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# Developing a Risk-Based Emergency Response Plan for PtX Technologies in Research Institutions: A Comparative Analysis with Industrial Best Practices


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## Abstract

As the world moves toward more sustainable energy solutions, Power-to-X (PtX) technologies, particularly those related to hydrogen production, have gained momentum as an effective way to store and utilize renewable energy. While large-scale industrial PtX facilities follow comprehensive risk management and emergency response protocols, research institutions that conduct similar operations do so under controlled laboratory environments with distinct safety measures tailored to their scale and purpose.

This study investigates how Aalborg University's Esbjerg Campus can develop a tailored, risk-based emergency response plan (ERP) for hydrogen-based Power-to-X (PtX) technologies. Recognizing that academic settings differ significantly from industrial plants in terms of safety structure, training, and regulatory obligations, the research compares the Esbjerg pilot site with the industrial Kassø PtX plant.

Through hazard identification (HAZID) in Table 6, Process Failure Mode and Effects Analysis (P-FMEA), and Bowtie Analysis, the study identifies critical risks, evaluates the institutional preparedness of the Esbjerg plant, and outlines a scalable ERP model aligned with best practices.

Findings reveal a need for stronger safety protocols, better training, and institutional alignment with national and EU directives. The final ERP proposal addresses these gaps and provides a replicable model for PtX-related hydrogen safety planning in research institutions.

Keywords: Power-to-X (PtX), Hydrogen Safety, Emergency Response Planning (ERP), Process FMEA, Bowtie Analysis, ATEX, Seveso III, Hydrogen Risk Assessment, Research Institutions, Industrial vs. Academic Safety.

## Preface

This report presents the findings of a master's thesis project conducted from February to June 2025 as part of a master's program in risk and safety management at Aalborg University. The study investigates emergency response planning for hydrogen-based Power to X (PtX) technologies in research institutions, with a particular focus on the planned PtX facility at Aalborg University's Esbjerg campus.

As Denmark expands its PtX infrastructure, particularly in Esbjerg, the need for comprehensive emergency response frameworks for hydrogen technologies becomes increasingly critical. Industrial PtX plants follow structured risk management protocols, and research institutions are also expected to adhere to standardized emergency preparedness plans. This thesis examines how emergency response strategies used in industrial PtX plants can be adapted for research environments to enhance safety, preparedness, and operational resilience.

This report is intended for:

- Researchers and academic institutions involved in the development of PtX technology.
- Risk and safety professionals specializing in hydrogen safety.
- Industry stakeholders involved in PtX plant operations and policy implementation.
- Government regulators and policymakers responsible for PtX safety standards and compliance.

### Report Structure

The report is structured to introduce key concepts gradually before presenting the research findings:

- Chapter 1 Introduction.
- Chapter 2 Methodology.
- Chapter 3 Context.
- Chapter 4 Regulations and Standards.
- Chapter 5 Stakeholder Analysis.
- Chapter 6 Risk Assessment.
- Chapter 7 Problem Analysis.
- Chapter 8 Discussion and Conclusion

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# Abbreviations

| | |
|---|---|
| ERP | Emergency Response Plan |
| ER | Emergency Response |
| PtX | Power to X |
| PPE | Personal Protective Equipment |
| OSHA | Occupational Safety and Health Administration |
| DNV | Det Norske Veritas |
| VR | Virtual Reality |
| SIL | Safety Integrity Level |
| LOPA | Layer of Protection Analysis |
| CCU | Carbon Capture and Utilization |
| PED | Pressure Equipment Directive |
| TPED | Transportable Pressure Equipment Directive |
| $LH_2$ | Liquid hydrogen |
| MEC | Microbial Electrolysis Cell |
| DAC | Direct Air Capture |
| RPN | Risk Priority Number |
| DOC | Direct Ocean Capture |
| P-FMEA | Process Failure Mode and Effects Analysis |
| HAZID | Hazard Identification |

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# 1.0 INTRODUCTION

The rising levels of carbon dioxide and the growing impact of global warming have driven the research community and industry to prioritize more efficient and environmentally friendly methods of generating power and heat (Figure 2). In response, the global shift toward sustainable energy solutions has intensified, with PtX technologies playing a significant role in this transition.

The Power to X technologies involve converting excess renewable electricity generated from sources such as wind turbines and solar farms into other forms of energy or valuable products (Figure 1). The "X" represents a variety of end uses, including power-to-hydrogen, power-to-methane, power-to-fuels, power-to-chemicals, power-to-ammonia, and even power-to-heat or power-to-food. These conversions enable the efficient storage and use of green energy for sustainable applications.

Hydrogen ($H_2$): Using renewable electricity, water is split into hydrogen and oxygen through electrolysis, producing green hydrogen.

Ammonia ($NH_3$): Green hydrogen is combined with nitrogen extracted from the air using the Haber-Bosch process, resulting in green ammonia.

Methanol ($CH_3OH$): Green hydrogen reacts with captured carbon dioxide in a catalytic process to create green methanol.

Synthetic Natural Gas (SNG): Methanation converts green hydrogen and carbon dioxide into methane, forming synthetic natural gas.

Fischer-Tropsch Fuels: A process known as Fischer-Tropsch synthesis transforms green hydrogen and carbon monoxide into liquid hydrocarbons, which can be used as synthetic fuels.

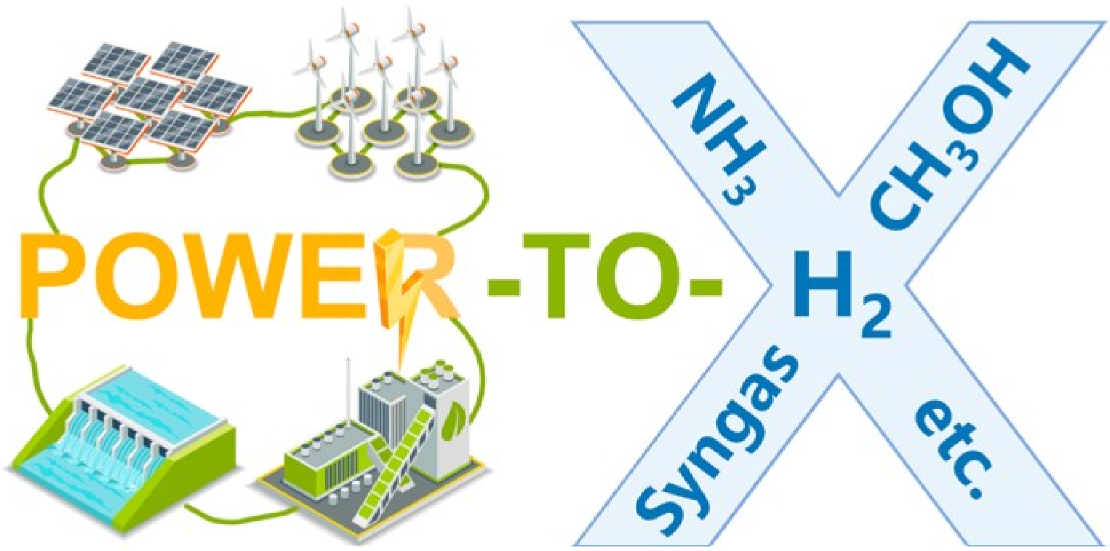


Figure 1: PtX byproducts

(byproducts resulting from PtX processes, such as ammonia, methanol, and other fuels)

Source: (Gong et al., 2021)

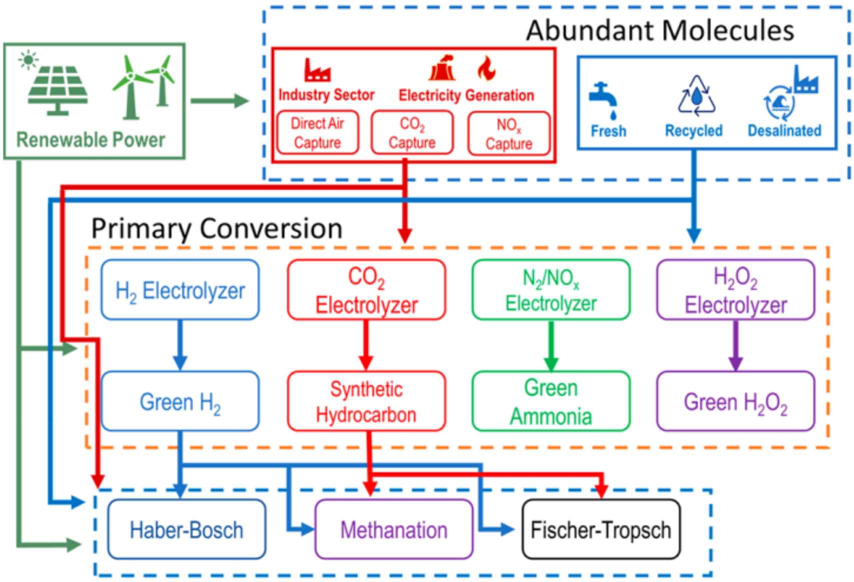


Figure 2: PtX Processess

(main process steps in PtX facilities: renewable energy input, electrolysis for hydrogen production, hydrogen storage, and downstream synthesis (e.g., methanol, ammonia).

Source: Daiyan et al., (2020)

Denmark is a global leader in renewable energy and has set ambitious goals to reduce greenhouse gas emissions by 70 percent by 2030, aiming for complete climate neutrality by 2050 (Klimaraadet, 2024). A key component of this transition is the advancement of Power to X technologies, particularly in hydrogen production, which is essential for decarbonizing heavy industry, shipping, and aviation. While PtX presents promising energy solutions, it also introduces new safety challenges requiring robust emergency response planning (*New Guideline for Safe and Faster Power to X*, n.d.). Aalborg University Esbjerg, a leading research institution, is crucial in advancing PtX technologies and developing best practices in risk management and emergency preparedness.

## The importance of PtX technologies

Power to X (PtX) technologies are crucial in integrating renewable energy sources into a sustainable energy system. By converting excess renewable electricity into hydrogen and other energy carriers, PtX offers a promising solution for energy storage and sector coupling (IRENA, 2017). With abundant offshore wind resources, Denmark is ideal for deploying PtX technologies. The government has set a target to develop 4 to 6 GW electrolysis capacity by 2030 (KEFM, 2022).

While PtX has significant potential, it also poses safety risks related to hydrogen storage, transport, and handling, which require comprehensive risk management strategies. Nevertheless, the advantages of PtX technologies, such as enabling decarbonization and improving energy storage, far outweigh the associated risks, paving the way for a brighter future for renewable energy (*New Guideline for Safe and Faster Power to X*, n.d.).

## Technological readiness level (TRL)

Denmark's PtX ecosystem is advancing through various stages of technological readiness. Electrolysis and carbon capture solutions are nearing full commercialization, with a technology readiness level (TRL) of 8-9. The Kassø plant, operational in March 2025, will utilize carbon capture technology to capture, purify, and liquefy bionic $CO_2$ to produce e-methanol (Miol & Miol, 2025).

On the other hand, emerging technologies such as Microbial Electrolysis Cells (MEC) are at a mid-development stage with a TRL of 4-6. Aalborg University Esbjerg employs several technological methods to produce hydrogen and other fuels. The facility utilizes Proton Exchange Membrane (PEM) technology alongside alkaline electrolysis for hydrogen production. Electrolysis uses renewable electricity to split water into hydrogen and oxygen. Other methods like Direct Air Capture (DAC), which captures carbon dioxide from the atmosphere, and Direct Ocean Capture (DOC), which extracts carbon dioxide from the ocean, are in use. The Microbial Electrolysis Cell technology employs an alkaline electrolyte, typically potassium hydroxide (KOH) or sodium hydroxide (NaOH), to split water ($H_2O$) into hydrogen ($H_2$) and oxygen ($O_2$) using electricity.

Despite these advancements, the widespread adoption of PtX faces technical and economic challenges, including infrastructure limitations and high production costs. Research institutions are critical in addressing these challenges through innovation and pilot projects. In recent years, research into PtX hydrogen technologies has seen significant growth, driven by government incentives, industry collaborations, and initiatives led by universities. Danish universities, including Aalborg University, are actively engaged in projects focused on improving electrolysis efficiency, carbon capture, and hydrogen storage. The rise in publications, patents, and funded projects related to PtX demonstrates the growing interest in optimizing hydrogen production and enhancing safety practices.

### Regulation

Universities engaged in PtX research not only comply with national and international safety regulations but also prioritize them. In Denmark, institutions adhere to the guidelines set by the Danish Working Environment Authority, which align with EU safety standards (Rigas, 2024).Furthermore, research involving hydrogen must follow industry best practices, including the Occupational Safety and Health Administration (OSHA) guidelines, where applicable (Rigas, 2024).

Universities provide a controlled yet dynamic setting for studying emergency planning related to PtX. While research institutions handle smaller quantities of hydrogen than large-scale industrial facilities, they face unique risks associated with experimental setups and academic environments (Schröder et al., 2015). As PtX hydrogen technologies evolve, ensuring safety in research institutions is crucial. This study will use universities as case studies to evaluate existing safety measures, identify gaps, and propose risk-based emergency response strategies. By comparing university protocols with industrial best practices, we aim to gain insights into enhancing safety frameworks within academic settings.

## 1.1 Motivation

This study is motivated by several important factors. Esbjerg is rapidly becoming a key center for PtX development, with large-scale projects driving the production of hydrogen-based fuels. As these facilities expand, it is increasingly crucial to ensure robust safety measures and effective emergency response planning to mitigate risks.

Aalborg University is also playing a significant role in PtX research, having already installed a PtX facility in partnership with Aalborg Port (Schou, 2025), and the Esbjerg campus is preparing to follow suit. The PtX plant in Esbjerg marks an increasing academic contribution to the advancement of PtX technology. However, research institutions operate differently from industrial facilities. Their experimental nature, frequent student involvement, and constantly evolving safety protocols create unique challenges in emergency response planning (Schröder et al., 2015).

Hydrogen presents significant safety concerns. With a flammability range between 4% and 75% and an extremely low ignition energy of just 0.02 mJ (Choi & Byeon, 2021), it is far more volatile than natural gas. This volatility necessitates specialized emergency response strategies to prevent and manage potential hazards (Choi & Byeon, 2021).

As Power to X technologies become more prevalent, the focus on safety protocols has intensified, particularly within industrial settings where comprehensive guidelines are well-established (New Guideline for Safe and Faster Power to X, n.d.). Resources such as the online Hydrogen Tools Portal emphasize that organizations working with hydrogen must develop and adhere to emergency response plans (Emergency Response | H2Tools | Hydrogen Tools, n.d.).

While limited published research specifically addresses academic institutions that handle or produce hydrogen fuel, several resources offer valuable guidance on safety practices applicable to such environments (Oneh, 2024).

## 1.2 Problem statement

Although more research institutions are adopting PtX technologies, their emergency response frameworks often focus on general laboratory hazards rather than the specific risks associated with hydrogen, creating gaps in preparedness and response effectiveness. Several sources though, offer valuable guidance on safety practices applicable to these environments.

This study explores three key questions:

1. How can research institutions create a risk-based emergency response plan tailored to PtX technologies, specifically Hydrogen?
2. What are the main differences between hydrogen safety frameworks in industry and academia?
3. How can risk assessment tools like FMEA and Bowtie Analysis enhance emergency preparedness?

## 1.3 Aim of the thesis

The above questions will guide the development of a comprehensive emergency response plan, integrating industrial safety principles with research institution-specific requirements.

The main goal of this thesis is to create a risk-based emergency response plan for PtX hydrogen technologies in the University campuses of Aalborg and Esbjerg. The aim is to align with industry best practices while considering the unique challenges of academic settings.

This study will:

1. Identify the key hazards and risks associated with hydrogen use in research institutions.
2. Compare emergency response strategies in industrial and academic environments.
3. Assess how risk analysis tools like FMEA and Bowtie Analysis can improve hydrogen safety planning.
4. Develop a structured emergency response framework based on best practices from industrial PtX facilities.
5. Recommend training programs and simulation-based safety exercises to strengthen emergency preparedness.

# 2.0 METHODOLOGY

This chapter outlines the research approach to developing a risk-based emergency response plan for hydrogen-based PtX technologies in research institutions. It thoroughly reviews best practices in emergency response for hydrogen PtX facilities, providing a foundation for the study. A comparative analysis is conducted between the PtX plant in Esbjerg and existing operational facilities to identify strengths, challenges, and areas for improvement. The researcher will utilize Risk Analysis tools like FMEA and Bowtie Analysis to evaluate explosion and leakage hazards, ensuring a data-driven understanding of potential risks. Based on these insights, a tailored emergency response framework is explicitly created for Esbjerg's PtX research environment, enhancing safety protocols and preparedness measures.

## 2.1 Research design and approach

The research employed a mixed-method approach, integrating qualitative and quantitative strategies to comprehensively understand safety challenges. An initial systematic literature and regulatory review examined key international standards such as ISO/TR 15916:2015, the NFPA 2 Hydrogen Technologies Code, the ATEX Directive, and the Seveso III Directive. National documents, including Denmark's PtX Strategic Action Plan and guidelines issued by Brand & Sikring, were also analyzed. This review identified critical regulatory requirements and best practices for hydrogen safety and emergency planning, establishing a foundation for subsequent analysis.

A comparative case study was conducted to benchmark the Esbjerg facility against existing operational PtX projects, particularly the Kassø PtX plant. The study evaluates emergency preparedness levels, regulatory compliance practices, risk management procedures, and incident handling strategies through this comparison. The findings highlight best practices and areas needing additional attention, informing the development of a more targeted emergency response plan for research environments.

To quantify potential risks, a Process FMEA was conducted, modeling hydrogen leakage and explosion scenarios based on available data and conservative assumptions. Parameters such as equipment failure rates, gas dispersion behavior, ignition probabilities, and overpressure impacts were assessed.

Given the limited operational information for the Esbjerg facility, data collection primarily relied on secondary sources. Key sources included technical documentation, public project disclosures, best practice guidelines from DNV (2023), national strategic documents, several discussions, and a walk-through with an academic staff member responsible for the PtX test site. Additional materials encompassed international safety standards, European regulations, scientific research on hydrogen incidents, and laboratory accidents (e.g., Zhang et al., 2020; Zheng et al., 2023), as well as guidelines from organizations such as the European Industrial Gases Association (EIGA).

## 2.2 Physical & Operational Boundaries

| Boundary Type | Research scope |
|---|---|
| Technology Boundary | Electrolysis systems (PEM, Alkaline, MEC)<br>Hydrogen storage & handling<br>Carbon capture units (DAC/DOC)<br>Synthesis systems (e.g., e-methanol) |
| Process Boundary | Hydrogen production process<br>Emergency scenarios (e.g., gas leaks, fire)<br>Laboratory-scale and pilot plant procedures |
| Geographic Boundary | Danish regulatory context<br>Campus Esbjerg test site<br>Aalborg Port pilot site<br>Neighbours to the Plants |
| Regulatory Boundary | Seveso III Directive (if applicable)<br>ATEX Directives<br>Danish Risk Order<br>Lab-specific procedures (work permits, access control) |
| Safety Scope | Risk assessment procedures (HAZID, FMEA)<br>Gas detection, ventilation, and emergency shutdown<br>Regular drills<br>Access and permit systems<br>Staff training/certification |

Table 1: System boundaries (Outlines the scope of analysis)

# 3.0 SETTING THE CONTEXT

PtX technologies convert surplus green electricity, often generated from wind and solar energy, into alternative energy carriers such as hydrogen, ammonia, or synthetic fuels. This process holds significant potential for reducing carbon emissions (Suleman & Nasir, 2023). It is increasingly crucial in countries like Denmark, where the energy transition is a national priority (KEFM, 2021).

However, because hydrogen is highly flammable and has a wide explosive range, risk management and emergency response are crucial components of the safety process.

To investigate whether emergency response plans used in industry can be adapted for academic settings, this chapter examines Denmark's national safety protocols, including the Regulatory Guide for Establishing PtX Plants and guidelines from the Danish Safety Technology Authority and Brand & Sikring, which emphasize streamlining safety procedures and preparing for emergencies.

Insights from DNV's Managing the Scale-Up of PtX (2023) highlight tools such as Quantitative Risk Assessment (QRA), Safety Integrity Level (SIL), and Layer of Protection Analysis (LOPA) as best practices for hazard mitigation.

Despite the increasing volume of research, a significant gap persists in the literature that directly addresses emergency response planning in academic settings. Most guidance assumes large-scale commercial operations rather than smaller, evolving research environments (Schröder et al., 2015).

## 3.1 Research on PtX technologies

Power to X involves various technologies that use electricity to produce hydrogen. The hydrogen produced is often referred to as 'green hydrogen' when sourced from renewable resources. This can serve as a clean fuel for transportation and industrial applications or be further processed into different fuels, chemicals, and materials. By enabling the conversion of renewable energy into versatile energy carriers, PtX plays a crucial role in building a more sustainable energy system, promising a bright future for clean energy (IRENA, 2017).

When hydrogen combines with nitrogen from the air, it produces ammonia, a compound with numerous applications. Hydrogen can also react with carbon in large industrial processes under high pressure and temperature to create various fuels and materials, including methane, methanol, gasoline, diesel, aviation fuel, and even plastics that have properties identical to their fossil-based counterparts. This process, known as Carbon Capture and Utilization (CCU), enables carbon to be sourced from exhaust gases emitted by waste-to-energy plants or biogas facilities. When the captured carbon comes from biomass (biogenic carbon), it is considered climate-neutral under UN calculation methods. Consequently, PtX fuels produced using biogenic $CO_2$ can be classified as $CO_2$-neutral overall.

Another method of obtaining carbon for PtX fuel production is direct air capture (DAC), which extracts $CO_2$ directly from the atmosphere. While this technology has significant potential to support the green transition in the long run, it remains in the early stages of development and must become more cost-effective (Figure 3, KEFM, 2021). Since biogenic carbon is a limited resource, atmospheric carbon capture provides a virtually unlimited alternative, making it a promising solution for sustainable fuel production in the future (KEFM, 2021).

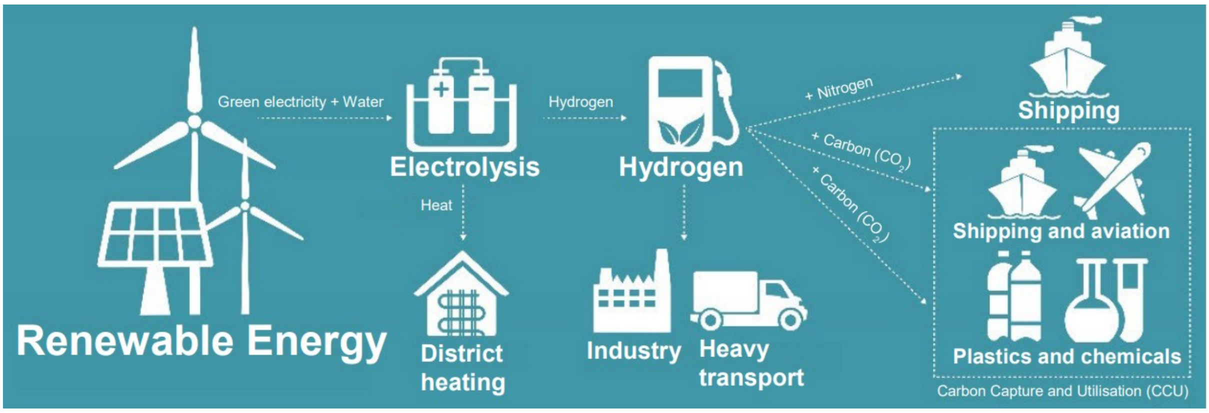


Figure 3: The entire production chain from renewable energy to the production of fuels.

Source: (KEFM, 2021)

## 3.2 Safety hazards in hydrogen production, handling and storage

Although recognized as a clean energy carrier, hydrogen poses several safety risks during its production, handling, storage, and transportation. These risks arise from its unique physical and chemical properties, such as its high flammability, low ignition energy, and wide flammability range. This report highlights the main safety concerns associated with hydrogen systems and reviews the mitigation measures outlined in Rigas (2024).

### Flammability and explosivity

Hydrogen creates flammable or explosive atmospheres when mixed with air. The ATEX Directive 2014/34/EU classifies areas where hydrogen is handled into hazardous zones (Zone 0, 1, and 2) (Rigas, 2024). One of the biggest concerns with hydrogen is that it can ignite at concentrations ranging from 4% to 75% in air (Choi & Byeon, 2021), making it highly combustible. Additionally, it requires an extremely low ignition energy of just 0.02 mJ, so even a small spark can trigger ignition (Tan et al., 2022). Furthermore, hydrogen burns rapidly, and flames are nearly invisible and colorless, making fires difficult to detect and extinguish (Gov, n.d), while also producing intense heat that poses risks to people and equipment.

### Material degradation and structural failure

Hydrogen's lightweight nature helps reduce certain risks, as it disperses quickly in open spaces, preventing dangerous accumulations (Dutta, 2014). However, its high permeability poses a challenge because hydrogen molecules can easily seep through materials, increasing the risk of leaks (Koohi-Fayegh & Rosen, 2019). Some metals exposed to hydrogen over time can experience embrittlement, weaken their structure, and potentially lead to failures in pipelines and storage tanks (Rasul et al., 2022), making the use of hydrogen-compatible piping and regular inspections essential.

| Items | Distance (M) |
|---|---|
| Technical and unoccupied buildings | 10 |
| Occupied buildings | 20 |
| Other LH2 fixed storage | 1.5 |
| Other LH2 tanker | 3 |
| Flammable gas storage | 8 |
| Open flame, smoking, welding | 10 |
| Public establishments | 60 |
| Overhead power lines | 10 |
| Railroads, property boundaries | 10 |

Table 2: Recommended safety distance for Liquid hydrogen

Source: EIGA. (10 June 2024). EIGA: European Industrial Gases Association. https://www.eiga.eu/.

## Venting Systems and Separation Distances

Proper venting systems are essential for safely discharging excess hydrogen. Based on hydrogen cloud dispersion modelling, the recommended separation distances include 10 meters from technical buildings, 20 meters from occupied buildings, 8 meters from flammable gas storage areas, 60 meters from public establishments, and placing vents at least 7 meters above ground level or at the storage tank level. These guidelines create a buffer zone that minimizes potential hazards (Table 2, EIGA, 2024).

## Human error

Operators are crucial, as they are the heart of safe hydrogen system management. Their role is not only important, but also integral. Mistakes can happen, but with their expertise and adherence to standard operating procedures, we can prevent hazardous conditions, equipment failures, and safety incidents.

## High pressure and cryogenic risks

Liquid hydrogen ($LH_2$) is stored in cryogenic tanks at extremely low temperatures (-253°C) (Abe et al., 2019). These extreme conditions can lead to leaks, ruptures, and breakage of containment materials. These tanks must be vacuum-insulated and made from materials resistant to hydrogen embrittlement (Ramirez-Vidal et al., 2022). It, therefore, requires highly specialized equipment to maintain these extreme conditions safely (Koohi-Fayegh & Rosen, 2019). To handle vaporization pressure, they have pressure-relief devices and venting systems (H. Wang et al., 2022). However, $LH_2$ storage introduces hazards such as rapid vaporization during spills, which can lead to the formation of flammable vapor clouds (Rigas & Sklavounos, 2005). The cryogenic nature of $LH_2$ also poses a risk of frostbite upon direct contact. Also, when $LH_2$ is spilled onto asphalt or poorly ventilated areas, air liquefaction and oxygen enrichment can increase fire hazards. As a result, flame arrestors and controlled venting systems are crucial for safe handling (Rigas & Sklavounos, 2005).

Compressed hydrogen is often stored in high-pressure cylinders or vessels at pressures up to 700 bar (Elberry et al., 2021). This method requires strict compliance with the Pressure Equipment Directive (PED) and the Transportable Pressure Equipment Directive (TPED) to ensure vessel integrity (Rigas, 2024). One of the primary hazards associated with compressed hydrogen is leakage, as hydrogen molecules are small enough to escape through microscopic openings. Early leak detection measures are crucial in preventing such leaks from escalating into safety incidents.

Beyond storage challenges, hydrogen poses several safety risks. Explosion hazards are a significant concern, especially in confined spaces where hydrogen can form dangerously reactive mixtures with air (Chang et al., 2022). If ignited, it can cause rapid combustion (deflagration) and generate pressure waves, resulting in severe structural damage (Johnravindar & Selvakumar, 2024). Detecting hydrogen leaks is another challenge, as the gas is both colorless and odorless, making it difficult to spot without specialized sensors (Gov, n.d.). In enclosed areas, undetected hydrogen can accumulate to hazardous levels, increasing the risk of fire or explosion. However, in controlled environments, some studies confirm the reduction of these fires and explosives (Li et al., 2018).

Aside from fire and explosion hazards, exposure to hydrogen can pose health risks. When present in high concentrations, it can displace oxygen, leading to asphyxiation (General Hydrogen Safety Facts, 2018). Additionally, contact with liquid hydrogen can cause severe cold burns and frostbite (Liquid Hydrogen Properties and Behaviors | H2Tools | Hydrogen Tools, n.d.).

## 3.3. Best Practices in industry and academic institutions

Emergency response (ER) is one of the four phases in emergency management, which include mitigation, preparedness, response, and recovery (Farahani et al., 2020). ER consists of actions and measures taken to reduce the impact of an emergency, such as a fire, explosion, or the release of toxic materials, and to protect people, the environment, and the process facility (Emergency Response Planning Software - Handling (Hazardous Materials, n.d.). ERP is thus a set of written procedures for managing emergencies that minimize the impact of the event and aid in recovery (ETool: Evacuation Plans and Procedures - Emergency Action Plan | Occupational Safety and Health Administration, n.d.). These written procedures take the form of legislation, directives, standards, or guidelines as outlined in Table 3.

Emergency response planning in industrial facilities is a critical aspect of safety management, especially for those involved in high-risk operations like PtX technologies. Effective industrial emergency response frameworks necessitate a systematic approach that incorporates risk management, stakeholder engagement, and continuous improvement. Essential practices include comprehensive risk assessments to uncover potential hazards, formulating detailed response protocols, and conducting regular training and simulation exercises for personnel (Longo et al., 2018). Importantly, involving stakeholders (Figure 4 and 5), such as local authorities and community members, is not merely a practice but a way to ensure a coordinated response across multiple sectors, making everyone feel included and part of a broader effort (Bioeconomy, 2020). Furthermore, continuous improvement through feedback loops and refining plans based on drills and incidents is crucial for adapting to emerging risks (Davis et al., 2017).

Razak et al. (2018) emphasize that effective response planning for chemical, radiological, or biological emergency events can be considered at three levels. At the organizational level, there should be policies and procedures to guide the response, such as clear protocols for hydrogen release scenarios.

At the technological level, Razak et al. (2018) explain that it can include decontamination, communication, and security. Additionally, simulation and virtual reality (VR) technologies can be integrated and have proven highly effective in enhancing the training and skill development of emergency responders. These advanced tools enable experiential learning, immersing trainees in realistic, high-pressure scenarios that closely replicate actual emergency situations (Cohen et al., 2013, Davis et al., 2016). By engaging in these interactive simulations, responders can refine their decision-making abilities, improve situational awareness, and develop effective stress management strategies. Research demonstrates that these methods are particularly effective in reinforcing procedural knowledge, ensuring that responders can efficiently apply protocols in dynamic and unpredictable environments (Davis et al., 2016). Furthermore, VR-based training provides a safe, controlled setting for emergency personnel to practice complex operations without the risks associated with real-world drills. This not only enhances response efficiency but also improves team coordination and adaptive critical factors in high-stakes emergency situations. Therefore, combining simulations and VR technologies represents a transformative approach to emergency response training, instilling confidence and readiness in real-world crisis scenarios.

At the individual level, attention is focused on the willingness to respond, PPE, knowledge, and competence of personnel. The role of personnel is crucial. They should be well-trained, equipped with appropriate PPE, and capable of handling emergencies. Training plays a vital role in building high-performing emergency response systems that ensure the seamless integration of personnel, equipment, infrastructure, and technology. Effective training programs enable emergency response teams to operate efficiently, reducing risks and enhancing overall preparedness. A comprehensive training framework should adopt a collaborative strategy, providing tailored training for each team member's specific roles and responsibilities. This targeted approach guarantees that all personnel acquire the necessary skills, knowledge, and decision-making capabilities to respond effectively to emergencies. Additionally, structured training improves teamwork and situational awareness, which is essential for a coordinated response. By simulating real-world emergencies, team members can develop quick-thinking abilities, practical communication skills, and the capacity to adapt under pressure. This ensures that response teams function cohesively, reducing response times and improving outcomes during critical situations. Ultimately, a well-designed training strategy enhances emergency preparedness by fostering a culture of continuous improvement and resilience in response systems.

## ERP for operating PtX Hydrogen plants

Due to the significant risks associated with hydrogen, even as a clean and efficient energy carrier (DNV, 2023), PtX facilities require tailored ERP for production, storage, and use to ensure operational safety. The following key elements should form the basis for a robust ERP for a PtX facility.

HAZID is the first step in ensuring that all critical risk factors are recognized and addressed proactively. Conducting a thorough risk assessment means identifying potential hazards associated with hydrogen and other chemicals involved in PtX processes.

Secondly, create step-by-step actions for different emergency scenarios, such as gas leaks, fires, and explosions. These actions follow industry best practices and regulatory standards to ensure a swift and coordinated response during emergencies.

Regular training programs and simulation exercises should help personnel become familiar with emergency procedures, enabling them to respond effectively in high-pressure situations (Cohen et al., 2013). Realistic drills and scenario-based training improve situational awareness, decision-making, and team coordination, which are essential for minimizing risks and preventing escalation.

DNV 2023's risk assessment framework offers structured methodologies for hazard identification, enhancing safety culture, and risk communication. These established safety protocols, based on Quantitative Risk Assessments (QRA) and fire/explosion studies (DNV, 2023), are designed for industrial hydrogen PtX facilities. Examples include facilities that implement measures like blast walls to mitigate explosion impacts, ventilation strategies to prevent gas buildup, and the separation of critical equipment to reduce fire risks.

## ERP for research institutions handling hazardous materials

The laboratory environments in academic research institutions often include a diverse group of individuals, such as students, faculty, and visiting researchers, working with hazardous chemicals. While handling hydrogen, they face distinct safety challenges due to varying levels of safety training and laboratory experience (Schröder et al., 2015). This diversity can heighten the risk of procedural errors and unsafe practices.

The need for robust emergency response planning in academic settings is further emphasized by findings from accident studies. For instance, in the study by Zhang et al. (2020), a Bayesian network-based risk assessment identified unsafe behaviors of laboratory personnel as significant contributors to gas leakage incidents in school laboratories. Additionally, the concentration of toxic gases was found to be a key factor influencing the severity of accidents, highlighting the importance of early detection and preventive controls (Zhang et al., 2020). Moreover, an analysis of over 850 recorded laboratory accidents revealed that explosions accounted for a significant proportion of incidents involving hazardous chemicals. This study indicated that the absence of trained supervisors, along with the use of specialized equipment and reactive chemicals, significantly increased the likelihood of severe outcomes. These findings suggest that universities must invest in both operational oversight and incident monitoring systems to enhance real-time response capabilities.

In a complementary perspective, Abedsoltan and Shiflett (2024) conducted a focused review of laboratory risk mitigation strategies, reinforcing the importance of emergency planning as part of a broader safety management framework. Their review identified risk assessment, hazard identification, emergency preparedness, regulatory compliance, and continuous safety training as cornerstones of an effective emergency response system. Key recommendations include forming dedicated emergency response teams, developing action plans tailored to laboratory-specific risks, and incorporating role-based safety training. Their comparative analysis between academic and industrial laboratories also emphasized the variability in safety cultures and resource allocation, suggesting that academic labs often fall short in documentation, consistency, and audit practices compared to their industrial counterparts.

# 4.0 REGULATION AND STANDARDS

Due to their unique physical and chemical properties, regulatory frameworks are essential for ensuring the safe use of hydrogen-based Power to X technologies. To manage these risks, international, regional, and national authorities have established guidelines that encompass every stage of hydrogen use, from production and storage to transportation and application in industrial and research settings (Rigas, 2024), as shown in Table 3.

National and EU-level policy frameworks have been crucial in shaping Denmark's strategy for renewable energy and grid modernization. The EU Green Deal and Denmark's national strategies have created a solid regulatory foundation for decarbonizing the energy sector. These policies have provided valuable incentives and subsidies for renewable energy projects and emerging technologies (European Commission, 2024).

Despite this progress, gaps remain, particularly regarding newer technologies like PtX. Regulatory inconsistencies and limited financial support are key barriers to faster adoption and integration of such innovations.

Denmark implements EU directives in national regulations through institutions such as the Danish Working Environment Authority (Arbejdstilsynet), which focuses on occupational safety, and the Danish Energy Agency (Energistyrelsen), responsible for technical approval and project permitting, particularly for PtX pilot projects. Denmark's PtX strategy incorporates risk-based permitting and environmental assessments, especially for new large-scale hydrogen facilities.

Regulations governing the risks associated with flammable gases, including hydrogen, primarily fall under the ATEX Directives and the Seveso III Directive. These regulations aim to prevent major accidents and mitigate their impact on people, infrastructure, and the environment. They are divided into several categories, each with a different legal authority. The laws established by the European Union require member countries to achieve specific goals while allowing them the flexibility to decide how to implement those goals within their legal frameworks (Table 3).

## 4.1 Directives

### *1. ATEX Directives (2014/34/EU and 1999/92/EC)*

The ATEX Directive 2014/34/EU sets the minimum safety requirements for equipment and protective systems in potentially explosive atmospheres (ATEX). Hydrogen forms explosive mixtures with air, so this directive applies to equipment and protective systems (PED 2014/68/EU) designed for ATEX environments, safety, and control devices that ensure the safe functioning of hydrogen-related equipment and components incorporated into ATEX-certified systems.

Part of the ATEX Directive 2014/34/EU) imposes safety obligations on employers to prevent the formation of explosive hydrogen-air mixtures whenever possible, eliminate potential ignition sources in areas where an ATEX atmosphere may form, and minimize explosion consequences through proper safety measures.

Employers must also conduct risk assessments to evaluate the likelihood of an explosive hydrogen-air atmosphere forming, the presence of ignition sources, and the potential impact of an explosion on personnel and infrastructure.

Workplaces handling hydrogen must classify areas based on ATEX risk levels marked as zone 0 for continuous or frequent presence of an explosive atmosphere, zone 1 for an ATEX atmosphere likely to occur occasionally during regular operation, and zone 2 for an ATEX atmosphere unlikely to occur during regular operation and, if present, lasts only briefly (Directive—1999/92 - EN—ATEX Directive—EUR-Lex, n.d.).

### *Pressure Equipment Directive (2014/68/EU) & TPED*

Research institutions that work with electrolysers or store compressed hydrogen must follow key EU safety regulations to handle pressurized systems safely.

The Pressure Equipment Directive (PED 2014/68/EU) covers the design, construction, and operation of stationary pressure equipment, such as hydrogen storage tanks connected to electrolysers.

The Transportable Pressure Equipment Directive (TPED) applies to portable hydrogen containers and ensures safety during handling and internal movement.

These regulations play a vital role in ensuring that hydrogen is safely contained, which is essential when developing emergency scenarios and conducting risk assessments for effective response planning (Directive—2014/34 - EN—ATEX Directive—EUR-Lex, n.d.).

### *Machinery Directive (2006/42/EC)*

The Machinery Directive (2006/42/EC) focuses on equipment safety with moving parts or potential ignition sources common in machines that generate and distribute hydrogen.

For university labs working with PtX systems, this directive helps ensure that mechanical safety is built into the design of their setups, reducing the risk of accidents during operation (Directive - 2014/34 - EN - ATEX Directive - EUR-Lex, n.d.).

### *Worker Safety Directives (98/24/EC & 1999/92/EC)*

The Worker Safety Directives, such as 98/24/EC and 1999/92/EC, set the minimum safety standards for workplaces where chemical agents are used and explosive atmospheres are at risk.

These directives are especially relevant in research institutions, where students and researchers frequently work with hydrogen and similar materials. They emphasise the importance of having clear safety procedures, proper training, and protective measures in place, all of which are essential elements of effective emergency planning (Directive—1999/92 - EN—ATEX Directive—EUR-Lex, n.d.).

### *Directive 89/391/EEC (OHS)*

Directive 89/391/EEC (OHS) provides legislative requirements for employers to ensure that their workers are safe while performing their work (*Directive 89/391 - EN—EUR-LEX*, n.d.).

### *Directive 2014/35/EU*

Directive 2014/35/EU directly addresses safety concerns related to the operation of high-voltage electrical equipment, such as transformers for a hydrogen plant (Directive 2014/35 - EN — Low Voltage Directive — EUR-LEX, n.d.).

### 2. Seveso III Directive (2012/18/EU)

The Seveso III Directive is a key regulation for industrial sites handling hazardous substances, including hydrogen. This directive mandates specific requirements for risk management, emergency planning, and accident prevention. These measures are particularly stringent for facilities storing large amounts of hydrogen or other flammable gases.

The Seveso Directive is also known as the Risk Order in Denmark. It is a pivotal piece of legislation that guides emergency response planning for facilities handling hazardous materials, including hydrogen. It mandates sites storing hydrogen above specific thresholds to conduct Quantitative Risk Assessments (QRAs), maintain detailed safety documentation, and prepare both internal and external emergency response plans. The directive specifically applies to facilities with 5 tonnes of hydrogen (Column 2 level), and more stringently, those with 50 tonnes or more (Column 3 level) vejprojecter.dk.

## 4.2 International Standards

These are nonbinding unless adopted by a country or organisation.

### ISO/TR 15916:2015

The ISO/TR 15916:2015, a comprehensive document, provides safety guidelines for handling hydrogen in its gaseous and liquid forms, as well as in alternative storage methods like hydrides. It outlines key safety concerns, potential hazards, and risks while detailing the properties of hydrogen relevant to safety, ensuring that you are well-informed and prepared for any situation.

### ISO 19880-1:2020

This international standard primarily outlines safety and performance requirements for hydrogen refueling stations, covering key areas such as delivery, storage, and compression. Although it is mainly focused on on-site operations, its recommendations for transportation, particularly the loading and handling of hydrogen onto trucks, offer valuable guidance. The standard emphasizes the use of secure transfer connections, including leak-tight seals and proper grounding, to minimize the risk of ignition or leaks during loading and unloading. It also establishes pressure control procedures for compressors and storage systems to maintain hydrogen stability during high-pressure transfers, which is crucial for safe and efficient long-distance transport.

### ISO/TC 197/WG 32

ISO/TC 197/WG 32, a specialized working group under the International Organization for Standardization's Technical Committee 197, is a key player in the development of safety and performance standards specific to liquefied hydrogen ($LH_2$) systems. The group's focus on hydrogen technologies and its responsibility for developing international standards make it a significant contributor to the growing infrastructure surrounding hydrogen production, storage, and transport. These standards cover equipment standardization, operational safety protocols, regulatory approvals, stakeholder assurance, and support for infrastructure development.

### ANSI/AIAA G-095A-2017

The ANSI/AIAA G-095A-2017 guideline, though originally developed for aerospace applications, is highly relevant to PtX facilities, where hydrogen is produced, stored, and used at scale. It provides comprehensive safety guidance across all phases of PtX operations, offering practical and applicable advice on hydrogen’s unique hazards, safe system design, materials compatibility, ventilation, leak detection, and emergency preparedness.

This guideline emphasizes the importance of risk assessment tools like HAZOP, FMEA, and QRA to proactively identify and manage potential hazards. As PtX technologies play an increasingly vital role in global decarbonization efforts, this standard helps ensure both safety and public trust. Compared to other international standards, it offers more detailed technical support for high-pressure and critical hydrogen systems, making it a valuable reference for large-scale PtX projects (*Guide to Safety of Hydrogen and Hydrogen Systems (ANSI/AIAA G-095A-2017)*, 2017).

### EIGA 06/19 Regulation

The EIGA 06/19 regulation, while focusing primarily on industrial liquid hydrogen infrastructure, offers directly transferable best practices for emergency planning such as alarm protocols, evacuation instructions, isolation of hydrogen source, public hazard alerts and engagement of emergency services. This regulation underscores the importance of safety measures, providing reassurance about the robustness of the safety protocols in place.

## 4.3 Industry Codes and best practices

## NFPA 2: Hydrogen Technologies Code

The NFPA 2 Hydrogen Technologies Code is a comprehensive international standard that defines the safety requirements for producing, storing, transferring, and using hydrogen in both gaseous ($GH_2$) and liquid ($LH_2$) forms. Developed by the National Fire Protection Association (NFPA), its primary goal is to establish fundamental safety measures across various hydrogen applications, including stationary systems, portable units, and hydrogen-powered vehicles.

Applying the principles outlined in NFPA 2 is essential for PtX research facilities due to the unique risks associated with hydrogen use. The physical properties of hydrogen, such as its high flammability and small molecular size, require careful handling and control strategies to prevent accidents and ensure safe operation.

One primary focus of the code is to mitigate risks associated with hydrogen release and asphyxiation. NFPA 2 emphasizes the importance of limiting the quantity of hydrogen stored indoors, installing reliable hydrogen detection systems, maintaining proper ventilation, and implementing automatic shutdown and alarm protocols. These measures are designed to swiftly identify and address leaks, thereby minimizing the risk of dangerous accumulations in enclosed spaces.

The code also addresses the dangers of overpressure and explosion hazards. It mandates pressure relief devices and establishes the minimum safe distance between the equipment and occupied areas. Additionally, it emphasizes regular maintenance to prevent equipment failures. Moreover, NFPA 2 guides the safe venting of hydrogen into the atmosphere and stresses the importance of eliminating ignition sources in critical areas.

Lastly, NFPA 2 provides comprehensive design and construction standards for hydrogen systems. These include specifications for piping materials, vent system configurations, and buffer storage requirements, all aimed at ensuring the mechanical integrity and operational safety of hydrogen installations.

## DNV Guidelines

The report "Managing the Scale-Up of PtX" (2023) provides risk management tools like QRA, LOPA, and SIL tailored for hydrogen projects.

Guidelines from Brand & Sikring and the Danish Energy Agency

Provides strategic documents that, while non-binding, are designed to harmonize safety planning and approval processes across municipalities.

Directive 2014/94/EU on the Deployment of Alternative Fuels Infrastructure (*Directive - 2014/94 - EN - EUR-LEX, n.d.).*

## Other relevant standards

ISO/IEC 80079 Series - Explosive atmospheres, Equipment and protective systems (Explosives. nd).

DS/EN 60079-29-1:2016/A1:2022- Eksplosive atmosfærer – Del 29-1: Gasdetektorer – Ydeevnekrav for detektorer til brandbare gasser.

ISO 31000 - Risk management (Risk guidelines)

| Category | Kassø Facility | Aalborg Port PtX Site | Campus Esbjerg PtX Site |
|---|---|---|---|
| Electrolysis Activity | ✅ 52 MW, active production | ✅ 120MW electrolysis | ✅ PEM, alkaline, and microbial electrolysis |
| Hydrogen Handling | ✅ 52MW electrolysis<br>✅ 8,000 tonnes/year, for e-methanol synthesis | ✅ 75000 tonnes/year (e-methanol) | ✅ Lab-scale hydrogen handling in containers |
| Seveso III Compliance | ✅ Yes (≥ 50 tonnes (upper tier Seveso site) | ✅ Yes (≥ 50 (upper tier Seveso site) | ❌ Not applicable at current scale |
| ATEX Directive Compliance Machinery Directive | ✅ Yes | ✅ Yes | ✅ Yes |
| ATEX Directive Compliance Pressure Equipment Directive (PED) | ✅ Yes | ✅ Yes | ✅ Yes |
| ATEX Directive Compliance Worker safety | ✅ Permit secured | ✅ Yes | ✅ Yes |
| NFPA 2: Hydrogen Technologies Code | ✅ Cannot verify | ✅ Cannot verify | ✅ Yes |
| ANSI/AIAA G-095A-2017 | ✅ Permit secured | | ✅ Yes |
| ISO/TR 15916:2015 | ✅ Permit secured | ✅ Cannot verify | ✅ Yes |
| EIGA 06/19 Regulation | ✅ Permit secured | ✅ Yes | ✅ Yes |
| DNV Guidelines | ✅ Permit secured | ✅ Yes | ✅ Yes |
| Emergency Response Plan (ERP) | ✅ Yes | ✅ Yes | ✅ In progress |
| Access Controls & Risk Permits | | ✅ Planned controlled access for companies | ✅ Standard lab access + experiment permit. |
| Institutional Responsibility | ✅ Commercial operator (European Energy) | ✅ Shared between university and port authorities | ✅ Academic & technical staff oversee lab site |
| Public Safety Zoning | ✅ Permit secured | ✅ Cannot verify | ✅ Fire access and spacing addressed in layout<br>✅ Yellow zones reserved for emergency vehicle access |

Table 3: Comparative legislative analysis of cases

(Identify gaps and opportunities to align research site safety with industrial standards).

# 5.0 STAKEHOLDER ANALYSIS

Hydrogen, a historical player in the energy sector for over two centuries, should not be underestimated. Its unique properties make it a promising and sustainable fuel source. However, for hydrogen to truly serve as a clean alternative to heavy fossil fuels, it must be widely adopted across key sectors such as transportation, construction, and power generation (IEA, n.d.).

As previously outlined, industries that work with hydrogen are subject to strict and specific regulatory frameworks. These regulations, designed to ensure safety and reliability, involve a variety of stakeholders, (Table 5) which will be identified and discussed in the following section.

## 5.1 Stakeholders

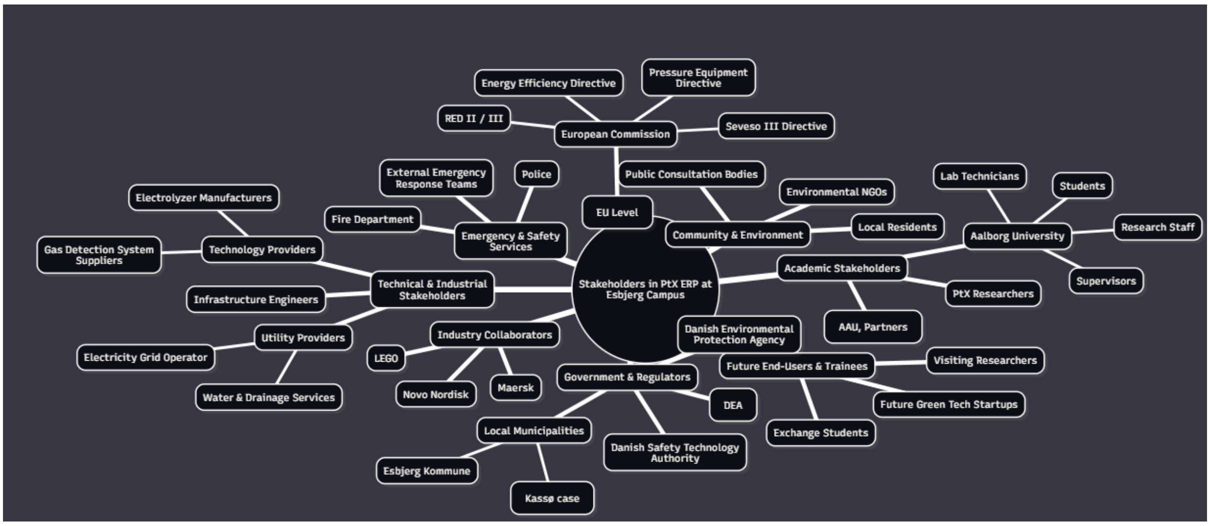


Figure 4: Stakeholder mind map for all 3 plants

These are the stakeholders involved in all three cases discussed in this report (Table 4 and 5)

| Stakeholder | Role | Relevance to Case Study Sites | Guideline/Requirement Followed |
|---|---|---|---|
| Project Developers (e.g., European Energy, AAU) | Design, fund, and implement PtX infrastructure | European Energy (Kassø), Aalborg University (pilot scaling)<br>Esbjerg Campus (in process) | Environmental assessments, permitting, safety planning |
| Municipal Authorities | Local planning, zoning, environmental and building permits | Sønderborg (Kassø), Aalborg Kommune, Esbjerg Kommune | Zoning plan, Building permits, Emergency approvals |
| Danish Energy Agency (DEA) | Oversees national PtX strategy, regulatory frameworks, connection to electricity/hydrogen | Provides guidance for all PtX cases | Regulatory Guide to PtX; Step 8 - Grid and hydrogen infrastructure |

| | | | |
|---|---|---|---|
| Danish Safety Technology Authority | Ensures compliance with gas and electrical safety | Applies to all cases with hydrogen electrolysis (e.g., Esbjerg site) | PED, TPED, electrical/gas installation registration |
| Danish Environmental Protection Agency | Grants environmental permits and oversees Seveso compliance | Kassø (large-scale production); Esbjerg (projected) | Environmental permit (§33), BAT, BREF, Risk Order (Seveso) |
| Academic & Research Institutions | Operate PtX labs, conduct pilot-scale experiments | Aalborg University, Esbjerg Campus (future setup) | Internal lab protocols, some external compliance |
| Emergency Services (Fire & Police) | Respond to and plan for accidents; approve fire safety and external emergency plans | Required for Seveso Column 3 installations (e.g., Kassø) | Fire safety permits, vulnerability assessment (Risk Order Step 4) |
| Technology Providers (e.g., electrolyser manufacturers) | Supply key systems like electrolysers and hydrogen storage units | Relevant to all sites depending on tech maturity (e.g., 17.5 MW units in Kassø) | Equipment must meet PED, TPED, Machinery Directive standards |
| Community/Public | Stakeholders living near facilities, affected by environmental and safety risks | Kassø community (receives district heating), Esbjerg local population | Public consultation in zoning and environmental assessment |
| End users (e.g., Maersk, LEGO, Novo Nordisk) | Use green fuels produced from PtX (e.g., e-methanol) | Kassø Plant off-takers | Must align with GHG reduction goals under EU RED II |
| Regulatory Bodies (EU and DK) | Set laws and directives impacting hydrogen safety, emissions, and infrastructure | Overarching across all cases | EU Directives (RED II, Seveso III), Danish Energy and Planning Acts |
| University Researchers<br>Lab technicians<br>Students<br>Visitors | Use infrastructure | ERP for their Safety | Training |

Table 4: Stakeholders

(Involved in the PtX plant (Kassø, Aalborg University and Esbjerg).

| | | |
|---|---|---|
| High<br><br><br><br>Interest | **Keep satisfied**<br>Emergency services (Police and Fire)<br>Local community<br>Lab technicians<br>Institution<br>Insurance companies | **Keep informed**<br>European Energy<br>Danish Energy Agency<br>AAU Institution<br>University researchers<br>Danish Environmental Protection Agency<br>Danish Safety Technology Authority<br>Esbjerg Kommune<br>Community<br>Researchers |
| | **Monitor**<br>Students | **Manage closely**<br>DEA |

| | | |
|---|---|---|
| Low | Visitors<br>End users<br>Police<br>Danish Working Environment Authority<br>Municipal fire and rescue services | Danish Environmental Protection Agency<br>Tech providers |
| Low | Power | High |

Table 5: Stakeholder analysis

### I. Keep Satisfied

### Danish Working Environment Authority (DWEA)

The DWEA, with its significant authority in ensuring workplace safety across Denmark, including PtX facilities, plays a crucial role. While its interest in any single PtX project may be relatively low, considering its broad scope across industries like food production, pharmaceuticals, and construction, its regulatory power is substantial. Therefore, it is important to keep it satisfied through compliance with occupational health and safety standards, even if day-to-day engagement is minimal.

## Danish Safety Technology Authority

The Danish Safety Technology Authority is a key entity within the Danish Ministry of Business and Growth, dedicated to ensuring safety across all technological aspects. Since 2004, it has been setting standards for accidents, fires, and explosions in Denmark, playing a significant role in PtX plants. The agency is fully responsible for all gas installations and facilities, overseeing electrical safety and managing authorizations for gas and electricity. Its influence on PtX projects is substantial, making it crucial to maintain a close working relationship with them.

## European Environment Agency

The European Union actively supports the advancement of PtX technologies through various mechanisms. It establishes a comprehensive policy and regulatory framework aimed at achieving its binding 2030 renewable energy target of at least 45.2%, guided by the Renewable Energy Directives (RED II and RED III), which set specific goals for renewable hydrogen. Additionally, the EU provides financial support for PtX-related projects and research initiatives. By fostering alliances and strategic partnerships between industry stakeholders and public authorities at national and local levels, the EU promotes coordinated development. It also supports the expansion of energy infrastructure projects that enhance the integration of renewable energy sources and PtX technologies across the continent.

## II. Manage Closely

### Project Developers (e.g., European Energy, Aalborg University)

Project developers, including European Energy and Aalborg University, are the primary stakeholders driving project planning, implementation, and operation. Their significant power arises from direct control over design, funding, and execution. Their interest is equally substantial because a safety incident, such as a hydrogen fire, could harm the project's reputation, disrupt operations, or result in considerable financial losses. They must remain engaged at all stages through proactive risk management and comprehensive emergency planning, ensuring their secure involvement.

### Emergency Services (Fire & Police)

Emergency services, including fire and police teams, are both powerful and highly invested in the safe operation of PtX sites. They are on the front lines in the event of an accident and play a key role in approving fire safety measures and emergency response plans. Ongoing coordination, training exercises, and feedback loops are crucial for maintaining close cooperation with them, ensuring they feel valued and integral to the process.

### Municipal Authorities (e.g., Esbjerg and Sønderborg Kommunes)

Local authorities wield significant influence through permitting, zoning, and emergency approval processes. Their interest is also substantial since they are accountable to the local population. Close collaboration ensures that safety plans align with local regulations and community expectations.

## III. Monitor with Minimum Effort

### Technology and Equipment Suppliers

While equipment manufacturers, such as electrolyzer and valve producers, provide critical hardware, their role in ongoing safety operations is limited. They typically show less commitment and interest once systems are installed. However, it remains essential to verify that the supplied components comply with technical and safety standards, such as PED and TPED, to prevent future hazards.

## IV. Keep Informed

### Community and General Public (e.g., Kassø and Esbjerg residents)

Local communities are deeply concerned about the safe operations of nearby hydrogen facilities, particularly regarding risks such as explosions or gas leaks. However, they have limited control over these operations. Transparent communication, public hearings, and accessible emergency information are essential for maintaining public trust and a social license to operate.

### Danish Safety Technology Authority & Danish Environmental Protection Agency

These national agencies influence safety and environmental compliance but often act through established regulations rather than daily involvement. Their interest is significant as PtX aligns with broader national and EU climate strategies. Keeping them regularly informed with reports and audit outcomes is essential for smooth operations.

## 5.2 The Kassø Plant

The Kassø Green Methanol Plant in Figure 5 and Figure 6, located in Southern Denmark, represents a significant advancement in sustainable fuel production. Developed by European Energy, this facility is poised to become the world's largest commercial e-methanol plant upon its completion in 2024. Its primary goal is to address the urgent need for carbon-neutral fuels in industries such as shipping, aviation, and chemicals, which are under increasing pressure to reduce $CO_2$ emissions (State of Green n.d.).

### Innovative Approach to Green Fuel Production

The Kassø plant employs an innovative method to produce e-methanol by combining renewable energy sources with advanced chemical processes:

The facility is directly connected to the 304 MW Kassø Solar Park, the largest in Northern Europe, ensuring a consistent supply of green electricity for its operations (State of Green n.d.). Furthermore, by utilizing three 17.5 MW electrolysers, the plant produces approximately 6,000 tonnes of green hydrogen each year by electrolyzing 90,000 tonnes of water sourced from its own boreholes and a local water company (State of Green n.d.). Additionally, green hydrogen is combined with around 45,000 tonnes of biogenic $CO_2$, captured from a nearby biogas plant, and processed through an in-house developed methanol synthesis method to yield up to 42,000 tonnes of e-methanol annually (State of Green n.d.).

In March 2025, European Energy successfully produced the first batch of e-methanol at the Kassø facility. This initial production used biogenic $CO_2$ sourced from the Tønder Biogas facility. This delivery marks a significant step in scaling up green fuel production, as the captured $CO_2$ will be combined with green hydrogen to create e-methanol. The plant is expected to boost production to an annual capacity of 42,000 tonnes of e-methanol by the second quarter of 2025 (Renewable Carbon News, 2025).

Figure 5: The Kassø Plant site
Source (https://stateofgreen.com/en/wp-content/uploads/2024/10/Image-18_-Kasso_European-Energy-min-1536x1152.jpg)

Figure 6: The Kassø Plant site
Source : (https://europeanenergy.com/wp-content/uploads/2025/03/dji-0669.jpg.webp)

## Environmental and Community Benefits

Beyond producing green fuels, the Kassø plant also supports the local community and environment by harnessing excess heat generated during e-methanol production to provide sustainable district heating for up to 3,300 households in the Aabenraa municipality. This exemplifies effective sector coupling and energy utilization (PV Europe, 2023).

The construction and operation of the plant provide local employment opportunities, creating over 100 full-time jobs during the construction phase and about 30 permanent positions upon completion (State of Green n.d.).

The Kassø Green Methanol Plant stands as a testament to innovative renewable energy solutions, addressing critical environmental challenges while promoting economic growth and community development.

## 5.3 The Aalborg plant

The Aalborg Power to X plant in Figures 7 and 8 is part of Denmark’s transition to sustainable energy solutions. Originally located at the Aalborg Campus, it has been relocated to the port of Aalborg to facilitate larger-scale production of green fuel. The plant produces green fuels by capturing carbon from sources such as smoke emissions, food waste, and wastewater. This initiative, led by European Energy in collaboration with the port of Aalborg, aims to establish a 120 MW electrolysis and e-methanol production facility. The facility occupies a 25-hectare site at Aalborg’s Eastern Port and is designed to produce approximately 75,000 metric tons of e-methanol annually. This output is double the capacity of European Energy’s ongoing PtX project in Kassø, Aabenraa, Southern Denmark. The primary goal of the Aalborg plant (Figures 7 and 8) is to support the transportation sector by providing green e-methanol, aligning with the industry's demand from major companies such as Maersk and Circle K (Pedersen, 2024).

Although this project will become operational in 2025, it is currently undergoing regulatory approvals and detailed technical planning. The European Energy is exploring carbon capture options to enhance the plant’s efficiency. Additionally, the company is working toward integrating solar energy into the project, pending approval for new solar parks near the site.

### Community Benefits

A crucial aspect of this development is its role in Aalborg’s energy transition strategy. The facility is expected to supply around 10% of the heat currently provided by Nordjylland Power Station, aiding efforts to phase out coal-fired power generation.

The project supports Denmark’s climate and energy policies by expanding PtX infrastructure to facilitate large-scale hydrogen and e-fuel production, strengthening Aalborg’s position as a hub for green energy technology and innovation, and improving sector integration by utilizing surplus heat from Aalborg’s district heating network.

In addition to the above benefits, the project also generates 10-15 new jobs in the initial operational phase, with the potential for further employment growth as the PtX sector expands.

Figure 7: PtX plant at Aalborg Campus
Source (https://www.aaudxp-cms.aau.dk/media/dpljk2hk/methanol-synthesis-reactor-close.jpg?width=1920&format=webp)


Figure 8: PtX plant at the port of Aalborg
Source (https://portofaalborg.dk/wp-content/uploads/2023/03/20230331-a.jpg)

# 6.0 RISK ASSESSMENT

The Esbjerg facility in Figure 10 focuses on hydrogen production through electrolysis, temporary storage, and the experimental use of hydrogen in research contexts. Since the system's design is already established, the study employs a Process Failure Mode and Effects Analysis (P-FMEA) to evaluate potential risks at each operational phase. Additionally, a Bowtie analysis, which is a visually engaging tool, is utilized to illustrate critical scenarios such as hydrogen leakage and to outline both preventive and mitigative safety barriers. Risk analysis or assessment involves the systematic use of information to identify, evaluate, and communicate uncertainties that may affect the achievement of objectives, as well as establish the adequacy of mitigation options (Aven, 2019).

## 6.1 HAZID

The first step in risk assessment is identifying the risk. According to the ISO, risk identification is primarily conducted to find, recognize, and describe risks that might help or prevent an organization from achieving its objectives" (ISO guidelines 2018).

Hazard Identification (HAZID) provides an overview of a system, its components, (Table 1) and the associated risks. HAZID addresses potential and broader hazards that may arise from plant operations, environmental factors, and mechanical impacts, as indicated in Table 6

| Hazard Scenario | Source of Hazard | Consequences | Mitigation Measures |
|---|---|---|---|
| Electrolyser overheating due to cooling system failure. | Cooling system pump failure. | Hydrogen accumulation, fire/explosion risk. | Install redundant cooling and temperature monitoring. |
| Electrical fault in electrolyser. | Short circuit or component failure. | Fire, equipment damage, risk of explosion. | Electrical inspection routines, surge protection, emergency shutoff systems |
| Compressor seal failure, resulting in a hydrogen leak. | Compressor wear and tear, poor sealing, and mechanical fatigue. | Uncontrolled hydrogen release, fire hazard. | Routine maintenance and a leak detection system. |
| Ignition from a nearby heat source. | Open flame, overheated machinery. | Hydrogen ignition, fire spread. | Hazard zoning, ignition source control, and ATEX compliance. |
| Ventilation system failure. | Mechanical fault or power outage. | Hydrogen accumulation in confined spaces. | Backup ventilation, continuous monitoring, and power backup systems. |
| Over-pressurisation of hydrogen storage tanks. | Faulty pressure relief valve. | Explosion, facility damage, injury. | Double-layered pressure relief system and monitoring. |
| CO2 absorber leak in DAC system. | Seal degradation or structural crack. | Health hazard, environmental CO2 release. | Use corrosion-resistant materials and routine inspections. |
| Hydrogen leaks from a corroded valve. | Aging metal components and poor inspection. | Fire, gas exposure, and delayed containment. | Regular inspection. |

| | | | |
|---|---|---|---|
| Electrical short circuit near hydrogen lines. | Faulty wiring, exposed terminals. | Ignition of hydrogen, electrical fire. | Use explosion-proof equipment and ensure grounding, as well as conduct electrical inspections. |
| Gas detector malfunction in the electrolysis container. | Sensor calibration drift or hardware failure. | Undetected leak, delayed emergency response. | Install redundant gas sensors, and perform periodic calibration. |
| The operator connects the hydrogen line to the wrong inlet. | Lack of training or mislabelled connections. | Gas release, possible asphyxiation, or fire. | Standardized labelling, training, and double-check protocols. |
| The system loses control of critical parameters. | Software bug or cyber interference. | Process instability, increased failure risk. | Secure System with backups and cyber protection. |
| Improper handling by users. | Lack of training or supervision. | Personal injury, incorrect valve operation, spill, or release. | Targeted training, supervision, and operational checklists. |
| Emergency shutdown fails during hydrogen release. | Mechanical or software malfunction. | Escalation of incident, uncontrolled hazard. | Routine emergency system testing and fail-safes. |
| External tampering or vandalism. | Unauthorised access. | Equipment sabotage, gas release, and delayed response. | Security surveillance, access control, and incident response drills. |

Table 6: Identifying Hazards

## 6.2 P-FMEA

Process Failure Mode and Effects Analysis (P-FMEA) in Table 8, is a proactive tool used to systematically identify potential points of failure within a process, understand their root causes and impacts, and rank them based on severity, likelihood of occurrence, and ease of detection as seen in Table 7. This approach is particularly well-suited to the Esbjerg campus case (Figure 10), where the technical layout and operating procedures of the PtX system are already established. By analyzing each stage from electrolysis and compression to hydrogen storage and handling, P-FMEA helps highlight weaknesses in equipment performance, human operation, and procedural safeguards. The result is a prioritized list of potential failures, each assigned a Risk Priority Number (RPN), which serves as a guide for implementing targeted risk reduction measures.

The context here involves providing the scale definitions from Table 7 alongside the P-FMEA tables, Table 8, which detail the failure modes, causes, and consequences for the specific subsystems.

To calculate the Risk Priority Number (RPN), the following formula was used:

$RPN = S \times O \times D$, where S represents Severity, O signifies Occurrence, and D denotes Detectability. The calculated RPN values are utilized to identify the most critical failure modes within the system. These failure modes will be analyzed and discussed in the following sections.

System: Hydrogen PtX Plant
Subsystem:
Component:
Design Lead:
Core Team:

Potential
Failure Mode and Effects Analysis
(Process FMEA) Process FMEA
Key Date 04/05/2025

| Process step | Potential Failure Mode(s) | Potential Effect(s) of Failure | Sev | Potential Cause(s) | Prob | Det | RPN | Recommended Action(s) |
|---|---|---|---|---|---|---|---|---|
| Electrolysis | Electrical fault in elctrolyser | Fire, equipment damage and explosion | 8 | Short circuit, faulty wiring, equipment aging | 4 | 4 | 128 | Inspections and Emergency shutdown |
| Electrolysis | Cooling system fail due to over heating | Hydrogen accumulation, explosion risk | 9 | Pump Failure | 6 | 6 | 324 | Temperature monitoring, cooling systems |
| Hydrogen Compression | Seal failure, Hydrogen leak | uncontrolled hydrogen release, fire hazard | 9 | Wear, poor sealing, fatigue | 6 | 6 | 324 | Routine maintenance, leak detection |
| Hydrogen compressor | Embrittlement of storage vessls | uncontrolled hydrogen release, fire hazard | 8 | | 3 | 3 | 120 | Inspection and replace old metals |
| Hydrogen storage | Ventilation stops | Hydrogen accumulation, explosion risk | 8 | Mechanical fault, p | 3 | 6 | 144 | Backup ventilation, Continuous monitoring, Power backup |
| Hydrogen storage | Gas detection sensor failure | Undetected hydrogen leak | 7 | Hardware fail, Broken sensor | 5 | 6 | 210 | Implement advanced control system to adjust during severe weather conditions |
| Hydrogen storage | Over-pressurisation of hydrogen storage tanks | Explosion, injury, facility damage | 9 | Faulty valve | 5 | 5 | 225 | Double-layered pressure relief, monitoring |
| Emergency shutdown failure | System fails to shut down | Rise in hazard | 8 | Mechanical/software malfunction | 4 | 7 | 224 | Routine testing |
| External Tampering | unauthorised access | Saboutage, gas leak | 7 | security breach | 2 | 7 | 98 | Souveyance, access control, drills |
| Hydrogen handling | Leak not detected in time | Gas release, fire, asphyxiation | 7 | Lack of training, human error | 7 | 6 | 294 | Regular inspection |
| hydrogen handling | Electrical short | Ignition and fire | 9 | Sensor failure | 4 | 4 | 144 | |
| Hydrogen handling | Operator error, wrong connection | Gas release, fire, asphyxiation | 6 | Lack of training, mislabeling | 6 | 5 | 180 | Standardized labeling, training, double-check protocols |

Table 7: FMEA for various Hazards

| Effect | SEVERITY of Effect | Ranking |
|---|---|---|
| Catastrophic | Explosion and death | 10 |
| Extreme | Possible serious injury, equipement loss | 9 |
| High | Serious system failure or environmental hazard | 8 |
| High | None compliance with regulation | 7 |
| Moderate | partial shutdown, damage repairable | 6 |
| Moderate | Process inefficient, delay, minor repairs | 5 |
| Low | Minor reduction in performance, minimal damage | 4 |
| Minor | Noticeable but safe error | 3 |
| Very Minor | Minor disruption, no injury or loss | 2 |
| None | No impact on personnel or process | 1 |

Table 8a

| PROBABILITY of Failure | Ranking |
|---|---|
| Very High: once per day (almost inevitable) | 10 |
| High: Frequent (weekly) | 9 |
| High: Regular failures | 8 |
| Moderately high: Observed occasionally | 7 |
| Moderate:known to happen sometimes | 6 |
| Moderate:Rare but possible | 5 |
| Low likelyhood | 4 |
| Very unlikely | 3 |
| Extremely rare | 2 |
| Fully controlled/ never observed | 1 |

Table 8b

| Detection | Likelihood of DETECTION | Ranking |
|---|---|---|
| Absolute Uncertainty | Virtually impossible to detect | 10 |
| Very High | Extremely difficult to detect | 9 |
| High | Very difficult to detect | 8 |
| Low | Difficult to detect/limited effectiveness | 7 |
| Moderate | Somewhat easy to detect | 6 |
| Moderate high | Moderately easy to detect | 5 |
| High | Detection likely under control | 4 |
| Very high | Should be detected | 3 |
| Almost certain | Very easy to detect through controls | 2 |
| Certain | Easy to detect/highly effective | 1 |

Table 8c

Table 8a, 8b, 8c, for S, O, D scale definition

| Failure Mode | Severity | Occurrence | Detectability | RPN | Interpretation |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| Cooling system failure | 9 | 6 | 6 | 324 | Highest risk. Requires immediate mitigation, such as cooling upgrades. |
| Seal failure in the compressor | 9 | 6 | 6 | 324 | High fire risk from hydrogen leaks. Prioritize maintenance and leak detection. |
| Operator error in hydrogen handling | 6 | 6 | 5 | 180 | Moderate risk but correctable with training. |
| External tampering | 7 | 2 | 7 | 98 | Lower RPN, but still dangerous if exploited. Improve surveillance and access control. |

Table 9: RPN results

## Hydrogen storage

After reviewing the results from the P-FMEA analysis in Tables 8 and 9, it is evident that most risks center around the compressor chamber. This may be due to wear and tear, embrittlement, and the potential for cracks in the cylinder, which can affect the compressor. The resulting Risk Priority Number is 324, derived from S = 9, O = 6, and D = 6. The severity score of 9 indicates that embrittlement in the cylinders can cause significant damage, such as cracks. This shortens the equipment's lifespan and, more importantly, leads to hydrogen gas leakage. Wear and tear can also result in a loss of efficiency and output. An occurrence score of 6 indicates that this issue is not rare. It is well known that hydrogen can cause embrittlement under pressure and can be easily absorbed by metal surfaces over time. A detectability score of 5 indicates that the crack is not easily detectable. This might be due to its slow development and the absence of clear warning signs until considerable damage has occurred.

## Electrolysis

The cooling system, which is part of the electrolysis process, also achieves a remarkably high score, with an RPN of 324. A severity of 9 indicates that, in the event of an accident, there will be severe damage to both property and people. An occurrence rating of 6 suggests it may happen in certain situations, and a detectability rating of 6 also indicates that it can be detected in specific circumstances.

## Hydrogen handling

Failure and seal failure in the compressor present the most urgent issues. Both have the highest risk scores and could lead to serious accidents, including hydrogen leaks or explosions, as shown in Table 7. These problems demand prompt action. Prioritizing improvements to cooling systems, ensuring regular maintenance, and implementing advanced leak detection should be essential.

Operator error raises another concern, although it is less critical. Mistakes such as connecting the wrong hoses or mishandling valves can still lead to fires or gas leaks. Fortunately, this risk can be reduced through improved training and more transparent labelling.

Additionally, although external tampering is less likely, it could still pose a danger if it were to occur. Unauthorized access might trigger a leak or worse. It is essential to enhance site security and surveillance, just in case.

Table 7 indicates that the P-FMEA analysis focuses on managing technical risks through effective maintenance and monitoring, while also enhancing human safety practices and security to achieve overall safety.

## 6.3 Bowtie Analysis

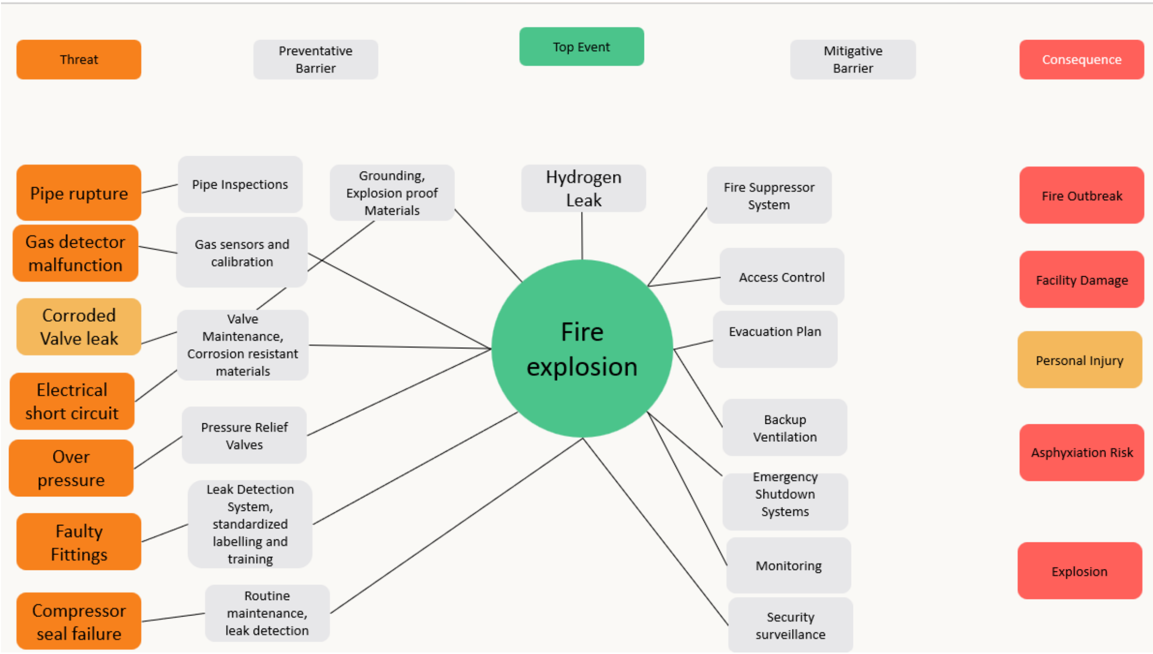


Figure 9: Bowtie Analysis of a potential hydrogen leak leading to a fire explosion

Figure 9 illustrates a comprehensive risk pathway for one of the most critical scenarios in hydrogen-based PtX facilities: a fire explosion resulting from a hydrogen leak. This visual aid effectively connects the potential causes or threats of the incident with preventive barriers, and the possible consequences with mitigative measures, all centered around the 'Top Event'-a hydrogen leak that escalates into a fire explosion.

Top Event: Hydrogen Leak → Fire Explosion

A hydrogen leak, identified as the pivotal event, is at the center of the Bowtie diagram. This can result in a fire or explosion if not properly managed. Due to hydrogen's wide flammability range and low ignition energy, leaks create a high-risk situation that requires multiple layers of control.

On the left side of the diagram are various threats. These conditions or events could trigger a hydrogen leak. They range from pipe ruptures due to wear, corrosion, or physical damage; gas detector malfunctions or calibration failures; corroded valve leakages from chemical degradation; electrical short circuits near hydrogen flow areas; overpressure due to faulty compression or failed relief systems; faulty fittings and mechanical connections; and compressor seal failures from thermal or mechanical stress.

To reduce the likelihood of the top event occurring, several preventive barriers are shown in grey boxes. These include Routine pipe inspections and valve maintenance, Use of corrosion-resistant materials, Installation and calibration of gas sensors, Pressure relief valves to manage overpressure, Implementation of leak detection systems, Explosion-proof electrical materials and system grounding, Standardized labelling and user training.

These controls are designed to reduce the occurrence score in FMEA and enhance system resilience.

On the right-hand side, the diagram outlines the potential consequences if the hydrogen leak is not prevented and leads to ignition. These consequences include Fire outbreak and facility-wide damage, Risk of explosion, Asphyxiation hazards in confined spaces, Personal injury or fatalities, Operational disruptions, and regulatory liabilities

To limit these impacts, several mitigative barriers are included:

Fire suppression systems (e.g., sprinklers, foam, gas suppression)

Access control to limit exposure in hazardous zones

Evacuation plans and defined emergency exits

Backup ventilation systems to reduce gas concentration

Emergency shutdown systems for rapid isolation

Continuous monitoring and alarm systems

Security surveillance for tamper prevention and early detection

The above analysis reinforces the risk pathways identified in the FMEA and highlights the need for layered safety systems in PtX research environments. For Esbjerg Campus, where hydrogen production and handling will be conducted in an academic setting, the presence of both preventive and mitigative barriers is essential to ensure safe experimentation and compliance with best practices.

# 7.0 FINDINGS

A comparative analysis between the planned hydrogen-based PtX facility at Aalborg University's Esbjerg Campus and the already operational Kassø PtX plant aims to identify gaps, limitations, and opportunities that can inform the design of a robust Emergency Response Plan (ERP) tailored to the unique needs of research institutions.

## 7.1 Main system functionalities

Aalborg University is developing another PtX test site at Campus Esbjerg, a project crucial to the future of sustainable energy. This site aims to advance research in green hydrogen production, carbon capture, and energy storage technologies. One central focus area is hydrogen production through Proton Exchange Membrane (PEM) electrolysis and alkaline electrolysis, along with experimental methods such as Microbial Electrolysis Cells (MEC). The MEC technology introduces a new strategy where bacterial cultures within a bioreactor, stimulated by a small voltage, help split water into hydrogen, potentially offering a less expensive alternative to conventional electrolysis methods.

Another key technological focus is on carbon dioxide capture, using Direct Air Capture (DAC) and Direct Ocean Capture (DOC) methods. These aim to extract $CO_2$ from the atmosphere and seawater, respectively, which can then be combined with hydrogen to synthesize carbon-neutral fuels.

### Layout and Safety Design of the Esbjerg PtX Test Site

The Campus Esbjerg site, Figure 10, as illustrated in the official fire and rescue plan (*Brandplan, Indsatsforhold*), is carefully designed to prioritize safety and accessibility.

### Container Setup

The hydrogen and PtX systems are housed inside modular containers, organized in a fenced-in area. Each container connects to a centralized gas supply infrastructure.

### Safety Distances

Critical minimum distances are maintained between containers, gas closets, and buildings to reduce explosion risks. As shown in Table 2, there is a mandatory clearance zone (marked with yellow hatching) around the operational containers, ensuring that no unauthorized structures or obstacles are placed near the experimental area.

### Fire and Rescue Access

A dedicated fire access road (marked with orange arrows) wraps around the site. This road is strategically located to ensure that fire trucks can approach the containers rapidly in the event of an emergency. The design also includes specific fire assembly points and exits routes, clearly defined for safe evacuation. The red signage marks existing fire road signs that must be maintained or repositioned for optimal visibility.

## Automatic Gas Safety Systems

The site will be equipped with individual gas detectors inside each container. Should a gas leak be detected, the entire gas supply system will automatically shut down at the main storage point. Valves are designed to be normally closed, ensuring that if power is lost, the gas flow is immediately cut off to minimize hazards.

## Access Control and Laboratory Procedures

Access to the test site is tightly controlled. Users must complete standard laboratory safety training and fill out access forms and workplace permits. These documents require users to outline their planned activities, potential hazards, and mitigation strategies. Once completed, they are reviewed by safety officers to ensure that all necessary precautions are in place before work can commence. Lab work is only permitted during working hours, 08:00–16:00 when staff are present to oversee activities and respond to incidents if needed.

Currently, the Esbjerg site's external plant-specific safety protocols are still under development, and standard university laboratory procedures are being used temporarily. Staff have acknowledged the need for more comprehensive safety systems as the facility becomes operational. As the plant moves towards full operation, additional focus will be needed on refining safety protocols, implementing specialized training for users, and possibly developing dedicated PtX emergency response procedures tailored to the unique risks associated with hydrogen and carbon-based systems.


Figure 10: Esbjerg Ptx Plant

(Highlights where key units (e.g., electrolysers, storage tanks) are physically located).

## 7.2 Comprehensive analysis between Esbjerg PtX plant vs operational facilities (Kassø Plant).

### Site Context and Operational Scale

The Kassø plant, developed by European Energy, is a commercial-scale facility designed to produce up to 42,000 tons of e-methanol annually using 17.5 MW electrolyzers. It combines renewable electricity with green hydrogen and biogenic $CO_2$, primarily serving off-takers such as Maersk and LEGO, as shown in Figure 4. The site operates under industrial safety regulations and includes district heating systems, as well as formal Seveso compliance, stakeholder Table 2.

In contrast, the Esbjerg PtX facility is currently under development as a research-focused plant, aimed at pilot-scale hydrogen production, student training, and experimental PtX applications. It will function within a university environment, catering to a diverse user group that includes researchers, lab technicians, and students.

The identified problem in the above situation is that, while the Kassø facility benefits from mature industrial safety infrastructure, Esbjerg's academic nature introduces experimental variability and less formalized operational control.

### Emergency Response Framework

Kassø's commitment to safety is evident in its fully developed emergency response plan, coordination with municipal fire services, Fire suppression systems, Seveso Column 3 compliance, Regular emergency drills, and safety audits. This comprehensive approach to safety should reassure stakeholders (Tables 4 and 5) that Kassø is prepared for any potential emergency.

On the other hand, Esbjerg, while still finalizing its ERP for Hydrogen PtX facilities, has the potential to significantly enhance its emergency planning. The absence of formal emergency planning currently creates a critical gap in preparedness for hydrogen-related incidents; however, with the right strategies and resources, this gap can be effectively addressed.

Notably, a walkthrough interview conducted with a lead representative of the Esbjerg PtX facility revealed that while several access restrictions, ATEX-approved rooms, hydrogen and oxygen alarms, and ventilation mechanisms are already planned or installed, a central ERP system for handling leaks, explosions, or system failure is not yet operational. For example, hydrogen alarms and gas shutoff systems are designed to automatically isolate gases in the event of an incident. However, there is currently no integrated protocol or simulation training for handling such failures.

While the Esbjerg team currently relies heavily on card-access control, compartmentalized storage of compressed gases, and designated technician oversight, there is potential for growth. By addressing the existing gaps in redundancy, real-time response planning, and wider stakeholder training, the team can inspire confidence in their ability to enhance their emergency preparedness.

## Regulatory Compliance

Kassø complies with a broad range of national and EU directives. The Seveso III Directive, Pressure Equipment Directive (PED), Transportable Pressure Equipment Directive (TPED), and the Environmental permits (Risk Order)

Esbjerg has undergone its permitting and construction phases. Although it is plans to produce very small tonnage of hydrogen, it is expected to follow relevant legislation and add clarity or modify on how academic labs will meet industrial-scale PtX regulatory standards.

## Training, Human Factors, and Institutional Readiness

At Kassø, personnel are trained and certified to handle hydrogen systems. Emergency procedures are well-practiced, and staff roles are clearly defined.

In contrast, the Esbjerg campus has no formalized hydrogen safety training program for researchers, students, or lab technicians. This lack of training not only increases the potential for human error but also poses a significant risk to the safety of all individuals involved in the project. Additionally, the presence of rotating users and students with varied experience levels further exacerbates this risk.

Although Esbjerg lacks structured training, laboratory guidelines are used, and access to the plant is restricted with training and levels of approval from the facility head, as well as supervisor for the test. Moreso, the lab technician as well as the researchers are present to train and guide participants on the projects to be carried out.

## Infrastructure and Backup System

Kassø incorporates advanced technical safeguards that range from Fire suppression systems, Backup power, Hydrogen leak detection systems, and Emergency shutdown infrastructure.

The Esbjerg PtX setup has been designed, and installations are ongoing. Most of the safety systems have been put in place, and the others need to be installed according to plan. The walkthrough further revealed several backup plans—for example, emergency drainage and power cutoffs. The presence of burglary alarms, two escape routes, and LED lights for guidance in case of power outages all highlight a robust risk management structure.

| Category | Observed/Implemented at Esbjerg |
|---|---|
| Access Control & Security | Card access for all lab containers, restricted access to gas storage, keys held by designated lab technician (Jeppe). |
| ATEX Certification | ATEX-certified lab with explosion-proof lighting, dual escape routes, and ventilation. |
| Gas Storage & Control | Dedicated gas storage cabinets for $H_2$, $O_2$, $N_2$, and $CO_2$; cabinets locked and only accessible by lab staff. |
| Emergency Escape Routes | Dual escape routes available (including a secondary hill route); some labs have breakable windows for emergency exit. |
| Monitoring & Digital Systems | A computer room is set up and prewired for future real-time monitoring dashboards. |
| Alarms & Sensors | An alarm system exists for burglary; however, hydrogen, oxygen, and CO2 alarms are required but not yet fully installed. |
| Drainage & Waste Handling | Dedicated surface water and wastewater drainage system; strict separation of chemical waste. |
| Process Safety Setup | Clear separation of power and signal cables to prevent interference; pressurized air and water systems are in place. |
| Process Infrastructure | Equipment containers designated for $CO_2$ capture, electrolysis (hydrogen production), and methanol synthesis. |

Table 10: Existing safety features and gaps at Esbjerg Ptx plant

| Category | Kassø Plant (Industrial) | Esbjerg PtX (Academic) |
|---|---|---|
| Status | Fully operational | Under development |
| Primary Objective | Green fuel production | Research & training |
| Regulatory Compliance | Seveso, PED, TPED, §33 | In progress, unclear scope |
| ERP Availability | Established and tested | Laboratoy guidelines<br>Full scale not yet defined |
| Personnel Safety Training | Industrial standard training | Laboratory use training |
| Risk Management Tools | QRA, safety audits, drills | Preliminary (FMEA, Bowtie) |
| Emergency Infrastructure | Installed and functional | Partially planned |
| Human Error Risk | Trained personnel | High variability in users |

Table 11: Summary of Comparative Insights

This analysis highlights that while Kassø sets a strong example of industrial best practices in hydrogen safety and emergency planning, the Esbjerg PtX project currently lacks similar systems and preparedness. As the Esbjerg facility progresses, it must proactively implement a risk-based emergency response framework that addresses both the hazards of hydrogen and the complex academic environment in which it functions.

The insights gained from this comparison, Table 11, particularly from the onsite talk with experts and system walkthroughs, are instrumental in guiding the development of a site-specific Emergency Response Plan.

## 7.3 A proposed Risk-Based ERP for the Esbjerg plant

The development of a tailored Emergency Response Plan (ERP) for Aalborg University's Esbjerg Campus PtX facility is a crucial step in addressing the unique operational risks present in this academic research setting. The Esbjerg facility, designed primarily for experimentation and training, involves a diverse and frequently changing group of users. These conditions introduce additional challenges in ensuring consistent adherence to safety protocols, particularly when working with high-risk substances like hydrogen. This chapter proposes a risk-based ERP built on both qualitative assessments, including insights from facility walkthroughs, and quantitative tools such as Process FMEA and Bowtie analysis.

The primary objective of this ERP is to establish a coherent strategy for preventing, detecting, and responding to incidents such as hydrogen leaks, ignition, or system failure. The plan enhances operational resilience while supporting the university's educational and research missions by minimizing the likelihood and severity of these scenarios. Importantly, it is also fully aligned with Danish and EU regulations, including Seveso III, the Pressure Equipment Directive (PED), and ATEX guidelines for explosive atmospheres, ensuring our complete compliance.

### Risk Identification and Prioritization

A crucial first step in the plan is to identify and prioritize risks. Based on the earlier FMEA, hydrogen release due to compressor wear and tear failure was rated as one of the highest-priority risks. Consequently, the plan emphasizes routine maintenance, early detection, and quick intervention. Hydrogen, oxygen, and $CO_2$ sensors, preferably ATEX-certified, should be installed throughout the facility and connected to a centralized emergency shutoff system that isolates gas supplies upon detecting a leak. These alarms should be both audible and visual to ensure prompt awareness and response.

### Emergency Detection and Alert Systems

Infrastructure plays a crucial role in emergency management. While the Esbjerg PtX facility has already incorporated several ATEX-approved features, including lighting and ventilated chemical closets, the ERP calls for additional enhancements. These enhancements include redundant ventilation systems, illuminated emergency escape signage, and dual escape routes in all laboratories and ATEX-designated areas. It is also recommended that monitoring for gas pressure and system performance be digitized to enable real-time oversight and fault detection.

## Training and Simulation

Given the experimental nature of the Esbjerg plant, focused training and simulations are crucial. All staff and students must undergo hydrogen safety training that includes emergency protocols and behavior guidelines. Simulation drills should be conducted biannually, recreating scenarios like gas leaks and forced evacuations. This training should also encompass visitor briefings and lab technician audits to promote a consistent safety culture among users.

## Emergency Communication and Coordination

Emergency communication is another pillar of the ERP. A structured notification protocol should be implemented, which includes designated emergency contacts, an alert system that combines SMS and email, and clear instructions for reporting incidents. These procedures must be displayed in all laboratories, with updated safety data sheets (SDS) and checklists situated at all access points.

## Incident Response Procedures

Roles and responsibilities must be defined within the ERP. The facility's lab technician, safety officer, researchers, and maintenance staff should have clearly outlined roles during an emergency. This accountability includes recordkeeping and ensuring that all training, drills, and safety actions are documented for institutional learning and continuous improvement.

## Stakeholder Integration and Accountability

This ERP builds upon Esbjerg's existing infrastructure, including card-controlled access and segregated storage for compressed gases. However, the integration of these components into a comprehensive safety system remains incomplete. Therefore, this section recommends finalizing and sharing ERP documentation across departments and assigning oversight to a dedicated safety officer. Collaboration with municipal fire and emergency services is also essential, particularly during planning and simulation exercises.

The proposed ERP represents a realistic and research-sensitive response framework that connects industrial best practices with academic flexibility. The plan addresses technical vulnerabilities and human factors by prioritizing risk-based strategies, promoting a safer environment for hydrogen experimentation and innovation.

# 8.0 DISCUSSION AND CONCLUSION

## 8.1 Discussion

This study explored how Aalborg University Esbjerg could develop a customized, risk-based emergency response plan (ERP) for hydrogen-based PtX technologies. The researcher identified critical safety challenges related to hydrogen use in academic research settings and compared them with those in industrial PtX operations. By utilizing risk analysis tools, assessing Danish and EU regulatory frameworks, and proposing a practical response framework, the researcher effectively addressed the study's research questions and met all outlined objectives.

**Research Question 1: How can research institutions create a risk-based emergency response plan tailored to PtX technologies, specifically Hydrogen?**

Institutions like Aalborg University Esbjerg can develop effective ERPs by identifying critical operational risks, such as hydrogen leaks, equipment failures, and human error, using structured methods like Hazard Identification (HAZID), as shown in Table 6, and Process FMEA. These findings informed the development of customized mitigation strategies, including the integration of hydrogen gas sensors, automated emergency shutoff valves, accessible escape routes, and regular simulation-based drills. Additionally, it is essential to align these plans with relevant technical standards, including ATEX for explosive environments and the Pressure Equipment Directive (PED) for pressure equipment safety.

**Research Question 2: What are the main differences between hydrogen safety frameworks in industry and academia?**

The analysis demonstrated that industrial facilities, such as the Kassø PtX plant, must comply with extensive legislative requirements, including regular audits, incident reporting obligations, and oversight from multiple agencies. At higher education institutions like Aalborg University Esbjerg, PtX systems do not meet legislative thresholds (e.g., Seveso thresholds) and instead operate under internal laboratory safety protocols, which may not always effectively address hydrogen-specific risks.

Additionally, industrial facilities are equipped with dedicated safety measures, including blast walls, gas collection domes, redundant power systems, and automated monitoring units. In contrast, academic PtX setups typically operate in limited physical spaces and with limited equipment, relying heavily on shared infrastructure. However, the Esbjerg PtX plant plans to use chimneys as collection domes for CO2 capture.

Thirdly, industrial facilities employ dedicated emergency coordinators and typically have on-site fire teams or contracts with professional responders. Academic labs depend on lab technicians and external emergency services, with response times varying based on university coordination.

Industrial employees receive regular, structured safety training focused on hydrogen risks, often enhanced with VR simulations or role-based drills. Academic labs support students and visiting researchers with varying levels of technical and safety training, leading to inconsistencies in emergency response readiness.

In the industry, safety is an essential component of operational performance, integrated into organizational systems like Safety Integrity Level (SIL) and ongoing risk monitoring. In academia, the freedom to research can sometimes result in fragmented safety enforcement and delays in adopting new safety technologies.

**Research Question 3: How can risk assessment tools like FMEA and Bowtie Analysis enhance emergency preparedness?**

In applying both tools during this study, the student found that FMEA facilitated the prioritization of failure modes based on severity, likelihood, and detectability, making it easier to allocate safety resources effectively. Bowtie Analysis proved especially useful in mapping risk pathways and identifying where preventive and mitigative barriers should be placed. These tools enhanced the reliability and clarity of the ERP developed, transforming emergency planning from a reactive to a proactive approach.

In addition to answering the research questions, the first objective of identifying the key hazards of hydrogen was achieved by constructing a HAZID table and conducting a P-FMEA. This process allowed for the isolation of significant hazards, such as compressor seal failures, coolant system breakdowns, and human error. These risks were ranked and analyzed based on their potential impact.

**Objective 1:** Identify the key hazards and risks associated with hydrogen use in research institutions is achieved in chapter through HAZID and P-FMEA.

**Objective 2: Compare emergency response strategies in industrial and academic environments.**

Comparing Kassø's industrial safety protocols to Esbjerg's academic setting revealed differences in regulatory enforcement, stakeholder collaboration, and preparedness levels.

Industrial facilities like Kassø are regulated under frameworks such as Seveso III and are subject to routine inspections, environmental permits, and mandatory coordination with emergency services. In contrast, academic institutions often fall below regulatory thresholds and may not be subject to the same external oversight, leading to varied interpretations and inconsistent implementation of safety protocols.

Furthermore, safety planning entails coordinated efforts among developers, municipalities, fire services, and national industry authorities, ensuring clearly defined responsibilities. At Esbjerg, collaboration often remains internalized within the university, frequently depending on a limited number of technical staff and researchers. This decentralization can lead to communication gaps and hinder preparedness.

Industrial PtX sites benefit from permanent technical staff, standardized safety drills, and dedicated emergency infrastructure. In academic labs, preparedness varies across departments, and emergency training is not always systematically implemented. Personnel turnover and the presence of untrained students further challenge consistent safety enforcement.

**Objective 3: Assess how risk analysis tools like FMEA and Bowtie Analysis can improve hydrogen safety planning.**

By practically applying these tools, a structured, data-driven safety plan was established that identified key risks and their controls. These tools improved hazard visibility and offered a systematic approach to designing a resilient ERP.

**Objective 4: Develop a structured emergency response framework based on best practices from industrial PtX facilities.**

Drawing on insights from Kassø and guidance from agencies like DNV and the Danish Energy Agency, the researcher developed a practical and scalable ERP for the Esbjerg Campus. It features real-time monitoring, gas shutoff systems, and clearly defined emergency roles.

**Objective 5: Recommend training programs and simulation-based safety exercises to strengthen emergency preparedness.**

Recognizing the diverse user base in academic labs, this proposal advocates for mandatory safety training sessions, scenario-based drills, and lab-specific briefings to enhance the readiness of all personnel handling hydrogen.

## 8.2 Recommendation

Considering the observed strengths at the Esbjerg PtX site, recommendations as shown in Table 12 are made for system integration, simulation-based response validation, and personnel training:

The campus already includes robust physical safety measures (e.g., ATEX rooms, escape routes, dedicated drainage). These should now be integrated into a comprehensive, documented emergency response plan that aligns with national and EU standards.

| Category | Observed/Implemented at Esbjerg | Remaining Gaps / Recommendations |
|---|---|---|
| Access Control & Security | Card access for all lab containers, restricted access to gas storage, keys held by designated lab technician (Jeppe). | Already in place. Continue training users on access protocol enforcement and update logs. |
| ATEX Certification | ATEX-certified lab with explosion-proof lighting, dual escape routes, and ventilation. | Maintain certification and ensure alarms (hydrogen, oxygen, CO2) are integrated and regularly tested. |
| Gas Storage & Control. | Dedicated gas storage cabinets for $H_2$, $O_2$, $N_2$, and $CO_2$; cabinets locked and only accessible by lab staff. | Integrate automated alarm-triggered shutoff valves for immediate containment in case of leaks. |
| Emergency Escape Routes. | Dual escape routes available (including a secondary hill route); some labs have breakable windows for emergency exit. | Ensure signage and training mark all exits and secondary routes for users and visitors. |
| Monitoring & Digital Systems. | A computer room is set up and prewired for future real-time monitoring dashboards. | Complete dashboard setup with live feeds from hydrogen detectors and other critical process controls. |
| Alarms & Sensors. | An alarm system exists for burglary; hydrogen, oxygen, and CO2 alarms are required but not yet fully installed. | Immediate installation and integration of gas and breathable air quality alarms into ERP. |
| Drainage & Waste Handling. | Dedicated surface water and wastewater drainage system; strict separation of chemical waste. | Maintain protocols and label materials clearly; ensure all waste collection adheres to chemical hazard handling standards. |
| Process Safety Setup. | Clear separation of power and signal cables to prevent interference; pressurized air and water systems are in place. | Continue to implement safe installation practices and routine checks for leaks, insulation wear, and signal integrity. |
| Process Infrastructure. | Equipment containers are designated for $CO_2$ capture, electrolysis (hydrogen production), and methanol synthesis. | Update ERP to reflect changing configurations and ensure coordination across all units. |

Table 12: Recommendations

Other recommendations to consider include standardizing ERP documentation across academic departments and specifying emergency procedures for hydrogen-related incidents. This will ensure that all research groups follow uniform and specific emergency protocols. The consistency in these procedures will help reduce confusion during emergencies and coordinate safety efforts across various disciplines working on hydrogen-related projects.

Additionally, conduct routine safety drills in close coordination with local fire and emergency services. These exercises should simulate realistic hydrogen-related scenarios and aim to enhance situational awareness, evaluate communication protocols, and assess the effectiveness of the institution's emergency preparedness.

It is essential to make hydrogen safety training mandatory for all researchers, technicians, and students involved in PtX projects. This training should be tailored to each role and include hands-on simulations, emergency drills, and refresher sessions. It must be designed to ensure that each individual feels valued and included in the safety efforts, considering the dynamic nature of personnel turnover in academia. Formalizing Safety Training Programs is a crucial component of our safety strategy. By implementing mandatory safety inductions and simulations for new staff, students, and visitors, we ensure that everyone is equipped with the knowledge and skills to respond effectively in emergencies. This will cover modules on using emergency exits, recognizing alarms, and proper gas handling.

Finally, it is advisable to encourage ongoing dialogue with regulatory authorities such as the Danish Safety Technology Authority and the Danish Energy Agency. Regular communication ensures that institutional safety practices remain compliant with evolving national and EU regulations and facilitates the adaptation of industrial best practices to academic settings.

## 8.3 Conclusion

This study effectively addressed all research questions and achieved its five objectives. It reveals that hydrogen use in academic PtX environments presents distinct challenges that require tailored emergency preparedness. By applying risk analysis tools and adapting industrial best practices to the research context, a scalable ERP framework for Aalborg University's Esbjerg Campus was developed. This provides a valuable model that can support safe hydrogen research and education in other institutions exploring PtX technologies.

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## List of figures



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