

Article

Expansion of Next-Generation Sustainable Clean Hydrogen Energy in South Korea: Domino Explosion Risk Analysis and Preventive Measures Due to Hydrogen Leakage from Hydrogen Re-Fueling Stations Using Monte Carlo Simulation

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Abstract: Hydrogen, an advanced energy source, is growing quickly in its infrastructure and technological development. Urban areas are constructing convergence-type hydrogen refilling stations utilizing existing gas stations to ensure economic viability. However, it is essential to conduct a risk analysis as hydrogen has a broad range for combustion and possesses significant explosive capabilities, potentially leading to a domino explosion in the most severe circumstances. This study employed quantitative risk assessment to evaluate the range of damage effects of single and domino explosions. The PHAST program was utilized to generate quantitative data on the impacts of fires and explosions in the event of a single explosion, with notable effects from explosions. Monte Carlo simulations were utilized to forecast a domino explosion, aiming to predict uncertain events by reflecting the outcome of a single explosion. Monte Carlo simulations indicate a 69% chance of a domino explosion happening at a hydrogen refueling station if multi-layer safety devices fail, resulting in damage estimated to be three times greater than a single explosion.

Keywords: hydrogen; risk assessment; domino explosion; Monte Carlo simulation



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1. Introduction

The rise in fossil fuel consumption due to population and economic expansion has led to global warming from the release of greenhouse gases, leading to a growing focus on hydrogen and sustainable energy sources [1–5]. Expanding hydrogen-related infrastructure is essential in urban areas by adding more onsite hydrogen refueling stations or mobile offsite hydrogen charging stations with storage containers, compressors, and chargers [6–8]. Nevertheless, the difficulties in building hydrogen refueling stations include financial challenges and choosing suitable sites. Therefore, current charging facilities for gasoline, LPG, and LNG are being repurposed to enhance convergence-type hydrogen refueling stations (LPG-LNG-Gasoline-Hydrogen) [9].

Hydrogen's broad flammable range and high explosion risk due to leaks and its strong explosive power necessitate the construction of process safety facilities and systems [10–12]. Frequently, accidents involving fire and explosions caused by human mistakes have been observed in chemical facilities [13]. Despite being well-established, there is still a potential for fire and explosion caused by human error in process safety facilities and systems. This poses a limitation on the operation and growth of convergence-type hydrogen refueling stations in urban areas [14–16]. Therefore, further safety enhancements are necessary as the urban area expands, based on analyzing risk and damage distances through quantitative risk assessment of convergence-type hydrogen refueling stations [17].

Recent studies on hydrogen facility risk assessment primarily concentrate on the worst-case scenario for each process unit, with many focusing on safety against fire and

explosions by simulating a single explosion. Cirrone et al. (2023) conducted a quantitative analysis of fire and explosion risks in hydrogen storage facilities, examining methods to reduce these risks and improve overall safety [18]. Li et al. (2010) conducted a quantitative risk evaluation for hydrogen refueling stations in urban areas characterized by dense populations and heavy traffic, considering the proximity of hydrogen-related infrastructure and machinery [19]. Shi et al. (2020) conducted dispersion and combustion modeling of hydrogen refueling stations using BRANN-based non-invasive methods that incorporated modeling and results from various statistical approaches [20]. Abohamzeh et al. (2021) confirmed that various CFD softwares are being used to model safety distances for explosion and jet fires at hydrogen refueling stations [21]. Yu et al. (2017) examined how the barrier wall, flame length, and flame deflection angle reduction rate can help reduce risks and ensure stability at a hydrogen refueling station by utilizing a custom FireFOAM solver [22]. Park et al. (2021) developed F-N (Frequency-Number of death) curves to assess the dangers of installing hydrogen refueling stations in urban locations and proposed safe distances based on hydrogen release and jet flame tests [23]. Jallais et al. (2018) applied simplified explosion curve methods such as TNO (Toegepast Natuurwetenschappelijk Onderzoek) multi-energy or BST (Baker–Strehlow–Tang) to determine the explosion load intensity involved in VCE (vapor cloud explosion) [24]. Explosion strength was determined using the strength index, which correlates with the mass flow rate of the accident release. Suzuki et al. (2021) need to assess jet fire risks with a quantitative risk assessment (QRA) of state-of-the-art HRS models, identifying critical scenarios that pose the greatest risk to the environment [25]. Tanaka et al. (2007) released pressurized hydrogen with a nozzle size of 0.8–8.0 mm at the dispenser and within the storage room in a full-scale model before igniting it [26]. Evidence from experiments was given to demonstrate the safety of the hydrogen refueling station.

Due to the intricate and unpredictable nature of chemical processes in plants, most fire and explosion incidents can trigger a chain reaction explosion. To avoid such catastrophic events, safety distances, and protective measures have been put in place to minimize risks. Various safety measures like process safety valves, gas detectors, flame arrestors, emergency isolation valves, dikes, firewalls, water spray, trenches, and fireproofing are employed to prevent or reduce the risk of fire or explosion [27]. For preventing or mitigating the risk of fire or explosion, various facilities, such as process safety valves, gas detectors, flame arrestors, emergency isolation valves, dikes, firewalls, water spray, trenches, and fireproofing are used [28]. Nevertheless, research has been carried out on this subject due to the frequent domino explosions in chemical processes [29]. He and Weng (2020) used a Monte Carlo simulation (MCS) to determine the overall risk distribution for all accident scenarios. They first obtained the dynamic distribution of individual risks from serial explosion accidents, using probability parameters for single explosions [30]. This predictive model was tested against the Bayesian network approach and used for the modeling and risk evaluation of LPG chemical plants to demonstrate its trustworthiness. Zhou and Reniers (2018) examined the impact within units impacted by the cascading effect triggered by a fire in the chemical processing sector through the use of a matrix-centric method [31]. Landucci et al. (2017) showed that by conducting a precise systematic and quantitative examination of safety barriers in process facilities, the domino effect can be reduced [32]. Khakzad et al. (2017) confirmed the domino effect caused by a fire in a chemical plant [33]. By taking into account the impact of fire protection systems, the event tree and dynamic Bayesian network were used to measure the temporal evolution and spread of the fire domino effect. Jia et al. (2024) found that it was difficult to make intelligent decisions based on the environment and various conditions with existing energy management strategies to solve problems with complex conditions. To this end, deep reinforcement learning, a data-based optimization technology, was used. An energy management strategy was established [34]. This deep reinforcement learning can learn optimal strategies by interacting with an unknown environment to maximize a predetermined reward. Additionally, deep

reinforcement learning can easily cope with uncertainty in optimization problems through complex systems and numerous iterations [35].

Nevertheless, there have been no studies conducted on the domino effect caused by hydrogen refueling station facilities; as a result, quantitative risk assessments have not been undertaken [36]. There is a shortage of data on accidents related to hydrogen, such as accident frequency and probability, so there has been no research done on predicting the range of risk and damage for chain explosions. Yet, the risk of widespread explosions at storage facilities and hydrogen refueling stations is significant due to the proximity of high-pressure storage tanks, increasing the chance of chain reactions between facilities [37]. Therefore, thorough simulations are required to ensure preventative safety measures like proper safety distances and barriers are in place for hydrogen refueling stations [38].

The purpose of this study was to evaluate the damage caused by a domino explosion at a convergence hydrogen refueling station located in an urban area by applying Monte Carlo simulation through deep reinforcement learning. To the best of our knowledge, this is the first study to present the damaging effects of a domino explosion at a hydrogen refueling station. A quantitative risk assessment was conducted using explosion variables required for risk assessment for each hydrogen facility, and data on a single explosion at a hydrogen refueling station was obtained. Based on the results of a single explosion, the probability, and impact of a domino explosion were evaluated at a convergence hydrogen refueling station by assuming the worst-case scenario that could occur when all multi-layer protective devices fail to function properly. After deep reinforcement learning, the damaging impact was quantitatively predicted using MCS simulation, and the impact was confirmed by comparing it to a single explosion. In Sections 2.1 and 2.2, the process of choosing a hydrogen refueling station for convergence and assessing single explosion data through quantitative risk assessment was explained. In Sections 2.3 and 2.4, a single explosion data was defined as a parameter, and deep reinforcement learning was employed. Section 2.5 provided a quantitative comparison between a single explosion and a domino explosion. With these findings in mind, we aimed to utilize them as essential information to implement strict safety regulations during the installation of a convergence hydrogen refueling station in urban areas.

2. Materials and Methods

2.1. Selection of Risk Assessment Site

The damage range and impact caused by fire and explosion of a convergence-type hydrogen refueling station were investigated. The chosen analysis location was an urban setting (Seoul, Republic of Korea) that would be significantly affected by an explosion, and within this location, a hydrogen refueling station of the convergence type that is currently functioning was chosen. Figure 1 shows the convergence-type hydrogen refueling station (1 km × 1 km) on satellite maps used for evaluating impact damage. It is situated over 300 m away from a nearby apartment complex and residential area which has around 23,000 residents. Lately, with the possible expansion of hydrogen refueling stations to urban areas to make them more accessible to consumers, the requirement for evaluating damage impact has arisen, and this site was chosen for our research.

2.2. Accident Scenario of Hydrogen Facility

The damage range and impact of a single explosion and fire were first calculated by selecting accident scenarios for each facility of a hydrogen filling station that was a convergence-type hydrogen refueling station. The PHAST software (DNV, Høvik, Norway) was utilized. Developing accident scenarios based on incidents that have happened at current hydrogen refueling stations is a frequently employed approach; nevertheless, there is no accident scenario information accessible for South Korea. Therefore, this research used SAND 2009-0874 (2009) from the Sandia National Laboratory to gather details on the capacity, pressure, and frequency of leaks for each hydrogen facility [39]. The frequency of cumulative fatalities from jet fires caused by leaks in tube trailers is reported to be higher

than in other facilities. In the event of a catastrophic accident known as a domino explosion, it is believed that a fire causes a domino reaction leading to a tube trailer explosion. Figure 2 displays the configuration and starting area of the hydrogen refueling station convergence. The explosion's impact radius was determined by analyzing the catastrophic rupture caused by overpressure from a single explosion. Details on the accident risk for each part of the hydrogen refueling station are given in Table 1. This information was utilized in accident scenarios, and the parameters for a single explosion from a fire were also used in domino explosions. Among the types of accidents that can occur at convergence-type hydrogen refueling stations, the damage caused by overpressure has a substantial impact [40]. According to the literature, an impact standard was set based on the level of damage to buildings and properties inflicted by overpressure [41]. To verify the impact of hydrogen, the extent of damage was estimated up to the area affected by 3.5 kPa. The degree of damage to the building and properties according to pressure is shown in Table 2. As the analysis outcomes can differ according to the wind speed and atmospheric stability in different regions, the wind speed and atmospheric stability at the convergence-type hydrogen refueling station location were determined using data from the Korea Meteorological Administration [42]. Table 3 presents wind speed, atmospheric stability, and temperature by night and day by season. In the case of catastrophic rupture, it was confirmed that the damage range result was obtained regardless of the wind speed parameter. Table 4 presents the number of workers, number of vehicles, user population based on the daily usage of the convergence hydrogen refueling station, and social risks were analyzed based on that information. Nevertheless, as there was no user information available for the convergence hydrogen refueling station, data for the hydrogen refueling station was utilized in the research. The pressure, temperature, mass, leak frequency, and weather information of the storage facilities used in a single explosion.



Figure 1. Location of the convergence hydrogen refueling station used in the risk analysis.

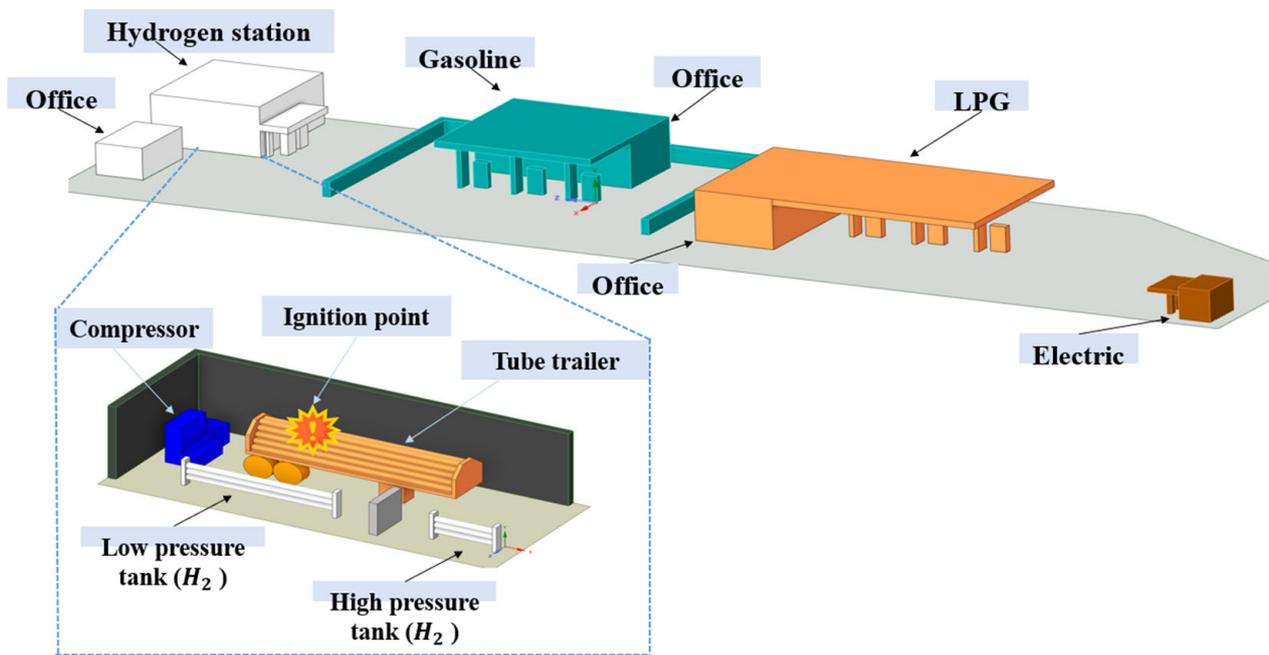


Figure 2. Schematic diagram of convergence hydrogen refueling station layout and ignition point.

Table 1. Risk for each component of the hydrogen refueling station.

Components	Title 2			Leak Scenario	Leak Frequency (/Year)
	Pre. (MPa)	Temp. (°C)	Mass × Number		
H ₂	20	40	340 kg × 2	Small Leak	1.07×10^{-3}
				Medium Leak	3.21×10^{-4}
				Large Leak	1.80×10^{-4}
				Cat. Rupture	5.00×10^{-7}
				Small Leak	3.47×10^{-3}
				Medium Leak	2.09×10^{-4}
H ₂	82	40	0.343 m ³ × 2	Large Leak	1.02×10^{-4}
				Cat. Rupture	5.00×10^{-7}
				Small Leak	3.47×10^{-3}
				Medium Leak	2.09×10^{-4}
				Large Leak	1.02×10^{-4}
				Cat. Rupture	5.00×10^{-7}
Dispenser	70	-40	-	Small Leak	7.06×10^{-4}
				Medium Leak	1.85×10^{-4}
				Large Leak	9.88×10^{-5}
Compressor	82	40	-	Small Leak	2.76×10^{-3}
				Medium Leak	2.62×10^{-6}
				Large Leak	4.24×10^{-6}
Priority Panel	82	40	-	Small Leak	1.20×10^{-3}
				Medium Leak	8.32×10^{-5}
				Large Leak	3.84×10^{-5}

Table 2. Level of damage to building and property under pressure.

Pressure(kPa)	Levels of Damage to Buildings and Property under Pressure
3.5	Small damage (Large and small windows usually shattered: Occasional damage to window frames)
17	Medium damage (Concrete or cinderblock walls, not reinforced, shattered)
35	Serious damage (Wooden utility poled snapped: tall hydraulic press In the building slightly damaged)
83	Total collapse (Probable total destruction of buildings; Heavy machine tools moved and badly damaged)

Table 3. Weather information (Seoul, Republic of Korea).

Weather (Seoul)	Wind [m/s]	Pasquill Stability Class	Temperature [K]
Summer day	5	D	303.15
Winter day	2.5	F	268.15
Summer night	3	D	293.15
Winter night	2	F	283.15

Table 4. Users of convergence-type hydrogen refueling stations in this study.

Population	Operator	Vehicle	People
Day	8	80	150
Night	4	20	40

2.3. Selection of Domino Explosion Parameters

For a domino explosion at convergence-type hydrogen refueling stations, defining uncertain event parameters is necessary to assess the quantitative impact of a single explosion before setting accident scenarios. Additionally, an explosion occurring in an open space is anticipated as a result of safety devices failing to consider the worst-case scenario when creating a scenario for a domino explosion. Therefore, this study utilized environmental parameters, data values from individual explosion results, and escalation factors as parameters for analyzing domino explosions involving tube trailers. A foundational framework was created to predict potential harm caused by the accident's material, type, outcome (consequence analysis model), and escalation factor determined from the findings. The resulting parameters for the extent of damage and impact of a single explosion were obtained using PHAST, a QRA software (Version 8.71). The models were combined to apply QRA to domino explosions, creating the basic models shown in Figure 3.

The value of a single explosion data from PHAST analysis was employed as a parameter for reinforcement learning in Monte Carlo simulation. Repeated episodes were used to train a machine-learning model to predict the outcomes of a domino explosion. The basic model in Figure 3 was used to establish parameters, with escalation factors (i.e., thermal radiation and blast wave) being applied separately to the initial single explosion to create random accidents in hydrogen facilities. If a domino effect did not happen, the process went back to calculating the probability of the accident and continued to create the domino effect through repetitive tasks. These repeated procedures were utilized to predict the probability of accidents and the extent of damage caused by a domino explosion. Figure 4 illustrates the diagram of the accident impact evaluation.

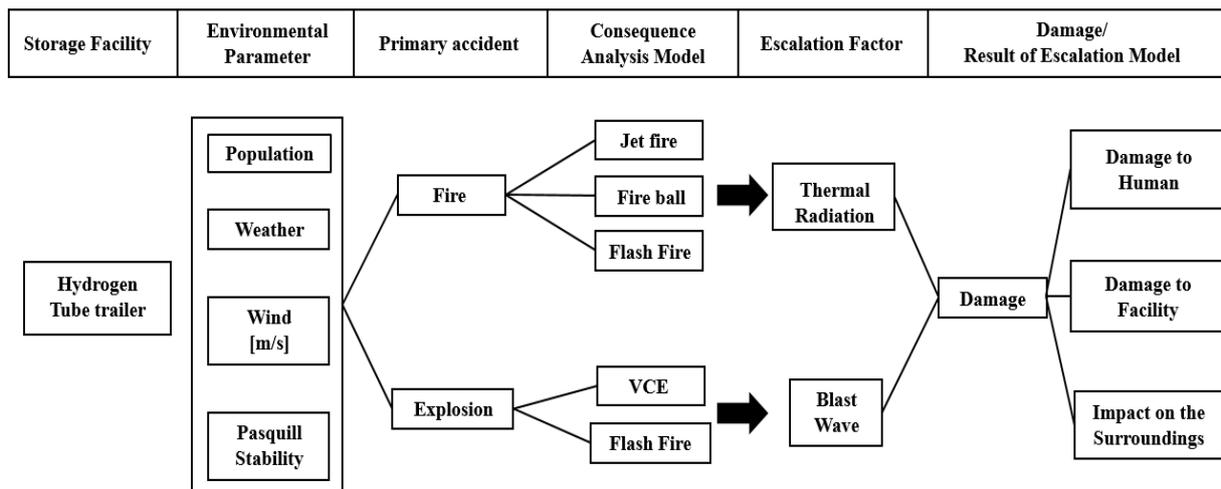


Figure 3. Basic model for application to the domino explosions.

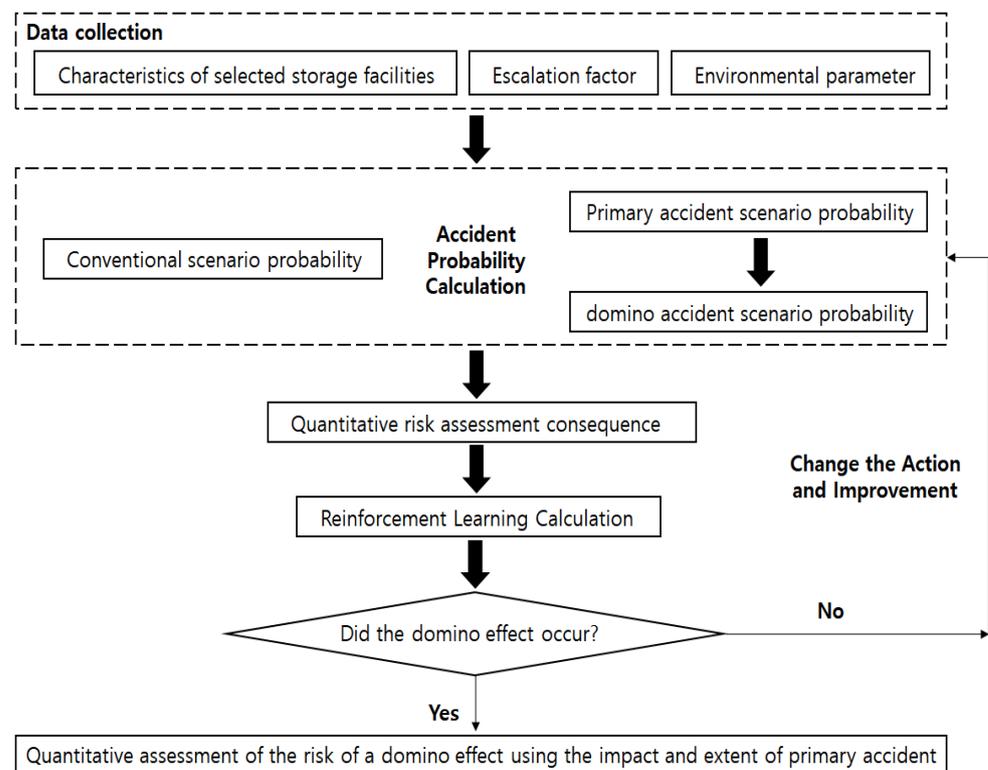


Figure 4. Flowchart of the method based on field theory and MCS.

2.4. Algorithm Procedure for the Monte Carlo Simulation-Based RL (Reinforcement Learning)

Monte Carlo algorithms are primarily utilized for identifying the best strategies in situations where there is a lack of understanding of the environment, and they necessitate sequences of samples involving state, actions, and rewards. Episodic operations are conducted to calculate the expected return in state (S) under a specific policy (π). Monte Carlo simulation involves evaluating every possible outcome at every stage and then finding the average of the outcomes. Table 5 displays the algorithm pseudo-code for MCS using reinforcement learning [43].

Table 5. Algorithm of MCS-based Pseudo code reinforcement learning (RL).

```

Function MCS Training:
# Train a RL agent by MCS algorithm
Input: a random target policy  $\pi$ 
Initialize:
     $V(s) \in \mathbb{R}$ , arbitrarily, for all  $s \in S$ 
    Returns(s)  $\leftarrow$  an empty list, for all  $s \in S$ 

Repeat forever (for each episode):
    Generate an episode following  $\pi$ :  $S_0, A_0, R_1, \dots, S_{T-1}, A_{T-1}, A_{T-1}, R_T$ 
     $G \leftarrow 0$ 
    Loop for each step of episode,  $t = T - 1, T - 2, \dots, 0$ :
         $G \leftarrow G + R_{t+1}$ 
        Unless  $S_t$  appears in  $S_0, S_1, \dots, S_{t-1}$ :
            Append  $G$  to Returns ( $S_t$ )
             $V(S_t) \leftarrow$  average (Returns ( $S_t$ ))

```

2.5. Prediction of the Domino Effect Using the Monte Carlo Model

Recently, the possibility of a domino explosion, a more complex disaster than a single explosion, has been raised at the hydrogen refueling station [36]. Therefore, this study examined the potential risk of both a single explosion and a domino explosion. A single explosion data-based MCS was utilized to estimate the probability and extent of damage caused by a domino explosion. MCS is a mathematical method used to forecast the likely result of an uncertain event. Obtaining the outcomes of this computational algorithm involves thorough and repeated random sampling using agent reinforcement learning [44].

By utilizing the value function, the agent transforms into an individual who evaluates the desirability of being in a certain state, determines the desired future state, and plans the actions needed to reach that state. By using fixed input values for a single explosion, the state-value function graph was utilized to confirm the range of estimated values for an uncertain event known as a domino explosion, leading to a predicted result. A value function graph represents a series of repetitive tasks happening randomly as an agent identifies the current state in a predetermined environment and seeks to maximize the reward through an action [40]. The Monte Carlo algorithm involves iterating episodes to enhance the cumulative reward in the environment via reinforcement learning, which is achieved by repeating the episode [45,46]. The anticipated cumulative reward is a domino explosion, achieved through numerous iterations to maximize the cumulative reward. This research utilized reinforcement learning with the Bellman equation to implement an algorithm through these MCSs [47].

$$\text{Policy} = \pi(s, a) \quad (1)$$

$$V_{\pi}(s) = E_{\pi}([G_t | S_t] = s) \quad (2)$$

Policy, as shown in Equation (1), refers to defining the probability (or preference) of what action (a) an agent will choose in a specific state (s). $V_{\pi}(s)$ denotes the state value and E_{π} represents the expectation for π when executing policy. G_t represents the return value at step t , and S_t indicates it is in at step t . In this manner, the state value function creates a relationship between the behavior of the current state and the next state, which is called the Bellman equation. Rearranging the Bellman equation helps uncover how the present and future states are related, resulting in Equation (3).

$$V^{\pi}(s) = E_{\pi} [R_{t+1} + \gamma G_{t+1} | s_t = s] \quad (3)$$

The policy function that obtains the maximum accumulated reward expected in reinforcement learning is called the optimal policy, and the equation that improves and implements this optimal policy is called the Bellman optimal equation. The study utilized

the Monte Carlo algorithm in Python for data processing, with Google Colaboratory employed to visualize the algorithm's outputs as a data graph. Later, the Monte Carlo algorithm was executed N times to validate the convergence value. Through iterative evaluation, the probability of a chain explosion was evaluated through N repetitions. Through the performance of these processes, a method of updating the random initial value to increase reliability is presented in Equation (4). Here, k is the value for the number of iterations, and for better evaluation, go to the next step through k + 1. When the iterative calculation process continues until the final convergence value is reached and it converges to a specific value, the desired accumulated expected reward is achieved [48,49].

$$V_{k+1}(s) = \sum_a \pi(s, a) \sum_{k'} p_{ss'}^a [r_{ss'}^a + \gamma V_k(s')] \quad (4)$$

2.6. Steps to Apply the Monte Carlo Model

Figure 5 illustrates the in-depth MCS procedure for the domino explosion. Initially, parameters for the domino explosion were established using data values obtained from a single explosion. Following reinforcement learning with the Monte Carlo simulation technique, accurate outcomes were computed using the state-value function in an iterative process to predict the likelihood of a domino effect with machine learning. The specific procedures are outlined below:

1. The data for a single explosion and the mathematical model for the convergence-type hydrogen refueling station were selected according to Figure 5. The parameters changed whenever each episode progressed, and the initial value setting determined the range of the domino explosion.
2. Through reinforcement learning, an agent learns by observing the environment. The agent receives information by continuously monitoring which of the three high-risk hydrogen facilities will experience an accident first, the type of accident (fire or explosion), and the possibility of a chain reaction explosion due to an accident.
3. Improved results were obtained by repeating a sufficient number of simulations to perform accurate predictions. Compensation for negative outcomes led to achieving representative results by regulating the conditions and executing fresh strategies to enhance policies. Deriving the maximum expected cumulative compensation for a domino explosion was achieved through policy enhancement.
4. Analyzing the state value function obtained from the Monte Carlo simulation confirmed the probability and range of damage for the uncertain event leading to the domino explosion.

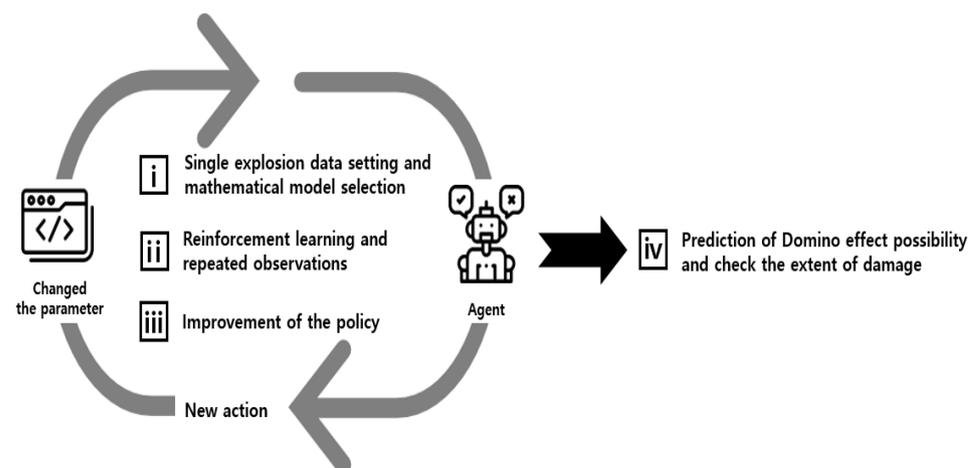


Figure 5. Schematic diagram of Monte Carlo simulation of domino explosion.

3. Results

3.1. Jet Fire and Fireball Analysis

The parameters of uncertain events for domino explosions at hydrogen refueling stations were determined based on the damage range and impact of a single fire. The tube trailer was the most affected and impacted of all six types of hydrogen filling station facilities during the jet fire and fireball. Nonetheless, the dispenser, compressor, and priority panel had negligible damage effects. The damage range according to a single jet fire and fireball is shown in Figure 6. The impact damage exceeding the impact standard of Intensity Level 1 (i.e., 4 kW/m^2), which is the effect of radiant heat flux, showed the largest impact damage with 22.5 m and 164.1 m, respectively. Figure 6a shows that the jet fire generated from the tube trailer was greatly influenced by the wind. Furthermore, the fireball's damage radius exceeded that of the jet fire in Figure 6b.

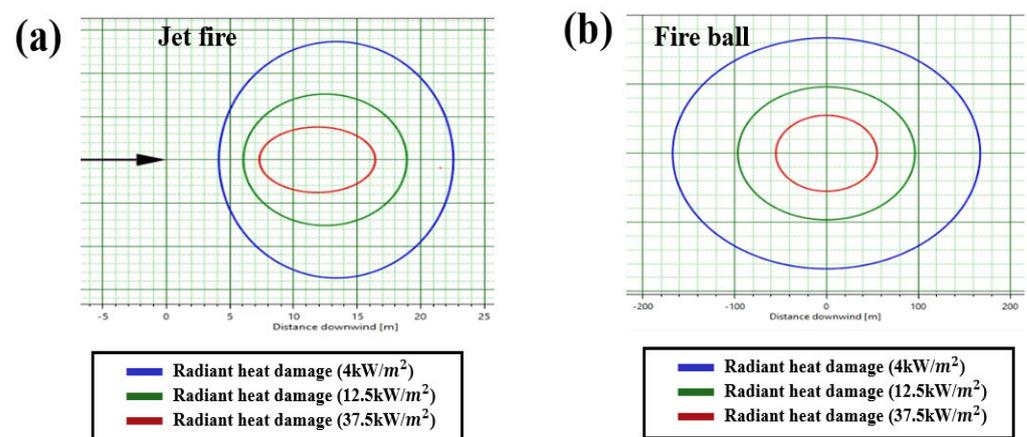


Figure 6. Comparison of damage range between jet fire and fireball. (a) Jet fire and (b) fireball.

3.2. Analysis of a Single Explosion

The level of destruction varied in specific worst-case situations due to the combination of wind speed and atmospheric stability during a fire [50]. Nevertheless, the variations in explosions caused by overpressure were minimal when considering the impact of wind speed and atmospheric stability. Furthermore, the extent of damage from a fire in the QRA was relatively small in comparison to the extent of damage from an explosion. Therefore, the fire did not have a major impact on the domino explosion.

This study utilized PHAST software to determine the parameters of uncertain events for domino explosions at a convergence-type hydrogen refueling station and analyze the damage range and effects of individual explosions. Using the PHAST software for analysis, it was shown that the tube trailer had the highest explosion damage range and impact out of all the hydrogen facilities, mirroring the findings of Sandia National Laboratory. The damage range obtained through the simulation of a single explosion is shown in Figure 7. The impact range exceeding 3.5 kPa, which caused little damage, was approximately 304 m from the point of occurrence of the accident, as shown in Figure 7a. The explosion's impact radius, which led to the complete collapse, measured 32.5 m. Figure 7b depicts the explosion's impact area as analyzed on a map. The scope of destruction caused by a single explosion did not reach places with many large apartment buildings but did impact nearby residential areas. The summary of impact damage analysis results from Figure 7 can be found in Table 6. However, the PHAST results verified that different from fires, explosions caused by overpressure are not greatly impacted by weather conditions.

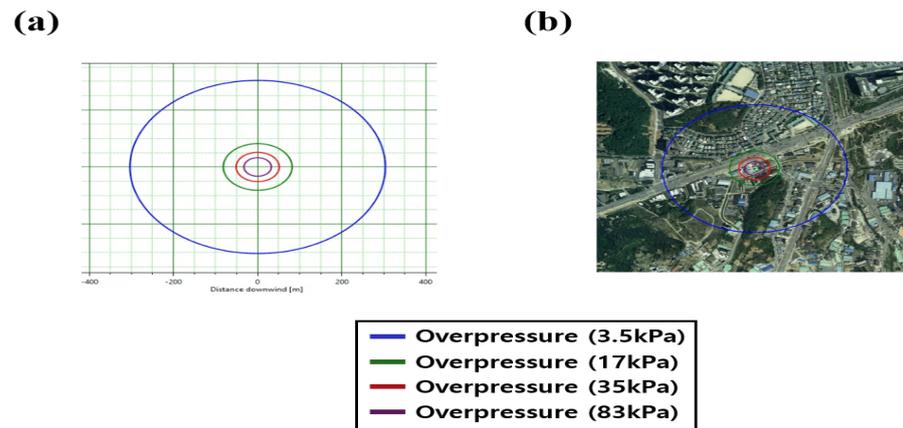


Figure 7. (a) Catastrophic rupture of tube trailer derived from PHAST software and (b) catastrophic rupture of tube trailer shown on the map.

Table 6. Tube trailer catastrophic rupture impact damage analysis.

Components	Leak Scenario	Overpressure (kPa)	Explosion Impact (m)
Tube trailer	Catastrophic rupture	3.5	304
		17	81.7
		35	51.3
		83	32.5

3.3. MCS Simulation for the Domino Effect

If the safety devices of the convergence hydrogen refueling station fail to function properly in a worst-case scenario, the domino explosion's damage was assessed through MCS simulation. In creating the scenario of the accident, it was hypothesized that an overpressure happened in the tube trailer leading to an explosion due to factors like thermal radiation and explosion waves. The extent of the domino explosion's impact was validated by analyzing a state-value function graph utilizing a Monte Carlo algorithm derived from single explosion data collected from QRA.

The results of reinforcement learning at distances of 500 m and 1000 m for the impact range are illustrated in Figure 8. Reinforcement learning in the learning graphs was carried out based on the specific parameters, with the x-axis representing the number of learning iterations and episodes. The Y-axis is a state-value function, with the v-value indicating the average over numerous episodes. Since the accumulated expected reward in the Monte Carlo algorithm is a domino explosion, the value on the y-axis is expressed as the probability of occurrence of a domino explosion. Figure 8a,b indicates that the domino explosion parameters were not adequately learned and did not reach a specific value in the learning graph when the learning was conducted fewer than 1000 times, leading to unreliable outcomes. In Figure 8a, the results of increasing the explosion damage range to 500 m were displayed, with successful learning achieved after completing over 1000 episodes.

As the learning cycle increases, it converges to a constant result value. Based on the presented learning results, it was verified that the domino effect can take place within a broad region. The results of expanding the explosion damage range to 1000 m using MCS simulation are shown in Figure 8b. When learning more than 1000 episodes based on 500 m and 1000 m, algorithm learning was carried out smoothly and the domino explosion event could be predicted. However, in the case of Figure 8b, after running the algorithm over 1000 times, it was confirmed that the graph reached a specific value and successfully obtained the outcome for the domino explosion. Additional research was conducted in this study to increase the domino explosion's reach to 2000 m and 3000 m, but after 2500 learning

sessions, a specific value was not reached. As a result, it was determined that it was beyond the domino explosion's influence range. When the expected maximum cumulative reward of the domino explosion did not occur, learning was performed to automatically improve the algorithm, such that a domino explosion could occur by changing the environmental factors or escalation factors. Therefore, the probability of a domino explosion was 69%, achieved by maximizing the expected reward from repeated tasks. However, convergence did not occur if the explosion damage range was ≥ 1 km.

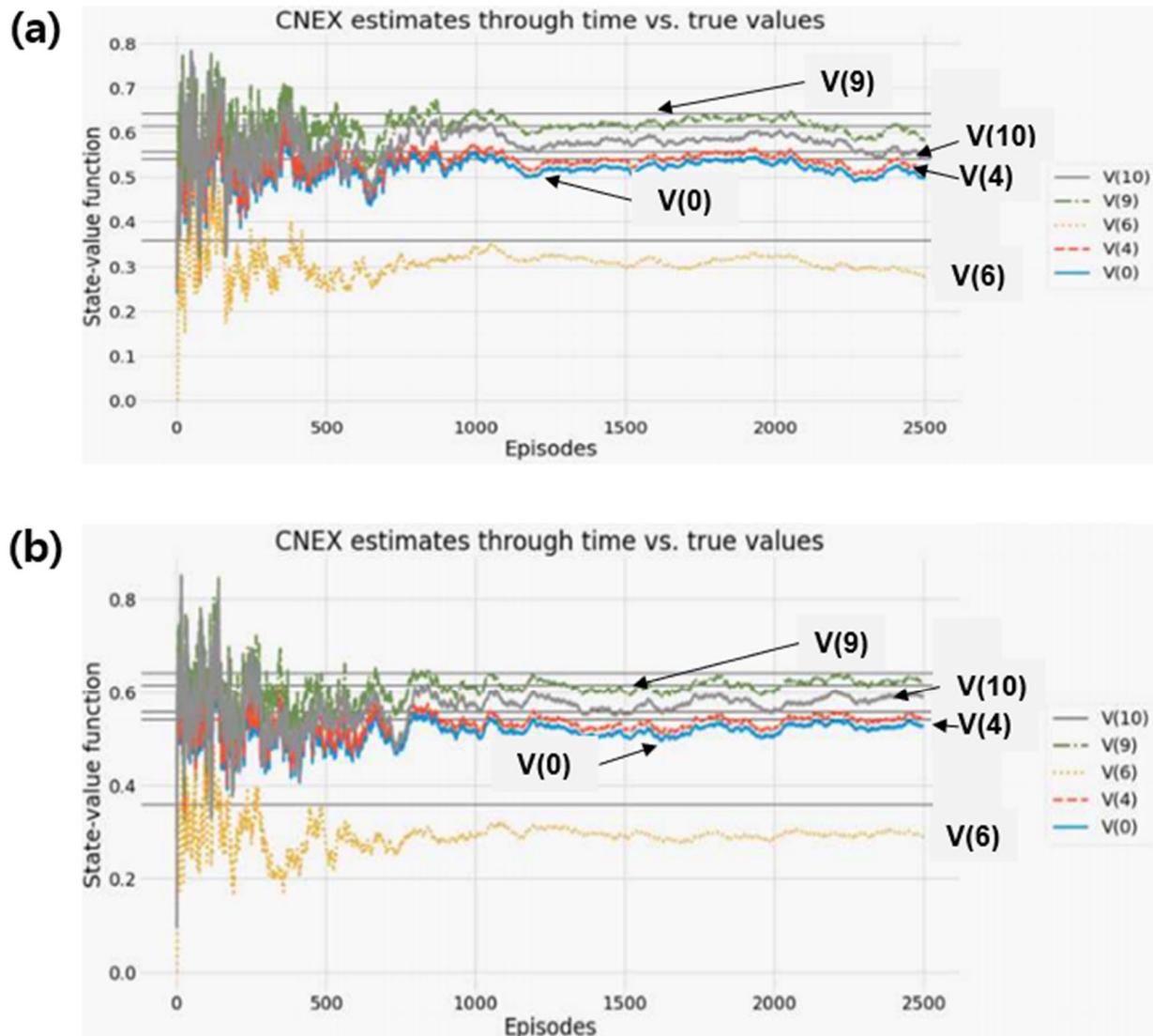


Figure 8. Explosion range learning graph using Monte Carlo simulation: (a) 500 m and (b) 1000 m.

These findings indicate that in the event of a domino explosion at a hydrogen refueling station, the extent of explosion damage can reach up to 1 km. Figure 9 displays the extent of damage from a single explosion as determined by QRA, and the extent of damage from a domino explosion as determined by MCS on a map. An accident of this magnitude could result in a catastrophe due to the proximity of some residents living within 1 km of the accident site. Therefore, the MCS utilized in this research took into account the worst possible situation, anticipating that the actual explosion would result in minimal damage. If the actual safety devices work properly, it is believed that only a minor explosion will occur and not a domino explosion.

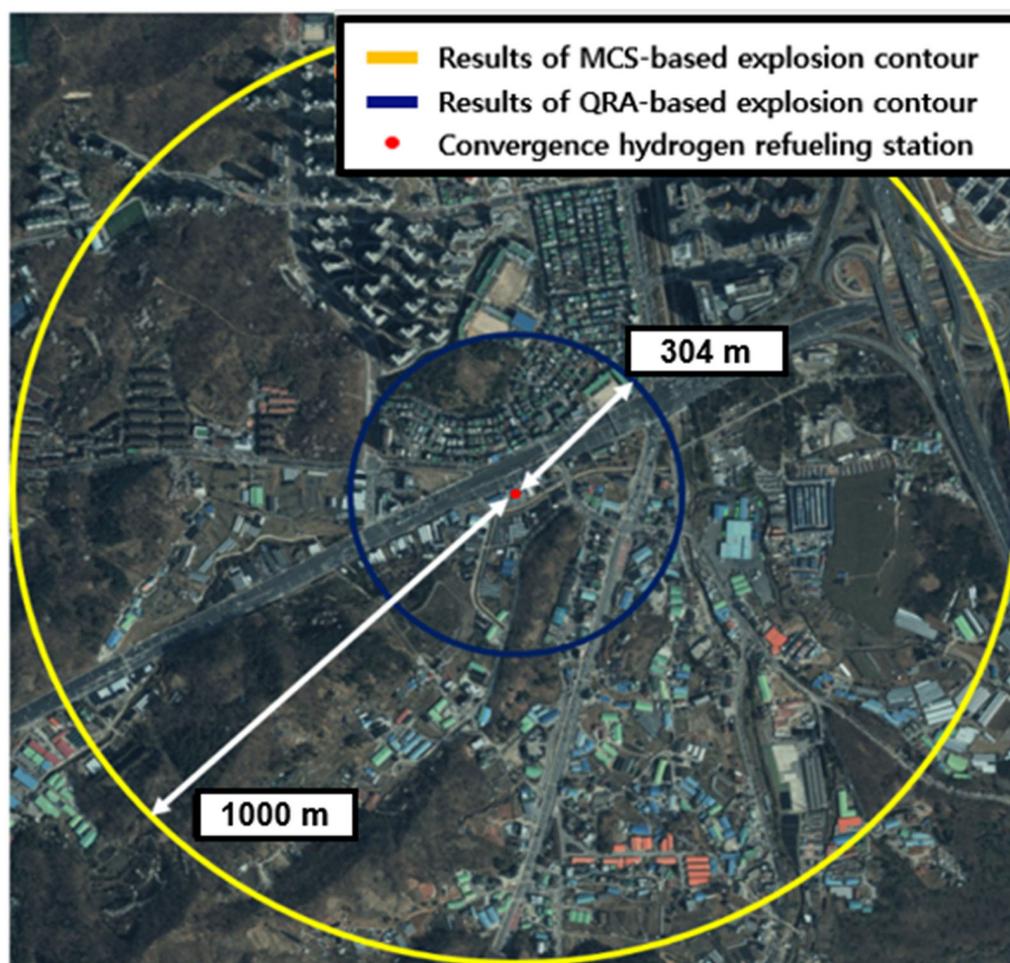


Figure 9. Comparison of the impact range of a single explosion (304 m) and a domino explosion (1000 m).

4. Conclusions

As South Korea is installing more convergence-type hydrogen refueling stations in urban areas, there is a need for research on both single explosions and domino explosions between facilities related to hydrogen's chemical properties. In this study, we applied Swiss cheese theory and considered the worst-case scenario in which multi-layer protective measures such as safety equipment and safety devices fail to work effectively. Through MCS simulation, the probability and extent of damage from a domino explosion involving a tube trailer were forecasted, leading to the following findings.

1. PHAST software was used to conduct a quantitative risk assessment for a single explosion and found that the hydrogen tube trailer had the most significant effect on the explosion. The distance at which an explosion would occur due to excessive pressure, resulting in minor damage, was around 304 m from the point of explosion.
2. After analyzing a single explosion using PHAST, a study on the consequences of a domino explosion was carried out using MCS, revealing a 69% probability of a domino explosion following a container rupture. Moreover, the range of damage exerted by the 3.5 kPa standard, where small damage (i.e., large and small windows are broken) occurs, was approximately 1000 m.
3. The range of influence between a single explosion and a domino explosion differed by more than three times, showing that a convergence-type hydrogen refueling station in an urban area could lead to a major disaster without proper safety measures.

This study identified the possibility of a domino explosion and the radius of damage in the event of an explosion, but as installations increase in urban areas, it is necessary to accurately derive the risk through a more reliable quantitative risk assessment.

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References

- Wei, R.; Lan, J.; Lian, L.; Huang, S.; Zhao, C.; Dong, Z.; Weng, J. A bibliometric study on research trends in hydrogen safety. *Process Saf. Environ. Protect.* **2022**, *159*, 1064–1081. [CrossRef]
- Al-Fatesh, A.S.; AL-Garadi, N.Y.A.; Osman, A.I.; Al-Mubaddel, F.S.; Ibrahim, A.A.; Khan, W.U.; Alanazi, Y.M.; Alrashed, M.M.; Alothman, O.Y. From plastic waste pyrolysis to fuel: Impact of process parameters and material selection on hydrogen production. *Fuel* **2023**, *344*, 128107. [CrossRef]
- Osman, A.I.; Mehta, N.; Elgarahy, A.M.; Hefny, M.; Al-Hinai, A.; Al-Muhtaseb, A.H.A. Hydrogen production, storage, utilization and environmental impacts: A review. *Environ. Chem. Lett.* **2022**, *20*, 153–188. [CrossRef]
- Hassan, Q.; Sameen, A.Z.; Salman, H.M.; Jaszczur, M.; Al-Jiboory, A.K. Hydrogen energy future: Advancements in storage technologies and implications for sustainability. *J. Energy Storage* **2023**, *72*, 108404. [CrossRef]
- Aydin, M.I.; Dincer, I. An assessment study on various clean hydrogen production methods. *Energy* **2022**, *245*, 123090. [CrossRef]
- Bao, Z.; You, S.; Hu, Z.; Wen, Y. Coordinated operation of hydrogen refueling and fast charging combo station under normal and contingent conditions. *Energy Conv. Econ.* **2020**, *1*, 171–183. [CrossRef]
- Perna, A.; Minutillo, M.; Micco, S.D.; Jannelli, E. Design and costs analysis of hydrogen refueling stations based on different hydrogen sources and plant configurations. *Energies* **2022**, *15*, 541. [CrossRef]
- Li, Y.; Wang, Z.; Shi, X.; Fan, R. Safety analysis of hydrogen leakage accident with a mobile hydrogen refueling station. *Process Saf. Environ. Protect.* **2023**, *171*, 619–629. [CrossRef]
- Intralink UK. The Hydrogen Economy South Korea: Market Intelligence Report. Available online: <https://www.intralinkgroup.com/Syndication/media/Syndication/Reports/Korean-hydrogen-economy-market-intelligence-report-January-2021.pdf> (accessed on 10 November 2023).
- Chang, X.; Bai, C.; Zhang, B. The effect of gas jets on the explosion dynamics of hydrogen-air mixtures. *Process Saf. Environ. Protect.* **2022**, *162*, 384–394. [CrossRef]
- Moon, S.B.; Lim, S.M.; Bang, I.C. Analysis of hydrogen and dust explosion after vacuum vessel rupture: Preliminary safety of Korean fusion demonstration reactor using MELCOR. *Int. J. Energy Res.* **2018**, *42*, 104–116. [CrossRef]
- Shang, S.; Zhang, J.; Zhang, J.; Luo, T.; Bi, M.; Jiang, H.; Li, Y.; Gao, W. Study on the effect of explosion suppression equipment on hydrogen explosions. *J. Loss Prev. Process Ind.* **2023**, *83*, 105046. [CrossRef]
- Jung, S.; Woo, J.; Kang, C. Analysis of severe industrial accidents caused by hazardous chemicals in South Korea from January 2008 to June 2018. *Saf. Sci.* **2020**, *124*, 104580. [CrossRef]
- Qian, J.; Li, X.; Gao, Z.; Jin, Z. A numerical study of unintended hydrogen release in a hydrogen refueling station. *Int. J. Hydrogen Energy* **2020**, *45*, 20142–20152. [CrossRef]
- Tan, W.J.; Ban, Z.H.; Chen, B.; Kim, K.L.; Siwayanan, P.; Choong, T.S.Y.; Lau, K.K. Enhanced mitigation of fire and explosion risks due to hydrogen leakage using targeted nitrogen nozzle spray approach. *ACS Chem. Health Saf.* **2022**, *29*, 309–318. [CrossRef]
- Park, B.; Kim, Y.; Park, J.O.; Lim, O.K. Jet flame risk analysis for safe response to hydrogen vehicle accident. *Sustainability* **2023**, *15*, 9884. [CrossRef]
- Kwon, D.; Choi, S.K.; Yu, C. Improved safety by cross analyzing quantitative risk assessment of hydrogen refueling stations. *Int. J. Hydrogen Energy* **2022**, *47*, 10788–10798. [CrossRef]
- Cirrone, D.; Makarov, D.; Molkov, V. Rethinking “BLEVE explosion” after liquid hydrogen storage tank rupture in a fire. *Int. J. Hydrogen Energy* **2023**, *48*, 8716–8730. [CrossRef]
- Li, Z.; Pan, X.; Ma, J. Quantitative Risk Assessment on a Hydrogen Refueling Station in Shanghai. *Int. J. Hydrogen Energy* **2010**, *35*, 6822–6829.
- Shi, J.; Chang, Y.; Khan, F.; Zhu, Y.; Chen, G. Methodological improvements in the risk analysis of urban hydrogen fueling station. *J. Clean. Prod.* **2020**, *257*, 120545.

21. Abohamzeh, E.; Salehi, F.; Sheikholeslami, M.; Abbassi, R. Review of hydrogen safety during storage, transmission, and applications processes. *J. Loss Prev. Process Ind.* **2021**, *72*, 104569.
22. Yu, X.; Yan, W.; Liu, Y.; Zhou, P.; Li, B.; Wang, C. The flame mitigation effect of vertical barrier wall in hydrogen refueling stations. *Fuel* **2022**, *315*, 123265. [[CrossRef](#)]
23. Park, B.; Kim, Y.; Paik, S.; Kang, C. Numerical and experimental analysis of jet release and jet flame length for qualitative risk analysis at hydrogen refueling station. *Process Saf. Environ. Protect.* **2021**, *155*, 145–154. [[CrossRef](#)]
24. Jallais, S.; Vyazmina, E.; Miller, D.; Thomas, J.K. Hydrogen jet vapor cloud explosion: A model for predicting blast size and application to risk assessment. *Process Saf. Environ. Protect.* **2018**, *37*, 397–410. [[CrossRef](#)]
25. Suzuki, T.; Shiota, K.; Izato, Y.; Komori, M.; Sato, K.; Takai, Y.; Ninomiya, T.; Miyake, A. Quantitative risk assessment using a Japanese hydrogen refueling station model. *Int. J. Hydrogen Energy* **2021**, *46*, 8329–8343. [[CrossRef](#)]
26. Tanaka, T.; Azuma, T.; Evans, J.A.; Cronin, P.M.; Johnson, D.M.; Cleaver, R.P. Experimental study on hydrogen explosions in a full-scale hydrogen filling station model. *Int. J. Hydrog. Energy* **2007**, *32*, 2162–2170. [[CrossRef](#)]
27. Xu, Y.; Reniers, G.; Yang, M.; Yuan, S.; Chen, C. Uncertainties and their treatment in the quantitative risk assessment of domino effects: Classification and review. *Process Saf. Environ. Protect.* **2023**, *172*, 971–985. [[CrossRef](#)]
28. Nolan, D.P. *Handbook of Fire and Explosion Protection Engineering Principles for Oil, Gas, Chemical, and Related Facilities*, 1st ed.; Gulf Professional Publishing: Houston, TX, USA, 2019; pp. 279–302.
29. Ji, J.; Tong, Q.; Khan, F.; Dadashzadeh, M.; Abbassi, R. Risk-based domino effect analysis for fire and explosion accidents considering uncertainty in processing facilities. *Ind. Eng. Chem. Res.* **2018**, *57*, 3990–4006. [[CrossRef](#)]
30. He, Z.; Weng, W. Synergic effects in the assessment of multihazard coupling disasters: Fires, explosion, and toxicant leaks. *J. Hazard. Mater.* **2020**, *388*, 121813. [[CrossRef](#)] [[PubMed](#)]
31. Zhou, J.; Reniers, G. A matrix-based modeling and analysis approach for fire-induced domino effects. *Saf. Environ. Protect.* **2018**, *116*, 347–353. [[CrossRef](#)]
32. Landucci, G.; Necci, A.; Antonioni, G.; Argenti, F.; Cozzani, V. Risk assessment of mitigated domino scenarios in process facilities. *Reliab. Eng. Syst. Saf.* **2017**, *160*, 37–53. [[CrossRef](#)]
33. Khakzad, N.; Lanfucci, G.; Reniers, G. Application of dynamics Bayesian network to performance assessment of fire protection systems during domino effects. *Reliab. Eng. Syst. Saf.* **2017**, *167*, 232–247. [[CrossRef](#)]
34. Jia, C.; Zhou, J.; He, H.; Li, J.; Wei, Z.; Li, K. Health-conscious deep reinforcement learning energy management for fuel cell buses integrating environmental and look-ahead road information. *Energy* **2023**, *290*, 130146. [[CrossRef](#)]
35. Jia, C.; He, H.; Zhou, J.; Li, J.; Wei, Z.; Li, K. Learning-based model predictive energy management for fuel cell hybrid electric bus with health-aware control. *Appl. Energy* **2024**, *355*, 122228. [[CrossRef](#)]
36. Park, B.; Kim, Y.; Lee, K.; Paik, S.; Kang, C. Risk assessment method combining independent protection layers (IPL) of layer of protection analysis (LOPA) and RISKCURVES software: Case study of hydrogen refueling stations in urban areas. *Energies* **2021**, *14*, 4043. [[CrossRef](#)]
37. Omatick, T.; Zhang, D.; Blais, M.S.; Mossolly, M.; Renzi, P.; Kurz, R.; Freund, S.; Harvey, S. Usage. In *Machinery and Energy Systems for the Hydrogen Economy*, 1st ed.; Brun, K., Allison, T., Eds.; Elsevier Inc.: New York, NY, USA, 2022; pp. 251–304.
38. Nakayama, J.; Misono, H.; Sakamoto, J.; Kasai, N.; Shibutani, T.; Miyake, A. Simulation-based safety investigation of a hydrogen fueling station with an on-site hydrogen production system involving methylcyclohexane. *Int. J. Hydrogen Energy* **2017**, *42*, 10636–10644. [[CrossRef](#)]
39. LaChance, J.L.; Houf, W.G.; Fluier, L.; Middleton, B. *Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards*; Sandia Report (SAND2009-0874); Sandia National Laboratories: Albuquerque, NM, USA, 2009.
40. Dadashzadeh, M.; Ahmad, A.; Khan, F. Dispersion modeling and analysis of hydrogen fuel gas released in an enclosed area: A CFD-based approach. *Fuel* **2016**, *184*, 192–201. [[CrossRef](#)]
41. Center for Chemical Process Safety. *Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs*, 1st ed.; American Institute of Chemical Engineers: New York, NY, USA, 1994; pp. 247–336.
42. Korea Meteorological Administration. Weather Information. Available online: <https://www.weather.go.kr/> (accessed on 13 October 2023).
43. Hao, Z.J.; Maio, F.D.; Zio, E. Monte Carlo Tree Search-based Deep Reinforcement Learning for Flexible Operation & Maintenance Optimization of a Nuclear Power Plant. *J. Saf. Sustain.* **2023**, *in press*. [[CrossRef](#)]
44. Huang, K.; Chen, G.; Khan, F.; Yang, Y. Dynamic analysis for fire-induced domino effects in chemical process industries. *Process Saf. Environ. Protect.* **2021**, *148*, 686–697. [[CrossRef](#)]
45. Furen, Z.; Jiao, L.; Xiumei, X. Analysis and stimulation on LPG Station Explosion Hazards based on Monte-Carlo Method. In Proceedings of the 2011 Fourth International Symposium on Knowledge Acquisition and Modeling, Sanya, China, 8 October 2011; pp. 104–107.
46. Red, A.; Abdolhamidzadeh, B.; Abbasi, T.; Rashtchian, D. FREEDOM II: An improved methodology to assess domino effect frequency using simulation techniques. *Process Saf. Environ. Protect.* **2014**, *92*, 714–722. [[CrossRef](#)]
47. Singh, V.; Chen, S.; Singhania, M.; Nanavati, B.; Kar, A.; Gupta, A. How are reinforcement learning and deep learning algorithms used for big data based decision making in financial industries—A review and research agenda. *Int. J. Inf. Manag. Data Insights* **2022**, *2*, 100094. [[CrossRef](#)]
48. Morales, M. *Grokking Deep Reinforcement Learning*, 1st ed.; Manning Publications: Shelter Island, NY, USA, 2020; pp. 1–55.

49. Benzi, M.; Evans, T.M.; Hamilton, S.P.; Pasini, M.L.; Slattery, S.R. Analysis of Monte Carlo accelerated iterative methods for sparse liner systems. *Numer. Linear Algebra* **2017**, *24*, e2088. [[CrossRef](#)]
50. Li, Y.; Wang, Y.; Lai, Y.; Shuai, J.; Zhang, L. Monte Carlo-based quantitative risk assessment of parking areas for vehicles carrying hazardous chemicals. *Reliab. Eng. Syst. Saf.* **2023**, *231*, 109010. [[CrossRef](#)]

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