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Hazard Identification and Risk Assessment of Biogas Plant with Proton Exchange Membrane Fuel Cell Technology

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ABSTRACT

Biogas-fed proton exchange membrane fuel cell (PEMFC) plants offer a sustainable energy solution, but their operation can pose significant hazards and risks. Ensuring the safety of these plants is paramount, especially given the potential for fires, explosions, and chemical exposures. This study evaluated hazards and risks in biogas-fed proton exchange membrane fuel cell (PEMFC) plants using six analytical methods: Dow's fire and explosion index (FEI), Dow's chemical expo-sure index (CEI), Hazard and Operability Study (HAZOP), Risk Matrix Analysis (RMA), Bayesian Network (BN) and ALOHA® software hazard modelling. The FEI analysis revealed that the anaerobic digester and bio-gas storage tank exhibited severe hazards (FEI =170), thereby signifying the highest risks within the plant. CEI analysis revealed the spread of the highest hydrogen sulfide (H_2S) concentration up to 129 meters from the anaerobic digester and storage tank location. Further assessment was conducted, calculating risk values using the RMA and performing additional HAZOP analysis specifically for these units. The results confirmed similar risk levels (4-20) between the units, except for a higher explosion risk in the storage tank. The novelty of this research lies in the application of Bayesian Network (BN) analysis. In addition to assessing the hazards associated with PEMFC, our BN analysis reveals that the risk of fire attributed to PEMFC ranges between 10% and 18%, while the risk of explosion falls within the range of 3% to 17%. Based on the hierarchy control concept, several effective mitigation controls were proposed to enhance the safety of biogas-fed PEMFC plants. In future research, a deeper exploration of human error and equipment malfunctions within

hazard modelling is crucial for a more precise hazard assessment.

Keywords: Hazard identification; risk assessment; biogas; PEM fuel cell; sewage treatment plant

INTRODUCTION

As the world faces the challenges of energy scarcity and escalating environmental threats, more focus is being shifted towards renewable energy sources, such as biogas. Biogas is generated from organic waste, such as from the livestock industry, which contributes to 14.5% of all human-made waste and contains greenhouse gases such as nitric oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) (Aini 2018; Boscolo et al. 2020). Given the urgent need to address climate change, signaled by rising global temperatures, the conversion of this waste into energy becomes a critical endeavor (NASA 2020). One technology that can be utilized for this process is Proton Exchange Membrane fuel cells (PEMFC), which can efficiently use biogas to generate power. However, as we venture into this territory, it becomes vital to identify and assess the potential hazards and risks of biogas plants utilizing this technology. This article aims to explore these aspects, paving the way for a safer and more sustainable approach to energy generation.

Biogas, which is produced by the degradation of organic materials using bacteria, is a promising bioenergy resource (Obaideen et al. 2022). Biogas is primarily composed of 55-70% CH_4 (methane) and 30-45% CO_2 (carbon dioxide), with trace amounts of other compounds. Methane can be flammable, especially when mixed with air. CO_2, when concentrated, can reduce the amount of breathable oxygen. Ammonia (NH_3) can cause respiratory and skin irritation. Carbon monoxide (CO) is toxic and interferes with oxygen transport in the body. Hydrogen sulfide (H_2S) has a distinct "rotten egg" odor and is harmful in large concentrations. The presence of oxygen (O_2) can support combustion. Hydrogen (H_2) is flammable. Volatile organic compounds (VOCs) include various organic chemicals, some of which have health or environmental effects. Siloxanes can decompose into silica upon combustion, leading to equipment damage. Therefore, understanding and addressing the properties of these compounds is essential for safe biogas handling (Atelge et al. 2021). Biogas derived from sewage treatment plant (STP) sludge has been found to contain the highest methane content, ranging from 60% to 70%, compared to other substrates (Jamaluddin et al. 2021). Various pre-treatment methods can be applied to the raw material to maximize the biogas yield per quantity of solid waste (Lamb & Pollet 2020). These methods include the use of chemical, thermal, and biological techniques, or a combination, which can break down the complex structure of sludge (Agustini et al. 2018; Liu et al. 2020). Among these pre-treatment methods, thermal pre-treatment is widely implemented on an industrial scale due to its potential to increase organic matter solubilization and inhibit pathogens. Moreover, further enhancement in biogas production can be achieved by adding acid or base supplements during thermal pre-treatment (Khanh Nguyen et al. 2021).

The urgent need for clean and sustainable sources of energy has prompted the development of green technology for sewage and treatment systems worldwide. Biogas production from organic waste materials has emerged as a potential solution to this problem (Atilgan et al. 2023; Frankowski & Czekała 2023). The production of biogas not only generates renewable energy, but also addresses waste management issues. Various types of waste, such as municipal solid waste, can also be incorporated into the process feed to produce biogas. Countries such as Kenya have been using waste-to-biogas technology to handle waste efficiently and reduce greenhouse gas emissions from the burning of solid wastes (Abubakar et al. 2022). Biogas generation can provide a renewable energy source while also generating valuable by-products such as potassium, phosphorus, and carbon (Jamaluddin et al. 2021). However, the process of wastewater treatment itself can contribute to environmental pollution, with greenhouse gas emissions being a major concern due to energy usage and land usage for sludge (Aziz et al. 2020). A study by Gautam et al. (2021) reported that wastewater treatment plants contribute approximately 3-4% of global greenhouse gas emissions (Gautam & Agrawal 2021). They also suggest that adopting energy-efficient technologies and renewable energy sources can help to mitigate these emissions.

H_2 technology has emerged as a promising solution to mitigate greenhouse gas emissions (Soam & Börjesson 2020). Fuel cells that produce green energy with H_2 as the fuel are one example of H_2 technology. An excellent demonstration of a fuel cell employed in sewage treatment plants is the implementation of PEMFCs in the plant, which generates electricity from the spontaneous redox reactions of feed H_2 and O_2 through an electrochemical process (Lim et al. 2019). In the sewage treatment plant, H_2 is extracted from the biogas generated from sewage waste. The extracted H_2 is then further processed to obtain pure H_2, which is stored in a storage tank as the fuel for PEMFCs. PEMFCs can be easily maintained and have a high level of reliability, as they operate at low temperatures, resulting in less damage to system parts (Behling 2012). With a start-up time of just 30 seconds, high electrical efficiency (around 55%), high energy density, quick response to dynamic loads, good heat output, and long operational life cycle (around 40,000–50,000 hours), PEMFCs are an excellent choice for use in transportation and other high-power electronic applications (Baroutaji et al. 2021; Chandan et al. 2013). In fact, the U.S. Department of Energy has identified PEMFCs as an ideal replacement for internal combustion engines in transport applications due to their low emissions of CO_2, which result in lower atmospheric pollution (Lebai Rodin et al. 2020; Husaini et al. 2018).

Biotechnological processes pose various risks, including chemical synthetic process hazards and biohazards due to the presence of pathogens, creating a pathogenic area. A study by Moreno and Cozzani (2018) investigated the hazard and risk for industrial biological processes, and their findings suggested that the deviation in biogas flow and pressure contributed to the highest risk in the biotechnological process. Based on the findings, the authors then propose safety barriers for each hazard that was identified in the study (Casson Moreno & Cozzani 2018). In general, the level of risk can be evaluated from the probability of the occurrence and the scale of the loss. A low-risk system has a low probability of loss with small consequences, while a high-risk situation leads to significant losses with a higher probability of occurrence (Geng et al. 2023). In the case of biogas plants, potential hazards can arise from various sources, such as leaks in storage tanks and distribution networks, unintentional effluent discharges, sewage system overflow due to control failures or unusual downpours, and hazardous substances in biogas raw materials (Boscolo et al. 2020).

In order to effectively manage these risks, hazard assessment methods such as the Fire & Explosion Index (FEI) and Chemical Exposure Index (CEI) are widely used in various industries to identify, analyze, and evaluate hazards. The FEI serves as the foundation for numerous applications and extensions, helping staff and safety administrators recognize important situations and problems relevant to fire and explosion in industrial sites (Danzi et al. 2018; Janošovský et al. 2022). Danzi et al. (2018) utilized fire and explosion risk index methods to analyze the risk of chemical process plants and evaluated the FEI, Mond Index, and Safety Weighted Hazard Index (SW&HI). The results suggested that FEI can be used to analyze a hazard, but this method tends to underestimate the degree of hazard, while the SW&HI method has been proven to have broader applicability and could be chosen as a basis for a risk index method (Danzi et al. 2018).

On the other hand, the CEI is a risk index method used to determine the relative acute health threat to humans in chemical plants and nearby areas in the event of potential chemical releases. It ranks toxicity hazards based on five factors, as described in studies by (Etowa et al. 2002) and (Casciano et al. 2019). The study by Etowa et al. (2002) implemented FEI and CEI to evaluate the DOW indices of the vessel involved in the Bhopal plant incident. The research explores the effect of change in parameters such as operating pressure and temperature on the change of FEI and CEI values. The work by the authors is intended to revolutionize the concept of inherently safe process design towards implementation and focusing on the inherent safety features from the Dow indices is believed to be significant for achieving this (Etowa et al. 2002).

Another critical aspect of risk management is the use of Hazard and Operability (HAZOP) analysis (Riemersma et al. 2020). This method is employed to analyze, detect, and predict design flaws, operational procedure issues, and other potential hidden hazards in the chemical engineering process (Zhou et al. 2020). HAZOP analysis can be performed during the technological design, installation, operation, and modernization stages. Zhou et. al (2020) performed HAZOP analysis on the process of light hydrocarbon separation and studies the effect of deviation of parameters on the hazards in the plant. The study proposed an intelligent HAZOP method and studied the simultaneous occurrence of multiple deviations on the system based on a specific duration. The results concluded that deviation duration is a crucial analysis factor as the dynamic simulation of the hazard can represent the process more accurately to the actual process (Zhou et al. 2020). In addition to investigating the hazards presented by the biogas plant, it is crucial to examine the potential risks associated with the fuel cell itself, specifically the PEMFC (Proton Exchange Membrane Fuel Cell). As the PEMFC also deals with flammable biogas, it introduces additional hazards that must be addressed. Furthermore, the thermal energy generated by the PEMFC can potentially lead to fire and explosion risks (Ahmed et al. 2020). It is worth noting that there exists a type of PEMFC, known as high temperature PEMFC or HT-PEMFC, which operates at elevated temperatures. Therefore, it is of utmost importance to study and understand how this temperature range may contribute to potential hazards. Furthermore, the plant design of a biogas-fed PEMFC power generation plant itself can introduce fire risks. The high temperature of the PSA (Pressure Swing Adsorption) product gas, which is subsequently directed to the PEMFC, has the potential to ignite fires or create unexpected intense heat sources near the hydrogen (H_2) tank. This increased heat could raise the pressure within the H_2 tank and associated pipelines, leading to possible failures in the PEMFC unit or even rupture of the H_2 tank. Additionally, inadequate ventilation within the PEMFC system or elevated temperatures in its vicinity may cause the electrical components to overheat, resulting in fire or, in extreme cases, an explosion. Therefore, it is crucial to comprehend the hazards associated with PEMFCs in order to mitigate these risks effectively (Sarsama et al. 2017).

Therefore, to assess the hazards associated with PEMFC, a Bayesian Network (BN) analysis is conducted. BN is a probabilistic graphical model that effectively captures uncertainty within a given domain. The data used for risk analysis often comprises complex information, encompassing both qualitative expert opinions and numerical data. BN provides a powerful probabilistic tool that can handle this complexity. By utilizing BNs, it becomes possible to model the relationships between various parameters and causes that contribute to hazards.

Additionally, BNs enable the calculation of the probability of a hazard occurring under specific conditions. This allows for real-time hazard identification, as any new information or updates can easily be incorporated into the BN model, ensuring the results remain current. The application of BN has demonstrated its usefulness in various risk assessment domains, including decision making, tunnel safety, flooding risks, forensic assessment, and transportation network analysis (Kaikkonen et al. 2021). This study aims to improve the safety of biogas-fed PEMFC power generation plants by identifying potential hazards and appropriate risk assessment methods for the case study. The power plant design utilized sewage waste as the source for biogas production. Each high-risk operational unit in the plant design was carefully examined and identified. The identified hazards serve as guidelines for proposing control measures to reduce potential risks associated with biogas PEMFCs in a power generation plant. While previous studies have touched upon the inherent risks associated with biogas-fed PEMFC power generation plants, there remains a gap in the comprehensive evaluation of these risks using a combination of analytical methods. Existing literature primarily focuses on individual risk assessment methods or addresses the general safety concerns of PEMFCs. However, a holistic approach that integrates multiple analytical tools, especially the probabilistic capabilities of BN, to assess and mitigate the hazards of biogas-fed PEMFC plants is still lacking. This study seeks to bridge this gap by offering a multi-faceted risk assessment, aiming to enhance the safety protocols and provide actionable insights for the design and operation of biogas-fed PEMFC power generation plants.

METHODOLOGY

In this study, hazard identification and risk assessment were conducted based on a generic biogas plant system shown in Figure 1 as a basis for analysis. The Proton Exchange Membrane Fuel Cell (PEMFC) unit was integrated into the system as shown in the same figure. In order to focus on areas that could have significant impacts from a loss prevention perspective, only process units that were deemed significant, such as the anaerobic digester unit and storage tank, were evaluated during the assessment process.

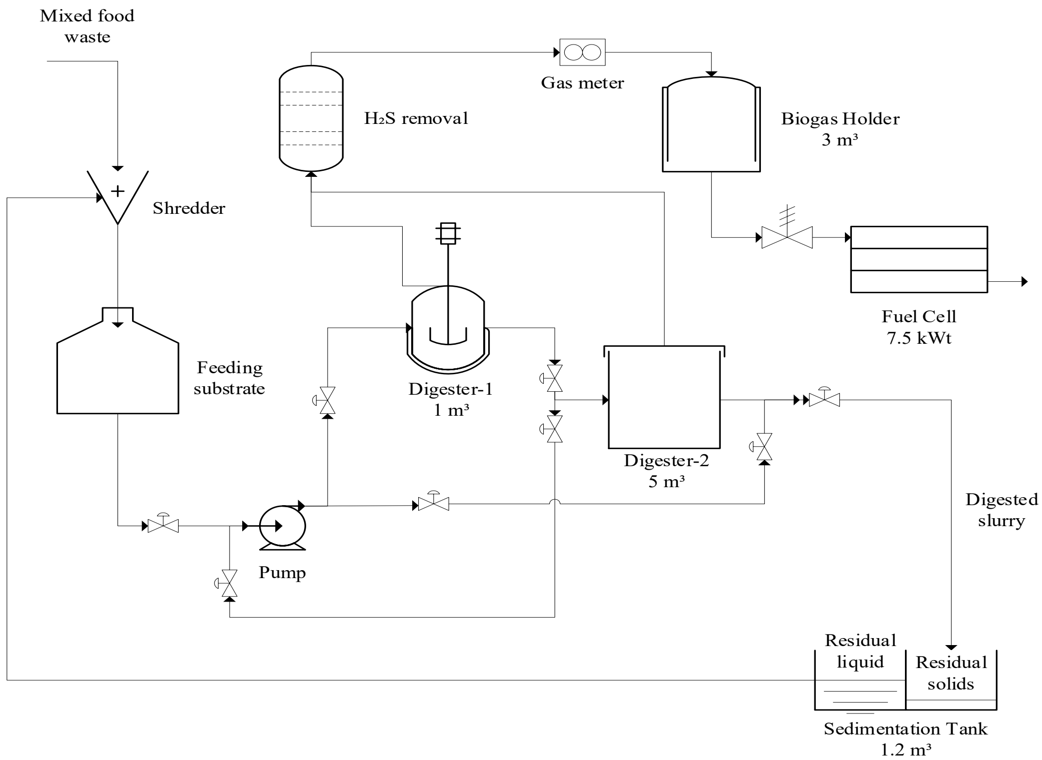

FIGURE 1. General scheme of biogas plant with integrated PEMFC unit

FIRE AND EXPLOSION INDEX (FEI)

The FEI is an important method used in the assessment and management of potential hazards in the operation of biogas-fed PEMFCs power generation plants. The FEI technique is based on the 7th edition of Dow's Fire and Explosion Index Hazard Classification Guide, published by the American Institute of Chemical Engineers (AIChE, 1994).

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TABLE 1. Overview of parameters used in FEI calculation.

Material	Material Factor	Operating Temperature	Operating Pressure
Methane, hydrogen sulfide, carbon monoxide, hydrogen	21	Anaerobic Tank: 30°C Storage Tank: 30°C	Anaerobic Tank: 5 bar Storage Tank: 5 bar

CHEMICAL AND EXPOSURE INDEX (CEI)

The Chemical Exposure Index (CEI) was used to assess the potential hazards related to chemical release incidents in the biogas-fed PEMFCs power plant. To determine the operational unit with the highest probability of causing an accident, potential chemical release incidents were identified. Emergency Response Planning Guidelines (ERPGs) or Dow Emergency Exposure Planning Guidelines (EEPGs) were determined based on the Dow Chemical Exposure Index Guide by AIChE (AIChE 2010).

The ERPG/EEPG has three phases, including ERPG-3/EEPG-3, ERPG-2/EEPG-2, and ERPG-1/EEPG-1. The highest level, ERPG-3/EEPG-3, is the most dangerous design phase. The calculation of the CEI began with the determination of the airborne quantity (AQ) for the highest toxic material involved, namely hydrogen sulfide. Table 2 provides an overview of the parameters used in the determination of the CEI and Table 3 represents the ERPG values of H_2S that are used for the CEI calculation (CAMEO Chemicals 2022).

TABLE 2. Overview of parameters used in the CEI calculation.

Material	Diameter of pipe leakage (mm)	Operating Temperature	Operating Pressure
Hydrogen sulfide	10	30°C	5 bar

TABLE 3. H_2S ERPG values for the CEI calculation.

Component	Molecular weight	ERPG-1 ((ppm	ERPG-2 ((ppm	ERPG-3 ((ppm	(AQ (kg/s
Hydrogen sulfide	34.1	0.1	30	100	0.05931

Based on the ERPG values and airborne quantity for H2S, the CEI and hazard distance (HD) is calculated using Eq.1 and Eq.2 below:

$$CEI = 655.1\sqrt{\frac{AQ}{ERPG-2}} \quad (1)$$

$$HD = 6551\sqrt{\frac{AQ}{ERPG}} \quad (2)$$

RISK MATRIX ANALYSIS

The Risk Matrix Analysis (RMA) is conducted focusing on the Anaerobic Digester (AD) and biogas storage tank unit. RMA begins with the identification of potential hazards or risks associated with the AD and biogas storage tank. These identified risks are then categorized based on their probability and the severity of their potential consequences. The probability is often categorized into levels such as "rare", "unlikely," "moderate," "likely," and "almost certain," while the severity can be labeled as "negligible", "minor", "significant", "major," and "catastrophic." with ratings from 1 to 5. By multiplying the values of probability with the severity on a matrix, risk values can be calculated, which allows for visual representation and prioritization.

The analysis identifies the potential hazards relevant to the system, taking into account factors such as toxicity, flammability, explosiveness, and reactivity. Subsequently, comprehensive data on process design, equipment selection, and operational conditions are collected and evaluated, with a primary focus on hazards previously identified in relevant studies, particularly within the anaerobic digester and biogas storage tanks. The inherent safety indicators are then weighted and aggregated, assigning appropriate weights that accurately reflect their significance within the system. Finally, the risk values are calculated and interpreted within the specific context of the anaerobic digester and biogas storage tanks, enabling the identification of the most dangerous unit in the PEMFC biogas plant (Kovačević et al. 2019).

HAZARD AND OPERABILITY STUDY (HAZOP)

The anaerobic digester and storage tank are identified as high-risk units in the biogas process due to the large amounts of toxic and flammable materials present. When the biogas is released from the anaerobic digester, it contains high levels of water vapor, CH_4, CO_2, and H_2S. In addition, H_2S can react with water vapor to produce hydrosulfuric acid, which can further oxidize to form sulfuric acid and lead to equipment corrosion (Choudhury et al. 2019).

The hazards identified from the Fire & Explosion Index (FEI) and Chemical Exposure Index (CEI) analyses were further analyzed using the Hazard and Operability (HAZOP) method, with a focus on the anaerobic digester and biogas storage tank. The details of the HAZOP method are elaborated in Choi & Byeon (2020). Table 4 shows the study nodes for each high-risk unit operation, along with its parameters.

TABLE 4. Study nodes and parameters for anaerobic digester and biogas storage unit

Unit Operation	Study Node	Parameter
Anaerobic digester	Temperature	Inside anaerobic digester tank
	Flow Rate	Inlet pipeline
	Pressure	Outlet pipeline, control valve
Biogas Storage Tank	Temperature	Inside biogas storage tank
	Flow Rate	Inlet pipeline
	Pressure	Outlet pipeline, control valve

HAZARD MODELING SIMULATION USING ALOHA® SOFTWARE

The study was conducted at a sewage treatment plant in Kuala Lumpur, Malaysia, where the worst weather conditions were chosen based on meteorological forecasts for the area.

During the study period, no storms were experienced, and the area only had extreme heat with a wind speed of approximately 13 km/h. Table 5 presents the location data along with the corresponding meteorological conditions, which were used for the hazard modeling simulation.

TABLE 5. Data input for hazard modeling simulation using ALOHA.

Parameter	Information
Location	Kuala Lumpur, Malaysia
Wind direction	South
Wind Speed	3.62 m/s
Air Temperature	$34^{o}C$
Cloud cover	5 tenths
Stability class	D
Relative humidity	50%

To ensure realism and account for common occurrences, the accident was assumed to be caused by a leak from a hole in the anaerobic digester and biogas storage tank. This leak was identified as the main cause of the fire and explosion in the biogas generation plant. The tank's operating parameters, including a temperature of 30°C, pressure of 5 bar, and gas content of 1263 tons/h, were considered for the simulation of the accident using ALOHA® software for both the biogas storage tank and anaerobic digester. All the data obtained from the risk assessments previously were simulated in ALOHA® software to obtain hazard dissemination data and develop accident prevention measures in biogas plants with the integration of PEMFCs technology.

BAYESIAN NETWORK (BN) ANALYSIS ON PEMFC

In addition to the hazards posed by the anaerobic digester and biogas storage tank, there is also the potential for hazards associated with the Proton Exchange Membrane Fuel Cell (PEMFC). Hence, it is crucial to identify and assess the hazards related to PEMFC. The hazard identification analysis for the PEMFC system utilizes the Bayesian Network (BN) approach. It should be noted that this analysis specifically focuses on the PEMFC system alone, as the overall analysis, including the biogas plant, employs different methods of analysis. The process of conducting hazard identification using the BN model is illustrated in Figure 2.

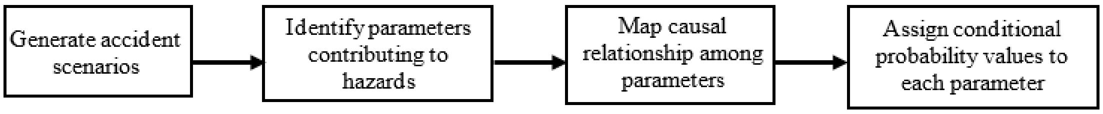

FIGURE 2. Methodology on hazard identification using BN analysis

In this study, the hazard evolution framework for the PEMFC system is established by adopting the methodology developed by Cozzani et al. (2015) for the PEMFC system and adopted the BN model developed by Abg Shamsuddin et al. (2022). To identify the final hazards in the PEMFC system, it is necessary to first investigate the potential causes and parameters that may lead to hazards, and subsequently map these scenarios into the BN model. In this study, various accident scenarios are generated, with a particular focus on fire and explosion hazards due to their high likelihood.

These scenarios serve as the basis for identifying the parameters or factors that contribute to the risks associated with fire and explosion. The identified parameters are presented in Table 6. The next step involves establishing the causal relationships among these parameters, mapping out how they influence one another. Finally, conditional probability values are assigned to each parameter, allowing for a quantitative assessment of the associated risks (D. S. N. A. Shamsuddin et al. 2022).

TABLE 6. Parameters with corresponding states

Parameters	States
Combustibility of chemical	Yes No
Operating Temperature	High Low
Reformer Leakage	Yes No
Blower Fault	Yes No
Pipe Rupture	Yes No
PEMFC fault	Heater Heat Exchanger Combustor PEMFC stack No Fault
Ignition Source	Yes No
Human Error	Mistake No mistake
Operating Pressure	High Low
Confinement	High Low
Concentration of combustible gas	High Low

STANDARD OPERATING PROCEDURE (SOP)

In order to establish a standardized approach for managing the identified hazards and risks, Standard Operating Procedures (SOPs) were developed based on the hazard and risk data obtained. The main objective of an SOP is to minimize the occurrence and severity of potential accidents and risks. The development of the SOP followed the concept of hierarchy control, which includes five hierarchies, namely elimination, substitution, engineering control, administrative, and personal protective equipment, as recommended by the Department of Occupational Safety and Health (DOSH Malaysia 2008). Following the development of the SOP, it was compared with the SOPs published in the relevant countries to evaluate its feasibility and compliance with established standards. This comparison will ensure that the developed SOP is aligned with international best practices and guidelines for risk management in the biogas power generation industry.

RESULTS AND DISCUSSION

DESIGN OF BIOGAS-FED PEMFCS POWER GENERATION PLANT

The process flow for the biogas-fed Proton Exchange Membrane Fuel Cell (PEMFCs) power generation plant is illustrated in Figure 3. The feed process for biogas production was obtained from the sewage treatment plant, followed by H_2 reformation to increase the H_2 content. PEMFCs were then used to generate electricity from the H_2 produced. The plant design was a combination of various reference derivatives, which were incorporated to enhance the efficiency of generating electricity using PEMFCs.

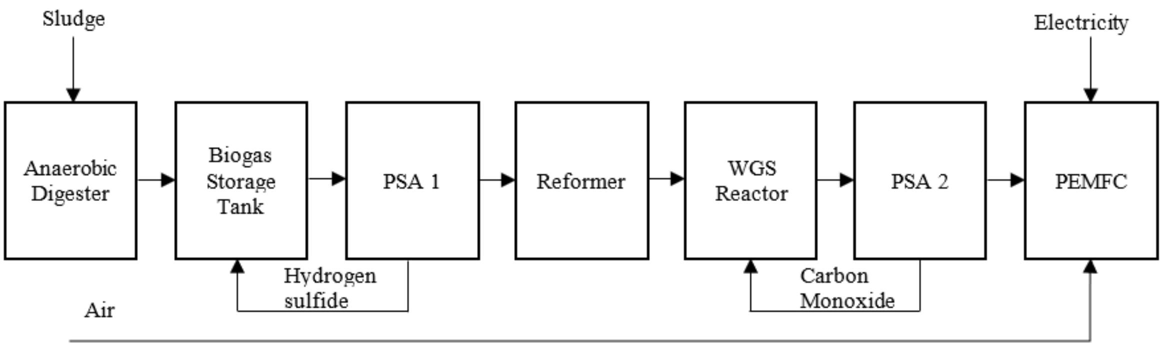

FIGURE 3. Biogas generation process flow using PEMFCs

The main reactor feed for the anaerobic digestion process was 1300 ton/h of sludge processed by the STP. This feed was then processed by mesophilic bacteria to produce biogas, which mainly consisted of CH_4, followed by CO, CO_2, H_2, and small amounts of H_2S.The renewal production of H_2 is vital for the operation of PEMFCs, as they use H_2 as the fuel for PEMFCs. In the biogas production process, the biogas from the storage tank contains H_2S, which can act as a catalyst inhibitor. Therefore, biogas is subjected to desulfurization to remove sulfur from the process. The remaining biogas is then compressed to high pressure, which increases the efficiency of the process. This compression is performed before H_2 renewal, as it is more effective than compression after renewal. The high-pressure biogas is then introduced into the furnace to raise the temperature to 500°C, promoting high CH_4 conversion and high chemical kinetic reaction during H_2 renewal.

This process requires the use of a heterogeneous catalyst, and nickel (Ni) has been found to be the best catalyst from an economic standpoint. Ni possesses high catalytic activity, leading to increased H_2 production (M. R. Shamsuddin et al. 2021).The reformer produced H_2 and CO in a 3:1 ratio, with small amounts of CO_2. The resulting syngas was cooled to 300 °C and then passed through a water-gas shift (WGS) reactor. A temperature of approximately 300 °C was required at the WGS reactor to achieve high CO_2 conversion. The gas upgrading or purification process was the final step required before the H_2 could be used as feed for the PEMFCs. To increase efficiency, H_2 purification was conducted through a separation process using pressure swing absorption (PSA). Gas adsorption increases with pressure. During the gas upgrading process, 1200 tons/h of H_2 with a purity of 99.99% was produced and directed to the PEMFCs at the required minimum temperature of 80 °C. The utilization of this H_2 through the PEMFCs generated 102 kW of electricity.

FIRE AND EXPLOSION INDEX (FEI) ANALYSIS

The biogas-fed Proton Exchange Membrane Fuel Cell (PEMFCs) plant underwent analysis with the FEI method to assess the hazard level of each operating unit. The highest Fire & Explosion Index (FEI) value was determined for each operating unit, with the anaerobic digester and biogas storage tank having the highest FEI values. These units were identified as severe-level hazard types compared to the other operating units. The summary of FEI calculation is presented in Table 7.

TABLE 7. FEI for various process units in PEMFC biogas plant.

Process Units	FEI Values	Degree of Hazard
Biogas Storage Tank	170	Severe
Anaerobic Digester	168	Severe
PEMFC	66.15	Moderate
Furnace	132.3	Heavy
WGS	90.7	Moderate
Reformer	100.8	Intermediate
PSA 2	81.9	Moderate
PSA 1	152.88	Heavy
Condenser	71.4	Moderate

The degree of hazard for the corresponding FEI values were determined based on guidelines provided by AIChE (AIChE, 1994). Based on the FEI analysis, it was found that the biogas storage tank has the highest FEI values, followed by the anaerobic digester with values higher than 160. According to Dow's FEI classification of hazard, these values indicate a severe degree of hazard followed by the furnace and PSA 1 which possess a heavy degree of hazard according to the FEI. This is a critical finding, as it suggests that extra safety measures and protocols should be implemented for these two units to ensure the safety of workers and the surrounding environment.

These results are consistent with findings from other studies, which have shown that accidents specifically caused by biogas production from anaerobic digestion tanks through pipe connections pose a high risk of explosions (Boscolo et al. 2020). Additionally, the furnace and PSA 1 unit were found to have a heavy degree of hazard, indicating that they also pose a significant risk. The reformer was identified as having an intermediate degree of hazard, while the PEMFC, WGS, PSA 2, and condenser units were identified as having a moderate degree of hazard.

Notably, no process unit was identified to have a light degree of hazard, which further emphasizes the importance of implementing safety measures across all units in the plant. These findings are summarized in Table 7.

Overall, the FEI analysis conducted in this study provided valuable insights into the degree of hazard posed

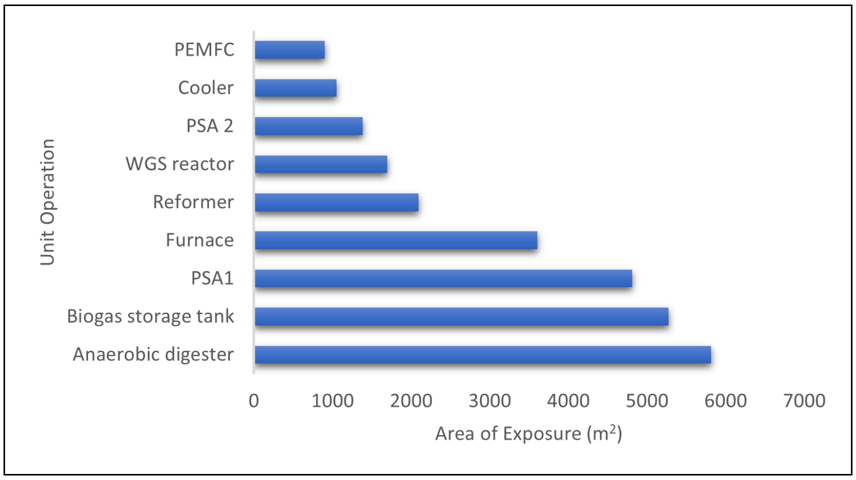

FIGURE 4. Area of each exposure for different process units in the plant

by each operating unit in the biogas-fed PEMFCs plant. These findings can be used to inform the development of safety protocols and measures to minimize the risk of accidents and ensure the safety of workers and the surrounding environment. In this study, FEI analysis was conducted as the preliminary analysis for the risk assessment. As the biogas storage tank and anaerobic digester are identified as the process units with highest degree of hazard, they became the main focus of the study to ensure that the worst-case scenario can be evaluated in case of an accident in the plant.

The FEI values were utilized to determine the area of exposure for each process unit and the results are represented in Figure 4. Based on Figure 4, the area of exposure was the highest for the anaerobic digester unit followed by the biogas storage tank as these units were the components with a severe degree of hazard based on the FEI analysis. This is mainly due to the high content of flammable and toxic gases that are present in these units that contributed to higher risk.

In light of the severe degree of hazard associated with the biogas storage tank and anaerobic digester, it is also important to consider the potential domino effect in the case of any failure or accidents that might occur at these process units. The domino effect refers to a chain reaction of incidents or accidents that occur as a result of a single initial event, leading to escalating consequences and widespread damage if not effectively controlled. Given the severe degree of hazard identified for the biogas storage tank and the anaerobic digester, these units become critical focal points for evaluating the potential domino effect. A failure or incident in these units could trigger a series of subsequent events, with each event amplifying the overall impact and potential for harm. For example, a failure or pipe rupture of the biogas storage tank could result in the release of flammable gases, which could ignite and lead to a fire. This fire could then spread to neighboring units, such as the furnace or PSA 1, thereby causing further damage and potentially triggering additional incidents. The domino effect can quickly escalate the severity of an initial incident, jeopardizing the safety of personnel and the integrity of the entire plant.

CHEMICAL EXPOSURE INDEX (CEI) ANALYSIS

The results from the Fire & Explosion Index (FEI) analysis revealed that the anaerobic digester and biogas storage tank posed the highest hazards among the process units, indicating their selection as a focal point for hazard and risk assessment in this study. The parameter sets for Chemical Exposure Index (CEI) calculations were utilized to determine the CEI value for H_2S, which was found to be 23.47. Figure 5 illustrates the hazard distance of hydrogen sulfide based on the CEI analysis.

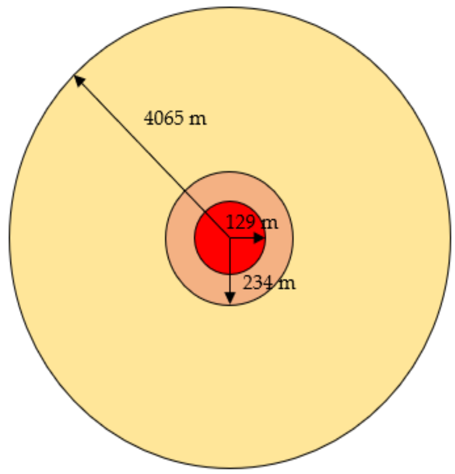

FIGURE 5. Hazard distance of hydrogen sulfide from CEI analysis

Figure 5 demonstrates that the highest concentration of H_2S was in the area around 129 m (ERPG-3), presenting a high risk and danger to anyone in the vicinity. This was followed by the hazard distance of 234 m (ERPG-2) and 4065 m (ERPG-3). Operating units with H_2S gas content pose significant risks and dangers, and the toxic nature of H_2S indicates that humans can withstand the smell of H_2S at air concentrations between 0.0005 and 0.3 ppm, with levels beyond this range being detrimental to one's health (Malone Rubright et al. 2017). Moreover, CH_4 gas content can reduce the O_2 content in the air, creating a state of asphyxia. The findings of this study are consistent with a previous study on an Italian plant, where the CH_4 content was identified as a respiratory hazard, accounting for 96.8%–98.5% of respiratory health damage caused by biogas (Macor & Benato 2020). Therefore, the anaerobic digestion tank operating units and biogas storage tanks were the focus of this study's hazard identification and risk assessment (Boscolo et al. 2020). This approach was taken based on the evaluation of risk from both the FEI and CEI analysis which has shown that these two units possess the highest risk as they contain high concentrations of biogas, which contribute to a significant degree of hazard in the plant.

RISK MATRIX ANALYSIS (RMA) ANALYSIS

The results of the Fire & Explosion Index (FEI) and Chemical Exposure Index (CEI) studies revealed that both the anaerobic digester and biogas storage tanks had similar hazard values and were identified as the units with the highest risks and dangers. To further assess the inherent safety of these units, Risk Matrix Analysis (RMA) analysis was conducted. Three operating units in the biogas-fed Proton Exchange Membrane Fuel Cell (PEMFCs) plant were evaluated, and the RMA values for the anaerobic digester and biogas storage tanks were determined to compare the most dangerous units. The hazard identification study considered the hazards involved in each operating unit, the process operating conditions and the impact of the hazards present. Table 8 summarizes the safety indices calculated for the anaerobic digester and biogas storage tanks.

TABLE 8. Risk level identified for anaerobic digester and storage tank from RMA analysis.

Risk	Unit Operation	Probability rating	Severity rating	Risk Value	Risk Level
Poisoning due to high toxicity	Anaerobic digester	4	5	20	High risk
	Storage tank	4	5	20	High risk
Explosion caused by high-pressure unit	Anaerobic digester	3	5	15	High risk
	Storage tank	4	5	20	High risk
Fire due to the presence of flammable gases	Anaerobic digester	4	4	16	High risk
	Storage tank	4	4	16	High risk
Chemical exposure to corrosive substances	Anaerobic digester	2	2	4	Low risk
	Storage tank	2	2	4	Low risk
Difficulty in breathing	Anaerobic digester	2	4	8	Moderate risk
	Storage tank	2	4	8	Moderate risk
Infection due to pathogenic environment	Anaerobic digester	2	4	8	Moderate risk
	Storage tank	1	4	4	Low risk

One key difference among the three methods used in this study (FEI, CEI, and RMA) is the extent of involvement of each operating unit level. The results may differ as the anaerobic digestion tanks vary in terms of their frequency of high-risk events. While the FEI and CEI studies found that the anaerobic digester unit and the biogas storage tank unit had similar hazard and risk values, the RMA analysis revealed that the anaerobic digester had even higher risks and dangers compared to the biogas storage tank.

If we only consider the risk of fire and explosion, the biogas storage tank may have a higher risk level than the anaerobic digester tank. However, when the toxicity is taken into account, the anaerobic digester tank poses a higher risk due to the probability, frequency and severity of the toxicity event, which increases the overall risk value. This discussion aligns with findings reported in a journal publication, which highlighted that anaerobic digesters are one of the most critical operating units in biogas processes.

This is due to the presence of flammable CH_4 gas and microorganisms in the digestive process posing a high risk of infectious diseases and even death (Nag et al. 2020; Wang et al. 2020). These findings highlight the importance of conducting multiple hazard identification and risk assessment methods to obtain more accurate results.

HAZOP ANALYSIS

After identifying the most high-risk operating units through the RMA analysis, further assessment was conducted on the anaerobic digester unit by performing a Hazard and Operability (HAZOP) analysis. This analysis identified expected problems around the inlet and outlet pipes, as well as the tank itself, which could lead to damage. Table 9 summarizes the HAZOP analysis for the anaerobic digester, including problems related to pipes, such as leakage, breakage, clogging, and control valve failure.

TABLE 9. HAZOP analysis for the anaerobic digester unit.

Guide Word	Deviation	Causes	Consequences	Action
		Parameters: Flow		
None	No Flow	Valve on drainage pipe is closed	Disruption of digestion process due to vacuum in digestion tank.	Ensure valve operation to avoid vacuum situations.
		Sludge inlet blocked	Sludge not entering the system	Regular visual inspection of inlet channels.
		Broken pipe	Dissemination of acetogenic and methanogenic bacteria to environment	Maintain pipes; provide sterile tools in the area.
Low	Content Leak	Leakage in the digestion tank	Sludge decreases over time; Delay in biogas production; Release of H2S to environment	Regular visual inspection; Install hydrogen sulfide detectors.
	Biogas Delay	Old gas intake time	Delay in biogas production	Inspection and timely maintenance.
High	Content Overpressure	Control valve failure	Sludge reaches maximum level, leading to overflow; Increased tank pressure	Install remote high-pressure control for PRV-1.
	Sludge Overflow	Flow exceeds limit	Overflow from tank	Remote control for high-pressure relief valve, PRV-1; Tool controls in place.
	Pressure Increase		Increased pressure	Preventive maintenance on pipes.
		Parameter: Temperature		
Guide Word	Deviation	Causes	Consequences	Action
High	High Temperature	Temperature exceeds 122°C in digestion tank	Microbes will die	Maintenance prevention
None	System Non-Responsive	Microbial activity too low in digestion	System shutdown by automatic emergency closure	Install an automatic emergency closure system
	Fire Risk	Gas prone to ignition	Fire hazard	Install high temperature alarm
	High Environmental Temperature	External high temperature	Increased internal pressure	Install insulation on digestion tank
	Explosion Risk	High internal pressure	Digestion tank explosion	Install an automatic emergency closure system
Low	Low Temperature	Temperature drops below 20°C in digestion	Slow microbial growth	Maintenance prevention
	Reduced Biogas Production	Lower microbial activity due to cold	Reduced biogas output	Install a low-temperature alarm
	Low Environmental Temperature	External low temperature	Inefficient digestion process	Install insulation on digestion tank
	Excessive Sludge Dampness	Overhydration	Sludge becomes too wet	Monitor and adjust moisture content

continue ...

... cont.

Parameter: Pressure				
Guide Word	Deviation	Causes	Consequences	Action
Low	Low Pressure in tank digestion	Leak in tank digestion	Reduced biogas output, biogas takes longer time	Scheduled maintenance, visual inspection of tank, install gas flow rate meter
	Valve control failure	Gas release	Dangerous gas released to environment	Maintenance prevention for valve, install hydrogen sulfide detector in tank area
High	High pressure in tank digestion	Valve control failure	Tank likely to explode, biogas cannot be channeled	Install emergency alarm, automatic closure system, gas flow rate meter
	Temperature too high	Process temperature rises	Microbes die, digestion process interrupted	Install emergency temperature alarm, temperature control system, gas flow rate meter

The recommended actions to overcome these problems mainly involve improving maintenance and monitoring services. The main problems identified for the anaerobic digester unit were the failure of the high-pressure controller on the tank and the common cause of accidents, which is leakage. The recommended actions to address these issues involve installing a more advanced controller system and developing a thorough emergency plan in case of controller failure.

These findings provide valuable insights into the main problems and necessary actions to overcome these issues for the highest operating unit, the anaerobic digester. However, due to the wide variety of practical situations and plant designs worldwide, the results of the HAZOP and accident analysis may need to be revised, and the knowledge stored in the database should be updated based on expert experience (Wang et al. 2020).

HAZARD AND RISK MODELING OF METHANE GAS DISPERSION USING ALOHA® SOFTWARE

In this section, the hazard and risk modeling of methane gas dispersion is discussed. Methane gas, which is the main byproduct of anaerobic digestion, was modeled to understand its behaviors of dispersion and to further understand how it may pose a threat with dispersion. The atmospheric conditions that can influence the severity and extent of hazard effects due to gas or fire emissions were explored, particularly in relation to the Gaussian model. The Gaussian model was used to understand the dispersion of gas in a neutral moving gas cloud and how the turbulence produced by higher wind speeds can impact the diffusion and mixing of the gas with the surrounding air. Figure 6 provides a clear representation of the potential hazards posed by CH_4 dispersion by presenting the threat zone of thermal radiation. The red zone indicates the most hazardous area, while the yellow zone represents the least hazardous area.

This provides valuable insights into the risks that could arise due to methane gas dispersion and helps identify areas that require special attention in terms of safety measures.

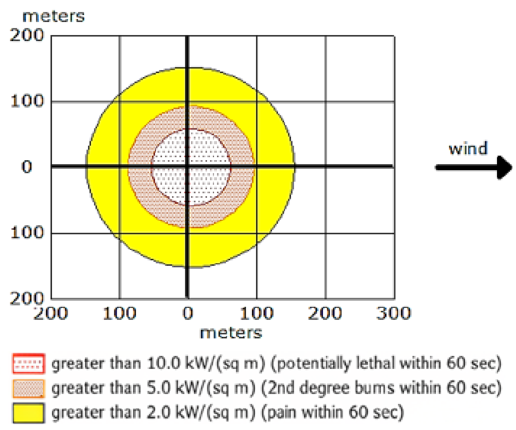

FIGURE 6. Thermal radiation threat zone of methane gas.

In this study, the meteorological conditions of the Kuala Lumpur area, which was the study site, were analyzed to understand the extent of heat and toxicity spread from the tank with high CH_4 gas content. The meteorological conditions caused the heat to spread to up to 150 meters from the tank with high CH_4 gas content, resulting in severe danger as shown in Figure 6. Within this distance, individuals may experience light injury within 60 seconds, while those within 50-100 meters may suffer from second-degree fire within the same duration. In the worst-case scenario, those within 50 meters or less are at high risk of death due to fire, highlighting the potential risks associated with CH_4 gas in terms of thermal radiation from jet flames. It should be noted that the findings presented in this study are based on the assumption that there are no obstacles or slopes present. However, the presence of slopes can significantly affect the spread and combustion of flammable gases, as demonstrated in the study by Sun (2022) (Sun et al. 2023). Therefore, it is important to consider the potential impact of terrain and other environmental factors on the safety of biogas-fed PEMFCs plants. Similar findings were observed in studies conducted by Setiyono (2018) at an Indonesian biogas plant, where the same parameters were taken into account (Saras Hanifati Setiyono 2018). From the results of the study, it was found that the red area, indicating an explosion hazard, was in an area of 1.8 kilometers with a CH_4 concentration of 50,000 ppm. These results were also based on the quantity of CH_4 gas, wind speed, and atmospheric stability. Therefore, these findings emphasize the importance of considering these important parameters in hazard and risk modeling of methane gas dispersion.

HAZARD AND RISK MODELING OF CARBON MONOXIDE DISPERSION USING ALOHA® SOFTWARE

The CO hazard and risk modeling was conducted in the same study area as the CH_4 gas hazard study, with the same selected area data. Results from the CO gas hazard and risk modeling showed that the toxic diffusion was propagated according to the wind direction, as depicted in Figure 7. The figure highlights the spread of CO moving towards the right in the direction of the wind. The red zone, representing the worst hazard, is considerably smaller than the yellow zone. This observation underlines how the wind parameter plays a critical role in influencing the hazard level.

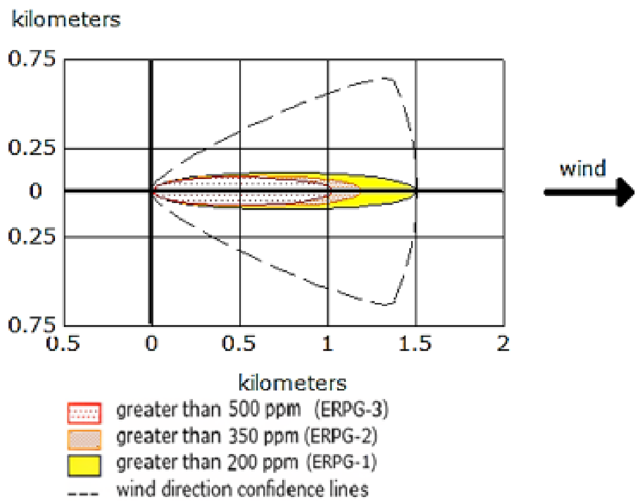

FIGURE 7. Toxic threat zone of carbon monoxide gas.

The wind speed in the Kuala Lumpur area was found to be relatively low, with the highest recorded speed being 13 km/h. This means that the diffusion of toxic gases resulting from CO hazards is limited in distance, with a maximum spread of up to 1.5 km from the location of the biogas storage tank and anaerobic digester tank. Within this area, people in the vicinity are expected to experience symptoms that are below the level of ERPG-1. This indicates that any adverse health effects caused by exposure to the toxic gas are only temporary and can be reversed. The area within 1-1.2 km from the source is still likely to experience reversible health effects or symptoms that can hinder an individual's ability to take protective action. However, the area within 1 km from the biogas storage tanks and anaerobic digester tanks location is the most hazardous, with the highest concentration of CO gas. In this zone, the health effects of toxic inhalation may not be reversible and could cause permanent damage. Workers or members of the public within this range are at a high risk of death or serious injury. It is critical to take appropriate measures to mitigate the risk of CO gas dispersion in this area.

These findings are consistent with published data indicating that large tanks with high pressure and high biogas content of 3000 m^3 can pose a life-threatening risk due to the potential fire from the released gas within approximately 30 m. The danger zone is also associated with explosions and gas poisoning, with the concentration of toxic gas cloud accumulation having a distance of about 20 m from the source (Stolecka & Rusin 2021).

Figure 8 provides insights into the toxic threat zone resulting from the dispersion of H_2S gas caused by leakage of the anaerobic digester tank and biogas storage tank. Both units had the same toxic threat zone, as they contained the same amount of H_2S and were exposed to the same meteorological conditions.

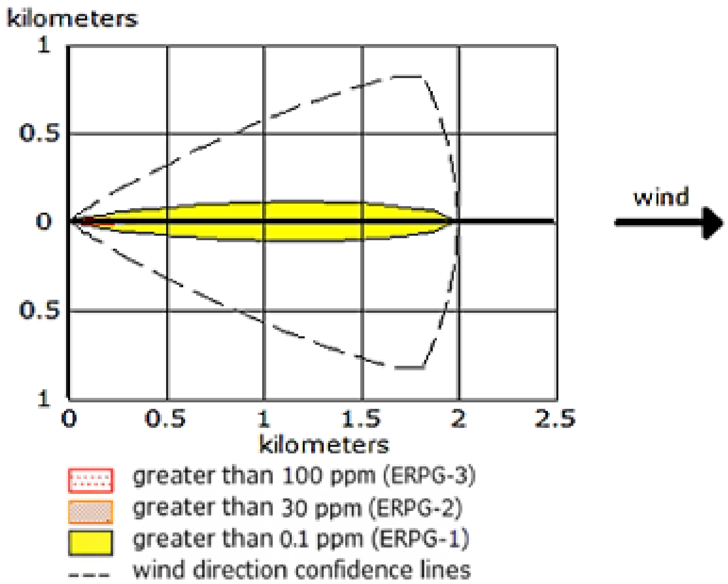

FIGURE 8. Toxic threat zone of hydrogen sulfide gas

As shown in Figure 8, the toxic threat zone caused by the dispersion of H_2S gas can extend up to a distance of 2 km from the location of the biogas storage tank and anaerobic digester tank. Within this zone, the concentration of H_2S gas can exceed 50 ppm, which is known to cause respiratory disorders and eye irritation for workers exposed to this area for an hour. However, it is worth noting that the pungent smell of H_2S can extend beyond the 2 km zone and up to 3.5 km from the sources of leakage. While the concentration of H_2S in this area may be low, it is still worth taking caution and avoiding prolonged exposure, as long-term exposure to low levels of H_2S can still result in mild health effects, such as nausea and dizziness.

These findings are consistent with previous studies that have used ALOHA® modelling to simulate the dispersion of H_2S toxic gas. According to previous studies that used ALOHA® modelling to simulate the accidental dispersion of H_2S toxic gas, concentrations similar to the levels observed in the present study (around 10-20 ppm) can cause a range of symptoms, including dizziness, sore throat, itchy eyes, and fatigue (Kulinič & Maruta 2016). These symptoms can be an indication of the adverse health effects of exposure to low levels of H_2S and highlight the importance of monitoring and controlling the spread of this gas to prevent harm to workers and the public.

BAYESIAN NETWORK ANALYSIS ON HAZARDS ASSOCIATED WITH PEMFC

This study aims to analyze the factors and parameters that contribute to the risk of fire and explosion within the Proton Exchange Membrane Fuel Cell (PEMFC) system. The analysis primarily focuses on various faults that can occur within the system, including blower, heater, heat exchanger, and combustor faults. This focus is crucial because faults like blower malfunctions can disrupt the airflow, potentially leading to overheating and an increased risk of fire. Additionally, the factor of pressure is also investigated as a sudden and uncontrolled increase in pressure, possibly due to the failure of pressure control mechanisms, can result in a more severe incident, such as an explosion.

Therefore, the Bayesian Network (BN) analysis conducted in this study specifically examines these identified factors and parameters. The relationships between these parameters are represented in a probabilistic graphical model, as seen in Figure 9. The detailed findings from the BN analysis are provided in Table 10. This is important to gain a deeper understanding of how they contribute to the overall risk of fire and explosion within the PEMFC system.

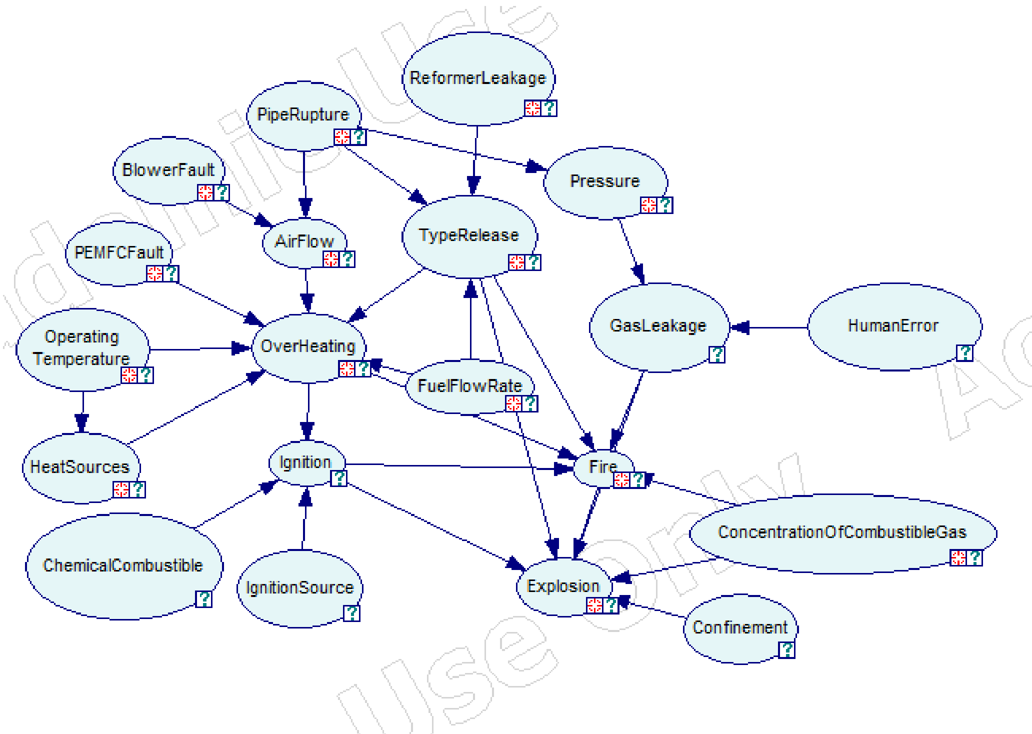

FIGURE 9. Probabilistic graphical model of BN analysis

TABLE 10. Risk probability values calculated using BN model

Factors	Details	Risk probability of Fire (%)	Risk probability of Explosion (%)
Temperature	Low	11	4
	Medium	12	4
	High	13	4
Pressure	Low	12	4
	Medium	14	9
	High	16	14
PEMFC component faults	No Fault	10	3
	Blower	12	4
	Heater	18	5
	Heat Exchanger	18	5
	Combustor	18	5
Accident scenarios			
	Pipe rupture	10	5
	Gas leakage	18	17

By analyzing the relationships and dependencies between these factors, the study aims to provide valuable insights into the potential hazards associated with the PEMFC system and enhance safety measures accordingly. The BN model employed in this study focuses on investigating the main factors that contribute to the risk of fire and explosion within the PEMFC system. These factors include temperature, pressure, faults in PEMFC components, and accident scenarios.

One of the factors analyzed is temperature, and it is observed that there is a clear trend indicating that higher PEMFC temperatures lead to a slight increase in the risk of fire, from 11% to 13%. However, the increase is not considered significant. This can be attributed to the system's handling of a small amount of fuel at any given time, which limits the impact of temperature on the overall risk of fire. Furthermore, appropriate safety measures are assumed to be in place to mitigate the risk from escalating. For instance, a blower is utilized to maintain temperature control when it reaches high levels. These findings suggest that while higher temperatures do contribute to the risk of fire, their influence is relatively minor due to the system's design and safety measures. On the contrary, it is noteworthy that the temperature of the PEMFC system does not appear to have any influence on the risk of explosion, as the risk remains at a constant 4% regardless of the temperature.

This observation can be attributed to the conditions required for an explosion to occur, which may not be directly influenced by the temperature alone. The key conditions for an explosion are the presence of fire, oxygen, and an ignition source (Abg Shamsuddin et al. 2023). Since the risk of fire does not significantly increase with temperature, it logically follows that the temperature does not exert any influence on escalating the risk of explosion either. However, when pressure is varied, a significant increase in the risk of explosion is observed, rising from 4% to 14%. This can be explained by the fact that when gases are exposed to heat or increased pressure, reactions occurring may trigger an explosion. This finding is supported by the research conducted by Shamsuddin et al. (D. S. N. A. Shamsuddin et al. 2022), which confirms that higher pressure increases the risk of explosion.

The highest contributing factors to the risk of fire and explosion are related to faults in PEMFC components. Components such as the blower, heater, and heat exchanger contribute to the highest risk of fire, which is calculated to be 18%. These faults are closely associated with temperature-related issues, explaining their significant influence on the risk of fire.

However, their impact on the risk of explosion is relatively minor. Reducing the risk of fire and explosion involves ensuring proper maintenance of the PEMFC system to prevent faults. It was revealed that having no faults in the PEMFC system can reduce the risk of fire to 10% and the risk of explosion to 3%. Moving on to accident scenarios, the highest risk of fire and explosion is associated with the gas leakage scenario, resulting in an 18% risk of fire and a 17% risk of explosion. In fact, explosion due to gas leakage is common in fuel cell systems, as supported by Braun et al. (Braun et al. 2012) and Xiao-long et al. (Xiao-Long et al. 2017). Gas leakage scenario is also common cause of accidents in most chemical plant including biogas plant (Rosli et al. 2022).

In summary, the risk of fire ranges from 10% to 18%, while the risk of explosion ranges from 3% to 17%, indicating that fire scenarios are more likely to occur in this case study. It is also worth noting that explosion scenarios are relatively rare under normal conditions, occurring only at a 3% risk. However, under extreme conditions, the risk of explosion increases to 17%. This wide range for explosion risk suggests that only extreme conditions contribute to the heightened risk.

STANDARD OPERATING PROCEDURE (SOP)

One of the key outcomes of the hazard and risk assessments conducted in the study is the development of a recommended Standard Operating Procedure (SOP) for the safe operation of biogas-fed Proton Exchange Membrane Fuel Cell (PEMFCs) plants. The SOP proposes safety measures to mitigate and reduce the hazards associated with various types of hazards around the power plant.

The proposal of these safety measures is based on the risk and danger data obtained through various methods, such as Fire Explosion Index (FEI), Chemical Exposure Index (CEI), Risk Matrix Analysis (RMA), Hazard and Operability (HAZOP), and ALOHA® software. To ensure the effectiveness of the SOP, a hierarchical pyramid approach was adopted, where Table 11 presents the hierarchy of controls to mitigate and reduce the hazards in the biogas-fed PEMFCs plant. The SOP is designed to be written in general terms so that it can be applied to worldwide applications.

However, it is important to note that the SOP should be revised and customized to comply with the specific weather and conditions of each location in the world. This is particularly important because such factors can have a significant influence on the analysis (Yang et al. 2022). By implementing the recommended SOP, operators can effectively manage the hazards associated with the biogas-fed PEMFCs plant and reduce the likelihood of accidents and incidents. The SOP includes measures such as proper training of personnel, use of personal protective equipment, regular equipment maintenance and inspection, emergency response planning, and monitoring of gas concentrations in the plant. These measures, when properly implemented, can greatly reduce the risk of harm to personnel and the environment.

TABLE 11. Hierarchy of controls to reduce risks and dangers in biogas plants

Hierarchy control	Safety measures
Elimination	• To prevent fires, all flammable materials and ignition sources should be removed from the area near the biogas storage tank and anaerobic digestion tank. • When filling or emptying the biogas storage tank, it is important to monitor pressure fluctuations and ensure that the operating unit has good accessibility.
Substitution	• Replacing the fiberglass coating on the anaerobic digestion tank with a new coating that has superior UV protection and can maintain the operating temperature. • Replacing any damaged relief valves, control valves, or pipes in the biogas pipeline plant with new ones to ensure effective control of hazardous materials in case of leakage or release
Engineering Control	• Ensure proper and regular maintenance of PEMFC system. • Installation of highly sensitive pressure sensors with AI pressure controller to initiate shutdown for PEMFC unit. • During plant layout planning, ensure that the biogas blowers, biogas storage tanks, electrical installations, and earth point are arranged in such a way as to facilitate easy handling and use of biogas, as well as maintenance arrangements. • Install control valves on certain pipes to prevent the occurrence of biogas backflow and to control the flow of biogas in the pipeline. • Install methane and hydrogen sulfide gas detectors in the storage tank and digestion tank areas to detect the use of leaks or releases of toxic gases. This will enable the early detection of any gas leaks and allow for quick and appropriate action to be taken. • Perform corrective and preventive maintenance on the required operating unit according to its specifications and record for future maintenance. This will help to prevent equipment failure and ensure that the plant operates smoothly. • Supply air manually or technically in enclosed areas to reduce the concentration of flammable gases in the event of a gas leak. This can help to reduce the risk of explosion in the event of a gas leak. • Install an automatic shut-off system if operating conditions and parameters exceed the specified limit values to prevent any explosion. This is an important safety measure that can help prevent catastrophic incidents. • Any biogas waste and sludge that comes out must be treated first before being released into the environment to prevent the release of toxic substances into the environment. This is an important environmental safety measure that must be followed at all times. • Monitor biogas and sludge flow rates to ensure adequate hydrogen gas production by installing gas flow rate meters. This will help ensure that the plant is producing hydrogen gas efficiently and effectively. • Install high-pressure alarms on biogas storage tank units and anaerobic digestion tanks to prevent any explosions from occurring. This will enable the early detection of any high-pressure situations in the tanks and allow for appropriate action to be taken.
Administrative	• Ensure adequate space for emergency access. • Conduct regular safety audits to identify potential hazards and ensure that all safety procedures and equipment are up to date. • Develop a system for reporting and investigating incidents and near misses to improve safety measures and prevent future accidents. • Develop an emergency plan that includes protocols for responding to different types of emergencies, such as gas leaks, fires, and power outages. Emergency simulations should be carried out annually. • Ensure that safety records are regularly updated to include data on accidents that have occurred at biogas plants. • Install safety signs in the plant area to prohibit the carrying of flammable materials and smoking, as both hydrogen gas and methane gas are highly flammable. • Ensure that fire extinguishers are easily accessible in designated areas, and routinely verify the expiration dates to guarantee that they are always in proper working condition for timely fire suppression.
Personal Protective Equipment (PPE)	• In areas near the anaerobic digester tanks and biogas storage tanks where there is a risk of low oxygen content leading to asphyxia, self-contained breathing apparatus (SCBA) should be used. • Provide personal protective equipment (PPE) for all staff and ensure that they are trained in how to properly use and maintain the PPE. • Wear eye and face protection to prevent injuries from debris, sparks, and splashes of sludge while working near anaerobic digestion tanks.

CONCLUSION

In summary, this study contributed to the hazard identification and risk assessment in biogas-fed Proton Exchange Memberan Fuel Cell (PEMFC) plants. The findings emphasize the critical importance of ensuring the safety of such plants, given their potential for utilizing biogas produced from various organic waste sources to generate electricity using PEMFCs. The study employed various methods such as Fire Explosion Index (FEI), Chemical Exposure Index (CEI), Risk Matrix Analysis (RMA), Bayesian Network (BN), hazard modeling via ALOHA® software, to comprehensively analyze and evaluate the risks associated with the operation of biogas-fed PEMFC plants. Through these analyses, the biogas storage tank and anaerobic digester were identified as the units posing the highest hazards and risks among the equipment studied. To further assess the safety of the plant, the RMA was determined, revealing that the anaerobic digester presented an even higher risk compared to the biogas storage tank due to the presence of pathogenic hazards. The comparison with other journal publications confirmed that the anaerobic digester had the highest acceptable hazard and risk values compared to other process units. Additionally, the study investigated the influence of meteorological conditions and the biogas concentration on the severity of accidents, which is depicted by toxic gas dispersion and explosion area around the biogas plant using ALOHA software. This research introduces the novel application of Bayesian Network (BN) analysis to the study of hazards in PEMFC. Beyond the general assessment of associated hazards, the BN analysis provides specific insights. It estimates that the risk of fire due to PEMFC is between 10% and 18%, while the risk of explosion is between 3% and 17%. The use of BN in this context offers a detailed and quantitative approach to risk evaluation for PEMFCs, which is a distinctive contribution of our study.

This analysis highlights the key findings regarding the risk of fire and explosion in the PEMFC system. Temperature alone does not significantly impact the risk, while pressure plays a crucial role in the likelihood of an explosion. Faults in PEMFC components, particularly the blower, heater, and heat exchanger, are the primary contributors to the risk of fire. The gas leakage scenario presents the highest risk for both fire and explosion. Overall, proper maintenance and safety measures are crucial in mitigating these risks and ensuring the safe operation of PEMFC-based power generation plants. Based on the findings, the study proposes several effective mitigation controls derived from the hierarchy of controls concept. These recommendations offer a roadmap for plant operators to implement safety measures that significantly reduce the risk of accidents and hazards in the plant. Thus, this research enhances the current understanding of inherent risks and safety measures in the context of biogas-fed PEMFC plants, contributing to a valuable framework for hazard mitigation in the renewable energy sector. Based on the findings, the study proposes several effective mitigation controls derived from the hierarchy of controls concept. These recommendations offer a roadmap for plant operators to implement safety measures that significantly reduce the risk of accidents and hazards in the plant. Thus, this research enhances the current understanding of inherent risks and safety measures in the context of biogas-fed PEMFC plants, contributing to a valuable framework for hazard mitigation in the renewable energy sector.

FUTURE WORK

Future work can include a comparison between the FEI manual method and modelling using the Risk Analysis Screening Tool software, which is globally used for the Dow index. Other hazard identification methods could also be explored, such as Bayesian Network analysis in addition to FEI, CEI, HAZOP, and RMA methods, to compare the hazard results produced. It is important to note that FEI mainly focuses on the quantity of flammable gases, while CEI mainly focuses on the quantity of toxic gas release. Therefore, it may not account for other hazards such as human error or malfunctions that could also result in accidents.

A more comprehensive analysis that combines various methods is recommended for more accurate results. Additionally, the findings obtained from the analysis in this study can be used to estimate the total loss in case of an accident. Economic losses and life losses can be predicted for each analysis, such as with FEI. This way, a better understanding of the potential impact of an accident can be obtained, leading to better preparation. Collaboration with biogas companies is essential for obtaining real data and tailoring the standard operating procedures (SOPs) to the specific needs of each biogas plant. This would benefit both parties, as having an SOP that is tailored to the specific plant's needs can help prevent accidents and minimize eco-nomic and reputational losses.

Additionally, this collaboration can help in gathering more data and identifying potential hazards that may not have been identified in the current study, leading to a more comprehensive analysis of the risks involved. Therefore, it is highly recommended to collaborate with biogas companies around the world to establish a standard SOP for biogas-fed PEMFCs operation that can be used with varied weather and conditions of biogas plants. Lastly, it should be noted that an undesired incident not only causes economic loss but also tarnishes a company's good reputation in the community. Hence, the findings of this study should be taken into account by biogas companies to establish safe and efficient biogas-fed PEMFCs plants worldwide.

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DECLARATION OF COMPETING INTEREST

None

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