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A Case Study of System Reliability and Availability of Blue Hydrogen Production

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The transition toward a low-carbon future has positioned hydrogen as a critical energy carrier, with blue hydrogen emerging as a bridge between conventional fossil fuels and cleaner alternatives. Blue hydrogen is produced by reforming natural gas with carbon capture and storage (CCS) to reduce CO_2 emissions, representing an intermediary solution between grey and green hydrogen. However, ensuring the reliability of the complex systems (e.g. the hydrogen production systems) is critical for economic feasibility, operational safety, and environmental sustainability.

This paper analyses the system reliability of blue hydrogen production technologies, evaluating the challenges in reliability modelling and assessment specific to these systems. It addresses key issues such as the integration of multiple technologies, data limitations, operational risks, and the performance of critical equipment. Through this analysis, the study highlights the importance of robust reliability engineering frameworks towards the challenges of blue hydrogen systems.

Keywords: Blue hydrogen, Reliability, Availability, Maintenance, System failures, Hydrogen production.

1. Introduction

During the global energy transition, hydrogen plays a critical role for energy carrier. Among the various forms of hydrogen, blue hydrogen is one of the essential transitional solutions. Blue hydrogen can be produced via Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR) of natural gas, with Carbon Capture and Storage (CCS) technologies used to capture CO_2 emissions.

Although blue hydrogen offers benefits for the energy transition, there are complex technologies involved from hydrogen production to CO_2 transportation and storage systems. All of the systems need to function consistently to avoid economic losses, safety hazards, and environmental impacts. Failures in critical components such as reactors, hydrogen compressors, affect the system's performance and reliability severely. The reliability and availability of such systems should be systematically evaluated to prevent failures that could lead to production losses, or inefficient operations. However, according to literature review, there is a lack of comprehensive studies evaluating the reliability of these systems from production to storage.

This paper addresses the system reliability and availability evaluations of blue hydrogen systems by evaluating the challenges in reliability and maintenance issues with diverse technologies, failure data collection and usage, and operational risks associated with critical equipment.

The objective of this paper is to apply the RAM methodology for evaluating the reliability and availability of blue hydrogen systems, focusing on SMR hydrogen production (auxiliary and utility systems are not part of the study). Carbon capture and CO_2 storage components are not a focus in the current paper. This paper identifies potential failure modes for different critical systems/equipment and calculates overall system reliability, with a case study illustrating practical application.

2. SMR technology on Hydrogen Production

SMR is the most common technology for producing hydrogen. In this process, natural gas reacts with steam under high pressure and temperature in the presence of a catalyst to produce hydrogen and carbon monoxide. The carbon monoxide is further reacted with steam in a water-gas shift reaction to produce additional hydrogen and carbon dioxide. This method is widely used due to the abundance of natural gas and the efficiency of hydrogen extraction. However, it might be less efficient compared to Autothermal Reforming, which integrates the heat generated in the reaction to enhance hydrogen production. Typical equipment units included in the SMR reforming process are:

- Reformer Furnace: Provides high-temperature conditions (around 800-1,000°C) for the methane-steam reaction. Typically a large furnace with catalyst-filled tubes.
- Catalysts: Nickel-based catalysts are commonly used to facilitate the reforming reaction.
- Shift Reactors: Low- and high-temperature water-gas shift reactors are used to convert CO into CO_2 and produce more hydrogen.
- Heat Exchangers: Recover heat from the hot gases to improve the system's efficiency.

3. Methodology of the study

3.1. *Step 1: Identify equipment and assess equipment criticality*

The production system can be divided into subsystems/equipment such as reactors, Pressure Swing Adsorption (PSA) unit, compressors, storage tanks.

However, not all components will be equally critical to system performance and reliability. The first step would be identify the critical equipment whose failure or malfunction could result in substantial impacts, such as:

- Operational downtime or significant reductions in production efficiency.
- Increased safety risks or hazards, such as leaks in pressurized systems or failures in hydrogen containment.
- Elevated costs from cascading failures or frequent maintenance.

To evaluate the criticality of equipment/ components, the following systematic approach is recommended:

Identify Failure Modes: Analyze each component to determine potential failure modes, failure causes, and failure consequences.

Assess Impact on System Performance: Determine the effect of each failure mode on the overall system. For example, reactor or compressor failure might cause a complete hydrogen production shutdown, whereas valve might have localized or globalized effects depends on the location of the valve and the functionality.

The technique applied for criticality classification can be performing Failure Modes, Effects, and Criticality Analysis (FMECA) based on systematic system/equipment review.

3.2. *Step 2: Collect Failure Data*

For hydrogen related equipment, most of the failure and repair data are not sufficiently available from databases. There are several ongoing research or industrial work on establishing the hydrogen reliability databases. Task 2 in the current research project Hydrogeni WP 4.2 is putting on effort on developing the framework for hydrogen reliability databased.

Failure and Repair data for each component based on historical data, operating conditions, and maintenance records provides essential input for the reliability and availability analysis. Example of Failure data includes failure rate, failure modes, failure causes, failure mechanism. Example of repair data includes downtime, mobilization time, active repair time, run down/ramp up time, post repair time.
Relevant definitions are provided in below:

- Failure data: data characterizing the occurrence of a failure event (ISO 20815, 2010)
- Failure mode: effect by which a failure is observed on the failed item. (ISO 20815, 2010)
- Failure rate: limit, if this exists, of the ratio of the conditional probability that the instant of time, T, of a failure of an item falls within a given time interval, [t, (t + Δt)] and the length of this interval, Δt, when Δt tends to zero, given that the item is in an up state at the beginning of the time interval, See ISO 14224:2006, Clause C.3 for further explanation of the failure rate. (ISO 20815, 2010)

- Mobilization time: Mobilization of spares, personnel, maintenance resources. (OREDA, 2015)
- Active Repair Time (MTTR): The part of the maintenance time during which a maintenance action is performed on an item, either automatically or manually, excluding logistic delays. (OREDA, 2015)
- Restart delay= Run-down/ramp-up+ post repair: Any operational time needed to rundown/ ramp-up production before/after equipment repair.

An illustration of different phases of downtime is illustrated in the Figure 1.

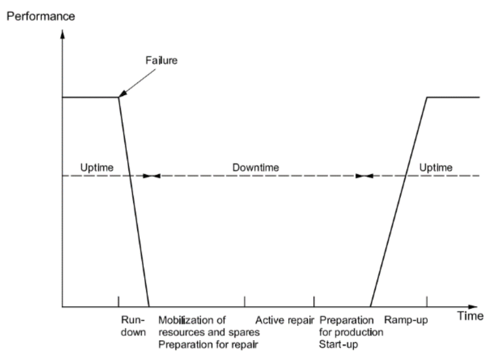

Fig. 1. Illustration of downtime associated with a failure event (ISO 20815, 2010)

3.3. *Step 3: Reliability and RAM Modelling and calculation*

The reliability model and reliability block diagrams (RBDs) or Markov models need to be developed to visualize system reliability and availability. There are different reliability modelling approaches:

3.3.1. *Fault Tree Analysis (FTA)*

Fault Tree Analysis (FTA) is a top-down approach to failure analysis that begins with identifying an undesirable event (e.g., system failure) and works downward to uncover root causes or component failures that lead to this event. To perform a FTA, it needs to first identifying top-level failures, and then decomposing the top-level failures into sub-events which can cause the failures and break down the event into more sub level events. The failure causes need to be analysed to identify and analyze the root causes of these sub-events. Then based with quantified the likelihood of each event, the overall system reliability can be calculated.

3.3.2. *Reliability Block Diagrams (RBD)*

RBD is a graphical method used to represent the relationship between components in a system. Components are arranged in blocks based on their configuration (series or parallel). This method allows for the visualization of how individual component reliability or availability affects the overall system reliability.

3.3.3. *Markov Models*

Markov models are particularly useful for dynamic systems where component states change over time. Components can transition between operational, failed, and repair states. This method allows for modelling repairable systems, such as compressors or pumps, and calculating overall system reliability over time.

3.3.4. *Software simulation*

Different software are developed to perform dynamic simulations. In this study, Miriam RAM Studio is used as software simulation tool for production availability estimation. Miriam RAM Studio provides advanced capabilities for reliability, availability, and maintainability analysis, supporting complex system modelling and simulation. It is a cloud-based production performance simulation tool developed for the oil & gas and process industries. Miriam RAM compares alternatives for increased productivity, estimates expected cost and downtime each year of operation, and computes the influence of an individual item in the loss of production.

3.4. *Step 4: Present the Reliability and RAM Modelling results*

Commonly used parameters in reliability assessments include:

- Mean Time Between Failures (MTBF)
- Mean Time to Repair (MTTR)
- Equipment Failure Rate (λ)
- Availability (A): A=MTBF/(MTBF+MTTR)

Relevant definitions can be found in ISO 20815 and IEC 60050-191.

3.5. *Step 5: Sensitivity Analysis*

The purpose of the sensitivity study is to understand how variations in system parameters, operational scenarios, design configurations, etc. affect overall system performance. This study helps identify critical components or factors that have the most significant impact on system reliability and availability. By conducting a sensitivity analysis, organizations can improve the design, optimize maintenance, spare part, and resource allocation more effectively.

Scenarios that can be performed in sensitivity studies include:

- Redundancy Levels: Studying the effect of adding or removing redundancy in system components.
- Component Failure Rates: Analyzing how changes in individual component failure rates impact overall system reliability and availability.
- Repair Times: Evaluating the effect of varying repair times on system availability.
- Maintenance Strategies: Assessing the impact of different maintenance schedules and strategies on system performance.
- Resource Availability: Investigating the impact of varying levels of maintenance resources (e.g., personnel, spare parts) on system downtime and availability.
- Operational Conditions: Examining how different operational conditions influence system reliability.

4. Case Study

4.1. *System Overview*

An illustrative example for Steam methane reforming system is developed based on the case study presented in (Oni, et al. 2022).

The illustrative example of SMR process includes a reforming reactor, water shift reactors (WGS, high-temperature and low-temperature), syngas purification, CO2 compression, transportation, sequestration, and hydrogen storage. The process flow diagram in Figure 2 shows the main equipment/skids included in the process.

In this example, hydrogen production process begins in a reforming reactor, where methane from natural gas reacts with steam under high temperatures (700–1,000°C) and pressures (20–40 bar) in the presence of nickel-based catalysts. This produces syngas, a mixture of hydrogen and carbon monoxide, which is further processed in WGS reactors.

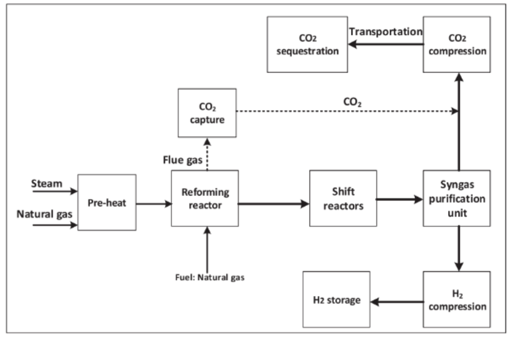

Fig. 2 Illustrative SMR process (Oni, et al. 2022)

In the WGS stage, the syngas is fed through two reactors arranged in series. The high-temperature shift reactor uses iron-chromium oxide catalysts to convert carbon monoxide into carbon dioxide while producing additional hydrogen. The low-temperature shift reactor, utilizing copper-zinc-alumina catalysts, further reduces residual carbon monoxide levels. The hydrogen-rich gas is purified using amine scrubbing and PSA unit, ensuring high purity. If Carbon Capture and Storage (CCS) is implemented, carbon dioxide emissions from the purification unit are compressed and transported for storage, enhancing environmental reliability.

4.2. *Equipment identification and criticality evaluation*

Key equipment for each process parts, with criticality and typical failure modes are analyzed:

(i) Pre-heat

Function: Methane and steam must reach a high temperature (typically 400–600°C) before entering the reforming reactor to ensure the reaction starts efficiently. The pre-heat function here is to ensure that incoming gases are at a compatible temperature, to reduce thermal stress and possibility of potentially damaging the catalyst and reactor structure.

Critical equipment in this process: Heat Exchangers, e.g. in Shell and Tube

Equipment Reliability: The shell and tube heat exchanger is widely used in reforming process due to its ability to handle high-pressure and high-temperature conditions. In this setup, one fluid (such as flue gas or hot syngas) flows through the tubes, while the other fluid (such as methane and steam) flows over the tubes in the shell. This arrangement provides efficient heat transfer and is robust enough for the demands of SMR applications.

In general, shell and tube heat exchangers are robustness in high-pressure and high temperature environments, and have a proven track record for reliability. They are designed to handle a wide range of temperatures (up to 1,000°C) and pressures. The typical failure modes for S&T heat exchanger including:

- Corrosion: Over time, heat exchangers can be prone to corrosion. Materials used in SMR S&T heat exchangers often include alloys that resist such corrosion, but they still require regular monitoring and maintenance.
- Fouling and Scaling: The build-up of contaminants on the heat exchange surfaces can reduce efficiency and increase pressure drop across the unit. Regular cleaning and maintenance is needed to mitigate this issue.
- Thermal Fatigue: Due to the significant temperature gradients between the hot gases and cooler fluids, thermal fatigue can occur, which may eventually cause cracking or failure of the heat exchanger tubes.

(ii) Reforming Reactor

Function: Converts methane and steam into syngas (hydrogen and carbon monoxide) through high-temperature reactions facilitated by nickel-based catalysts.

Critical equipment in this process: Reforming Reactor

Equipment Reliability: The reliability of reforming reactor dependent on material integrity under high-pressure and high-temperature conditions. Failure modes often include catalyst degradation and thermal fatigue of the reactor vessel.

(iii) Water-Gas Shift (WGS) Reactors

Function: Converts carbon monoxide in syngas to carbon dioxide and additional There can be two stage reactors.

Critical equipment in this process: One High-Temperature Shift Reactor, one Low-Temperature Shift Reactor

Equipment Reliability: Water-Gas Shift (WGS) reactors are generally reliable but are sensitive to catalyst poisoning and thermal cycling. Catalyst poisoning can occur due to contaminants in the feed gas, leading to reduced reaction efficiency and increased downtime for catalyst regeneration or replacement. Thermal cycling, caused by frequent temperature fluctuations, can lead to mechanical stress and potential damage to reactor components, thereby impacting overall reliability. Ensuring proper feed gas purification and stable operating conditions are crucial for maintaining the reliability of WGS reactors.

(iv) Syngas Purification Units (Amine Scrubber/PSA)

Function: Removes impurities such as carbon dioxide, resulting in high-purity hydrogen.

Critical equipment in this process: Amine Scrubber, PSA Unit, 2x100% hydrogen transfer pumps.

Equipment Reliability: Amine scrubber and PSA unit might have issues include fouling, which occurs when contaminants accumulate on surfaces, leading to reduced efficiency and increased maintenance. Corrosion is another significant concern, particularly for the Amine scrubber, as the chemicals involved can be highly corrosive, causing degradation of metal components over time. This can result in equipment failures and costly repairs.

According to Nguyen (Nguyen, 2023), PSA plays an important role in separating hydrogen from impurities in synthesis gas. PSA systems are chosen for their low energy consumption, precision, and ease of operation, as they do not require rotating equipment or circulation solutions (Yang, 1987). PSA units function through four stages: adsorption, depressurization, purge, and repressurization. These units often incorporate multiple adsorbers ("polybed") to maintain continuous throughput. Although additional beds improve performance, they also increase operational complexity. The first commercial PSA unit, featuring four adsorbers, was installed in 1966 (Yang, 1987), and currently, there are approximately 1,000 polybed PSA systems in operation worldwide.

In the (Nguyen, 2023) paper, the failure rate for the 4-bed hydrogen PSA system is computed by assuming that any critical failure from the valves leads to the failure of the corresponding adsorber line, causing system failure. This assumption allows for the calculation of the mean failure rate of one line by summing the mean failure rates of the five corresponding valves. However, the detailed failure data for the adsorbers is not included in PSA failure rate calculations.

In addition, the adsorber is presented in a simplified manner in the (Nguyen, 2023) paper without including the detailed instrumentations and other sub-units, etc. According to the vessel equipment boundary defined in OREDA, as shown in Figure 3, the inlet, outlet, pressure relief and drain valves are specifically excluded from the failure data collected for vessels. The only valves are calibration valves and instrument valves that form a pressure boundary (e.g. block valves, control valves, calibration valves, local indicators/gauges).

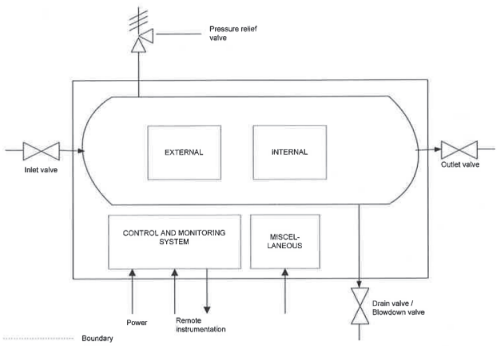

Fig. 3 Equipment boundary defined in OREDA for vessels (OREDA, 2015)

However, there is no failure data collected in OREDA for the adsorbers. We use general vessel data from OREDA for illustration purpose as data for adsorbers. The total critical failures for a vessel are 91 per 1 million hours. The critical failures modes distribution for a general vessel is shown in Table 1.

Table 1. Critical failures modes distribution for a general vessel in OREDA

Failure modes distribution-Critical failures	No of failures in 106 hours
Abnormal instrument reading	46
External leakage - Process medium	7
Fail to start on demand	1
Fail to stop on demand	1
Parameter deviation	24
Plugged/Choked	5
Spurious stop	1
Other	5
Unknown	1

From the data, it is evident that over 75% of critical failures in vessels are attributed to the control and monitoring systems. This insight is critical for evaluating maintenance mobilization time, spare part requirements, and maintenance planning. The failure distribution of control and monitoring system also indicate the need for robust maintenance strategies focusing on these systems to enhance reliability and reduce downtime.

(v) Compression and Storage Systems

Function: Compresses purified hydrogen for storage in high-pressure tanks.

Critical equipment in this process: 3 stage Hydrogen Compressors, 1 Storage Tank

Equipment Reliability: The compressor is subject to high mechanical stress and thermal cycling, making some potential wear, leaks, and premature failure if not properly maintained. The compressor's sealing materials must exhibit high resilience to withstand the pressures, temperatures, and corrosive environments in which they operate. More failure modes related with rotating equipment is also relevant.

The storage tank is subject to internal pressure fluctuations, which can lead to fatigue, deformation, or leakage over time.

4.3. *Data input*

Failure rate data for each component is gathered from industry databases (e.g., OREDA) or based on engineering judgment when there is no data available.

The mobilization time and restart delay are project-specific and depend on various factors such as the complexity of the system, availability of resources, geographical location, and the readiness of the team. Additional considerations include the type of equipment involved, type of failure modes related to each equipment, the extent of maintenance or repair required, and potential logistical challenges. Effective planning and coordination with suppliers and contractors are also crucial in minimizing delays and ensuring a smooth restart process.

In this study, for illustration purpose, we assumed all equipment have 5 hours personnel mobilization time and 1 hours restart delay in average. It is also assumed that all equipment has needed spare parts in case of failure, which means there is no spare mobilization time.

The equipment configuration and collected reliability and maintenance data used as input to RAM modelling is not shown in the paper but in the Hydrogeni Task 1 Memo (Gao & Bucelli. 2025).

4.4. *Reliability Modelling*

The RAM model in below is established in by using Miriam RAM studio tool. The RAM model representing simplified system about the SMR production. In the Miriam model, each process stage (square boxes in the figure) contains at least one equipment unit. The process stage is named after the main equipment, but the process stage may contain several other equipment units (valves, drives). For the RAM model, 2000 replications with 30 years lifetime are used when running the simulation. Note that the production availability model is a logical representation, not necessarily equal to the physical flow.

The RAM model produced for the SMR production system is presented in Figure 4.

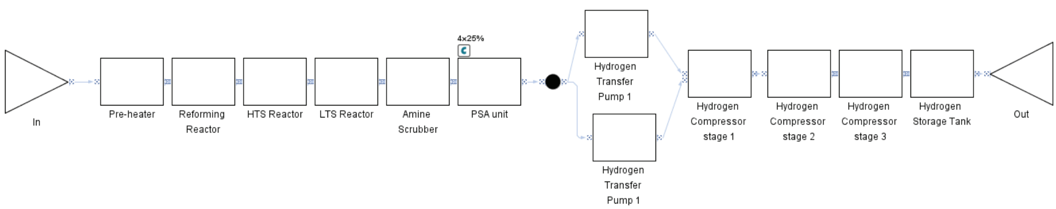

Fig. 4 RAM model for SMR production system

4.5. *Results*

The system's overall availability is 98.7%, with the hydrogen compressors contributing the most to system failures due to reactor and compressor issues.

Equipment contribution to overall production loss is presented in the Table 2.

The case study identifies critical equipment contribute to production loss which is the compressors, which have lower MTBF values and longer mobilization and repair time. Redundancy in the components or proactive maintenance strategies could significantly improve the system's reliability.

- Hydrogen compressors are most failure-prone and lowest availability due to internal and external leakage, low output, overheating, parameter deviation, etc., with longer repair times for some of the critical failure modes.
- Reliability and availability of a single Hydrogen Transfer Pumps could be low due to complexity and rotating properties, however, the 2x100% pumps have no significant contribution to production loss, due to the redundant configuration.
- Pre-heaters, Reforming reactors, LTS and HTS reactors, and Amine scrubbers show higher availability compare with compressors due to less rotating parts, most of the failures could be on the control and monitoring part which can be repaired in short time.
- Storage tanks demonstrate the lowest failure rates, reflecting their more passive role but with criticality in long-term operations.

The planned maintenance activities are not included in the study. Maintenance consideration could be:

- Reforming Reactor: Requires routine inspection for thermal stress and material degradation. Preventive maintenance and catalyst regeneration are crucial. Reliability aligns closely with OREDA data for high-temperature pressure vessels.
- WGS Reactors: Catalyst health monitoring significantly enhances reliability. Maintenance should align with defined routine catalyst replacement in maintenance program.
- Syngas Purification: Maintenance should focus on corrosion control and valve reliability. Study indicate PSA units are less reliable than other vessels due to much more instruments, valves and vessels involved and more complexed operational condition.
- Compression Systems: High-pressure hydrogen compressors require frequent seal inspections and lubrication to ensure consistent reliability.

The current model established in this study is for simplified process and built on high equipment level, study at detailed level can be performed with the similar methodologies. Sensitivity studies can be established to evaluate different design, operation and maintenance scenarios.

Table 2. Equipment contribution to overall production loss

Equipment	Production unavailability
Hydrogen compressor stage 1	0,24%
Hydrogen compressor stage 2	0,24%
Hydrogen compressor stage 3	0,24%
Pre-heater	0,14%
LTS Reactor	0,1%
HTS Reactor	0,1%
PSA unit	0,09%
Amine Scrubber	0,09%
Reforming Reactor	0,09%
Hydrogen Storage Tank	0,01%

5. Conclusions

This paper presents a methodology for calculating the reliability and availability of blue hydrogen production systems. The case study demonstrates that by application this approach, bottlenecks, e.g. key failure points and suggesting areas for improvement can be highlighted. Future work should focus on obtaining more hydrogen specific failure data and developing models for more complexed scenarios: e.g. different hydrogen production technologies, hydrogen transportation, CO_2 capture, storage and transportation that integrate renewable energy sources with blue hydrogen production.

By leveraging reliability data and implementing them into the reliability/RAM model, it helps with the system designers to identify the bottlenecks in design, operators can develop maintenance schedules and spare part tailored to the most failure-prone equipment, improving uptime and overall process safety.

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