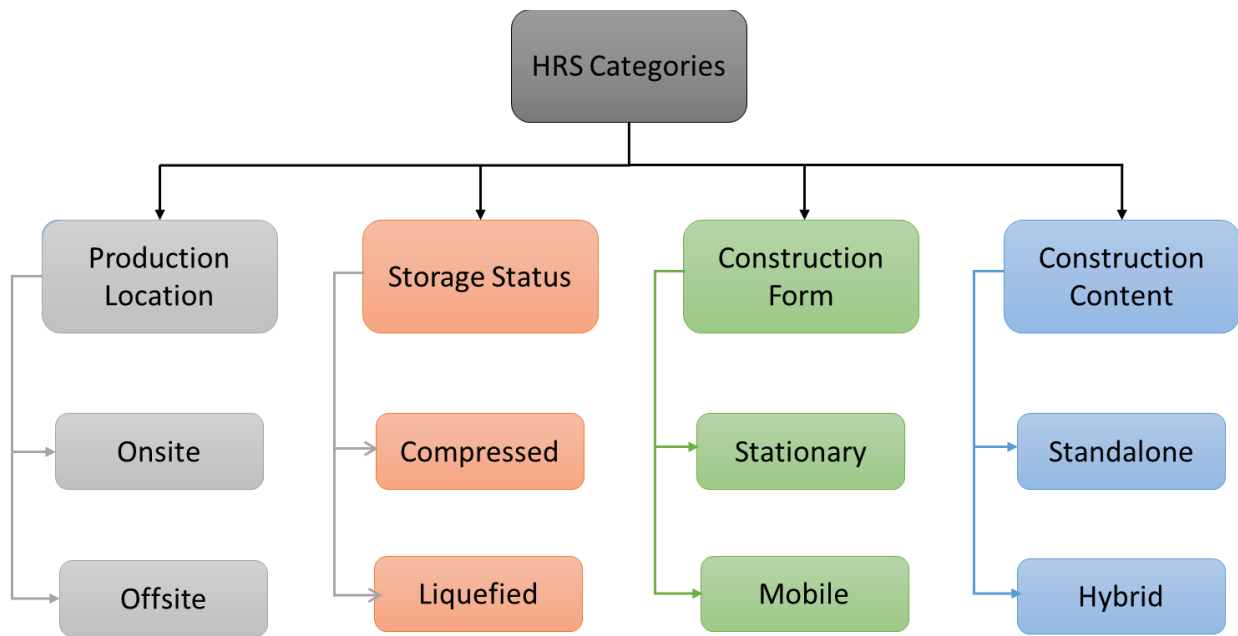


Figure 2-1. Hydrogen refueling station categories

2.1.1 Importance of Safety and Risk Management in Hydrogen Refueling

As hydrogen continues to develop as a fuel source, its hazardous aspects cannot be overlooked. This is especially critical given the heightened public attention on hydrogen due to its flammability and more pronounced hazardous characteristics compared to conventional fuels, as summarized in Table 2-1.

Table 2-1: Hydrogen Properties Compared to Conventional Fuels [30-32]

	Fuels		
Parameters	Hydrogen	Methane	Gasoline
Flammable range in air (vol%)	4-75	4.3-15	1.4-7.6
Minimum ignition energy (mJ)	0.02	0.28	0.24
Limiting oxygen index (vol%)	5.0	12.1	11.6
Burning velocity in air (cm/s)	265-325	37-45	37-43
Diffusion coefficient (cm ² /s)	0.61	0.16	0.05
Buoyant velocity in air (m/s)	1.2-9.0	0.8-6.0	Non-buoyant
Ignition Point (K)	843.0	923.0	700.0
Laminar flame speed (m/s)	2.10	0.38	0.42
Density at 0°C and 1 atm (kg/m ³)	0.09	0.67	4.40

This concern is further heightened by several reported incidents involving hydrogen [8]. For example, the Hindenburg disaster in 1937 [33], the 1986 Space Shuttle Challenger explosion [34], and the 2011 Fukushima Daiichi nuclear power plant explosion led to the formation of a hydrogen cloud near the reactor [33]. Additionally, a hydrogen gas explosion occurred at an Air Product plant in Santa Clara, California, in 2019 [35]. These accidents have not only caused injuries but also damaged industrial facilities, academic buildings, and governmental facilities [36]. Table 2-2 provides a brief overview of some incidents involving hydrogen [37].

Table 2-2: Summary of Selected Hydrogen-Related Incidents

Region in country	Location of incidents	Incident type	Fatality / Injury	Year	References
Hindenburg, Lakehurst, USA	Naval Air Station	Fire	36/0	1937	DiLisi [38]
Netherlands	N/R*	Explosion	4/40	1972	Rigas and Sklavounos [39]

Region in country	Location of incidents	Incident type	Fatality / Injury	Year	References
Gujarat, India	Chemical Plant	Explosion	5/35	1977	Rigas and Sklavounos [39]
Kennedy space-center, Florida, USA	space center	Explosion	7/119	1986	Lipartito and Butler [40]
Geneo, Italy	N/R*	Explosion	3/2	1988	Mohammadfam and Zarei [37]
Pasadena, Texas, USA	Chemical plant	Explosion	23/314	1989	Bethea [41]
USA	Pipeline	(Jet) fire	7/8	1989	Rigas and Sklavounos [39]
Czechoslovakia	N/R*	Explosion	15/26	1990	Rigas and Sklavounos [39]
Hong Kong, China	Power plant	Explosion	2/19	1992	Mohammadfam and Zarei [37]
Hillsborough, Tampa, Florida, USA	Power station	Fire and Explosion	3/50	1999	Mohammadfam and Zarei [37]
Panipat, India	Refinery	Fire	5/0	1999	Mohammadfam and Zarei [37]
Muskingum, Ohi, USA	Power plant	Explosion	1/10	2007	H2tools [42]
Columbia, USA	University Biochemistry Laboratory	Explosion	0/4	2010	H2tools [43]
Fukushima, Japan	Nuclear power plant	Explosion	0/0	2011	Yanez, Kuznetsov [44]
Santa Clara, California, USA	Hydrogen Fueling Station	Explosion	0/2	2019	Vilas [45]
Gangneung, Korea	Hydrogen Tank at Technopark	Explosion	2/6	2019	Vilas [45]
Baerum, Norway	Uno-X fueling station	Fire and explosion	0/2	2019	Vilas [45]
California, USA	Hydrogen fueling station	Fire and explosion	0/0	2023	News [46]

*N/R means Not Reported

As indicated in Table 2-2, recent incidents at HRSs have occurred at HRS. This upward trend in incidents can be attributed to the recent adoption of hydrogen as an energy source, leading to the

global installation of many HRS. Incidents at these stations, including fires and explosions during refueling or resulting from equipment failures, warrant serious consideration [37].

2.1.2 Purpose and Scope of the Review

This review presents a detailed investigation of international safety and risk assessments within hydrogen refueling infrastructures, with a particular focus on Hydrogen Refueling Stations (HRSs). The primary aim is to contribute to the enhancement of global HRS safety standards and protocols.

Building upon foundational research such as the studies conducted by Suzuki, Shiota [47], which evaluated Japanese HRSs with respect to their production locations and safety design standards, this review seeks to expand the scope of examination. Previous investigations highlighted that while there is sufficient assessment for compressed HRSs suitable for societal use, they are limited by geographical scope and lack extensive data on various types of HRSs, pointing towards the necessity for a more global and inclusive approach. Furthermore, there was an observed shortfall in detailed reporting on the risk assessment tools utilized, revealing an area ripe for deeper exploration.

In response, this review intends to meld global insights to forge a comprehensive understanding of the inherent risks, and the safety protocols employed across HRS operations worldwide. This includes a critical look into risk assessment approaches in HRSs, detailing methodologies, tools, and illustrative case studies

The scope of this study is confined to published journal articles directly addressing the safety and risk assessments of hydrogen refueling stations. The literature review is conducted through the Scopus database utilizing keywords such as “hydrogen refueling station safety”, “hydrogen fueling

station risk assessment”, “consequence modeling of hydrogen refueling station”, “safety assessment of hydrogen fueling stations”, “hydrogen storage safety”, and similar terms. The search yielded a total of 212 articles after filtering. We excluded articles related to hydrogen safety but not directly linked to hydrogen refueling station safety and risk assessment, resulting in a selection of only 44 articles.

2.2 Risk Assessment in Hydrogen Refueling stations

Risk Assessment, a crucial aspect of risk management, is the comprehensive procedure of identifying, analyzing, evaluating, and mitigating risks [48]. Risks can be assessed at various levels, such as organizational, departmental, project, individual activity, or specific risks. The Risk Management Principles and Guidelines (International Electrotechnical Commission IEC 31010) are the reference document for conducting risk assessments according to specified criteria [49].

The Risk Management-Principles and Guidelines define the risk assessment activities as follows:

- Risk identification: Involves systematically understanding the system in question, comprehending the conditions that could lead to risks (both internal and external), and determining the potential outcomes.
- Risk analysis: This step, which precedes risk identification, thoroughly handles the identified risks to ensure full comprehension. It involves examining their sequences, corresponding consequences, and likelihood. Ensuring confidence in estimated risk levels is paramount in risk analysis. Therefore, examining the results' sensitivity to changing conditions and assumptions cannot be viewed in isolation.
- Risk evaluation benchmarks the results against the risk acceptance criteria developed in the risk management process to determine if further treatment is necessary. Risk treatment

involves implementing various options to mitigate the risks. Finally, the implementation is assessed to determine the acceptability of the remaining risk [49, 50].

2.2.1 Risk Assessment Techniques

Although knowledge-based and data-driven approaches are applied to risk assessment studies, most risk assessment studies encountered for HRS adopt the knowledge-based approach, following traditional methods such as HAZOP, HAZID, QRA, and sometimes combinations of two or more. Computational Fluid Dynamics (CFD) simulations are also used for different accidental scenarios, providing insights into physical phenomena. A brief description of some of the methods is given below.

- **Hazard Identification (HAZID)**

HAZID is a qualitative risk assessment technique aimed at identifying the risks in a facility at the preliminary design stage. The study was conducted by experts, including the chairman, project manager, production manager, process engineer, health safety and environment (HSE) engineer, etc. [51]. Inputs required for HAZID include process engineering drawings, plant layout, operating descriptions, etc. The team examines the causes and consequences of identified hazards, identifies safety features, and makes suggestions for improvements if necessary. All HAZID sessions are documented in tables containing implemented safeguards and new suggestions to reduce the likelihood or consequences [52].

- **Failure Mode and Effect Analysis (FMEA)**

FMEA is a risk assessment method used to examine the reliability of a safety barrier at its early design or operation stage to improve its design, schedule maintenance, or choose alternative options [53]. Critically investigating failures involves a more rigorous technique called failure

mode, effect, and criticality analysis (FMECA), which is a semi-quantitative method [49]. For FMEA, a team consisting of the Project manager, maintenance, production, instrument, and quality control engineer is established. Detailed information about the system elements, operating environments, failure conditions, and consequences must be provided. Flow charts and drawings are also necessary as inputs [51]. At the end of the FMEA session, a worksheet containing failure modes, effects, causes, existing controls, criteria used for definitions, and recommended actions are reported.

- Hazard and Operability Analysis (HAZOP)

HAZOP is also a qualitative technique used to identify possible deviations from design intent and investigate their causes and consequences in an existing or planned process or system. HAZOP investigates existing measures planned to reduce the occurrence or effects of each deviation [49, 54]. It is carried out by a team of experts led by a Facilitator, with members including process engineers, health safety and environment (HSE) engineers, system operators, equipment vendors, and other engineers. Inputs for the study include the Piping and Instrumentation Diagram (P&ID), specification sheets, process control and logic diagrams, operating and maintenance procedures, and other drawings. The HAZOP exercise involves dividing the P&ID into nodes based on equipment with the same operating conditions [53]. A list of keywords is defined and linked to parameters chosen based on the system under study. HAZOP concludes by documenting all sessions containing deviations, causes, consequences, safety barriers, and actions taken to address the assessed problems and their responsible parties [53].

- Quantitative Risk Analysis (QRA)

QRA is a technique to investigate the possibility of damage due to a potential accident. The significant steps of QRA include describing the system, selecting an accident scenario, evaluating

the frequency, modeling consequences, estimating risk, and evaluating it [49, 54]. Finally, we express the assessed risk in terms of individual and societal risks. Individual risk represents the chance that an accident's impacts will affect an individual at a specific location, while societal risk indicates the likelihood of an accident affecting a fraction of the population [51]. The results are then reviewed to make decisions based on the defined acceptable death or injury probability criteria.

2.2.2 Risk Acceptance Criteria

Risk Acceptance criteria are an essential parameter determining whether a risk is acceptable. Depending on the methodology used for the risk assessment, two main criteria are employed: a risk matrix and threshold value. For example, qualitative methods like FMECA use a risk matrix, while quantitative methods use threshold values, as seen in QRA, where the consequences and occurrence frequencies are numerically expressed [48, 49].

2.3 Overview of HRS Safety and Risk Assessment Studies

For the hydrogen energy industry to achieve its goals, safety is paramount for hydrogen infrastructures, including HRSs [47]. The rapid growth of the hydrogen economy relies on ensuring the safety of refueling, the handling process, and public perception. HRSs are prone to accidents like current fuel facilities, and various incidents are presented (As seen in Table 2-2). Thus, ensuring safe station design is crucial [27, 55]. Developing inherently safer processes and reducing risks to as low as reasonably practicable are the main goals behind the process safety philosophy [27].

Several studies reporting risk assessments of HRS are extensively analyzed in the following sections, for offsite and onsite HRS. Here, we describe some characteristics of the 45 HRS safety

and risk assessment articles. Figure 2-2 illustrates the distribution of the articles in different geographical locations. The figure shows that most articles originate from Asian countries, with Japan leading the list with 17 articles. China is the second location with 10 articles, Korea with 7 articles, and the United States of America (USA) with 4. The United Kingdom (UK), Australia, Malaysia, Norway, and Italy each have 1 study.

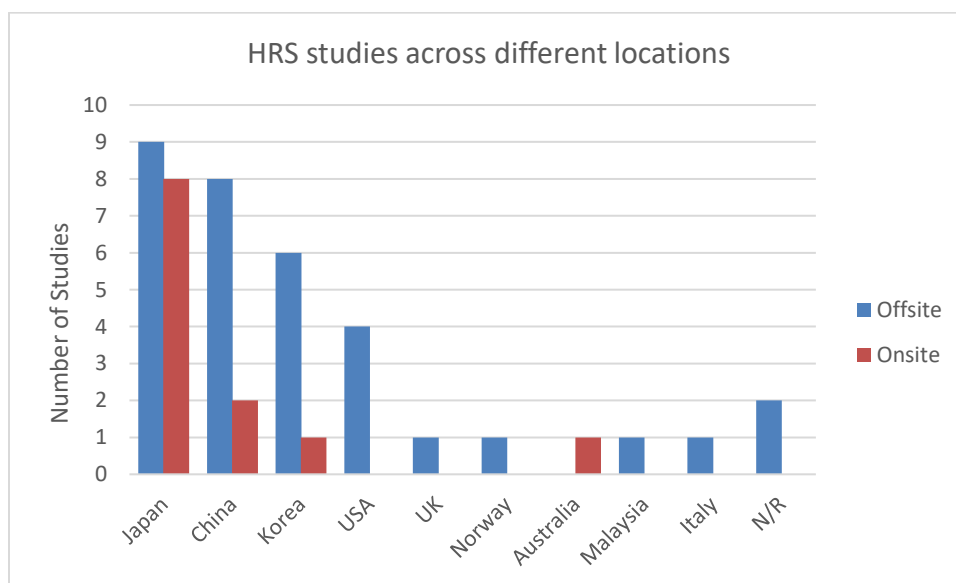


Figure 2-2: Summary of HRS Safety Studies Based on Regional Locations

Additionally, the 2 articles have not mentioned their locations. The figure also shows that onsite HRS studies are significantly concentrated in Japan. It was observed that there are no active HRSs in the Middle East and Africa. As a result, the Middle East region does not report any offsite or onsite HRS risk assessment studies.

2.3.1 Examining the risk Assessment Framework on Offsite HRS

Offsite HRS refers to a type of hydrogen dispensing station where hydrogen is supplied via gaseous hydrogen pipelines, tube trailers, metal hydride storage systems, and liquid hydrogen

tankers/trucks. In this regard, several offsite HRS risk assessment studies are reported in the literature.

Suzuki et al., 2021 for instance, conducted a detailed QRA of a new Japanese HRS model to determine the main accident scenario posing significant risk in the vicinity of the HRS station. They identified that the jet fire scenario is the leading risk contributor in all considered risk ranking points within and outside the station. Within the HRS battery limits, risk contours of 10^{-3} and 10^{-4} per year are confined, and risk contours of 10^{-5} and 10^{-6} per year extend outside the HRS. The use of firewalls is an effective risk mitigation measure against Jet fire [56]. Table 2-3 summarizes key information from selected offsite HRS safety and risk assessment studies, providing insights into the HRS risk assessment and management strategies.

- Insight from off-site risk assessment studies

A total of 33 offsite HRS studies are available, comprising 24 studies from compressed HRS, 6 for liquefied HRS, 1 study combining compressed and liquefied HRS, and 2 studies for hybrid HRS (hydrogen and gasoline in the station). Each entry in the table outlines the type of inventory, considered scenarios, methodology used, risk analysis software tools, and additional notes. The table shows that Asian countries reported the most, with Japan leading the list with 9 articles. China is the second location with 8 studies, and Korea comes next with 6 studies. The USA has 4 studies, while the UK, Malaysia, Norway, and Italy each have 1 study, and 2 articles did not identify their locations. The table also highlights the year in which the study was carried out.

The analysis considered several scenarios yet integrating them is challenging due to their large number and specific nature. However, the critical scenarios encountered are mainly hydrogen leakages, full-bore ruptures, and catastrophic ruptures. From our analysis, hydrogen leakage

occurs in many pieces of equipment, such as compressors, tube trailer fittings, priority panels, and tank fittings. Full-bore rupture is associated with equipment such as tube's flexible hoses and pipe works, while catastrophic rupture occurs in compressors, dispensers, tube trailers, and storage vessels. The equipment contributing to higher HRS risk, as mentioned in the literature, are compressors, dispensers, tube trailers, and storage vessels. Considering that each scenario results in different types of fires and explosions, as seen in the table, choosing the proper method (and software) to identify hazards and conduct risk analysis.

Figure 2-3 and Figure 2-5 depict the diverse methods and software tools applied for risk assessment of HRS from the literature. Figure 2-3 indicates that QRA, HAZOP, consequence analysis, and Bayesian Network (BN) are the most used methods, with QRA being the most prominent. This indicates that semi-quantitative and quantitative methods are more generally used. Notably, some articles have used more than one methodology.

According to each country, Figure 2-4 showcases the risk analysis methodology mentioned in the literature. Japan, for example, uses several methods such as QRA, HAZOP, FMEA, BN, and consequence analysis. This is also the case with China and USA. This indicates that there is no single preferred method over the other. However, Korea adheres to one methodology in its analysis, which is QRA. This may be due to the country's regulations required for HRS. The UK uses consequence analysis, Malaysia uses the SHIPP method, Italy uses QRA, and Norway uses HAZID and BN methods.

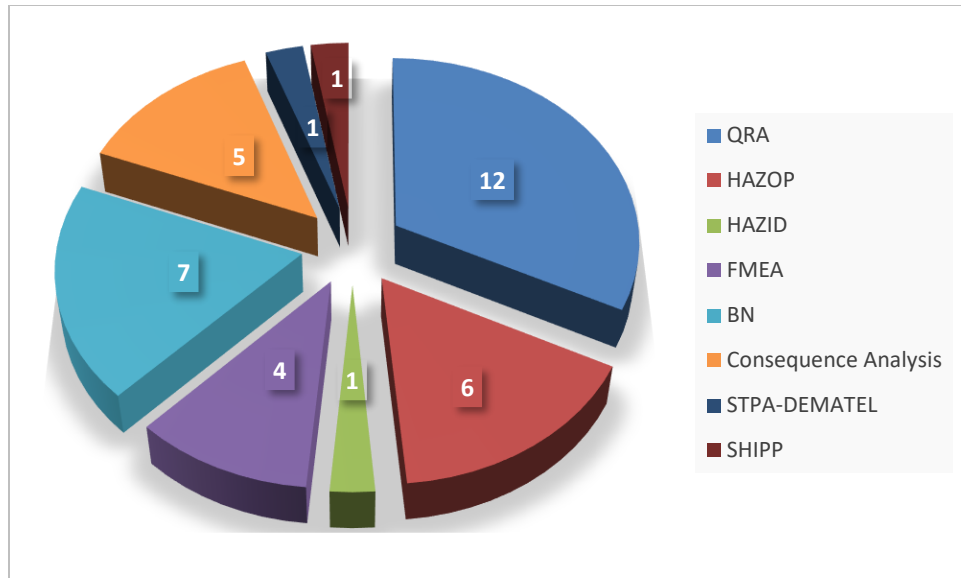


Figure 2-3: Methodologies of the Selected Studies

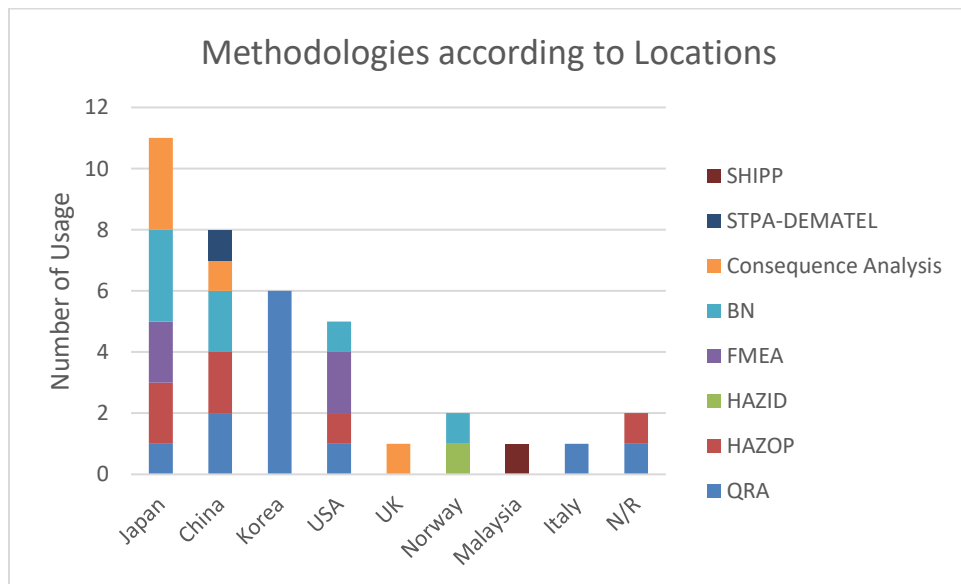


Figure 2-4: Risk Assessment Methodologies across locations.

From Figure 2-6, PHAST received the bulk of the distribution of software tools for risk assessment. Moreover, HyRAM and CFD tools (FLACs, ANSYS Fluent) are also commonly applied. About 12 articles do not apply the use of any software for their studies. Therefore, the software tools for

modeling include PHAST, HyRAM, and CFD tools. RISKCURVES is also an emerging software currently in use. HyRAM+ and Hy-KoRAM are specifically designed for hydrogen applications.

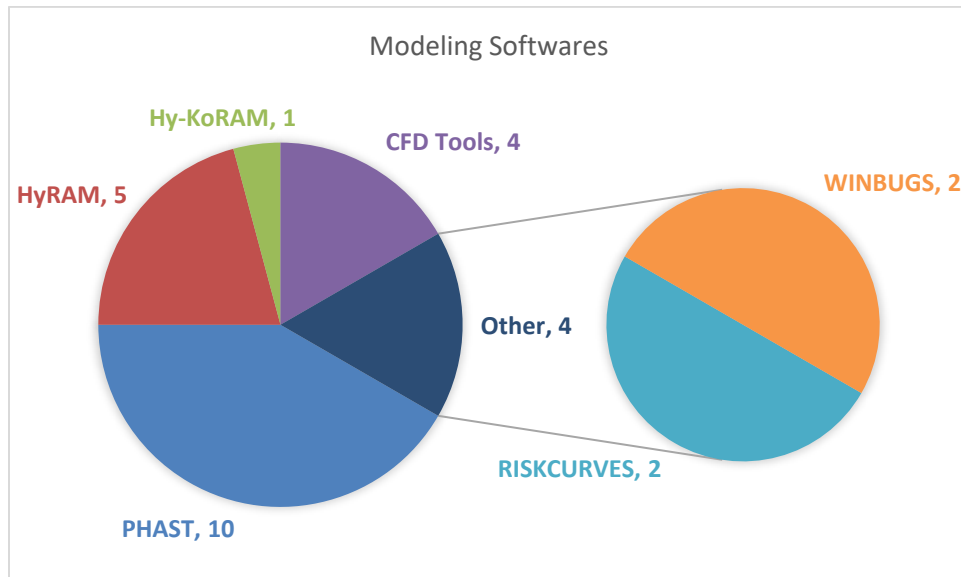


Figure 2-5: Software for Risk Analysis

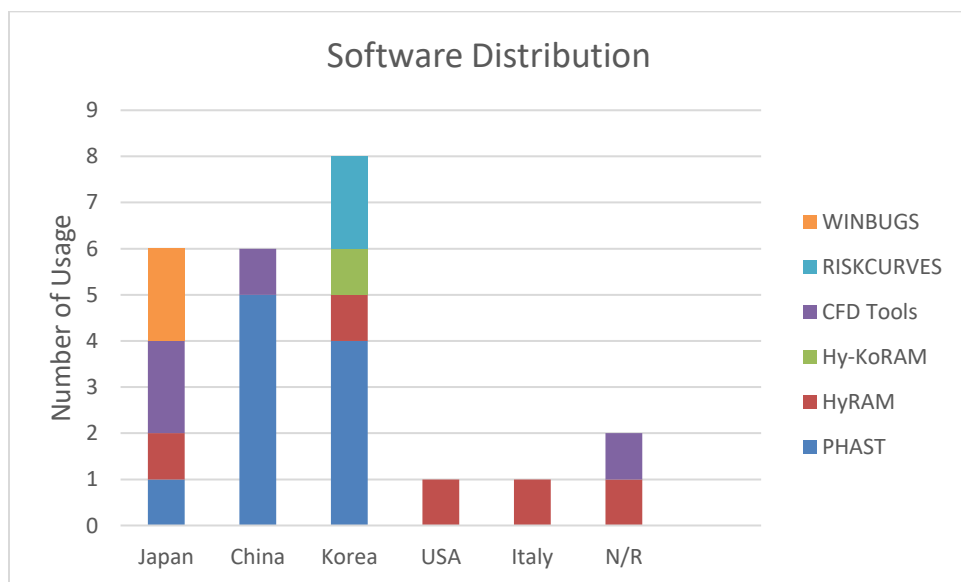


Figure 2-6: Distribution of software across locations.

Figure 2-6 presents insights into the use of software for analysis based on countries. Again, Japan uses different software, including CFD tools, WINBUGS, HyRAM, and PHAST, indicating a lack of adherence to a single tool. However, China and Korea predominantly use PHAST, while the USA and Italy employ HyRAM.

Table 2-3: Safety and Risk Assessment studies for off-site HRSs

S/N	Location (Year)	Inventory Type	Scenarios	Methodology	Software Tool for Risk Analysis	Notes	Reference
1	Japan (2008)	Compressed Hydrogen	Leak	Consequence Analysis	ANSYS-Fluent	Barriers affect gas diffusion	[57]
2	Japan (2008)	Compressed Hydrogen	- Explosion - Jet Flame	HAZOP + FMEA	N/A	Scenarios present high risk, and a 6m safety distance is adequate	[58]
3	Japan (2009)	Liquefied Hydrogen	- Explosion - Jet Flame	HAZOP + FMEA	N/A	Effective safety measures reduce the risks.	[59]
4	Japan (2016)	Gasoline + Liquefied Hydrogen	Gasoline Pool fire	Consequence Analysis	ANSYS-Fluent	The hydrogen tank's emissivity should be kept lower than 0.2, and 8.5m is the least safety distance.	[60]
5	Japan (2018)	Compressed Hydrogen	Leak	BN (Time Correlation Model)	WINBUGS	Uncertainty in estimating accident data increases with long operation time.	[61]
6	Japan (2019)	Compressed Hydrogen	Leak	BN (Parameter-based models)	N/A	The failure rate can vary significantly based on the life parameter and estimator chosen for reliability predictions.	[62]
7	Japan (2019)	Compressed Hydrogen	- Jet fires, - Explosions - Flash fires.	Consequence Analysis	HyRAM	Appropriate safety distances could be evaluated for these scenarios.	[63]
8	Japan (2020)	Compressed Hydrogen	Leak	BN	WINBUGS	- Leak rates are estimated based on time, hole size, and non-parametric methods. - The higher the leak rate, the more frequent the inspection interval should be.	[64]

S/N	Location (Year)	Inventory Type	Scenarios	Methodology	Software Tool for Risk Analysis	Notes	Reference
9	Japan (2021)	Compressed Hydrogen	Leaks	QRA	PHAST	Jet fire risk is unacceptable; hence, mitigation measures are suggested.	[56]
10	China (2010)	Compressed Hydrogen	Leak from - Compressor - Tube trailer fittings. - Tank fittings. Full bore rupture of - Tube's flexible hose - Pipe works. Catastrophic rupture of - Tube trailer. - Compressor - Storage tube - Dispenser.	HAZOP	PHAST	Risk from compressors exceeds threshold values; hence, risk mitigation measures are implemented for them.	[65]
11	China (2010)	Compressed Hydrogen	Leak from - Compressor - Tube trailer fittings. - Tank fittings. Full bore rupture of - Tube's flexible hose - Pipe works. Catastrophic rupture of - Tube trailer. - Compressor - Storage tube - Dispenser.	HAZOP	PHAST	- Vapor clouds and physical explosions have the longest effect distances. - The harm distance is a function of the inventory, pressure, geometry, velocity, and height. - Elevating the equipment effectively reduces distances.	[66]
12	China (2014)	Compressed Hydrogen	Leak from - Tube trailer fittings, - Booster compressor, - Vehicle fittings. Full bore rupture of - Tube's flexible hose	QRA	PHAST	- Booster compressors have the highest risk. - The largest financial loss is presented by tube storage failure.	[67]

S/N	Location (Year)	Inventory Type	Scenarios	Methodology	Software Tool for Risk Analysis	Notes	Reference
			• Pipe works. - Catastrophic rupture of • Compressor, • Tube trailer, • Storage vessel.				
13	China (2018)	Compressed Hydrogen	• Leak	Dynamic Bayesian Network (DBN)	PHAST	• A clear view of potential risk is achieved in each local area.	[68]
14	China (2023)	Compressed Hydrogen	• Leak	DEMATEL-STPA	N/A	• Identified the system-level losses, hazards, and control behaviors. • Identified 24 undesired consequence accidents from 10 control actions	[69]
15	China (2023)	Liquefied Hydrogen	• Leak • Catastrophic rupture	QRA	PHAST	• Individual and societal risks exceeded the acceptance criteria. • Effective measures include detectors, breakaway couplings, and elevating the compressor.	[70]
16	China (2023)	Liquefied Hydrogen	• Leak	Consequence Analysis	ANSYS-Fluent	• 313.2m is the least safe distance in the event of explosions.	[71]
17	China (2023)	Compressed Hydrogen	• Leak	DBN	N/A	• Leakage probabilities and consequences were estimated. • Human and corrosion factors are the most enhancing factors.	[72]
18	Korea (2019)	Compressed Hydrogen	• Tube Trailer Rupture. • Dispenser hole leakage	QRA	PHAST	• A safety barrier is added to the compressor and dispenser to prevent hydrogen releases.	[73]

S/N	Location (Year)	Inventory Type	Scenarios	Methodology	Software Tool for Risk Analysis	Notes	Reference
19	Korea (2021)	Compressed Hydrogen	Leak	QRA	RISKCURVES	Active and passive independent protection layers effectively reduce risks.	[74]
20	Korea (2021)	Compressed + Liquefied hydrogen	- Equipment rupture - Dispenser leak	QRA	PHAST	Tube trailer and liquid storage vessel rupture pose unacceptable risks.	[75]
21	Korea (2021)	Compressed Hydrogen	- Gas plume dispersion - Jet Flame - Heat Flux	QRA	HyRAM + RISKCURVES	- Pressure and leak diameter affect the overall station safety. 29m safety distance was suggested	[76]
22	Korea (2022)	Compressed Hydrogen	- Tube-trailer rupture. - Leak	QRA	PHAST	Risks are mainly within the acceptable zone.	[77]
23	Korea (2022)	Compressed Hydrogen	Leaks from - Compressor - Dispenser - Priority panel. Catastrophic rupture of - Compressed gas facility	QRA	Hy-KoRAM + PHAST	- Damage range and impact on radiant heat and flame length were determined. - The damage range and impact for Hy-KoRAM gives a higher risk than PHAST.	[78]
24	USA (2009)	Compressed Hydrogen	- Leak - Storage vessel overpressure.	FMEA + HAZOP + FTA	N/A	- FMEA determines the highest failure components. - HAZOP examines leaks and storage vessel overpressure. - FTA for storage vessel overpressure gives low occurrence frequency.	[79]
25	USA (2009)	Compressed Hydrogen	- Jet fire - Flash fire	QRA (NFPA approach)	N/A	Separation distances are adversely affected by operating pressure and leakage frequency data.	[80]

S/N	Location (Year)	Inventory Type	Scenarios	Methodology	Software Tool for Risk Analysis	Notes	Reference
26	USA (2012)	Liquefied Hydrogen	- Leak - Catastrophic rupture	BN	N/A	- Liquefied hydrogen transportation is riskier than compressed. - Pipeline transport is the most attractive	[81]
27	USA (2022)	Liquefied Hydrogen	Leak	FMEA + ESD + FTA	HyRAM	Data gaps needed for enhanced QRA were identified.	[82]
28	Norway (2011)	Compressed Hydrogen	- Jet fire - Flash fire	HAZID + BN	N/A	Monetary loss estimation from scenarios is quantified using BN results	[83]
29	UK (2010)	Compressed Hydrogen	- Ignited Jet release. - Premixed hydrogen-air explosion	Consequence Modeling	N/A	- The released gas requires some time before it forms an explosive mixture. - The peak overpressure is inversely related to the distance from the front open end.	[84]
30	Italy (2018)	Compressed Hydrogen	- Unignited release - Jet fire - Explosion	QRA	HyRAM	- Safety distances were determined for all scenarios. - Protection and mitigation measures were also identified.	[85]
31	Malaysia (2014)	Liquefied Hydrogen	Leak	FTA + ETA + System hazard identification and prevention (SHIPP)	N/A	Provided indications that can effectively be used in risk-based decisions.	[86]
32	N/R (2023)	Liquefied Hydrogen	Leak	HAZOP + Bowtie + IV-SFS	N/A	- Jet fire is the most expected scenario. - Equipment failure is the major contributor to the leak.	[87]

S/N	Location (Year)	Inventory Type	Scenarios	Methodology	Software Tool for Risk Analysis	Notes	Reference
33	N/R (2017)	Compressed Hydrogen	• Gas dispersion • Jet fires • Explosions	QRA	FLACs + HyRAM	• The model extends using detailed geometry models to all aspects of risk management.	[88]

*N/R means Not Reported, *N/A means Not Applicable.

2.3.2 Examining the Risk Assessment Framework on on-site HRS

Onsite HRS constitutes another HRS type where hydrogen is generated in the station based on fuel processing technologies or water electrolysis. Selected literature on onsite HRS safety studies has been summarized in Table 2-4 to provide a comprehensive understanding of HRS risk assessment and management strategies.

For instance, Suzuki et al. (2021) identified several accident scenarios in an LOHC HRS employing MCH/Toluene system using HAZOP [89]. They analyzed dehydrogenation, toluene loading, and MCH unloading as the only process units. The scenarios were identified based on whether ignition occurred after the material was released or during the process. The explosion of the cloud formed by gaseous toluene and oxygen in the vent line linked to the tank was the credible accident scenario identified in this study. Following this HAZOP study [89], they experimentally studied the minimum ignition energy (MIE) of the toluene/hydrogen/air system while altering the hydrogen contents and the equivalence ratio [90]. Using the MIE as a risk indicator, they evaluated the potential explosion risks for such mixtures in the storage tanks. They concluded that the hydrogen vapor present in the tank should be kept below 1.0 vol.% to maintain the risk of ignition at an acceptable limit. They also proposed using a membrane separation unit to strip hydrogen for the safe operation of the HRS.

- Insight from on-site risk assessment studies

A total of 12 onsite HRS safety and risk analysis studies were summarized across various locations. As seen in the table, Japan leads the list with 8 studies, China is the second location with 2 studies, and Korea and Australia come next with 1 study each. Each column in the table highlights the type of inventory, considered scenarios, methodology used, risk analysis software tools, and additional notes. Notably, specific inventories are attached to some countries; for example, all Japan HRS

studies use methylcyclohexane (MCH), China uses water from electrolysis, and the only study from Korea and Australia uses formic acid and natural gas, respectively.

Several scenarios involved in onsite HRS studies were examined. In Japan, critical scenarios were identified, including hydrogen leakage in many pieces of equipment, such as dispenser piping, accumulator piping, and compressor piping. Additionally, other scenarios include material leakage (MCH, toluene), automobile collision, pool fires, flash fires, explosions, heat radiation, etc., which led to measures such as minimum separation distances, barrier systems, rupture-type vent systems, etc., to enhance safety measures and reduce fatal risks to acceptable limits. Scenarios identified in China include gas leaks, jet fires, flash fires, and explosions, emphasizing safety distances to avoid fatalities from these scenarios and the effect of windspeed and direction on the harmful locations. Only 1 study was assessed from Korea, which highlights active safety systems on the HRS to mitigate explosion risks.

The methods applied for risk assessment of HRS from the literature are visualized in Figure 2-7. HAZOP, HAZID, QRA, BN, and security risk analysis are employed in general. HAZOP and HAZID are the most used methods, as seen in the figure. Each methodology addresses specific scenarios, including gas dispersion, pool fires, jet fires, flash fires, explosions, etc., using software tools like PHAST, CFD Tools, RISKCURVES, etc. In Figure 2-8, the distribution of methodologies from different locations has been presented. Japan, which has the largest number of onsite studies, uses several methods; hence, no single method is strictly applied in the region. On the other hand, China used consequence analysis and HAZOP, and finally, the only articles in Korea and Australia used HAZID and BN, respectively. Finally, qualitative and sometimes semi-quantitative methods are mainly adopted for risk assessments in onsite HRS applications.



Figure 2-7: Risk Assessment Methodologies used on onsite HRS.

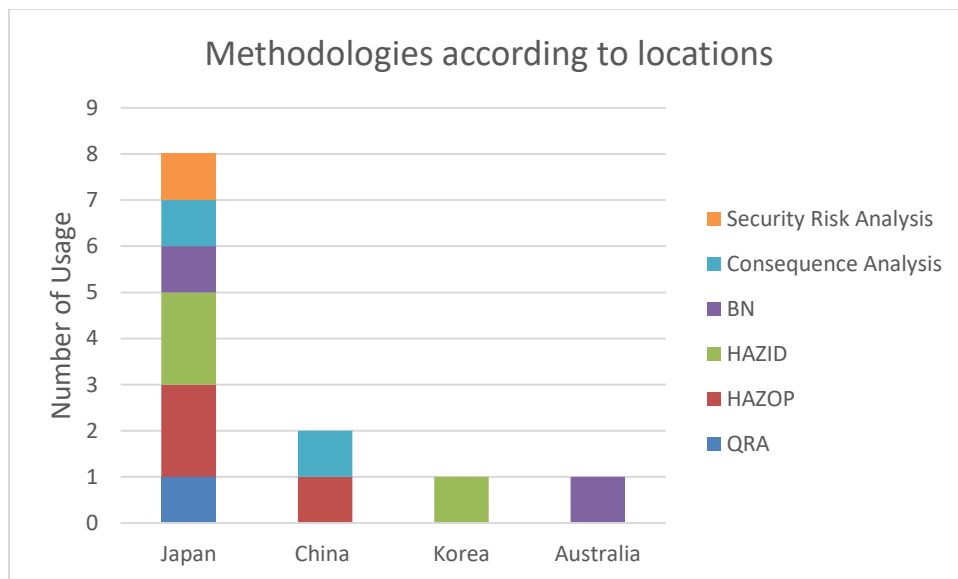


Figure 2-8: Risk Assessment methods according to locations.

Figure 2-9 visualizes a distribution of the modeling software used. CFD tools (FLACs and ANSYS Fluent) are applied most, followed by PHAST software. Based on locations, Japan largely uses CFD tools for onsite HRS, followed by PHAST, while SimulationX is used only once. While

China uses both PHAST and CFD tools for the 2 studies, Korea explores RISKCURVES for its study. Therefore, CFD tools are suitable for onsite HRS safety studies, especially in Japan.

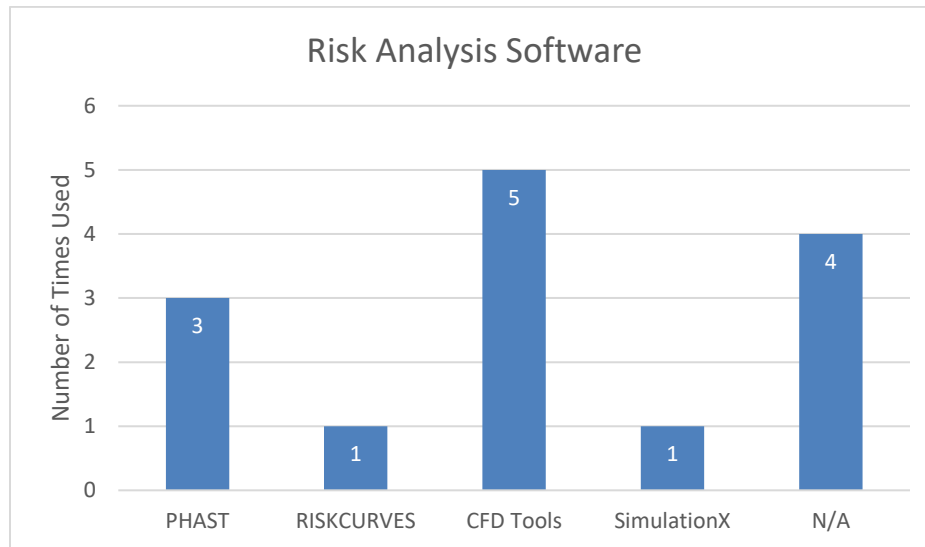


Figure 2-9: Distribution of Software used for Risk Analysis on onsite HRS.

Table 2-4: Safety and Risk Assessment studies for onsite HRSs

S/N	Location	Inventory type	Scenarios	Methodology	Software Tool for Risk Analysis	Notes	Reference
1	Japan (2016)	MCH	• Chemical leak • Automobile Collision • Earthquake	HAZID	N/A	• Identified 314 potential hybrid scenarios for the coexistence of gasoline and MCH.	[91]
2	Japan (2017)	MCH	• Hydrogen release from safety vent during emergency • MCH/Toluene leak from liquid storage pipes	HAZID	PHAST+ANSYS + SimulationX	• Process equipment can be damaged due to toluene or MCH pool fire. • Suggested mitigation and prevention measures such as rupture-type vent system.	[92]
3	Japan (2017)	MCH	• Hydrogen leaks from hydrogen storage pipes. • MCH/Toluene leak from dehydrogenation system pipes	Consequence Analysis	FLACs	• Small chemical leaks and explosion effects for all scenarios. • High heat effects within the perimeter of the station require treatment	[93]
4	Japan (2018)	MCH	• Hydrogen leak from hydrogen storage pipes. • MCH/Toluene leak from liquid storage pipes	Bayesian inference model (BIM)	FLACs	• Negligible chemical leaks and explosion effects. • High heat radiation within the perimeter of the station needs treatment	[94]
5	Japan (2019)	MCH	Leak from • Dispenser piping, • Accumulator piping • Compressor piping	QRA	FLACs	• The least separation distance is 6m, and a 3m barrier height could reduce fatal risk to below the acceptable limit.	[95]
6	Japan (2019)	MCH	Leak from • MCH supply truck • Dehydrogenation reactor Money theft from a cashier	Security risk Analysis	PHAST	• Analyzed knock-on events and implemented additional measures.	[96]

S/N	Location	Inventory type	Scenarios	Methodology	Software Tool for Risk Analysis	Notes	Reference
7	Japan (2021)	MCH	• MCH/Toluene pool fire • Hydrogen jet fire, • Vapor gas explosion, • Flash fire. • Explosion of gas mixtures	HAZOP	N/A	• Examined safety measures for each scenario using Current regulations.	[89]
8	Japan (2022)	MCH	• Explosion	HAZOP	N/A	• Toluene vapor inside storage tanks in the presence of hydrogen could ignite.	[90]
9	China (2016)	Water Electrolysis	Leak in • Reaction vessel • Tube-trailer fittings. • Compressor • Buffer storage fittings. Full bore rupture of • Tube's flexible hose • Pipe works. Catastrophic rupture of • Tube-trailer. • Reaction vessel • Compressor • Storage tubes • Dispensers	HAZOP	PHAST	• Compressors contribute the highest risks; the longest jet flame and flash fires lead to the longest harm distance with 1% fatality. • 23m distance from the hydrogen storage to avoid fatalities from jet fire attacks.	[97]
10	China (2019)	Water Electrolysis	• Leak • Explosion	Consequence Analysis	FLACs	• The most significant harm is presented by the explosion of the storage tank, which is affected by windspeed and direction.	[98]
11	Korea (2023)	Formic acid	Leak from • Dispenser Catastrophic rupture of • Tube-trailer. • Hydrogen buffer tank • PSA unit • WGS reactor • Dehydrogenation reactor	HAZID	RISKCURVES	• Active safety systems on gaseous HRS enabled the system to function within acceptable limits	[99]

S/N	Location	Inventory type	Scenarios	Methodology	Software Tool for Risk Analysis	Notes	Reference
			Formic acid tank				
12	Australia (2023)	Natural gas	Leak	HEART-BN-BWM	N/A	The scenario is due to the pressure relief valve maintenance procedure.	[100]

* N/A means Not Applicable

2.4 Conclusions

Hydrogen, as an adaptable energy carrier, plays a pivotal role in integrating renewable energy systems. Its capacity to store excess energy from intermittent renewable sources like solar and wind power is crucial in addressing the inconsistency of energy production. Hydrogen serves as a bridge, enabling more efficient utilization of renewable energies and reducing dependence on fossil fuels. However, realizing hydrogen's full potential hinges on overcoming the challenges associated with its storage and transportation.

Hydrogen Refueling Stations (HRSs) play an essential role in enabling Fuel Cell Vehicles (FCVs) to operate, as they both play a significant role in sustainable energy strategies and contribute to reducing greenhouse gas emissions in the transportation sector. Historical incidents have highlighted the critical importance of safety in adopting and developing hydrogen technologies. It is essential to have comprehensive safety protocols and risk assessment methodologies, especially for hydrogen refueling stations. This includes developing technological measures, regulatory frameworks, and public education to mitigate risks and promote a safety culture around hydrogen use.

This paper reviews international HRS safety and risk assessment studies based on regional locations. HRSs can be categorized into two main categories based on production location: offsite and onsite HRS. Asian countries contributed significantly to the most publicly available HRS safety studies, especially Japan, which reports on both offsite and onsite HRS safety studies. Moreover, in terms of risk assessment methods, semi-quantitative and quantitative approaches (such as QRA) are more generally used for offsite HRS safety studies, while qualitative and sometimes semi-quantitative approaches (such as HAZID) are mainly adopted for risk assessments in onsite HRS applications.

In conclusion, hydrogen's role as a cornerstone of a sustainable and decarbonized energy future depends on a multifaceted approach that includes not only technological advancements in storage and safety but also strategic planning in infrastructure development, policy formulation, and stakeholder engagement. As the global community shifts towards cleaner energy sources, hydrogen emerges as a versatile and promising option. Its challenges must be addressed comprehensively and collaboratively, with the convergence of research, industry, and policy playing an instrumental role in unlocking hydrogen's full potential in the future energy landscape.

CHAPTER 3 (Part 2) Quantitative Risk Assessment of Hydrogen

Refueling Station: A Case Study of Saudi Arabia

3.1 Introduction

With the rapid advancement of fuel cell electric vehicles, hydrogen Refueling Stations (HRSs) have become essential to the new energy infrastructure. By the end of 2023, 921 HRSs were operational across 40 countries, with significant growth anticipated [29]. However, safety incidents at HRSs have raised concerns regarding industry growth and public perception, while posing risks to operations, personnel, and nearby facilities [21, 70]. Thus, addressing the potential risk associated with HRSs and implementing mitigation strategies are crucial for the safe and sustainable expansion of hydrogen infrastructure.

To mitigate the risks posed by incidents at HRSs, safe distances are often implemented as robust safety measures [101]. Safe distance is defined as the minimum space separating a hazard source and specific targets at risk, including personnel and nearby structures [101, 102]. Carefully designed safe distances help ensure risks levels are acceptable to station workers, structures, and the general public [101].

Safe distances for HRSs can be determined through codes and regulations or via quantitative analysis of standard HRS designs. Codes and regulations from organizations like the National fire protection association (NFPA), International Code Council (ICC), and International Fire Code (IFC) [101] define safe distances based on the targets exposed to potential accident [101]. Table 3-1 presents the safe distance requirements for five leading countries in hydrogen infrastructure. Nevertheless, relying solely on codes and regulations to determine safe distance may be insufficient as hydrogen infrastructure continues to evolve. Changes in HRSs operations, such as

expanding station capacity, increased operational pressures, onsite hydrogen production, diverse deployments of locations, and varying population density necessitate more adaptive safety approaches. Therefore, determining safe distances using quantitative analysis should be given significant consideration to address the changing needs of hydrogen infrastructure.

Table 3-1. Hydrogen refueling stations safe distances compared across various nations [21]

Locations	UK (m)	Japan (m)	USA (m)	Germany (m)	China (m)
Hydrogen equipment	-	-	-	0.5-1	3-15
Non-hydrogen equipment	-	-	-	2	4-8
Internal fire	5	-	12	1-5	12-14
External fire	8	8	3-4.6	-	20-40
Internal roads	8	-	3	-	2-5
Warehouse	5	-	0	-	5-15
External construction	-	-	2	-	12-50

‘-’ symbol in the table indicates that values should be evaluated through quantitative analysis

Quantitative analysis of safe distances for HRSs employs two approaches: consequence-based and risk-based approach [21, 103]. In consequence-based approach, safe distances are determined using consequence models and relevant harm criteria. Meanwhile, in risk-based approach, safe distances are determined when probabilistic models are used to translate physical models to frequency data, considering the chances of component failures, leakages, and ignition. The resulting risk is quantified by combining the incident consequences and their frequencies [103].

The consequence-based approach has been widely studied, focusing on the effects of severe incidents and factors influencing safety distances for HRSs. These studies include the work of Zhiyong et al., who defined the most extended harm effect distances for the most severe incidents

(confined vapor cloud explosions and physical explosions) and monitored the parameters influencing the distances for HRS, including release inventory, height, diameter, angle, velocity and pressure [65]. In 2016, Sakamoto et al. determined the safe distance for liquid hydrogen storage tanks while exploring the effect of gasoline pool fire in a hybrid (gasoline-hydrogen) station [60]. Liang et al. identified several safe distances (e.g., lethal area, harmful area, and lethal distance) due to accidental effects of leakage and explosion in a renewable HRS employing Flame Accelerator Simulator (FLACS) software. They further explore the impact of windspeed, leak, and wind direction on the consequences [98]. Moreover, Hirayama et al. investigated the effects of jet fires, flash fires, and explosions to examine safe distances for HRS due to hydrogen release from dispensers using Hydrogen Risk Assessment Model (HyRAM) software [63]. Li et al. analyze the hydrogen release in a mobile HRS using numerical models, obtained minimum safe distance due to overpressure, and examine the effect parameters such as low ambient wind speed and direction on hydrogen leakage and diffusion [71]. However, such studies remain narrow in focus dealing only with the consequence of incidents rather than the frequencies at which they occur.

The risk-based approach has been extensively applied to examine HRS safe distances, focusing on the probabilistic assessment of incident scenarios and their mitigation measures. For instance, Russo et al. investigated safe distances by conducting Quantitative Risk Assessment (QRA) using HyRAM software on an HRS. They further pointed out mitigation and protection measures to lessen the determined safe distances [85]. Gye et al. conducted QRA on a highly confined urban hydrogen station. The main incident scenarios considered, hydrogen discharge from the filling machine and explosion of the tube trailer, pose unacceptable risks due to low frequency and high consequences. Additional mitigations were suggested, after which risk reduction was down to tenfold, and ALARP region was achieved for individual risk and societal risk, respectively [73].

Yoo et al. analyze liquid and gaseous HRS using QRA, considering rupture of hydrogen storages and tube trailers as the worst incidents. The study indicates that liquid HRS poses less risk than gaseous HRS and suggests additional safe systems necessary for risk reduction [75]. Suzuki et al. conducted a detailed QRA of a new Japanese HRS model to determine the main incident scenario posing significant risk in the vicinity of the HRS station. They identified that the jet fire scenario is the leading risk contributor in all considered risk ranking points within and outside the station. Within the HRS battery limits, risk contours of 10^{-3} and 10^{-4} per year are confined, and risk contours of 10^{-5} and 10^{-6} per year extend outside the HRS. The use of firewalls is an effective risk mitigation measure against Jet fires [56]. Le et al. uses QRA to explore the effect of design metrics on the safety of hydrogen energy storage systems. The study indicates that pressure and hydrogen storage volume significantly affect the system's risk assessment and, subsequently, its risk acceptance criteria, thereby necessitating risk mitigations [104]. Other studies based on safe distances for risk-based approach have been done by [22, 36, 67, 70, 77, 78, 95]. In view of all that has been mentioned so far, acceptable risks levels guide the definition of HRSs safe distances.

At the moment, there is no commercial HRS in Saudi Arabia. Only a pilot scale HRS was commissioned by a joint effort led by Aramco and Air Products company in 2019, located at the latter's premises in Dhahran Techno Valley Science Park, with the capacity to feed 6 Toyota Mirai FCEVs [18]. Additionally, Saudi Arabia is exploring partnerships with companies from Europe and North America to build local manufacturing capabilities of FCEVs [19]. For this reason, risk assessments must be carried out for these stations. In this work, the objective is to conduct a quantitative risk assessment of a hypothetical gaseous HRS case study in Saudi Arabia to determine the safe distances and individual risk and its contours.

3.2 Methodology

The risk assessment framework for hydrogen refueling stations (HRS) is presented in Figure 3-1. The framework comprises several steps. The HRS model is selected and fully defined. Following this, a Hazard Identification (HI) process is conducted, documenting a list of potentially hazardous incidents relevant to the station. Frequency Analysis (FA) is then used to estimate the probabilities and failure rates for each hazardous event. Next, a Consequence Analysis (CA) is performed to determine the extent of damage from explosion and heat radiation in the selected scenarios. Results from both the frequency and consequences analysis stages are integrated to derive the risk levels in terms of risk contours. Scenarios deemed to pose negligible risk are excluded from further analysis. For the remaining scenarios, additional safety measures are implemented, and the risks are reassessed. This iterative process continues until all identified risks are reduced to an insignificant level [58]. This study utilizes GEXCON RISKCURVE (version 12.4.0) software for risk modeling.

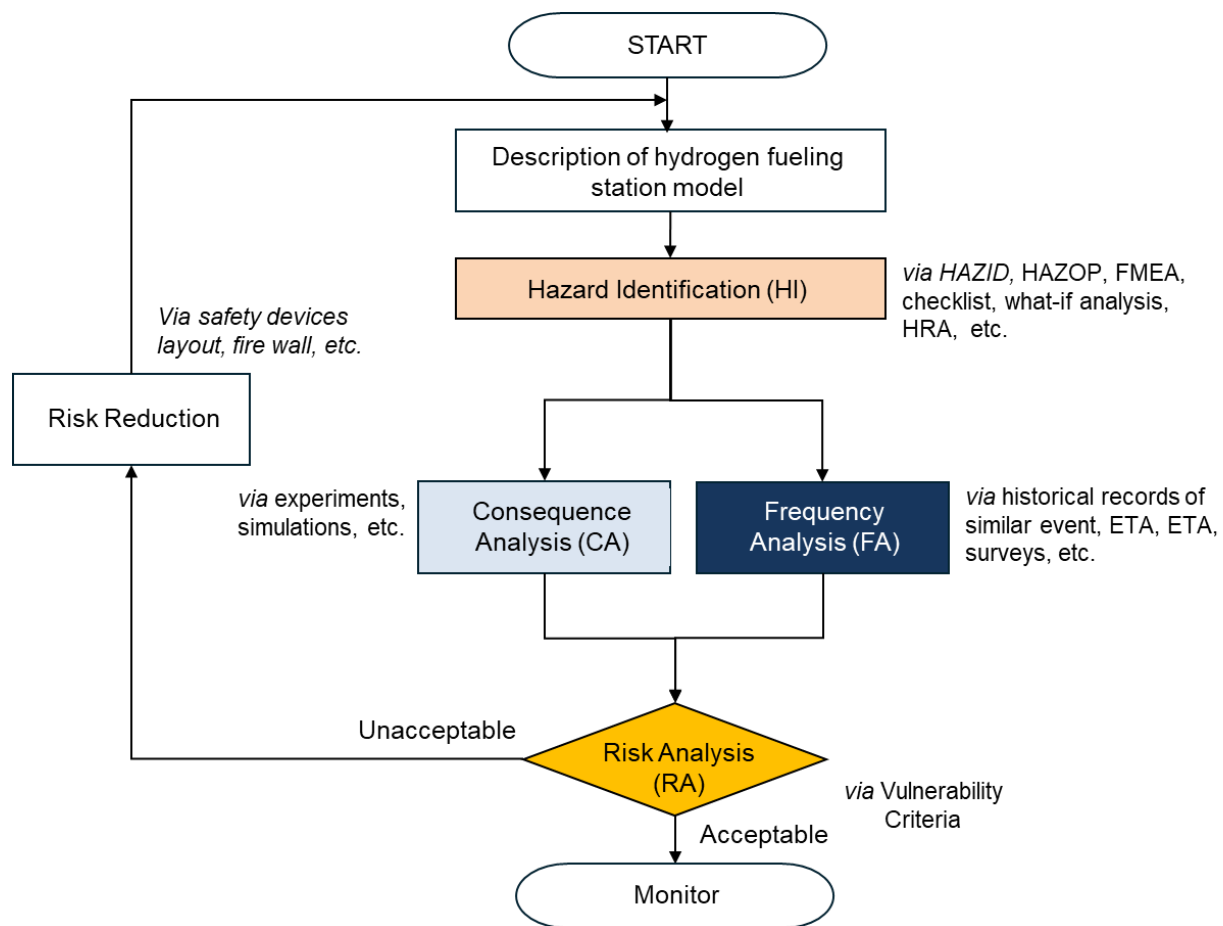


Figure 3-1. Risk Assessment Methodology

3.2.1 Scenario of the Hydrogen Refueling Station

3.2.1.1 HRS Site Selection

This study assumes the future installation of HRSs in the Kingdom, focusing on the densely populated area such as the Eastern Province. While Saudi Arabia's national population density averages 17.43 people/km² as indicated in Figure 3-2 [105, 106], the Eastern province shows significantly higher population concentration—Dammam, for instance, reaches 1500 people/km² as detailed in Table 2.

To simulate realistic scenarios for evaluating hydrogen station safety, an existing gasoline station is selected as a potential HRS site instead of proposing a new facility. This decision is made considering the challenges of acquiring new land in densely populated cities and the practicality of repurposing existing fueling infrastructure. Integrating hydrogen refueling capabilities into existing stations for gasoline or natural gas is a reasonable and efficient approach to adapting infrastructure for future energy demands in such urbanized areas.

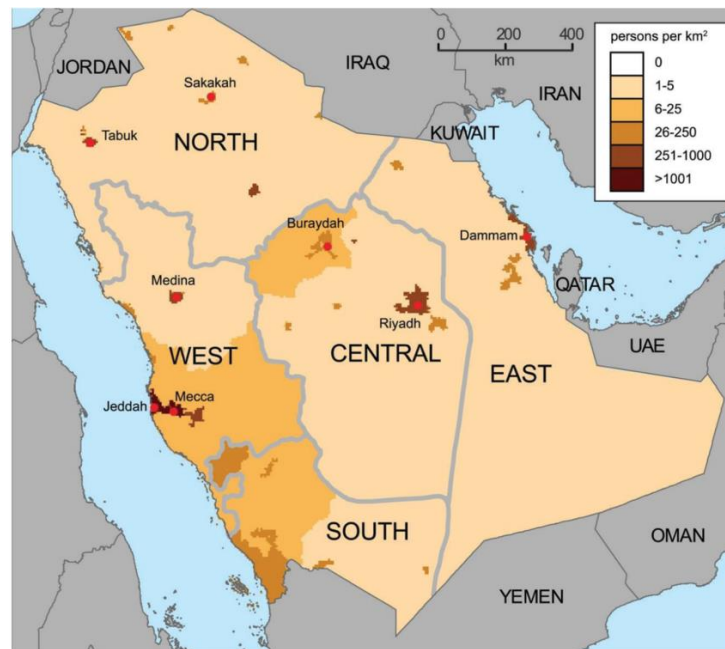


Figure 3-2. Population density of Kingdom of Saudi Arabia, regional divisions [105]

Table 3-2. Population densities for Eastern province cities

Cities	Dammam	Al Khobar	Dhahran	Jubail	KSA
Density (people/km ²)	1500	1387	521	774	17.43

The proposed hypothetical gaseous HRS is proposed at an existing gasoline station located on Prince Sultan Road in Al Danah Ash Shamaliyah of Dharan Eastern Province. The station spans

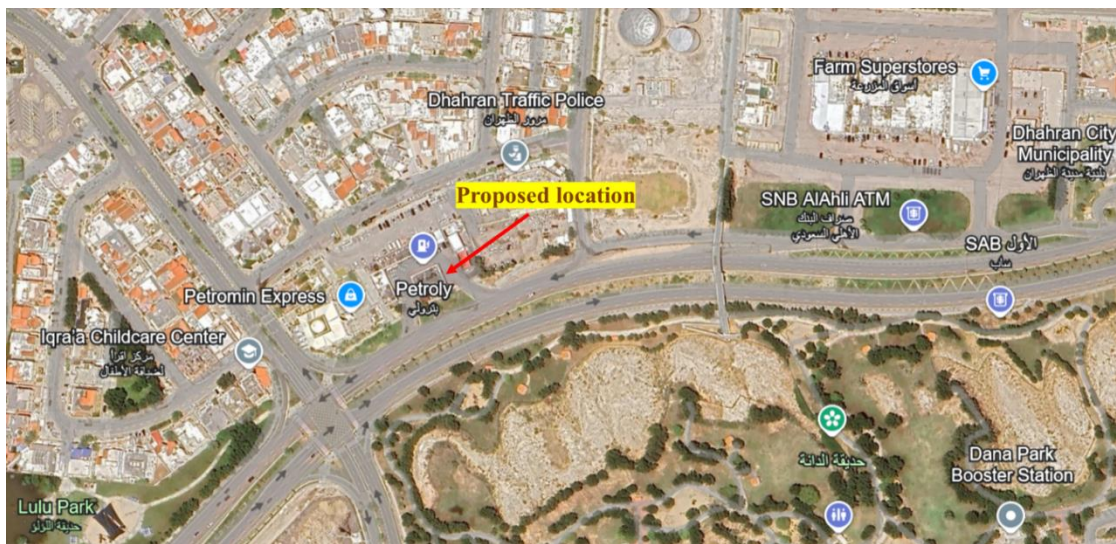
16 m in width and 38 m in length offering space to accommodate HRS infrastructure while ensuring accessibility.

Figure 3-3 a and b illustrate the HRS's geographical location of the proposed HRS and its surroundings. As illustrated in Figure 3-3 b, the proposed HRS site is proximally situated to several critical infrastructures: Automotive service, 44 meters to the West; a child care center, 137 meters to the Southwest; Dhahran Traffic Police Station, 78 meters to the Northeast; residential buildings, 66 meters to the North; a parking lot, 32 meters to the East; and Prince Sultan Road, merely 20 meters to the South of the station.

This placement highlights both the challenges and opportunities of integrating hydrogen refueling capabilities into existing urban infrastructure, requiring a balance between safety considerations and practical constraints.



(a)



(b)

Figure 3-3. Geographical location of the Hydrogen Refueling station

3.2.1.2 Hydrogen Refueling Station Design Scheme

In this case study, a dispenser pressure of 70 MPa is assumed, consistent with standard practices in similar projects. To create a realistic commercial scenario for Saudi Arabia, a Japanese offsite HRS model with a 70 MPa dispensing system, as proposed by Suzuki, Shiota [20], is selected. This model closely matches the layout and scale of the chosen location, as depicted in Figure 3-3(a).

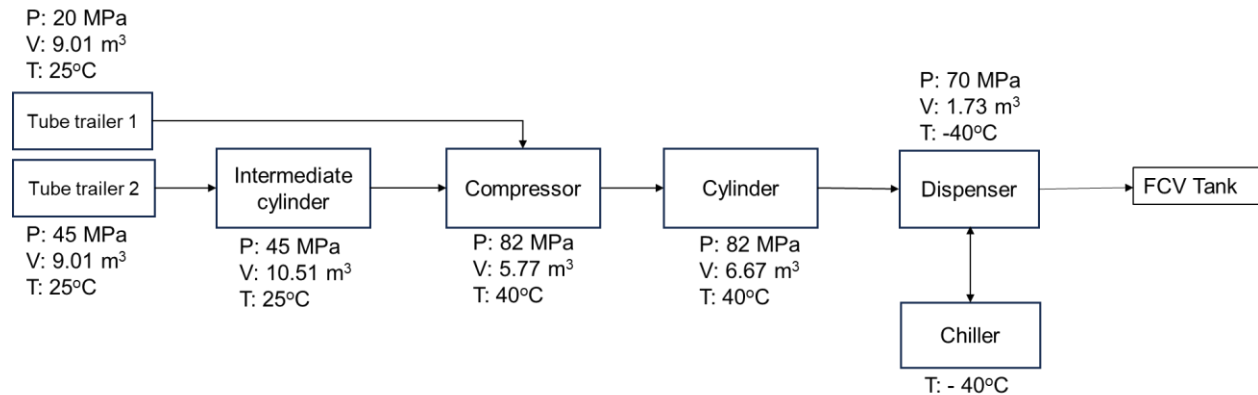


Figure 3-4. General flow scheme of the hydrogen refueling station model

The general flow scheme of the HRS is consist of six nodes, as shown in Table 3-3 below. Error! Not a valid bookmark self-reference. **Table 3-3. Operating conditions for the hydrogen refueling station model**

Node	Sub node	Inventory (m ³)	Temperature (° C)	Pressure (MPa)
Tube Trailer	a	9.00	25	20
	b	9.01	25	20
	c	9.00	25	20
2-inch Pipe	a	788.4	25	0.6
Intermediate cylinder	a	9.00	25	45
	b	10.51	25	45
	c	10.51	25	45
	d	9.00	25	45
Compressor	a	5.77	40	82
	b	5.77	40	82

	c	5.77	40	82
	d	5.77	40	82
	e	5.77	40	82
Cylinder	a	5.77	40	82
	b	6.77	40	82
	c	6.67	40	82
	d	6.67	40	82
Dispenser	a	1.73	25	70

The general flow scheme of the HRS is consist of six nodes, as shown in Table 3-3

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Node	Sub node	Inventory (m3)	Temperature (° C)	Pressure (MPa)
Tube Trailer	a	9.00	25	20
	b	9.01	25	20
	c	9.00	25	20
2-inch Pipe	a	788.4	25	0.6
Intermediate cylinder	a	9.00	25	45
	b	10.51	25	45
	c	10.51	25	45
	d	9.00	25	45
Compressor	a	5.77	40	82
	b	5.77	40	82
	c	5.77	40	82
	d	5.77	40	82
	e	5.77	40	82
Cylinder	a	5.77	40	82
	b	6.77	40	82
	c	6.67	40	82
	d	6.67	40	82
Dispenser	a	1.73	25	70

The process description for this design scheme is as follows:

1. Tube trailer Node: Hydrogen, produced offsite, is transported to the station via tube trailers at pressures of 19.6 MPa and 45 MPa.

2. 2” Pipe Node: Incoming hydrogen undergoes pressure reduction through a 2” pipeline and pressure regulator, decreasing the pressure to 0.6 MPa before entering the compressor.
3. Intermediate Cylinder Node: This node consists of five cylinders that store gaseous hydrogen from the 45 MPa tube trailer for use by the compressor.
4. Compressor Node: Hydrogen from the pipe is pressurized to 82 MPa by a compressor that operates at a constant flow rate of $340\text{Nm}^3/\text{h}$, irrespective of the inlet and outlet pressures.
5. Cylinder Node: The compressed hydrogen at 82 MPa is stored in storage tubes arranged in three-cylinder banks. The hydrogen is then supplied to the dispenser.
6. Dispenser Node: The hydrogen stream heading to the dispenser is cooled to -40°C in an onsite refrigeration unit. Hydrogen at a pressure of 10-80 MPa is charged to the FCV tank from the dispenser, a process that takes approximately 3 minutes.

3.2.1.3 Weather Condition

The study evaluates the safety and operational performance of the proposed HRS under summer and winter conditions typical of the Eastern Province of Saudi Arabia. As presented in Table 3-4, the summer conditions include an ambient temperature of 45°C , a relative humidity of 48%, and a Pasquil stability class F (very stable weather), which indicates highly stable atmospheric conditions that could exacerbate gas dispersion hazards. The winter conditions include an ambient temperature of 15°C , a relative humidity of 78%, and a Pasquil stability class F. The predominant wind direction is eastward, and natural solar radiation levels reach a peak intensity of 6 kW/m^2 for summer and 0.6 kW/m^2 in the winter, based on the average daily maximum solar radiation recorded for the region [25]. These conditions represent the most challenging scenarios the HRS may encounter, ensuring the safety evaluation accounts for worst-case environmental factors.

Table 3-4. Environmental conditions for the proposed HRS location [25].

Parameter	Summer	Winter
Ambient temperature (° C)	45	15
Relative humidity (%)	48	78
Windspeed (m/s)	5	2
Stability class	F	F
Wind direction	E	E

3.2.1.4 Population Data

The number of people in the HRSs and surrounding is detailed in Table 3-5. This involved Administration building, shopping mall, car parking, nearby mosque, and Dhahran cars impound.

Table 3-5. Population data for the HRSs location

Number of people	HRS	Administration office	Shopping mall	Dhahran cars impound	Parking	Road	Mohammad Bin Fahad Mosque
Day	5	45	80	25	70	300	120
Night	5	3	120	40	40	140	95

*The numbers are hypothetical, assumed based on journals such as [76, 108].

3.2.2 Hazard Identification

Hazard identification for the proposed HRS is conducted using two complementary methodologies: Hazard and Operability (HAZOP) studies and Failure Mode Effect and Criticality Analysis (FMEA). These methods are systematically applied to ensure a comprehensive evaluation of potential hazards, focusing on both the design and operational phases of the HRS.

The primary initial event identified through this analysis is loss of containment, specifically the unintended release of compressed hydrogen from process equipment, piping, or associated components. Such events may result from various failure mechanisms, including pipe corrosion, valve malfunction, or filling hose rupture [21]. Identifying these scenarios forms the foundation for subsequent consequence and risk analyses.

In alignment with the methodology proposed by Suzuki, Shiota [21], this study defines six critical nodes for Hazard and Operability (HAZOP) analysis: (1) tube trailer (comprising three parallel subunits: a–c), (2) 2-inch pipe, (3) intermediate cylinder (comprising four parallel subunits: a–d), (4) compressor (comprising five parallel subunits: a–e), (5) cylinder (comprising four parallel subunits: a–d), and (6) dispenser.

FMEA further examines the failure modes of these six key equipment nodes, focusing on their failure frequencies. These frequencies are treated as the rates of initiating incidents (F_I), providing a quantitative basis for evaluating the likelihood of potential failure scenarios critical to hydrogen system safety.

3.2.3 Consequence Analysis

Consequence analysis quantifies the outcomes of identified hazards, focusing on their potential to cause injury, structural damage, and environmental impacts. For hydrogen releases, the two primary consequences considered in this study are jet fires and vapor cloud explosions (VCE) [2, 28]. Jet fire modeling focused on the heat radiation flux, estimating potential harm to nearby individuals and structures based on flame length and thermal intensity. For VCEs, structural or human damages due to overpressure are assessed. To perform this analysis, the GEXCON

EFFECTS software (ver. 12.4.0) is employed to model the thermal and physical effects of these scenarios.

- **Dispersion model for Jet Fire**

The Cook model is employed to model the dispersed heat energy flux from jet fires [112]. Based on the model, the length of the gaseous jet flame (L) and radius of the flame (R_s) at a distance s along the centerline are determined using Eqs (1) and (2). The radiation intensity at a specific point (I) is calculated as a product of the flame emissive power (E_s) and a dimensionless geometric view factor (F), as shown in Eqn (3). Here, Q and ΔH_c denote the quantity of heat and heat of combustion, respectively.

$$L = 0.00326 (Q\Delta H_c)^{0.478} \quad (1)$$

$$R_s = 0.29s[\log_{10}(L/s)]^{0.5} \quad (2)$$

$$I = E_s F \quad (3)$$

- **Explosion Model for VCE**

The Netherlands Organization for Applied Scientific Research (TNO) multi-energy model is adopted to calculate explosion overpressure [113]. The critical determinants for explosion energy in this model are the level of congestion and the amount of flammable material in the vapor cloud. The governing equations for scaled distance (r'), scaled overpressure (P'_s), and peak overpressure (P'_{dyn}) are given below in Eqn (4)- (6). Here, P_s , P_a , P_{dyn} , and r stand for scaled, peak side-on, absolute dynamic overpressure, and distance from the explosion center, respectively.

$$P'_s = \frac{\Delta P_s}{P_a} \quad (4)$$

$$P'_{dyn} = \frac{\Delta P_{dyn}}{P_a} \quad (5)$$

$$r' = \frac{r}{\left(\frac{E}{P_a}\right)^{1/3}} \quad (6)$$

$$E = m\Delta H_{combustion} \quad (7)$$

This model is characterized by ten curves tagged 1-10 obtained from plotting scaled distance versus scaled overpressure. Ten (10) represent the most enormous explosion with the highest confinement/congestion, while 1 represents the weakest explosion with no or lowest level of confinement [113].

- **Criteria for Safe Distances**

The heat radiation and explosion overpressure thresholds leading to casualties were established in Table 3-6 below according to the purple book [114].

Table 3-6. Thermal Radiation and Explosion overpressure vulnerabilities[114].

Hazard/Exposure scenario	Threshold level	Probability of fatality assumed (%)	
		Indoor	Outdoor
Jet fire, spray or pool fire	9 kW/m ²	-	10
	37.5 kW/m ²	0	100
Explosion	< 0.1 Barg	0	0
	> 0.2 - 0.3 Barg	2.5	0
	> 0.3 Barg	100	100

3.2.4 Frequency Analysis

Event frequency analysis is related to the analysis of initial failure frequency of components leakage and the frequency of incidents such as fire, explosions, and other accidents that resulted from the leakage [70].

This work adopted the initial failure frequencies of component developed by HyRAM because the program was developed mainly for hydrogen systems [115]. They reported frequency data for nine components, including cylinders, filters, compressors, flanges, hoses, joints, valves, and instruments. Various components leaks were classified based on the size of the leakage hole, which included small-hole leakage, medium-hole leakage, large-hole leakage, and complete rupture corresponding to 0.01%, 0.1%, 1%, 10%, 100%, respectively of the pipeline flow area. For conservatism, releases from equivalent diameter of circular hole are assumed, and leak size denotes diameter of the circular hole [115].

The frequency of final incidents can be estimated using one of the frequency analysis techniques. Event Tree Analysis (ETA) is adopted in this study because it is effective approach to explore an event's occurrence, it is immediately represented and can be probabilistically described [116]. The ETA developed by Groth and Hecht [117] shown in Figure 3-5 is employed in this study. The ETA specifies the various events that occur after hydrogen release. Once a leak occurs, it is detected and isolated resulting in safe gas dispersion. If not, immediate ignition may occur leading to jet fire. When immediate ignition does not occur, ignition may be delayed, causing explosion as the most dominant occurring event. If there is no ignition at all, then safe gas dispersion will occur at the end.

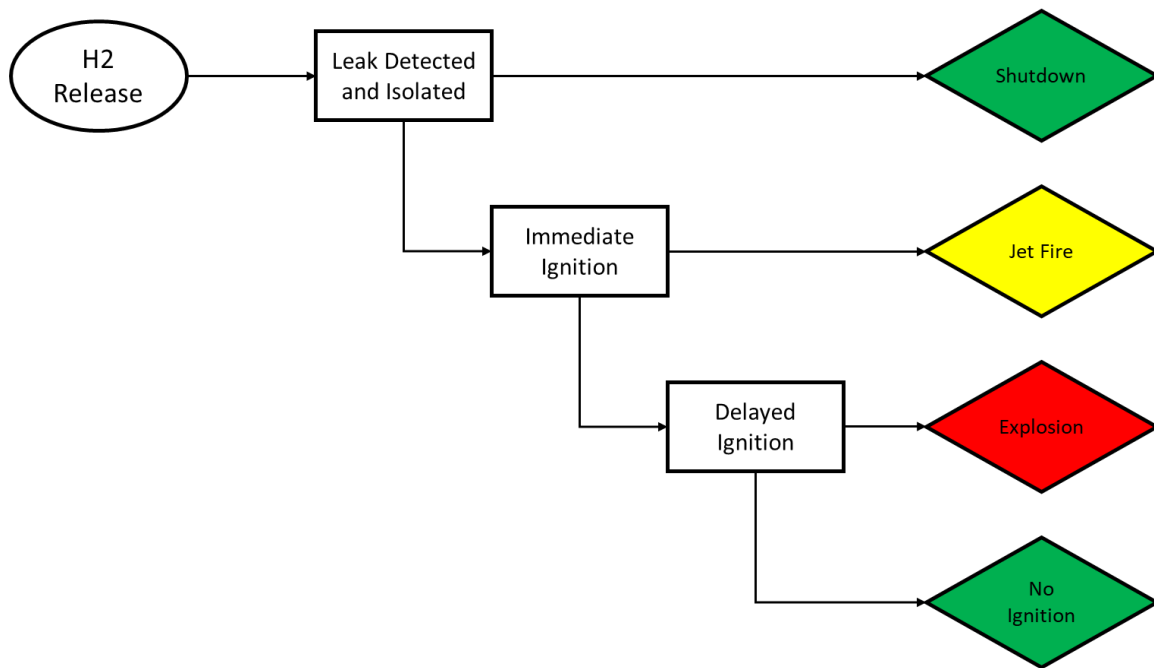


Figure 3-5. Event Tree Diagram for the HRS accident consequences [117]

From the ETA shown in Table 3-7, the frequency of gaseous hydrogen release was calculated and shown in Table 3-8. This study utilizes hydrogen ignition probabilities from HyRAM presented in Table 3-7 which presented probabilities of delayed and immediate ignition varying with mass flowrate of hydrogen releases (calculated from discharge modeling) [118].

Table 3-7. Probability of hydrogen ignition [118]

Leak flowrate (kg/s)	Probability of delayed ignition	Probability of Immediate ignition
< 0.125	0.004	0.008
0.125 - 6.250	0.027	0.053
> 6.250	0.12	0.23

Hydrogen leakage detection and isolation failure probability is related to the probability of failure of fire and gas detection capacity, required by NFPA 2 [109]. There is data unavailability for gas and flame detectors, but fire and gas detection system correspond to safety integrity (SIL) level 2

which has an unavailability less than 0.01. Groth, LaChance [109]. Therefore, a value of 10^{-2} probability of leak detection and isolation is assigned in the present study.

Table 3-8 presents the calculated initial failure frequencies using parts count for each component identified from the nodes and sub nodes in the model P&ID and the outcome frequency for each scenario in the HRS.

Table 3-8. Leak sizes, release rates, and components failure frequencies for each node.

Node	Component	Leak type	Leakage size (mm)	Release rate (kg/s)	Incident release frequency (yr ⁻¹)	Incident outcome frequency (yr ⁻¹)
Tube Trailer	a	Very small leak	0.063	0.0000364	2.50E-02	2.00E-06
		Minor leak	0.2	0.000367	3.50E-03	9.94E-07
		Medium leak	0.63	0.00364	9.86E-04	2.80E-07
		Large leak	2	0.0367	5.32E-04	1.39E-07
		Rupture	6.3	0.364	2.65E-04	7.89E-08
	b	Very small leak	0.063	0.0000364	3.64E-02	3.91E-08
		Minor leak	0.2	0.000367	5.09E-03	4.25E-08
		Medium leak	0.63	0.00364	1.49E-03	2.11E-08
		Large leak	2	0.0367	6.67E-04	1.40E-07
		Rupture	6.3	0.364	3.57E-04	6.78E-08
	c	Very small leak	0.063	0.0000364	2.95E-02	2.92E-06
		Minor leak	0.2	0.000367	3.86E-03	1.45E-06
		Medium leak	0.63	0.00364	1.46E-03	4.08E-07
		Large leak	2	0.0367	3.04E-04	2.02E-07
		Rupture	6.3	0.364	1.59E-04	1.19E-07
2 in Pipe	a	Very small leak	0.505	0.0000742	9.91E-01	5.92E-08
		Minor leak	1.6	0.000745	6.45E-02	5.34E-08
		Medium leak	5.05	0.00742	3.41E-02	2.65E-08
		Large leak	16	0.0745	1.19E-03	1.89E-07
		Rupture	50.5	0.742	5.63E-04	9.12E-08
Intermediate cylinders	a	Very small leak	0.063	0.000077	7.99E-02	2.36E-06
		Minor leak	0.2	0.000776	2.18E-02	1.17E-06
		Medium leak	0.63	0.0077	1.61E-02	3.09E-07
		Large leak	2	0.0756	7.58E-03	1.53E-07
		Rupture	6.3	0.77	7.32E-03	1.17E-07
	b	Very small leak	0.063	0.000077	8.86E-02	5.79E-08

Node	Component	Leak type	Leakage size (mm)	Release rate (kg/s)	Incident release frequency (yr ⁻¹)	Incident outcome frequency (yr ⁻¹)
		Minor leak	0.2	0.000776	1.19E-02	2.43E-08
		Medium leak	0.63	0.0077	3.18E-03	1.20E-08
		Large leak	2	0.0776	1.12E-03	8.40E-08
		Rupture	6.3	0.77	5.58E-04	4.05E-08
	c	Very small leak	0.063	0.000077	1.14E-02	7.93E-05
		Minor leak	0.2	0.000776	1.50E-03	3.93E-05
		Medium leak	0.63	0.0077	1.99E-04	5.16E-06
		Large leak	2	0.0776	8.31E-05	2.56E-06
		Rupture	6.3	0.77	3.02E-05	2.73E-06
	d	Very small leak	0.063	0.000077	5.71E-03	1.35E-06
		Minor leak	0.2	0.000776	7.51E-04	9.53E-08
		Medium leak	0.63	0.0077	9.96E-05	4.73E-08
		Large leak	2	0.0756	4.15E-05	2.99E-07
		Rupture	6.3	0.77	1.50E-05	1.44E-07
Compressor	a	Very small leak	0.063	0.000127	7.99E-02	6.39E-06
		Minor leak	0.2	0.00128	2.18E-02	3.17E-06
		Medium leak	0.63	0.0127	1.61E-02	1.75E-06
		Large leak	2	0.127	7.58E-03	8.66E-07
		Rupture	6.3	1.115	7.32E-03	1.29E-06
	b	Very small leak	0.063	0.000127	2.46E-01	6.37E-07
		Minor leak	0.2	0.00128	3.15E-02	6.07E-07
		Medium leak	0.63	0.0127	1.16E-02	3.01E-07
		Large leak	2	0.127	1.86E-03	3.88E-06
		Rupture	6.3	1.115	9.70E-04	1.87E-06
	c	Very small leak	0.063	0.000127	6.26E-02	7.09E-06
		Minor leak	0.2	0.00128	1.96E-02	3.52E-06
		Medium leak	0.63	0.0127	1.56E-02	9.53E-07
		Large leak	2	0.127	7.44E-03	4.73E-07
		Rupture	6.3	1.115	7.26E-03	2.54E-07
	d	Very small leak	0.063	0.000127	1.14E-02	1.26E-07
		Minor leak	0.2	0.00128	1.50E-03	8.92E-08
		Medium leak	0.63	0.0127	1.98E-04	4.43E-08
		Large leak	2	0.127	8.26E-05	2.96E-07
		Rupture	6.3	1.115	2.98E-05	1.43E-07
	e	Very small leak	0.063	0.000127	1.41E-04	9.14E-07

Node	Component	Leak type	Leakage size (mm)	Release rate (kg/s)	Incident release frequency (yr ⁻¹)	Incident outcome frequency (yr ⁻¹)
		Minor leak	0.2	0.00128	7.12E-06	4.53E-07
		Medium leak	0.63	0.0127	1.56E-04	1.20E-07
		Large leak	2	0.127	1.39E-05	5.96E-08
		Rupture	6.3	1.115	1.24E-05	1.60E-08
Cylinders	a	Very small leak	0.063	0.000127	4.12E-02	7.91E-09
		Minor leak	0.2	0.00128	5.37E-03	6.65E-09
		Medium leak	0.63	0.0127	1.89E-03	3.30E-09
		Large leak	2	0.128	4.07E-04	1.60E-08
		Rupture	6.3	1.115	2.07E-04	7.71E-09
	b	Very small leak	0.063	0.000127	6.52E-02	4.57E-07
		Minor leak	0.2	0.00128	8.86E-03	2.27E-07
		Medium leak	0.63	0.0127	2.22E-03	6.01E-08
		Large leak	2	0.128	8.96E-04	2.98E-08
		Rupture	6.3	1.115	4.51E-04	7.97E-09
	c	Very small leak	0.063	0.000127	1.32E-06	3.95E-09
		Minor leak	0.2	0.00128	6.86E-07	3.32E-09
		Medium leak	0.63	0.0127	2.70E-07	1.65E-09
		Large leak	2	0.128	1.37E-07	7.97E-09
		Rupture	6.3	1.115	9.65E-08	3.84E-09
	d	Very small leak	0.063	0.000127	4.03E-02	6.39E-06
		Minor leak	0.2	0.00128	5.28E-03	3.17E-06
		Medium leak	0.63	0.0127	1.01E-03	1.75E-06
		Large leak	2	0.128	3.21E-04	8.66E-07
		Rupture	6.3	1.115	1.32E-04	1.29E-06
Dispenser	a	Very small leak	0.063	0.000127	1.35E-01	6.37E-07
		Minor leak	0.2	0.00128	4.06E-02	4.02E-06
		Medium leak	0.63	0.0127	3.37E-02	1.94E-06
		Large leak	2	0.128	1.55E-02	3.88E-06
		Rupture	6.3	1.12	1.49E-02	1.87E-06

3.2.5 Probability of Fatality

This process involves utilizing probabilistic or deterministic models such as probit equations [104, 113, 119] to determine the vulnerability of targets to radiative heat flux, overpressure, and toxic effects. The Eqn (7) predicts the probability of fatality resulting from an accident:

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{P_r-5} e^{-s^2/2} ds. \quad (8)$$

P_r represents the probability unit (Probit) based on a dose of harmful load recipient category, as defined by Eqn (8). Here, a and b represent empirical constants that reflect the hazardous specifics of harmful load and the susceptibility of the recipients to the load, while D represents the dose of the load (for radiation or overpressures) exposed over a given time.

$$P_r = a + b \ln(D) \quad (9)$$

The dose for jet fire radiation is equivalent to the product of time and the quantity of heat raised to the power of 4/3. Therefore, probit equations for jet fire and explosion are given as Eqs (9) and (10):

$$P_r = a + b \ln(I \times Q^{4/3}) \quad (10)$$

$$P_r = a + b \ln(P_o) \quad (11)$$

The following Table 3-9 provides the empirical constants for radiation heat flux and overpressures based on the purple book.

Table 3-9. Probit Equations

Damage	Empirical constants		Impact
	a	b	
Heat flux	- 39.83	3.0186	1 st degree burn
	-43.14	3.0186	2 nd degree burn
	-36.38	2.56	Death
Overpressure	- 77.1	6.91	Death (pulmonary hemorrhage)
	-15.6	1.93	Ruptured eardrum
	-23.8	6.91	Damage of structure
	-18.1	2.79	Damage of glass

3.2.6 Risk Estimation

3.2.6.1 Individual Risks

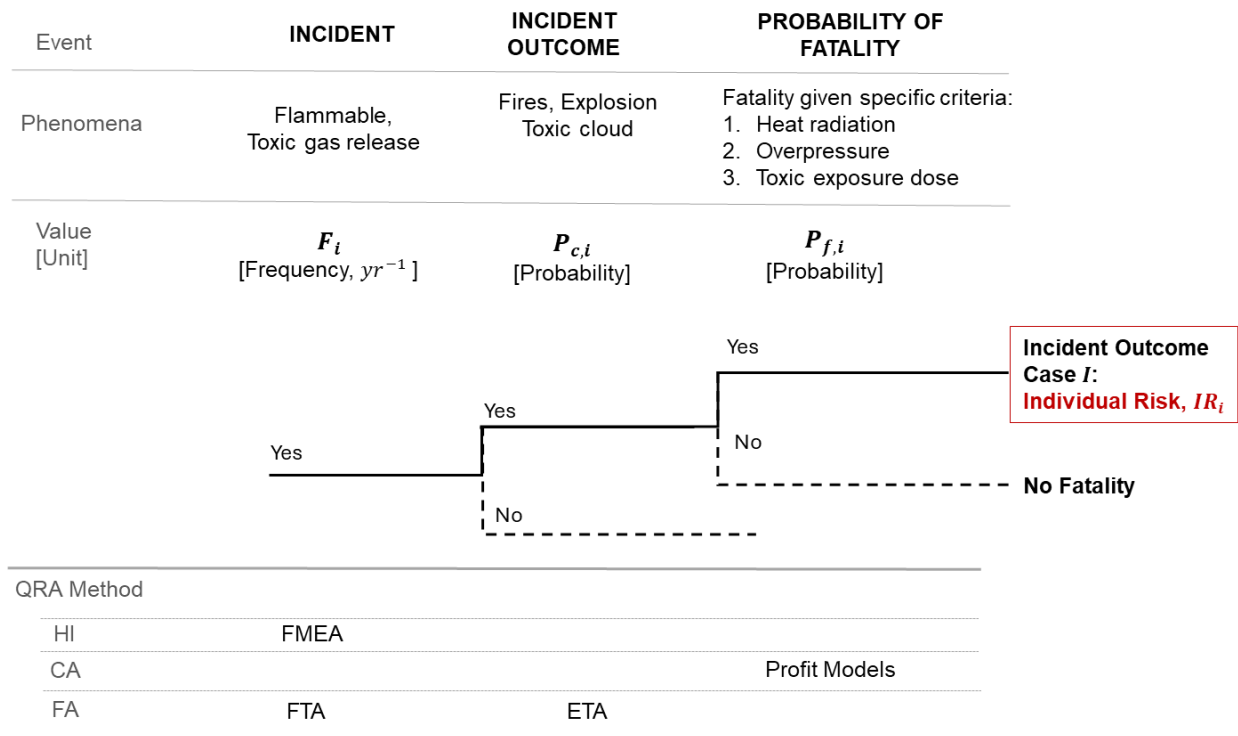


Figure 3-6. Integrated Framework for IR Calculation Using Multiple QRA Methods [2].

Individual Risk (IR) quantifies the probability of fatality at a specific location due to hazardous events. As shown in Figure 3-6. Integrated Framework for IR Calculation Using Multiple QRA Methods [2]. Figure 3-6, it is calculated by integrating the frequency of events defined by incident scenarios with the probability of these events resulting in fatalities [17]. Mathematically, IR is expressed as Eq (12).

$$IR_{x,y} = \sum_{i=1}^n IR_{x,y,i} \quad (12)$$

where $IR_{x,y}$ is the total individual risk of fatality at geographical location x,y [chances of fatality/yr], $IR_{x,y,i}$ is the individual risk of fatality at geographical location x,y , from incident outcome case i [chances of fatality/yr.], and n is the total number of incident outcome cases considered in the analysis.

The inputs to Eq. (12) are obtained from

$$IR_{x,y,i} = f_i \times P_{f,i} \quad (13)$$

where f_i is the frequency of incident outcome case i [yr^{-1}] and $P_{f,i}$ is the probability that incident outcome case i will result in a fatality at location x,y , from the consequence and effect models.

The inputs to Eq. (2) are obtained from,

$$f_i = F_I \times P_{O,i} \times P_{OC,i} \quad (14)$$

where F_I is the frequency of incident I , which has incident outcome case i as one of its incident outcome cases [yr^{-1}], $P_{O,i}$ is the probability that the incident outcome, having i as one of its incident outcome cases, occurs, given that incident I has occurred, and $P_{OC,i}$ is the probability that

incident outcome case i occurs given the occurrence of the precursor incident I and the incident outcome corresponding to the outcome case i .

3.2.6.2 Societal Risks

To estimate the risk associated with the public, a group risk or societal risk (SR) can be determined in the form of FN curve, representing frequency (F) on a logarithmic scale on y axis and the number of victims (N) on x axis. In a similar manner to individual risk, the societal risk can be estimated by the equation 14 below to express the number of victims (N) affected by each incident i [74],

$$N_i = \sum_{x,y} P_{x,y} P_{f,i} \quad (15)$$

where $P_{x,y}$ is the number of people present at the location (x,y) and the population applied in estimating societal risk has been presented in **Error! Reference source not found..**

As Low As Reasonably Practicable (ALARP) concept is used to select the SR risk criteria. In this approach, the FN curve is divided into three distinct regions: acceptable risk, allowable risk (ALARP), and unacceptable risk. Calculated SR falling within the acceptable risk region requires no further mitigation. Risks within the ALARP region should be reduced preferably, while risks in the unacceptable region are acceptable under any circumstances. The maximum and minimum acceptable risk threshold for a probability of one fatality is taken as 10^{-3} yr^{-1} and 10^{-5} yr^{-1} respectively, based on Netherland's ALARP criteria, where N is the number of victims [70, 120].

3.3 Results and Discussion

3.3.1 Safe Distances Estimation using Consequence-Based Analysis

Safe distances for the hypothetical HRS in Saudi Arabia were estimated using GEXCON EFFECTS software, focusing on two primary scenarios: jet fires and VCEs. These estimations were conducted under two environmental conditions (average summer and winter ambient conditions) to explore the effect of varying environmental effects typical of Saudi Arabia's Eastern Province, as detailed in the methodology. Based on the consequence calculations, hazardous distances were determined for all incident scenarios for people and equipment and summarized in Table 3-12 and Table 3-12. In these tables, a “0” indicates that the overpressure peak for those incidents does not meet the specified injury criteria, while a “-” symbol denotes no safe distance requirement for that scenario.

As shown in the tables, hazardous distances are dependent on the size of the leak hole. Very small leaks result in shorter hazardous distances, which increase as the hole size increases from minor, medium to large, reaching the largest distance in the case of rupture scenario. The hazardous distances for individuals exposed to jet fire thermal radiation and explosion overpressure are observed to be larger than those for equipment. Additionally, distances resulting from VCEs tend to be larger than those associated with jet fire scenarios as demonstrated in the tables. For very small leaks, no VCE occurred for all incidents. Table 3-10 and Table 3-11 summarizes the safe distances for personnel and equipment at each node for both conditions.

Table 3-10. Safe distances for HRS Nodes based on Jet Fire and VCE Scenarios for Summer

Node	Distances for People (m)		Distances for Equipment (m)	
	Jet fire	VCE	Jet fire	VCE

Tube trailer	20.0	108.0	18.0	43.0
2-inch pipe	31.2	137.0	27.5	55.0
Int. cylinder	27.4	134.3	23.7	54.0
Compressor	34.1	158.0	29.4	63.5
Cylinder	33.5	157.0	29.0	63.2
Dispenser	35.0	151.1	30.4	60.8

Table 3-11. Safe Distances for HRS Nodes Based on Jet Fire and VCE Scenarios for Winter

Node	Distances for People [m]		Distances for Equipment [m]	
	Jet Fire	VCE	Jet Fire	VCE
Tube trailer	20.0	108.0	17.0	43.0
2-inch pipe	30.0	137.0	26.0	55.0
Intermediate cylinder	26.5	134.3	22.3	54.0
Compressor	32.3	158.0	27.8	63.5
Cylinder	32.3	157.0	27.9	63.2
Dispenser	33.8	151.1	29.2	60.8

The results reveal significant variability in safe distances across the six nodes, reflecting differences in the severity of potential hazards. For jet fire scenarios in summer conditions, the dispenser node required the greatest separation distance for personnel (35 m) and equipment (30.4 m) likely due to its direct involvement in fueling operations, which increases the risk of flame impingement. The safe distances due to winter conditions for jet fire scenarios for the dispenser node are 33.8 m and 29.2 m for personnel and equipment respectively. The values are slightly lower than for summer conditions.

For VCE scenarios, harm zones were considerably larger than those for jet fires. The compressor node had the most extensive safe distance requirements, with 158 meters for personnel and 63.5 meters for equipment. This is consistent with the high-pressure conditions and large hydrogen

volumes managed by the compressor. Similarly, the cylinder and dispenser nodes required significant separation distances due to their potential for large-scale explosions. The VCE scenarios are not affected by varying weather conditions because the safe distances were observed to be the same for both summer and winter conditions as shown in Table 3-10 and Table 3-11.

The analysis underscores the critical need for stringent safety measures and strategic placement of high-risk nodes like compressors and dispensers within HRS layouts. VCE scenarios generated substantially larger harm zones than jet fires, especially for nodes such as compressors and cylinders, emphasizing the importance of explosion risk mitigation. Additionally, the distances required for equipment were consistently shorter than those for personnel, reflecting the higher vulnerability of humans to thermal and overpressure effects.

These results provide essential guidelines for the design and operation of HRS facilities. High-risk nodes should be positioned at sufficient distances from critical infrastructure and areas of high personnel density. Mitigation strategies, such as firewalls, explosion venting, and advanced detection systems, are imperative for nodes with extensive harm zones. Furthermore, the large harm zones identified for personnel safety necessitate robust evacuation protocols and effective emergency response measures, particularly in densely populated areas.

As indicated by the analysis, hazardous distances increase with leak size, progressing from very small to large leaks and reaching their maximum in rupture scenarios. VCEs generally produced larger harm zones than jet fire scenarios. For very small leaks, no VCEs occurred across the analyzed incidents. The maximum hazardous distances for personnel were 35 m for jet fire radiation and 158 m for VCE overpressure, both associated with compressor rupture scenarios. For equipment, these values were 30.4 m for jet fire radiation and 63.5 m for VCE overpressure.

Table 3-12. Calculated hazardous distances for HRS Case Study (Summer Season)

Node	Sub node	Incident	Leak size (mm)	Event type	Harm distance (m)			
					People		Equipment	
					Heat radiation (9 kW/m ²)	Overpressure (7 kPa)	Heat radiation (37.5 kW/m ²)	Overpressure (20 kPa)
Tube trailer	a	very small leak	0.063	Jet Fire	1.02	-	0.895	-
				VCE	-	0	-	0
		Minor leak	0.2	Jet Fire	1.02	-	0.895	-
				VCE	-	0	-	0
		Medium leak	0.63	Jet Fire	1.02	-	0.895	-
				VCE	-	0	-	0
		Large leak	2	Jet Fire	7.15	-	6.14	-
				VCE	-	22	-	7
		Rupture	6.3	Jet Fire	20	-	18	-
				VCE	-	108	-	43
2-inch Pipe	a	very small leak	0.505	Jet Fire	1.02	-	0.895	-
				VCE	-	11.48	-	3.75
		Minor leak	1.6	Jet Fire	1.635	-	1.51	-
				VCE	-	24.75	-	8.1
		Medium Leak	5.05	Jet Fire	3.27	-	3.83	-
				VCE	-	120	-	48.1
		Large leak	16	Jet Fire	11	-	9.52	-
				VCE	-	28	-	9
		Rupture	50.5	Jet Fire	31.2	-	27.1	-
				VCE	-	137	-	55
Intermediate cylinders	a	very small leak	0.063	Jet Fire	1.02	-	0.895	-
				VCE	-	0	-	0
		Minor leak	0.2	Jet Fire	1.62	-	1.47	-
				VCE	-	4	-	0
		Medium leak	0.63	Jet Fire	3.6	-	3.2	-

Node	Sub node	Incident	Leak size (mm)	Event type	Harm distance (m)			
					People		Equipment	
					Heat radiation (9 kW/m ²)	Overpressure (7 kPa)	Heat radiation (37.5 kW/m ²)	Overpressure (20 kPa)
		Large leak	2	VCE	-	13	-	4
				Jet Fire	9.8	-	8.44	-
		Rupture	6.3	VCE	-	28	-	9
				Jet Fire	27.4	-	23.7	-
				VCE	-	134.3	-	54
Main Compressor	a	very small leak	0.063	Jet Fire	1.02	-	0.895	-
				VCE	-	0	-	0
		Minor leak	0.2	Jet Fire	1.64	-	1.51	-
				VCE	-	4	-	0
		Medium Leak	0.63	Jet Fire	4.36	-	4	-
				VCE	-	15.8	-	5.15
		Large leak	2	Jet Fire	12.3	-	10.58	-
				VCE	-	33.5	-	11
Cylinder	a	very small leak	0.063	Jet Fire	1.02	-	0.895	-
				VCE	-	0	-	0
		Minor leak	0.2	Jet Fire	1.64	-	1.51	-
				VCE	-	4	-	0
		Medium leak	0.63	Jet Fire	1.02	-	0.895	-
				VCE	-	0	-	0
		Large leak	0.2	Jet Fire	12.48	-	10.78	-
				VCE	-	34	-	11
Dispenser	a	very small leak	0.063	Jet Fire	33.45	-	29	-
				VCE	-	157	-	63.2
				Jet Fire	1.02	-	0.895	-

Node	Sub node	Incident	Leak size (mm)	Event type	Harm distance (m)			
					People		Equipment	
					Heat radiation (9 kW/m ²)	Overpressure (7 kPa)	Heat radiation (37.5 kW/m ²)	Overpressure (20 kPa)
				VCE	-	0	-	0
		Minor leak	0.2	Jet Fire	1.64	-	1.51	-
				VCE	-	4.05	-	0
		Medium leak	0.63	Jet fire	4.51	-	4	-
				VCE	-	15	-	4.9
		Large leak	2	Jet fire	12.4	-	10.72	-
				VCE	-	31.4	-	10.25
		Rupture	6.3	Jet fire	35	-	30.4	-
				VCE	-	151.1	-	60.8

Table 3-13. Calculated Safe Distances for HRS Case Study (Winter Season)

Node	Sub node	Incident	Leak size (mm)	Event type	Harm distance (m)			
					People		Equipment	
					Heat radiation (9 kW/m ²)	Overpressure (7 kPa)	Heat radiation (37.5 kW/m ²)	Overpressure (20 kPa)
Tube trailer	a	very small leak	0.063	Jet Fire	1.02	-	0.895	-
				VCE	-	0	-	0
		Minor leak	0.2	Jet Fire	1.31	-	1.17	-
				VCE	-	2.78	-	0
		Medium leak	0.63	Jet Fire	1.31	-	1.17	-
				VCE	-	4.82	-	1.57

Node	Sub node	Incident	Leak size (mm)	Event type	Harm distance (m)			
					People		Equipment	
					Heat radiation (9 kW/m ²)	Overpressure (7 kPa)	Heat radiation (37.5 kW/m ²)	Overpressure (20 kPa)
		Large leak	2	Jet Fire	7	-	6	-
				VCE	-	22	-	7
		Rupture	6.3	Jet Fire	20	-	17	-
				VCE	-	108	-	43
2-inch Pipe	a	very small leak	0.505	Jet Fire	1.02	-	0.895	-
				VCE	-	7	-	0
		Minor leak	1.6	Jet Fire	1.635	-	1.51	-
				VCE	-	14	-	0
		Medium Leak	5.05	Jet Fire	3.66	-	3.22	-
				VCE	-	53	-	17
		Large leak	16	Jet Fire	10.6	-	9.14	-
				VCE	-	28	-	9
		Rupture	50.5	Jet Fire	30	-	26	-
				VCE	-	137	-	55
Intermediate cylinders	a	very small leak	0.063	Jet Fire	1.02	-	0.895	-
				VCE	-	0	-	0
		Minor leak	0.2	Jet Fire	1.33	-	1.2	-
				VCE	-	3.56	-	0
		Medium leak	0.63	Jet Fire	3.3	-	3.1	-
				VCE	-	13	-	4
		Large leak	2	Jet Fire	9.44	-	8.12	-
				VCE	-	28	-	9
		Rupture	6.3	Jet Fire	26.45	-	22.27	-
				VCE	-	-	-	-

Node	Sub node	Incident	Leak size (mm)	Event type	Harm distance (m)			
					People		Equipment	
					Heat radiation (9 kW/m ²)	Overpressure (7 kPa)	Heat radiation (37.5 kW/m ²)	Overpressure (20 kPa)
				VCE	-	134.3	-	54
Main Compressor	a	very small leak	0.063	Jet Fire	1.02	-	0.895	-
				VCE	-	0	-	0
		Minor leak	0.2	Jet Fire	1.64	-	1.51	-
				VCE	-	4	-	0
		Medium Leak	0.63	Jet Fire	4.07	-	3.59	-
				VCE	-	15.8	-	5.15
		Large leak	2	Jet Fire	11.63	-	9.98	-
				VCE	-	33.5	-	11
		Rupture	6.3	Jet Fire	32.26	-	27.82	-
				VCE	-	158	-	63.54
Cylinder	a	very small leak	0.063	Jet Fire	1.02	-	0.895	-
				VCE	-	0	-	0
		Minor leak	0.2	Jet Fire	1.64	-	1.51	-
				VCE	-	4	-	0
		Medium leak	0.63	Jet Fire	4.1	-	3.59	-
				VCE	-	16	-	5
		Large leak	0.2	Jet Fire	11.96	-	10.3	-
				VCE	-	34	-	11
		Rupture	0.63	Jet Fire	32.33	-	27.88	-
				VCE	-	157	-	63.2
Dispenser	a	very small leak	0.063	Jet Fire	1.02	-	0.895	-
				VCE	-	0	-	0

Node	Sub node	Incident	Leak size (mm)	Event type	Harm distance (m)			
					People		Equipment	
					Heat radiation (9 kW/m ²)	Overpressure (7 kPa)	Heat radiation (37.5 kW/m ²)	Overpressure (20 kPa)
		Minor leak	0.2	Jet Fire	1.64	-	1.51	-
				VCE	-	4.05	-	0
		Medium leak	0.63	Jet fire	4.3	-	3.65	-
				VCE	-	15	-	4.9
		Large leak	2	Jet fire	11.96	-	10.29	-
				VCE	-	31.4	-	10.25
		Rupture	6.3	Jet fire	33.84	-	29.2	-
				VCE	-	151.1	-	60.8

3.3.2 Individual Risk Results

The risk-based analysis of the HRS was conducted using GEXCON RISKCURVE software, which generated Individual risk (IR) contours. Individual risk for an HRS represents the chances that an individual is killed in the station while being present at the site every day for the whole year, irrespective of the time spent at the site. Figure 3-7 presents the HRS's individual risk iso-contour signifying the total sum of risk from each of the six nodes (Tube trailer, 2-inch pipe, intermediate cylinder, compressor, cylinder, and dispenser). It can be observed that all the risk contours 10^{-5} , 10^{-6} , 10^{-7} , 10^{-8} , and 10^{-9} yr^{-1} covered the entire HRS. The 10^{-5} yr^{-1} contour covers the whole station, shopping mall, and some parts of the parking area indicating that the individuals inside the contours are exposed to that value. Additionally, some locations including Dhahran car impound, parking, and the highway are contained within the 10^{-6} yr^{-1} contour which is not acceptable according to the risk acceptance criteria of 10^{-6} yr^{-1} .

Moreover, the contribution of risk to the station from each node is analyzed by adding risk ranking point at any location within the HRS. Table 3-14 below presents risk values and percent contribution for the six 6 nodes at the risk ranking point. The node with the highest contribution to the individual risk is the compressor node with a risk value of $3.78\text{E-}06 \text{ yr}^{-1}$ contributing 35.85% of the total IR, then the intermediate cylinder node follows with a risk value of $3.03\text{E-}06 \text{ yr}^{-1}$ contributing 28.65% of the total IR. The high risk can presumably be due to the high chance of hydrogen releases due to high pressures. Among the nodes, the 2-inch pipe contributes the lowest with a risk value of $9.12\text{E-}08 \text{ yr}^{-1}$ contributing 0.86% of the total IR. Because the primary risk contributors are the compressor and intermediate cylinder nodes, safety measures should be given prominence to this equipment.



Figure 3-7. Individual risk contours for the HRS

Furthermore, it was deduced that the primary accident scenario was a vapor cloud explosion (VCE) for the rupture scenario from all the involved components. Again, taking the risk ranking point for instance, VCE constitutes $1.01\text{E-}06\text{yr}^{-1}$ with a contribution of 95.93% of the total IR for the risk ranking point. While the contribution from other nonsignificant scenarios (jet fire) was around 4.07% with a risk of $4.31\text{E-}07\text{yr}^{-1}$. Generally, the initial failure frequency of equipment has a great influence on individual risk estimation. Therefore, the analysis reflects that compressor and intermediate cylinder rupture scenario as the highest contributor to the risk, followed by significant risks from dispensers and cylinder.

Table 3-14. Individual risk contribution from each node

Node	Contribution (%)	IR value (yr⁻¹)
Tube trailer	3.03	3.20E-07
2-inch pipe	0.86	9.12E-08
Intermediate cylinder	28.65	3.03E-06
Compressor	35.85	3.78E-06
Cylinder	12.46	1.31E-06
Dispenser	19.13	2.02E-06
Total	100%	1.06E-05

3.3.3 Societal Risk Results

The SR analysis of the HRS was conducted using GEXCON RISKCURVE software, which generated the FN curve. The analysis was carried out for the locations and within the population listed in Table 3-2. Figure 3-8 displays the FN curve for the hypothetical HRS under study. The lower and upper risks serve as guidelines for risk assessment. ALARP region is the area between these two lines. The result of the SR given by the red line indicated that the total risk falls within the ALARP region. Therefore, measures of risk mitigation should be applied to reduce the risk to an acceptable level.

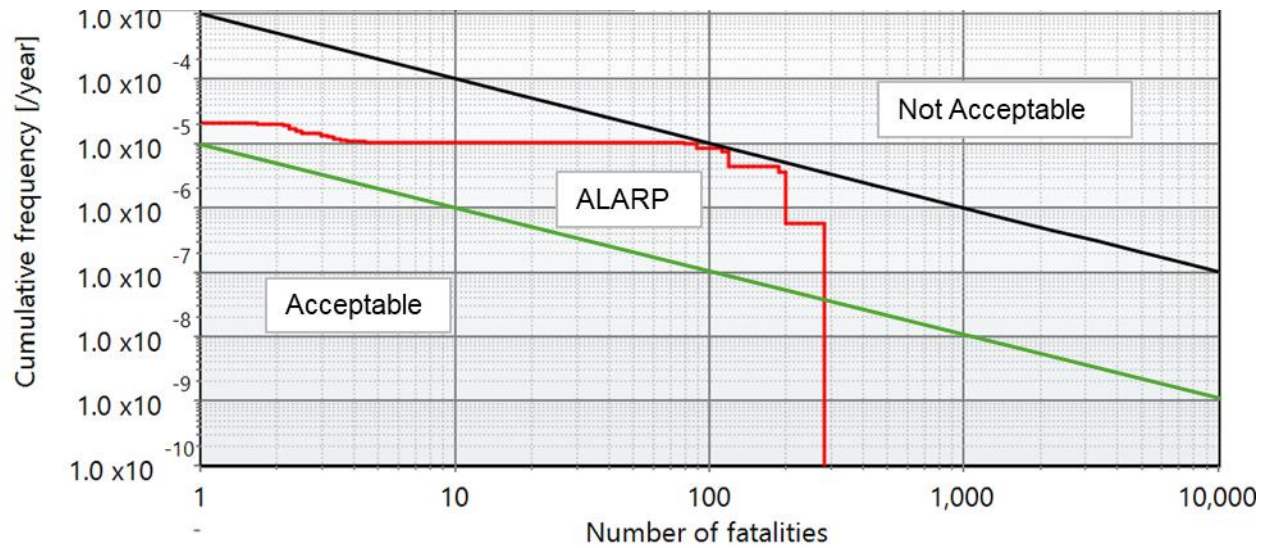


Figure 3-8. FN curve for the HRS

3.4 Conclusions

This study conducted a case-specific quantitative risk assessment (QRA) for hydrogen refueling stations (HRSs), tailored to the unique environmental and operational conditions of Saudi Arabia. By integrating consequence-based and risk-based approaches, the research emphasizes critical safety considerations for the design and operation of HRS facilities in urban areas and high-temperature environments.

The risk-based analysis, performed using GEXCON RISKCURVE software, quantified Individual Risk (IR) and Societal Risk (SR) through contour mapping and FN curve respectively. The highest risk zones ($IR = 10^{-5}$ per year) were concentrated around the dispenser, compressor, and intermediate cylinders, which collectively contributed over 80% of the total risk. The compressor alone accounted for 35.85% of the IR, reflecting its critical role in hydrogen pressurization and storage at high pressures. The FN curve indicates that the HRS total risks fall within the ALARP region, necessitating the need to apply risk reduction measures. These results highlight the

disproportionate impact of certain nodes on overall safety and the need for targeted interventions, such as enhanced leak detection systems, improved equipment integrity, and robust emergency isolation mechanisms.

The comparison between consequence-based safe distances and risk-based IR contours revealed that consequence-based analysis provides conservative harm zones, while risk-based analysis identifies areas of elevated fatality probability based on incident likelihood. This dual-perspective approach ensures that both immediate physical hazards and probabilistic risks are adequately addressed, fostering public trust and compliance with ALARP criteria.

From a regulatory perspective, the study identifies gaps in existing global safety standards, which often fail to address the unique climatic and demographic conditions of regions like Saudi Arabia. The results provide actionable insights for policymakers, urban planners, and industry stakeholders to develop location-specific safety guidelines. Integrating these findings into regulatory frameworks and urban planning strategies can foster public confidence and support the safe expansion of hydrogen infrastructure.

CHAPTER 4 CONCLUSION

The main conclusions of this work have been categorized as the following:

4.1 Towards hydrogen economy: Reviewing risk assessment measures

This work presented a review of international HRS safety and risk assessment studies based on regional locations. The goal after this review is to determine the best suited methodology with respect to the risk assessment of hydrogen refueling stations. HRSs studies have been categorized into two main divisions based on production location: offsite and onsite HRS. Asian countries contributed significantly to the most publicly available HRS safety studies, especially Japan, which reports on both offsite and onsite HRS safety studies. Moreover, in terms of risk assessment methods, semi-quantitative and quantitative methods are more generally used for offsite HRS safety studies, while qualitative and sometimes semi-quantitative methods are mainly adopted for risk assessments in onsite HRS applications.

4.2 A Quantitative Risk Assessment of Hydrogen Refueling Stations: A case study of Saudi Arabia.

This study provides a quantitative risk assessment for a hypothetical HRS in Saudi Arabia, identifying Vapor Cloud Explosion (VCE) scenarios as the most significant contributors to individual risks. The analysis emphasizes that compressor and intermediate cylinder nodes require enhanced safety measures due to their high-risk potential. Furthermore, safe distances vary depending on the equipment and personnel exposure, with the maximum safe distance determined for personnel in VCE scenarios. The findings underscore the importance of adopting risk-based approaches in planning and operating HRSs, highlighting the role of tailored safety measures in

mitigating risks. By advancing the understanding of safe distance requirements and risk contributions, this research lays the groundwork for safer hydrogen infrastructure in Saudi Arabia and similar regions, ensuring that safety does not impede the transition to a hydrogen-based economy.

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Vitae

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Academic Background :

EDUCATION

B.Eng., Chemical Engineering | Ahmadu Bello University Zaria, Nigeria. February 2020

Research: *Identification of Hazards due to Selected Home-made Chemicals in Zaria*

MSc., Chemical Engineering | King Fahd University of Petroleum and Minerals, Dhahran
Sudi Arabia. December 2024.

WORK EXPERIENCE

King Fahd University of petroleum and Minerals, Dhahran, Saudi Arabia. August
2022 - Present

Graduate Student- SERiD Lab

Responsibilities:

- Teaching Assistant in Process safety Engineering Course (CHE 581)
- Teaching Assistant in Process Optimization Course (CHE 561)
- Instructing and grading CHE 309 and CHE 409- Experimental Process Engineering Course

Junior Process Safety Engineer, Lagos Nigeria. August
2020 – August 2022

PetroPlat Energy Limited

Responsibilities:

- PFD and P&ID Development
- Line List and Equipment list Preparation
- PSV Sizing Calculation and Report

- Process Datasheet Development
- Development of Commercial and Technical Tenders for Technical Safety Scope of Work
- Prepared HAZOP report for Nitrogen Enhancement Project HAZOP – NLNG
- Participated in CFD Studies Deflagration Analysis Project Total – OML100 Flare Reduction Project
 - Prepared assumption register
 - Prepared CFD studies report
 - Implementing client comments
 - Preparing client response sheet.
- Participated in Dropped Object Studies Project Total – OML 100 Flare Reduction Project
 - Prepared assumption register
 - Dropped object studies calculation - Exceedance Curve
 - Prepared of Dropped Object Studies report
- Participated in the (NLNG) – New Boil-off Gas Compressor Project
 - LOPA/SIL Workshop – team assessed the integrity of the available Independent Protection Layers to ensure that the residual risk is below the company’s risk tolerance level.
 - HAZOP Workshop – team analyzed potential causes of deviation from the design intent of the new facility, the consequences and proposed effective safeguards and sets of HAZOP and Non-HAZOP Recommendations
 - Bowtie Workshop
- Participated in HI Development Project (SHELL)
 - Assisted in preparing documents such as Performance Standards, Client Response Sheet
 - Assisted in Updating a section of the Study such as Ship Collision Study.
 - Assisted in Compiling HAZID worksheet in Excel.
 - Attended HAZID Workshop
 - Attended ALARP Workshop
 - Assisted in preparing documents such as Performance Standards, Client Response Sheet

Trainee Engineer, Nigerian Gas Marketing Company (NGMC)
2018 – November 2018

January

Field Operator, Pressure Regulation and Metering station (PRMS), Obajana.

Responsibilities:

- Participated in routine plant operations, recording process conditions from the Plant for fiscal purposes.
- Participated in the commissioning and shutdown of CNG Plant- substation.
- Participated in the Calibration of Barton Chart Recorder by the maintenance team.
- Health Safety and Environment (HSE) Engagement.

RESEARCH PUBLICATIONS

1. **Journal:** Industrial and Engineering Chemistry Research.

Title: “n-Butane Oxidation to Maleic Anhydride: Reaction Mechanism and Kinetics Over VPO catalyst”. (Published).

Team: Bashir Hashim, Dr. Mohammed Mozahar Hussein, Wasim Ullah Khan, Dwi Hanktoko, Galal Atef Nasser, Mohammed A Sanhoob, Akolade Idris Bakare, Nilenindran Govender, Syed Ahmed Ali.

2. **Journal:** International Journal of Hydrogen Energy

Title: Quantitative Risk Assessment of Hydrogen Refueling Stations: A Case Study for Saudi Arabia (Under Review).

Team: Bashir Hashim, Dr. Sunhwa Park, Yoojeong Oh, Dr. Umer Zahid, Medhat Ahmed Nemitallah.

SKILLS AND SOFTWARES

- Microsoft Packages (Excel, Word & PowerPoint)
- Technical Report Writing
- Autodesk AutoCAD- Basics
- Aspen HYSYS and Aspen Plus- Basics
- DNV GL PHAST and SAFETI (for Consequence Modelling & Quantitative Risk Assessment)
- GEXCON EFFECTS and RISKCURVES (for Consequence Modelling & Quantitative Risk Assessment)
- PIPENET- Basics

OTHER CERTIFICATIONS

- Spray/Sprinkler & Transient Modules| PIPENET
March 2021
- Consequence Modelling of Process Accidents
September 2020

MEMBERSHIP CERTIFICATIONS

- Graduate Student Member, American Institute of Chemical Engineers (AIChE)
- National Society of Chemical Engineers (NSCHE)
- Nigerian Society of Engineers (NSE)

HONOURS AND AWARDS

- Zazzau Connects Merit Awards 2022
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