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Enabling Dry Low Emission Hydrogen Combustion in an Existing Combined Heat and Power Plant: A Preliminary Risk Assessment

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This paper presents a Failure Modes, Effects and Criticality Analysis (FMECA) of a retrofitted dry low emission (DLE) hydrogen combustion technology in an existing gas turbine, potentially operable with natural gas/hydrogen mixtures up to 100% hydrogen. The FMECA assessment is not limited to the gas turbine itself, it also involves a combined heat and power plant, currently designed for natural gas. Failure modes and their effects are identified and analyzed to define possible safety concerns associated with the retrofitted gas turbine and the connected systems and processes. Known and existing mitigation measures are also addressed, with the goal of identifying potential knowledge gaps and future research activities, referring to the "as low as reasonably practicable" (ALARP) principle. Aiming at a comprehensive representation of the most relevant scenarios in terms of failure probability, failure consequence and detectability, suitable mitigation strategies are identified. The analysis allows for the identification of additional data necessary for a complete quantitative risk assessment, supporting the implementation of dedicated risk mitigation strategies within the overall conversion process of heat and power plants.

Keywords: Hydrogen, Gas Turbine, Risk Assessment, Safety, FMECA, Risk Analysis, Combined Heat-Power

1. Introduction

The adoption of hydrogen in gas turbine power plants has been a recognized strategy for carbon-free power generation for years, despite reservations about the actual hydrogen supply capacity (European Commission, Secretariat-General 2020) and the cyclical fluctuations in natural gas prices that have prevented continued investments in this field. Consensus has grown over the last two decades in indicating hydrogen-fired gas turbines as a suitable means to facilitate the penetration of renewable fuels in different sectors (Slowinski et al. 2023). In the long-term scenario, hydrogen gas turbines may in fact produce significant amounts of clean power into the grid – given a sustainable hydrogen production value chain – which can mitigate the known intermittency of conventional green power production facilities (ETN, 2024), such as wind turbines. This is enabled by significant energy storage and dispatchable power availability (Bellotti et al. 2022). In support of this claim, a first demonstration of an integrated industrial power-to-gas-to-power (P2G2P) solution – operating with 100% green hydrogen – was achieved within the European project HYFLEXPOWER, resulting in the operation of an advanced dry-low emission hydrogen gas turbine for a few hours. (Parsania et al. 2024).

The feasibility of large scale P2G2P plants is currently under investigation, and the existing literature on the topic highlights challenges and showcases the necessity for localized hydrogen production units (Rigaud et al. 2022) , along with import potential (Choi et al. 2024). For example, converting excess grid into hydrogen by means of water electrolysis may be a promising solution, but it would require considerable storage dimensions to allow continuous operation, while intrinsically suffering from loss of energy efficiency due to conversion processes. In this sense, the development of retrofit solutions for existing gas turbines supports such solutions – especially in the short-term scenario – as it may promote the commercial demand of hydrogen.

In view of a gradual increase of hydrogen supply affordability, technology development effort should consider infrastructure compatibility, adherence to rapidly evolving safety standards and pollutant emission containment. As such, an adequate control over nitrogen oxide (NOx) emissions must be guaranteed for various combustion technologies and products (Bothien et al. 2019; York et al. 2024). Simultaneously, operational flexibility is key for gas turbines, meaning that a quick start-up must be ensured at almost any time, along with operability at any possible load and – in the case discussed – using various mixtures of natural gas and hydrogen.

A previous full-scale demonstration of hydrogen operation in gas turbines was addressed in a previous work (Baker Hughes, 2024). A dual shaft 17.1 MW gas turbine, namely the NovaLT™16 – manufactured by Baker Hughes – was extensively characterized in terms of performances and emissions. Although requiring further technology development to reduce NOx emission below policy thresholds (Cerutti et al. 2023), safe and smooth operation was achieved and ensured throughout the established 190 fired-hours, 70 of which characterized by a rising hydrogen-to-natural gas ratio up to 100% hydrogen. Following a similar rationale, a large-scale demonstration of a retrofitted gas turbine is planned within the HyPowerGT project, funded by the European Union (HyPowerGT Project*,* 2023), which aims at reaching a TRL7 for the DLE hydrogen gas turbine. This implies the development of a fully retrofittable technology to existing gas turbines, thus providing opportunities to reinterpret existing assets in the power sector, including Combined Heat and Power (CHP) applications. Guidance on how to analyze hydrogen-related hazards has been object of discussion for decades (NASA, 2003), especially addressing concerns on fire development and deflagration/detonation transition, the hydrogen wide flammability range, its ignition energy and flame speed. Despite these efforts, a comprehensive understanding of the risks associated with the implementation of hydrogen-powered gas turbines is still missing, and a debate on the design of optimal prevention strategies has been ongoing for years – encompassing the mitigation of self-ignition phenomena, which can follow the sudden release of compressed hydrogen (Dryer et al. 2007), and the release of unburnt hydrogen at the turbine exhaust, which may contribute to the hydrogen build-up near hot walls, potentially resulting in explosive atmospheres. Therefore, this paper proposes a Failure Mode, Effect and Criticality Analysis (FMECA), based on the risk management framework ISO 31000. To show the adopted approach, a simplified risk management process is shown in Figure 1.

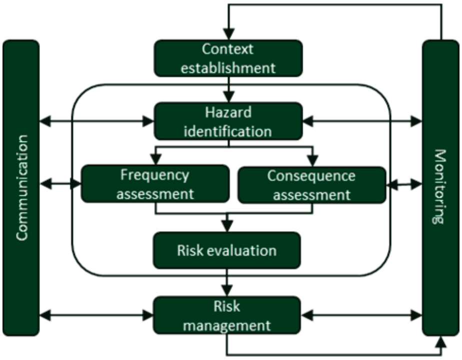

Figure 1: Conventional Risk Management framework.

Figure 1 highlights the core phases of a risk management approach, showing the risk analysis in the steps included in the rounded box. Such steps are hazard identification, frequency and consequences assessment, and risk evaluation – achieved by comparison with risk acceptance criteria (i.e., ALARP principle). Therefore, risk is assessed and evaluated qualitatively and quantitatively depending on the scope of the work, the availability of data, and the engineering and design process stage. The adoption of a FMECA – established and well-known by industry – within the current work allows for a tailored study of the retrofitted DLE technology into an existing CHP system. In particular, the analysis focuses on the potentially novel hazards introduced through the retrofitting of the DLE hydrogen technology into the gas turbine in question, which enables handling mixtures of natural gas and hydrogen with concentrations up to 100% hydrogen in continuous operation, guaranteeing low NOx emission. Conventional hazards related to turbines operating with 100% natural gas are therefore excluded by the analysis, given that the scientific novelty of this work does not lie in their assessment. In any case, this work lays the foundation for future detailed assessments that will investigate further the relevant scenarios identified by the current paper. In other words, this work shows:

- The single and/or combined failure modes of the retrofitted gas turbine, identified in connection with the CHP system.
- The most likely effects associated with the identified failure modes, evaluated in terms of severity of their impacts (i.e., consequence level, including injuries and casualties).
- The proposal of adequate safety and good design measures aimed to mitigate, control and prevent the identified risk scenarios.

2. Case Study

As an existing industrial use case, LUCART's paper production facility in Porcari (Lucca, IT) was selected, where a NovaLT™12 dual shaft 12.5 MW gas turbine was previously installed for cogeneration, obtaining good performances in terms of NOx emissions. This experience was rooted in a thorough evaluation of the key elements of the plant, analyzing the fuel line and auxiliary systems, and enabling the plant for the future use of mixtures of natural gas and hydrogen up to 50% hydrogen. At the time of this work, hydrogen is expected to be either fueled into the turbine from the grid (when available) or from a fixed storage system – which allows various mixing levels with natural gas, provided by the grid at 24 bar and compressed up to 32 bar. In this light, the previous installation (Baldini et al. 2024) provides considerable insight to the current work. Along with this, a previous fuel gas dispersion test was performed on a NovaLT™16, equipped with gas detection and variable ventilation flow (Ricco et al. 2024), with the goal of validating CFD models for quantitative risk assessment (Lucherini et al. 2024). Similarly to the current scenario, the exhaust of the gas turbine was connected to a diverter, which can discharge either through a chimney – typically at startup and at low gas turbine loads – or redirect the exhaust gas to the heat recovery steam generator (HRSG). The HRSG is hence equipped with buffer air injected immediately downstream the diverter. The analysis reported in the following sections concerns the plant in its current configuration, thus providing knowledge for the upgrade of the existing subsystems and HRSG, while also indicating further installations required.

3. Methodology

Product and process safety, as well as Health Safety and Environment (HSE) rely on established methodologies to effectively identify hazards and mitigate risk. Several established tools are available for the analysis of hazardous scenarios, including:

- Hazard Identification (HAZID),
- Hazard and Operability Study (HAZOP), and
- Failure Modes Effects and Criticality Analysis (FMECA).

An FMECA provides a structured framework to evaluate potential failure modes promoting and leading to hazardous scenarios. The FMECA framework is typically implemented to identify all possible failure modes and prioritize the ones associated with high risk levels – based on failure frequency and consequence severity. Additionally, the detectability of a specific failure mode can also be addressed. Hence, this approach enables the definition of a prioritized list of hazardous events based on their criticality, followed by the implementation of safety measures to tackle the expected risk levels. This tool – characterized by flexibility, adaptability, and industrial acceptance – is therefore deemed to be suitable for the analysis performed in the study, especially considering that the final configuration of both the use case and the turbine product are still to be completely defined. Finally, this study refers to conventionally adopted and internationally recognized safety standards, such as the ISO 12100 (Safety of machinery - General principles for design – Risk assessment and risk reduction) and the ISO 21789 (Gas turbine applications – Safety).

3.1 *Failure Modes, Effects and Criticality Analysis (FMECA) Procedure*

The adopted FMECA procedure is shown in Figure 2, highlighting the core phases and steps followed within this work.

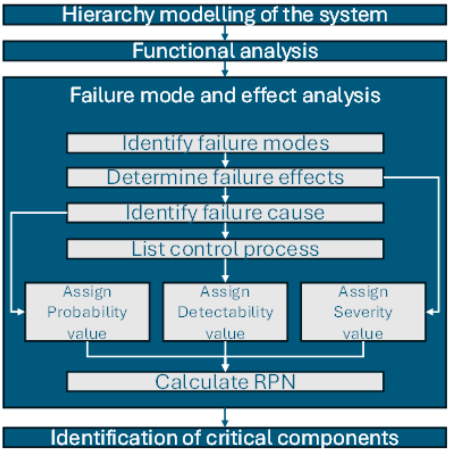

Figure 2: FMECA flowchart.

The identification of failure modes aims at pinpointing those that might lead to total or partial loss of functionality, as well as any other issue (e.g., design marginality). The effect of operating conditions (e.g., extreme temperature, dry environment, presence of dust) and other aspects (e.g., material compatibility) that can foster specific failure modes is also discussed. Examples of guidewords – used to identify the relevant failure modes for the retrofit of the natural gas turbine to hydrogen – are cracks and cracked equipment; deformed; loosened; leaking; fractured; oxidized; or short circuited (electrical issues). One (or more) immediate effect(s) for each failure mode is identified. Effects can be related to the closest component or/and to the system in general. Examples are noise; erratic operation of a component or equipment unit; intermittent operation; release of hydrogen; fire and/or explosion. One (or more) cause(s) for each identified failure mode is identified. Causes can be either internal (to the system or equipment unit) or external. Examples are incorrect/incompatible material; over-stressing; insufficient lubricant capability; inadequate maintenance; failure mechanisms such as yield; fatigue; material instability; creep; wear and corrosion. Several types of control processes can be implemented, ranked from preferred to least preferred, with the aim of achieving an early detection of the cause of failure and/or the failure mechanisms, potentially leading to corrective actions before major effects. Only existing control processes are listed. Future control measures might be required for those failures deemed as critical scenarios.

3.2 *System Representation*

The FMECA procedure is performed to analyze the hydrogen-promoted failure mode in the gas turbine retrofit from natural gas to 100% hydrogen. This analysis refers to the plant shown in Figure 3.

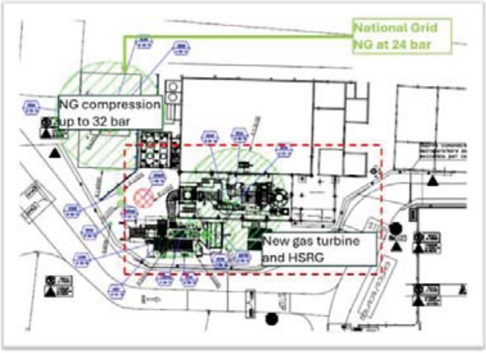

Figure 3: View of the Porcari CHP with highlighted critical areas.

A 12.5 MW gas turbine receives compressed natural gas from the national grid and provides heat to an HRSG. The view of the plant shown in Figure 3 highlights the areas defined for the operation, with the natural gas coming from national grid. Assuming hydrogen will be blended into natural gas in the short-term scenario, the current plant is not equipped with hydrogen storage, compression and distribution units, but this system is compatible with the installation of a hydrogen tank in the next future. The existing system is divided into three nodes, as follows:

- Node 1 Power generation unit (PGU).
- Node 2 Fuel system.
- Node 3 PGU exhaust and HRSG.

These three nodes are shown in Figure 4. The auxiliary systems (such as fuel, oil, electrical components) are treated as part of the specific node they are associated with.

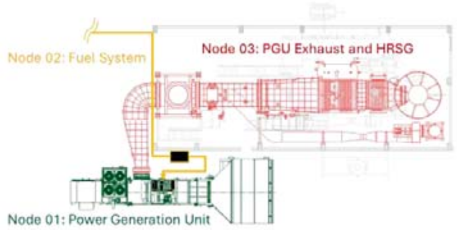

Figure 4: System representation of the three main nodes.

3.3 *Acceptability Criteria*

The probability (P), severity (S) and detectability (D) classes used in the FMECA analysis are presented in Table 1, Table 2 and Table 3, respectively.

Table 1: Probability Class Definition. ("Military Standard Procedures for Performing a Failure Mode, Effects and Criticality Analysis," 1977).

Class (P)	Description
5	Frequent
4	Reasonably probable
3	Occasional
2	Remote
1	Extremely unlikely

Table 2: Severity class definition. ("Military Standard Procedures for Performing a Failure Mode, Effects and Criticality Analysis," 1977).

Class (S)	Description
4	Catastrophic
3	Critical
2	Marginal
1	Minor

Table 3: Detectability class definition. ("Potential Failure Effects Analysis (FMEA)" 2008).

Class (D)	Description
5	Very remote
4	Very low
3	Moderate
2	High
1	Certain

A value (P, S, D) is assigned to all the identified failure modes. Once the classes are assigned, a Risk Priority Number (RPN) is calculated, defined as the product of P, S, and D – and assigned to each failure mode. RPN ranges from 0 to 100. The acceptability criteria can be divided into three cases. RPN above 20 is considered "unacceptable". S equal to 4 requires risk reduction measures for acceptability. RPN between 10 and 19 are considered as "acceptable with condition of measures to reduce the risk according to the ALARP principle".

4. Results and Discussion

The identified failures modes are discussed and analyzed in this section, resulting from in-site knowledge, expert elicitation and operational experience. A two-day in-person FMECA workshop was organized among the partners of the HyPowerGT project. The information collected was organized in an FMECA sheet, and its results are henceforth narratively presented, followed by an extract of the FMECA sheet.

4.1 *Node 1 – Power Generation System*

Node 1 includes the PGU (gas turbine, its enclosure, its package, except for the portion of the fuel line within the enclosure). The updated package design of the NovaLT™16 was considered as reference for the use case of this work, depicted in Figure 5.

Figure 5: Node 1 – NovaLT™16 gas turbine and its package, designed for up to 100% hydrogen.

A total of 15 failures were identified for Node 1. The highest RPN was calculated as 12 (failure 1-a), falling into the ALARP area of the RPN acceptability criteria. It consists of hot air leaking from a flanged connection into the gas turbine enclosure, which was evaluated as a potential source of ignition given a hydrogen gas release within the same environment.

Considering the installation of temperature measurement points within the enclosure, the occurrence of undetected leaks was evaluated as low. In the scenario of a crack in the fuel system piping, large leaks of hydrogen towards the enclosure are expected, potentially leading to fire or explosion; among the identified failures, one was assigned a severity class (S) equal to 4 (failure 1-b), which is to be managed according to the proposed criteria. This scenario should be considered as critical, requiring considerable attention for the knowledge transfer to the retrofit turbine in the HyPowerGT project, hinting at the necessity for ad-hoc criteria, possibly different from the existing configurations for processing natural gas. In other words, the choice of the most adapt materials for pipes and valves – otherwise subject to embrittlement (Giannini et al. 2024) – as well as the connections of the fuel system, are fundamental to prevent loss of containment scenarios in proximity of the machine enclosure (or in other areas where hydrogen can potentially accumulate and cause a confined fire and/or explosion).

In addition, gas and fire detectors, coupled with the mechanical ventilation, work as means to increase the detectability of the failure, therefore reducing the RPN.

4.2 *Node 2 – Fuel Distribution Line*

A simplified scheme of Node 2 is proposed in Figure 6. The fuel gas system includes the external shut-off (e-SOV) and vent (e-Vent) valves, which are located outside the gas turbine enclosure. Moreover, as part of the gas turbine package, a complete double block and bleed system (GT-SOV1, GT-SOV2 and GT-Vent) is installed within the enclosure, upstream of the gas control valves (GCVs) which feed the combustion unit. A total of 20 failures modes were identified for Node 2. Among those, two were calculated with a RPN equal to 12 (failure 2-b and 2-c), falling into the ALARP zone, and one equal to 24 (failure 2-a, classified as unacceptable).

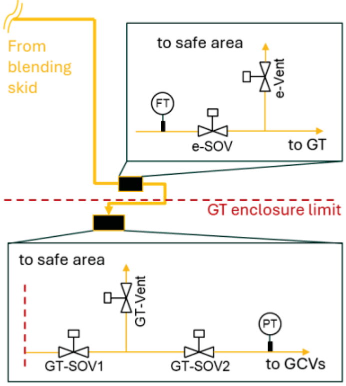

Figure 6: Node 2 – Fuel Distribution System.

A total of five failures modes ended up in the severity class 4 (unacceptable), namely failure 2-a, 2-c, 2-d, 2-e, 2-f. The failure associated with a RPN of 24 (failure 2-a) consists of a leak of hydrogen towards the environment, resulting in a flammable cloud, ignition and fire with or without explosion. Again, the matter of material compatibility with hydrogen is a key preventive barrier to avoid loss of containment within the machine unit (severity class assigned to 4). It should be noted that a generic "conservative assessment" was adopted throughout the study, which is deemed to result in an overall overestimation of the RPS values, thus promoting the adoption of conservative safety measures. Moreover, the uncertainty on the location and characteristics of the areas surrounding the turbine fuel feed line (immediately outside the machine enclosure) is a second reason for the adoption of conservative RPNs. Additionally, lifting protocols – as well as ignition control and reliable gas detection systems outside the machine enclosure – are identified as measures that can contribute to reduce the RPN, thus approaching the ALARP region. However, failure 2-a currently falls within the "unacceptable" category, therefore requiring additional safety barriers (to be defined and implemented).

A relevant identified failure mode resulting in RPN equal to 12 (ALARP zone, failure 2-b) is related to hydrogen gas releases due to partially damaged valves on the gas inlet line in proximity to the machine unit. Failure 2-b is associated with a consequence severity equal to 2 because of an expected release rate less pronounced than the 2-a case. The identified consequences involve the formation of a flammable cloud outside the machine enclosure, potentially affecting Node 1 from the enclosure ventilation intake duct, reaching flammable concentrations and then igniting while confined with severe consequences for both people and equipment. Alternatively, hydrogen gas releases inside the machine enclosure may be induced by cracks in the flexible hoses (Failure mode 2-c). This failure is represented by an RPN equal to 12, but in a severity class of 4, thus considered unacceptable. In fact, a hydrogen release gas within the machine enclosure can potentially result in a confined fire and/or explosion with potential severe consequences for people and the environment. The hydrogen laminar flame speed – higher than conventional hydrocarbon-based fuels – and the enhanced tendency for hydrogen-air mixture deflagrations to transition to detonation (DDT) (Kuznetsov et al. 2005), are contributing factors to the expected high severity of this scenario. Failure 2-c is anyway assessed at a lower RPN level than failure 2-a, because the machine unit design can be controlled (in terms of material and detection systems) and overall, established information is available from NovaLT™16 experience (Ricco et al. 2024) to confidently assess this scenario unlikely and generally manageable. Additional identified failures modes with severity class equal to 4 are associated with confined explosions inside the machine enclosure, caused by either leaking valves (Failure 2-d), or single items operation failures (Failure 2-e, Failure 2-f). As an example, a shut-off valve unexpected closure or a position failure of the gas control valve during gas turbine normal operation can cause a loss of flame, while a residual amount of unburnt hydrogen could be released through the machine (Node 1), to the exhaust line (Node 3). Existing controls such as flame detectors or valve position feedback signals can improve the detectability class, contributing to reducing the risk towards acceptable values.

A further evolution of the current analysis may address updated modelling strategies to assess the effects of the accidental release of unburnt hydrogen in the exhaust, as investigated in (Lemmi et al. 2024; 2025). This becomes imperative in cases where the gas turbine (equipped with the new DLE technology) is connected to a large pre-existing system (i.e., the HRSG), making any further modification complex or inconvenient.

4.3 *Node 3 – Exhaust Line*

Node 3 is depicted in Figure 7. A total of 8 failures modes were identified for the exhaust, resulting in one failure associated with a RPN in the "unacceptable" region (24, Failure 3-a).

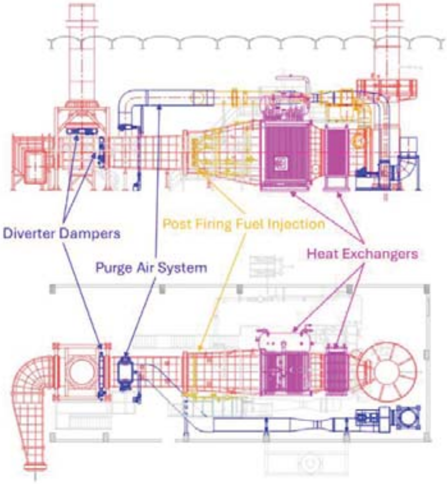

Figure 7: Node 3 – Exhaust Line, lateral and top view.

Additional failures modes are related to the presence of flammable cloud in the exhaust line, similarly to Node 1. Table 4 proposes a summary of all the failure evaluated in the "unacceptable" and ALARP regions.

Table 4: Overview of failures exceeding acceptability criteria.

ID	Failure mode	Effects	Acceptability criteria
1-a	Hot air flange leaking.	Ignition source due to hot air in case of hydrogen leak.	RPN=12 (ALARP)
1-b	hydrogen leak due to piping cracks or leaking valves.	Flammable clouds and fire and/or explosion upon ignition.	S=4 (unacceptable)
2-a	Hydrogen leaks towards environment (due to cracks).	Flammable clouds and potential fire and/or explosion upon ignition.	RPN=24 S=4 (unacceptable)
2-b	Hydrogen leaks towards environment (due to damaged valve gaskets).	Flammable clouds and potential fire and/or explosion upon ignition.	RPN=12 (ALARP)
2-c	Hydrogen leaks towards enclosure due to crack in flexible hoses.	H_2 concentration in flammability range and fire and/or explosion if ignited in confined space.	S=4 (unacceptable)
2-d	Hydrogen leaks towards enclosure (due to cracks).	H_2 concentration in flammability range and fire and/or explosion if ignited in confined space.	S=4 (unacceptable)
2-e	Spurious operations of fuel valves leading to no or lower availability of fuel	Reduced machine availability, unburned hydrogen in the machine and exhaust line	S=4 (unacceptable)
2-f	Fuel valve too open.	The turbine is unable to respond to varying loads, possible overspeed (the acceleration can be very high).	S=4 (unacceptable)
3-a	Hydrogen gas accumulation and pocketing.	Fire and/or confined explosion upon ignition.	S=4 RPN=24 (unacceptable)

In conclusion, the identified critical failures resulting in scenarios exceeding the acceptability threshold (either RPN ≥ 20 or severity class S above 4) are:

- Hydrogen leaks towards the machine enclosure, with accumulation, ignition and confined fire and/or explosion.
- Hydrogen leaks towards the environment (from valves and connections).
- Hydrogen leaks towards enclosure (from flexible hoses, valves, connections, spurious operations, and varying loads.
- Hydrogen trapped in exhaust line, specifically in external insulation.

5. Conclusions

A FMECA assessment of hazardous events associated with the retrofitting of a DLE hydrogen combustion technology on an existing gas turbine – operable with variable natural gas/hydrogen mixtures up to 100% hydrogen – is proposed within this work. The selected case study represents a potential application of DLE hydrogen technology, and it consists of a CHP plant currently fueled with natural gas.

The FMECA was selected as an established, flexible, and open-ended safety engineering tool for risk assessment, which proved to be effective in classifying hazards and identifying the required mitigations, with the possibility of developing guidelines for design upgrades. It is believed that this work may provide additional insight into the identification of hydrogen-related hazards in real-world applications, relevant to support the retrofit of existing turbo machinery systems, along with gas storage units and compression stations. The failures modes associated with a severity of 4 (1-b, 2-a, 2-c, 2-d, 2-e, 2-f, 3-a) must be re-evaluated with the inclusion of reactive safety barriers, which can reduce the consequence severity and remove potential safety concerns. The failures in the ALARP region (1-a, 2-b) should be treated as potential concerns, but safety measures could be discussed based on case-specific characteristics. Overall, the 2-a failure mode seems to be the most critical (RPN = 24 and S=4), which hints at the importance of controlling hydrogen leakages from valves during operation – both preventive and reactive safety barriers could be designed to minimize the risk of this scenario.

Obviously, additional work is required to provide a complete quantitative risk assessment, which may support future reliability analysis and uncertainty evaluations, including:

- A detailed analysis of the identified hydrogen release scenarios.

- The inclusion of ad-hoc mitigation measures, including design improvements, control strategies and procedural safeguards.
- A validation of the identified RPNs through novel operational experience and consequence modelling.

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