Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira, Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria
 Published by Research Publishing, Singapore.
doi: 10.3850/ESREL2026061419_esrel26-p26066-cd

Combining Event Tree Analysis and System-Theoretic Process Analysis for Hydrogen Refueling Station Safety

Dikshya Bhandari

Faculty of Science and Technology, University of Stavanger, Norway, Dikshya.bhandari@uis.no

Jon Tømmerås Selvik

Faculty of Science and Technology, University of Stavanger, Norway, jon.t.selvik@uis.no

Hydrogen refuelling stations are complex socio-technical systems where safety outcomes emerge from interactions among technical components, human operators, and organizational structures. Traditional risk assessment methods, such as the Event Tree Analysis model, analyze accident sequences and estimate probabilities of hydrogen releases; however, they struggle to capture nonlinear dependencies, timing effects, and feedback dynamics. This paper applies System-Theoretic Process Analysis together with Event Tree Analysis to the same hydrogen compressor leak scenario to identify gaps in traditional event-based risk assessment and explore how the two methods can be meaningfully combined. Event Tree Analysis maps accident progressions, and System-Theoretic Process Analysis identifies unsafe control actions, feedback delays, and organizational factors influencing barrier performance. Linking System-Theoretic Process Analysis causal factors to Event Tree Analysis sequences illustrates how technical, human, and organizational interactions influence accident progression. Combining these methods provides a better way to assess hydrogen safety risks and capture both direct and emergent contributors to accidents.

Keywords: Event Tree Analysis, System-Theoretic Process Analysis, Hydrogen Safety, Risk Assessment, Socio-Technical Systems, Systems Thinking

1. Introduction

Hydrogen systems are deployed to support fuel cell vehicles and energy storage as part of the global transition to cleaner energy. However, hydrogen's high flammability, rapid dispersion, and low ignition energy pose significant safety risks that must be carefully managed (Park et al., 2025). Recent incidents in Norway (2019), the United States (2023), and South Korea (2019) (Kim & Kim, 2019; Panel, 2021; Shah et al., 2025), show that traditional safety measures are often insufficient.

These incidents highlight that hydrogen systems are not only technically demanding but also complex socio-technical systems. Safety outcomes emerge from interactions among technical components, human operators, and organizational arrangements. Accidents cannot always be explained by isolated equipment failures alone. Instead, they may result from combinations of delayed feedback, human decisions, procedural mismatches, and organizational constraints, particularly in emerging hydrogen applications with limited operational experience (Subedi et al., 2025).

Among the many applications of hydrogen, refuelling stations are particularly critical due to their high-pressure operation, frequent human interaction, and potential for rapid escalation of accidents. Understanding risk in hydrogen refuelling stations, therefore, requires that account for both technical performance and human and organizational influences on system behavior (Navajas et al., 2025).

Recent review studies show that hydrogen risk assessment remains largely dominated by traditional, event-based methods (Min et al., 2025). Event Tree Analysis (ETA), recommended in standards such as IEC 31010 (2019), is commonly applied to describe accident sequences and estimate the likelihood of different outcomes following an initiating event. ETA is well established because it is structured, transparent, and easy to communicate, making it compatible with regulatory and industrial decision-making. However, ETA relies on simplifying assumptions, including linear event progressions, binary success–failure outcomes, and independence between events (Rausand & Høyland, 2004). These assumptions make ETA useful for mapping

possible accident pathways, but inadequate for capturing timing, sequencing, or dynamic interactions between technical, human, and organizational components in complex hydrogen systems (De Carvalho, 2011; Hollnagel, 2016).

To improve ETA, several extensions have been proposed, including the Continuous Event Tree (Karanki et al., 2018). Dynamic Event Tree Analysis (DETA), Fuzzy Event Tree Analysis (FETA) (Purba et al., 2020), Multistate Event Tree Analysis (META) (Marcoulaki, 2013), and Bayesian Event Tree Analysis (BETA) (Scott et al., 2022). These methods account for uncertain events, how events evolve over time, and multiple possible outcomes. However, they still focus primarily on technical components and rarely consider human or organizational factors (Wiltbank & Palmer, 2021).

System-theoretic safety approaches provide a fundamentally different way of thinking about safety in complex systems. Within the System-Theoretic Accident Model and Processes (STAMP), accidents are viewed not as linear chains of failures, but as outcomes of inadequate control and insufficient enforcement of safety constraints within the system (Leveson, 2004). System-Theoretic Process Analysis (STPA) builds on this perspective by examining how unsafe control actions, missing or delayed feedback, and flawed process models can allow hazardous system states to arise across technical, human, and organizational levels (Leveson, 2013). Rather than asking only what sequence of events may occur, STPA focuses on why a system may permit unsafe conditions. This perspective is particularly relevant for hydrogen refueling stations, where small delays in sensor feedback, operator response, or shutdown logic can strongly influence accident severity.

Although STPA has gained increasing attention in research, traditional ETA still dominates hydrogen safety practice. This creates a conceptual challenge for the risk and safety profession, as fundamentally different safety logics are applied to the same system. Understanding what each method reveals, what it overlooks, and how these differences influence safety decisions is therefore essential.

In this context, the objective of this paper is to show how Event Tree Analysis (ETA) and System-Theoretic Process Analysis (STPA) can be applied to the same hydrogen compressor leakage scenario at an off-site hydrogen refueling station, to identify gaps in traditional event-based risk assessment and to consider how the two methods can be combined in some meaningful way. ETA is used to represent potential accident sequences and the performance of safety barriers, while STPA is applied to explain why barriers may succeed or fail by identifying unsafe control actions, delays in feedback, and organizational influences on system behavior. To summarize this relationship, we present Figure 5, which links the causal factors identified by STPA to the corresponding points in the ETA. Figure 5 shows how human, technical, and organizational factors interact to influence the performance of safety barriers.

2. Event Tree Analysis

ETA is a probabilistic technique developed to model how an initiating event can lead to different accident scenarios. Originally developed for the nuclear industry, it is now widely used in chemical processing, offshore oil and gas, and transportation. In an ETA, the analysis begins with the initiating event placed at the left side of a diagram. From there, the diagram extends horizontally, branching at each safety function to show its possible success or failure. Probabilities assigned to each branch allow analysts to estimate the likelihood of different outcomes, which provides a transparent view of accident progression (Andrews & Dunnett, 2002).

Traditional ETA assumes precise probabilities and a single initiating event with binary, independent paths. In practice, data limitations and dependencies between events challenge these assumptions (Ferdous et al., 2009). ETA provides a static, hardware-focused view and cannot capture the timing, sequencing, or dynamic evolution of system states, nor complex interactions between technical, human, and organizational components (Acosta & Siu, 1991). To overcome these limitations, advanced ETA methods have been developed, such as the continuous ETA, the DETA (Karanki et al., 2018), FETA (Purba et al., 2020), META (Marcoulaki, 2013), and BETA (Scott et al., 2022). BETA incorporates probabilistic updating to model dependencies and uncertainty; DETA introduces time-dependent interactions; and META allows for outcomes beyond simple success or failure. These developments improve the modeling of complex event progressions; they remain primarily technical, focusing on

probabilistic relationships between components rather than on human or organizational factors.

3. System-Theoretic Process Analysis

System-Theoretic Process Analysis (STPA) is a hazard analysis method derived from the System-Theoretic Accident Model and Processes (STAMP) framework developed by Nancy Leveson (Leveson, 2004). Unlike traditional probabilistic methods that trace linear chains of component failures, STAMP was developed to address the challenges of modern socio-technical systems, where behavior emerges from complex interactions, digitalization, and non-linear cause–and–effect relationships. In these systems, accidents are often the result of inadequate coordination, mismatches between human and machine understanding, or poorly defined safety responsibilities rather than isolated component failures. STAMP therefore provides the conceptual foundation by framing safety as the enforcement of constraints within a hierarchical control structure.

STPA builds on this perspective by operationalizing how safety constraints can be violated. It analyzes how control actions, interactions, and feedback may become inadequate and lead to hazards. STPA conceptualizes safety as a dynamic control problem in which human, technical, and organizational components interact continuously to maintain system stability (Leveson, 2013). The STPA process consists of four main analytical steps, as shown in Figure 1.

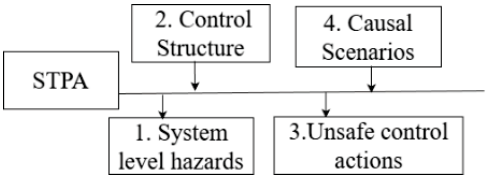

Figure 1: Overview of the STPA process

First, analysts define the accidents to be prevented, the associated system-level hazards, and the safety constraints and functional requirements that must be maintained. Second, a functional control structure is developed to represent how controllers (e.g., operators, software, management) interact with controlled processes. Each controller uses a process model, a mental or computational representation of system behavior, to make control decisions. Third, potential Unsafe Control Actions (UCAs) are identified, which represent situations where control actions could lead to hazards. Finally, analysts determine the causal scenarios explaining how these unsafe actions could occur, such as due to incorrect process models, delayed or missing feedback, or conflicting safety constraints across system levels (Fleming & Leveson, 2015; Leveson, 2016).

4. Case Study: Hydrogen Refuelling Station

Hydrogen refueling stations receive hydrogen either through on-site production or through off-site delivery from a central plant. This study focuses on an off-site hydrogen refueling station in an urban area where hydrogen is transported in tube trailer trucks equipped with high-pressure cylinders. Upon arrival, the hydrogen is recompressed and stored in tanks at varying pressure levels (low, medium, and high pressure) before being dispensed to vehicles (Yang & Ogden, 2007). During these high-pressure operations, heat is generated, which can increase the risk of hydrogen leaks or explosions. Compared to conventional fuel stations, hydrogen refueling stations present higher risks due to the properties of hydrogen and the handling processes. Any uncontrolled hydrogen release could result in significant harm to people and damage to infrastructure (Mosleh et al., 2025; Yoo et al., 2021).

The analysis concentrates on a representative initiating event, hydrogen leakage from the compressor, to model potential accident scenarios and explore how system-level interactions influence risk propagation and mitigation. In such stations, hydrogen is typically delivered at about 40–45 MPa and then compressed to the storage pressures of the cascade tanks up to 75 MPa for H70 dispensing or 40 MPa for H35 dispensing before being supplied to vehicles (Xu et al., 2022). These high-pressure operations make components such as compressors, valves, and storage vessels critical from a safety standpoint.

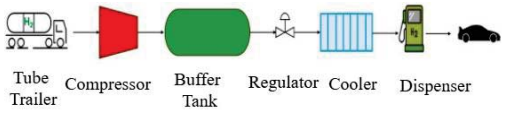

Figure 2: Schematic layout of an off-site hydrogen refueling station adapted from Hoseyni et al. (2024)

Figure 2 illustrates the key components, including the tube trailer, compressor, buffer tanks, pressure regulators, cooler, dispenser, and vehicle. Hydrogen is delivered via high-pressure tube trailers, recompressed and stored in tanks at varying pressures, then dispensed to fuel cell vehicles.

5. Combined Application of ETA and STPA in a Hydrogen Refuelling Station

Using the hydrogen refueling compressor leak case, this section applies ETA and STPA. First, the ETA representation is presented, followed by the STPA analysis, after which the two methods are combined to illustrate their complementary roles.

5.1 ETA analysis

Figure 3 shows the event tree for a hydrogen leak from the compressor. Starting from the initiating event, the tree maps possible accident sequences: immediate ignition leading to a jet fire, delayed ignition leading to a vapor cloud explosion, or intervention by safety barriers such as the Automatic Emergency Shutdown (AESD) or manual shutdown. Probabilities can be assigned to each branch to estimate the likelihood of different outcomes.

This ETA example illustrates how a single initiating event can propagate through the system, which highlights critical points where safety barriers act to prevent escalation. It provides a clear, visual representation of accident pathways in hydrogen refueling stations.

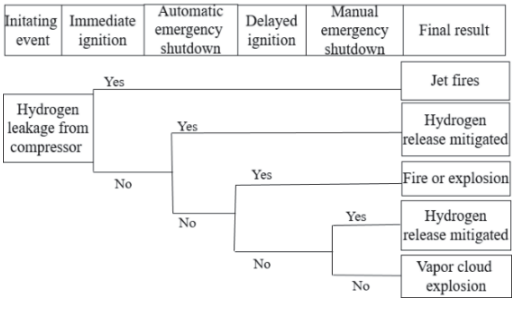

Figure 3: Event tree for a hydrogen leakage from the compressor at an off-site refueling station.

5.2 STPA analysis

After modeling the hydrogen compressor leak scenario with ETA, STPA will be applied to the same case to identify additional information that ETA alone may not capture. The analysis begins by identifying system-level hazards and constraints, then describes the control structure, lists unsafe control actions, and presents their causal scenarios.

5.2.1 ***System-level hazards and constraints***

Hazards and safety constraints in the hydrogen compressor subsystem highlight where technical, human, and organizational controls are critical:

- Hydrogen release from the compressor: Leaks may occur due to seal failure, packing deterioration, fatigue, corrosion, or mechanical malfunction. The compressor must remain fully sealed at all times. Any leak must be detected immediately, and the system must either stop it automatically or alert operators for rapid intervention.
- Control system failure: The automatic shutdown system or pressure control may fail to respond to abnormal conditions. Control systems must continuously monitor critical parameters and shut down the compressor automatically if unsafe conditions are detected. Daily testing and maintenance are required to ensure reliable operation.
- Sensor failure or delay: Pressure, temperature, or hydrogen concentration sensors may fail or provide delayed feedback, preventing timely detection of a leak. Sensors must remain fully operational at all times, providing accurate and timely feedback to the control system and human operators.
- Operator fails to detect leaks or abnormal conditions: Human operators may fail to detect abnormal conditions, respond too slowly, or execute emergency procedures incorrectly. Operators must quickly detect any hydrogen leak, fire, or equipment problem, follow emergency shutdown and isolation procedures, and evacuate as instructed. Operators must stay prepared through training, rest management, and regular drills.
- Overpressure or mechanical malfunction: Compressor failure, valve blockage, or pressure control malfunction could result in hydrogen release or rupture. Pressure relief and control systems must prevent overpressure, and any malfunction must trigger immediate isolation and shutdown until safe operation is verified.

- Hydrogen accumulation in confined or poorly ventilated areas: Leaked hydrogen collects in enclosed spaces, increasing the risk of explosion. Adequate ventilation shall be maintained at all times to prevent hydrogen buildup. Continuous gas monitoring shall detect any accumulation and activate alarms or ventilation systems automatically.

5.2.2 *Control structure*

The compressor subsystem in the hydrogen refueling station operates as a controlled process where hydrogen is pressurized and transferred into storage containers. Safe operation relies on the coordinated interaction of multiple controllers, including human operators and automatic control modules. The human operator monitors hydrogen pressure, flow, and concentration, and can remotely initiate emergency shutdowns or isolate the compressor in case of abnormal conditions. The automatic control module continuously receives sensor data, executes control logic, starts the compressor when hydrogen is detected, regulates valves and motor drives, and triggers alarms or automatic shutdowns when unsafe conditions are identified. Actuators, including pneumatic valves and motor drives, implement the commands from the controllers to maintain hydrogen flow and pressure. Sensors provide real-time feedback on pressure, flow, and hydrogen concentration, closing the control loop and enabling timely corrective actions. The compressor is also influenced by disturbances such as fluctuations in hydrogen supply, environmental conditions, power interruptions, or operational errors, which may challenge safe operation. Figure 4 illustrates the STPA control structure of the compressor subsystem, showing how human and automated controllers, sensors, actuators, and the controlled process interact. This structure highlights where UCAs could occur, where feedback may be delayed or missing, and where organizational or procedural factors could compromise safety, providing a basis for hazard analysis and mitigation.

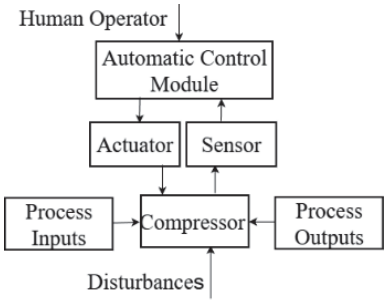

Figure 4: STPA control structure of the hydrogen compressor subsystem.

5.2.3 *Unsafe control actions*

This section lists unsafe control actions in the hydrogen compressor subsystem that could lead to hazards if not properly managed:

- Automatic controller fails to start the compressor when hydrogen enters
- Operator fails to stop the compressor during an emergency
- The automatic system starts the compressor when the hydrogen supply is absent
- Operator opens pneumatic valve during a leak
- Delay in starting emergency shutdown
- Valve closure applied too late
- Compressor continues running after hydrogen storage reaches maximum pressure.
- Emergency shutdown stopped prematurely
- Failure to update emergency shutdown procedures.
- Insufficient operator training for abnormal situations.
- Delayed maintenance of sensors and valves

5.2.4 *Causal scenarios*

In Table 1, each unsafe control action identified in Section 5.2.3 is analyzed to determine its potential causal scenarios, including technical, human, and organizational factors.

Table 1: Unsafe control actions and their causal scenarios.

Unsafe Control Action	Possible Causal Scenarios
The automatic controller fails to start the compressor	Sensor fails to detect hydrogen entry; controller software bug; power supply interruption
Operator fails to stop compressor during an emergency	Operator distracted, misreads alarm, or delays due to unclear procedure
The automatic system starts the compressor when the hydrogen supply is absent	Sensor misreading, control logic error, or equipment malfunction.
Operator opens pneumatic valve during a leak	Miscommunication, misunderstanding of the situation, and insufficient monitoring.
Delay in starting the emergency shutdown	Sensor delay, operator response time too slow; communication failure
Valve closure applied too late	Pneumatic valve actuators malfunction: control command delayed
Compressor continues running after hydrogen storage reaches maximum pressure	Controller fails to recognize high-pressure condition; sensor malfunction
Emergency shutdown stopped prematurely	Operator decision error, incomplete system feedback, and misjudgment of hydrogen levels

6. Reinterpreting ETA through an STPA Perspective

Figure 5 shows how a traditional ETA of a hydrogen compressor leakage scenario can be interpreted through an STPA perspective. The purpose of the figure is not to replace the ETA structure, but to introduce STPA-inspired causal questioning at key points in the event sequence in order to interpret safety barrier performance beyond binary success–failure assumptions.

In the ETA, hydrogen leakage is treated as an assumed initiating event, followed by sequential binary branching related to immediate ignition, automatic emergency shutdown performance, delayed ignition, and manual emergency shutdown. This structure enables the identification of possible accident outcomes, such as jet fires, fire or explosion, vapor cloud explosion, or successful mitigation. However, ETA treats safety barriers as black-box elements: outcomes such as "automatic emergency shutdown failure" or "manual shutdown delayed" are recorded as binary events without explaining why these failures occur or how socio-technical factors influence barrier effectiveness.

From an STPA perspective, both the automatic emergency shutdown and manual emergency shutdown are understood as control actions embedded in a socio-technical system. Their performance depends on interactions among technical components, human decision-making, procedures, and organizational conditions. Rather than asking only whether a barrier succeeds or fails, STPA asks why control was inadequate under the conditions present at the time of the event.

To avoid increasing the complexity of the event tree, this STPA perspective is incorporated through "why" questions placed next to key ETA branching points, such as "why was the AES inadequate?" and "why was operator intervention ineffective?" This approach reflects the STPA perspective that barrier performance is not inherently binary: control actions may be fully effective, partially effective due to delays, or ineffective due to incorrect responses. These distinctions are captured through causal explanations associated with each branching point, rather than through additional event tree branches.

By embedding STPA causal reasoning into the ETA structure, Figure 5 demonstrates how the two approaches complement each other. This combined perspective supports hazard identification and safety improvements, particularly in dynamic, interaction-heavy systems such as hydrogen refueling stations.

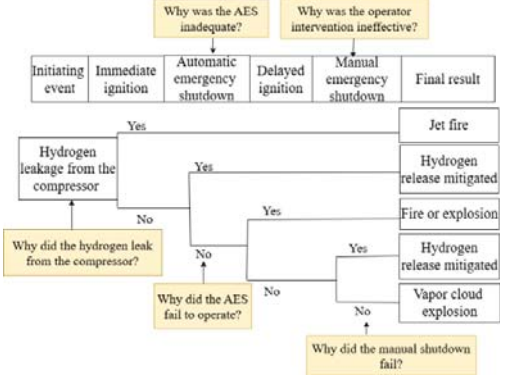

Figure 5: STPA perspective embedded into a traditional ETA for a hydrogen compressor leakage scenario

7. Discussion

The results of the analysis show that ETA and STPA provide different but complementary perspectives when applied to the same hydrogen compressor leak scenario. These differences reflect fundamentally different safety perspectives: ETA is grounded in a linear, event-based view of accident causation, whereas STPA is based on a system-theoretic perspective that challenges linear cause–and–effect assumptions by focusing on control, feedback, and interactions across system levels. ETA is a traditional risk assessment method that maps potential accident sequences and identifies where safety barriers, such as automatic shutdowns, should be placed. It provides probabilities for different outcomes, but it cannot explain why these barriers might fail under real operational conditions. For example, in the compressor leak scenario, ETA indicates whether the automatic shutdown succeeds or fails, but cannot show whether failures result from delayed operator response, sensor errors, or misconfigured control logic.

Unlike ETA, STPA is not a probabilistic risk assessment method. It does not provide numerical probabilities. Instead, it identifies the system-level causal factors that can compromise safety, including unsafe control actions, delayed feedback, sensor malfunctions, operator errors, and procedural or organizational gaps. By focusing on interactions and feedback loops, STPA captures non-linear, emergent behaviors that ETA cannot represent. In our case study, STPA shows scenarios such as operators opening valves incorrectly during a leak, delays in emergency shutdown, or inadequate maintenance procedures that could escalate minor events into major accidents.

When STPA perspectives are applied alongside ETA, they strengthen the analysis by explaining why certain event tree branches may fail or succeed and by identifying critical points for intervention. Linking these causal factors to ETA branches supports targeted improvements, including operator training, procedural revisions, verification of control logic, and redundant sensing. This combined approach also highlights unintended consequences that ETA alone might miss. For example, how delayed human responses or ambiguous procedures could undermine an otherwise reliable automatic shutdown. At the same time, it captures both direct outcomes, such as accident sequences, and emergent behaviors, such as barrier failures, providing a more complete, system-level understanding of hydrogen refueling station safety.

We demonstrated this approach for a hydrogen compressor leak, but it can be applied to other high-risk, socio-technical systems to improve safety understanding and decision-making. This understanding of why barriers may fail helps engineers and safety managers to prioritize interventions across technical, human, and organizational factors that are often overlooked in traditional risk assessment.

Even though STPA has several advantages, it also has limitations. Its outcomes depend on analyst judgment, which can introduce subjectivity. It can also produce complex causal structures that may be difficult to interpret or prioritize. Additionally, STPA does not provide quantitative probabilities for accident outcomes, unlike ETA, and modelling all interactions in complex systems can be time-consuming. Awareness of these limitations ensures that STPA is applied effectively and supports future improvements in hydrogen system risk assessment by complementing the traditional risk assessment rather than replacing it.

8. Conclusion

This paper shows that applying ETA and STPA to the same hydrogen compressor leakage scenario provides a complementary understanding of safety in hydrogen refuelling station safety. Analyzing the same initiating event through two fundamentally different safety logics shows limitations of relying solely on traditional, event-based risk assessment in complex socio-technical hydrogen systems.

Applying an STPA perspective to the ETA explains why barriers might fail, pinpointing unsafe control actions, delayed feedback, and socio-technical interactions that shape accident progression. This approach strengthens the ETA by capturing both accident sequences and system-level interactions, showing how socio-technical factors influence safety and supporting better-informed decisions on technical design, operational procedures, and organizational practices, without replacing traditional risk assessment.

Acknowledgement

The authors are thankful to the Norwegian Research Council and Consortium Partners in FME HyValue (Norwegian Center for Hydrogen Value Chain Research) for financial support and the possibility to publish this paper. RCN Project number: 333151.

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