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Developing a new framework for techno-economic hydrogen energy risk management through probabilistic R.Graph

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ABSTRACT

In the quest for sustainable energy, hydrogen stands out as a green energy vector. However, its adoption is hindered by safety, environmental, and efficiency challenges due to the risks of hydrogen leakage. Traditional risk management methods in the literature show limitations, especially when assessing continuous variables and the probabilistic nature of risks. To bridge this gap, this paper introduces the Probabilistic R.Graph method—an enhancement of the deterministic R.Graph model. This novel approach excels in quantitative risk management, enabling a more nuanced assessment of risks by factoring in continuous variables and probabilities. It assists in assessing the economic, safety, and environmental consequences of risks, recognizing the acceptable levels of risk for decision-makers through a straightforward and understandable cause-and-effect diagram. Applied to a steam-reforming hydrogen generation unit, the Probabilistic R.Graph method helped categorize leakage scenarios in the low, medium, and high and assess their cascading effects on safety, economy, and environment. It enabled the identification of preventive measures that are both effective and economical, such as pressure relief valves. The method proved particularly valuable in prioritizing safety risks like health injuries and fatalities due to their greater severity over other considerations like economic loss. This paper validates the method's practicality in real-world settings, especially for enhancing safety and sustainability in hydrogen energy systems.

1. Introduction

The transition to a sustainable energy future is of utmost importance in our efforts to combat climate change and reduce our dependence on fossil fuels. In this context, hydrogen has emerged as a clean and versatile energy carrier that has garnered significant attention for its potential to contribute to a low-carbon economy [1]. Hydrogen can be produced from a wide range of domestic resources, including natural gas, coal, biomass, solar, wind, and nuclear energy. Various methods are employed to generate hydrogen, such as steam reforming, gasification, electrolysis, and thermochemical cycles [2]. These diverse production techniques allow for flexibility and adaptation to different resource availability and technological advancements. Furthermore, hydrogen finds application in various sectors, making it a highly versatile energy source. It can be utilized in power generation, heating systems, transportation (including fuel cell vehicles), and various industrial processes [3].

However, it is crucial to acknowledge that hydrogen also presents potential and unexpected risks, particularly in relation to its leakage throughout the value chain encompassing production, delivery, and end-use [4,5]. Hydrogen leakage which is one of the trended topics in hydrogen safety publications [6], is undeniably the primary cause of hydrogen-related incidents [7]. The leakage of hydrogen can have adverse impacts on safety, the environment, and the climate. As hydrogen is highly flammable, it poses the risk of fires or explosions if it accumulates in confined spaces [8]. Additionally, hydrogen leakage can influence atmospheric chemistry and contribute to the prolonged lifetime of methane and other greenhouse gases, exacerbating climate

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change concerns [9]. Moreover, hydrogen leakage can lead to economic losses due to wasted energy and reduced efficiency in the overall system. Given these risks, it becomes imperative to investigate the sources, rates, and effects of hydrogen leakage comprehensively [10]. This involves examining the entire value chain and identifying potential vulnerabilities and accidents [11]. Furthermore, it is critical to investigate the long-term viability of safety barriers and new technologies designed to effectively prevent or mitigate hydrogen leakage, thereby contributing to the development of robust hydrogen safety standards and codes [12]. We can strive to improve safety measures and develop innovative solutions to reduce the risks associated with hydrogen leakage by investing in research and development.

The investigation of hydrogen leakage encompasses evaluating the efficacy of safety barriers, such as leak detection systems, safety shutdown systems, ventilation and gas monitoring systems, fire suppression and protection systems, safety training, procedures, and maintenance and inspection programs. In addition, it involves assessing the potential of emerging technologies, including advancements in leak detection, safety systems, and infrastructure design [13,14]. These technologies aim to reduce the likelihood of hydrogen leakage and mitigate its impacts. To determine the sustainability of these safety measures and technological innovations, a comprehensive analysis is required. This analysis should consider the environmental impact, economic viability, technical feasibility, and regulatory compliance aspects of the proposed solutions. It is crucial to ensure that these measures effectively mitigate risks, enhance system reliability and availability, are compatible with existing infrastructure, and contribute to the overall sustainable development of hydrogen generation.

Hydrogen leakage is a potential risk for the hydrogen economy that needs to be addressed by research and regulation. Several studies have reviewed the key issues concerning hydrogen safety, including hydrogen incident investigation, hydrogen leakage and diffusion, hydrogen ignition, and explosion. Among these studies, a sizable portion concentrated on identifying the factors that influence hydrogen leakage by simulating hydrogen leakage or probabilistic assessment of the leakage factors in various facilities. For example, Hong et al. [15] studied the hydrogen self-ignition hypothetical theories, and the deflagration-to-detonation transition process. They also identified safety challenges in hydrogen utilization, including insufficient data, standards, and regulations. Possible solutions include enhancing hydrogen sensors, valves, and catalysts. Mohammadfam and Zarei [16] utilized HAZOP, PRA, ETA, and consequence simulator software, PHAST 6 to perform a comprehensive quantitative risk analysis on a hydrogen production plant in an oil refinery. They identified the main hazardous sources, the incident outcomes, the frequencies of the initial events and incident outcomes, the vulnerability areas, and the societal risk of the hydrogen plant. Sakamato et al. [17] analyzed the accidents involving hydrogen fueling stations in Japan and the USA based on the leakage types. The authors classified the accidents into four categories: leakage due to damage and fracture of main bodies, leakage from flanges, valves, and seals, leakage due to external impact, and leakage due to other factors and identified the safety issues associated with the design, installation, operation, and maintenance of hydrogen fueling stations in both countries. Yuan et al. [18] performed a CFD-based numerical investigation of the leakage and explosion scenarios in China's first liquid hydrogen refueling station (LHRS) in Pinghu to analyze the effects of the layout of the LHRS, leakage parameters, and local meteorological conditions on the low-temperature hazards and explosion hazards of the LH2 leakage. Gao et al. [19] conducted a safety analysis of leakage in a nuclear hydrogen production system. The authors studied the influence of various factors on hydrogen leakage and diffusion, such as wind speed, leakage direction, leakage diameter, leakage height, and leakage angle. The PHARA model was created by Wei et al. [20] to perform consequence analysis in order to improve the safety and layout of hydrogen refueling stations (HRSs), as well as evaluate and control the risks associated with hydrogen refueling stations in urban environments. Xing et al. [21] conducted an investigation on how different design parameters, such as storage capacity, mass flow rate, storage pressure, and storage temperature, affect accidents resulting from hydrogen leakage in hydrogen storage systems. Their approach entails utilizing a quantitative risk assessment methodology that encompasses data collection, hazard identification, frequency analysis, consequence evaluation, and risk assessment. Wang et al. [22] employed a Computational Fluid Dynamics (CFD) tool, along with a site-specific 3D geometry model to assess the risks associated with hydrogen leaks from fuel cell trucks at hydrogen refueling stations. CFD-based models also utilized in combination with predictable models to anticipate disasters and the behavior of leaked hydrogen in hydrogen facilities [23,24].

Wang and Gao [25] presented a dynamic risk analysis method using dynamic Bayesian network for hydrogen refueling stations to determine the critical fundamental events affecting the hydrogen leakage probability and proposed corresponding measures to reduce the risk. Ghasemi Pirbalouti et al. [26] proposed an advanced framework for leakage risk assessment of hydrogen refueling stations using interval-valued spherical fuzzy sets (IV-SFS). They integrated the Bow-tie analysis and IV-SFS to deal with the subjectivity and uncertainty of the risk assessment process. They applied their framework to real hydrogen refueling stations and illustrated the causality of undesired events and the decision-maker's thoughts about risk management. They found that jet fire was the most likely accident in the case of liquid hydrogen leakage, and that equipment failure was the most likely cause of hydrogen leakage. Haugom and Friis-Hansen [27] developed a model based on the Bayesian network in order to determine the importance of factors that can have an effect on the consequences of hydrogen leakage. In order to identify various scenarios resulting from leakage in liquid hydrogen storage systems and learn about the data needed for quantitative risk assessment, Correa-Jullian and Groth [28] developed a model using FTA, FMEA, and ESD methods. Zhang et al. [29] presented a fuzzy dynamic Bayesian network-based dynamic risk assessment approach for hydrogen leakage at hydrogen facilities. The research examined the main risk factors that contribute to hydrogen leak explosions and developed a dynamic Bayesian network model using the Bow-Tie model. The model utilizes expert scoring and fuzzy set theory to ascertain event prior probabilities.

Some studies investigated other aspects of hydrogen risk management, including Kahligh et al. [30] proposed a risk-constrained energy management model for an isolated multi-energy microgrid that incorporates hydrogen storage and liquified natural gas (LNG). The authors used the information gap decision theory method to deal with uncertainties in various energy sources and demands and to provide both robust and opportunistic strategies. The results showed that the proposed model could achieve different levels of profit depending on the risk attitude of the decision maker. Yazdi et al. [31] proposed a holistic taxonomy of resilience performance, a novel qualitative resilience assessment method using intuitionistic fuzzy logic, and a practical case study on a hybrid wind-hydrogen power plant. They identified the most critical resilience indicators and sustainability contributing factors for hydrogen energy infrastructure and provided a useful tool for decision-making and policymaking. Azadnia et al. [32] examined the risks and challenges of implementing a green hydrogen supply chain in Europe, focusing on hard-to-abate sectors such as steel, chemical, cement, and refinery industries. The authors identified 43 risk factors in 7 categories based on expert opinions and ranked them using the best-worst method. They also proposed mitigation strategies and policy recommendations for the most important risk factors. The paper highlights the need for supportive standards and regulations for green hydrogen production and distribution in Europe. Pasman et al. [33] provided an overview of the new technologies and processes that are being developed to achieve decarbonization and reduce greenhouse gas emissions, such as hydrogen, batteries, and electrification. They also discussed the potential hazards and risks associated with these technologies and processes, which are often unknown or poorly understood.

Fig. 1. Various risk management tools in hydrogen risk management.

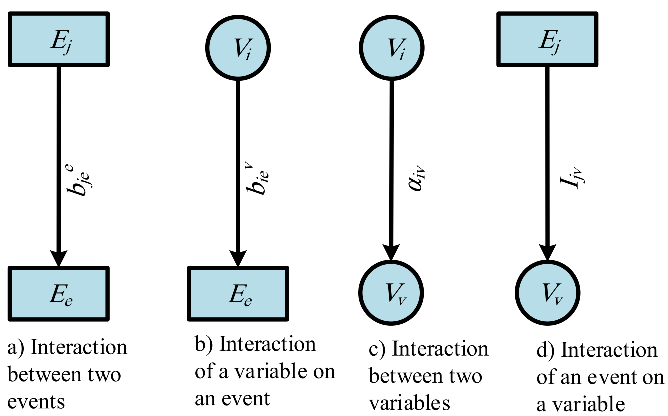


Fig. 2. Different scenarios of influence in deterministic R.Graph method.

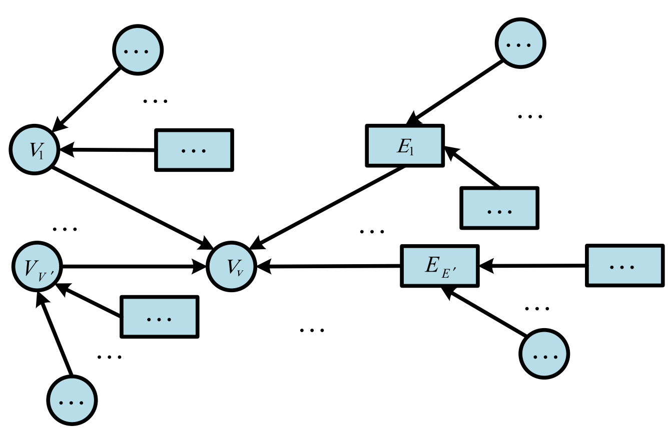


Fig. 3. A typical R.Graph diagram.

They emphasized the need for hazard identification and scenario definition, as well as the use of data and standards to facilitate safety analyses and inherently safer design.

Fig. 1 illustrates the different tools and methods that are employed in hydrogen risk management.

Using each method in hydrogen risk management has its own limitations. For example, in certain risk management issues, decision-makers are interested in determining the extent of change in various risks associated with the occurrence of specific events [34]. Since many variables in the real world have a continuous nature, it is necessary to develop an appropriate model that can determine the predicted percentage of change in the desired variables. However, most existing methods in the field of hydrogen risk management assume discrete values for risk factors and assign probabilities of occurrence and non-occurrence to each discrete value, treating them as scenarios [35]. Consequently, due to the consideration of discrete values, these methods do not provide a reliable estimate of the continuously predicted values for decision-makers [35]. To address these challenges, which can introduce uncertainty into the decision-making process of safety engineers, it is essential to employ more advanced models. One of the newly developed methods in the literature is the deterministic R.Graph method [35], which offers an innovative approach for predicting the effects of risk factors on each other and has the capability to account for continuous changes in risk factors. While this model does have also some limitations, such as assuming certainty in the problem, which makes it unsuitable for probabilistic cases, it can be useful in addressing the deficiencies of the current model in hydrogen risk managment.

Therefore, the aim of this research study is to develop a probabilistic model of R.Graph to assess the impacts of hydrogen leakage on safety, operational integrity, and the environment in a generation unit. Additionally, the study aims to identify and recommend the best technological tools and methods for reducing the occurrence probability and minimizing the impacts of various risks associated with hydrogen leakage. The ultimate goal is to enhance safety design and risk management practices, ensuring the safe operation of the hydrogen generation unit while mitigating potential hazards and environmental impacts.

The paper is organized as follows: In Section 2, a brief definition of the deterministic R.Graph method and the concept of risk is provided. In Section 3, the proposed probabilistic R.Graph method and framework for hydrogen leakage risk management and safety planning are presented. Section 4 includes a case study on hydrogen leakage risk management in a hydrogen generation unit, solved using the proposed framework from Section 3, along with the discussion. Section 5 comprises the conclusion, discussion, and future research directions of the current study.

2. Preliminaries

In this part, the main definitions of deterministic R.Graph are proposed, which are prerequisites for proposing probabilistic R.Graph in Section.

2.1. Deterministic R.Graph method

The R.Graph method is a deterministic chain of acyclic causal factors affecting each other, in which the aim is to examine the percentage of change in each of the factors due to changes in other factors or the occurrence of different events within a constant time interval, assuming the certainty of events. In this method, the concepts are defined as follows [35]:

Variable: Any factor that can accept a value and quantity as intensity. If there is a cause-and-effect relationship between two variables, a change in the causal variable can lead to a change in another variable. In the R.Graph method, the *i*-th variable is represented as V_i and shown in the form of a circle.

Event: An element that cannot be defined with a specific intensity or quantity and is generally represented as either zero or one. The occurrence of an event can trigger other events or lead to changes in the values of other variables. In the R.Graph method, event *j* is represented as $E(j)$ and shown as a rectangle.

Factor: Each of the variables or events is referred to as a factor.

Parent: In the presence of a cause-and-effect relationship between two factors, the one that influences the other factor is called the parent.

Different scenarios of the effects of events and occurrences on each other are illustrated in Fig. 2, and a type of R.Graph is shown in Fig. 3.

Definition 1. In the R.Graph method, risk or deviations can be defined as the precise deviation of a parameter from its changed value, which can be determined using Eqs. (1) and (2) [35].

$$R = \frac{|Changed\ value\ - Initial\ value|}{Initial\ value} \tag{1}$$

where, if e_2 represents the changed value and e_1 represents the initial value, the risk (effect) value is determined using Eq. (2)

$$R = \frac{|e_2 - e_1|}{e_1} \quad R \geq 0 \tag{2}$$

Definition 2. In the R.Graph method, the way of influencing different factors is represented through the R.Graph matrix ($R^{R.Graph}$) as follows [35]:

$$R^{R.Graph} = \begin{bmatrix} V-V = \begin{array}{c|cccccc|} & \boldsymbol{V_1} & \boldsymbol{V_2} & \dots & \boldsymbol{V_v} & \dots & \boldsymbol{V_V} \\ \boldsymbol{V_1} & 0 & \alpha_{12} & \dots & \alpha_{1v} & \dots & \alpha_{1V} \\ \boldsymbol{V_2} & \alpha_{21} & 0 & \dots & \alpha_{2v} & \dots & \alpha_{2V} \\ \dots & \dots & \dots & 0 & \dots & \dots & \dots \\ \boldsymbol{V_v} & \alpha_{v1} & \alpha_{v2} & \dots & 0 & \dots & \alpha_{vV} \\ \dots & \dots & 0 & \dots & \dots & 0 & \dots \\ \boldsymbol{V_V} & \alpha_{V1} & \alpha_{V2} & 0 & \alpha_{Vv} & \dots & 0 \end{array} & V-E = \begin{array}{c|cccccc|} & \boldsymbol{E_1} & \boldsymbol{E_2} & \dots & \boldsymbol{E_e} & \dots & \boldsymbol{E_E} \\ \boldsymbol{V_1} & b_{11}{}^{v} & b_{12}{}^{v} & \dots & b_{1e}{}^{v} & \dots & b_{1E}{}^{v} \\ \boldsymbol{V_2} & b_{21}{}^{v} & b_{22}{}^{v} & \dots & b_{2e}{}^{v} & \dots & b_{2E}{}^{v} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \boldsymbol{V_v} & b_{v1}{}^{v} & b_{v2}{}^{v} & \dots & b_{ve}{}^{v} & \dots & b_{vE}{}^{v} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \boldsymbol{V_V} & b_{V1}{}^{v} & b_{V2}{}^{v} & \dots & b_{Ve}{}^{v} & \dots & b_{VE}{}^{v} \end{array} \\ E-V = \begin{array}{c|cccccc|} \boldsymbol{E_1} & 0 & b_{12}{}^{e} & \dots & b_{1e}{}^{e} & \dots & b_{1E}{}^{e} \\ \boldsymbol{E_2} & b_{21}{}^{e} & 0 & \dots & b_{2e}{}^{e} & \dots & b_{2E}{}^{e} \\ \dots & \dots & \dots & 0 & \dots & \dots & \dots \\ \boldsymbol{E_e} & b_{e1}{}^{e} & b_{e2}{}^{e} & \dots & 0 & \dots & b_{eE}{}^{e} \\ \dots & \dots & \dots & \dots & \dots & 0 & \dots \\ \boldsymbol{E_E} & b_{E1}{}^{e} & b_{E2}{}^{e} & 0 & b_{Ee}{}^{e} & \dots & 0 \end{array} & E-E = \begin{array}{c|cccccc|} \boldsymbol{E_1} & 0 & b_{12}{}^{e} & \dots & b_{1e}{}^{e} & \dots & b_{1E}{}^{e} \\ \boldsymbol{E_2} & b_{21}{}^{e} & 0 & \dots & b_{2e}{}^{e} & \dots & b_{2E}{}^{e} \\ \dots & \dots & \dots & 0 & \dots & \dots & \dots \\ \boldsymbol{E_e} & b_{e1}{}^{e} & b_{e2}{}^{e} & \dots & 0 & \dots & b_{eE}{}^{e} \\ \dots & \dots & \dots & \dots & \dots & 0 & \dots \\ \boldsymbol{E_E} & b_{E1}{}^{e} & b_{E2}{}^{e} & 0 & b_{Ee}{}^{e} & \dots & 0 \end{array} \end{bmatrix} \tag{3}$$

$, v = 1, \dots V, e = 1, \dots, E$

where

$$\begin{cases} \forall i = 1, \dots, V \ and \ \forall j = 1, \dots, E, \ I_{jv}, \alpha_{iv} \ \in \mathbb{R} \\ \forall i = 1, \dots, V \ and \ \forall j = 1, \dots, E, b_{ie}{}^{v}, b_{je}{}^{e} \in \{0, 1\} \end{cases}.$$

According to Eq. (3), the R.Graph matrix is composed of four separate submatrices, indicating the influences of the risks of variables on other variables, the influences of the risks of variables on events, the influences of the risks of events on variables, and the influences of the risks of events on other events. Furthermore, in the above equation, α_{iv} represents the risk of variable *v* due to a 100% risk in variable *i*. As the R.Graph is non-cyclic, if α_{iv} takes a value, then $\alpha_{vi} = 0$. Additionally, I_{jv} represents the risk of variable *v* due to the occurrence of event *j*. In the above equations, $b_{je}{}^{e}$ and $b_{ie}{}^{v}$ indicate the susceptibility of event *e* occurring due to event *j* and the variable V_i, respectively. If $b_{je}{}^{e}$ and $b_{ie}{}^{v}$ take the value of one, it indicates the susceptibility of event *e* occurring due to event *j* and the variable *i*. If they are zero, it indicates non-susceptibility. Here, as the R.Graph is non-cyclic, if $b_{je}{}^{e} = 1$ and $b_{ie}{}^{v} = 1$, we will have $b_{ej}{}^{e} = 0$ and $b_{ei}{}^{v} = 0$.

Definition 3. The risk of variable V_v, denoted as $R(V_v|Par(V_v))$, can be defined as follows [35]:

$$R(V_v|Par(V_v)) = \left(\sum_{i=1}^{\acute{V}} \alpha_{iv} R(V_i|Par(V_i)) + \sum_{j=1}^{\acute{E}} I_{jv} \right) \times (1 - AR_v{}^{v}) \tag{4}$$

In the above equation, I_{kv} represents the influence of events that are parents of V_v, and E_j also affects their risk. Additionally, $AR_v{}^{v}$ indicates the acceptable level of risk for variable V_v, which has a value between zero and one.

Given that the R.Graph method is a new approach, in the probabilistic section, more attention is focused on deriving its relationships and concepts.

3. The proposed method

This section describes a new framework for risk management called "Probabilistic R.Graph" based on the deterministic R.Graph method to examine the impact of a chain of potential factors on various variables under investigation. In this new framework, first, assuming the probabilistic nature of the model, we define the concepts of variable and event in the probabilistic mode, which differ in interpretation from the deterministic mode, as follows:

Variable: A variable is a factor that exhibits intensity when a cause-and-effect relationship exists between two variables. In cases where such a relationship is established, a change in the causal variable can result in a corresponding alteration in the affected variable. Similarly, when a causal relationship exists between a single variable and an event, a modification in the cause variable can influence the probability of the occurrence of the associated event.

Event: An entity that has a probability. The probability of an event occurring can cause an increase or decrease in the occurrence of other events or a change in the values of other variables.

Definition 4. In the probabilistic R.Graph method, the influence of different factors is represented through the R.Graph matrix ($R^{R.Graph}$) according to Eq. (5). It illustrates how the factors interact and impact each other within the framework.

$$R^{R.Graph} = \begin{bmatrix} E-E & E-V \\ V-V & V-E \end{bmatrix} \quad (5)$$

According to Eq. (5), similar to the deterministic R.Graph model the probabilistic R.Graph matrix is formed by four separate sub-matrices, where $V-V$ and $E-V$ matrices are obtained from Eq. (3) and for two other matrices due to probabilistic nature of the model, we have the following new definitions:

$$V-E = \begin{array}{c} \\ V_1 \\ V_2 \\ \cdots \\ V_v \\ \cdots \\ V_V \end{array} \overset{\begin{array}{cccccc} E_1 & E_2 & \cdots & E_e & \cdots & E_E \end{array}}{\begin{bmatrix} b_{11}{}^v & b_{12}{}^v & \cdots & b_{1e}{}^v & \cdots & b_{1E}{}^v \\ b_{21}{}^v & b_{22}{}^v & \cdots & b_{2e}{}^v & \cdots & b_{2E}{}^v \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ b_{v1}{}^v & b_{v2}{}^v & \cdots & b_{ve}{}^v & \cdots & b_{vE}{}^v \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ b_{V1}{}^v & b_{V2}{}^v & \cdots & b_{Ve}{}^v & \cdots & b_{VE}{}^v \end{bmatrix}}, v = 1,\ldots V, e = 1,\ldots,E, \forall i = 1,\ldots,V, \quad (6)$$

in Eq. (6), $V-E$ represents the matrix depicting the influence of variables on events. In this matrix, E_e represents the e-th event, and $b_{ve}{}^v$ indicates the extent of the probability change of E_e due to a 100% change and risk in the v-th variable. It is worth noting that in this relation, if $b_{ve}{}^v$ takes a certain value, it signifies the susceptibility of e events to occur due to the risk in the i-th variable, and if it is zero, it indicates the insensitivity.

$$E-E = \begin{array}{c} \\ E_1 \\ E_2 \\ \cdots \\ E_e \\ \cdots \\ E_E \end{array} \overset{\begin{array}{cccccc} E_1 & E_2 & \cdots & E_e & \cdots & E_E \end{array}}{\begin{bmatrix} P(E_1) & b_{12}{}^e & \cdots & b_{1e}{}^e & \cdots & b_{1E}{}^e \\ b_{21}{}^e & P(E_2) & \cdots & b_{2e}{}^e & \cdots & b_{2E}{}^e \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ b_{e1}{}^e & b_{e2}{}^e & \cdots & P(E_e) & \cdots & b_{eE}{}^e \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ b_{E1}{}^e & b_{E2}{}^e & 0 & b_{Ee}{}^e & \cdots & P(E_E) \end{bmatrix}}, e = 1,\ldots,E, \forall j = 1,\ldots,E, \quad (7)$$

in Eq. (7), $E-E$ represents the matrix depicting the influence of events on other events. In this matrix, $b_{je}{}^e$ indicates the extent of risk and percentage change in the probability of event e due to the occurrence of event j. It is worth noting that in this formula., if $b_{je}{}^e$ takes a certain value, it signifies the susceptibility of event e to occur due to the occurrence of event j, and if it is zero, it indicates insensitivity. It is worth mentioning that the main diagonal represents the initial probability of each event, i.e., $P(E_e)$ is equal to the probability of event e occurring given that event e has no parents.

Definition 5. The increase or decrease in the changes in the probability of event E_j based on the changes in the occurrence of event E_i can be obtained using Eq. (8) when E_j directly affects the occurrence of E_j.

$$R(E_j|E_i) = b_{ij}{}^e R(E_i) \quad (8)$$

in Eq. (8)), $b_{ij}{}^e$ represents the degree of influence of event E_i on E_j, and $R(E_i)$ indicates the changes in event E_i based on other factors. It is worth mentioning that this type of modeling is well-known as probabilistic structural modeling, and its details are discussed in the EXIT cross-impact analysis method [36]. Generally, structural methods are approaches that do not require explicit probability assessments and only model the interdependencies among scenarios. This characteristic distinguishes structural modeling techniques from other types of simulations or models.

Similarly, we can determine the increase or decrease in the changes in the probability of event E_j based on the changes and risks in variable V_i using Eq. (9).

$$R(E_j|V_i) = b_{ij}{}^v R(V_i) \quad (9)$$

In this relation, $b_{ij}{}^v$ represents the degree of influence of variable V_i on E_j, and $R(V_i)$ indicates the changes and risks associated with variable V_i in relation to other factors.

Definition 6. Similar to Definition 5, the risk and changes in variable V_v can be defined in terms of the changes in the occurrence of E_i or the changes in variable V_v, according to Eq. (10).

$$\begin{cases} R(V_v|E_i) = I_{iv} R(E_i) \\ R(V_v|V_i) = \alpha_{iv} R(V_i) \end{cases} \quad (10)$$

In this equation., I_{iv} represents the risk of variable V_v due to the occurrence of event E_i, and α_{iv} represents the changes in variable V_v due to a percentage change in variable V_i.

Definition 7. In general, the changes in the probability of E_j based on the changes in the occurrence of E_i can be defined in different scenarios as direct impact (when E_i is the parent of E_j) or indirect impact (when E_i is not the parent of E_j but still has an effect), using Eq. (11).

$$R(E_j|E_i) = \begin{cases} b_{ij}{}^e R(E_i) + \sum_{e=1}^{E} b_{ej}{}^e R(E_e|E_i) + \sum_{i=1}^{V} b_{ij}{}^v R(V_i|E_i) & E_i \epsilon Par(E_j) \\ \sum_{e=1}^{E} b_{ej}{}^e R(E_e|E_i) + \sum_{i=1}^{V} b_{ij}{}^v R(V_i|E_i) & E_i \notin Par(E_j) \end{cases} \quad (11)$$

As observed, Eq. (11) consists of three terms when E_i is the parent of E_j.The first term represents the direct impact of E_i on the probability of E_j. The second term represents the indirect impact of E_i, meaning that E_i affects other events that directly influence E_j. The third term represents the indirect impact of E_i on V variables, which in turn directly affects E_j.

Table 1
Suggested severity degrees of different risk types.

Risk Type	Severity Level	Weight (γ_i)	Severity Description
Safety	Low	3	Negligible safety risks, minimal impact on personnel or public safety.
	Moderate	5	Some safety concerns, potential for minor injuries or incidents.
	High	7	Significant safety risks, potential for serious injuries or incidents.
	Very high	9	Critical safety risks, potential for life-threatening situations.
Economic	Low	1	Minimal economic impact, manageable costs, and easily recoverable losses.
	Moderate	3	Moderate economic impact, some financial burden, and recoverable losses.
	High	5	High economic impact, significant financial costs, and notable disruptions.
	Very high	7	Very high economic impact, substantial losses, and long-lasting consequences.
Environment	Low	2	Negligible impact on climate change, minor contribution to greenhouse gases.
	Moderate	4	Moderate impact on climate change, noticeable greenhouse gas emissions.
	High	6	Significant impact on climate change, substantial greenhouse gas contribution.
	Very high	8	Very high impact on climate change, critical greenhouse gas emissions.

Based on Eq. (11), the impacts on the probability of E_j in terms of changes in a specific variable V_i can be defined as Eq. (12).

$$R(E_j|V_i) = \begin{cases} b_{ij}{}^{v}R(V_i) + \sum_{e=1}^{E} b_{ej}{}^{e}R(E_e|V_i) + \sum_{v=1}^{V} b_{ij}{}^{v}R(V_v|V_i)\ V_i \epsilon Par(E_v) \\ \sum_{e=1}^{E} b_{ej}{}^{e}R(E_e|V_i) + \sum_{v=1}^{V} b_{ij}{}^{v}R(V_v|V_i)\ V_i \notin Par(E_j) \end{cases} \quad (12)$$

Eqs. (11) and (12) can be defined for the variable V_v in terms of the probability changes of E_i and the risk V_i by utilizing Eqs. (13) and (14).

$$R(V_v|E_i) = \begin{cases} I_{iv}R(E_i) + \sum_{e=1}^{E} I_{ev}R(E_e|E_i) + \sum_{k=1}^{V} \alpha_{kv}R(V_k|E_i)\ E_i \epsilon Par(V_v) \\ \sum_{e=1}^{E} I_{ev}R(E_e|E_i) + \sum_{k=1}^{V} \alpha_{kv}R(V_v|E_i)\ E_i \notin Par(V_v) \end{cases} \quad (13)$$

$$R(V_v|V_i) = \begin{cases} \alpha_{iv}R(V_i) + \sum_{e=1}^{E} I_{ev}R(E_e|V_i) + \sum_{k=1}^{V} \alpha_{kv}R(V_k|V_i)\ V_i \epsilon Par(V_v) \\ \sum_{e=1}^{E} I_{ev}R(E_e|V_i) + \sum_{k=1}^{V} \alpha_{kv}R(V_k|V_i)\ V_i \notin Par(V_v) \end{cases} \quad (14)$$

Definition 8. In Eqss (11) to (14), the risk of an event or variable is

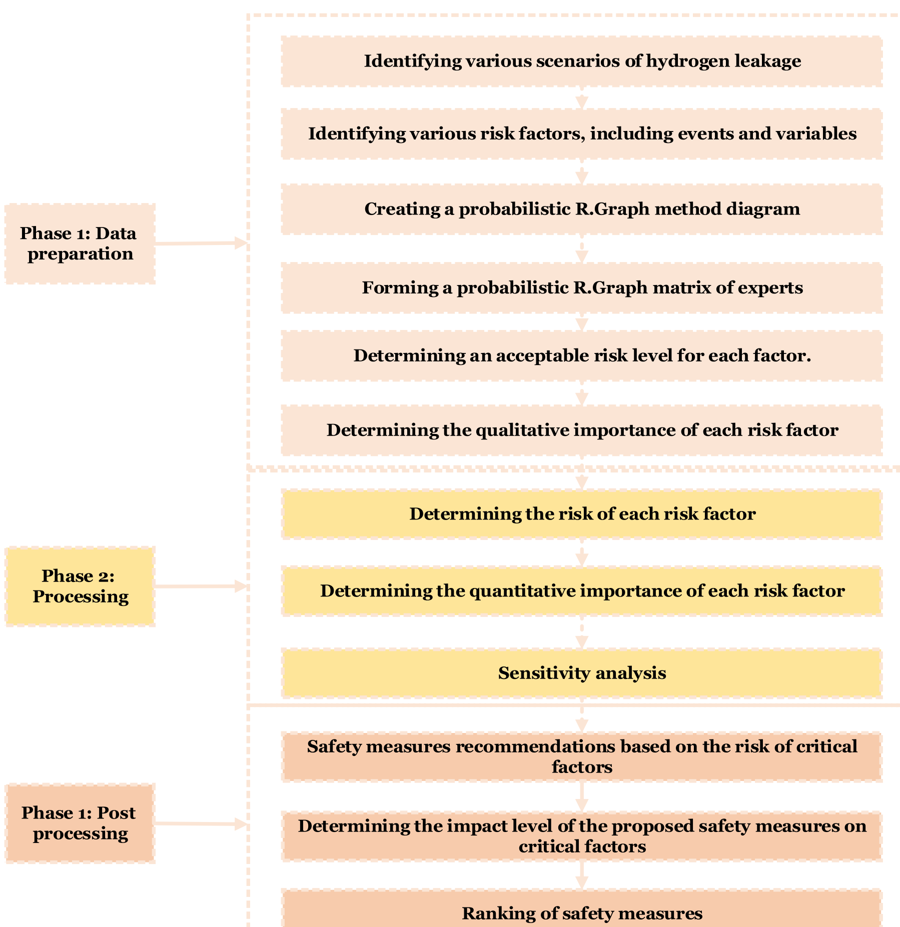


Fig. 4. The proposed framework of hydrogen risk management.

defined in terms of a specific event or variable. It is possible to define the probability changes of an event (Eq. (15)) or the changes in risk of a variable (Eq. (16)) in terms of all its parents.

$$\begin{cases} R(E_j|Par(E_j)) = \sum_{i=1}^{V} b_{ij}{}^{v} R(V_i|Par(V_i)) + \sum_{e=1}^{E} b_{ej}{}^{e} R(E_e|Par(E_e)) \times (1 - AR_j) \\ R(E_j) = P(E_j)(1 - AR_j) \ \text{ if } E_j \text{ has no parent} \end{cases} \tag{15}$$

$$R(V_v|Par(V_v)) = \left(\sum_{i=1}^{V} \alpha_{iv} R(V_i|Par(V_i)) + \sum_{j=1}^{E} I_{jv} R(E_i|Par(E_i)) \right) \times (1 - AR_i) \tag{16}$$

In Eqs. (15) and (16), AR_j and AR_i represent the acceptable risk percentage for a 100% risk in event E_j and variable V_i. Whereas $1 - AR_j$ and $1 - AR_i$ represent the percentage of risk that is not acceptable and becomes a concern. In general, the acceptable risk matrix for E events and V variables can be represented by AR_i, and it can be defined using Eq. (17).

$$AR = [AR_1, \vdots AR_i \ldots, AR_{E+V}] \tag{17}$$

$0 \leq AR_i \leq 1$ where

It should be noted that in the probabilistic R.Graph method, we have assumed that the occurrence of risks in each factor is always attributed to the realization of an event. Consequently, only events are considered that may not necessarily have parents (preceding events). In this scenario, the risk associated with these parentless events is calculated using Eq. (15) in the second mode.

See example 1 based on Fig. 4 in Appendix 0.

Definition 9. In the R.Graph method, assuming that the total number of variables is represented by V and the total number of events is represented by E, the relative importance of each factor is obtained based on its impact on the risk of variables and the probability of events, using Eq. (18).

$$\begin{cases} w_i{}^{v} = \dfrac{\sum_{v=1}^{V} \gamma_v |R(V_v|V_i)| + |R(V_i)| + \sum_{e=1}^{E} \gamma_e |R(E_e|V_i)|}{\left(\sum_{i=1}^{V} \sum_{v=1}^{V} \gamma_v |R(V_v|V_i)| + \gamma_i |R(V_i)| \right) + \left(\sum_{j=1}^{E} \gamma_j |R(E_j)| + \sum_{e=1}^{E} \gamma_e |R(E_e|E_j)| + \sum_{v=1}^{V} \gamma_v |R(V_v|E_j)| \right)} \\ w_j{}^{e} = \dfrac{\gamma_j |R(E_j)| + \sum_{v=1}^{V} \gamma_j |R(V_v|E_j)| + \sum_{e=1}^{E} \gamma_e |R(E_e|E_j)|}{\left(\sum_{i=1}^{V} \sum_{v=1}^{V} \gamma_v |R(V_v|V_i)| + \gamma_i |R(V_i)| \right) + \left(\sum_{j=1}^{E} \gamma_j |R(E_j)| + \sum_{e=1}^{E} \gamma_e |R(E_e|E_j)| + \sum_{v=1}^{V} \gamma_v |R(V_v|E_j)| \right)} \end{cases} \tag{18}$$

where the relative importance of i-th factor or its severity is denoted by γ_i.

Proof. In the deterministic R.Graph method, the relative importance of each factor is obtained as follows [24]:

$$\begin{cases} w_i{}^{v} = \dfrac{\sum_{v=1}^{V} |R(V_v|V_i)| + |R(V_i)|}{\sum_{i=1}^{V} \sum_{v=1}^{V} (|R(V_v|V_i)| + |R(V_i)|) + \sum_{j=1}^{E} \sum_{v=1}^{V} |R(V_v|E_j)|} \\ w_j{}^{e} = \dfrac{\sum_{v=1}^{V} |R(V_v|E_j)|}{\sum_{i=1}^{V} \sum_{v=1}^{V} (|R(V_v|V_i)| + |R(V_i)|) + \sum_{j=1}^{E} \sum_{v=1}^{V} |R(V_v|E_j)|} \end{cases}$$

In this relation, the relative importance of each factor is determined based on its own risk value and its impact on the risk of others. If we expand it based on the risk in probabilistic values and the influence of variable values on the probabilities and also consider the relative importance of each factor denoted by γ_i, which does not exist in the deterministic method, the relation is proven.

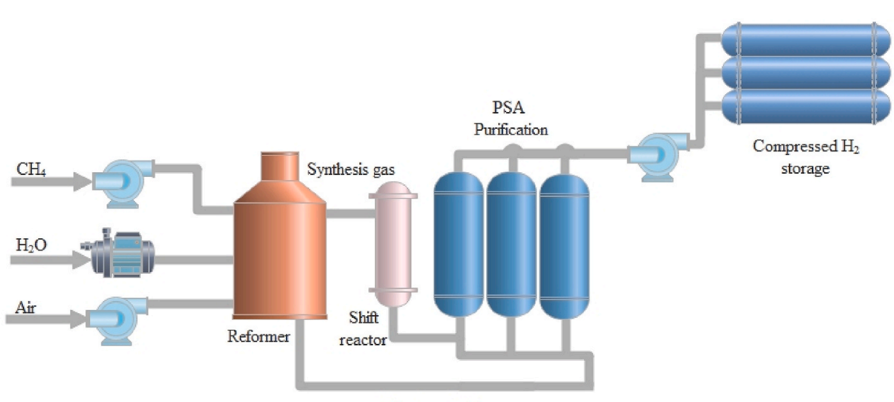


Fig. 5. Hydrogen production process.

Table 2
The selected factors in hydrogen leakage risk management.

Factor	Definition	Factors Affected	Severity Category	Rating (1–9)
E0 - Hydrogen Leakage	The occurrence of hydrogen leakage. Hydrogen leakage refers to the unintended release of hydrogen gas from its intended containment.	E1, E2, E3	Safety	7
E1 - Low Hydrogen Leakage	Low Hydrogen Leakage denotes the occurrence of minor or low-level hydrogen leaks. These leaks may not pose immediate safety risks, but they require attention and management.	E4, E5, E6, E7, V1, V2	Safety	5
E2 - Medium Hydrogen Leakage	Medium Hydrogen Leakage represents leaks of a higher magnitude compared to low-level leakage. They may pose moderate safety risks and require prompt response and mitigation.	E4, E5, E6, E7, V1,V2	Safety	7
E3 - High Hydrogen Leakage	High Hydrogen Leakage signifies substantial and critical hydrogen leaks that can lead to significant safety hazards and immediate response is crucial to prevent adverse consequences.	E4, E5, E6, E7, V1,V2	Safety	9
E4 - Frostbite	Frostbite occurs when human tissues are exposed to extremely cold temperatures, often due to handling or storing cryogenic hydrogen.	V3, V4	Safety	5
E5 - Asphyxiation	Asphyxiation happens when the concentration of hydrogen gas displaces oxygen in the air, posing a serious risk to human life.	V3, V4	Safety	7
E6 - Fire	Fire represents the uncontrolled combustion of hydrogen gas, leading to flames and heat release. Fires can cause injuries and property damage.	V1, V2, V3, V4, V7, V8	Safety	9
E7 - Explosion (Blast)	Hydrogen Blast refers to an incident where a release of hydrogen gas occurs resulting in a sudden and violent explosion. This event poses serious safety risks to personnel, equipment, and surrounding areas.	V1, V2, V3, V4, V7, V8	Safety	9
V1 - Hydrogen Loss (Variable)	Hydrogen Loss represents the amount of hydrogen lost due to leakage.	V5	Economic	3
V2 - Greenhouse Gas Emission	Greenhouse Gas Emission refers to the release of greenhouse gases, including those resulting from hydrogen fires.	V6	Environmental	6
V3 - Human Deaths	Human Deaths represent the tragic loss of human life resulting from hydrogen-related incidents, such as asphyxiation, fires, or explosions.	V6, V15	Safety	9
V4 - Human Injuries	Human Injuries include physical harm and health issues caused by exposure to hydrogen-related hazards, such as fires or asphyxiation.	V6, V15	Safety	9
V5 - Reduced Hydrogen Supply	Reduced Hydrogen Supply refers to a decrease in the availability or accessibility of hydrogen due to hydrogen loss.	V9, V13	Economic	3
V6 - Standard/ Regulatory Violations	Standard/Regulatory Violations occur when hydrogen-related safety standards and regulations are not followed.	V14	Safety	3
V7 - Equipment Damage	Equipment Damage includes harm to machinery, instruments, or infrastructure resulting from hydrogen-related incidents, particularly fires.	V10, V11	Economic	5
V8 - Structural Damage	Structural Damage encompasses harm to buildings, facilities, or structures caused by hydrogen-related incidents, particularly fires.	V10, V11	Economic	5
V9 - Reputation Damage	Reputation Damage refers to the negative impact on the organization's image and brand resulting from reduced hydrogen supply.	V12	Economic	3
V10 - Downtime and Production Loss	Downtime and Production Loss represent the reduction or cessation of productive activities due to equipment or structural damage.	V15	Economic	5
V11 - Repair and Maintenance Costs	Repair and Maintenance Costs include expenses associated with restoring and maintaining equipment or structures damaged during incidents.	V15	Economic	5
V12 - Loss of Market Share	Loss of Market Share denotes the decline in an organization's market position resulting from reputation damage or supply disruptions.	V16	Economic	7
V13 - Logistic Disruption	Logistic Disruption refers to interruptions or delays in the supply chain caused by reduced hydrogen supply.	V15	Economic	5
V14 - Legal Penalties	Legal Penalties represent financial sanctions or legal consequences imposed on an organization due to regulatory violations.	V15	Economic	3
V15 - Total Cost	Total Cost encompasses the overall financial impact resulting from various factors, including safety risks, economic losses, and reputation damage.	V16	Economic	7
V16 - Energy Sales Revenue	Energy Sales Revenue represents the income generated from selling hydrogen or hydrogen-based products.		Economic	7

Suggested relative importance of each factor and severity degrees of different risk types is presented in Table 1.

3.1. Statement 1. the sensitivity analysis on the R.Graph matrix can be performed separately on each of the constituent matrices as follows

a) Sensitivity analysis on the $\boldsymbol{V-V}$ matrix

If we perform sensitivity analysis on the $V-V$ matrix considering the changes in the influence of variable V_i on other variables as ΔV_{iv}, then the overall sensitivity of the problem to variable V_i can be calculated using Eq. (19).

$$S|\Delta V_{iv} = \sum_{e=1}^{e} R(E_e|V_i + \Delta V_{iv}) - \sum_{e=1}^{e} R(E_e|V_i) + \sum_{v=1}^{V} R(V_v|V_i + \Delta V_{iv}) - \sum_{v=1}^{V} R(V_v|V_i) \tag{19}$$

where $S|\Delta V_{iv}$ represents the sensitivity of the problem with respect to ΔV_{iv}, which can be positive or negative. Additionally, $\sum_{e=1}^{e} R(E_e|V_i + \Delta V_{iv}) - \sum_{e=1}^{e} R(E_e|V_i)$ indicates the cumulative effect on probability values for ΔV_{iv}, and $\sum_{v=1}^{V} R(V_v|V_i + \Delta V_{iv}) - \sum_{v=1}^{V} R(V_v|V_i)$ represents the cumulative effect on the risk of variables for ΔV_{iv}. Essentially, changing the sensitivity on variable V_i means summing up all the rows related to V_i in the $V-V$ matrix with ΔV_{iv} and calculating the changes in the overall risk for that.

b) Sensitivity analysis on the $\boldsymbol{E-V}$ matrix

If we perform sensitivity analysis on the $E-V$ matrix considering the changes in the influence of event E_i on other variables as ΔE_{iv}, then the overall sensitivity of the problem to event E_i can be calculated using Eq. (20).

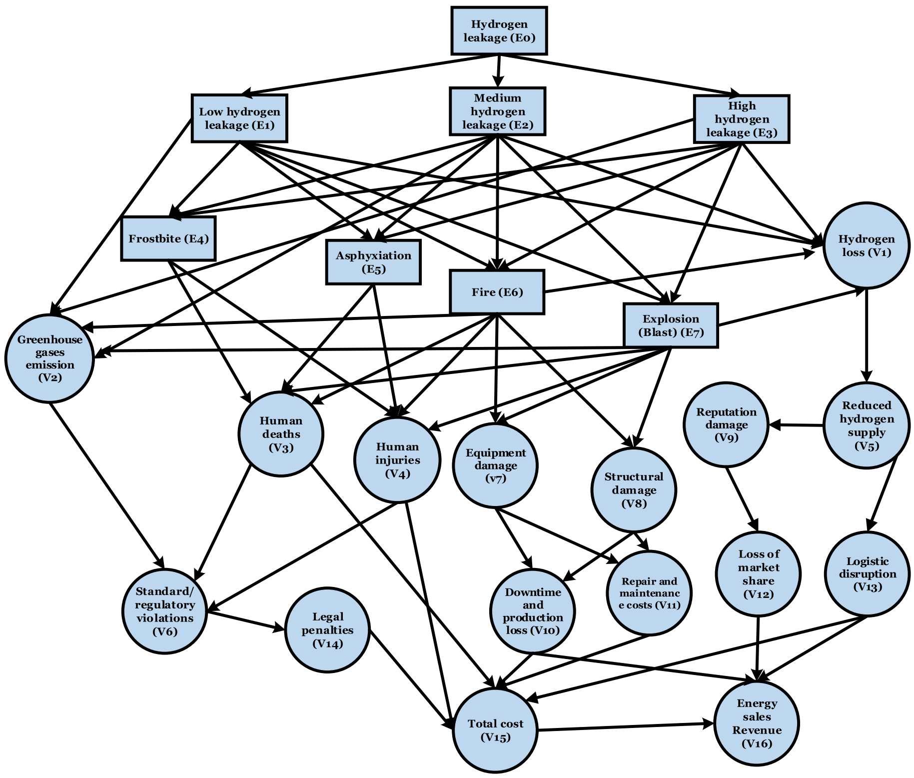


Fig. 6. Chain of factors and their impact and vulnerability in hydrogen leakage risk management.

Table 3
The $E-E$ matrix.

	E0	E1	E2	E3	E4	E5	E6	E7
E0	0.02	0.6	0.25	0.15	0	0	0	0
E1	0	0	0	0	0.1	0.1	0.55	0.45
E2	0	0	0	0	0.1	0.2	0.55	0.45
E3	0	0	0	0	0.3	0.7	0.5	0.5
E4	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0
E7	0	0	0	0	0	0	0	0

$$S|\Delta E_{iv} = \sum_{e=1}^{e} R(E_e|E_i + \Delta E_{iv}) - \sum_{e=1}^{e} R(E_e|E_i) + \sum_{v=1}^{V} R(V_v|E_i + \Delta E_{iv}) - \sum_{v=1}^{V} R(V_v|E_i) \tag{20}$$

where $S|\Delta E_{iv}$ represents the sensitivity of the problem with respect to ΔE_{iv}, which can be positive or negative. Additionally, $\sum_{e=1}^{e} R(E_e|E_i + \Delta E_{iv}) - \sum_{e=1}^{e} R(E_e|E_i)$ indicates the cumulative effect on probability values for ΔE_{iv}, and $\sum_{v=1}^{V} R(V_v|E_i + \Delta E_{iv}) - \sum_{v=1}^{V} R(V_v|E_i)$ represents the cumulative effect on the risk of variables for ΔE_{iv}. Essentially, changing the sensitivity on event E_i means summing up all the rows related to E_i in the $E-V$ matrix with ΔE_{iv} and calculating the changes in the overall risk for that.

c) Sensitivity analysis on the $\boldsymbol{E-E}$ matrix

If sensitivity analysis on the $E-E$ matrix is performed considering the changes in the influence of event E_i on other events as ΔE_{ie}, then the overall sensitivity of the problem to event E_i can be calculated using Eq. (21).

$$S|\Delta E_{ie} = \sum_{e=1}^{e} R(E_e|E_i + \Delta E_{ie}) - \sum_{e=1}^{e} R(E_e|E_i) + \sum_{v=1}^{V} R(V_v|E_i + \Delta E_{ie}) - \sum_{v=1}^{V} R(V_v|E_i) \tag{21}$$

where $S|\Delta E_{ie}$ represents the sensitivity of the problem with respect to ΔE_{ie}, which can be positive or negative. Additionally, $\sum_{e=1}^{e} R(E_e|E_i + \Delta E_{ie}) - \sum_{e=1}^{e} R(E_e|E_i)$ indicates the cumulative effect on

Table 4
The $E-V$ matrix.

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16
E0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0.03	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0.05	0.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0.1	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0.5	0.4	0.4	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0
E7	0.5	0.2	0.4	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0

Table 5
The $V-V$ matrix.

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16
V1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
V2	0	0	0	0	0	0.47	0	0	0	0	0	0	0	0	0	0
V3	0	0	0	0	0	0.33	0	0	0	0	0	0	0	0	0.3	0
V4	0	0	0	0	0	0.19	0	0	0	0	0	0	0	0	0.4	0
V5	0	0	0	0	0	0	0	0	0.5	0	0	0	0.5	0	0	0
V6	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
V7	0	0	0	0	0	0	0	0	0	0.47	1	0	0	0	0	0
V8	0	0	0	0	0	0	0	0	0	0.53	1	0	0	0	0	0
V9	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0
V10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.36
V11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0
V12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
V13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.2
V14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0
V15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.24
V16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

probability values for ΔE_{ie}, and $\sum_{v=1}^{V} R(V_v|E_i+\Delta E_{ie}) - \sum_{v=1}^{V} R(V_v|E_i)$ represents the cumulative effect on the risk of variables for ΔE_{ie}. Essentially, changing the sensitivity on event E_i means summing up all the rows related to E_i in the $E-E$ matrix with ΔE_{ie} and calculating the changes in the overall risk for that.

d) Sensitivity analysis on the $\boldsymbol{V-E}$ matrix.

If sensitivity analysis on the $V-E$ matrix is performed considering the changes in the influence of variable V_i on other events as ΔV_{ie}, then the overall sensitivity of the problem to variable V_i can be calculated using Eq. (22)

$$S|\Delta V_{ie} = \sum_{e=1}^{e} R(E_e|V_i+\Delta V_{ie}) - \sum_{e=1}^{e} R(E_e|V_i) + \sum_{v=1}^{V} R(V_v|V_i+\Delta V_{ie}) - \sum_{v=1}^{V} R(V_v|V_i) \tag{22}$$

where $S|\Delta V_{ie}$ represents the sensitivity of the problem to ΔV_{ie}, which can be positive or negative. Additionally, $\sum_{e=1}^{e} R(E_e|V_i+\Delta V_{ie}) - \sum_{e=1}^{e} R(E_e|V_i)$ indicates the total impact on the probability values for ΔV_{ie}, and $\sum_{v=1}^{V} R(V_v|V_i+\Delta V_{ie}) - \sum_{v=1}^{V} R(V_v|V_i)$ represents the total impact on the risk of variables for ΔV_{ie}. Essentially, the change in sensitivity to variable E_i means that in the $V-E$ matrix, all rows related to V_i are summed with ΔV_{ie}, and the overall risk changes for the problem are calculated accordingly.

3.1.1. Consistency assessment

In the probabilistic R.Graph method, the data is obtained from experts. However, experts may make mistakes in judgment, which can lead to inefficient use and transfer of specialized knowledge. It has been shown that human decision-making is inconsistent among individuals and within individuals. Several sources can contribute to this inconsistency, including the nature of the problem, the decision criteria of the judge, uncertainty in the judge's knowledge, or randomness in judgments [37]. One aspect that should be considered in the probabilistic R. Graph method is the examination of assessment inconsistencies. Therefore, before and after obtaining results using the proposed method, the following two conditions should be checked:

$$R(V_v)^{min} \leq R(V_v|Par(V_v)) \leq R(V_v)^{max} \tag{23}$$

$$R(E_j)^{min} \leq R(E_j|Par(E_j)) \leq R(E_j)^{max} \tag{24}$$

in Eq. (23), $R(V_v)^{min}$ and $R(V_v)^{max}$ represent the minimum and maximum possible risk values that $R(V_v|Par(V_v))$ can adopt. Similarly, in Eq. (24), $R(E_j)^{min}$ and $R(E_j)^{max}$ represent the minimum and maximum possible variations that $R(E_j|Par(E_j))$ can take.

It is worth noting that all events and variables may not simultaneously influence a factor. Therefore, in relationships, precision must be exercised to consider the maximum and minimum levels of concurrent influence of the factors in question.

3.1.2. Application of R.Graph in safety measure analysis

The probabilistic R.Graph method is presented as a framework for analyzing risk based on the predicted changes in the variables of interest within an organization, taking into account management factors such as acceptable risk factors. However, this method can also serve as a useful tool for examining the effects of various safety actions on the risks of variables or events, enabling appropriate planning for the implementation of preemptive actions.

It should be noted that any safety action that positively affects the risk value of one variable or event may have a negative impact on the risk value of other variables. If the percentage of improvement and worsening in the risk value of factor *i* (event or variable) which is shown by F_i due to the implementation of *j*-th action is indicated by $PR(F_i)^j$ and $NR(F_i)^j$, respectively, the adjusted risk value considering safety action *j* can be obtained using Eq. (25).

$$R(F_i)^m = R(F_i) \times (1-\theta) \tag{25}$$

in this equation, $R(F_i)$ represents the risk value without considering any acceptable risk values, and $R(F_i)^m$ represents the adjusted risk value. Additionally, we have:

$$\theta = \begin{cases} PR(F_i)^j & \text{Risk improving} \\ -NR(F_i)^j & \text{Risk worsening} \end{cases} \tag{26}$$

Eq. (25) defines the variable θ, where $PR(F_i)^j$ represents the risk improvement, and $-NR(F_i)^j$ represents the risk worsening due to the *j*-th safety action.

Finally, the overall impact of the *j*-th action on the entire problem considering the cost of its implementation, denoted by TE^j, can be calculated using Eq. (27):

$$TE^j = \frac{\sum_{i=1}^{V} R(F_i)^m - \sum_{i=1}^{V} R(F_i)}{C_j} \tag{27}$$

where C_j is the cost of implementation of *j*-th strategy and greater values of TE^j indicate greater utility of the proposed actions in reducing risk.

Table 6
The $V-E$ matrix.

	E0	E1	E2	E3	E4	E5	E6	E7
V1	0	0	0	0	0	0	0	0
V2	0	0	0	0	0	0	0	0
V3	0	0	0	0	0	0	0	0
V4	0	0	0	0	0	0	0	0
V5	0	0	0	0	0	0	0	0
V6	0	0	0	0	0	0	0	0
V7	0	0	0	0	0	0	0	0
V8	0	0	0	0	0	0	0	0
V9	0	0	0	0	0	0	0	0
V10	0	0	0	0	0	0	0	0
V11	0	0	0	0	0	0	0	0
V12	0	0	0	0	0	0	0	0
V13	0	0	0	0	0	0	0	0
V14	0	0	0	0	0	0	0	0
V15	0	0	0	0	0	0	0	0
V16	0	0	0	0	0	0	0	0

Table: Acceptable risk values for each of the factors

E0	E1	E2	E3	E4	E5	E6	E7	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16
0	0	0	0	0	0	0	0	0.3	0.1	0	0.1	0.3	0.4	0.2	0.2	0.4	0.1	0.1	0.3	0.1	0.4	0.1	0.1

Table 7
The risk values of different factors.

Factor	Risk without considering AR	Risk
E0	0.02	0.02
E1	0.012	0.012
E2	0.005	0.005
E3	0.003	0.003
E4	0.0026	0.0026
E5	0.0043	0.0043
E6	0.0109	0.0109
E7	0.0092	0.0092
V1	0.0109	0.0076
V2	0.0084	0.0076
V3	0.0098	0.0098
V4	0.0071	0.0064
V5	0.0109	0.0053
V6	0.0085	0.0048
V7	0.01	0.008
V8	0.01	0.008
V9	0.0055	0.0016
V10	0.01	0.0072
V11	0.02	0.0144
V12	0.0016	0.0004
V13	0.0055	0.0024
V14	0.0085	0.0029
V15	0.0179	0.012
V16	0.0093	0.0054

3.2. The framework of hydrogen energy risk management using proposed probabilistic R.Graph

In this section, a proposed model framework for risk management utilizing the probabilistic R.Graph is presented in the context of hydrogen energy. As discussed in section 3, the purpose of developing the probabilistic R.Graph method is to provide a comprehensive model to analyze possible variations in the organization's desired parameters based on various factors in the field of hydrogen leakage risk management. The aim is to determine preventive measures and assess relative readiness to cope with such risks. The summarized steps of the proposed method are as follows:

Phase One: Data preparation.

Step 0: *Identification of Risk Set, Events, and Variables Affecting Each Other Resulting from Hydrogen Leakage and Severity and Acceptable Level of Risk for Each of Them*

In this stage, the desired risks arising from hydrogen leakage are identified and evaluated based on organizational criteria. The interrelationships between various risks (variables and events) are determined through expert opinions. Subsequently, a cause-and-effect diagram is drawn to illustrate the influence of factors on each other. Furthermore, experts are requested to determine specific percentages for the effects and hazards of events on variables ($E-V$ matrix) and the impact of variables on each other ($V-V$ matrix). They are also asked to assess the impacts of events on the probability of other events ($E-E$ matrix) and the impact of variables on the probability of events ($V-E$ matrix). Moreover, the relative importance of each factor is considered based on its consequences, using Table 1 in the decision-making process. Finally, considering the organization's policies, objectives, and perspectives, the values relevant to the acceptance of variable risks are determined.

Phase Two: Processing.

Step 1: *Determining the Risk of Each Factor and Examining the Consistency of the Results*

Now, based on the obtained R.Graph matrix and acceptable risk matrices (AR), the risk level of each variable and the percentage changes in probabilities are calculated. Subsequently, the consistency of the re-

Table 8
Ranking results of factors and their sensitivity analysis values.

Factor	Weight (Considering severity)	Rank	Weight (Without severity)	rank	$(S_i\|\Delta_1 = 0.1)$	$(S_i\|\Delta_1 = 0.2)$	$(S_i\|\Delta_1 = -0.1)$
E0	0.2827	1	0.2703	1	0.0474	0.0948	−0.0474
E1	0.1019	4	0.1364	2	0.0213	0.0427	−0.0213
E2	0.0623	5	0.0596	5	0.0089	0.0178	−0.0089
E3	0.0574	6	0.0427	6	0.0053	0.0107	−0.0053
E4	0.0045	21	0.0061	21	0.0008	0.0016	−0.0008
E5	0.0127	16	0.0122	18	0.0013	0.0027	−0.0013
E6	0.1352	2	0.1006	3	0.0118	0.0236	−0.0118
E7	0.1089	3	0.081	4	0.01	0.0199	−0.01
V1	0.0136	15	0.0303	9	0.0012	0.0023	−0.0012
V2	0.0157	13	0.0175	15	0.0007	0.0015	−0.0007
V3	0.0345	7	0.0256	11	0.002	0.0041	−0.002
V4	0.0221	12	0.0165	16	0.0013	0.0027	−0.0013
V5	0.0082	18	0.0183	14	0.0012	0.0025	−0.0012
V6	0.0056	19	0.0124	17	0.0003	0.0006	−0.0003
V7	0.0274	9	0.0367	8	0.0021	0.0043	−0.0021
V8	0.0282	8	0.0378	7	0.0021	0.0043	−0.0021
V9	0.0014	23	0.0032	23	0.0001	0.0003	−0.0001
V10	0.0141	14	0.0188	13	0.0014	0.0029	−0.0014
V11	0.0226	11	0.0303	9	0.0016	0.0032	−0.0016
V12	0.0007	24	0.0007	24	0	0.0001	0
V13	0.0049	20	0.0066	20	0.0005	0.001	−0.0005
V14	0.0022	22	0.0048	22	0.0003	0.0006	−0.0003
V15	0.0242	10	0.0231	12	0.0011	0.0022	−0.0011
V16	0.009	17	0.0086	19	0	0	0

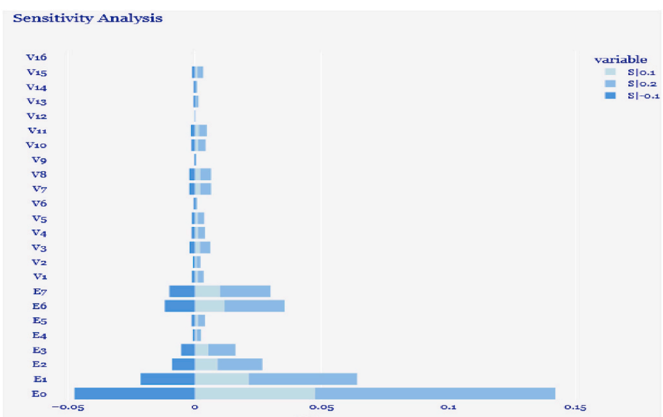


Fig. 7. Sensitivity analysis results for different values.

sults is examined using Eqs. (23) and (24).

Phase Three: Post-Processing.

Step 2: *Calculation of Weights for all Variables and Events*

In this step, the importance of each factor, whether a variable or an event, is determined based on its severity using Eq. (18)

Step 3: *Sensitivity Analysis*

To identify the sensitivity analysis of various factors in their input parameters, considering different values for ΔV_{iv}, ΔV_{ie}, ΔE_{iv}, and ΔE_{ie}, the sensitivity changes on the values of variables, events, and obtained risks are calculated.

Step 4: *Proposal of Safety Measures*

In the final step, based on the obtained results, safety actions are proposed, and factors are ranked according to their impact-to-cost ratio. The proposed model framework can be observed in Fig. 4.

4. Case study

The case study focused on a specific steam-reforming hydrogen generation unit with a capacity of 1000 Nm3/h, which utilizes natural gas and steam to produce hydrogen and carbon dioxide. The steam reforming process is the reaction of hydrocarbons with water to produce hydrogen. Natural gas is the most commonly used hydrocarbon in this process. The process of steam methane reformer consists of two main sections. In the first step, H_2 and CO are produced through the reaction of hydrocarbon with water at a temperature between 400 and 800°. Eq. (28) illustrates the methane reaction with water. This section is named reforming and produces about 75% hydrogen. Compressors, desulfurizers, preheat section, steam reformer, heat recovery and shift reactor are included in this section. Pressure swing adsorption (PSA) which is the second section, purifies hydrogen to 99% purification and decreases CO concentration to less than five ppm. Fig. 5 depicts the overall scheme of the steam methane reforming process.

$$CH_4 + H_20 + heat \rightarrow CO + 3H_2 \quad (28)$$

This case study aims to investigate the impact of hydrogen leakage on parameters and target variables in a petrochemical company within a specific timeframe, using the proposed probabilistic R.Graph model, and to explore some safety measures for mitigating these effects. We conducted a comprehensive investigation into the various risk factors associated with hydrogen leakage in a hydrogen generation unit. These included safety risks (such as asphyxiation, fire, and explosion), environmental risks (including greenhouse emissions), economic risks (such as hydrogen loss and increased operational and maintenance costs), technical risks (such as equipment damage), regulatory risks (non-compliance with standards or regulations and potential fines or penalties), and market risks (loss of competitiveness or market share). Through a comprehensive analysis, we examined the causal relationships between these risk factors, considering the impacts and consequences of various hydrogen leakage rates. We also evaluated the potential for cascading effects, where a change in one risk factor could amplify or influence other risk factors. As a result, eight categories of events and sixteen variables that are directly or indirectly affected by hydrogen leakage in this organization during this timeframe have been identified and determined, as outlined in Table 2. Furthermore, based on the mode of influence, the causal relationships among the factors have been identified by relevant experts and illustrated as an R.Graph diagram, depicted in Fig. 6. Subsequent to the acquired information, results analysis, and research findings, they can be observed in sections 4.1 to 4.7.

4.1. Collected data and information based on the case

In the initial phase, the R.Graph matrix is determined based on Fig. 4. Then, submatrices, $E-E$ $E-V$ and $V-V$ matrices are obtained based on experts' views on this basis. It is observed that the $V-E$ matrix is either zero or non-existent (Table 6).

A group of experts from the field of risk management and hydrogen energy were requested to collaborate in the research, with different demographic characteristics.

The experts were asked to analyze the potential impact and risk of events on each of the affected events (Table 3) and variables (Table 4). They were also asked to estimate the effect (risk) of each variable on other variables in case of a 100% increase in the influential variable (Table 5).

For instance, the experts were asked the following question to determine the impact of the "Hydrogen Loss" variable change on the variable "Reduced Hydrogen Supply":

For Variable 1 (Hydrogen Loss), what is the percentage change in the variable "Reduced Hydrogen Supply" (V5) if Variable 1 changes?

The relevant questionnaire can be found in Appendix 1. Furthermore, a specialist familiar with the organization's policies was asked to determine acceptable risk values for each variable (Appendix 2), which are presented in Table 5. For example, the specialist was asked:

For Variable V1 (Hydrogen Loss), what is the acceptable risk or change in value according to the organization's goals? For every 100% change in Variable V1.

4.2. Determining risk for each variable

In this stage, using equations (15) and (16) and considering acceptable risk values for each variable, the changes in the probabilities of events and the changes in the variable values are calculated. For example, the risk and variations in Event $E4$ "Frostbite" which are influenced by Events $E1$ "low hydrogen leakage", $E2$ "medium hydrogen leakage" and $E3$ "high hydrogen leakage" with the assumption of $AR=0$ and the values from Table 4, according to Eq. (15), is calculated as follows:

$$Par(E4)=\{E1,E2,E3\}\rightarrow R(E4)=b_{14}{}^{e}R(E1)(1-AR_5)+b_{24}{}^{e}R(E2)(1-AR_5)+b_{34}{}^{e}R(E3)(1-AR_5)=0.0026$$

The variations in probabilities for Events $E1$ and $E2$ and $E3$ denoted as $R(E1)$, $R(E2)$ and $R(E3)$ determined using Table 3 and Eq. (15) as follows:

$$\begin{cases} Par(E1)=\{E0\}\rightarrow R(E_2)=b_{01}{}^{e}R(E0)(1-AR_2)=0.6\times 0.02\times(1-0)=0.012 \\ Par(E2)=\{E0\}\rightarrow R(E_3)=b_{02}{}^{e}R(E0)(1-AR_3)=0.25\times 0.02\times(1-0)=0.005 \\ Par(E3)=\{E0\}\rightarrow R(E_3)=b_{03}{}^{e}R(E0)(1-AR_4)=0.15\times 0.02\times(1-0)=0.003 \end{cases}$$

where

$$P(E0)=0.6\rightarrow R(E0)=P(E0)(1-AR_1)=0.02\times(1-0)=0.02$$

The risk values for other events and variables, both considering the coefficient of acceptable risk and without it, are displayed in Table 7.

4.3. Determining the weight of each factor and sensitivity analysis

In this step, to prioritize all factors for risk management planning and to determine and analyze safety measures, the importance of each factor is specified and ranked. The results can be seen in Table 8. Additionally, to assess the overall sensitivity of the problem to an increase or decrease in the constant value for events and variables, for simplicity, if we consider the probabilistic R.Graph matrix according to Eq. (5) as a unit matrix, i.e., $R^{R.Graph}=\begin{bmatrix} E-E & E-V \\ V-V & V-E \end{bmatrix}$, where the number of rows and columns is equal to the total number of events and variables, sensitivity analysis can be performed on each row of the respective matrix.

In this case, there is no difference between events and variables, and sensitivity analysis is calculated for each factor's changes. Now, three different scenarios can be considered for sensitivity analysis as follows:

Scenario 1: The impact of each factor (both events and variables) on other factors is considered 0.1 higher, meaning the respective row for each factor is summed with 0.1.

Scenario 2: The impact of each factor (both events and variables) on other factors is considered 0.2 higher, meaning the respective row for each factor is summed with 0.2.

Scenario 3: The impact of each factor (both events and variables) on other factors is considered 0.1 lower, meaning the respective row for each factor is subtracted by 0.1.

If the sensitivity analysis values for each factor in these three scenarios are represented by indices $(S_i|\Delta_1=0.1)$، $(S_i|\Delta_1=0.2)$ and $(S_i|\Delta_1=-0.1)$ respectively, the results of the sensitivity analysis can be observed in Table 8 and Fig. 7 based on this information.

4.4. Robustness analysis

The resilience of an analytical approach refers to its ability to withstand minor, intentional modifications in method variables without significant impact [35]. As demonstrated in the sensitivity analysis outlined in Section 4.3, we previously assessed the influence of a consistent alteration in the values of a factor on the cumulative risks associated with all variables. This section delves further into an exploration of the repercussions that slight adjustments in all factors might have on the ultimate outcomes. Given that the probabilistic R.Graph method primarily yields factor rankings, we intentionally introduce errors into the values of each factor (i.e., within every column of Tables 3–5) to gauge the ensuing effects on the overall factor ranking. To achieve this, three levels of errors—3%, 6%, and 10%—are incorporated into the values associated with each factor. Subsequently, we individually scrutinize the impact of each factor on the ranking results, as detailed in Tables 9–11. In these tables, distinctions from the baseline scenario are highlighted in blue to emphasize varying ranks.

4.5. Comparison of results with other methods (validation of results)

The aim of this section is to compare the results obtained from the probabilistic R.Graph method with other existing methods in the literature. As the proposed method is based on changes in variables and probabilistic structure, the results of the R.Graph method cannot be directly compared with any of the existing methods because each method has its own specific assumptions and different input concepts. However, for comparison, we can use the fuzzy cognitive map [38] and the EXIT methods [25] with the assumption that the inputs of the probabilistic R.Graph have a similar interpretation to the inputs of the other methods, considering certain simplifying assumptions.

Table 9
Results of robustness analysis at the 3% error level.

Changed Factor	E0	E1	E2	E3	E4	E5	E6	E7	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16
	Rank																							
E0	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E1	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E2	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E3	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E4	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E5	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E6	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E7	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V1	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V2	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V3	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V4	1	4	5	6	21	16	2	3	15	13	7	12	18	19	9	8	23	14	11	24	20	22	10	17
V5	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V6	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V7	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V8	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V9	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V10	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V11	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V12	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V13	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V14	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V15	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V16	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
Without Error	1	4	5	6	21	16	2	3	15	13	7	12	18	19	9	8	23	14	11	24	20	22	10	17

The comparison results of the rankings obtained from the probabilistic R.Graph model and the rankings based on the overall impact criterion of the EXIT method and the centrality criterion of the fuzzy cognitive map approach are presented in Table 12 and Fig. 8.

4.6. *Assessing the priority of safety measures*

In this section, experts propose specific safety measures aimed at diminishing potential risks across various factors, as evident in Table 13. Furthermore, the interrelations among these measures across different factors are illustrated in Fig. 9, where safety actions are depicted as orange events.

Now using the influence matrix of safety measures which is obtained by Appendix 3 on various factors (Table 14) and using Eqs. (25)–(27). The effectiveness of each measure considering its cost is obtained and the measures are ranked (Table 15).

4.7. *Findings and managerial discussions*

- The culmination of our research offers not just numerical data but a strategic roadmap for decision-makers navigating the intricate landscape of hydrogen risk management within steam-reforming hydrogen generation units. Beyond various measurements, the findings provide a nuanced lens, offering profound insights to guide informed decision-making. Table 7 acts as a compass, intricately detailing the terrain of risk factors and their potential impacts. Among the notable revelations, maintenance and repair costs, along with total costs, emerge as the towering pillars with the highest maximum risk values. This underscores their pivotal role in shaping the overall risk landscape, urging decision-makers to allocate resources and attention judiciously. Conversely, the minimal risk associated with the loss of market share signals its secondary role in the broader risk mosaic. These risk values transcend mere metrics; they serve as predictive indicators, quantifying the potential impact of each factor on the comprehensive risk landscape.
- Navigating the labyrinth of risk complexity, Table 8 introduces a dynamic layer by considering severity implications and ripple effects. Hydrogen leakage emerges as the linchpin, orchestrating all risk values and solidifying its status as the most pivotal factor. The interplay of severity introduces a dynamic shift in importance – events like blasts and fires garner attention, especially when considering their predictability. Conversely, overlooking severity highlights the paramount importance of low hydrogen leakage due to its higher likelihood, amplifying its influence on other factors. Despite this dynamic interplay, the least influential variable remains steadfast – loss of market share, indicating its limited impact on the comprehensive risk assessment, irrespective of the context.
- The sensitivity analysis, vividly depicted in Table 8 and Fig. 6, illuminates the landscape of predictability and high impact. Hydrogen leakage, fire, and explosion events emerge as focal points demanding strategic attention and proactive preventive measures. The heightened sensitivity linked to equipment and structural damage underscores their pivotal role in influencing the risks of other factors. As the influence of these variables fluctuates, decision-makers gain actionable insights into how the risks of other factors respond to changing scenarios. This knowledge becomes instrumental in tailoring interventions and allocating resources effectively, ensuring a dynamic and adaptive approach to risk management.
- To assess the robustness of the model's ranking results against minor errors in input data, a robustness analysis was conducted. Three error levels, namely 3%, 6%, and 10%, were introduced in the input data based on the findings in Tables 9–11. The analysis revealed that the introduction of errors had minimal impact on the ranking results. Specifically, very slight changes were observed in the rankings of Variable 4 (Human Injuries) and Variable 6 (Greenhouse Emissions) across all error levels. Moreover, there were alterations in the ranks

Table 10
Results of robustness analysis at the 6% error level.

Changed Factor	E0	E1	E2	E3	E4	E5	E6	E7	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16
	Rank																							
E0	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E1	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E2	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E3	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E4	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E5	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E6	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E7	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V1	1	4	5	6	21	16	2	3	14	12	7	13	18	19	9	8	23	15	11	24	20	22	10	17
V2	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V3	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V4	1	4	5	6	21	16	2	3	15	13	7	12	18	19	9	8	23	14	11	24	20	22	10	17
V5	1	4	5	6	21	16	2	3	14	12	7	13	18	19	9	8	23	15	11	24	20	22	10	17
V6	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V7	1	4	5	6	21	16	2	3	15	12	7	13	18	19	8	9	23	14	11	24	20	22	10	17
V8	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V9	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V10	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V11	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V12	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V13	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V14	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V15	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V16	1	4	5	6	21	16	2	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
Without Error	1	4	5	6	21	16	2	3	15	13	7	12	18	19	9	8	23	14	11	24	20	22	10	17

of Variable 1 (Hydrogen Loss) and Variable 10 (Downtime) at the 6% and 10% error levels, along with minor adjustments in the rankings of Variable 5 (Asphyxiation) and Variable 15 (Total Cost). Overall, the results demonstrate that the model's outcomes exhibit a low sensitivity to minor errors in the input data, emphasizing the robustness of the obtained rankings.

- The managerial implications gleaned from these results transcend the conventional boundaries of risk assessments. The findings provide a comprehensive playbook for decision-makers, offering not just data but strategic intelligence to fortify risk management strategies. This strategic guidance is indispensable in fostering safety, operational integrity, and sustainability within the evolving landscape of clean energy systems, ensuring a resilient and secure future for hydrogen-based energy infrastructures. Armed with these insights, decision-makers can confidently navigate the complexities of risk, leading to safer, more resilient, and sustainable energy practices.
- In Section 4.5, we meticulously dissect the outcomes of our proposed probabilistic R.Graph method through a comparative lens, juxtaposing it against two alternative methodologies: fuzzy cognitive map and EXIT. While certain congruencies echo through the results, unmistakable divergences surface, underscoring the distinctive nature of the probabilistic R.Graph method. It is paramount to recognize that our innovative approach stands on a different philosophical footing compared to conventional methodologies. The crux of differentiation lies in the treatment of system inputs, where the probabilistic R.Graph method takes a departure from the established norm. Unlike its counterparts, which often dwell on correlation or impact, our method pivots on the profound consideration of change, presenting a unique perspective in risk assessment. The interplay between factors further illuminates our method's singularity. We chart a distinctive path, outlining a methodology that intricately factors in relationships between various elements, departing from the conventional norms observed in fuzzy cognitive map and EXIT. The portrayal and representation of diverse factors within our analysis carve a different narrative, contributing to the nuanced differentiation that sets the probabilistic R.Graph method apart. A key facet that adds another layer of distinction is our method's inherent acknowledgment of the static nature of certain factors. This acknowledgment introduces an additional dimension to our risk assessment framework, offering a holistic and comprehensive perspective that extends beyond the purview of traditional methodologies.
- Table 15 serves as a visual tableau, elucidating the rankings of safety measures derived from the impact-cost analysis within the probabilistic R.Graph model. A captivating revelation surfaces as ventilation and air exchange claim the highest rank, exerting substantial influence on mitigating risks associated with fire, explosion, and asphyxiation. Following closely are leak detection systems and pressure relief valves, securing subsequent ranks, each playing a pivotal role in the safety architecture. An intriguing takeaway from these rankings is the opportunity for strategic resource allocation. By assigning weights to each sensitivity measure, decision-makers gain a strategic vantage point, enabling the formulation of an investment strategy that aligns with predetermined budgets. While the paramount focus invariably leans towards detecting and mitigating leakages in safety management, a judicious safety plan becomes indispensable. This all-encompassing plan should cater to diverse scenarios and factors crucial to the organization's well-being, recognizing the potential triggers for inaccuracies and subsequent incidents.
- In addressing concerns about the repeatability of the case study, it's important to highlight that the primary focus was on the rank and order of risk factors rather than precise quantification. The Probabilistic R.Graph method excels in offering a comprehensive understanding of risk factor prioritization, allowing strategic resource allocation based on relative risks. The study implemented an

Table 11
Results of robustness analysis at the 10% error level.

Changed Factor	E0	E1	E2	E3	E4	E5	16	E7	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16
	Rank																							
E0	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E1	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E2	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E3	1	4	6	5	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E4	1	4	5	6	20	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	21	22	10	17
E5	1	4	5	6	21	15	16	3	16	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E6	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
E7	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V1	1	4	5	6	21	16	16	3	14	12	7	13	18	19	9	8	23	15	11	24	20	22	10	17
V2	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V3	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V4	1	4	5	6	21	16	16	3	15	13	7	12	18	19	9	8	23	14	11	24	20	22	10	17
V5	1	4	5	6	21	16	16	3	14	12	7	13	18	19	9	8	23	15	11	24	20	22	10	17
V6	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V7	1	4	5	6	21	16	16	3	15	12	7	13	18	19	8	9	23	14	11	24	20	22	10	17
V8	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V9	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V10	1	4	5	6	21	16	16	3	15	12	7	14	18	19	9	8	23	13	11	24	20	22	10	17
V11	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	10	24	20	22	11	17
V12	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V13	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V14	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
V15	1	4	5	6	21	16	16	3	15	13	7	12	18	19	9	8	23	14	11	24	20	22	10	17
V16	1	4	5	6	21	16	16	3	15	12	7	13	18	19	9	8	23	14	11	24	20	22	10	17
Without Error	1	4	5	6	21	16	16	3	15	13	7	12	18	19	9	8	23	14	11	24	20	22	10	17

interactive environment to minimize errors, fostering collaboration between experts and a moderator. While human decision-making variability is acknowledged, the structured approach enhances consistency. Achieving identical results with different expert groups might be challenging, but the method's strength lies in maintaining the relative order of risks, providing consistent insights across evaluations and scenarios. The study encourages further exploration and validation, recognizing that perfect repeatability may be elusive, but the method's robustness in preserving risk order enhances its reliability and applicability.

- In the presented case study, our scrutiny of outcomes was conducted without delving into the root causes of hydrogen leakage. It is crucial to emphasize that the probabilistic R.Graph method extends beyond outcome examination, akin to the fault tree and bow-tie methods. This method possesses the unique capability to scrutinize the causes of leakage incidents and associated risks comprehensively. By leveraging interconnected nodes and probabilistic relationships, the probabilistic R.Graph method becomes a potent toolkit for dissecting the intricate causality of leakage events. This not only enables informed decision-making but also facilitates the formulation of targeted risk mitigation strategies. Through the incorporation of both causal factors and potential consequences, the method unfolds a holistic approach to risk assessment, empowering stakeholders to proactively address underlying vulnerabilities and fortify the resilience of leak-prone systems.
- The probabilistic R.Graph method encompasses measures and variables that undergo changes in values and probabilities. Instances may arise where the initial value of a factor is unknown or set to zero. In such scenarios, one viable approach involves examining the impact on the complement of that factor. For instance, when investigating the percentage change in hydrogen loss with an initial value of zero, the effect on hydrogen utilization can be assessed. This is achieved by quantifying the reduction in full hydrogen capacity, equivalent to 100%, signifying the corresponding increase in hydrogen loss. This principle extends to variables such as equipment damage, human deaths, and similar factors, enhancing the method's adaptability in scenarios with incomplete or zero-initialized data.
- In the realm of algorithmic interpretation, the probabilistic R.Graph method stands out. Interpretability, in this context, reflects the ease with which causes and effects are observed, enabling the prediction of outcomes. Causality-based algorithms, exemplified by the proposed probabilistic R.Graph method, boast simple interpretability. Their results can be effectively communicated to decision-makers, rendering them more reliable for managers actively engaged in all stages of the analysis. This characteristic fosters collaborative decision-making, ensuring that stakeholders can contribute meaningfully to risk assessment and management processes.
- Traditional modeling techniques often grapple with difficulties, especially when specific statistical data is elusive or when extracting relationships from quantitative prediction models becomes challenging. In such predicaments, the probabilistic R.Graph method emerges as a beacon. It offers an alternative that leverages the insights provided by knowledgeable individuals, representing the best available data in situations where conventional approaches fall short.
- The probabilistic R.Graph method, recognized as a robust tool for modeling and simulating systems, draws strength from data obtained from field experts. It provides a suitable and interpretable framework for decision-makers and modelers alike. Data collection and aggregation can take various forms, including interviews, workshops, surveys, the Delphi method, questionnaires, or a combination of these approaches. Additionally, the method accommodates expert opinions gathered anonymously through online questionnaires, facilitating direct discussions of results. This comprehensive approach ensures that decision-makers have access to valuable,

Table 12
Comparison of probabilistic R.Graph method results with fuzzy cognitive map and EXIT methods.

Fuzzy cognitive maps	Rank	EXIT	Rank	Proposed method (Considering severity)	Rank (Without severity)	Weight	rank
1	20	0.02	1	0.2827	1	0.2703	1
1.88	12	0.012	4	0.1019	4	0.1364	2
1.75	13	0.005	20	0.0623	5	0.0596	5
2.55	3	0.003	22	0.0574	6	0.0427	6
0.8	22	0.0026	23	0.0045	21	0.0061	21
1.5	16	0.0043	21	0.0127	16	0.0122	18
4.2	1	0.0109	5	0.1352	2	0.1006	3
3.8	2	0.0092	13	0.1089	3	0.081	4
2	8	0.0109	5	0.0136	15	0.0303	9
1.57	15	0.0084	16	0.0157	13	0.0175	15
1.93	11	0.0098	11	0.0345	7	0.0256	11
1.49	17	0.0071	17	0.0221	12	0.0165	16
2	8	0.0109	5	0.0082	18	0.0183	14
1.99	10	0.0085	14	0.0056	19	0.0124	17
2.47	5	0.01	8	0.0274	9	0.0367	8
2.53	4	0.01	8	0.0282	8	0.0378	7
0.8	22	0.0055	18	0.0014	23	0.0032	23
1.66	14	0.01	8	0.0141	14	0.0188	13
2.3	6	0.02	1	0.0226	11	0.0303	9
0.5	24	0.0016	24	0.0007	24	0.0007	24
1.2	18	0.0055	18	0.0049	20	0.0066	20
1.05	19	0.0085	14	0.0022	22	0.0048	22
2.09	7	0.0179	3	0.0242	10	0.0231	12
1	20	0.0093	12	0.009	17	0.0086	19

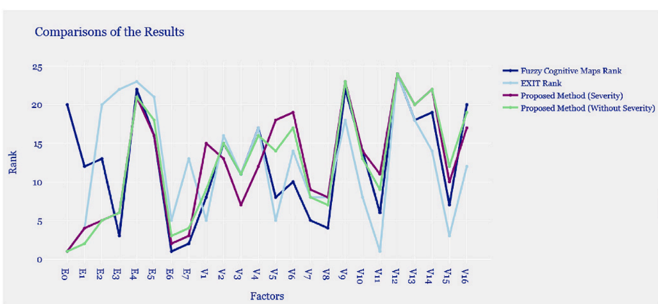


Fig. 8. Comparison of results.

expert-driven data, enhancing the reliability and applicability of the probabilistic R.Graph method in diverse scenarios.

- In the proposed framework, information about indirect interactions between system components is extracted based on direct interactions. In essence, direct interactions are input data, and the usefulness of the model relies on analyzing indirect interactions. This is crucial because in a complex network with various factors, casual events and chains of consequences can be intricate and lengthy. Additionally, the proposed method can identify the importance of a system component, even if it might not appear directly related to another element. For instance, in cases where certain seemingly essential components might be nullified or neutralized by network interactions.
- This study introduces a groundbreaking Probabilistic R.Graph method for quantitative risk management, addressing the probabilistic nature of data and modeling changes in probabilities. Noteworthy novelties include the method's high explainability, consideration of acceptable risk for diverse risk types, and the incorporation of weights and severity for all risk factors in economic, safety, and environmental contexts. The proposed method offers a comprehensive approach by quantifying risk factors and guides the ranking of preventive measures based on their effects across various risk categories. This novel contribution provides decision-makers with a nuanced understanding of risk factors, enabling informed and prioritized risk management strategies in the realm of sustainable energy. However, the proposed probabilistic R.Graph method is based on a developed simplification assumption, referred to as the limitation of the method, which includes: It assumes that relationships between variables are unknown, and statistical data is unavailable. It posits that data is obtained from experts, and the risk of each variable involves a linear combination of the variations of influential variables, as well as independent consideration of impactful events on a variable. However, the process of calculating the risk of each variable is explained in detail in Section 3. Overall, the amount of data required to confidently determine the risk of a variable based on other variables depends on the level of correlation between variables and the number of variables; statistical methods such as regression analysis can be used for this purpose.

5. Conclusion

In navigating the dynamic landscape of transitioning to sustainable energy, hydrogen emerges as a pivotal and eco-friendly energy carrier. However, the inherent risks accompanying hydrogen leakage pose formidable challenges to safety, the environment, and operational efficiency. This study pioneers a groundbreaking solution—the Probabilistic R.Graph method—an advanced iteration of the deterministic R. Graph model. This method strives to redefine quantitative risk management by introducing distinctive features such as simplicity, a probabilistic framework, and unparalleled explainability, making it a pioneering tool for comprehensive risk assessment, especially in safety risk management.

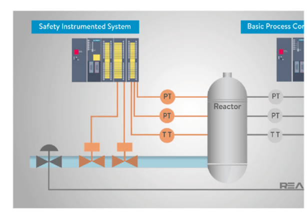
This study rigorously investigated potential hydrogen leaks at a steam-reforming hydrogen generation unit, categorizing them as low, medium, or high risk. Beyond direct impacts, we systematically assessed cascading effects on economic, safety, and sustainability factors, offering nuanced insights into risk implications. The methodology served as a guide for identifying preventive measures, emphasizing options that effectively reduce both the probability and severity of leaks, while considering impacts and costs. The results highlighted that safety issues, such as injuries and fatalities, held greater severity than economic concerns, like market share losses. Consequently, solutions prioritized reducing both leak probability and severity, with a focus on cost-effective measures such as pressure relief valves. This strategic prioritization aligns with the overarching goal of ensuring the safe and sustainable use of hydrogen in the evolving clean energy landscape. The Probabilistic R.Graph method empowers comprehensive risk management by quantifying leak likelihoods and dependencies. Integration of

Table 13
The suggested safety measures.

Safety measures	Comprehensive Definition	Factors Affected	Picture
P1 - Leak Detection Systems	Sophisticated and automated setups designed to detect and locate hydrogen leaks in facilities or equipment. These systems utilize various sensors, such as acoustic, thermal, or chemical sensors, to monitor the environment continuously. Once a leak is identified, the system triggers alarms and notifies relevant personnel to take prompt action. Early detection of leaks allows for timely interventions, preventing the escalation of hydrogen leakage incidents.	E1, E2, E3	
P2 - Flame and Gas Detectors	Advanced devices that continuously monitor the presence of flames and specific gases, including hydrogen, within facilities or designated areas. Equipped with various detection technologies such as infrared, ultraviolet, or catalytic sensors, these detectors promptly alert personnel when hydrogen or other gases reach dangerous levels. By providing early warnings, Flame and Gas Detectors aid in preventing potential asphyxiation hazards (E5) resulting from hydrogen leaks, ensuring timely evacuation and response.	E5	
P3 - Pressure Relief Valves	Crucial safety valves installed in hydrogen-containing systems to protect them from excessive pressure buildup. These valves automatically release excess pressure, preventing the risk of explosions or ruptures. By effectively relieving pressure during abnormal events, such as over-pressurization, Pressure Relief Valves mitigate the negative effects of low, medium, and high hydrogen leakage incidents (E1, E2, E3) and reduce the likelihood of equipment damage (V7).	E1, E2, E3	
P4 - Ventilation and Air Exchange	Systems that play a vital role in ensuring a safe hydrogen environment by promoting the circulation of fresh air and reducing hydrogen concentrations within enclosed spaces. These systems facilitate the removal of hydrogen gas and other potential hazardous gases, contributing to the prevention of asphyxiation risks (E5) as well as the mitigation of fire (E6) and explosion (E7) hazards associated with hydrogen buildup.	E5, E6, E7	
P5 - Fire Suppression Systems	Automated and robust setups designed to detect and suppress hydrogen fires promptly. These systems utilize various techniques such as water deluge systems, gaseous agents, or foam to control and extinguish hydrogen fires effectively. By swiftly containing and suppressing fires, Fire Suppression Systems help prevent widespread damage, reduce equipment damage (V7), and structural damage (V8), and limit the potential for reputational damage (V9).	E6	

(*continued on next page*)

Table 13 (*continued*)

Safety measures	Comprehensive Definition	Factors Affected	Picture
P6 - Fire Fighting Systems	Encompass a range of equipment, including fire extinguishers, hoses, and fire blankets, as well as trained personnel prepared to respond to hydrogen fire incidents. These systems play a crucial role in the early stages of fire incidents, allowing for quick intervention and containment. By effectively combating fires, Fire Fighting Systems contribute to the reduction of energy sales revenue loss (V2), human deaths (V3), human injuries (V4), equipment damage (V7), and structural damage (V8).	V2, V3, V4, V7, V8	
P7 - Safety Instrumented Systems	Integrated setups designed to detect abnormal conditions and automatically take safety actions to prevent incidents. In the context of hydrogen risks, SIS can initiate shutdowns, isolate areas, or activate other safety measures in response to critical events. By swiftly and automatically responding to incidents, Safety Instrumented Systems reduce the likelihood of low, medium, and high hydrogen leakage (E1, E2, E3) and their potential negative consequences.	E1, E2, E3	
P8 - Redundancy and Backup Systems	Entail duplicating critical components or implementing backup measures to ensure continuous operation even if primary systems fail. In the case of hydrogen loss (V1), having redundant components ensures a steady supply of hydrogen, minimizing disruptions and downtime (V10). The availability of backup systems helps prevent prolonged interruptions, reducing repair and maintenance costs (V11) and potential loss of market share (V12).	V1	
P9 - Blast Walls and Blast Shields	Serve as protective barriers designed to minimize the impact of explosions and blasts that may occur due to hydrogen leaks or ignition events. These structures are strategically placed to contain and direct the force of explosions away from critical areas, reducing the potential for injuries (V3, V4) and structural damage (V8). By providing a physical barrier against the effects of explosions, Blast Walls and Blast Shields contribute to safeguarding personnel and equipment.	V2, V3, V4, V7, V8	

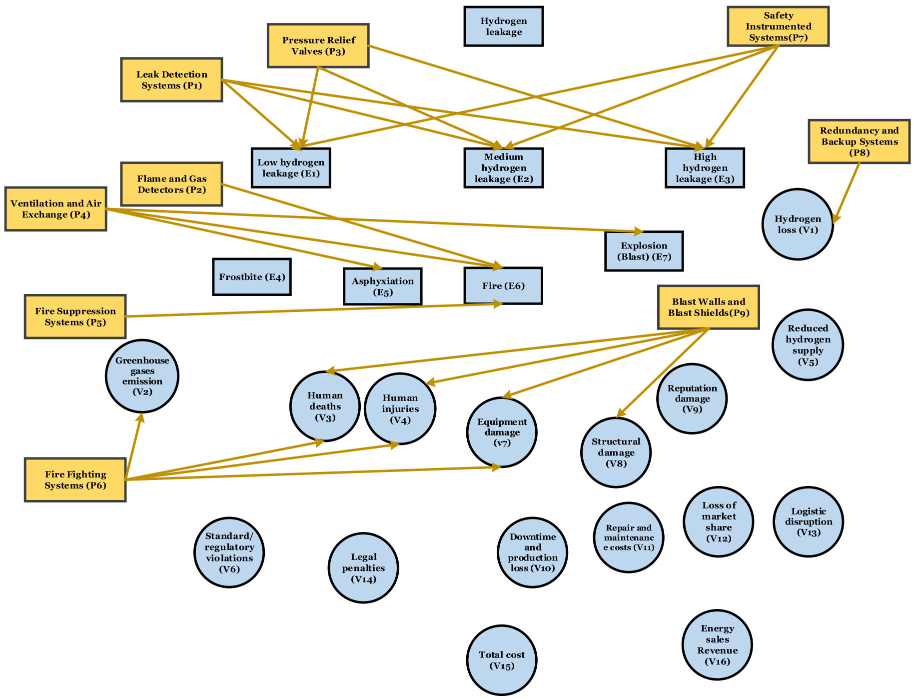


Fig. 9. The interaction of safety measures on different factors.

Table 14
Safety measures influence matrix.

	E1	E2	E3	E4	E5	E6	E7	V1	V2	V3	V4	V5	V6	V7	V8
P1	0.6	0.8	0.95	0	0	0	0	0	0	0	0	0	0	0	0
P2	0	0	0		0.8	0	0	0	0	0	0	0	0	0	0
P3	0.2	0.3	0.6	0	0	0	0	0	0	0	0	0	0	0	0
P4	0	0	0	0	0.7	0.4	0.5	0	0	0	0	0	0	0	0
P5	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0
P6	0	0	0	0	0	0	0	0	0.3	0.6	0.5	0	0	0.4	0.4
P7	0.7	0.5	0.2	0	0	0	0	0	0	0	0	0	0	0	0
P8	0	0	0	0	0	0	0	0.6	0	0	0	0	0	0	0
P9	0	0	0	0	0	0	0	0	0	0.7	0.6	0	0	0.6	0.6

Table 15
Safety measures ranking.

Measure	Effectiveness	Cost (0–100)	Utility	Rank	Weight
P1	0.143082	40	0.003577	2	0.247
P2	0.006857	30	0.000229	9	0.016
P3	0.059432	30	0.001981	3	0.137
P4	0.077372	20	0.003869	1	0.267
P5	0.05005	40	0.001251	5	0.086
P6	0.049679	60	0.000828	7	0.057
P7	0.11287	70	0.001612	4	0.111
P8	0.0235	90	0.000261	8	0.018
P9	0.061015	70	0.000872	6	0.06

emerging technological innovations further mitigates both the frequency and impact of such events. A holistic evaluation of strategies spanning environmental, economic, technical, and regulatory spheres becomes imperative for ensuring hydrogen's sustainability. We recommend that policymakers, industry stakeholders, and researchers utilize these insights for informed decision-making. Embracing the provided recommendations and making investments in research and development will pave the way for a safer and more reliable infrastructure, ensuring the protection of public safety, the environment, and expediting the transition to a greener, more resilient energy future.

Linearity is one of the main assumptions of the R.Graph method, but linearity is not always valid in some impact analysis issues. It is suggested that in cases where sufficient data for statistical interpretation are available, simplified assumptions should be eliminated, and consequently, new assumptions can be used as the basis for future research topics in the current study. For example, in cases where significant data values are available for statistical interpretation, supervised methods [39] and unsupervised methods [40] can be utilized to estimate the risks of variables. Additionally, the probabilistic R.Graph model has been considered in both static and non-cyclic states. The development of dynamic models based on this [41] and considering other uncertainties [42] in input data, such as incomplete [43] or fuzzy states [44], are introduced as future recommendations.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Chat GPT and Bing AI in order to edit and write some parts of the paper. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.03.199.

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