© Universiti Tun Hussein Onn Malaysia Publisher's Office

IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Dynamic Hazard Identification on Solid Oxide Fuel Cell system using Bayesian Networks

Dyg Siti Nurzailyn Abg Shamsuddin[1], Andanastuti Muchtar[2,3], Darman Nordin[1], Faisal Khan[4], Lim Bee Huah[2], Masli Irwan Rosli[1,2*], Mohd Sobri Takriff[1,5]

[1]Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor Darul Ehsan, 43000, MALAYSIA

[2]Fuel Cell Institute, Universiti Kebangsaan Malaysia, Bangi, Selangor Darul Ehsan, 43000, MALAYSIA

[3]Department of Mechanical & Manufacturing Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor Darul Ehsan, 43000, MALAYSIA

[4]Artie McFerrin Department of Chemical Engineering, Texas A&M University, 400 Bizzell St, College Station, TX 77843, UNITED STATES

[5]Chemical & Water Desalination Program, College of Engineering, University of Sharjah, University City, Sharjah, 27272, UNITED ARAB EMIRATES

*Corresponding author

DOI: https://doi.org/10.30880/ijie.2022.14.02.014
Received 27 November 2021; Accepted 20 March 2022; Available online 02 June 2022

Abstract: Accidents are expected when operating Solid Oxide Fuel Cell (SOFC) unit system in a plant due to its complexity and operating conditions. SOFC system which consists of risky components such as combustor, reformer, heaters and SOFC stack poses risk of fire and explosion especially due to its high operating temperature. In addition, other factors such as failure rate components, quantity materials, gas leakage and chemical characteristics involved further increase the risks to an alarming level. In reality, these conditions are evolving depending on the current situation which make it challenging in determining the actual risks. Since SOFC technology is still emerging and not widely used, the studies on hazard identification on SOFC system is very minimal. The present work develops a new hazard evolution framework for SOFC system which is mapped into Bayesian network model using open-source software programs, GeNie to bring dynamics in identifying risks and hazards. This allow all potential hazards to be updated in real-time to ensure safe implementation of SOFC unit system in a plant. With this, all factors and evolving conditions contributing to the risks can be estimated with higher precisions to reduce the accidents probability. Sensitivity analysis is also carried out to determine how input parameters influencing the identified hazards. Results showed the probability of fire and explosion occurring in SOFC system is approximately 21% and 7% respectively. Operating conditions (temperature and pressure) are identified as the main causes contributing to the risks. Higher temperature increases risks of Fire from 17% to 21% while higher pressure increases the risks of Explosion from 7% to 18%. The current work identified the occurrence of final hazards in SOFC system dynamically and can be served as guideline for safer implementation of SOFC.

Keywords: Solid oxide fuel cell system, dynamic hazard identification, bayesian network, fire, explosion

Corresponding author: masli@ukm.edu.my

1. Introduction

Solid Oxide Fuel Cell (SOFC) is an efficient conversion unit which converts gaseous fuel (i.e. hydrogen, biogas and natural gas) to electrical energy and heat through electrochemical reaction with oxidant. The combustion process by SOFC is one of the cleanest combustion process thus electrical energy produced is considered as green energy because it produces very low emissions of greenhouse gases. High efficiency of SOFC make SOFC technology a promising candidate to replace conventional combustion engines and further expand its potential in many application such as transportation, marine, residential and especially in power generation plant [1]. Despite their huge advantages, the high cost of the technology due to its high operating temperature impeded wider application. Many research has been conducted to overcome this challenges while maintaining the high efficiency of SOFC. Recent research suggests lowering the high temperature (800ºC-1000ºC) to intermediate temperature (400ºC-700ºC) [2] to reduce the fabrication and material cost. This is carried out by using metallic interconnectors in SOFC stack cell and thin electrolyte. However, this lead to other challenges which are the reduction of excess overpotentials observed for O_2 reduction reaction and the fabrication of thin electrolyte [3].

This is supported by [4] where environmental performance must be improved to reduce the overall cost of SOFC technology which is by discovering possible material replacements and most impacting manufacturing processes.From the literature review, most study on SOFC system focus on improving efficiency and lowering the cost of SOFC system but has very minimal evaluation on the safety aspect of SOFC system. There are three main reasons why safety issues related to SOFC system must be addressed and pay attention to. First, the feed to SOFC system is a flammable fuel which raise safety concerns. The presence of the flammable fuel in the system has already making the SOFC system to be at risk of fire. Improper handle of the flammable fuel lead to a more serious problem such as explosion. Secondly, this drawback is even exaggerated when the operating temperature of SOFC system is very high which is up to 1000ºC. This is because the flash point of fuel fed into SOFC system is only 500ºC which is lower than the operating temperature of SOFC. Flash point is defined as the lowest temperature for a liquid to be heated to form ignitable mixture in the presence of ignition source. In the case of a fuel at a temperature below its flash point, there isn't enough vapor to facilitate combustion [5]. However in this case, the SOFC operating temperature is 1000ºC which is way higher than the flash point. This means it can easily be ignited and will burn in most environment in the presence of ignition sources. Thirdly, SOFC system which consists of high-risk components such as heater, reformer, combustor and heat exchanger further increase the risk of fire and explosion. According to [6] there are many sources of energy that may create explosive environment. The sources of ignition includes hot or heated surfaces such as heater, heat exchanger and reformer which may cause ignition when in contact with flammable fuel of SOFC. Flames and hot gases are also among the most effective sources of ignition. Even a small flame may ignite explosive atmospheres let alone high risks unit such as combustor from the SOFC system. Other sources of ignition comes from mechanically generated sparks, electric apparatus, and electric current which can easily be obtained from the components connected to the SOFC system.

Application of SOFC technology involves other process such as reforming and CHP generation is integrated with a few system and devices to function properly. Therefore the presence of high risk components such as reformer and combustor which involves with the high temperature of flammable fuel most likely contribute to the risks of fire and explosion. This is mainly due to the gas leakage by the SOFC stack and failure of the high risk components of SOFC system. According to [3], gas leakage from SOFC stack which is through electrolyte interface is unavoidable. Although there are sealing system available to avoid the gas leakage, [4] stated that in real operation on the long run, some gas leakage is still unavoidable as the sealing system can only reduce the release and does not completely stop the leakage. [4] further investigated why gas leakage are still happening despite commonly provided the sealing system and concluded that it is actually due to pressure difference and concentration gradient between anodic and cathodic compartments. It is also caused by performance degradation of the sealing system over long run. Gas leakage affect the composition of the flowing mixture thus flammable mixture might be present whenever there is a gas leakage. This becomes dangerous when the released gas is in contact with the high operating temperature of the stack, ignition might occur which lead to fire incident. Gas leakage also resulted in increased in internal stack temperature and imbalance thermal of the whole system which then affected the overall efficiency of the system. Imbalance thermal or thermal gradients occurred not only reduced the overall efficiency of the SOFC system, but also cause the whole system to be unsafe thus, issues with thermal gradients need to be taken seriously. Besides gas leakage, thermal gradients can also be caused due to reformer failure. According to [7], reformer failure leads to higher levels of methane in reformate fuel and this increased the rate of internal reforming process and eventually leads to dangerous level of SOFC stack operating conditions. This undoubtedly contribute to the risks of fire or explosion. This is just one of a few causes which contribute to the risks.

The most noteworthy ones are the hazard and operability study (HAZOP) which was developed by Chemical Industries Association in year 1970 [8] and is still used widely until today. Other well-known methods used are Failure Mode and Effect Analysis (FMEA), Inherent Hazard Analysis, Fault Tree Analysis (FTA), Failure Modes, Effects and Criticality Analysis (FMECA), 'What if?' Analysis, Bow-Tie Analysis (BTA) and etc. A total of 40 methods of hazard identification was analyzed by Glossop et al [9] and concluded that each method has its own strength and weaknesses. Despite their proved advantages, most hazard identification method has limited capability to learn from early warnings and new risk notions [10]. This was supported by [11] where they claims that these conventional methods are static in nature which may lead to unreliable results. This is because when it is static, any information updates are difficult to incorporate. For instance, when operational parameters such as temperature or pressure are constantly changing, these changes or updates also changes the results and analysis. Since conventional method are static, these changes are hard to incorporate thus any changes in the results cannot be detected and actual conditions cannot be captured which then produce inaccurate results. Any modification due to the changes has to be done manually which is time consuming and impractical. This inflexibility also is not suitable for a large-scale application which leads to inaccurate safety assessment. Therefore, a more dynamic approach is required.

The idea of bringing dynamic into hazard identification has already been integrated into risk assessment in the past few years to learn and investigate new and emerging technologies which is why this dynamic method will be utilized in this study to identify hazards from the emerging technology, the SOFC technology. The development of dynamic hazard identification technique includes the Dynamic Risk Assessment (DRA) [12], Dynamic Procedure for Atypical Scenarios Identification (DyPASI) [13] and risk barometer [14]. DRA integrates Bayesian failure mechanism (probability updating) with consequence assessment, DyPASI is based on the improvement of conventional BTA method in which it is able to update the bow-tie results and risk barometer is a risk indicator which is suitable to be integrated with both bow-tie analysis and Bayesian Network (BN). In this study, DRA is applied with the integration of Bayesian Network. In comparison to the conventional method, DRA is distinguished for its supplementary steps: probability updating and accident analysis which represent the dynamic approach. The purpose of this work is to develop Bayesian simulation model of hazard evolution in SOFC system and dynamically identify hazards in SOFC system and analyze causes and parameters contributing to the risks of fire and explosion. The proposed model is specifically for SOFC system and the dynamic feature applied in this study allow identification of varying hazards due to the varying input.

In this paper, factors and causes from SOFC system which contribute to the risk of fire and explosion are investigated and analyzed. Early identification and possibly correction of any type of faults consisted in SOFC system is crucial to reduce the risks of hazards and promote safer implementation of SOFC technology. Hazard identification, which is the first major step in risk assessment is crucial in preventing and mitigating adverse hazards in the SOFC system. Hazard identification can be applied anytime of the process development either at early stage of the design or during the existing operation process. It plays a crucial role in risk assessment as it can determine what could possibly be wrong in a process such as determination of causes of deviations from normal operations, risky areas and equipment. Though identifying all hazards are impossible, many methods have evolved over decades to effectively identify most hazards which allow risks to be estimated to a satisfactory level. This paper is divided to five sections. Section 2 described overview of BN and Section 3 presented the methodology on dynamic hazard identification with BN model. The proposed model enable input to dynamically change anytime during the process and BN model can make corresponding prediction of probability ranking for fire and explosion. Next, section 4 presented proposed Bayesian simulation model based on mapping algorithm and the simulation results. Finally, section 5 presented the sensitivity analysis to analyze parameters which contribute to the risks of fire and explosion the most.

2. Bayesian Network

Data available for the study of risk analysis are usually very complicated covering information from qualitative expert judgements or numerical investigations or both. Bayesian Network (BN) which is based on probability theory is a strong tool to deal with this complexity. BN is probabilistic graphical modeling technique to represent information about an uncertain domain, which is represented by an acyclic direct graph, with each node representing the qualitative part (random variables) and each edge represent the quantitative part (conditional probability). Utilizing the idea of conditional probabilities, the BN analysis is based on the specification of conditional probabilities of child nodes given states of parent nodes which is connected by causal links. The causal links represented by an arcs or arrows indicate direct probabilistic dependencies among the nodes. The variables may have multiple states to satisfy given logic and probability of each state is expressed by conditional probability conditioned by other states in the nodes [15]. BN is defined by updating prior probabilities based on given input variables also known as evidence which is based on observations. The evidence can either be deterministic or probabilistic evidence which can be obtained from process data of certain observations such as operational temperature and pressure [11]. The integration of Bayesian Network in risk assessment has proved to be useful in various technical field such as risk-based decision making, tunnel safety measures, assessment of flooding risks, forensic assessment and risk analysis of transportation network [16].

Based on this feature, BN suits perfectly for this current study because of a few reasons. First, the parameters and causes leading to hazards are various and consists of both deterministic and probabilistic evidence which represent situations in real practice. These complex information and data can be organized and incorporated easily by using BN model. Secondly, the causal links which encodes causal relations between all nodes allow hazard evolution be mapped accurately. From this, causes and parameters leading to final hazards can be observed clearly. Thirdly, BN model is capable to identify what hazard most likely to occur by calculating the probability ranking given the input variable (initial conditions). Finally, dynamic features of BN enable real-time hazard identification where any new information or updates regarding the initial conditions can be updated if the hazards are known and vice versa. This means the analysis can be either forward or backward analysis. Forward analysis means probability ranking of hazards are calculated given initial conditions while backward analysis means probability ranking of initial conditions are calculated given known hazards. There are, however some drawbacks of using BN model. Perhaps the most significant drawbacks of BN approach is that there is no universal accepted method for constructing the BN model. Therefore, the design of BN model for specific case study requires a significant amount of effort in order to obtain accurate model and results. For a case study which has very limited data such as SOFC system, subjective and logical belief is required when constructing the BN model. Inaccurate logical belief may affect the results therefore it is important to include the expert's belief if necessary. Despite the drawbacks, BN approach is still one of the best approaches to predict consequences because it can be used for both forward and backward analysis. This is important in this study as it can be applied in the case whether the accident ever happening or not. For example, in predicting what type of accident might occur, forward analysis of BN approach can be used. On the other hand, if the accident has already occurred, backward analysis can be carried out to analyze the causes that contribute to the occurrence of the accidents. This perhaps might be the biggest advantages of using BN approach as most neural networks for instance only produce meaningful output in feedforward direction. Another biggest strength of using BN approach is it can easily be extended. Adding new information usually requires modification or new system model constructed which requires significant amount of time and effort. Using BN approach on the other hand allow new information or evidence easily be incorporated into BN model which allow the results to be updated easily.

3. Dynamic Hazard Identification using BN Model

Fig. 1 shows summary of how dynamic hazard identification is conducted using BN model. The current study adopts the methodology developed by [11] to develop hazard evolution framework for SOFC system. In order to identify the final hazards in SOFC system, the causes and parameters which may lead to the hazards has to be investigated first before mapping the scenarios into BN. The following section described how the study on safety aspects of SOFC system created the hazard evolution. The developed model for SOFC system can be applied for other application of SOFC such as power generation plant, transportation or residential use. The difference will be the initial conditions which is according to a certain circumstances.

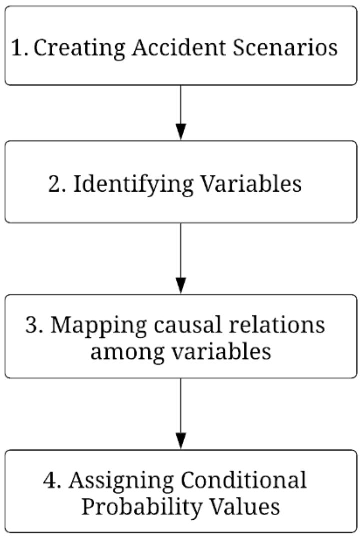

Fig. 1 - Summary of methodology on dynamic hazard identification using BN model

3.1 Creating Accident Scenarios

Accident scenarios or sequence are generated based on logic with respect to past experience and relevant knowledge[17]–[22] . In this study, the main components of SOFC system studied is based on generic SOFC system employing anode gas recycle as shown in Fig. 2. This includes fuel line, desulfurizer, ejector, reformer, SOFC stack, combustor, air preheater, heat exchanger, exhaust line, inverter and blower. Safety aspects of SOFC systems are investigated as shown in Table 1 and faults in each component of SOFC system which are contributing to the risk of fire and explosion are identified. Generally, faults in any part of the SOFC system will reduce durability and reliability of the system [25]. It is more intuitive to judge that given any faults in the system will be putting the whole system at risk of fire or explosion. With the SOFC safety studies, primary event can be identified for envisaging hazard scenarios. Fig. 3 shows the framework of creating accident scenarios where the initial conditions are divided into four main categories namely 1) operational conditions 2) mechanical failure 3) chemical characteristics and 4) site characteristics. The operational parameters refer to monitored variables such as unit capacity, mass flow, pressure and temperature. Mechanical failure refers to component faults such as blower, compressor, ejector, controller faults and etc. Chemical characteristic on the other hand refers to the properties of chemicals such as toxicity, combustibility, vapor pressure and so on. Finally, site characteristics refers to the condition of the surrounding environment such as weather condition and location and confinement. To reduce computational time, only relevant parameters with the SOFC system is included in BN model. For instance, operational conditions included in the developed BN model is only pressure and temperature while for site characteristics, only confinement is included.

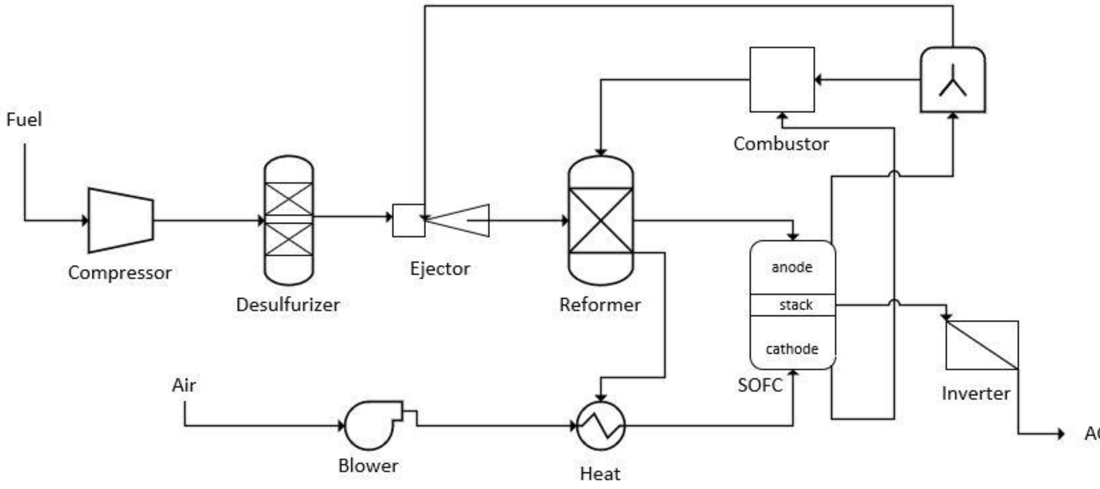

Fig. 2 - Generic SOFC system employing anode gas recycle [15]

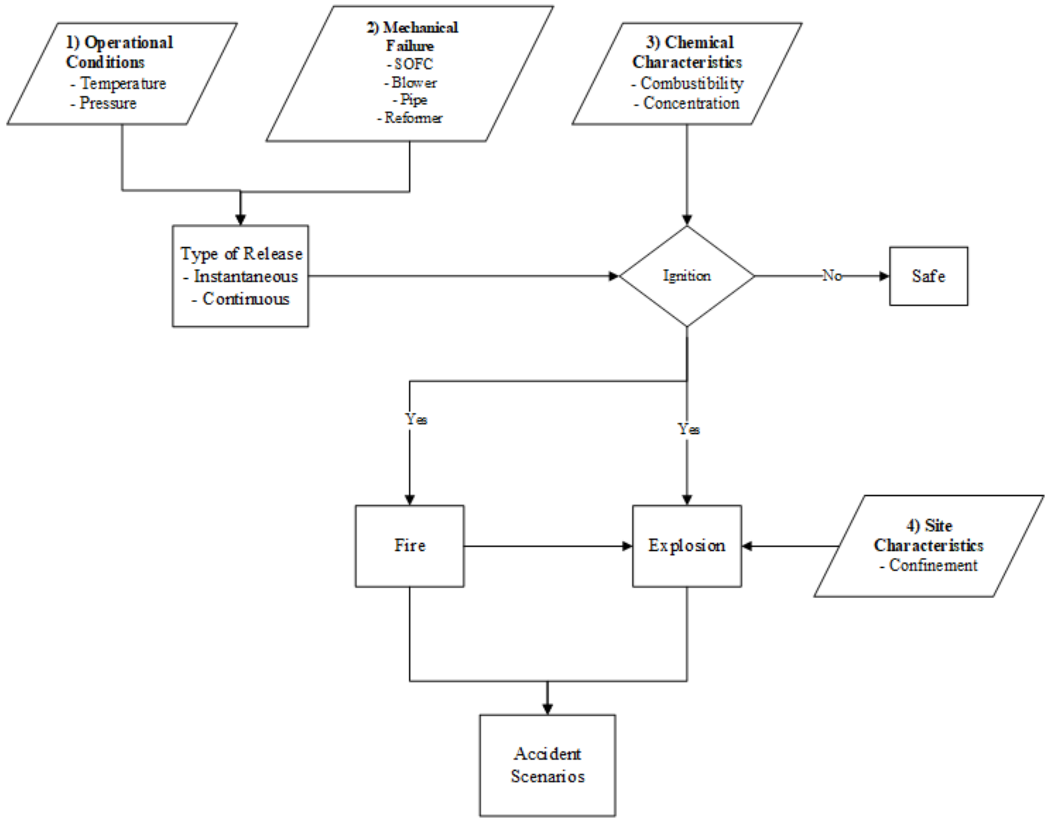

Fig. 3 - Framework of creating accident scenarios [26]

Table 1 - Studies on safety aspect of SOFC system

Causal Factors	Hazards Identified	Description	References
Blower fault	Fire	Blower faults disrupt air flow where it provides oxidant for electrochemical reaction and combustion reaction and also to remove excess heat in SOFC stack. Disruption of air flow due to blower faults cause overheating and may lead to fire.	[23]
Reformer fuel leakage fault	Fire	Reformer fuel leakage fault cause fuel entering the SOFC stack to reduce significantly. This also disrupt fuel and air flow rate thus raise concerns of overheating. There are a few possible areas where fuel gas leakage may occur. 1) Fuel reformer 2) Reactor 3) Pipe between reformer and SOFC stack 4) external pipelines between reformer and fuel gas flow meter	
Gas leakage from SOFC stack cells	Explosion	The electrolyte layer was found to have thinning and penetrating holes which confirmed the occurrence of gas leakage in the cells. This research found that not only the fuel efficiency decreases, but the gas leakage in the cells may leads to explosion due to high operating temperature as the fuel may mix with oxygen outside the cells.	[17]
Sealing Faults	Explosion	Sealing faults between the two compartments at the anode and cathode may leads to gas leakage from one electrode cell to the other which cause it to be at a risk of explosion.	[18]
Thermal expansion	Fire	The problems relating to the sintering of electrode, chemical diffusions in materials and thermal expansion are all due to high operating temperature which contribute to rapid degradation of SOFC performance and at a risk of overheating and fire. To overcome this is to develop SOFC system operating at lower temperature.	[24]
Ohmic loss, Concentration Electrochemical activation	Fire	The study suggests that the ohmic sources generated the most heat followed by electrochemical and activation sources while the heat produced by concentration sources is negligible compared from other sources.	[20]
Fuel-air gas mixture	Fire and explosion	As the concentration of fuel decreases, the gas mixture inside SOFC has lower concentration of flammable gas and reaches it lower flammability limit (LFL) in which the mixture cannot sustain combustion because there is too little fuel. In contrast, when the fuel concentration increases, the mixture has not enough oxygen to enable combustion thus the mixture reaches the upper flammability limit (UFL). When the methane concentration is between the LFL and UFL, the mixture is explosive and flammable.	[21]
SOFC stack	Fire	Overheating might occur in SOFC stack which is cause by malfunction of temperature controller or disruption of air flow rate due to blower faults. This increase the temperature stack which leads to system failure and might lead to fire depending on certain circumstances.	[22]

3.2 Identifying Variables

Once the accident scenarios are identified, the hazard evolution is break into discrete nodes to capture every step towards the final hazards. Variables stated in Fig. 3 are all considered as nodes. Each variable is considered as one node and each node has states defined. For instance, when defining the type of release, the node is set as two states consisting instantaneous and continuous. On the other hand, the “SOFC Fault” node has four states which are heater, heat exchanger, combustor, SOFC stack and no fault. Next, nodes are classified to match with different principles when mapped into BN model. According to [27], there are three type of nodes namely evidence, intermediary and query as shown in Table 2. Evidence node is input based on real time parameters or observations while query node is the predicted hazards or the final results. Intermediate node on the other hand are the transitional steps in the hazard evolution where it connects evidence and query nodes.

Table 2 - Classification of nodes

Evidence Node	Intermediary Node	Query Node
Blower Fault	Ignition	Fire
Pipe Rupture	Air flow	Explosion
Reformer Leakage	Heat Sources	
Operation Temperature	Overheating	
Chemical Combustible	Type of release	
Ignition Source	Fuel Flow Rate	
SOFC Fault	Gas Leakage	
Operation Pressure		
Human Error		
Concentration of combustible gas		
Confinement		

3.3 Mapping Causal Relations among Variables

Next step is to define edges for mapping causal relations among all the classified nodes in the BN model. Generally, evidence node independent from each other and is the direct cause of intermediary node while intermediary nodes influence the query node directly. Fig. 4 shows how BN model is initialized by starting from the evidence node to intermediary nodes and finally to the query nodes by using open-source simulation software, GeNIe.

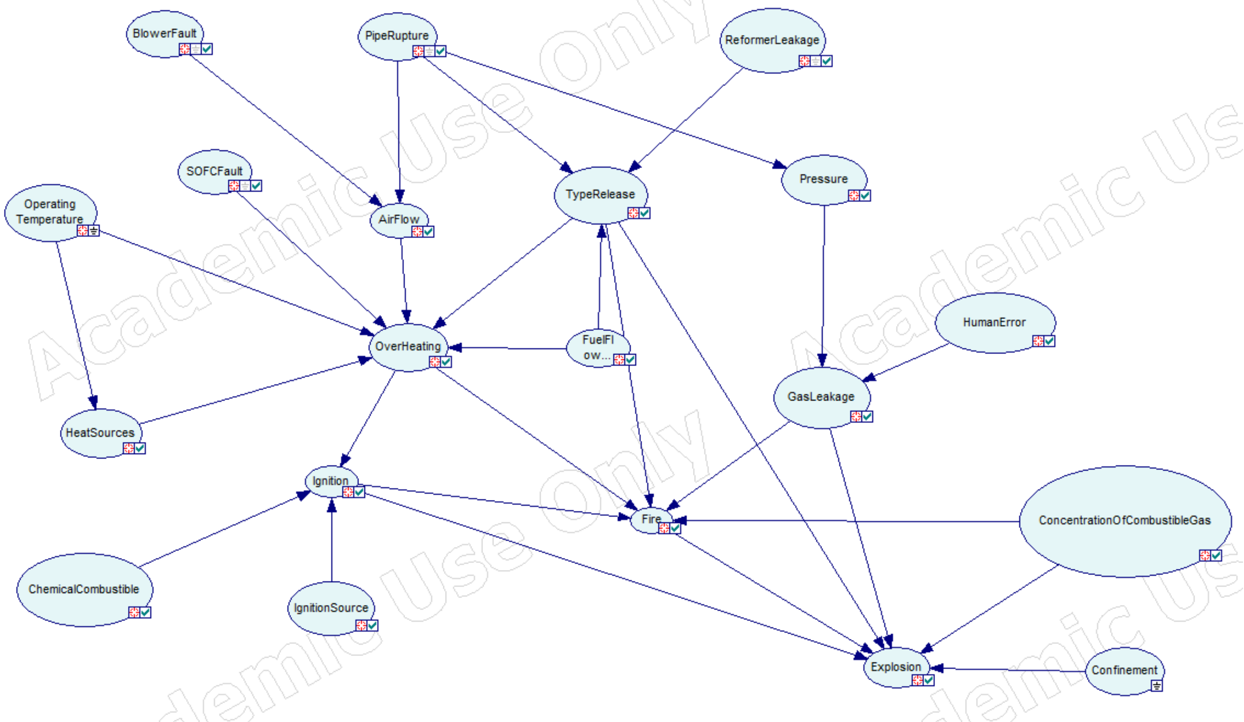

Fig. 4 - Framework of mapping causal relations among nodes

3.4 Assigning Conditional Probabilities

Conditional probability refers to probability of a certain results or event occurring given the occurrence of another event. It is a quantitative degree of belief to describe uncertainty. Once the framework of causal relations among nodes are developed, conditional probability is assigned to each of the nodes to carry out the simulation model. In this final step, conditional probability table (CPT) assigned is based on objective deduction such as from extracted data and subjective belief. Since safety study on SOFC system is very minimal, most data is not available thus the probability has to be assigned from subjective belief and logic as well [28]. Most conditional probability for SOFC failure components such as blower and pipe faults are extracted from literature while nodes such as operational conditions and site characteristics are based on subjective belief and logic. For example, the conditional probability of operational temperature and pressure is assigned to be 100% high and 100% low respectively. As mentioned before, the operating temperature of SOFC is as high as 1000ºC thus to author's belief, it is very high and may contribute to the risk of fire and explosion significantly therefore assigning the conditional probability for operational temperature to be 100%. The same goes with the operational pressure. Most the operating pressure of the SOFC system is only around 1 bar thus conditional probability assigned to the pressure node is 100% low.

4. Simulation Results

Table 3 shows better illustration of the states for each node. Qualitative description multi-states is used for the nodes to allow actual situation of each node to be captured effectively. For instance Overheating node has two states which is "Yes" or "No" with probability ranking calculated as 51% true and 49% false given conditional probabilities of "Heat Sources", "Operating Temperature", "SOFC Fault", "Airflow", "Type of release" and "Fuel Flow Rate". In this model, there is a total of 20 nodes including 11 evidence nodes, 7 intermediary nodes and 2 query nodes. In this study, the evidence node is set as high operation temperature, low pressure, involves with high combustible material, low failure rate for SOFC components, low concentration of combustible gas and high confinement assuming the component of SOFC are near with each other. This of course can be changed and updated according to the current condition of the system. The simulation results of BN model is shown in Fig. 5 where probability ranking of fire and explosion is calculated as 21% and 7% respectively which is rendered by using open-source simulation software, GeNIe. From the simulation results, the most credible hazards identified for SOFC system is fire.

Table 3 - Nodes with its corresponding states

Evidence node	States	Intermediary node	States	Query Nodes	States
Blower Fault	Yes	Ignition	Ignite	Fire	Fire
	No		No Ignition		No Fire
Pipe Rupture	Yes	Air flow	High	Explosion	Explode
	No		Low		No Explosion
Reformer Leakage	Yes	Heat Sources	Present		
	No		Absent		
Operation Temperature	High	Overheating	Yes		
	Low		No		
Chemical Combustible	Yes	Type of Release	Instant		
	No		Continuous		
Ignition Source	Yes	Fuel Flow rate	High		
	No		Low		
SOFC Fault	Heater	Gas Leakage	Leak		
	Heat Exchanger		No Leakage		
	Combustor				
	SOFC stack				
	No Fault				
Pressure	High				
	Low				
Human Error	Mistake				
	No Mistake				
Concentration of gas	High				
	Low				
Confinement	High				
	Low				

As shown in Fig. 5, the final hazards were influenced by many factors consisting many linear hazard progression. It can be observed that the final hazards are influenced by blower fault and pipe rupture which both disrupt the air flow and eventually cause overheating and leads to fire and explosion. Another scenario can be observed where high operating temperature and SOFC fault leads to overheating which leads to fire and explosion. Chemical Combustible on the other hand leads to the presence of ignition where it leads to the final hazards, fire and explosion. Since there are many factors contributing to the risks of fire and explosion, sensitivity analysis is conducted to investigate what parameters and causes greatly influence the final hazards which is presented in the next section.

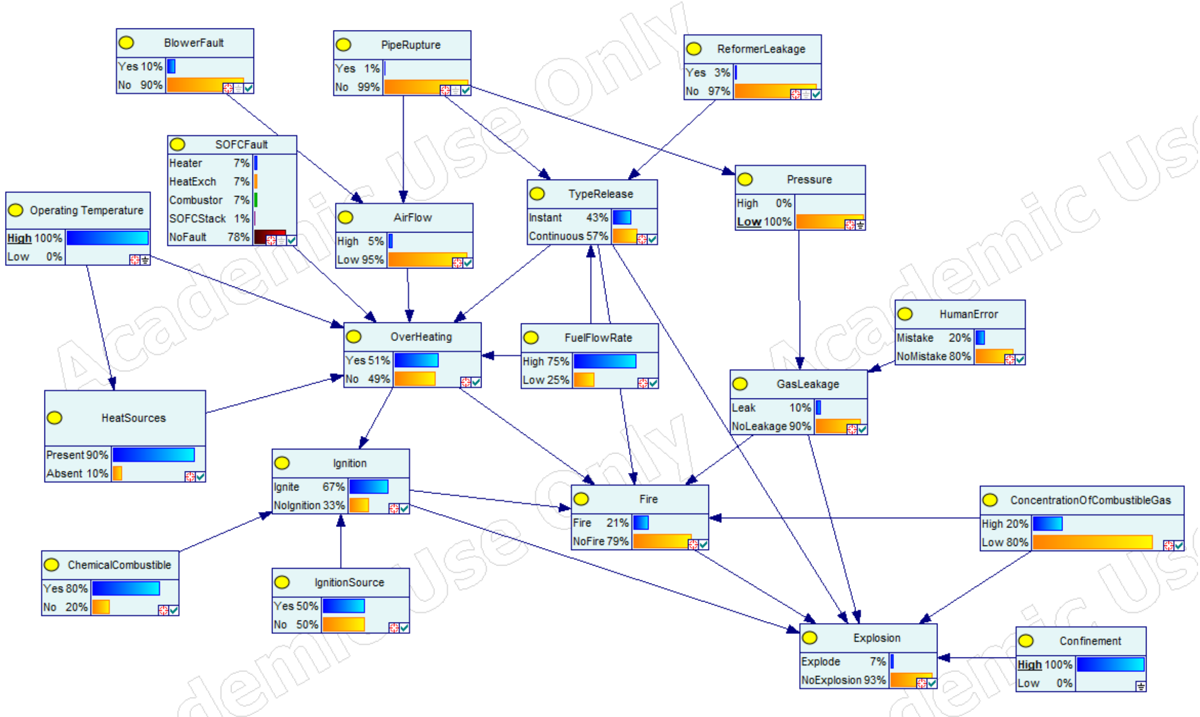

Fig. 5 - Bayesian Simulation results on SOFC system

5. Sensitivity Analysis

The sensitivity analysis is carry out by setting up the target parameters to be investigated. First, the SOFC component faults are investigated by setting it up as investigation target to see how much it influences the final hazards. Fig. 6 shows the results of the sensitivity analysis of the SOFC component faults. From the results, it was calculated that heater contribute 100% to the risks of fire and explosion. This means, the 7% set as the evidence node is contributing all 7% to overheating which eventually leads to fire and explosion. On the other hand, the least influencing evidence node for SOFC component faults is the SOFC stack which is only up to 15% from the 1% of the evidence node. This also means that out of all the SOFC component faults, the SOFC stack is the least influencing parameter contributing to the risks of fire and explosion. According to [29], solid ceramic electrolyte is the SOFC's main component. This solid metal oxide is an insulator that prevents electricity from flowing through which means main sources of ignition which is the occurrence of electrical sparks are unlikely to occur in SOFC stack compared to other components. Lower probability occurrence of the ignition sources led to lower risk of fire and explosion. The same principle can be applied for other components such as heater. From the analysis, heater is identified as the riskiest components in SOFC system contributing 7% to overheating. This is because heater which consists of many ignition sources such as hot surface and consist of electrical apparatus contribute to higher risks of fire and explosion.

Fig. 7 on the other hand shows the sensitivity analysis results for fire scenario. The top variables of the tornado plot represent the most influential parameters while the bottom variables of the tornado plot represent insignificant variables. In other word, the top variable is the most important parameters influencing to the final hazards. From the analysis, it was determined that the most influential parameters contributing to fire is due to overheating. As shown from Fig. 5, fire scenario depends directly on factors such as ignition, overheating, fuel flow rate, gas leakages and concentration of the combustible gases. Sensitivity analysis is carried out based on these five factors and revealed that overheating contributed the highest risks of fire compared to other factors. Overheating on the other hand is the intermediary nodes which connect initial conditions and the final hazards that cannot be modified as it is calculated given the initial conditions. To further understand what causes overheating, nodes (Initial conditions) connected to the overheating are further investigated by carrying out the sensitivity analysis shown in Fig.8. Initial conditions which are connected to overheating node includes operating temperature, heat sources, SOFC Faults, air flow, type of gas releases and fuel flow rate as shown in Fig. 5. This also means these conditions directly affect the probability of the occurrence of overheating. In this way, factors and parameters causing overheating can be identified to reduce the probability of fire occurrence. Out of all initial conditions which influence the overheating, operating temperature node contribute the highest risk to overheating with 18% deviation as shown in Fig.8. This means low temperature contribute 45% probability ranking of overheating and high temperature contribute the probability ranking of overheating up to 63%. This proved that fire scenario is one of the most credible hazard scenarios for SOFC system. This findings are supported by [22] where this recent studies indicated that overheating occur in SOFC stack are due to disruption of air flow or malfunction of temperature controller that causes higher temperature which led to overheating and eventually may lead to fire. On the other hand, Fig. 9 shows sensitivity results for explosion scenario. The top variables identified for explosion scenario is the pressure node. This means the pressure node is the most influential parameters contributing to the risk of explosion with deviations of 4%. This proved the occurrence of explosion scenario is very unlikely in SOFC system since the operating pressure of the system is considered low. However, if the operating pressure is increase, significant increase of explosion risks can be observed as shown in Fig. 10.

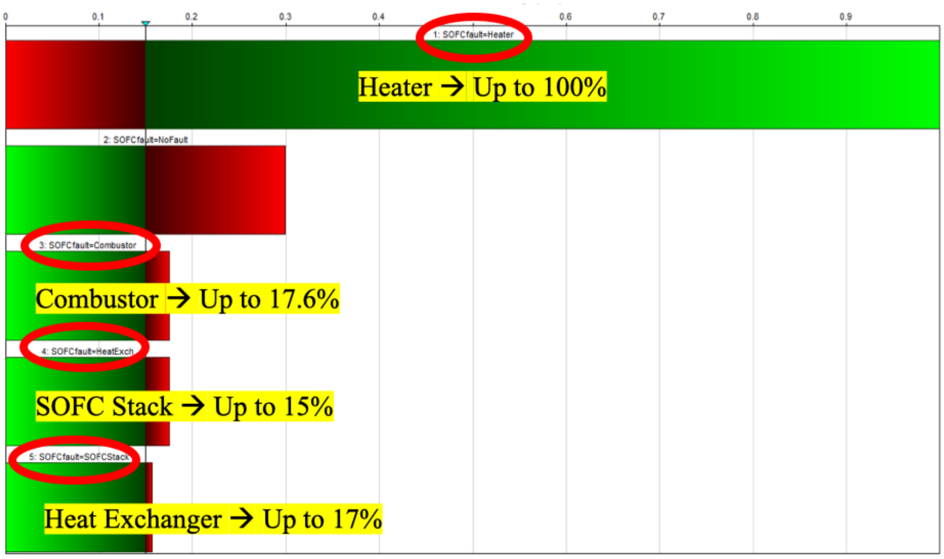

Fig. 6 - Sensitivity results for SOFC component faults

Fig. 7 - Sensitivity analysis results for fire scenario

From the sensitivity analysis shown in Fig. 7 – Fig. 9, it can be concluded that parameters contributing to the risks of fire and explosion the most are due to operating conditions. Further analysis is carried out to see how these operating conditions further influence the probability ranking of the risks by using the developed BN model. The evidence nodes (temperature and pressure) are varies to see how it influences the risks. The results shown in Fig. 10 where it can be observed that increasing the temperature would increase the risk of fire from 17% up to 21%. As mentioned before, the probability ranking for fire is calculated to be 21%. This is because the evidence node was set to be the highest which is 100%. On the other hand, the probability ranking for the occurrence of explosion scenario is calculated to be 7% because the evidence node was set to be the lowest. However, when the pressure is increase, it can also be observed that the risks of explosion also increased which is up to 18%. It is acceptable to claim that relationship between risks of fire and explosion and operating conditions are directly proportional until it reaches certain point. In comparison, [12] has conducted a series of case studies on risks of fire and explosion on conventional chemical plant using the same approach (BN model). The simulation results from the study showed that one of chemical plant located at Danvers, Massachusetts has the risks of explosion of 48% while another chemical plant located at Theodore, Alabama has the risks of fire and explosion scenarios with 11% and 17% risks respectively. From accident history, explosion incident indeed occurred in the plant located at Danvers, Massachusetts in year 2006 while no fire and explosion incidents ever reported to occur in the plant located at Theodore, Alabama [12].

Fig. 8 - Parameters influencing the overheating

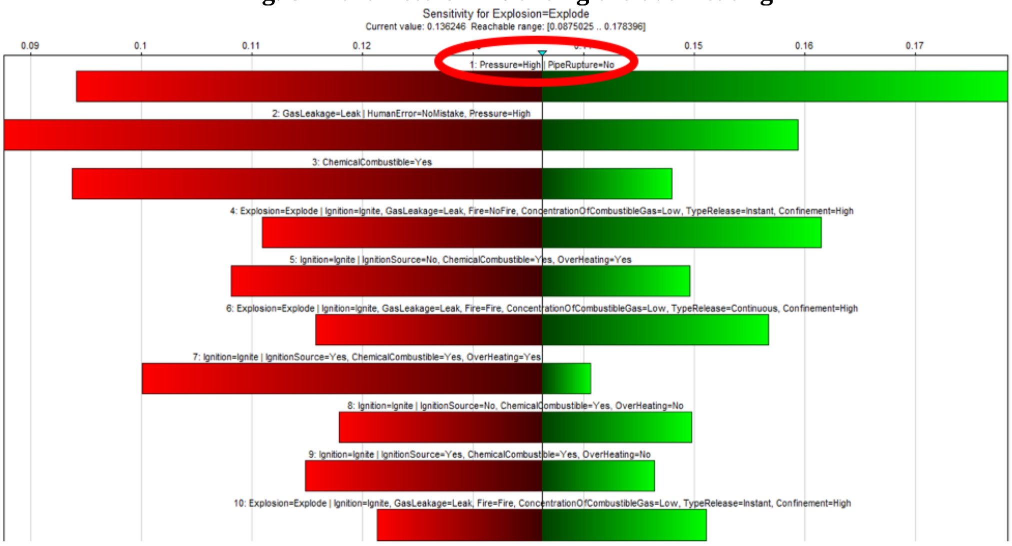

Fig. 9 - Sensitivity analysis results for explosion scenario

Therefore, there is no clear trend to conclude that SOFC plant is definitely safer than the conventional plant. This is because the risks of fire and explosion depends heavily on the situation of the plant itself, process parameters, materials involved in the plant, design layout and even the weather of the day. However, what can be presumed from the studies are having 48% risks of explosion are a very likely event to occur while 11% risks of fire and 17% risks of explosion are considered to be rare event to occur. Therefore, the risks of explosion and fire calculated in this study which is 7% and 21% respectively can be considered to be safe. In the case of sudden increased in pressures which increase the risk of explosion up to 18%, it is still considered to be a safe. Therefore, it is reasonable to assume that the fire and explosion scenario is unlikely to occur.

6. Conclusion

The current work developed hazard evolution framework for SOFC system and the probability ranking of the final hazards are determined which is 21% and 7% for fire and explosion respectively. From the simulation results, it can be concluded that fire and explosion scenario is very unlikely to occur in SOFC-plant. Sensitivity analysis is carried out to investigate which parameters contributing to the risks the most and results showed that operating conditions which is operational temperature influence the fire scenario the most while operating pressure parameter influence the explosion scenario the most. Relationship between the operating conditions and the final hazards are further analyzed and results showed that they are directly proportional to each other until it reaches certain point. The current work identified the occurrence of final hazards in SOFC system dynamically and can be served as guideline for safer SOFC implementation. The model developed can also assists in real-time hazard identification to accommodate parameter variation. Further improvement on CPT which is based on expert survey will be the focus in the next stage of work.

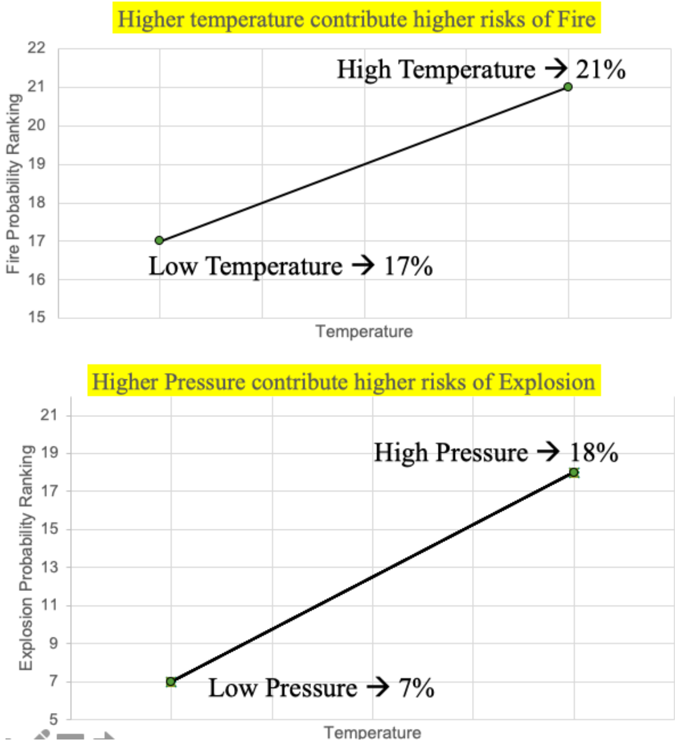

Fig. 10 - Relationship between operating conditions and final hazards

7. Acknowledgement

The authors would like to express gratitude to Universiti Kebangsaan Malaysia for providing laboratory facilities for the research and Ministry of Higher Education of Malaysia for supporting the research financially under the Transdisciplinary Research Grant Scheme TRGS/1/2019/UKM/01/1/2.

References

[1] T. Mori, R. Wepf, and S. P. Jiang, “Future prospects for the design of ‘state-of-the-art’ solid oxide fuel cells,” *J. Phys. Energy*, vol. 2, no. 3, p. 031001, Jul. 2020.

[2] N. F. Raduwan, A. Muchtar, M. R. Somalu, N. A. Baharuddin, and M. A. SA, “Challenges in Fabricating Solid Oxide Fuel Cell Stacks for Portable Applications: A Short Review,” *Int. J. Integr. Eng.*, vol. 10, no. 5, pp. 80–86, Nov. 2018.

[3] K. Chen *et al.*, “Direct application of cobaltite-based perovskite cathodes on the yttria-stabilized zirconia electrolyte for intermediate temperature solid oxide fuel cells,” *J. Mater. Chem. A*, vol. 4, no. 45, pp. 17678–17685, Nov. 2016.

[4] G. Brunaccini, “Solid oxide fuel cell systems,” *Solid Oxide-Based Electrochem. Devices*, pp. 251–293, Jan. 2020.

[5] J. Isac-García, J. A. Dobado, F. G. Calvo-Flores, and H. Martínez-García, “Determining Physical and Spectroscopic Properties,” *Exp. Org. Chem.*, pp. 145–175, 2016.

[6] S. Basu, “Instrumentation Safety Implementation and Explosion Protection,” *Plant Hazard Anal. Saf. Instrum. Syst.*, pp. 699–806, 2017.

[7] J. F. B. Rasmussen, P. V. Hendriksen, and A. Hagen, “Study of Internal and External Leaks in Tests of Anode-Supported SOFCs,” *Fuel Cells*, vol. 8, no. 6, pp. 385–393, Dec. 2008.

[8] A. Greco, A. Sorce, R. Littwin, P. Costamagna, and L. Magistri, “Reformer faults in SOFC systems: Experimental and modeling analysis, and simulated fault maps,” *Int. J. Hydrogen Energy*, vol. 39, no. 36, pp. 21700–21713, Apr. 2014.

[9] J. Y. Choi and S. H. Byeon, “Hazop methodology based on the health, safety, and environment engineering,” *Int. J. Environ. Res. Public Health*, vol. 17, no. 9, May 2020.
[10] M. Glossop MEng, A. Ioannides BEng, and J. Gould, “HSL/2005/58 REVIEW OF HAZARD IDENTIFICATION TECHNIQUES,” vol. 114, p. 2500.
[11] V. Villa, N. Paltrinieri, and V. Cozzani, “Overview on dynamic approaches to risk management in process facilities,” *Chem. Eng. Trans.*, vol. 43, pp. 2497–2502, 2015.
[12] P. Xin, F. Khan, and S. Ahmed, “Dynamic hazard identification and scenario mapping using Bayesian network,” *Process Saf. Environ. Prot.*, vol. 105, pp. 143–155, 2017.
[13] M. Kalantarnia, F. Khan, and K. Hawboldt, “Dynamic risk assessment using failure assessment and Bayesian theory,” *J. Loss Prev. Process Ind.*, vol. 22, no. 5, pp. 600–606, Sep. 2009.
[14] N. Paltrinieri, A. Tugnoli, J. Buston, M. Wardman, and V. Cozzani, “Dynamic Procedure for Atypical Scenarios Identification (DyPASI): A new systematic HAZID tool,” *J. Loss Prev. Process Ind.*, vol. 26, no. 4, pp. 683–695, Jul. 2013.
[15] O. E. H, H. S, and T. R. K, “Proactive indicators for managing major accident,” *SINTEF F24087*, 2013.
[16] L. Kaikkonen, T. Parviainen, M. Rahikainen, L. Uusitalo, and A. Lehikoinen, “Bayesian Networks in Environmental Risk Assessment: A Review,” *Integr. Environ. Assess. Manag.*, vol. 17, no. 1, pp. 62–78, Jan. 2021.
[17] R. J. Braun, T. L. Vincent, H. Zhu, and R. J. Kee, “Analysis, Optimization, and Control of Solid-Oxide Fuel Cell Systems,” *Adv. Chem. Eng.*, vol. 41, pp. 383–446, Jan. 2012.
[18] W. Xiao-Long, J. Su-Wen, X. Yuan-Wu, and L. Xi, “Fault analysis and diagnosis of solid oxide fuel cell system,” *Proc. IECON 2017 - 43rd Annu. Conf. IEEE Ind. Electron. Soc.*, vol. 2017-Janua, pp. 7146–7150, 2017.
[19] C. Jia, M. Han, and M. Chen, “Analysis of Gas Leakage and Current Loss of Solid Oxide Fuel Cells by Screen Printing,” *ECS Trans.*, vol. 78, no. 1, pp. 1533–1540, May 2017.
[20] C. Pijolat, “Screen-printing for the fabrication of solid oxide fuel cells (SOFC),” in *Printed Films: Materials Science and Applications in Sensors, Electronics and Photonics*, Elsevier Ltd., 2012, pp. 469–495.
[21] M. Kuhn and T. W. Napporn, “Single-Chamber Solid Oxide Fuel Cell Technology—From Its Origins to Today’s State of the Art,” *Energies 2010, Vol. 3, Pages 57-134*, vol. 3, no. 1, pp. 57–134, Jan. 2010.
[22] Y. Sahli, B. Zitouni, and B. M. Hocine, “Three-Dimensional Numerical Study of Overheating of Two Intermediate Temperature P-AS-SOFC Geometrical Configurations,” pp. 186–222, Apr. 2021.
[23] P. Weber, G. Medina-Oliva, C. Simon, and B. Iung, “Overview on Bayesian networks applications for dependability, risk analysis and maintenance areas,” *Eng. Appl. Artif. Intell.*, vol. 25, no. 4, pp. 671–682, Jun. 2012.
[24] C. Jia, M. Han, and M. Chen, “Analysis of Gas Leakage and Current Loss of Solid Oxide Fuel Cells by Screen Printing,” *ECS Trans.*, vol. 78, no. 1, pp. 1533–1540, May 2017.
[25] N. Yousfi Steiner *et al.*, “Application of fault tree analysis to fuel cell diagnosis,” *Fuel Cells*, vol. 12, no. 2, pp. 302–309, 2012.
[26] J. Yang, Z. Li, R. Bian, and Z. Su, “Fault diagnosis of SOFC system based on single cell voltage analysis,” *Int. J. Hydrogen Energy*, vol. 46, no. 48, pp. 24531–24545, Jul. 2021.
[27] A. Aziz, S. Ahmed, and F. I. Khan, “An ontology-based methodology for hazard identification and causation analysis,” *Process Saf. Environ. Prot.*, vol. 123, pp. 87–98, 2019.
[28] A. Darwiche, “Modeling and reasoning with Bayesian networks,” *Model. Reason. with Bayesian Networks*, vol. 9780521884389, pp. 1–548, Jan. 2009.
[29] P. Breeze, “The Solid Oxide Fuel Cell,” *Fuel Cells*, pp. 63–73, Jan. 2017.