

Tizita Belachew Tamirat

Cascading Failure Analysis in Green Hydrogen Production

Master's thesis in Master's thesis in reliability, availability, maintenance, and safety.

Supervisor: Yiliu Liu _NTNU | Massimo Santarelli_POLITO

Co-supervisor: Marta Bucelli_SINTEF

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ABSTRACT

Cascading failure analysis of green hydrogen production in response to adverse events, i.e., component failures and degradation, was the focus of this master's thesis. Safety and reliability are critical as the world transitions to hydrogen as a clean, sustainable energy carrier. The failure of one component in production plants increases the risk of system failure. This study aims to identify potential failure modes and causes of the domino effect in components, identify areas of limitations and gaps where these can have catastrophic consequences, and provide mitigation strategies on how to deal with them.

Failure mode and effect analysis (FMEA) and event tree analysis (ETA) were used to identify potential failure modes in the PEM electrolyzer system, as well as the interdependence of its components. Fuzzy logic is incorporated into the ETA to address the inherent uncertainties associated with failure probabilities and provide a more realistic assessment. In addition, a fuzzy risk matrix was used with the MATLAB software to justify the risk picture. The cascading failure initiated by the water purification system and internal failures within the PEM electrolyzer stack, such as degradation of the membrane electrode assembly, were assessed using these methods.

This study shows that in the green hydrogen production plant, the components are independent of one another. It focuses on major aspects directly affecting the reliability and safety of the electrolyzer. This thesis discusses the systematic process of identifying risks and analyzing the potential of green hydrogen cascade failure. The findings provide a systematic approach to risk identification and set effective mitigation measures to enhance the operational resilience and safety of next-generation green hydrogen plants for future sustainable energy growth.

Key words: Green hydrogen, Cascading failure, PEM electrolyzer, ETA, FMEA, mitigation strategies.

SAMMENDRAG

Kaskadeanalyse av feil i produksjon av grønn hydrogen som respons på uønskede hendelser, dvs. komponentfeil og degradering, var fokuset for denne masteroppgaven. Sikkerhet og pålitelighet er avgjørende ettersom verden går over til hydrogen som en ren, bærekraftig energibærer. Svikt i en enkelt komponent i et produksjonsanlegg øker risikoen for systemfeil. Denne studien tar sikte på å identifisere potensielle feilmoduser og årsaker til dominoeffekten i komponenter, identifisere områder med begrensninger og mangler der disse kan ha katastrofale konsekvenser, og gi avbøtende strategier for hvordan man skal håndtere dem.

Feilmodus- og effektanalyse (FMEA) og hendelsestreanalyse (ETA) ble brukt til å identifisere potensielle feilmoduser i PEM-elektrolyzersystemet, samt gjensidig avhengighet mellom komponenter. Fuzzy-logikk er innlemmet i ETA-en for å adressere de iboende usikkerhetene knyttet til feilsannsynligheter og gi en mer realistisk vurdering. I tillegg ble en fuzzy risikomatrise brukt med MATLAB-programvare for å rettfærdiggjøre risikobildet. Kaskadefeilen initiert av vannrensesystemet og interne feil i PEM-elektrolyserstakken, for eksempel degradering av membranelektrodeenheten, ble vurdert ved hjelp av disse metodene.

Denne studien viser at komponentene i det grønne hydrogenproduksjonsanlegget er uavhengige av hverandre. Den fokuserer på viktige aspekter som direkte påvirker påliteligheten og sikkerheten til elektrolyseren. Denne avhandlingen diskuterer den systematiske prosessen med å identifisere risikoer og analysere potensialet for kaskadefeil i grønn hydrogen. Funnene gir en systematisk tilnærming til risikoidentifisering og setter effektive avbøtende tiltak for å forbedre driftsrobustheten og sikkerheten til neste generasjons grønne hydrogenanlegg for fremtidig bærekraftig energivekst.

Nøkkelord: Grønn hydrogen, kaskadefeil, PEM-elektrolyser, ETA, FMEA, avbøtende strategier.

PREFACE

This thesis was carried out in the Reliability, Availability, Maintainability, and Safety (RAMS) department of Mechanical and Industrial Engineering at the Faculty of Engineering at the Norwegian University of Science and Technology (NTNU) as part of an Erasmus Mundus master's degree program specializing in Hydrogen Systems and Enabling Technology.

This research was conducted in the spring semester of 2025 and aims to investigate cascading failure concepts and analysis methods to assess the interdependency between different equipment in green hydrogen and to develop a risk picture for the stability of production. The idea of this project was proposed by FME HYDRO-GENi, a research centre in SINTEF Energy Research.

The analysis explores the propagation of failures from initial events to potential system-wide disruptions, with a focus on the impact of equipment interdependencies as a potential trigger of cascading failures. The purpose of this research is to provide insight into the critical limitations in green hydrogen production systems in terms of cascading failure scenarios. This study also proposes a framework of operational and preventive measures required to establish safer and more reliable hydrogen production facilities.

The reader of this report is expected to have a basic understanding of PEM electrolyzers, green hydrogen production equipment, hazard analysis, reliability engineering, and basic hydrogen production concepts. It is also expected to be familiar with the failure mode and effect analysis (FMEA), event tree analysis (ETA), and fuzzy logic approach.

CONTENTS

Abstract	i
Sammendrag	ii
Preface	iii
Contents	v
List of Figures	v
List of Tables	vii
Abbreviations	ix
1 Introduction	1
1.1 Background	1
1.1.1 Safety and Reliability Engineering for Green Hydrogen Production	2
1.2 Motivation and Problem Statement	2
1.3 Proposed Work	3
1.3.1 Research Objectives	3
1.3.2 Research Questions	3
1.3.3 Contributions of this study	3
1.3.4 Scope and limitations	4
1.4 Structure of the Thesis	4
2 Review of PEM Electrolyzer	5
2.1 Water Electrolysis Technology	5
2.1.1 Proton Exchange Membrane Water electrolyzer	6
2.2 Overview of Literature	9
2.3 Failure Mechanisms	11
2.3.1 Water Purification System Failure	12
2.3.2 Degradation of MEA	13
2.3.3 Propagation of Degradation	16
2.3.4 Explosive mixture of Hydrogen and oxygen	17

3	Review of CAF risk Analysis	20
3.1	Concept of Cascading Failure (CAF)	20
3.2	Qualitative and quantitative risk assessment (QRA)	21
4	Methods	23
4.1	System Boundary	24
4.2	Failure Scenarios	25
4.3	Qualitative Analysis	26
4.4	Consequence Analysis	27
4.5	Fuzzy Logic	27
5	Result and Discussion	29
5.1	Failure Mode Effect Analysis (FMEA)	29
5.2	Event Tree Analysis (ETA)	32
5.2.1	Deterministic Approach	32
5.2.2	Fuzzy-based Approach	34
5.2.3	Integrating Fuzzy Logic into Deterministic Approach Analysis	34
5.3	Implications of Cascading Failures	36
5.4	Fuzzy Risk Matrix	39
5.4.1	Fuzzy inference system	40
5.4.2	Defuzzification	41
5.5	Mitigation Methods/Strategies	43
5.5.1	Water Purification System Reliability	43
5.5.2	Mitigation method for membrane degradation	44
5.5.3	Mitigation for Explosive Mixture	44
5.5.4	Decoupling	46
6	Conclusion	47
6.1	Overview of Findings	47
6.2	Further Studies	48
	References	49
	Appendices:	57
	B - Proposed fuzzy rules	59
	C - Rule Interference	60

LIST OF FIGURES

1.1	Generic scheme of green hydrogen value chain configuration	1
1.2	Physical and Chemical properties of hydrogen adopted [6]	2
2.1	Water electrolysis Process	5
2.2	PEM Electrolyzer stack	7
2.3	Water Purification Unit adopted [30]	12
2.4	Pathway of water purification unit failure basedon [30]	12
2.5	Factors for MEA degradation	13
2.6	Main events leading to mechanical degradation of the membrane and their corresponding causes based on [11]	14
2.7	Chemical degradation causes based on [11]	14
2.8	Routes leading to the thermal degradation of the membrane based[11]	15
2.9	Degraded MEA—adopted from [44]	16
2.10	Main pathways leading to the formation of mixture within the elec- trolyzer based on [30]	17
2.11	Photograph of a stainless-steel fitting and nut drilled by an H ₂ /O ₂ flame formed inside the PEM stack adopted [44]	19
3.1	Cascading failure in terms of domino effect	21
3.2	QRA Process apodted[72]	22
4.1	Cascading Failure Analysis Flowchart	23
4.2	System boundary	24
4.3	A simplified process diagram showing the main operational compo- nents within the system boundary	25
4.4	Cascading scenario in hydrogen production	25
4.5	Risk matrix for qualitatively assessing failure scenarios	26
4.6	ETA approach under uncertainty adopted from [83]	28
5.1	Event tree for MEA degradation	33
5.2	Fuzzy-based Approach Steps	34
5.3	TFN to represent event probability	35
5.4	Triangular membership function to linguistic variables on fuzzy scale	35
5.5	Subsequent consequences of explosive mixture of H ₂ and O ₂ initi- ated by the failure of the water purification system and the MEA .	37
5.6	Fuzzy logic method for risk development in MATLAB	41
5.7	Defuzzification of the rule in MATLAB	41

5.8	Fuzzy surface of risk against frequency and severity	42
5.9	Mitigation techniques to improve water purification systems	43
5.10	Some mitigation techniques for reducing membrane degradation and failure based on [99]	44
A.1	Fault tree model top event MEA degeradation	57
A.2	Fault tree model top event excessive current density	58
B.1	Fuzzy IF-THEN rules	59
C.1	Rule Interference	60

LIST OF TABLES

2.1	State-of-the-art materials used in PEM electrolyzers adopted[28]	8
2.2	Table accidents related to water electrolysis adopted [5]	9
2.3	Overview of Literatures	10
2.4	Failure Mechanisms based on [28]	11
3.1	Definitions of the terms synonymous with CAFs adopted from [59]	20
5.1	FMEA - Loss of Function	30
5.2	FMEA Hydrogen and oxygen mixing failure scenarios [14]	31
5.3	Outcome event frequency of the MEA degradation	33
5.4	Linguistic terms with triangular fuzzy numbers from MATLAB	35
5.5	Defuzzified outcome event frequency	36
5.6	Potential consequences with explosive mixture of H ₂ /O ₂	38
5.7	Linguistic variables and risk categories based on [96]	39
5.8	Potential Mitigation Strategies based on [95]	45

ABBREVIATIONS

List of all abbreviations in alphabetic order:

- **AEM** Anion Exchange Membrane
- **ARIA** Analysis, Research, and Information on Accidents
- **ASTM** American Society for Testing and Materials
- **BN** Bayesian Network
- **BOP** Balance of Plants
- **BP** Bipolar plate
- **CCM** catalyst-coated membrane
- **CAF** Cascade Failure Analysis
- **EMARS** European Major Accident Reporting System
- **ETA** Event Tree Analysis
- **FMEA** Failure Mode and Effect Analysis
- **FTA** Fault Tree Analysis
- **GDL** Gas Diffusion Layer
- **HAZOP** Hazard and Operability Analysis
- **HIAD** Hydrogen Incidents and Accidents Database
- **HSE** Health safety Environment
- **HyCReD** Hydrogen Component Reliability Database
- **MEA** Membrane Electrode Assembly
- **PEM** Proton Exchange Membrane
- **PFSA** Perfluorosulfonic Acid
- **PERD** Process Equipment Reliability Data
- **QRA** Quantitative Risk Assessment
- **SBRA** Scenario-Based Reliability Analysis

INTRODUCTION

1.1 Background

Rising global energy consumption, climate change, and air pollution contribute to the need to switch to more efficient and carbon-free power generation. Green hydrogen is a promising solution for a more sustainable future [1]. Hydrogen has the potential to replace existing fossil fuels in several applications, including transportation, heating, and processing technologies, making it a key to a more sustainable energy future. To address this issue, the power sector is introducing additional renewable energy sources to the electrical grid, including wind turbines, photovoltaics, and RES-hydro power [2].

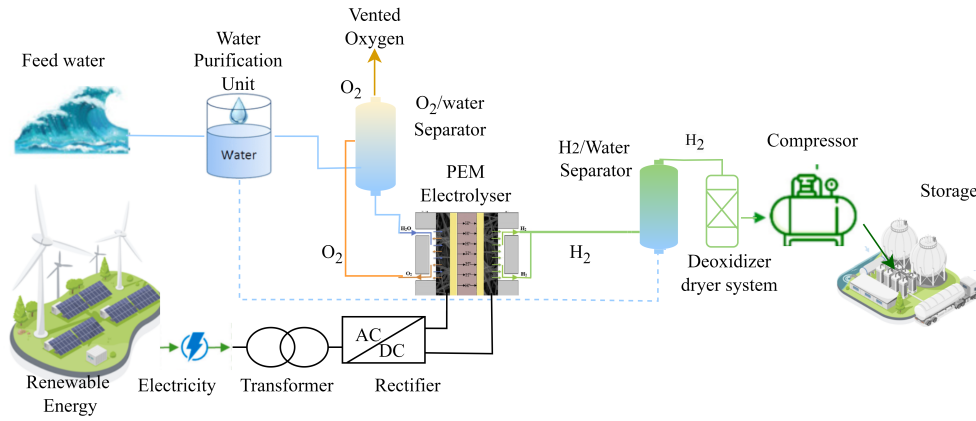


Figure 1.1: Generic scheme of green hydrogen value chain configuration

Green hydrogen is an emission-free fuel that is produced by utilizing renewable energy to split water into hydrogen and oxygen. However, the transition towards a hydrogen economy is related to resource allocation, infrastructure formation, and security concerns. For both economic and environmental benefits to be maximally reaped, a well-operating hydrogen economy is required. System safety is of utmost importance because improper handling of hydrogen can cause uncontrollable explosions. Depending on the levels of infrastructure complexity, green hydrogen production is interdependent [3].

1.1.1 Safety and Reliability Engineering for Green Hydrogen Production

The physical properties, chemical reactivity, and material compatibility of hydrogen have a significant impact on the performance, reliability, and safety of equipment throughout the hydrogen value chain. Hydrogen is the smallest and lightest element in the universe. It is a diatomic gas that is tasteless, colorless, and odorless in atmospheric conditions [4]. It is ideal for storing compressed gases or liquids due to its low density, non-toxicity, and non-corrosive properties [5].

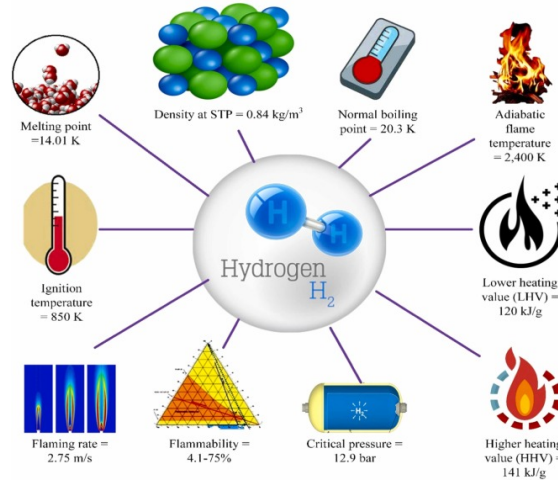


Figure 1.2: Physical and Chemical properties of hydrogen adopted [6]

Reliability and safety are crucial for infrastructure and technology development [7]. Reliability engineering applies scientific knowledge to components, equipment, plants, processes, or systems to ensure they perform as intended. It is useful throughout the life cycle, including design, development, and operation. It involves analyzing failure, detecting initial signs, forecasting reliability, and understanding how maintenance improves performance. Reliability engineering consists of three tasks: failure analysis, reliability assessment, and maintenance planning and analysis [8].

1.2 Motivation and Problem Statement

Green hydrogen's application as an emission-free energy carrier faces safety and reliability issues due to the susceptibility of cascading failure in complex production facilities. Current research shows a gap in systematic interdependency analysis and dynamic modeling of cascading failure propagation between integrated components in green hydrogen systems, particularly PEM electrolyzers and auxiliary units. The domino effect, a lack of understanding, heightens the risk of system failures, explosions, and financial losses, necessitating the identification of significant failure pathways, risk assessment, and development of mitigation strategies.

1.3 Proposed Work

1.3.1 Research Objectives

The goal of this thesis is to study cascading failure theory and to develop analysis methods to analyze the interdependence of different equipment components in the production of green hydrogen. The specific research goals are:

1. To find out the probable failure modes of PEM electrolyzers in green hydrogen production systems.
2. To analyze the interdependence between components and how failures cascade through the system.
3. To propose mitigation measures that increase the resilience and stability of green hydrogen production systems.

1.3.2 Research Questions

- What are the most critical PEM electrolyzer failure modes responsible for the occurrence of cascading failures in green hydrogen production?
- What are the critical failure pathways and scenarios having the greatest potential to lead to cascading failures?
- How can inherent uncertainties in the analysis caused by a lack of data be addressed?
- Which mitigation techniques, with a focus on preventing or reducing cascading failure events, can be identified and put into practice to improve the safety and resilience of green hydrogen production systems?

1.3.3 Contributions of this study

This study contributes toward developing methodologies and knowledge for assessing equipment interdependence in green hydrogen production, making it relevant to academia. This applies to improving the stability and resilience of green hydrogen production systems. The main contributions of this study to the analysis of interdependence and advancement of green hydrogen production systems are as follows:

- Cascading Failure Analysis: The study emphasizes the interdependent processes by which component failure creates a domino effect that results in system-level failure. Constructing the theoretical framework and substantiating the gaps in the research.
- Reliability Techniques: The thesis depicts how reliability and risk assessment techniques, integrated with fuzzy logic, are valuable to study green hydrogen production systems and promote their application in this new field.

1.3.4 Scope and limitations

The equipment used in the various phases of energy generation, hydrogen production, and hydrogen storage is interdependent in terms of function; that is, the failure of one device will affect the operation of the others. This thesis investigates cascading failure concepts in the hydrogen production phase, with a particular focus on the PEM electrolyzer, water purification system failure, and analysis methods for assessing interdependency between the electrolyzer and other green hydrogen equipment, as well as developing a risk picture for production stability. The thesis will look into cascading failures caused by the water purification system and internal failures of the PEM electrolyzer, such as membrane degradation and electrode corrosion within the electrolyzer stack. The thesis does not cover the following points:

- The analysis may involve simplifications of the PEM electrolyzer system and its interactions with other subsystems, but it does not cover a fully quantitative analysis due to the scarcity of failure data.
- Interactions with the broader energy grid and external factors beyond the immediate control of the hydrogen production plant are not fully captured.
- While the thesis focuses on the electrolyzer subsystem, it does not fully capture cascading failures that originate in other parts of the green hydrogen value chain (e.g., renewable energy sources, hydrogen storage).
- Due to company NDAs, it was unable to get relevant data related to the stack component degradation. Consequently, the assessment will be less detailed and accurate, and predictive models will be challenging to validate.

1.4 Structure of the Thesis

The thesis is structured as follows:

- Chapter 2: Literature Review—This chapter explores the state-of-the-art in green hydrogen production technologies.
- Chapter 3: Review CAF Risk Analysis: Highlights QRA in terms of a cascading failure analysis.
- Chapter 4: Methodology—This chapter explains the research design and analytical methods used for studying cascading failures in PEM electrolyzers and green hydrogen production.
- Chapter 5: Results and Discussion—This chapter presents the research results, interdependence, and recommends the mitigation approaches.
- Chapter 6: Conclusion and Recommendations—Chapters are concluded by summarizing the key findings and their implications and providing recommendations for both future research and practical application.

REVIEW OF PEM ELECTROLYZER

2.1 Water Electrolysis Technology

Water electrolysis is the process whereby water is split under the action of an electric current, producing hydrogen at the cathode and oxygen at the anode [9]. Pure gases produced at their respective electrodes can be simply separated and obtained as pure hydrogen and oxygen. Hydrogen production from water offers the distinct advantage, enabling its widespread implementation without being constrained by local reserves of fossil fuels or biomass. In the electrochemical process of water electrolysis, a water molecule is transformed and split into its constituent gases, hydrogen and oxygen [10]. The electromechanical process relies on applying electricity to facilitate the conversion of hydrogen and oxygen into their gaseous states.

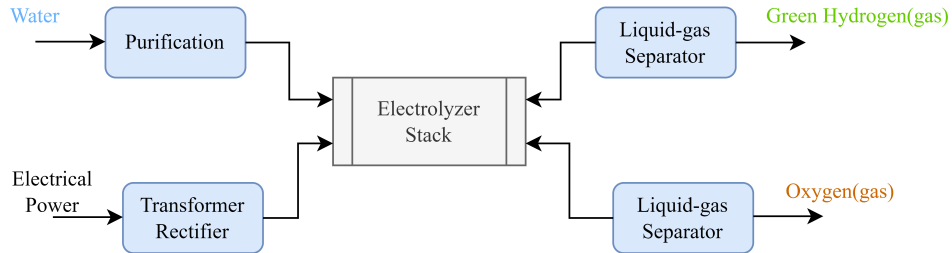
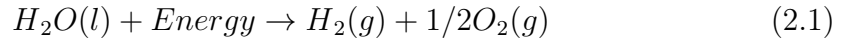


Figure 2.1: Water electrolysis Process

Four water electrolysis technologies are in use today, namely alkaline water electrolysis, solid oxide water electrolysis, polymer electrolyte membrane water electrolysis, and anion exchange membrane [5]. Not all electrolyzer technologies are suitable for coupling with intermittent renewable energy sources, and their performance involves trade-offs in factors like cost, noble metal usage, technology readiness, and flexibility. Water electrolyzers have three main levels: system, stack, and cell. The cell is the primary construction block, with coupling consisting of seals, frames, end plates, separators, and a stack. System-level components like cooling units and electrical transformers ensure system-level operation.

The PEM electrolyzer technology is most favorable for green hydrogen production, which provides several advantages for hydrogen production, including low-temperature operation, high purity capacity, high efficiency at high current densities, quick response to changing power inputs, seamless switching modes, compact design, and low carbon footprint. The solid electrolyte that conducts protons (Nafion) also contributes to these benefits due to its unique properties, such as being highly conductive, thin, and resistant to high-pressure operations via its low resistivity and excellent electrochemical stability [11]. Furthermore, the cell can function at high pressure, which allows end users to access hydrogen under such conditions [10]. This reduces the need for mechanical compression, which consumes a significant amount of energy and components vulnerable to hydrogen embrittlement, which leads to increasing maintenance costs [12].

2.1.1 Proton Exchange Membrane Water electrolyzer

A PEM electrolyzer operates by taking in water at the anode and splitting it into oxygen gas and hydrogen ions. The electrolyzer releases the produced oxygen into the oxygen-liquid separator. The current interacts with hydrogen ions and electrons, resulting in hydrogen gas that flows to a liquid-gas separator. PEM has a compact design, high current density (above 2 A cm^2), high efficiency (80-90%), fast response, operates at lower temperatures (20-80°C), and produces pure hydrogen (99.99%), and oxygen as by-products [13]. Along with the stack, the electrolysis system consists of mechanical and electrical parts that maintain an optimal temperature and pressure, transfer oxygen and hydrogen gas directly from the stack, and supply water for use in the electrolyzer stack [14].

- **Stack structure**

BPs, GDL, PEM, and electro-catalysts for the cathode and anode are the key parts of a PEM electrolyzer [15]. The MEA, the cell's key component, is typically formed by depositing catalyst layers on the membrane. Two porous transport layers (GDLs) are sandwiched on either side of the MEA [16]. The flow-field plates (BPs) enclose the two half-cells, transferring charge, mass, and heat while also connecting to an external power supply [17]. Hydrogen and oxygen products pass through the catalyst surface, GDL, and BPs before exiting the cell.

- **Membrane electrode assembly (MEA)**

Membrane electrode assembly (MEA) is the main component in an electrolyzer, which typically consists of a catalyst-coated membrane (CCM) and porous transport layers (PTLs). In a CCM, there is a piece of Nafion membrane that is sandwiched between two catalyst layer (CL) electrodes on each side (anode and cathode) [18]. The overall performance of the PEM electrolyzer, including diffusion, cell ohmic losses, and electrochemical reaction kinetics, is directly determined by MEA [19].

The membrane contains hydrophilic sulfonic acid side chains and hydrophobic Teflon-like backbones. The PFSA's can be categorized into various membrane types, including Nafion, Aciplex, Fremion, 3M, and short-side-chain (SSC), based on their length, side-chain chemistry, and equivalent weight [20]. DuPont's Nafion series membranes are a prime example of this type of membrane. The most popular membranes in this series are Nafion 117, 115, and 112, and the various numbers correspond to varying equivalent weights and thicknesses, which significantly affect the electrolyzer's overall performance [21]. The ionic conductivity is influenced by membrane thickness, and experimental evidence supports the idea that the thinner the membrane, the lower the ohmic resistance and the better the electrolyzer's performance [22].

• Gas Diffusion Layer

The GDL is a porous medium between the proton exchange membrane and the BPs [13]. The two-phase liquid/gas fluid is transported through the GDL channel to the catalyst layer, where the water is split into electrons, Oxygen, and protons at the catalyst anode. Oxygen returns via the GDL and catalyst layer to the separator plates and out of the cell [15]. Electrons move to the cathode side via the BPs and GDL, together with the external circuit. Protons also move via the PEM to the cathode, where they react with electrons to form hydrogen [23, 24]. Hydrogen moves through the GDL cathode and out of the cell.

• Bipolar plates (BPPs) and porous transport layers (PTLs)

BPPs and PTLs are multifunctional components that play critical roles in the transport of electric charge, heat, and species (reactant/product) and account for the majority of the stack [25]. Individual cells in a stack are separated by BPPs, which permit heat transfer and electrical contact between cells [26]. As a result, the PEM, along with its associated CLs, PTPTLs, and BPPs, is a critical component in determining large-scale hydrogen yields at higher current densities in the PEMWE. A highly oxidative and corrosive environment, particularly at the anode, is required to reduce interfacial contact resistance[27] .

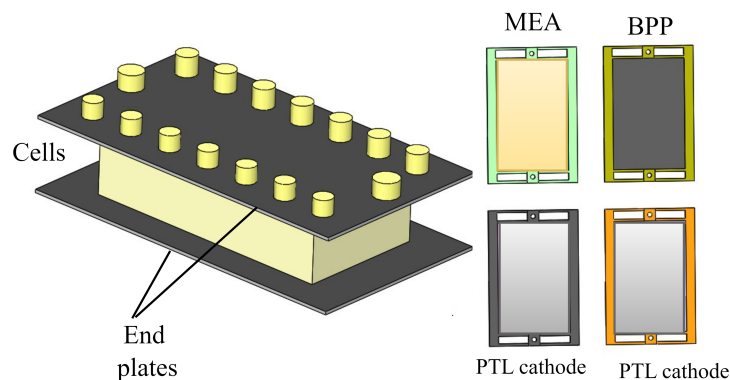


Figure 2.2: PEM Electrolyzer stack

Component	Material
Electrolyte	Perfluorosulfonic acid (PFSA)membranes
Separator	Solid electrolyte
Electrode catalyst/Anode	Iridium oxide
Electrode catalyst/Cathode	Platinum nanoparticles on carbon black
GDL/LGDL	Titanium, Graphite composite, Stainless metallic mesh
Bipolar plates	Titanium-coated stainless steel, Carbon fiber
Frames and sealing	Silicon, Viton

Table 2.1: State-of-the-art materials used in PEM electrolyzers adopted[28]

2.1.1.1 Safety issues of PEM electrolysis system

Efficient hydrogen production depends on the reliability of electrolytic cells in the electrolyzer [6]. The PEM electrolyzer's operation and safety are determined by system design and rating conditions, including temperature, pressure, voltage, current density, and power. Increasing the operating current density can improve the efficiency and performance of the PEM electrolyzer system to produce hydrogen [17]. However, manipulation of variables or parameters could introduce safety issues within the PEM electrolyzer due to membrane degradation or thinning. The membrane (MEA) is among the most expensive and lightest component of the PEM electrolyzer [18].

The operating conditions of the PEM electrolyzer could have a direct relationship with membrane degradation and failure. The main concern arises when the membrane degrades; small amounts of hydrogen produced at the cathode tend to cross over to the anode in a gaseous state. The permeation of hydrogen to the oxygen side poses a significant risk; the possibility of hydrogen mixing with oxygen results in an explosion [29]. In addition to membrane degradation, there are several potential safety concerns.

- Small leaks via imperfect sealing, impurities, and crossover
- High voltage, electrical short circuits, or discharges
- Excessive thermal stresses cause material degradation
- Hydrogen leakage from the stack

Year	Location	Cause	Consequence
1975	UK	Electrolyzer cell sludge accumulation	Electrolyzer destruction
1998	France	H ₂ enters into the O ₂ gas storage	O ₂ tank rupture
2005	Japan	Exposure of Ti electrodes to oxygen	Electrolyzer, pipes, peripheral equipment scattered
2019	South Korea	Presence of oxygen in the hydrogen buffer tanks	Electrolyzer, H ₂ storage tank compromised
2020	USA	Unknown	Damage Plant, nearby homes affected
2020	UK	Stack sealing damage	Damage to the electrolyzer stack
2021	Germany	Sludge accumulation in electrolyzer stack flow channels	Destruction of Electrolyzer
2022	France	KOH leak-initiated ignition	Fire

Table 2.2: Table accidents related to water electrolysis adopted [5]

2.2 Overview of Literature

The literature review conducted as part of this thesis reveals a significant research gap. The new technology of green hydrogen production lacks specific academic literature that directly tackles cascading failure phenomena. While the importance of reliability in this technology is growing, comprehensive research in green hydrogen is still in its early stages.

The literature review applied a two-pronged approach to establish a solid foundation for this study, as shown in Table 2.3. Includes component-focused reliability analysis of green hydrogen production. This section reviewed studies on failure modes, reliability assessment methodologies, and degradation models for electrolyzers. This provides a fundamental understanding of a component's behavior and dependability issues.

The lack of particular literature concerning cascading failures in green hydrogen led to the expansion of the review into more general cascade failure research and system reliability in other complex industrial and infrastructure networks. This broadened scope allowed for extracting theoretical perspectives, analytical methods, and lessons from interdependency, fault propagation, and the domino effect in other fields. Through its critical analysis of component-level reliability within green hydrogen systems and principles of cascading failure analysis from across multiple disciplines, this thesis aims to bridge the identified research gap.

Authors	Method	Highlights
[30]	FTA	Demonstrates how the fault tree analysis approach is suitable for reliability and availability analysis of the PEM electrolyzer BoP
[11]	FTA	Investigates the paths to cross-permeation and degradation of membranes in PEM electrolyzers using fault tree analysis.
[14]	FMEA	The highest-risk scenario involves hydrogen release, oxygen release, and mixing, primarily affecting the PEM electrolyzer, which was analyzed.
[5]	Database analysis, HIAD	Role of reliability engineering in producing green hydrogen, addressing gaps in application, and challenges in water electrolysis facilities.
[31]	Review articles	Examine state-of-the-art QRA studies for water electrolysis technologies. Identify five key gaps in the electrolysis QRA studies examined.
[29]	Bayesian structural modeling	Analyzes failure and reliability assessment methods at component and system levels.
[28]	Database Analysis, HyCReD	Recaps recent studies on the reliability and safety of water electrolysis systems.
[32]	STPA	Highlights the operational risks associated with PEM Electrolyzer and component reliability during dynamic operation, such as hydrogen leakage.
[15]	Review	Elaborate and delimit key concepts related to failure dependence and cascading failure. Propose future research directions on failure dependence and cascade failures.
[33]	Review Literature	Present the effects of cell degradation, operation, performance, and lifetime under a variety of conditions and materials on the components of PEM electrolyzers
[34]	Markov model	Develop a novel reliability analysis technique, Scenario-Based Reliability Analysis (SBRA), for component-based software systems.
[35]	CASCADE model	Three CAF models of system reliability were developed using system reliability metrics.

Table 2.3: Overview of Literatures

2.3 Failure Mechanisms

Component failure is one of the major concerns for producing green hydrogen [36]. Multiple failures are initiated by the failure of one component and result in a chain reaction of sequential effects that affect the remaining components [37]. There are various causes of cascading failure. It is a critical issue since it could compromise the longevity, safety, and effectiveness of these technologies. The failure mechanism in electrolysis systems, which defines the physical process by which damage or loss of function happens, is presented in Table 2.4.

Failure Mechanism	Description	Potential Impact
Inadequate design and installation errors	Errors in any stage of the system's lifecycle	Premature component failure and reduced performance
External Impacts	Physical damage caused by external forces (e.g. seismic events)	Structural damage, leaks, and system shutdown
Overpressure	Pressure exceeding the system limits due to operational errors or component failures	Rupture of components, leaks, explosions, and safety hazards
Material Degradation	Chemical and physical changes in the materials of the system over time	Reduced performance, component failure, and increase maintenance requirements.
Impurities	Presence of contaminants in the water	Catalyst poisoning, membrane degradation, and reduced performance
Abnormal Power Supply	Fluctuations, surges, or interruptions in the electrical power provided to the PEM system	Control system malfunctions, operational instability, and potential safety hazards
Failure in the Electrical/Activation System	Malfunctions within the electrical control and activation systems of the PEM system	Safety risks, operational errors, and inability to start or control the system
External Fires	Exposure to fire originates from sources outside the system itself	Catastrophic damage, component burning, release of hazardous substances, system destruction, and safety hazards

Table 2.4: Failure Mechanisms based on [28]

2.3.1 Water Purification System Failure

The role of the water purification system in providing ultrapure water directly impacts its reliable operation in the electrolyzer stack. To maintain a water quality that avoids potential hazards and ensures the integrity of the PEM electrolyzer, the elements shown in figure 2.3 water tank, activated carbon filter, particulate filter, reverse osmosis filters, deionized water tank, DI water pump (DIWP), and DI resin filters—are required [30]. Specifically, the activated carbon filter is vital to prevent corrosion and degradation of the electrolyzer materials, which could lead to system failure by the removal of chlorine and other chemicals.

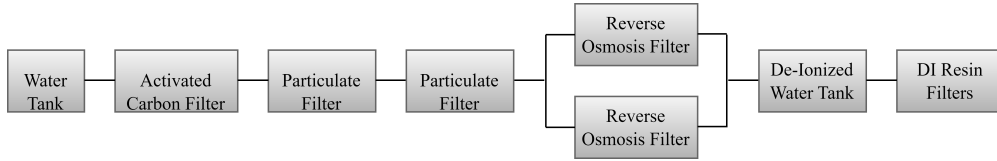


Figure 2.3: Water Purification Unit adopted [30]

Maintaining high water purity is critical, as contaminants can significantly impact stack and plant performance, resulting in increased maintenance costs. Following the purification stage, water enters the oxygen separation vessel, where oxygen is extracted and released. The water flows to a circulation pump and is then into the stack[30]. The oxygen separation vessel collects air and recirculates effluent from the stack. Single component failures can propagate and cause significant system problems, resulting in the introduction of impurities.

The particulate filter prevents the introduction of larger particles that could cause physical damage or blockages within the sensitive electrolyzer components. The reverse osmosis filters eliminate contaminants and impurities. The deionized water tank acts as a buffer to ensure a consistent supply of high-purity water, preventing fluctuations that could stress the system. These elements work together to supply highly purified water with a conductivity. Low conductivity is required for the safe and effective functioning of the stack. The specifications for PEM electrolyzer feed water depend on the specific electrolyzer technology; therefore, some systems might require a lower conductivity for safe and reliable operation. Nonetheless, long-term use of low-quality water accelerates the stack degradation [38].

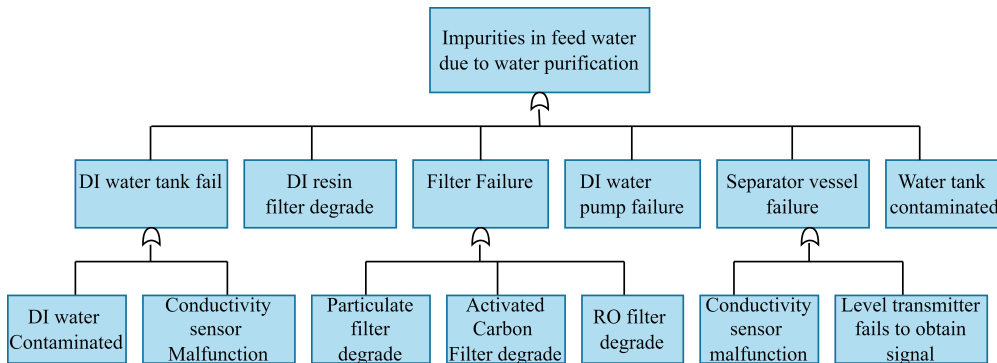


Figure 2.4: Pathway of water purification unit failure basedon [30]

2.3.2 Degradation of MEA

Degradation of membrane electrode assembly (MEA) is considered in this thesis for cascading failure analysis through different mechanisms of failure. It is a cumulative and natural process that severely limits PEM systems' durability, in contrast to transient failures. It involves complex chemical and physical changes through system components, which require multi-disciplinary analysis. Its interaction with other factors mandates durability assessment to be achieved from an integrated view point. The study of degradation mechanisms, diagnostics, and predictive modeling is essential to facilitate reliable PEM technologies [38].

Cascading failure typically starts with a limited failure or deterioration of a single cell in the electrolyzer stack. A host of issues can arise in the electrolyzer stack, causing dramatic performance loss and safety risks. Failures that cascade through the electrolyzer stack, creating a domino effect. While proper and preferable, the PEM electrolyzer suffers from performance degradations. The harsh operating environment of the electrolyzer leads to component degradation. Overpressure, overvoltage, and extremely acidic environments can all cause component degradation, and operating conditions such as high current density, temperature, and power load cycle significantly accelerate component degradation [39].

Many studies have been focused on water electrolysis system technology, enhancing PEM electrolysis system performance, and improving the rate or purity of produced hydrogen. Some experimental research investigates membrane degradation or PEM electrolyzer failures as a whole or system. The membrane degradation is also categorized into thermal, chemical, and mechanical degradation. Other than that, the bipolar plate of the electrolyzer can also degrade. It can then cause hydrogen embrittlement, passivation (the surface of the titanium BPs is readily corroded at high potential, humidity, and rich oxidation), and bipolar plate corrosion under acidic conditions [40]. Current collector degradation can either be chemical degradation or mechanical degradation. Different factors, including hotspots, can cause membrane degradation or membrane rupture.

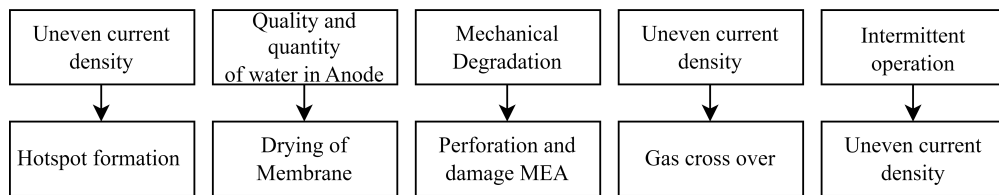


Figure 2.5: Factors for MEA degradation

Poor water management across the membrane could be the cause of the membrane breakdown since areas of the membrane won't be adequately hydrated if there isn't sufficient water present [29]. Mechanical degradation of the membrane in PEM electrolyzers can arise from various factors, with clamping pressure being a key contributor. While optimal clamping pressure enhances performance and cell lifespan, excessive pressure, often due to human error during installation, can be detrimental.

The excessive pressure can damage internal components like the catalyst-coated membrane (CCM) and reduce gas diffusion layer (GDL) porosity, hindering mass transport [41]. In addition, ineffective removal of heat from the system due to low water flow rates has the capability of raising the membrane temperature above safe operating levels [11].

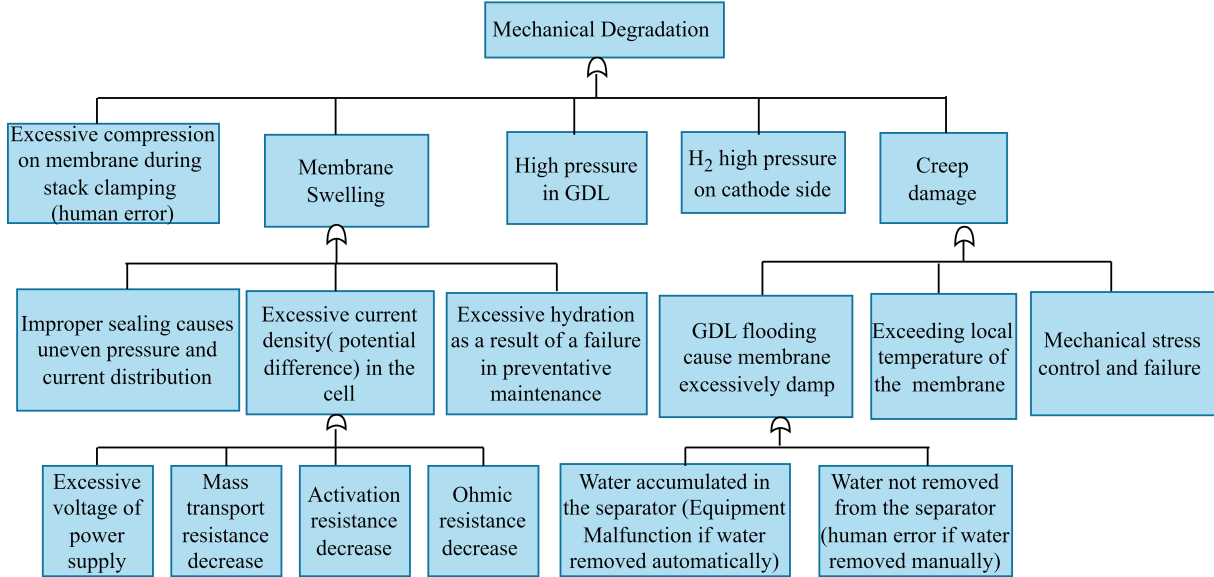


Figure 2.6: Main events leading to mechanical degradation of the membrane and their corresponding causes based on [11]

Chemical poisoning of the membrane, i.e., degradation of the chemical structure of the membrane. It is the chemical degradation of the chemical structure of the membrane and may adversely affect it as regards performance and life. One of the most frequent mechanisms of chemical degradation is the generation of hydrogen peroxide as a by-product of oxygen permeation. It has been widely studied, and several studies have observed this phenomenon, highlighting its significance in the process of dissolving oxygen across the membrane and water molecules [27, 42]. On reaching the hydrogen-rich cathode side, the permeated oxygen combines with hydrogen to produce a hydrogen-oxygen mixture. The formed peroxide, being highly recognized for its oxidative nature, is capable of attacking the structure of the polymer membrane, resulting in chain scission and subsequently weakening its integrity.

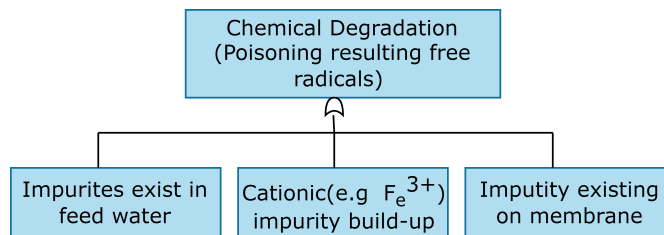


Figure 2.7: Chemical degradation causes based on [11]

The main degradation mechanisms, according to [43], are the dissolution of anode catalysts, membrane chemical deterioration, and the growth of semiconducting oxides on the metal components. The degradation of the mechanism is accelerated by shutdown modes, dynamic operation, and high current density. Dissolution is the primary degradation problem, resulting in the anode catalysts' irreversible deterioration. The applied potential is most likely related to the rate of iridium oxide (IrOx) dissolution during the oxygen evolution reaction (OER). In a few hours during normal operation, the membrane electrode assembly (MEA) would lose all the anode catalyst at the stated dissolving rates. Under the various operating modes of a PEM electrolyzer, the membrane and ionomer will gradually lose some of their unique features in addition to the anode catalyst degradation.

Exceeding the temperature limit in this instance is considered spontaneous and is caused by several variables, shown in the figure 2.8. The local membrane temperature will rise if the water temperature rises over the system's indicated operating limits because water comes into direct contact with the membrane from the anode side. Furthermore, insufficient heat removal from the system due to low water flow rates might raise the membrane temperature above safe operating limits [11].

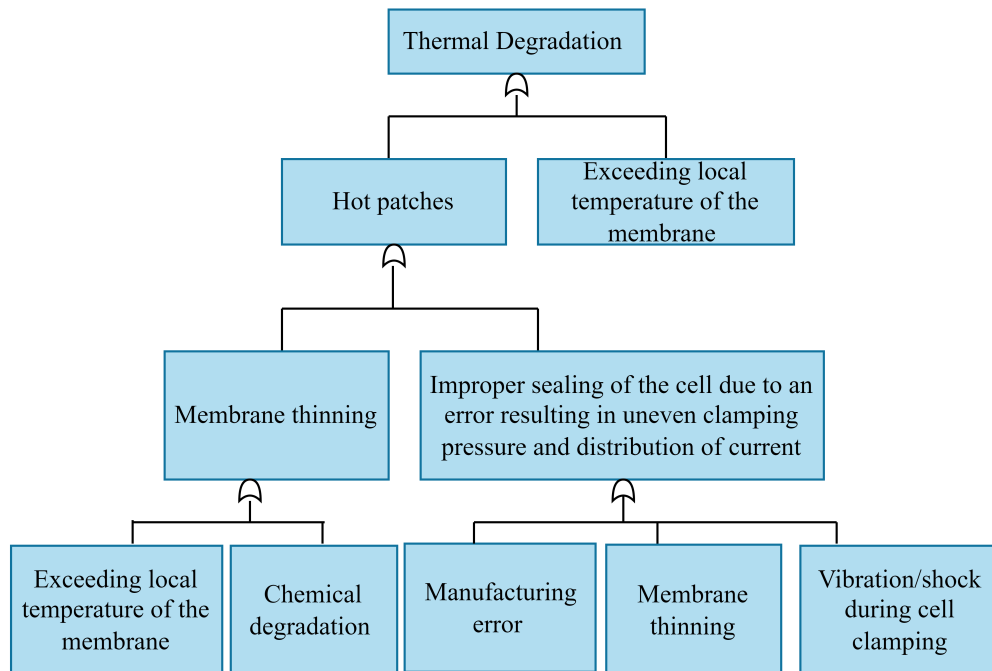


Figure 2.8: Routes leading to the thermal degradation of the membrane based[11]

More research on degradation processes demonstrates the mechanisms that might cause damage to a PEM cell or stack [44]. Enhancing cell efficiency while raising operational current density values is a crucial PEM performance problem. Using Nafion as a solid electrolyte, single PEM electrolysis cells have operated steadily for over 20,000 hours; however, excessive hydrogen levels in the oxygen product stream continue to be an issue for larger systems. High-pressure operations are probably the source of safety concerns.

2.3.3 Propagation of Degradation

Failure mechanisms and interactions are dependent and include common-mode degradation among components, and correlation demonstrates reliance on a component's total failure. Degradation has a domino effect on whether it can occur when one component's degradation behavior affects another. When a single cell fails, it can cause a chain of breakdowns in adjacent cells. Degradation in PEM electrolyzers is by a complex network of interdependencies [41].

Membrane degradation, initiated by chemical, mechanical, and thermal stresses, leads to increased permeability, reduced conductivity, and hotspot formation. Bipolar plates are prone to corrosion, hydrogen embrittlement, and passivation, resulting in increased electrical resistance and potential mechanical failure. Current collectors are corroded and eroded, contributing to contact resistance. These phenomena are interrelated, with membrane degradation favoring corrosion of other components.

A single cell failure can initiate a chain reaction of failure of neighboring cells. This can happen through a variety of mechanisms. Gas crossovers between a failed cell can put pressure on neighboring cells, leading to membrane swelling and further degradation [45]. Nonfunctioning cells can disrupt the present distribution in the stack, raising the current density in neighboring cells and quicker degradation. Hot spots could initiate thermal runaway and create instant temperature increases and subsequent degradations in the stack. The aggregation of degradations reduces the operational lifetime of the electrolyzer.

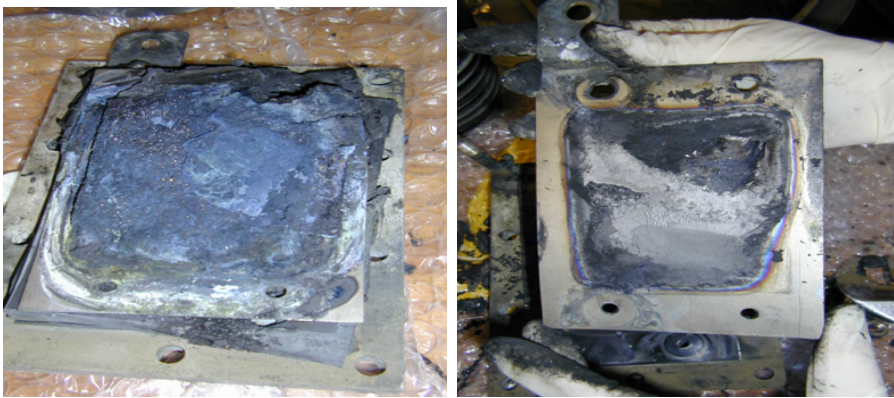


Figure 2.9: Degraded MEA—adopted from [44]

Technical malfunction, i.e., a fluctuation of the cell voltage or a reduction of gas purity, cannot be detected, and the process can rapidly lead to the destruction of the stack. The employed automaton for the supervision of the system detected a malfunction (sudden fall of current) and switched off the power supply; meanwhile, it was already too late to avoid the destruction of the stack. The combustion of non-metallic cell parts (MEAs and sealants) due to the failure of MEAs and cell sealants. The burned stack that was ruined in a few seconds [42].

2.3.4 Explosive mixture of Hydrogen and oxygen

PEM electrolyzer plants pose a significant risk of explosive conditions caused by a hydrogen/oxygen combination. This can result in an internal explosion in the electrolyzer stack or H_2/O_2 separator [46]. The failure of components in a PEM electrolyzer can be attributed to component failure modes such as gas channel obstacles, which disrupt hydrogen and oxygen transport by obstructing flow routes inside the gas diffusion layers. This may contribute to higher pressure drop, non-homogeneous distribution of gas, and mechanical stress. Severe unintended accidents can result in gas leaks and pressure buildup, and initiate safety issues such as H_2/O_2 mixing and combustion. Failure of the membrane, pump failure, and subsystem failure such as poor water management are causes for combustion of H_2/O_2 [30].

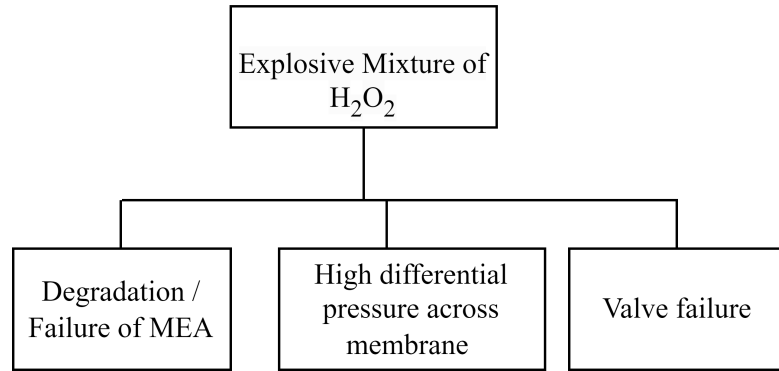


Figure 2.10: Main pathways leading to the formation of mixture within the electrolyzer based on [30]

After the solid polymer electrolyte has degraded, the second way in which it fails is to mix increasing amounts of hydrogen and oxygen gas near the hole and then ignite the hydrogen in the oxygen [44]. In addition to degradation of the membrane, other components of a PEM electrolyzer degrade. Bipolar plates can corrode, passivate, and undergo hydrogen embrittlement, particularly under acid conditions. Current collectors can fail by either mechanical or chemical reasons. Ambient influences like hotspots accelerate membrane degradation, resulting in a high degradation process that increases during service operation[43].

Membrane degradation boosts electrical resistance and gas crossover, reduces efficiency and even creating safety hazards. This calls for greater power requirements by power electronics, placing additional load on gas purification systems. Catalyst deactivation leads to a reduction in hydrogen yield, increased energy use, and quicker weakening of the stack, influencing power electronics, hydrogen storage, and downstream applications. Bipolar plate corrosion can negatively impact control systems, cooling systems, and pumps by blocking flow fields, increasing pressure drop, and affecting power electronics, maintenance, and stack replacement schedules. It can also cause water carryover, decreased product purity, and increased pressure drop.

The failure mechanisms of the PEM water electrolysis cell can ultimately lead to the destruction of the electrolyzer. It has been demonstrated that a two-step procedure involves first localizing the PEM degradation and then catalytically recombining the hydrogen and oxygen that are held in the electrolysis compartments [44]. Cross-permeation and membrane degradation in PEM electrolyzers, potentially forming an explosive mixture [11]. Electrolyzer failure due to degradation can result in the formation of a hydrogen-oxygen gas mixture. A hydrogen-oxygen gas mixture can form when an electrolyzer fails due to degradation. The formation of an explosive mixture of hydrogen and oxygen can be attributed to the permeation of oxygen or hydrogen molecules through their opposing sides.

Excessive hydrogen permeation in the cell is possible due to high cathodic pressure, mass transfer limits, and membrane degradation. Significant hydrogen permeation to the opposite side could result from operating at extremely high cathodic differential pressures [47]. A significant imbalance between the pressure on the two sides of the membrane is produced when the pressure exceeds a specific threshold known as the maximum pressure rating of PEM, the limit at which the membrane efficiently retains the gases on their respective sides, set by the manufacturer [48]. Due to changes in the membrane's structure and characteristics, such as an increase in pore size, the gas molecules can pass through the increased differential pressure, potentially increasing the permeability of gases [49]. The likelihood of cross-permeation, which results in the unintended mixing of gases, increases with the pressure difference. This can also occur even when there isn't any visible membrane damage. Therefore, to reduce the risk of cross-permeation, it is crucial to operate within the specified pressure range even if the membrane is not physically damaged [50, 51].

A malfunctioning pump that supplies low water flow causes insufficient hydrogen to be released if the optional water for circulation at the cathode is used. This leads to supersaturation or an excess dissolved hydrogen concentration. In the meantime, more dissolved hydrogen evolves with increasing current density, leading to a higher degree of supersaturation [52]. In many instances, the design of the cell, including factors such as flow field geometry and sinter porosity, can help alleviate the flow restriction [53]. Random pressure increases or membrane weakening can reduce mass transfer resistance. Elevated pressure accelerates convective transport of water from the anode and gas from the cathode, reducing diffusion limits. Membrane thinning can be attributed to exceeding the membrane's operational temperature limits or chemical poisoning, leading to the generation of free radicals [54, 55, 56].

Despite pressure being a significant factor in gas-permeation processes, research indicates that the influence of hydrogen supersaturation at the ionomer frequently exceeds the effects of pressure and even temperature alone on the PEM electrolysis system's performance [48]. In the water phase of the ionomer film, molecular hydrogen changes during the electrolysis process in an attempt to go into the vapor state. However, because of its limitations, this mass transfer mechanism gave rise to the idea of hydrogen supersaturation [57].

According to the experiment based there was proof of the burning process within the stainless-steel tubes utilized for recirculation of liquid-gas mixtures and water within the system [44]. The effect approached the pile, metal elbow connections being positioned approximately- approximately 20 cm away with tidy perforations, suspecting the development of a combustion flame from the stack. The diameter of the perforations was equal to internal tube diameter, which also corroborates the finding that a hydrogen- oxygen combustion flame initiated in the stack and propagated through the tubing. behaving like a torch. Whereas the flame temperature of a stoichiometric mixture can rise to 3200°C [58], and even with water vapor saturation, the temperature would likely still be too large to perforate the metal parts [44].



Figure 2.11: Photograph of a stainless-steel fitting and nut drilled by an H_2/O_2 flame formed inside the PEM stack adopted [44]

REVIEW OF CAF RISK ANALYSIS

3.1 Concept of Cascading Failure (CAF)

In complex systems, cascading failures occur when one component fails and influences the performance and condition of other dependent components, which in turn causes other components to fail [59]. CAFs are referred to by several names in current research, each with a specific focus: domino effects [60], escalating scenarios, competing failure processes [61, 62], propagated failure [63, 64], induced failures [65, 66], and fault propagation [67, 68].

Terms	Definitions
Induced failures	Component failure causes failure in other components.
Fault propagation	Non-critical component failures accelerate the degradation of critical components.
Propagated failures	Common causes of failures originate in system elements and affect others.
Domino effect	The propagation in time and space, and escalation resulted in increased severity of accidents in the chemical and process industry.
Escalating scenarios	The initial event escalates to a larger event with more severe outcomes.

Table 3.1: Definitions of the terms synonymous with CAFs adopted from [59]

While their definitions differentiate slightly, all terms refer to a phenomenon or scenario with three key components: the initial event, the propagation process, and the outcomes [59]. Furthermore, the root cause of these phenomena is linked to the presence of failure dependencies. CAFs result from structural or functional interactions between multiple components in complex systems [69]. Systems with a high level of failure dependence are especially vulnerable to CAFs. Cascading failures occur when an initial failure affects other systems. Cascading failures are characterized by a domino effect, which occurs when an initial occurrence has minimal impact but leads to serious consequences for subsequent failures.

Domino effect is a chain process in which an initial event in a single unit sets off successive events. These incidents in surrounding units through aggravation vectors. This occurs when an initiating event propagates within or to the nearby equipment, initiating one or more secondary events. These secondary events can, in turn, create higher-order events, resulting in more severe consequences than the original incident. The domino effect has a root cause, escalation vectors, one or more secondary events, and severe collective consequences. The "classic" cascading failure gives rise to a quick propagation of failures [59]. Investigating the cause-and-effect chain of an incident can result in a potentially dangerous situation, although the failure occurs over a long span of operation [70]. Further, the initiating event can be either a temporary or a permanent flaw. Time is an important parameter to consider while modeling cascading failures.

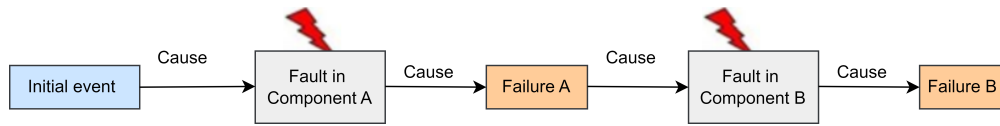


Figure 3.1: Cascading failure in terms of domino effect

3.2 Qualitative and quantitative risk assessment (QRA)

The interconnectedness of the components in green hydrogen production facilities implies that if one fails, it might lead to cascading failures, which can ultimately cause stability and safety concerns. Failure analysis provides insight into the causes, effects, and forms of failure. The process of reliability assessment involves using various statistical and probabilistic techniques to evaluate a system's dependability over time or prior to implementation. It is always conducted in the system design and development phase. To enhance QRA results and better understand the safety and dependability of hydrogen systems, several recent studies have highlighted the necessity for hydrogen-specific reliability data. It is undetermined how well existing generic data can predict failure rates for the hydrogen system because there is a lack of reliability data on hydrogen components [28].

Numerous safety studies, including Failure Mode and Effects Analysis (FMEA), Hazard Identification (HAZID), Hazard and Operability Studies (HAZOP), and Quantitative Risk Assessment (QRA), have to be carried out during the process plant's design phase [32]. Hazard identification is codified in regulations, and Process Hazard Analysis (PHA) is regarded as part of PSM. Hazard identification is controlled by codes, and Process Hazard Analysis (PHA) is also thought to be included in PSM. HAZOP has been widely popular since the 1970s and 1980s, and other methods like What-if analysis, Fault Tree Analysis (FTA), Event Tree Analysis, and Bow-tie analysis are also utilized [71]. These methods are essential to evaluate risks, reduce hazards, and suggest safeguarding actions. System safety and reliability are determined as key facilitators of the advancement of hydrogen technologies [7].

Techniques for both qualitative and quantitative risk assessment are essential for reducing risks and facilitating the adoption of hydrogen technology. Thorough research and quantification of the risks related to hydrogen systems are necessary for a safe and sustainable transition to hydrogen [72]. A systematic method termed QRA is used to assess risk and determine the effects of a hazardous event that might occur in or near facilities that normally handle hazardous substances such as hydrogen. Understanding a process's overall risk is the goal of QRA research, and the analysis should be carried out so that it can be independently confirmed, recreated, and compared, regardless of the methodology or individual conducting the analysis.

The analysis can predict accidents, fatalities, economic losses, environmental damage, and the impact of assumptions in a given scenario. QRAs can establish a framework for system design and preventative measures. QRA is a crucial instrument for ensuring the safe deployment of hydrogen technologies and is progressively integrated into the permitting process. It provides a scientific framework for designing and implementing essential hydrogen codes and standards [73]. This addresses both the U.S. National Fire Protection Association NFPA 2 Hydrogen Technologies Code and ISO 19880-1, an international standard for hydrogen filling stations [74].

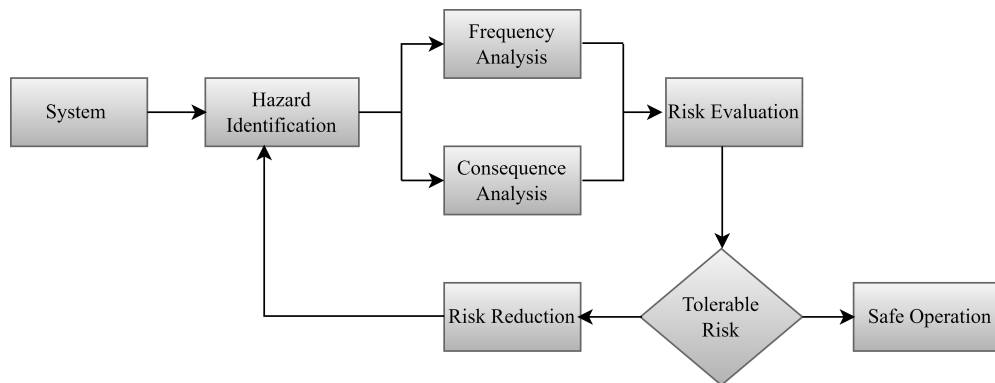


Figure 3.2: QRA Process apodted[72]

When conducting an analysis, the overall view of which events contribute the most to the risk is maintained throughout the process, as are the critical and most effective barriers, as well as the accuracy of the representative risk contours. As a result, the risk analysis should use the most expected levels of assumptions and the most realistic interpretations of the severity of the consequences of the evaluated scenarios can be expected to extend. After evaluating all of the risks and their potential consequences, the tolerable risk will be defined by modeling what events will cause damage and establishing an acceptable risk rate limit [75].

METHODS

This chapter proposes a procedural method of analysis. The approach was developed by applying FMEA for qualitative assessment and fuzzy logic event tree analysis to address uncertainty in safety analysis methods. The combined approach identifies possible failure modes, determines their consequences, and analyzes cascade effects that could bring dramatic system disruptions. Specifically, an FMEA of a published PEM electrolyzer design [76] is performed in accordance with the IEC 60812 (2018) FMEA standard [77] and in accordance with [14] guidelines. The subsequent FMEA is the foundation of the following ETA, with scope for a system and proposed mitigation action.

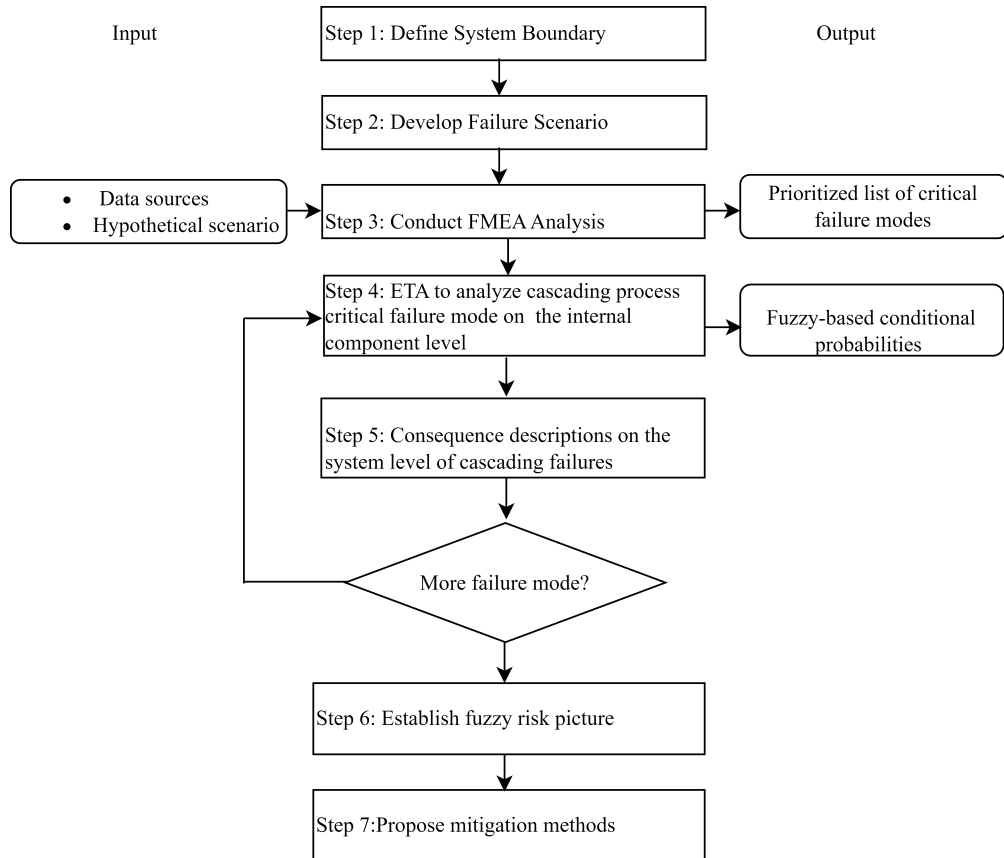


Figure 4.1: Cascading Failure Analysis Flowchart

As the objective of the research is to determine likely failure modes in the PEM electrolyzer system and the interdependence of the parts. This entails investigating in- internal problems within the PEM electrolyzer stack. The MEA is referred to as a critical and typically the weakest part of PEM electrolyzers, and its degradation is the largest safety issue because it can lead to the formation of an explosive gas mixture. FMEA enables the determination of the MEA's specific failure modes. The methods used examine how MEA degradation and other failures of parts within the PEM system can initiate and sustain cascading events. The approach recognizes that analysis will be forced to employ simplifications because sufficient data do not exist, but concentrates on key subsystems that most affect the operational safety and integrity of the electrolyzer.

4.1 System Boundary

The various components of the system are categorized according to their overall function. The electrolysis stack splits water into hydrogen and oxygen via electrical power. The stack consists of an anode, a membrane, a cathode, bipolar plates, and gas diffusion layers. The membrane must maintain the separation of the hydrogen and oxygen streams. Separators for oxygen and hydrogen are used to separate the generated gases from water. A back-pressure regulator, a variety of pipes, solenoids, non-return and pressure-relieving valves are used in conjunction with valves to regulate the flow of gases and water.

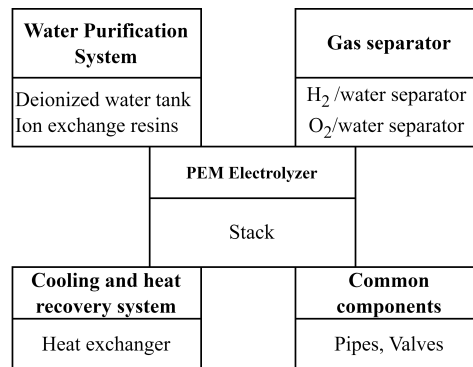


Figure 4.2: System boundary

The PEM operating systems operating can be different and have different levels of complexity. Certain strategic simplifications have been performed to make the analysis easier without changing the core results. A deionized (DI) water tank makes the water supply system and treatment easier by providing sufficient storage with low conductivity. DI water supplies to the oxygen-water separator through valves. The feedwater pump recirculates the mixed water through the system afterwards [30]. Water flow on the anode side of PEM is aided by feed water flow circulation system. The water flow is detected by the flow switch and offers a proper flow to the electrolyzer [6]. The Subsystems harmonize and interact with each other to complete the hydrogen production process [78].

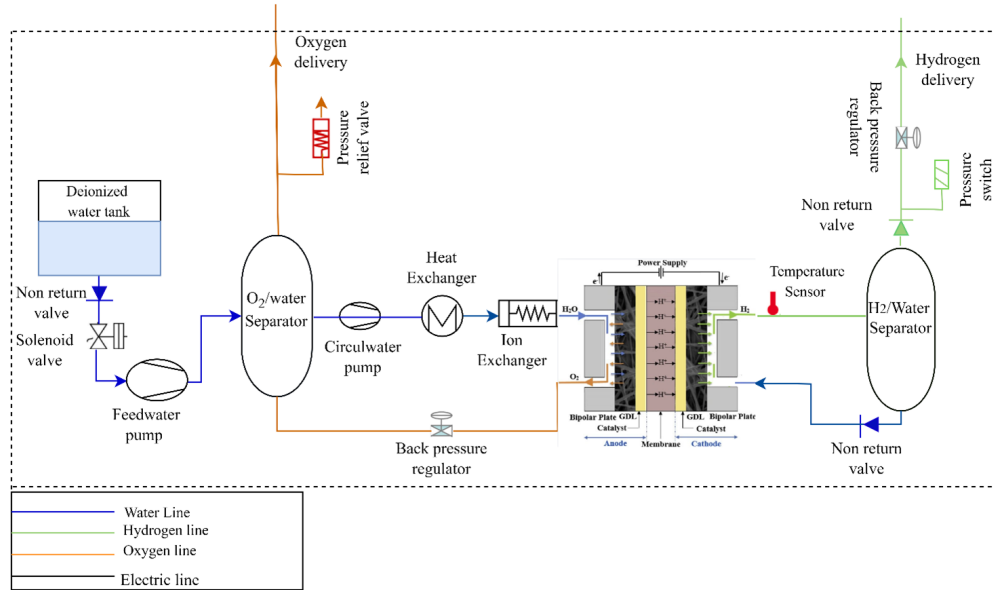


Figure 4.3: A simplified process diagram showing the main operational components within the system boundary

4.2 Failure Scenarios

The membrane-electrode assembly (MEA), a critical component of PEM electrolyzers, has the potential to be the weakest cell component in terms of performance, safety, dependability, and durability. The MEA is responsible for the vast majority of performance losses and mishaps during PEM water electrolysis [55]. Considering that MEA degradation is a failure mechanism that prioritizes loss of function, it also initiates a cascade of safety issues. When the MEA degrades, primarily due to chemical, mechanical, or thermal processes, the membrane's integrity is critical.

The degradation leads to the formation of an explosive gas mixture, making the degradation of MEA a primary safety concern [79]. Hydrogen and oxygen mixing in electrolyzers is a complex and high-risk scenario, with stated failure scenarios relating to the electrolyzer membranes' vulnerability to varied degradation circumstances. This risk is increased by functional group failures in the balance of the plant.

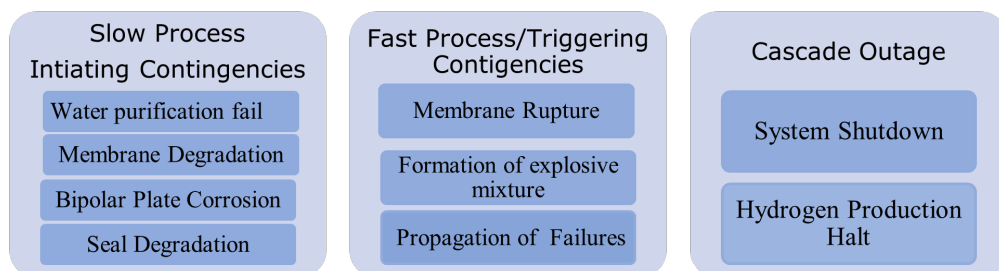


Figure 4.4: Cascading scenario in hydrogen production

4.3 Qualitative Analysis

A qualitative analysis was performed under the FMEA method. A qualitative risk matrix is used to assess the impact and likelihood of failure scenarios. A risk matrix is a visual tool that represents risk levels in terms of likelihood and severity, and it allows for the prioritization of process and design changes. For every scenario, the various combinations of severity and likelihood of occurrence result in a risk level that ranges from [80]. The severity and occurrence combinations that result in each qualitative risk level. Risks are generally accepted in the green area, but tolerance has to be demonstrated in the ALARP area (between green and red). The likelihood and severity categories and risk acceptance level are based on [28].

			Severity →				
			Negligible	Minor	Moderate	Significant	Catastrophic
			1	2	3	4	5
Likelihood →	Very high	7	Medium	Medium	High	High	High
	High	6	Low	Medium	Medium	High	High
	Moderate	5	Low	Low	Medium	Medium	High
	Low	4	Negligible	Low	Low	Medium	Medium
	Very low	3	Negligible	Negligible	Low	Low	Medium
	Unlikely	2	Negligible	Negligible	Negligible	Low	Low
	Remote	1	Negligible	Negligible	Negligible	Negligible	Low

Figure 4.5: Risk matrix for qualitatively assessing failure scenarios

The likelihood of occurrence in the PEM electrolyzer machine year was used to determine the probability of an event. A report by the EU Joint Research Commission estimates that the annual operation time is between 3000 and 5000 hours[79]. According to [14, 46], an electrolyzer is expected to have 4000 operational hours for this investigation. This helps integrate failure scenarios that have been found on different PEM electrolyzer systems. The following is a definition of the likelihood of occurrence categories (all are with relation to a similar system/facility).

1. Remote – not expected to happen, happens less than once in 1000 machine-years
2. Unlikely – expected to happen less than once per 100 machine-years
3. Very low – expected to happen less than once per 50 machine-years
4. Low – expected to happen more than once per 20 machine-years
5. Moderate – expected to happen less than once per 10 machine-years
6. High – expected to happen more than once per 5 machine-years
7. Very high – Failure expected to happen more than once per machine-year

The matrix constructed for this FMEA addressed risks involving facility personnel, users, and general population safety. Categories for severity were defined with the impact of an incident occurring in a full-scale hydrogen production facility to meet the previously stated scalability and applicability goals.

4.4 Consequence Analysis

In this study, consequence analysis was conducted through the application of event tree analysis with fuzzy logic. This method is used to systematically analyze all potential outcomes under uncertainty. In the analysis, the event-consequence model and outcome events are used sequentially in pre-incident operations to explore the initial event and potential consequence operations to identify potential risks (outcome events) that result from a mishap. Qualitative analysis in an event tree demonstrates potential outcomes from an initiating event, while quantitative analysis estimates the probability of such outcomes. Conventionally, quantitative event tree analysis relies on crisp probabilities to estimate outcome event probability or frequency [81].

Determining precise event probability estimates is frequently challenging; these inherent issues raise uncertainty in the ETA, lowering the overall credibility of the risk assessment process for decision-making. This frequently presents challenges due to insufficient data, inherent ambiguity, and imprecise component failure rates. The most fundamental limitation of an event tree is its limited access to valid data. As a result, applying fuzzy arithmetic operations to fuzzy integers provides a suitable way for analyzing an event tree.

4.5 Fuzzy Logic

This section introduces the rationale for using fuzzy logic as the primary analytical tool, building on the foundational understanding of mechanisms and their inherent uncertainties mentioned in previous sections. Fuzzy set theory provides a useful way to describe system reliability when subjective assessments, uncertain data, and approximations of system models need to be considered. Probability theory by itself cannot resolve the issue of bias. Fuzzy sets can be used to represent reliability information because it is frequently crisp. Furthermore, describing reliability with natural language expressions presents a useful way to better manage uncertainties [82]

Fuzzy logic uses a language with syntax and semantics to convert qualitative knowledge/judgments into numerical reasoning. In many engineering tasks, the probability of different risk items has not been thoroughly researched or quantified. The term computing with words was introduced to explain the notion of reasoning linguistically rather than with numerical quantities [83]. In this study, fuzzy logic is used to address uncertainty regarding probability and severity. The main purpose of this work is to describe various types of uncertainties in ETA using approaches such as fuzzy set theory and deterministic methods, where fuzzy is used to deal with subjective uncertainties of event probabilities.

The approach outlines in detail how fuzzy logic's ability to handle inaccuracy and qualitative relationships makes it a viable and effective method for assessing the propagation of failures and their possible outcomes. It defines the development of the fuzzy logic model, including the definition of fuzzy sets, membership functions, the formulation of fuzzy rules, and the inference mechanism, to address the particular uncertainties of cascading failure analysis in the context of green hydrogen production. Additionally, the data sources and the fuzzification and defuzzification process ensure a transparent and reliable methodology for obtaining meaningful insights into the safety and resilience of the system.

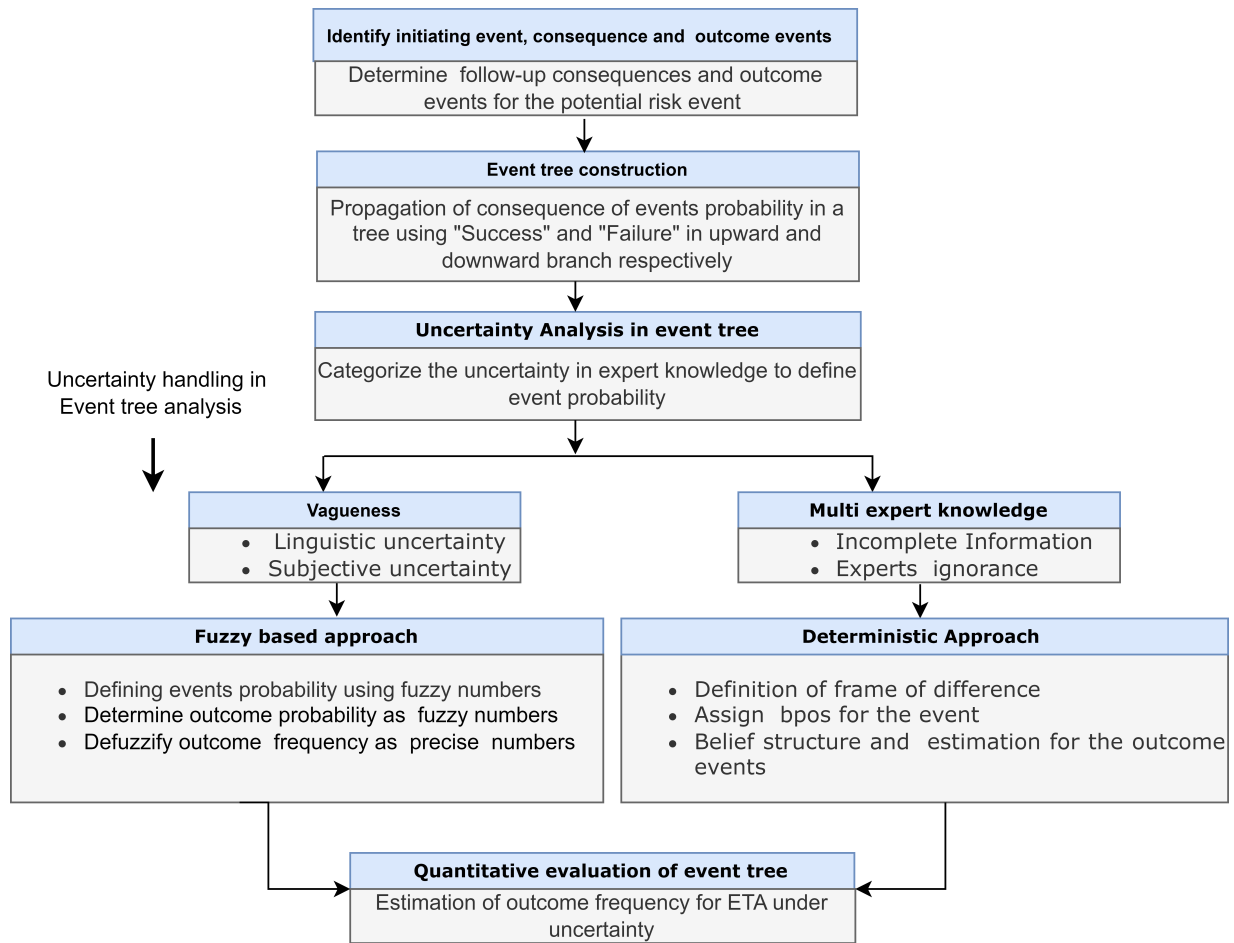


Figure 4.6: ETA approach under uncertainty adopted from [83]

RESULT AND DISCUSSION

The results of the analysis are presented in this chapter, together with a description of the findings and a summary of their implications for the safety, resilience, and dependability of green hydrogen plants. The focus is on how failure paths identified throughout the system propagate, especially those led by issues with the water purification system and membrane electrode assembly (MEA) degradation, and how proposed mitigations can improve operational stability.

5.1 Failure Mode Effect Analysis (FMEA)

FMEA is a technique for identifying, prioritizing, and mitigating potential system failures [84]. The failure modes, which define the functional manner in which the component fails, are based on [85]. When carrying out an FMEA for component failure modes, identify at least one failure mechanism that defines the physical process by which damage or loss of function happens [86]. Each failure mode and failure mechanism pair has several consequences, including explosive mixed gas, which could create an explosion or fire, dislodging or ejecting parts due to an internal pressurized gas leak, malfunction, and overflow.

FMEA was used in a systematic manner in this thesis to identify probable failure modes of the PEM electrolyzer system and component connectivity. The analysis is important since it shows how initiating events can propagate across the system, resulting in cascading failures. For purposes of conciseness, this thesis will only discuss the failure consequences that include the loss of function and hazardous gas mixing (hydrogen and oxygen release or mixing). Tables 4.1 and 4.2 present the specific outputs of FMEA; the insights gained from FMEA provide a useful foundation for comprehending possible hazards and informing the subsequent Event Tree Analysis (ETA).

Component	Failure mode	Potential Causes	Potential Effects	O	S	Risk	Cascading Effect
MEA	Pinholes Cracks	Mechanical stress manufacturing defects	Localized leaks gas crossover	4	5	High	Propagate to larger cracks, leading to rapid membrane failure [87, 88, 30]
MEA	Thinning	Uneven current, high temperature	Permeability Rupture	4	5	High	Accelerates degradation [89]
MEA	Localized Leaks	Pinholes, cracks, seal failures	Explosion, fire hazard	3	5	Med	Ignite other flammable ma- terials in the area
Catalyst Layer	Catalyst poisoning	Membrane degradation	Reduced reaction kinetics	-	-	-	-
GDL	Flooding	Gas crossover	Localized hot spots	2	5	Med	Corrosion of the bipolar plate
Bipolar Plates	Corrosion	Gas crossover, acidic environment	Leakage, structural damage	2	5	Med	Cell failure and system shutdown
Sealing Gasket	Leakage Degradation	Chemical attack, improper installation	Gas leaks	2	5	Med	System malfunction
Power supply	Overcurrent/ Overvoltage	Short circuit membrane failure	Safety hazards	4	5	High	System shutdown, Poten- tial damage to other compo- nents

Table 5.1: FMEA - Loss of Function

Component	Failure mode	Potential Causes	Potential Effects	O	S	Risk
Electrolyzer	Rupture	Overpressure corrosion and material defect	Hydrogen release, reduced efficiency	2	5	High
Electrolyzer	Abnormal Output-High	Control system malfunction	Gas overproduction Potential safety risk	2	5	High
Pump	Fail to Operate	Power failure, blockage, or mechanical failure	No fluid flow, system shutdown	2	5	High
H ₂ /water separator	Internal and external leak	Corrosion, seal failure, and mechanical damage	Reduced efficiency Explosion separator	2	5	High
Solenoid valve	Fail to operate	Electrical failure, mechanical blockage	Incorrect gas flow, system malfunction	2	5	High
Back pressure Regulator/O ₂	Full Plugging	Debris, corrosion, freezing	No oxygen flow, system shutdown	2	5	High
Pressure relief valve	Full blockage	Mechanical failure	Overpressure	2	5	High
Non-return Valve	Fail Closed	Corrosion and mechanical failure	Backflow of gases, potential contamination	2	5	High
Hydrogen pipe	Leak/rupture	Corrosion, mechanical damage, and overpressure	Hydrogen release, potential fire/explosion	2	5	High
Oxygen pipe	Full blockage	Corrosion, freezing, and external damage	No oxygen flow, system shutdown	2	5	High
Temperature indicator	Inaccurate reading	Electrical failure, corrosion, damage	Control system malfunction	2	5	High

Table 5.2: FMEA Hydrogen and oxygen mixing failure scenarios [14]

5.2 Event Tree Analysis (ETA)

An event tree is a graphical representation of all potential event sequences within a system [90]. It is applicable to analyze both continuously operating systems and those with components in standby or latent failure states. The analysis starts with an initiating event, which disrupts the normal operation of the system. The event tree then shows the sequence of events, specifying the system components' failure or success. Combining event probabilities from Failure Modes and Effects Analysis (FMEA) or Fault Tree Analysis (FTA) can quantify the event tree, and the hazard probabilities of each event chain can readily be calculated. Following an initiating event, which is an undesired component failure or external event, the event tree in safety-critical systems specifies a set of possible system consequences [83].

In this study, ETA is used systematically to identify potential failure modes in the PEM electrolyzer system and the interconnectedness of its components. It is used to predict the possible outcomes of critical events identified by the PEM electrolyzer's internal analysis. This allows us to completely comprehend how initial failures can propagate throughout the system and might result in cascading failures and a wide range of consequences, from total shutdown or viable risk prevention. Since ETA is systematic, it provides a simple graphical representation of such sequences of events, and thus it is a critical instrument for measuring the total reliability and safety of green hydrogen production.

5.2.1 Deterministic Approach

As scarcity-specific data for PEM electrolyzer components, the interdependencies, partial states of failure, and qualitative evaluations common in such complex systems are frequently difficult for conventional deterministic approaches to adequately model. According to the literature review, these rates were determined based on the acceptable degradation rate of a PEM electrolyzer of less than 14Vh^{-1} when the lifetime of the system is 10-20 years and with operating 4000 hours in a year, with an average degradation rate of 2% to 4% per year [91, 92, 24]

For this analysis, a continuous degradation at an average rate of 2 % annually was assumed to derive a quantitative estimate for the MEA's failure rate. A uniform temperature distribution within the cell, constant partial pressures at the current collector, and small variations in the gas solubility coefficients between water and the membrane are among the simplifying assumptions used in this estimation [84]. Based on these considerations, the estimated failure rate for the MEA due to 2 % annual degradation is approximately 2.31×10^{-2} per year.

Deterministic failure rates are essential to cascading failure analysis, but have limitations based on their dependence on average data and idealized assumptions, naturally unable to deal with uncertainties. The complex nature of MEA degradation These operations call for a more dynamic analytical framework like fuzzy logic.

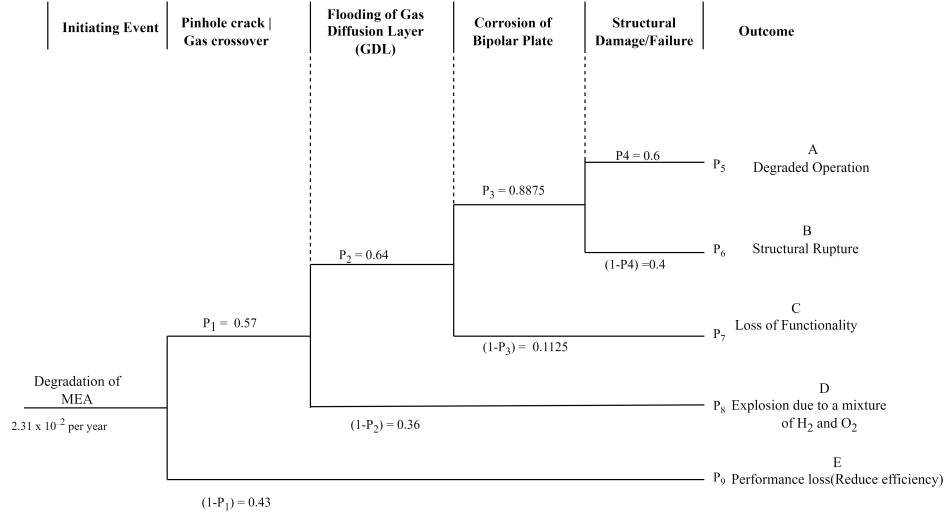


Figure 5.1: Event tree for MEA degradation

As specific data for PEM electrolyzer components are not available, the probabilities are based on the literature review [30, 33]. Further experimental research and relevant failure rate data are necessary to quantify these rates accurately. Addressing the control aspects related to operational procedures and integrity is critical, and the quantification may differ in the details of the operating system in real applications. The event probabilities are propagated into the different branches of the tree. Each branch generates a path that may lead to a specific outcome event, and five possible outcome events were identified. Assuming the events are dependent, the probability of a path or an outcome event is calculated by multiplying the probabilities associated with this path. Equation 5.1 is a general equation for calculating the frequencies of events that occur [83]. λ_i in this equation, denotes the frequency of the initiating event and outcome events

$$\lambda_i = \lambda \sum_{i=1}^n P_i \quad (5.1)$$

Outcome event	Frequency λ	Events per year
A	λ_5	4.49×10^{-3}
B	λ_6	2.99×10^{-3}
C	λ_7	4.73×10^{-4}
D	λ_8	9.93×10^{-3}
E	λ_9	9.9×10^{-3}

Table 5.3: Outcome event frequency of the MEA degradation

5.2.2 Fuzzy-based Approach

In hydrogen production, system failure rates are insufficient and imprecise. Fuzzy logic is also used in the event tree methodology to determine the probability of an undesirable event as well as the probability of potential consequences from an event, to reduce the effect of uncertainty and human error [83]. Fuzzy logic offers a language with syntax and semantics for converting qualitative knowledge/judgments into numerical reasoning. The term computing with words refers to the concept of reasoning linguistically rather than numerically. Fuzzy-based approaches help in addressing deficiencies inherent in binary logic. They effectively deal with an imprecision that arises due to subjectivity/vagueness and are helpful in propagating uncertainties throughout the risk analysis and decision-making process.

Fuzzy-based approaches are a type of interval analysis that addresses uncertain or imprecise data. A fuzzy number represents the relationship between an uncertain variable, event probability, and a membership function μ , which spans from 0 to 1. A fuzzy set extends classical set theory by allowing probability to have varying degrees of membership in a set P [83]. A fuzzy number may adopt any shape, but it should be justified by available information (normal, bounded, and convex). Triangular or trapezoidal fuzzy numbers (TFN or ZFN) are commonly used to describe linguistic variables [93].

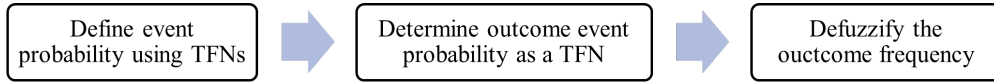


Figure 5.2: Fuzzy-based Approach Steps

5.2.3 Integrating Fuzzy Logic into Deterministic Approach Analysis

The deterministic approach shown in Figure 5.1 uses defined probabilities for branching events in the event tree, resulting in precise frequency values for the outcome events. However, real-world PEM electrolyzer failure processes frequently entail inherent uncertainties and ambiguity, which can be better addressed by incorporating fuzzy logic.

Define event probability using TFNs (fuzzy numbers)

Branching probabilities (P_1, P_2, P_3, P_4), crisp probabilities in the event tree, can be replaced with fuzzy probabilities. In assessing event probabilities, linguistic expressions such as likely, probable, and improbable are preferred over precise numerical values. Triangular fuzzy numbers (TFNs) are used to represent these linguistic judgments. A TFN, denoted as (p_L, p_m, p_R) , provides a range of possible probabilities, representing the minimum, most likely, and maximum values, respectively. The degree of membership μ_p within this range is determined by the cut level α , and varying these levels generates nested intervals (p_α) that offer a progressively refined representation of the probability of uncertain events.

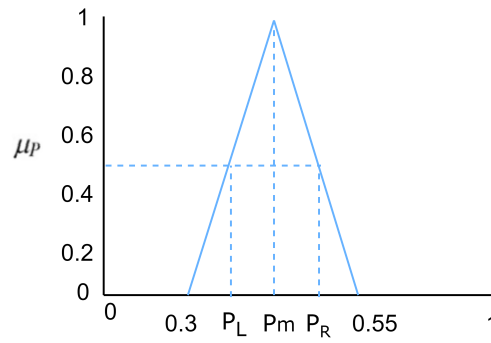


Figure 5.3: TFN to represent event probability

The qualitative grades are represented by TFNs to express the linguistic probabilities. The eight grades are highly improbable (HI), very improbable (VI), rather improbable (RI), improbable (I), probable (P), rather probable (RP), very probable (VP), and highly probable (HP). Triangular MF (membership function) is one of the simplest and most commonly used MFs for designing FLS. The fundamental attributes of triangular MFs, which differentiate them from other MFs, are that the boundary varies linearly from highest to lowest membership grade. There's only one discrete element having the highest membership grade [94].

Linguistic terms	Fuzzy numbers
Highly improbable (HI)	[0,0, 0.119049]
Very improbable (VI)	[0.0238095, 0.142857, 0.261905]
Rather improbable (RI)	[0.166667, 0.285714, 0.404762]
Improbable (I)	[0.309524, 0.428571, 0.547619]
Probable (P)	[0.452381, 0.571429, 0.690476]
Rather probable (RP)	[0.595238, 0.714286, 0.833333]
Very probable (VP)	[0.738095, 0.857143, 0.97619]
Highly probable (HP)	[0.880952, 1,1]

Table 5.4: Linguistic terms with triangular fuzzy numbers from MATLAB

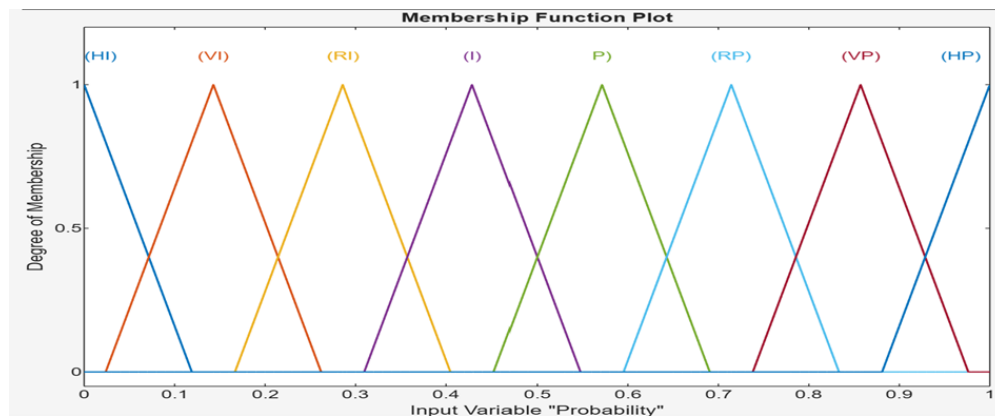


Figure 5.4: Triangular membership function to linguistic variables on fuzzy scale

Determine probability of outcome event as a TFN (fuzzy number)

Uncertainty in the event probability is represented by a TFN's membership function $\mu_p \in [0,1]$. Fuzzy intervals (i.e., nested intervals in a fuzzy number) with a membership grade μ_p greater than or equal to the α -cut value. In a TFN, the interval at the α -cut level is determined by the membership function using the following relationship:

$$P_\alpha = [PL + \alpha(Pm - PL), PR - \alpha(PR - Pm)] \quad (5.2)$$

The degree of uncertainty in event probability, represented by the membership function μ_p in event tree analysis, can either be the same or different for the events in a particular path. For ETA, these scenarios can be described using either the random α or the predefined α -cut. The outcome event probability is determined using fuzzy arithmetic operations [92]. The predefined α is used for this thesis. At a specific α -cut level, this specific cut level defuzzified to obtain the crisp probability for the event. Table 3.6 provides the defuzzified frequencies of outcome events. The event tree tree degradation event (MEA degradation) has a frequency of 2.31×10^{-2} per year. Multiply the outcome probability intervals by this frequency to get the outcome event frequency intervals.

α -cut level	Defuzzified outcome events frequency (events/year)				
	A	B	C	D	E
0.2	7.27E-03	8.545E-04	5.35E-03	9.81E-03	3.36E-03
0.4	7.20E-03	8.35E-04	5.31E-03	9.80E-03	3.32E-03
0.6	7.18E-03	8.15E-04	5.28E-03	9.78E-03	3.28E-03
0.8	7.12E-03	7.97E-04	5.25E-03	9.77E-03	3.24E-03
1.0	7.11E-03	7.89E-04	5.26E-03	9.93E-03	3.26E-03

Table 5.5: Defuzzified outcome event frequency

The explosive mixture of hydrogen and oxygen, which leads to an explosion, was identified as a high risk across all functional groups, and these conditions are likely to occur throughout the explosion, triggering a domino effect affecting pipelines, valves, and gas separators. This entire chain of events is regarded as high-risk by all functional groups due to the widespread involvement of components and the high vulnerability of electrolyzer membranes to degradation.

5.3 Implications of Cascading Failures

According to research studies and analysis, MEA degradation or electrolyzer failure is triggered by poor water quality due to a water purification system failure and other undesirable factors, resulting in a risky occurrence: the formation of an explosive mixture. An explosive combination of hydrogen and oxygen, along with

a structural rupture, is likely to cause a cascading failure of other components. Which has the potential to cause fire or explosion, can initiate a cascade failure from an internal compressed gas release, resulting in loss of function in critical systems and, eventually, an explosive mixture overflow in operating components; each of these events aggravates the others, creating a rapidly escalating scenario with potentially catastrophic consequences [104]. The potential for ignition leads to the subsequent escalation into hazardous events, including explosions and their associated consequences. While data availability limits a detailed quantitative analysis of the consequences, it is critical to recognize the potential hazards.

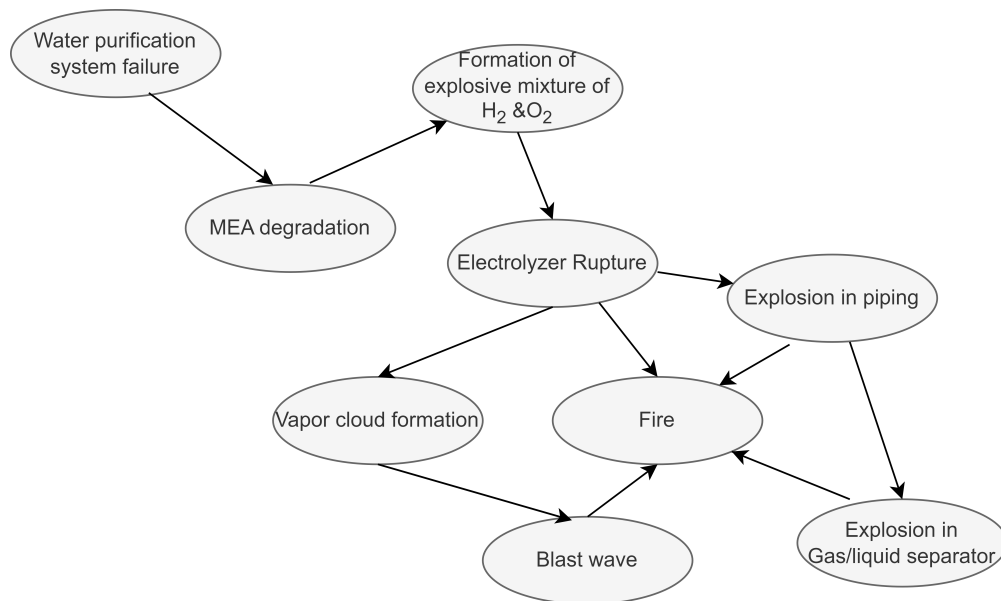


Figure 5.5: Subsequent consequences of explosive mixture of H_2 and O_2 initiated by the failure of the water purification system and the MEA

Critical to the severity of the consequence, such as the type of explosion and containment integrity, are potential routes to HSE effects. Although not necessarily unique to this system, these consequences indicate the potential dangers. Listed in 5.6, the identified potential consequences of H_2/O_2 are neatly categorized by nature and affected components. For instance, this categorization neatly separates the intrinsic energy release or dangerous phenomenon—i.e.,

- Explosion into sub-categories of confined, detonation, and unconfined/blast for propagation behavior
- Fire (more accurately, jet fire for release dynamics)
- Thermal hazard (radiation for mode of energy transfer)
- Pressure failure involves implosion for some mechanical failure, and process disturbance by backflow for deviation from intended operation.
- Domino effect for spread of inter-system causality

This categorization indicates the needed relevant safeguards/barriers by correlating mitigation with the inherent hazard type. Identification of the component or components involved, the mode of failure, and the immediate initiating cause (e.g., the accumulation of an explosive H_2/O_2 mixture with an internal ignition source) creates connectivity between events. These facilitate full risk modeling, optimization of design, and emergency planning preparations when these connected data points are combined. This type of presentation allows for the development of a focused risk assessment and risk reduction interventions.

Potential Consequences	Category	Component
Explosion in the cell stack	Explosion (Confined)	Electrolyzer stack
Jet fire after internal explosion	Jet Fire	Electrolyzer
An explosion in the piping between the cell stack and the separator	Explosion (Confined)	Piping
Immediate detonation	Detonation	Electrolyzer Stack Piping
Explosion in G/L separator	Explosion (Confined)	Separator
Blast, rupture, shrapnel Explosion (Unconfined/Blast)	System Structure	
Escalation to nearby stacks/separators after the explosion	Domino Effect	Entire System
Negative pressure after an explosion in the system (system remains closed)	Pressure Failure	Entire System
Loss of containment caused by backflow from other parts of the system	Process Disturbance	Piping/Valves
Heat radiation from the combustion reaction inside affects the equipment outside	Thermal Hazard (Radiation)	Entire System

Table 5.6: Potential consequences with explosive mixture of H_2/O_2

These consequences are derived and adapted from [95] "Safety Aspects of Green Hydrogen Production on an Industrial Scale," a public report and a comprehensive safety study on large-scale green hydrogen production. According to the report, "the analysis is for information only." Different companies, institutions, and authorities might decide to apply different approaches, criteria, and definitions.

5.4 Fuzzy Risk Matrix

A fuzzy risk matrix is used primarily to overcome the limitations of quantitative risk assessment methods. It effectively bridges the gap between qualitative descriptions of risk and a quantifiable risk assessment. The fuzzy model incorporates three basic subsystems: the Severity Fuzzy Logic System (FLS (S)), which assesses the severity of consequences for the incident scenario; and the Frequency Fuzzy Logic System (FLS (F)), which determines the fuzzy frequency of an incident scenario. The third subsystem, the Risk Fuzzy Logic System, or FLS (R), which creates the fuzzy risk matrix, takes input from both systems[96]. The final crisp risk index is created by using proper fuzzy arithmetic and fuzzy reasoning, and it is used for further decision-making in risk management processes.

Variables of risk factors	Linguistic (fuzzy set)	term	Range /year	Discourse
Frequency (F)	Very high		$(1 < F < 10^{-2})$	$X_F \in (10^{-8}, 1)$
	High		$(10^{-1} \leq F < 10^{-3})$	
	Moderate		$(10^{-2} \leq F < 10^{-4})$	
	Low		$(10^{-3} \leq F < 10^{-5})$	
	Very low		$(10^{-4} \leq F < 10^{-6})$	
	Unlikely		$(10^{-5} \leq F < 10^{-7})$	
	Remote		$(F < 10^{-6})$	
Severity (C)	Negligible		$1 < C \leq 2$	$X_C \in (1, 5)$
	Low		$2 < C \leq 3$	
	Moderate		$3 < C \leq 4$	
	High		$3 < C \leq 5$	
	Catastrophic		$C > 5$	
Risk category (R)	Negligible		$0 < R \leq 2$	$X_R \in (0, 5)$
	Low		$1 \leq R \leq 3$	
	Medium		$2 \leq R \leq 4$	
	High		$3 \leq R \leq 5$	

Table 5.7: Linguistic variables and risk categories based on [96]

The risk matrix is used to identify the risk category, which is one of the four categories listed in Table 5.7. This serves as the foundation for additional risk-control strategies. Though risk analysts often utilize them, processes that use qualitative language descriptors, such as "low," "high," or "possible," are extremely ambiguous and imprecise. When such value judgments are applied, uncertainty arises, but it is due to fuzziness rather than randomness [97].

Fuzzy sets are defined for certain linguistic factors such as frequency, severity of consequences, and risk in fuzzy logic, and they are equal to conventional independent variables. Fuzzy sets are composed of the categories chosen for each variable. A fuzzy set defined on a discourse universe is represented by a membership function (x) that accepts values from the interval $[0, 1]$.

5.4.1 Fuzzy inference system

A fuzzy inference system uses risk rules to map fuzzy input sets (frequency and severity) into fuzzy output risk sets. It is executed using fuzzy IF-THEN rules. The structure of fuzzy rules for the fuzzy risk matrix is as follows: If the frequency is f_n and the severity of the consequences is S_c , then the risk is r_z , where f_n , s_c , and r_z are the fuzzy sets for frequency, severity S , and risk R defined in the literature review.

A Mamdani fuzzy inference algorithm is used to convert the qualitative rules into quantitative findings. For the AND method and output set implication, the Mamdani model uses the min operator. Following the evaluation of the rules, each rule's output fuzzy set was utilized. The resulting output fuzzy risk category's aggregating output membership function is expressed as

$$\mu_R(r) = \max\{\min\{\mu_F^k(f_n), \mu_S^k(s_m), \mu_R^k(r_z)\}\}$$

where k is the number of rules, n is the number of fuzzy frequency sets, m is the number of fuzzy severity sets, and z is the number of fuzzy risk sets[97]. The Mamdani inference process involves the following steps:

1. Fuzzification of Inputs: The crisp input values for Probability, Severity, and Frequency are converted into fuzzy sets using the membership functions.
2. Rule Evaluation: The degree of membership of each input value in the antecedent part of each rule is determined. The 'AND' operator (minimum) is used to combine the membership degrees of the different parts of the antecedent.
3. Rule Aggregation: The output fuzzy sets of all the rules are aggregated into a single fuzzy output set. This is typically done using the maximum operator, which selects the highest membership degree across all rules.

Gaussian membership functions are used to represent these fuzzy sets, as shown in Figure 5.6. Gaussian membership functions are chosen to represent severity because they can model a more gradual and natural distribution of severity levels, often observed in real-world scenarios. It is important to note that the specific values and shapes of the membership functions can be adjusted based on the availability of data and expert knowledge. Furthermore, the flexibility of Gaussian membership functions is a significant advantage. Their shape is defined by two key parameters: the mean, which centers the peak of the curve at the point of highest membership, and the standard deviation, which dictates the curve's spread or width. It allows for precise adjustments based on data availability and expert knowledge, making it a valuable tool for assessing severity in complex scenarios.

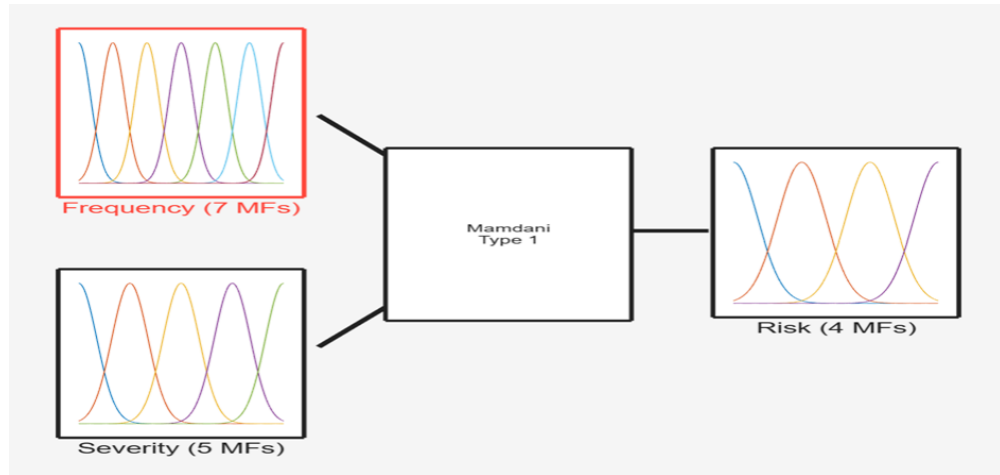


Figure 5.6: Fuzzy logic method for risk development in MATLAB

According to the proposed structure of the risk matrix, a combination of seven frequency categories and five severity categories (referred to as antecedents) results in 35 rules with 35 conclusions that represent risk categories provided in Appendix B. For instance, if the frequency is remote AND the severity is negligible, then the risk is acceptable.

5.4.2 Defuzzification

Defuzzification transforms a fuzzy integer into a crisp value. The technique of weighting and averaging the outputs of all separate fuzzy rules to produce a single output value. This output about the risk index is exact, defuzzified, and has a clear value. In this work, the center of area (COA) or centroid approach is used.

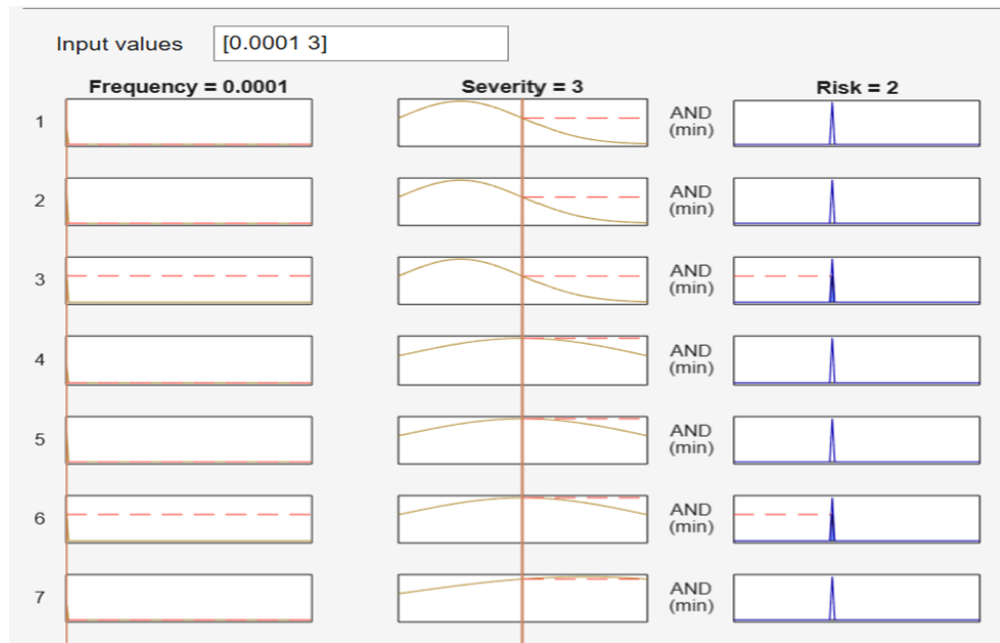


Figure 5.7: Defuzzification of the rule in MATLAB

5.4.2.1 Fuzzy risk surface

A three-dimensional plot that represents the mapping from two inputs (frequency and severity) to one output (risk) represents the relationship between frequency, severity, and risk. The risk surfaces present different risk regions according to the input parameters and can be used to assess risk. A nonlinear relationship between frequency, severity, and risk of overall system failure is shown in Figure 5.8, a surface plot. Risk commonly rises with both frequency and severity, but severity seems to have more of an impact.

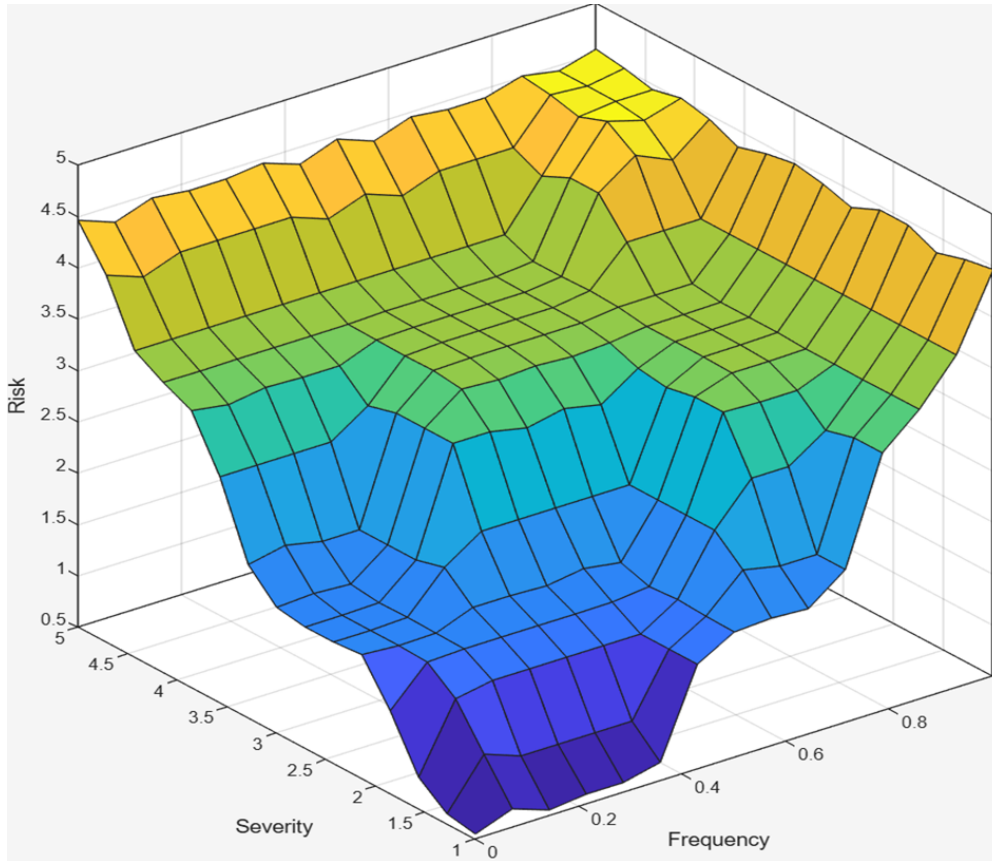


Figure 5.8: Fuzzy surface of risk against frequency and severity

The surface illustrates how the risk level changes as the input variables vary. This provides a valuable tool for understanding the sensitivity of the risk assessment to different combinations of input factors. In particular, low risk corresponds to low frequency and severity, whereas high risk occurs when both increase. Although severity is the main driver, frequency increases risk, especially at higher severity levels. It reveals complex interactions with some localized variations, where risk can actually go down even when input variables go up. Under this method, lowering the frequency of incidents contributes significantly to the overall risk assessment, and reducing high-severity incidents is also important.

The deterministic and fuzzy logic approaches to cascading failure assessment in green hydrogen production are discussed in the study. The deterministic approach, while it provides precise frequency values based on given probabilities and mean data, is limited by its employment of idealized assumptions and inability to accommodate the very uncertainties and vagueness of real system failures. In contrast with this, the fuzzy logic approach is brought forth to deal with the uncertainties and vagueness of system failure rates, addressing vagueness and uncertainty by converting qualitative data into numerical reasoning in the shape of linguistic terms and fuzzy numbers, thus drawing a more realistic conclusion of risk.

5.5 Mitigation Methods/Strategies

The performance of PEM electrolyzers depends upon design, assembly, operating conditions, material degradation, and contaminants. Mitigation mechanisms can be employed to reduce performance degradation and cascading effects, which would result in prolonged life and stable PEM electrolyzer operation. As a result, the improvement of capability, reliability, and system stability overall requires an overview strategy cognizant of mitigation techniques, with a focus on the most important areas of membrane degradation, water purification, and hydrogen/oxygen mixture control in the system.

5.5.1 Water Purification System Reliability

The reliability of the purification water system determines the overall performance and lifespan of the electrolyzer. The mitigation methods aim at the achievement of a non-interruptive, high-purity water supply. To maintain the water purity and system availability, order the higher priority items first, implement redundancy to major components such as the activated carbon filter (AF) and particulate filter (PF), improve frequency of checks, utilize advanced condition monitoring technologies, and conduct predictive maintenance.

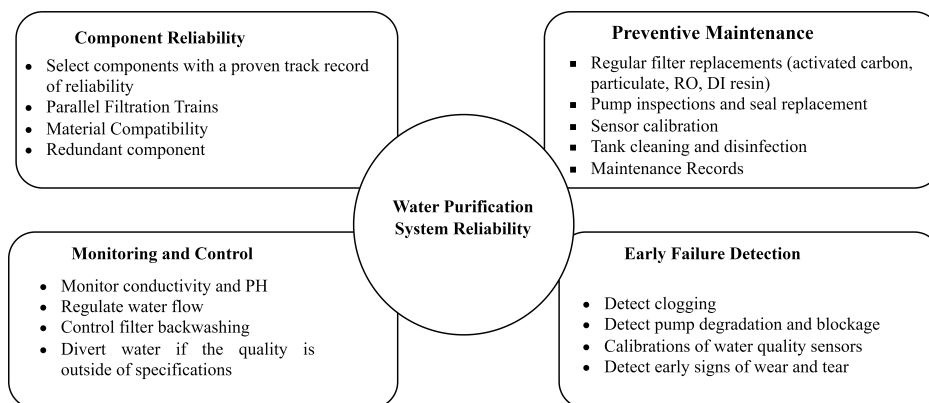


Figure 5.9: Mitigation techniques to improve water purification systems

5.5.2 Mitigation method for membrane degradation

Adequate membrane electrode assembly and clamping system design are essential to reduce non-uniform mechanical compression and prevent mechanical membrane failure [46]. Reinforcing the membrane can help reduce membrane creeping. The integration of an inert, non-conductive substance can reinforce the membrane. Additionally, membrane edge protection in the seal area is necessary, particularly under high mechanical loads for high-pressure sealing [52]. As cationic species can poison the membrane, for instance, Fenton-active metal cations (Fe^{2+}) increase hydroxyl radical ($\text{HO}\cdot$) formation from H_2O_2 and accelerate degradation. Using corrosion-resistant structural components (e.g., coatings or stable bulk material) is preferable, and substituting metal components (e.g., fittings, tanks, and pipes) [98] with polymer materials can help, although this is often impractical in high-pressure systems that rely on titanium or stainless steel. Proper thermal management is needed to avoid thermal degradation from hot spots or excess heat, both of which severely speed up membrane degradation [99].



Figure 5.10: Some mitigation techniques for reducing membrane degradation and failure based on [99]

5.5.3 Mitigation for Explosive Mixture

Some of the protection and precautions that may be employed in order to mitigate the impact of potentially explosive mixtures are gas analyzers, which constantly check for the oxygen and hydrogen content to identify unusual conditions early on. Upon ignition, containment buildings and explosion-proof equipment avoid damage; pressure relief systems protect equipment against overpressure by venting excess gas through valves; and equipment layout and spacing properly to reduce the effects of cascading and risky event consequences. Some techniques were proposed to restrict the frequency and severity of undesirable events, i.e., prevention measures and consequences relief methods, as tabulated in Table 5.8.

Mitigation Categories	Mitigation Method	Description and Purpose
Prevention	Water quality analyzers	Monitors water purity
	Material Selection	Improve corrosion resistance by top grade materials
	Reliable MEA and clamping System design	Manufacturing quality assurance minimizes mechanical failure due to stress
	Membrane Reinforcement	Using nonconductive, inert reinforcement enhances the membrane's durability
	Uniform Membrane Thickness	Even distribution of mechanical stress and ion transport
	Optimal Thermal Management	Preclude hot spots or overheating.
	Proper Operation and Maintenance	Incorporating an acceptable sequences and ramp-up/down procedures
Detection	Cell Voltage/Stack Voltage Analysis	Monitoring the cell and overall stack voltage for deviations
	Gas Quality Analyzers	Monitoring the purity of the produced hydrogen and oxygen
Control	Emergency Shutdown Systems (ESD)	Shutdown systems triggered by gas analyzers or other sensors
	Isolation Systems	Valves to isolate sections of piping or equipment in case of a leak
Mitigation	Pressure Relief Systems	Relieve overpressur protect against explosions
	Explosion Protection	Flame arrestors to prevent flame propagation
	Layout and spacing plant's layout to reduce the effects	Safety distances between equipment
	Protection from Secondary Effects	Splash screens to protect against splashes or projectiles

Table 5.8: Potential Mitigation Strategies based on [95]

5.5.4 Decoupling

Decoupling minimizes the coupling between dependent components, which is suitable for green hydrogen production plants [59]. The basic approach of the technique is to improve maintainability and reliability, which enables for greater independent operation and maintenance. It minimizes the system's susceptibility to CAFs. Decoupling methods can be implemented at any level of system life cycle, from the beginning design and production through ongoing improvement, maintenance, and operation. Based on earlier research, traditional decoupling methods involve the utilization of link-addition techniques, creation of redundancies, and the creation of physical separations (such as through the strategic positioning of safety barriers and safety distances).

According to previous research, common decoupling strategies include the use of link-addition techniques, the setting up of redundancies, and the establishment of physical separations (e.g., through the strategic placement of safety barriers and safety distances). These methods work by interrupting or reducing the pathways that failures use for propagation. Recent developments in the field of green hydrogen production specifically highlight decoupled low-temperature water electrolysis systems. This type of decoupling frequently involves dividing different phases or procedures within the electrolysis system itself to improve the efficiency [100].

The decoupling approach in the operational aspect of the green hydrogen plants is under research and development, and there is a lack of comprehensive studies. According to the proposed mitigation strategies in the previous section, decoupling maintenance can be applied with inherent interdependency complexity. By developing and applying more targeted, actionable maintenance activities that account for the heterogeneity of such dependencies, the work will not just contribute to the fundamental knowledge of failure avoidance, but it will provide actionable strategies for failure propagation avoidance as well, thereby making a significant contribution to green hydrogen production facility operational resilience, safety, and long-term viability.

CONCLUSION

6.1 Overview of Findings

The study is a systematic and practical approach to learning interdependency, i.e., cascading failure, due to the research gap and prevention of the hazards created by the domino effect. The finding of this thesis not only constitutes a research gap in an investigation of failure dependence on green hydrogen production plants but also contribute to the study of safe and reliable energy alternatives. Specifically, the research methodology and findings could be an integral part of an important role in driving the development of technical systems through strategic planning, an aspect that is significantly important for PEM electrolyzers and other dangerous components. The study indicates unwanted events and initiators for component failure and thus potential implications concerning the failure conditions.

To assess the vulnerability of the components within the scope of the study, a qualitative analysis was performed by failure mode effects analysis (FMEA). This step included the assessment of failure modes that could occur and the impact on other components in terms of domino effects. Event trees (ETA) were used to determine the potential outcome events in the internal analysis PEM electrolyzer. In addition, fuzzy logic based on the deterministic approach is applied to address the uncertainty of the probability, which provides a robust framework for identifying and analyzing potential failure scenarios and their propagation.

This study demonstrated the need for addressing uncertainties in evaluation. Risk analysis is an intricate process involving multiple characteristics that might be difficult to measure. This technique via fuzzy logic illustrates that its reasoning process is applicable in the field of reliability and risk analysis. Fuzzy logic accurately captures the imprecise nature of expert knowledge, operational parameters, and failure propagation across interconnected equipment.

The analysis findings of this study contributed to the propose of particular mitigation techniques to improve the safety and reliability of green hydrogen production. Preventive solutions to increase component reliability, real-time water quality monitoring methods, gas quality analyzers to determine the purity of hydrogen produced, emergency automatic shutdown to stop incidents from propagation, and splash screens to shield against projectiles or splashes from sequential effects are some examples of these precautions. The study also highlights how crucial it is to use components with a track record of reliability, and also discusses that maintenance decoupling is one of the methods to reduce the cascading failure effect, and includes these risk assessments in safety regulations and operational guidelines for the production of green hydrogen. This will ensure that future infrastructure development will take into account not just operational and financial advantages but also prioritize safety and reliability.

In conclusion, this study provides to concept of interdependency in terms of component failure in green hydrogen production and potential risk reductions. This framework will guide future research and development in the sector, adhere to regulations, industrial procedures, and safety measures. This work adds academic knowledge and has immediate and long-term implications for infrastructure safety, public health, security, and the quest for sustainable energy alternatives. By examining the failure causes of components and their impact on the overall system, the study supports efforts to shift to cleaner energy in general by ensuring reliable and safe production.

6.2 Further Studies

This thesis investigates the interdependency analysis under cascading failure conditions. Several assumptions were considered in this study due to the scarcity of knowledge on the novel topic and the variety of complicated interaction types involved. Thus, the study has limitations and has several important research gaps that must be filled in the future. Therefore, the study is limited in nature, with several critical research gaps that need to be addressed in the future as well. This section provides additional work recommendations to address the constraints of the existing thesis.

To produce green hydrogen, electrochemical equipment, mainly electrolyzers, needs to be integrated with renewable energy sources, like solar panels and wind turbines. The failure characteristics and statistical distributions of these constituent systems are different, as mentioned in the introduction part of this thesis. Critical cascading failure, however, exists at both the operational coupling and interface. The dynamic interaction between energy supply and electrochemical conversion develops a unique layer of complexity in the failure dependence of such hybrid green hydrogen production systems.

Since green hydrogen energy sources are dynamic, more intricate dynamic models that incorporate renewable energy sources and their effects on green hydrogen production are required. Future research should employ techniques such as time-dependent Markov models or dynamic Bayesian networks to capture the dynamics of how failure dependencies and the domino effect change over time and under various operating conditions. Establishing reliable failure-dependent models and broadening the theoretical framework are the two main pillars of this multidisciplinary approach.

This thesis highlighted the importance of decoupling maintenance activities. Future research needs to explore the use of big data analytics and machine learning to optimize it. Real-time sensor data, prior failure evidence, and operating conditions can be used to predict imminent cascade failures and schedule decoupling maintenance in advance, reducing downtime and risk. Accurate prediction models that are able to predict even longer cascading processes. To more accurately predict the emerging situations of the cascading process for more engineering systems.

Furthermore, conducting experiments in the degradation of MEA and explosive mixtures of hydrogen and oxygen to test failure dependence. Model simplifications and assumptions, along with the sensitivity of simulation results, can lead to errors. The experimental verification can be reciprocally confirmed with the simulation technique, confirming the simulation model's accuracy and excellence in portraying the process of failure cascade. Specifically, it helps the application of theoretical research findings to real-world systems and informs the modeling and behavior of complex systems with failure dependency.

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APPENDICES

A1 - Fault tree model

As specific data for PEM electrolyser components are not available, the failure rates of basic events are not included ("y=None"), transfer events(P037 shown in A.2), H075, and H076 are undeveloped events.

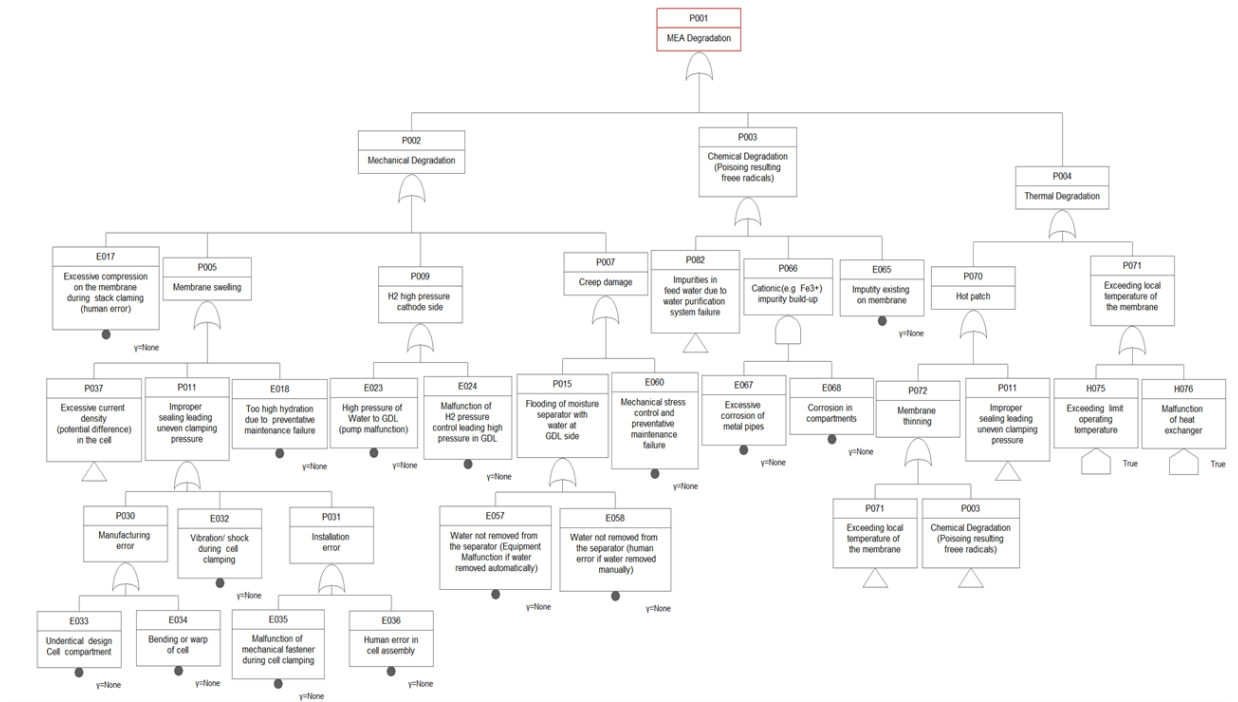


Figure A.1: MEA degradation qualitative screening, Fault Tree based on [11, 30, 80]

A2 - Fault tree

As specific probability data components are not available, the failure rates of basic events are not included(" y=None"), the events with triangular base are undeveloped events.

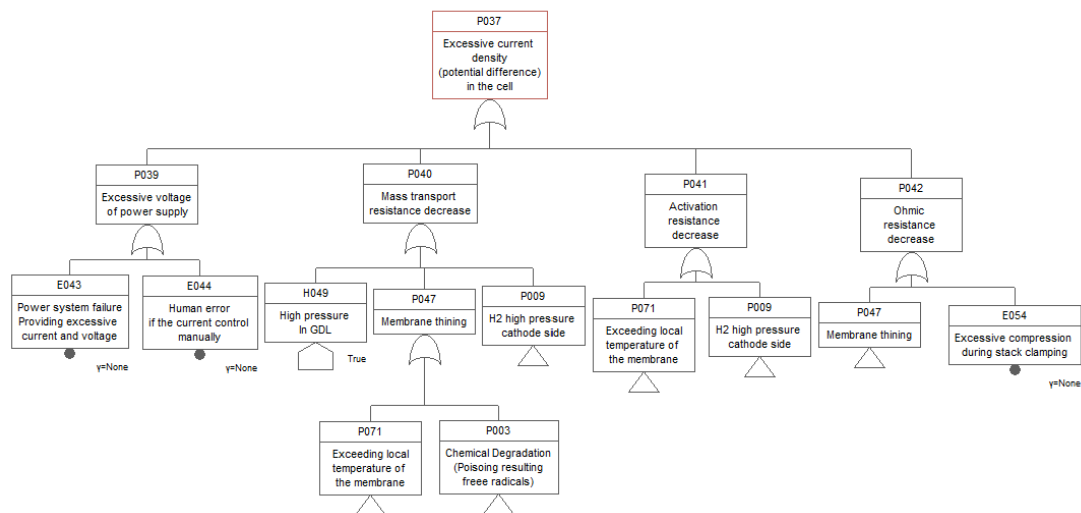


Figure A.2: Fault tree model top event excessive current density

B - PROPOSED FUZZY RULES

Fuzzy IF-THEN rules define the relationships between fuzzy input sets (frequency and severity of consequences) and the fuzzy output risk sets, forming the core of the fuzzy inference system used in the thesis.

	Rule	Weight	Name
1	If Frequency is Remote and Severity is Negligible then Risk is Negligible	1	rule1
2	If Frequency is Unlike and Severity is Negligible then Risk is Negligible	1	rule2
3	If Frequency is Very low and Severity is Negligible then Risk is Negligible	1	rule3
4	If Frequency is Low and Severity is Negligible then Risk is Low	1	rule4
5	If Frequency is Moderate and Severity is Negligible then Risk is Low	1	rule5
6	If Frequency is High and Severity is Negligible then Risk is Medium	1	rule6
7	If Frequency is Very High and Severity is Negligible then Risk is High	1	rule7
8	If Frequency is Remote and Severity is Negligible then Risk is Negligible	1	rule8
9	If Frequency is Unlike and Severity is Low then Risk is Low	1	rule9
10	If Frequency is Very low and Severity is Low then Risk is Low	1	rule10
11	If Frequency is Low and Severity is Low then Risk is Low	1	rule11
12	If Frequency is Moderate and Severity is Low then Risk is Medium	1	rule12
13	If Frequency is High and Severity is Low then Risk is Medium	1	rule13
14	If Frequency is Very High and Severity is Low then Risk is High	1	rule14
15	If Frequency is Remote and Severity is Moderate then Risk is Low	1	rule15
16	If Frequency is Unlike and Severity is Moderate then Risk is Low	1	rule16
17	If Frequency is Very low and Severity is Moderate then Risk is Medium	1	rule17
18	If Frequency is Low and Severity is Moderate then Risk is Medium	1	rule18
19	If Frequency is Moderate and Severity is Moderate then Risk is Medium	1	rule19
20	If Frequency is High and Severity is Moderate then Risk is Medium	1	rule20
21	If Frequency is Very High and Severity is Moderate then Risk is High	1	rule21
22	If Frequency is Remote and Severity is High then Risk is Medium	1	rule22
23	If Frequency is Unlike and Severity is High then Risk is Medium	1	rule23
24	If Frequency is Very low and Severity is High then Risk is Medium	1	rule24
25	If Frequency is Low and Severity is High then Risk is Medium	1	rule25
26	If Frequency is Moderate and Severity is High then Risk is Medium	1	rule26
27	If Frequency is High and Severity is High then Risk is High	1	rule27
28	If Frequency is Very High and Severity is High then Risk is High	1	rule28
29	If Frequency is Remote and Severity is Catastrophic then Risk is High	1	rule29
30	If Frequency is Unlike and Severity is Catastrophic then Risk is High	1	rule30
31	If Frequency is Very low and Severity is Catastrophic then Risk is High	1	rule31
32	If Frequency is Low and Severity is Catastrophic then Risk is High	1	rule32
33	If Frequency is Moderate and Severity is Catastrophic then Risk is High	1	rule33
34	If Frequency is High and Severity is Catastrophic then Risk is High	1	rule34
35	If Frequency is Very High and Severity is Catastrophic then Risk is High	1	rule35

Figure B.1: Fuzzy IF-THEN rules

C - RULE INTERFERENCE

Rule interference determines how fuzzy rules are applied and how the output fuzzy sets are aggregated and defuzzified to arrive at a crisp risk index.

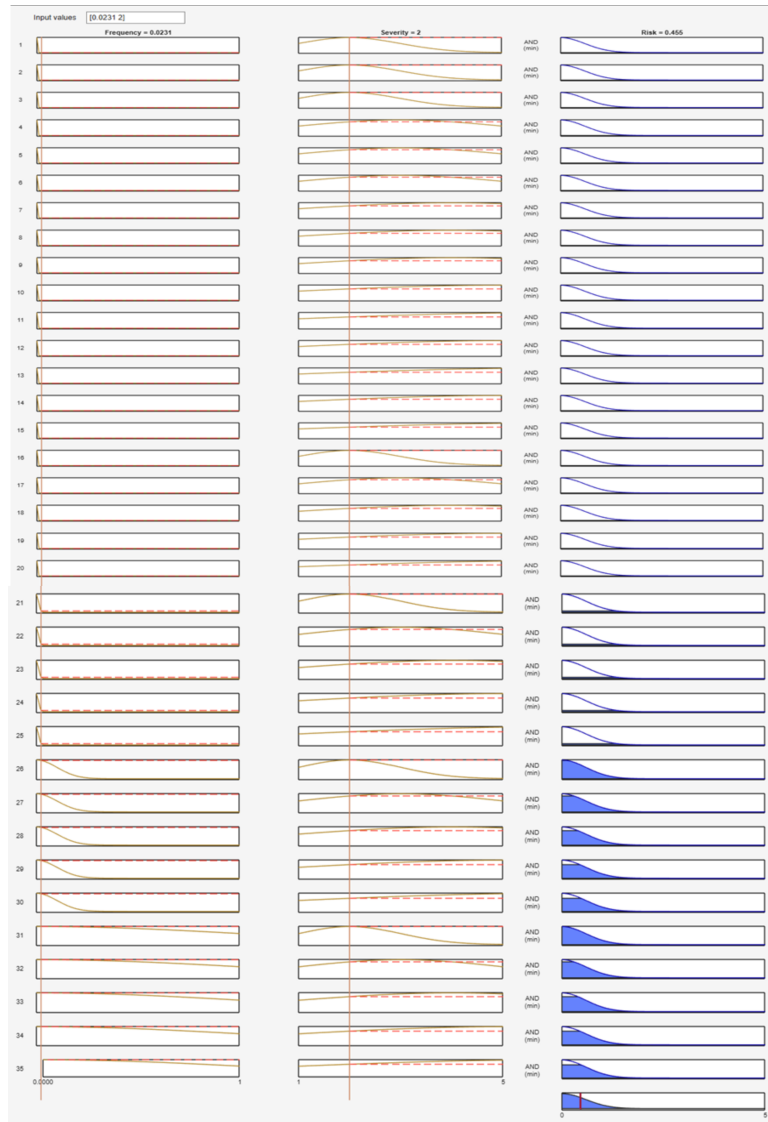


Figure C.1: Rule Interference

