

Quantitative Risk Assessment of a Production-Scale PEM Electrolyzer System Integrated with a Nuclear Power Plant

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Abstract: Integrating proton exchange membrane (PEM) electrolyzers with nuclear power plants (NPPs) offers a pathway for large-scale, low-carbon hydrogen production, but co-location introduces hazards that require rigorous probabilistic safety assessment. In this work, we present our new quantitative risk assessment (QRA) framework for a 1 MW PEM electrolyzer integrated with an NPP, spanning hazard identification through consequence modeling and site risk quantification. We began by conducting a detailed failure modes and effects analysis (FMEA), identifying more than 850 modal-level failure scenarios that could result in hydrogen, oxygen, or nitrogen releases, or hydrogen and oxygen mixing. We then constructed and parameterized fault trees for key top events using reliability data to quantify failure frequencies, identify minimal cut sets, and calculate risk reduction and achievement worth importance measures. These results allowed us to rank dominant risk contributors and propose targeted mitigation strategies. To address ignition probability, we developed Bayesian network models to provide traceable probabilities for immediate and delayed ignition. To model the consequences of immediate ignition, we analytically modeled jet fires for multiple release scenarios using the HyRAM+ software toolkit. We quantified explosion overpressures using Kingery–Bulmash, Baker, and TNO methods and performed finite element analysis to evaluate structural vulnerability of critical piping. Finally, we integrated frequency, ignition, and consequence models into the QRA framework and used it to calculate location-specific individual and site risk (LSIR and LSSR). We performed Monte Carlo simulations to propagate scenario-level and system-level uncertainties through the risk metrics and inform safety system design. These results support risk-informed design decisions and setback distances. This work establishes a structured, specific QRA methodology that supports the safe deployment of nuclear-enabled hydrogen production systems.

1. INTRODUCTION

Large-scale hydrogen production through integration with nuclear power plants (NPPs) can provide an economically valuable energy offtake while supplying hydrogen for chemical processing, steel reforming, energy storage, and other industrial applications. During periods of decreased grid demand, an NPP can continue operating at high capacity by directing electricity to an electrolyzer facility, which can improve capacity factor, cost-effectiveness, and operational flexibility. With near-term goals set by the U.S. Department of Energy (DOE) of producing 10 (million metric tons) MMT of clean hydrogen by 2030 and long-term goals of 50 MMT by 2050, safety codes and standards development has been identified as a key enabler for reaching these milestones [1]. Additionally, the Hydrogen Technology and Fuel Cell Technologies Office of the DOE multi-year program plan identifies the evaluation of risk-mitigating measures as a core objective for informing safety codes and standards [2].

Co-locating hydrogen production with nuclear generation creates a distinct risk-integration challenge because the required spatial proximity of the two facilities can expose nuclear safety-relevant structures, systems, and components to the consequences of hazardous hydrogen release scenarios. These scenarios must be evaluated not only with respect to hydrogen-facility personnel and equipment, but also with respect to nearby nuclear safety-significant structures, electrical interfaces, and siting constraints. In such systems, consequence effect distances, equipment placement, and secondary damage pathways become design variables that directly affect whether the coupled configuration is acceptable from a safety perspective.

The contribution of this work is the integration of PEM-specific hazard identification, fault-tree frequency modeling, Bayesian ignition modeling, consequence analysis, and location-specific risk metrics into a

single QRA workflow for nuclear-integrated PEM electrolysis. The paper synthesizes detailed analyses reported in prior work and demonstrates how their results can be used together to support risk-informed design decisions for component reliability, ignition prevention, sensor performance, and facility layout.

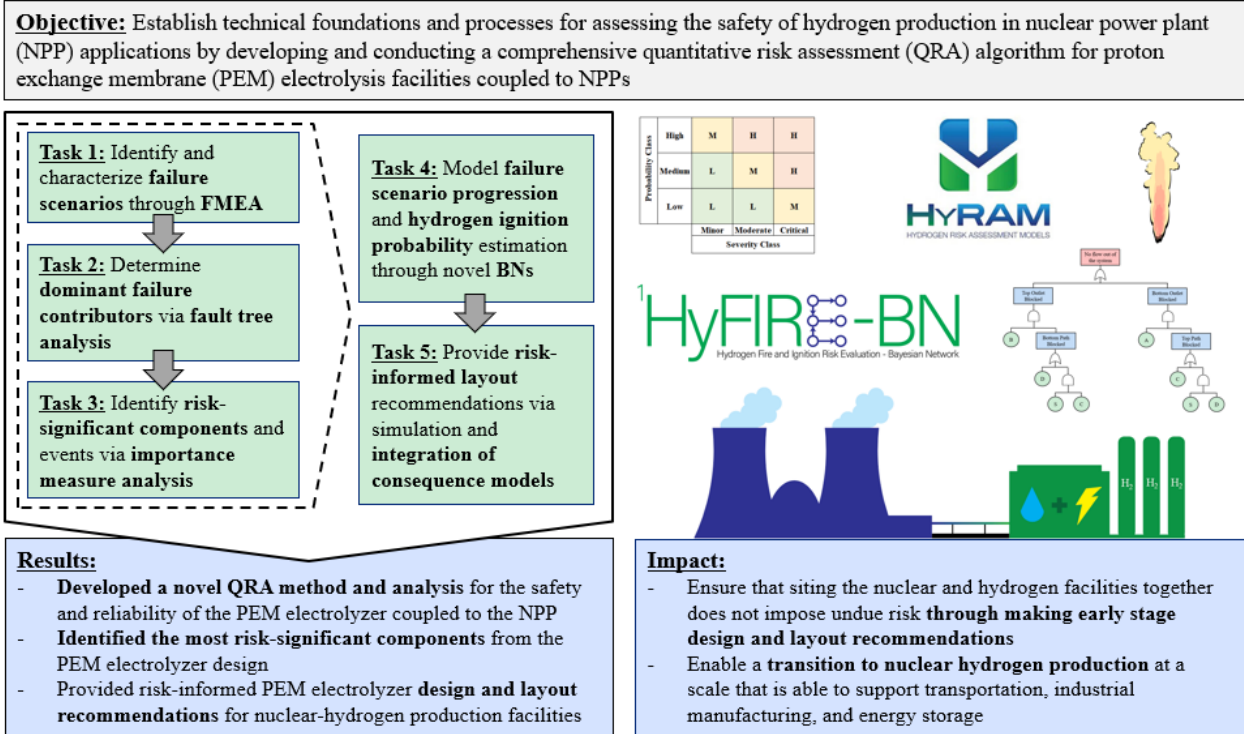
2. LITERATURE REVIEW AND RESEARCH GAP

Quantitative Risk Assessment (QRA) is a rigorous methodology used to evaluate the scenarios, frequencies, and consequences of undesirable events in complex engineering systems. The systematic QRA approach provides a repeatable scientific process that accounts for the factors and uncertainties influencing system risk. QRA has been used to modify the National Fire Protection Association's Hydrogen Technologies Code (NFPA 2) for separation distances for hydrogen fueling stations [3], to evaluate the safety of a lab-scale electrolyzer [4], and to provide design recommendations for light duty hydrogen vehicles [5]. Groth and Hecht [6] demonstrated the value that QRA has added to the hydrogen industry through the development and revision of codes and standards. The use of QRA to inform requirements and demonstrate compliance with standards for hydrogen fueling stations has been well established, with these practices also applicable to other hydrogen technology areas [8], [9], [10], [11]. While the electrolyzer stack itself has been a primary area of research in risk and reliability, relatively few studies have applied these analysis techniques to the PEM electrolyzer system. These papers are outlined in Al-Douri and Groth [12]. Additionally, although the utilization and transmission of hydrogen have been well studied from a risk perspective, a QRA aimed at informing the layout of coupled nuclear-PEM electrolysis plants for hydrogen production has not been completed [12].

Idaho National Laboratory (INL), in collaboration with Sandia National Laboratory (SNL), has published multiple reports regarding the coupling of a high-temperature electrolysis facility (HTEF), which uses Solid Oxide Electrolyzers (SOEs), to an NPP. Vedros et al. [13] conducted a Level I PRA on both a boiling water reactor (BWR) and a pressurized-water reactor (PWR) considering the addition of a heat extraction system to these reactors. This heat extraction system is a necessary component for providing appropriate steam and heat input to the electrolyzer. These PRAs were performed to demonstrate to the Nuclear Regulatory Commission (NRC) that NPP safety is not negatively affected by the addition of the heat extraction system or by the presence of a 100 MW HTEF at different separation distances. This analysis incorporated the report by Glover et al. [14] at SNL, which calculated hydrogen leak frequencies at various levels for an HTEF. They also characterized the consequences of detonations and jet fires to vital NPP structures using HyRAM and different analytical models. Using these results, Vedros et al. found that a 1 km separation distance is a more favorable placement than 0.5 km, but that 0.5 km is a feasible option. An additional report from Vedros et al. [15] expanded the original PRA of boiling and pressurized water reactors to include an updated heat exchanger design and the effects of electrical connections between the HTEF and the NPP. The report also includes a conceptual design for a 100 MW HTEF. These analyses confirm the separation-distance recommendations made in the original INL report. A final report by Christian et al. [16] further expanded the PRA to include the effect of a larger 1150 MW HTEF design, as well as continued research efforts for a 100 MW HTEF design. Due to the fundamental differences between PEM and SOE technologies, these results cannot be directly translated to a nuclear-hydrogen facility using PEM electrolysis.

In this work, we present a condensed summary of the methodology and results for a QRA of a PEM electrolyzer system. We evaluate the risks, including scenarios, probabilities, and consequences, associated with normal and standby operation. Figure 1 summarizes the methodology, key results, and impacts from the work. The QRA identifies risk-significant fires and detonations that could introduce new, previously uncharacterized hazards to infrastructure and safety-critical components in both the NPP and PEM electrolyzer systems. By advancing understanding of the hazards associated with operating a hydrogen facility at an NPP, we provide technical evidence to support appropriate risk mitigation for these facilities.

Figure 1: QRA Workflow for Nuclear-Integrated PEM Electrolysis



3. SYSTEM DESCRIPTION AND QRA SCOPE

We analyze a production-scale 1 MW PEM electrolyzer design shown in Figure 2. The system operates at 30 bar on the hydrogen side of the system and 70-80 °C at the stack. One electrolyzer system is capable of producing up to 18 kg of hydrogen per hour. A full piping and instrumentation diagram and description of the process flow is provided in [17] and [18]. For the QRA on the electrolyzer system, we decomposed the system into six functional groups: water processing and supply, water cooling, electrolysis, oxygen processing, hydrogen processing, and nitrogen supply. This decomposition preserves the process dependencies that are relevant to safety while keeping the analysis traceable at the component level. We considered four primary system-level undesirable events: hydrogen release, oxygen release, nitrogen release, and hydrogen-oxygen mixing. We further separated hydrogen-oxygen mixing by flow direction and operating mode because membrane degradation, pressure differences, standby behavior, and detection pathways differ between hydrogen migration to the oxygen side and oxygen migration to the hydrogen side.

To evaluate the effect that a hydrogen facility, consisting of multiple electrolyzer systems and auxiliary buildings, could have on the integrated NPP, we designed the model facility shown in Figure 3. The proposed facility design models 30 PEM electrolyzer units in parallel with a shared DI water supply and a common hydrogen drying skid. The facility design is intended to represent a generic PEM electrolyzer facility and is further documented in [19]. Although orientation and sizing will differ among implementations, the structures necessary for hydrogen production are expected to remain similar across design variants. In a nuclear-integrated setting, we consider the effects of hydrogen fires, explosions, or secondary releases on critical infrastructure and safety-relevant plant functions, in addition to the earlier focus on personnel, hydrogen equipment, and nearby structures from the electrolyzer system analysis. We focused on events that could propagate beyond the electrolyzer container or influence facility layout, including releases capable of accumulating flammable hydrogen-air mixtures and explosions capable of damaging adjacent piping or structures.

Figure 2: PEM electrolyzer system process flow diagram

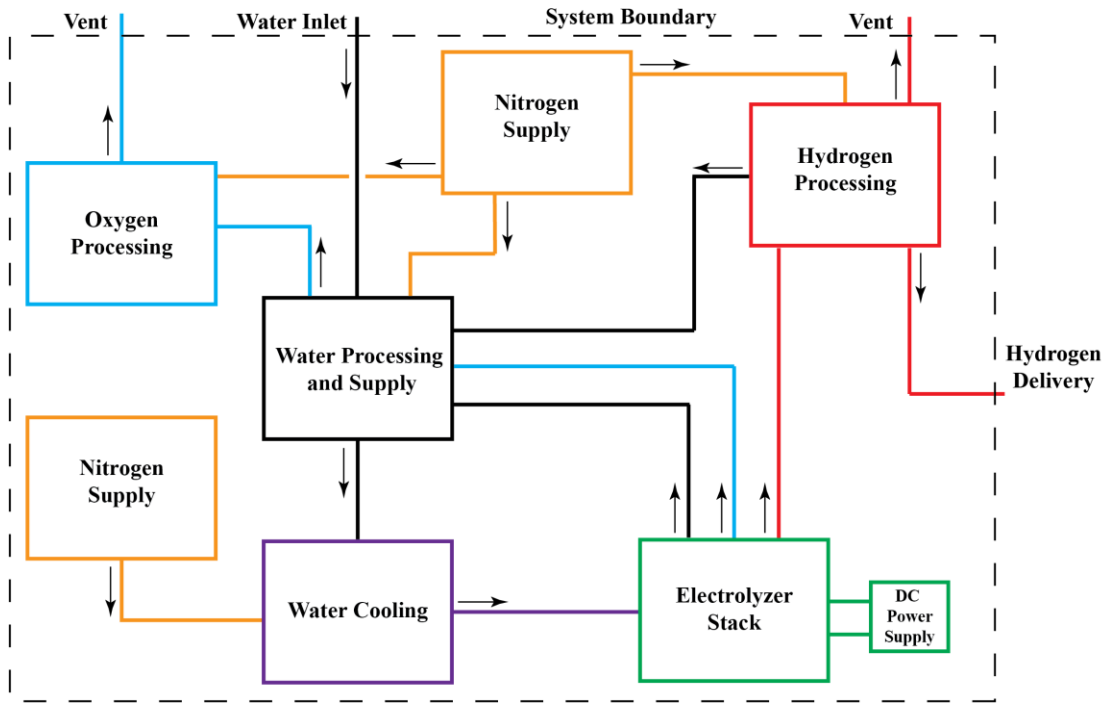
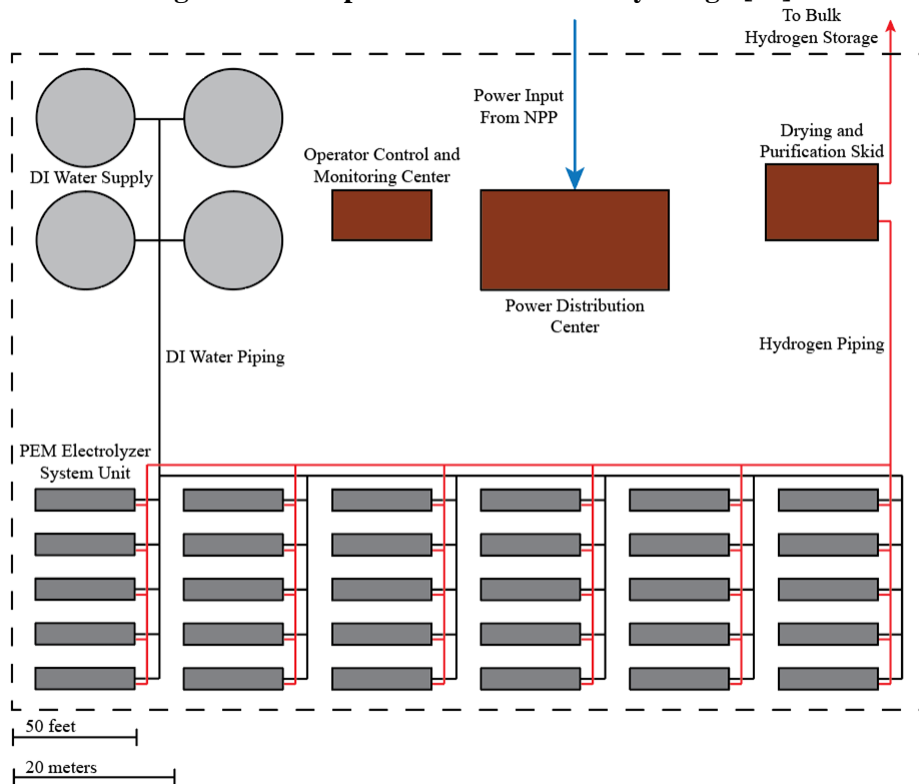


Figure 3: Example 30 MW PEM facility design [19]



4. QRA FRAMEWORK

Our work uses the systematic methodology of QRA to integrate hazard identification, frequency quantification, ignition modeling, consequence analysis, and risk-informed siting metrics. The FMEA defines credible failure scenarios. The fault trees quantify how combinations of component failures lead to top events. Importance measures identify where reliability improvements or redesign are most influential. Bayesian networks estimate the probability that a hydrogen release progresses to immediate or delayed ignition. Consequence models determine how far and how severely a jet fire or explosion could affect structures and personnel. Finally, location-specific individual risk (LSIR) and location-specific site risk (LSSR) translate scenario frequencies and consequences into spatial design guidance.

4.1. Failure Modes and Effects Analysis

We used failure modes and effects analysis (FMEA) to provide a systematic, component-level structure for early-stage design evaluation. For each component, we evaluated applicable failure modes, mechanisms, local effects, end effects, detection or mitigation functions, and qualitative severity and likelihood. We did not treat the resulting risk ranking as the final risk metric. Instead, we used it to make the scenario search reproducible and to determine which failure mechanisms warranted quantitative modeling. This process identified more than 850 modal-level failure scenarios and created a comprehensive basis for subsequent fault tree construction [17].

4.2. Fault Tree and Importance Measure Analysis

We translated the FMEA results into top-down Boolean fault tree models for system-level failure events. We developed separate fault trees for hydrogen migration to the oxygen side during normal operation, hydrogen migration to the oxygen side during hot standby, oxygen migration to the hydrogen side during hot standby, major hydrogen release, minor hydrogen release, hydrogen release from low-concentration lines, oxygen release, and nitrogen release [18]. We parameterized component failure probabilities with existing reliability data banks and available industry data where possible. The quantified fault trees produced top-event frequencies and minimal cut sets, which identify the combinations of failures sufficient to cause each top event.

We used risk reduction worth (RRW) and risk achievement worth (RAW) to evaluate component importance. RRW estimates how much system risk decreases if a component or event is assumed to be perfectly reliable. RAW estimates how much system risk increases if that component or event fails with certainty. Together, these measures distinguish between components that drive current risk and components whose failure would substantially erode safety functions. This distinction is important for redundant sensing systems because common-cause failures or shared environmental vulnerabilities can reduce the effectiveness of apparent redundancy.

4.3. Hydrogen Ignition Probability Modeling

A hydrogen release does not necessarily result in a jet fire or explosion. Ignition probability depends on release size, release dynamics, confinement, ventilation, electrostatic sources, hot surfaces, electrical equipment, debris, maintenance quality, human presence, and other coupled factors. A fixed lookup probability cannot adequately represent these dependencies. To address this limitation, we developed Bayesian networks for hydrogen ignition probability estimation. The networks represent immediate and delayed ignition pathways with directed acyclic graphs and conditional probability tables that connect influencing factors to ignition modes [20].

We designed the resulting model, HyFIRE-BN, as an intermediate approach between simple expert lookup tables and computationally expensive CFD-based ignition modeling. The model contains sufficient detail to represent causal mechanisms and design-specific conditions, while remaining simple enough for repeated QRA calculations and scenario comparison. We produced separate outputs for immediate ignition of leaks, immediate ignition of ruptures, delayed ignition of leaks, and delayed ignition of ruptures.

4.4. Consequence Modeling and Risk Integration

In the consequence stage, we evaluated both mechanical and thermal effects. We estimated vapor cloud explosion overpressures with Kingery-Bulmarsh, Baker, and TNO analytical models over varying accumulation times and release assumptions. We modeled jet fire behavior with HyRAM+ to estimate flame length, temperature profile, and heat flux for selected hydrogen release sizes. We used finite element analysis (FEA) to evaluate the vulnerability of exposed hydrogen piping to overpressure loading, with special attention to pipe length, supports, and anchorage. We then integrated these consequence outputs with scenario frequencies and ignition probabilities to calculate LSIR and LSSR for candidate layout options [19].

This integration converts a conservative deterministic spacing exercise into a risk-informed facility layout analysis. Deterministic thresholds identify where a selected overpressure value may be exceeded. Probabilistic metrics incorporate initiating release frequency, ignition likelihood, and the effects of scenario uncertainty on site risk. This approach produces design information that is more directly tied to the performance objectives of the integrated nuclear-hydrogen facility.

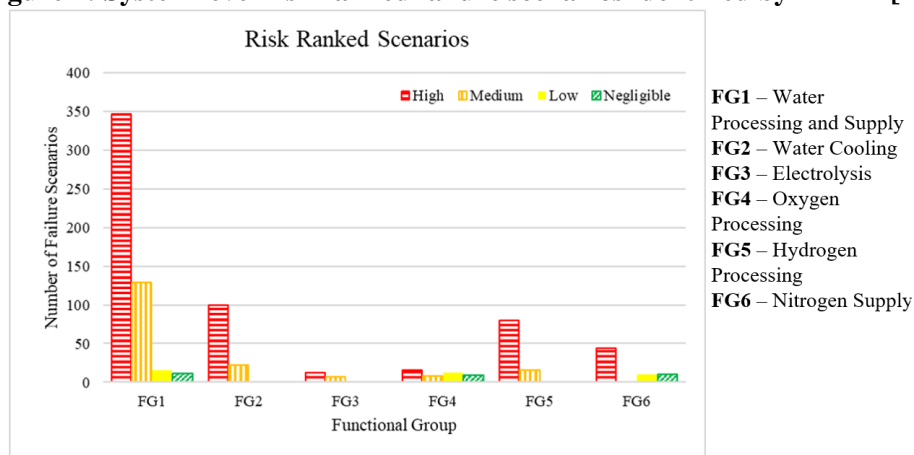
5. RESULTS

5.1. Failure Scenario Screening Results

The FMEA showed that the water processing and supply group contributed the largest share of high-risk scenarios. Many of these scenarios arise from water starvation, blocked valves, contamination, poor water quality, or failures that reduce the stack's ability to maintain proper water supply. These mechanisms can accelerate membrane degradation or create conditions that allow hydrogen crossover. The water cooling group also emerged as risk-relevant because insufficient heat removal can damage the stack and increase the likelihood of gas crossover. The hydrogen processing group introduced an additional safety concern because leaks or ruptures on the hydrogen side can accumulate in the containerized facility and produce a combustible mixture if detection and mitigation fail [17]. PEM electrolyzer risk also depends on water supply, water quality, cooling, and separation functions because these functions protect stack integrity and crossover margins. This insight is important for nuclear-integrated applications because standby, startup, and load-following operations can change stack conditions and shift the relative importance of crossover scenarios.

Across the workflow, each method advances the analysis. The FMEA creates the scenario inventory. The fault trees convert those scenarios into top-event frequencies and minimal cut sets. The importance measures identify reliability priorities. The ignition Bayesian networks quantify release progression. The consequence integration translates the results into spatial risk metrics. Together, these methods form an integrated design-oriented analysis rather than a collection of separate evaluations.

Figure 4: System level risk ranked failure scenarios identified by FMEA [17]



5.2. Fault Tree and Importance Measure Results

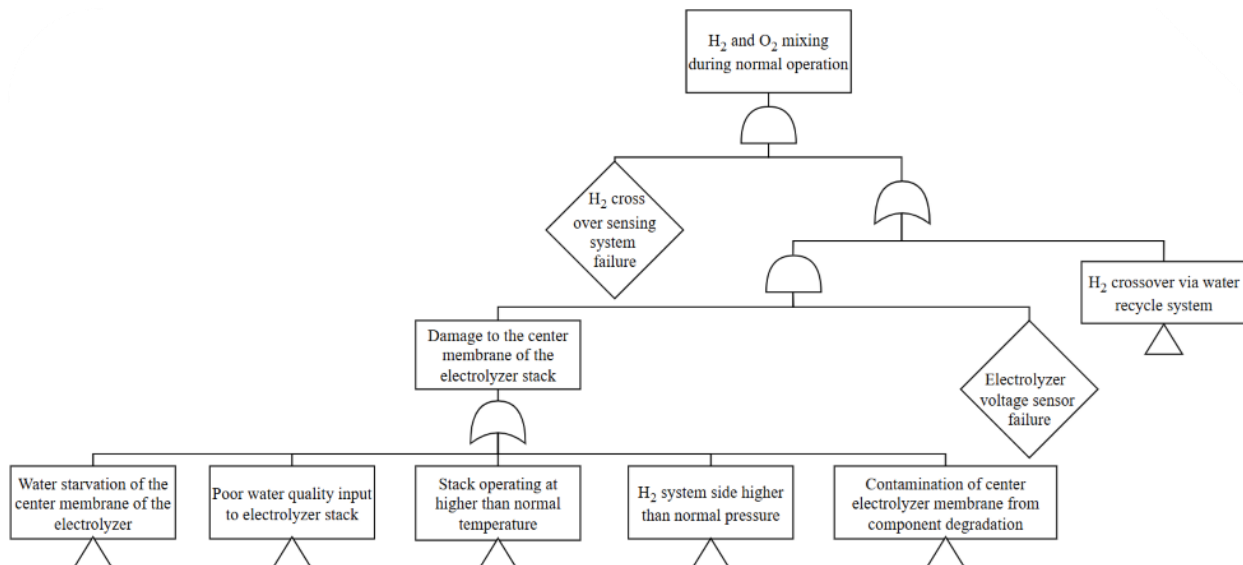
Hydrogen migration to the oxygen side of the system dominated the gas-mixing results. We calculated frequencies on the order of 10^{-2} failures per electrolyzer-year for both normal and hot standby operation. In contrast, oxygen migration to the hydrogen side during hot standby occurred on the order of 10^{-8} failures per electrolyzer-year [18]. This large difference reflects the pressure-driven tendency for hydrogen to cross toward the oxygen side and the system design features that create additional pathways through the water recycle subsystem.

The cut set results did not show single-point failures for the modeled top events, indicating that the baseline design includes multiple barriers or detection functions before system-level failure occurs. However, the analysis did reveal pairwise combinations that remain vulnerable to common-cause failures, particularly among interior hydrogen sensors. This finding affects how redundancy should be interpreted. Multiple sensors provide robust protection only when their failure mechanisms, placement, environmental exposure, power supply, calibration, and maintenance are sufficiently independent.

The fault tree and importance measure results also identified the water recycle subsystem as a major contributor to hydrogen migration to the oxygen side. When we removed the recycle line in a comparative redesign, the frequency of gaseous mixing decreased to approximately 10^{-9} failures per electrolyzer-year [18]. This result suggests that designers should eliminate the water recycle function when the process design allows, or otherwise add reliability to water level sensing, water sealing, and isolation functions that prevent gas migration through the recycle path. The oxygen-to-hydrogen crossover model also highlighted the need for reliable voltage monitoring for membrane degradation because voltmeter failure appeared in the top cut sets for oxygen migration to the hydrogen side.

For hydrogen release, the models showed that minor releases occurred approximately three orders of magnitude more frequently than major releases [18]. This result is important for risk management because small leaks may be less evident to pressure instrumentation but more likely to occur and accumulate in a containerized facility. Designers should also account for low-concentration hydrogen lines, even though they contain less hydrogen. Their leak frequencies had the same order of magnitude as other hydrogen leak pathways, and slow accumulation can still become safety-significant if detection or ventilation is insufficient.

Figure 5: Hydrogen migrating to the oxygen side of the system during normal operation model, created via fault tree analysis [18]



5.3. Ignition Probability Results

The Bayesian network ignition models estimated nominal immediate ignition probabilities of 0.068 for a hydrogen leak and 0.091 for a hydrogen rupture. There are higher estimated delayed ignition probabilities, with values of 0.115 for a leak and 0.167 for a rupture [20]. These results follow expected hydrogen behavior: rupture scenarios generally create more energetic release dynamics than leaks, while delayed ignition allows the cloud to disperse, interact with equipment, and reach a broader set of ignition sources.

The alternative case studies demonstrate the value of a causal model. A high-temperature hot surface increased immediate ignition probability to 0.121 for leaks and 0.143 for ruptures, while poor safety design had a stronger effect on delayed ignition and increased delayed leak and rupture probabilities to 0.304 and 0.336, respectively [20]. Human error, improper maintenance, internal or external debris, reflected shock ignition, and simultaneous oxygen or nitrogen releases also changed scenario progression probabilities. A fixed lookup ignition probability would obscure these design-dependent effects.

Table 1: Selected HyFIRE-BN Ignition Probability Results [20]

Case	Immediate leak	Immediate rupture	Delayed leak	Delayed rupture
Nominal	0.068	0.091	0.115	0.167
High temperature hot surface	0.121	0.143	0.175	0.210
Improper maintenance	0.072	0.110	0.206	0.242
Poor safety design	0.074	0.108	0.304	0.336
Human error	0.104	0.124	0.186	0.236

5.4. Consequence and Location-Specific Risk Results

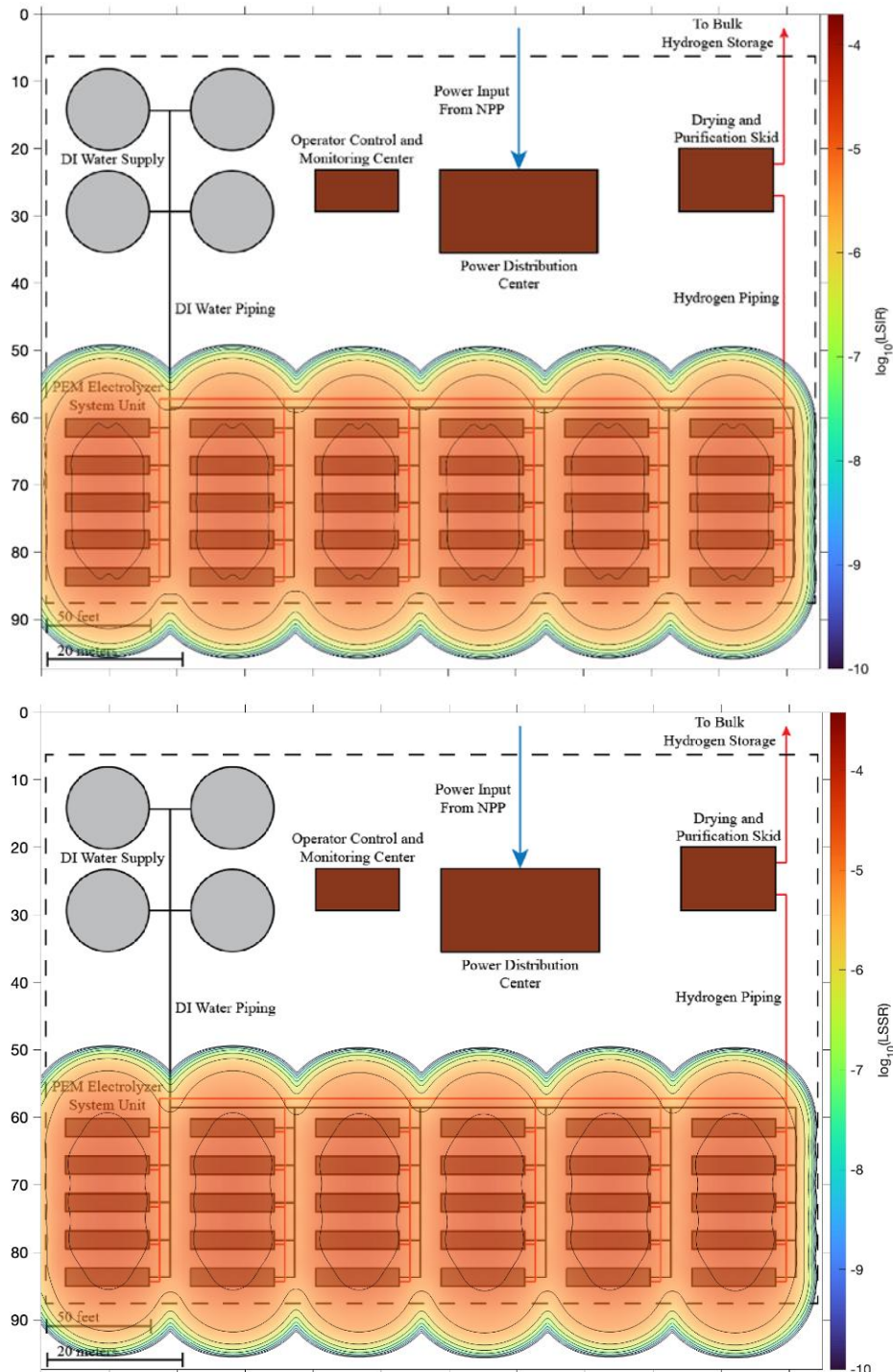
The explosion consequence analysis compared analytical overpressure models across hydrogen accumulation times and facility distances. The models showed that hydrogen piping exiting each electrolyzer container could experience explosion loading and could become a source of secondary hydrogen release. We used FEA of Schedule 80S AISI 316L stainless steel piping to identify the highest stress concentrations near fixed ends and anchorage points. For example, in the evaluated 1.0 m piping models, peak overpressures required to exceed yield strength ranged from approximately 0.126 MPa for 1 in nominal pipe size to 0.718 MPa for 4 in nominal pipe size [19]. These results show that support design and exposed pipe routing should be included in hydrogen facility risk management, not only in mechanical design.

Jet fire modeling produced shorter-duration thermal effects relative to the spatial concern created by overpressure. We therefore treated jet fires as important secondary hazards, especially for equipment directly in the flame path. However, explosion overpressure and secondary release potential drove the facility layout recommendations more strongly than jet fire heat flux. This result depends on prompt detection and proper safety component placement; poor detection or isolation could increase the relevance of thermal effects.

The integrated LSIR and LSSR results demonstrate the value of connecting likelihood and consequence. A deterministic interpretation of blast-resistant building thresholds suggested setback distances of approximately 26-37 m for critical infrastructure. When we integrated overpressure consequences with release frequencies, ignition probabilities, and location-specific risk metrics, selected layouts supported approximately 10 m separation while remaining below risk acceptance thresholds [19]. This finding should not be interpreted as evidence that a 10 m separation distance is deterministically safe. Rather, it indicates that a probabilistic analysis can reduce the conservatism inherent in worst-case deterministic screening and identify shorter separation distances that remain compliant with risk-acceptance criteria. We interpret the result as evidence for risk-informed layout evaluation rather than as a generic prescriptive distance.

Sensor response time also affected integrated risk, but the effect was nonlinear. Most deflagration models showed only limited LSIR increases beyond approximately 30 seconds of response time. The largest risk reduction occurred when response time improved into the 1-10 second range [19]. This provides a concrete target for sensor development and layout optimization: response improvements are most valuable when they are fast enough to interrupt early accumulation and ignition pathways.

Figure 6: Risk-Informed Layout and LSIR/LSSR Evaluation



6. RISK-INFORMED DESIGN IMPLICATIONS

The integrated QRA produces several design implications for nuclear-integrated PEM electrolysis. First, risk reduction should not focus only on stronger containment of hydrogen piping. Component reliability in water supply, water recycle, cooling, and membrane monitoring functions can substantially influence the probability of hydrogen-oxygen mixing. Because crossover can originate from stack degradation and water-side failures, design reviews should treat process water quality, valve blockage, water seal reliability, and cooling adequacy as hydrogen safety controls.

Second, sensor redundancy should be treated as a system property rather than as a simple detector count. The fault tree and importance measure analysis showed that common-cause failures among interior hydrogen sensors can remain risk-significant even when designers install multiple sensors. A robust design should consider independent power, calibration, placement, environmental qualification, diagnostic coverage, maintenance intervals, and voting or shutdown logic. For containerized PEM units, leak detection is especially important because minor hydrogen releases occur more frequently than major ruptures and may not trigger rapid detection by in-line pressure instrumentation.

Third, designers should evaluate the water recycle subsystem as a potential gas migration pathway. The comparative analysis showed a substantial reduction in gas mixing frequency when we removed the water recycle line. If removal is not feasible, the system should incorporate improved water level sensing, reliable water seals, isolation logic, and monitoring capable of detecting conditions that enable hydrogen transfer into the oxygen-water separator.

Fourth, ignition modeling should reflect the actual facility environment. Poor safety design and improper maintenance had large effects on delayed ignition probabilities, while high-temperature surfaces had strong effects on immediate ignition. Ignition probability is therefore not a static property of hydrogen alone. It depends on equipment condition, maintenance quality, ventilation, ignition source control, and operating context. Risk assessments that use a single generic ignition probability may miss design tradeoffs that are important for nuclear-hydrogen siting.

Finally, siting decisions should use probabilistic metrics in addition to deterministic threshold distances. Deterministic overpressure contours provide valuable screening information, but they can overstate land requirements when used alone. LSIR and LSSR allow designers to compare layout alternatives while preserving the contributions of release frequency, ignition probability, exposure, and consequence. For nuclear-integrated facilities, the objective is not only to avoid equipment damage, but also to maintain confidence that hydrogen production does not introduce unacceptable risk to nuclear plant functions.

7. CONCLUSION

This paper summarizes an integrated QRA of a PEM electrolyzer facility coupled to an NPP. We connected FMEA, fault tree analysis, importance measures, Bayesian network ignition modeling, analytical and numerical consequence models, and location-specific risk metrics. The analysis establishes a transparent method for evaluating the risk triplet for nuclear-integrated PEM electrolysis: credible failure scenarios, their likelihood, and their consequences.

The most important technical findings are that water processing and supply functions, cooling performance, water recycle pathways, membrane degradation detection, and interior hydrogen sensing are central to system risk. The FMEA identified more than 850 modal-level scenarios. The quantified fault trees showed that hydrogen migration to the oxygen side dominates gas mixing and that water recycle redesign can reduce mixing frequency by several orders of magnitude. The ignition Bayesian networks produced design-sensitive ignition probabilities, showing that maintenance, ignition source control, and safety design can substantially change immediate and delayed ignition likelihood. The consequence integration showed that

deterministic blast distances of 26-37 m for selected critical infrastructure may decrease to approximately 10 m in certain layouts when analysts apply probabilistic LSIR and LSSR criteria.

Together, these results show that QRA can provide actionable design guidance for nuclear-integrated hydrogen production. The framework supports component-level improvements, sensor performance targets, safety control evaluation, and facility layout decisions. Future work should extend the analysis to additional electrolyzer scales and configurations, incorporate external hazards and detailed nuclear plant response models, and continue improving hydrogen component reliability data and ignition model validation.

Acknowledgements

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