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AUTOMATED HYDROGEN REFUELING STATIONS: AN IN-DEPTH REVIEW OF SAFETY, AUTOMATION, AND INTELLIGENT TECHNOLOGIES

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ABSTRACT

Hydrogen refueling stations (HRS) are key enabling infrastructure for the widespread deployment of hydrogen-powered transportation. This review examines how automation improves the safety, reliability, and sustainability of HRS while contributing to more efficient station operation. The study is based on a structured literature review and an analytical framework driven by key performance indicators (KPIs) to compare reported HRS performance across different levels and forms of automation. The analysis shows that advanced automation technologies, including supervisory control and data acquisition (SCADA) systems, Internet of Things (IoT)-enabled sensors, predictive maintenance, and artificial intelligence, can enhance operational reliability, leak detection, fueling consistency, and equipment availability. Although automation has only a limited influence on the overall energy efficiency of the hydrogen value chain, it plays a crucial role in improving station safety and operational performance. The paper also discusses hybrid edge-cloud architectures and cybersecurity requirements in accordance with IEC 62443. Overall, the review identifies automation as a key enabler for the safe, reliable, and sustainable deployment of hydrogen refueling stations, supporting the transition toward a low-carbon energy future.

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1 INTRODUCTION

Because hydrogen is considered a potential solution to current global energy challenges and the transition toward sustainable energy sources, its use is expected to expand across a wide range of storage conditions and end-use applications. Hydrogen has several distinctive properties that make it an attractive energy carrier but also create significant challenges for storage, handling, and use. These include its low density, ease of ignition, and the formation of water as the primary product when hydrogen is used in fuel cells or combustion systems (AIChE, 2023; Lacoma, 2017). It plays a crucial role in fuel cell vehicles (FCVs) and hydrogen combustion engines, where it can serve as a nearly clean energy carrier when the input energy is derived from renewable sources (Čekerevac, 2024). At the same time, using hydrogen as an energy carrier requires substantial conversion and handling. Energy efficiency remains a challenge (McCarthy, 1995), as hydrogen undergoes conversion losses at different stages of its energy cycle. Water electrolysis typically achieves efficiencies of about 60–70%, while compression and storage introduce additional losses, and the final reconversion in fuel cell vehicles typically yields 40–60% efficiency (Čekerevac & Čekerevac, 2025). Overall round-trip efficiency is therefore considerably lower than direct electrical pathways, with reported values of approximately 30–40% depending on the system boundary and technology mix (Wagner et al., 2023; Franco & Giovannini, 2024). Table 1 summarizes these values.

These characteristics are particularly relevant to hydrogen refueling stations (HRS), where hydrogen must be received, stored, compressed, conditioned, transferred, and dispensed under tightly controlled conditions. Consequently, station operation depends on continuous monitoring and coordinated control of parameters such as pressure, temperature, flow, and hydrogen inventory. Automation can therefore influence not only HRS operational efficiency but also safety, reliability, and the ability to maintain consistent refueling performance.

The overall efficiency of the hydrogen pathway is further affected by the efficiency of the primary energy sources used for hydrogen production. Photovoltaic modules typically convert about 15–22% of incident solar radiation into electricity, whereas modern wind turbines achieve approximately 35–45% efficiency in converting wind kinetic energy into electricity. Including these conversion stages, the overall efficiency from primary renewable energy to usable electricity in an FCV may drop to about 5–15% (Benghanem et al., 2023; Nasser et al., 2022; Rahman et al., 2024).

Table 1. *Efficiency of the Hydrogen Energy Cycle*

Process stage	Efficiency	Reference
Electrolysis (PEM or alkaline)	60–70%	Wagner et al. (2023)
Compression and storage (35–70 MPa)	~90% (≈10% loss)	Franco & Giovannini (2024)
Transport and distribution	95–98%	Franco & Giovannini (2024)
Conversion in a fuel cell (PEMFC)	40–60%	Hatch (2025)
Overall round-trip efficiency	30–40%	Wagner et al. (2023)

Regardless of the production pathway, hydrogen intended for transport applications ultimately depends on a reliable network of hydrogen refueling stations. These stations are key to enabling the infrastructure needed for widespread adoption of hydrogen-powered transportation.

From a purely energy-efficiency perspective, automating hydrogen refueling stations can affect only a limited part of the hydrogen energy chain, mainly by reducing losses associated with compression, storage, and station operation. However, automation's primary value lies not only in improving operational efficiency but also in enhancing safety, reliability, and regulatory compliance. As hydrogen deployment expands and the number of refueling stations increases, these aspects become critical for large-scale implementation.

The transportation sector offers many opportunities for hydrogen applications. Although hydrogen vehicles have higher initial costs, they can provide a sustainable alternative. Since technological and economic barriers initially hindered commercialization, recent advances and growing environmental demands have brought hydrogen to the forefront. Hydrogen is also being explored as a potential fuel for industrial applications, where its potential to reduce greenhouse gas emissions could significantly advance global climate goals. Large-scale deployment of hydrogen technologies inevitably requires an extensive network of refueling stations serving a growing number of users, so the safety risks are more pronounced.

Automation plays an important role in enabling safe and efficient operation of hydrogen refueling stations (HRS) (Huy et al., 2024). Key processes in such stations include reception and storage, compression, distribution and refueling, monitoring and control, and safety protocols. In practice, hydrogen is received as a liquid or gas at low temperatures or high pressures. It can be compressed, if needed, for vehicle refueling or tank storage. This procedure should be continuously monitored through designed measures and protocols to prevent accidents. Hence, automation can be used for real-time control of parameters such as temperature, pressure, and flow rate; accurate and fast regulation of pressure and hydrogen quantities; management of storage and transfer; diagnostics and maintenance using sensors; ensuring safety and reliability by reducing human error and technical failures; constant monitoring and enabling faster responses to hazardous situations; cost optimization by decreasing manual intervention; and regulatory compliance through simplifying adherence to stringent safety and environmental standards.

Automation in HRS encompasses supervisory control and data acquisition (SCADA) systems, Internet of Things (IoT) enabled sensors, and safety interlocks. These systems continuously monitor hydrogen flow, pressure, and temperature and enable automated shutdown during anomalies. Integrating redundant sensors and real-time data analytics ensures reliability and compliance with ISO 19880 and NFPA 2 standards. Predictive maintenance builds on automation by using Key Performance Indicators (KPIs) such as compressor vibration, pressure stability, leakage rates, and refueling cycle times. Machine learning (ML) algorithms analyze these data, including anomaly detection, regression models, and reinforcement learning. Studies have shown that ML can improve leakage prediction and localization in HRS (Wang J. Et al., 2025; Yang et al., 2021). The HyAI project in Orkney demonstrated that AI-driven predictive analytics, combined with IoT sensors, improved fault detection accuracy and reduced downtime (Institution of Mechanical Engineers, 2022). Such approaches enhance both safety and operational efficiency. A critical design choice in automation is computing architecture. Edge computing enables low-latency processing of safety-critical data (e.g., leak detection, emergency shutdown), which is essential for achieving autonomy. Cloud computing offers scalable resources for long-term data storage, advanced analytics, and fleet-wide optimization. Recent Department of Energy (DOE) pilot projects on autonomous hydrogen fueling stations recommend hybrid architectures that combine edge autonomy for immediate safety responses with cloud-based predictive analytics for system-level optimization (Brown, 2024). Such a dual approach ensures both operational safety and continuous performance improvement.

This study examines hydrogen's pivotal role as a potential future fuel in sustainable energy system transitions, focusing on automation solutions. The first step describes the challenges and advantages of HRS, considering the role of automation. Next, the authors examine safety measures, including protective functions, leak detection, and fire protection systems. The following section focuses on intelligent systems and underlying technology, outlining a vision of interconnected stations powered by green energy. It explains future developments and innovations that will revolutionize the sustainable energy sector, while also prompting consideration of hydrogen's applicability in daily life. Beyond technical design and safety requirements, the paper analyzes cybersecurity because integrating digital monitoring, control, and communication systems introduces new vulnerabilities that must be managed alongside traditional engineering risks. The paper acknowledges the growing importance of cybersecurity by incorporating it into the scope of hydrogen infrastructure resilience and reliability, in line with emerging international standards such as IEC 62443 (International Electrotechnical Commission, 2019).

2 METHODOLOGY

This study adopts a structured, question-driven literature review to examine the role of automation in hydrogen refueling stations (HRS). The review combines an analytical framework based on defined research questions and measurable performance indicators with an iterative process of literature identification, evidence screening, source verification, and comparative synthesis. Rather than treating automation as a single technological intervention, the study examines its contribution across several interconnected aspects of HRS performance, including operational efficiency, fueling performance, reliability, safety, hydrogen losses, and economic performance. The methodological approach was developed iteratively alongside the study's analytical structure, allowing the literature search and evidence selection to respond to specific information needs identified during the analysis.

2.1 Research Scope and Questions

The study scope focuses on automation applied to hydrogen refueling stations and the extent to which automated monitoring, control, diagnostics, communication, and decision-support functions influence HRS performance. Particular attention is given to operational efficiency, fueling performance, reliability and maintenance, safety, hydrogen accounting and losses, and economic performance. Environmental aspects are considered only when directly related to the station's operation or energy performance, but environmental sustainability is not treated as an independent performance dimension.

The study is guided by the following research question (RQ):

RQ: How does automation in hydrogen refueling stations influence their operational performance, reliability, safety, and economic performance?

And sub-questions:

RSQ1: How does automation influence the energy performance of hydrogen refueling stations?

RSQ2: How does automation influence fueling performance, including fueling time and fueling-cycle compliance?

RSQ3: How can automation improve the reliability and maintenance performance of hydrogen refueling stations?

RSQ4: How does automation contribute to the safety performance of hydrogen refueling stations?

RSQ5: How can automation improve hydrogen accounting and support the identification and reduction of operational hydrogen losses?

RSQ6: What economic effects can automation produce in hydrogen refueling stations, and under what conditions can these effects be realized?

2.2 Literature Identification and Selection

Literature identification followed a structured, question-driven, and iterative search process. The search requirements were derived from the paper's analytical structure and the specific evidence needed to address each research question and performance indicator. For each identified information need, we formulated relevant keywords and term combinations and used them primarily in Google Search. The authors also considered relevant previous work that addressed the specific topic or provided a useful starting point for identifying additional sources. Search results were used to locate candidate studies, including publications accessed through academic repositories and platforms such as ResearchGate. Whenever possible, the content of the original publication was subsequently verified through the publisher or journal platform.

We initially assessed candidate publications by title and apparent relevance to the specific topic. We then examined potentially relevant studies through their abstracts and conclusions. Where a publication remained relevant, we reviewed its section headings and corresponding sections to identify specific findings, measurements, or technical information addressing the identified information need. Priority was given to evidence generated directly by the study under examination, particularly quantitative results and explicitly reported technical findings.

When several publications addressed the same issue, we preferentially selected sources most directly aligned with the paper's specific argument and information need to avoid duplicating evidence. We also examined reference lists of relevant publications when the required information was not available in the initially reviewed study, allowing us to identify potentially relevant primary or closely related sources. We repeated this process iteratively whenever we needed additional evidence during manuscript development.

The final selection therefore did not depend solely on the initial search results, but on the relevance, specificity, and evidential value of individual publications. Where sufficiently reliable and directly applicable evidence could not be identified, the respective issue was not developed as a substantive finding in the review.

2.3 Evidence Screening and Extraction

Candidate publications were screened progressively to determine whether they contained evidence directly relevant to the specific analytical need. The initial screening considered each publication's title, abstract, and conclusions. For studies that appeared relevant, we then examined the section headings and corresponding sections to locate specific findings, measurements, technical parameters, or methodological information related to the topic under consideration.

Particular attention was given to findings generated by the study itself. We preferentially extracted quantitative results, experimentally measured values, simulation outcomes, and explicitly defined technical parameters when they provided direct evidence for the respective performance indicator. Statements that merely repeated findings from other publications were treated primarily as leads to the underlying sources rather than as equivalent primary evidence.

When the required evidence could not be identified in the relevant sections of a publication, we examined its reference list to identify potentially useful primary or closely related sources. This additional search was particularly useful when a publication provided a general description of a phenomenon but lacked the specific quantitative or technical information required for the analysis.

The extraction process was iterative rather than limited to a single screening stage. When evidence remained insufficient or a technical statement required further clarification during manuscript development, we performed an additional targeted search. If sufficiently reliable and directly applicable evidence could not subsequently be identified, the respective statement was either reformulated to reflect the available evidence or excluded from the analysis.

2.4 KPI Framework and Analytical Structure

The evidence identified through the literature review was organized using a KPI-based analytical framework developed to provide a common structure for comparing heterogeneous HRS performance results. The framework was derived from the research questions and the analytical needs identified during the review, and it was used to classify reported findings by the aspect of station performance they addressed.

The selected performance dimensions comprise energy performance, fueling performance, reliability and maintenance, safety performance, hydrogen losses and mass-balance performance, and economic performance. Each dimension is represented by one or more measurable indicators, allowing reported results from different studies to be described using comparable performance concepts while retaining each study's original context and measurement conditions.

The KPI framework does not imply that all indicators can be directly compared across studies. We considered differences in station configuration, operating conditions, system boundaries, measurement methods, and definitions when interpreting the reported results. The framework therefore provides a consistent analytical structure for the synthesis rather than imposing a uniform measurement procedure on heterogeneous source data.

Figure 1 and Table 2 summarize the principal KPIs and their mathematical definitions. These indicators provide the basis for the subsequent analysis of automation-related effects on HRS performance and for the comparative synthesis presented in Section 7.

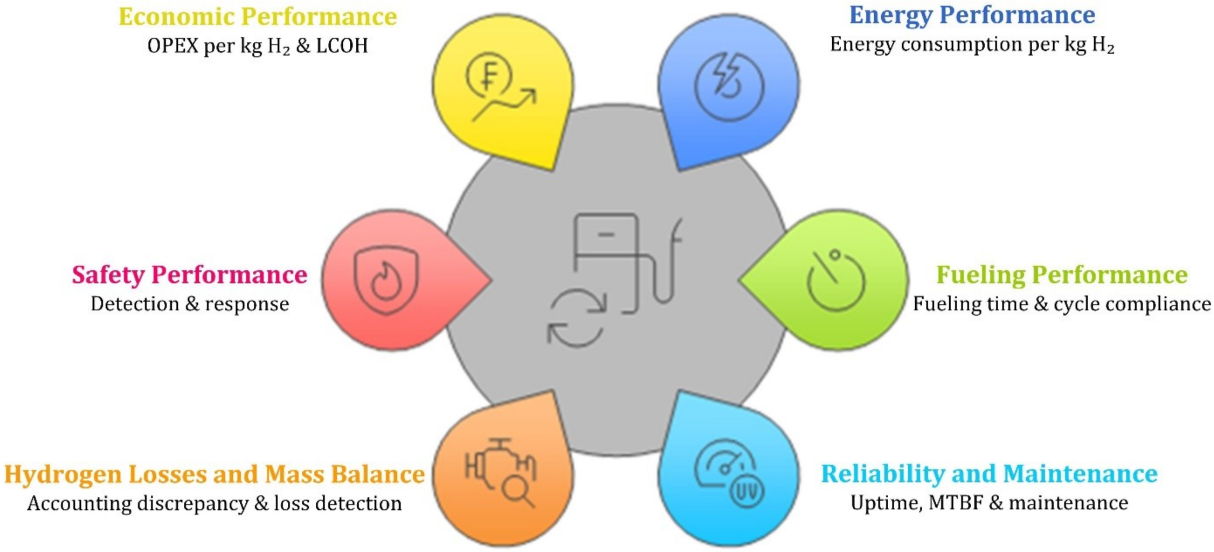

Figure 1. *Key Performance Indicators for Hydrogen Fueling Stations.*

Table 2. *Mathematical Model of Performance Indicators for Hydrogen Fueling Stations*

Performance dimension	KPI	Mathematical model
Energy performance	Energy consumption	$E_{kg} = \frac{\sum E_i}{m_{H_2}}$
Fueling performance	Fueling-cycle compliance	$Compliance = \frac{N_{compliant}}{N_{total}} \cdot 100$
Reliability & maintenance	Availability (uptime)	$Availability = \frac{T_{available}}{T_{scheduled}} \cdot 100$
	MTBF	$MTBF = \frac{T_{operating}}{N_{failures}}$
Safety performance	Leak-detection latency	$t_{detect} = t_{alarm} - t_{onset}$
	Safety event rate	$r_{events} = \frac{N_{events}}{N_{fills}} \cdot 1000$
Hydrogen losses & mass balance	Hydrogen accounting discrepancy	$L_{H_2} = \frac{m_{in} - m_{accounted}}{m_{in}} \cdot 100$
Economic performance	OPEX per kg H_2	$C_{OPEX} = \frac{OPEX}{m_{H_2}}$

2.5 Comparative Synthesis and Attribution

The selected evidence was comparatively synthesized to examine how automation-related functions relate to changes in HRS performance across the defined KPI dimensions. The comparison considered not only the reported performance values, but also the operating conditions, station configuration, control strategy, measurement approach, and system boundaries under which the results were obtained. This approach was necessary because the reviewed studies differ substantially in experimental conditions, station architecture, performance definitions, and result reporting methods.

We distinguished reported improvements in overall station performance from improvements specifically attributable to automation. When automation was introduced alongside changes in equipment, process configuration, operating conditions, maintenance procedures, or energy sources, the reported improvement was interpreted as a combined system effect unless the source provided sufficient evidence to isolate automation's contribution. Conversely, results supported by controlled comparisons, operational data, or explicit evaluation of an automation-related intervention were treated as stronger evidence of an automation-specific effect.

The strength and relevance of the evidence were therefore considered in relation to its origin and methodological context. Experimental measurements and operational data from HRS facilities were given particular attention, while simulation and modelling studies were used to complement empirical evidence and to examine relationships that are difficult to isolate under field conditions. The synthesis did not attempt to produce a single aggregated numerical effect of automation; instead, it identified recurring performance trends, quantified reported improvements where appropriate, and examined the conditions under which these improvements were observed.

This comparative approach also provided the basis for distinguishing direct evidence from broader system-level effects and for identifying limitations in attributing observed performance changes to automation alone. The resulting synthesis is presented through the KPI-based analysis in Section 7 and the consolidated evidence in Table 6.

2.6 Iterative Synthesis and Final Formulation

The synthesis and formulation of the review followed an iterative process in which the analytical structure and evidence base were progressively refined throughout the manuscript's development. An initial structure was established from the research scope and questions, after which the literature was used to develop a preliminary interpretation of each topic. As we identified and verified additional evidence, we revised individual statements, performance values, and interpretations to reflect the most directly applicable findings.

Particular attention was given to the consistency between the evidence and the claims made in the manuscript. Statements that were insufficiently supported, overly general, or based on evidence that could not be reliably attributed to the relevant automation function were either reformulated, qualified, or excluded. Where different studies reported similar findings, we consolidated the evidence rather than presenting it repeatedly, while retaining differences in operating conditions and methodological context where they affected interpretation.

The final formulation therefore reflects an iterative process of literature search, evidence verification, comparison, and revision. This process maintained a clear distinction between findings directly supported by the reviewed literature and interpretations derived from the overall synthesis. The final structure reflects this synthesis and provides the basis for discussing HRS automation performance and its future development.

3 HYDROGEN AS A FUTURE FUEL

3.1 Strengths and Challenges of Hydrogen

This section avoids discussing the general characteristics of hydrogen, as numerous investigations have extensively explored this topic in depth. Instead, it focuses on major characteristics relevant to its application as a fuel, emphasizing specific properties of the facilities under consideration (Brown, 2024; Čekerevac et al., 2022).

Hydrogen is the most promising future fuel because its unique characteristics offer environmentally friendly solutions to reduce pollution and improve energy efficiency. Hydrogen's primary advantage is that it leaves only water vapor as a byproduct when combusted in internal combustion engines (ICE) or used in FCs, thereby contributing significantly to environmental conservation. Unlike fossil fuels such as diesel, petrol, liquefied petroleum gas (LPG), and compressed natural gas (CNG), hydrogen produces no carbon dioxide emissions. It thus greatly helps combat climate change (Čekerevac, 2024). However, hydrogen combustion in internal combustion engines (ICEs) produces nitrogen oxides (NOx) emissions, which pose significant risks to air quality and human health. Hydrogen impurities can also lead to additional toxic emissions, including carbon monoxide (CO), soot particles, and sulfur dioxide (SOx). Therefore, it is necessary to develop advanced technologies to minimize NOx emissions in hydrogen internal combustion engines.

Several advanced technologies can reduce NOx emissions in hydrogen ICEs. Precise air-fuel mixture control enables fine-tuning of the combustion process, sustaining optimal temperatures and reducing NOx formation. Exhaust gas recirculation (EGR) lowers combustion temperature by recirculating exhaust gases (primarily water vapor), thereby reducing NOx formation.

Selective Catalytic Reduction (SCR) reduces NOx emissions by converting them to harmless nitrogen and water using a reducing agent such as urea or ammonia. Additionally, the real-time emission monitoring of advanced sensors enables dynamic optimization of engine parameters, thereby improving efficiency. Combustion chamber pressure and temperature conditions, along with combustion chamber design improvements, result in more homogeneous flame distribution and lower peak temperatures, thereby reducing NOx emissions. These measures significantly reduce NOx emissions, dispelling concerns about hydrogen's feasibility for ICE applications.

One of hydrogen's most prominent advantages is its high lower heating value per unit mass, ranging from 120 to 142 MJ/kg. Compared with gasoline, which has a lower heating value of approximately 42–44 MJ/kg, and with compressed natural gas (CNG), which has a higher heating value of 45–50 MJ/kg, hydrogen's high energy density enables higher efficiency in transport and industrial applications. In FCs, hydrogen generates electrical energy via electrochemical processes with minimal energy loss, demonstrating its superior energy-conversion efficiency.

FCs are crucial for harnessing hydrogen's potential. These cells transform hydrogen's chemical energy into electrical energy via electrochemical reactions. Polymer membrane fuel cells (PEMFCs) are commonly used in vehicles. They offer high efficiency, quick startup, low operating temperature (around 80 °C), and exceptional environmental compatibility, as they produce only water as a byproduct. These attributes make FCs an ideal choice for sustainable transportation systems (Čekerevac, 2024).

Beyond its environmental and energy benefits, hydrogen offers significant flexibility in production. It can be obtained from various sources, including solar and wind power. However, production methods significantly impact their environmental footprint and purity. For example, water electrolysis powered by renewable energy (Green Hydrogen[1]) has minimal environmental impact, whereas production using fossil fuels (Brown Hydrogen) has a much greater adverse environmental impact.

Despite its many advantages, hydrogen faces challenges. Its low density requires storage at high pressures, often up to 70 MPa, or at extremely low temperatures below 20 K to remain liquid. These technical and infrastructural demands significantly increase the complexity of its broader adoption. Additionally, production and infrastructure development costs significantly limit its current global use. Hydrogen quality and purity are essential to minimizing environmental impact. This is one reason why Green Hydrogen, produced via electrolysis using renewable energy, is preferred over hydrogen derived from fossil fuels.

3.2 Challenges and Role of Automation

Hydrogen production, storage, and transportation involve inherent risks that must be carefully managed. Production processes involve risks associated with temperature, pressure, and explosive mixtures, underscoring the need for robust safety measures. The same problems plague hydrogen transportation. Although pipelines are cost-effective for bulk transportation, they are prone to fatigue- and embrittlement-induced material degradation. Transport by truck or ship is more expensive and requires stringent safety precautions. Liquid hydrogen (LH_2) transport enables higher-density storage but incurs energy losses due to evaporation, whereas ammonia transport uses established infrastructure but requires additional energy for hydrogen extraction. Storage is also implicated, wherein hydrogen is compressed, liquefied, or stored using materials such as metal hydrides. These practices

[1] A systematic color-coding scheme has been introduced to clarify distinctions among hydrogen types, facilitating tracking of production methods and sustainability impacts.

must balance energy efficiency, safety, and cost while addressing concerns such as leakage, equipment durability, and high energy demand. New practices, such as underground storage in salt caverns or aquifers, are feasible but geographically constrained and pose contamination threats. End users, especially vehicle drivers, are at risk during operation and refueling. High-pressure refueling increases the risk of equipment failure or explosion, and liquid hydrogen requires specialized equipment to prevent cryogenic burns. Evaporation during refueling creates flammable mixtures, and incompatibility between vehicle and station standards increases operational risk. Technological developments in materials science and energy systems significantly mitigate these concerns, thereby enabling safer processes for hydrogen production, distribution, storage, and utilization. Automation can play an important role in mitigating these hazards at the HRS level, as systems such as leak-detection sensors, automatic fire-suppression systems, and automated processes minimize human error while enhancing overall safety.

These challenges and the mitigating role of automation are further quantified in Section 7, where performance outcomes are systematically compared and analyzed.

4 SAFETY AND PROTECTION OF AUTOMATED HRS

Hydrogen refueling stations (HRS) require preventive, monitoring, and protective measures because hydrogen is highly flammable and can form combustible mixtures over a wide range of concentrations. Safe operation therefore depends on the early detection of abnormal conditions and on reliable protective functions capable of rapidly limiting or interrupting hazardous processes. In automated HRS, these functions can be integrated with sensors, control systems, safety interlocks, alarms, and emergency shutdown mechanisms. This section examines the principal safety and protection functions relevant to automated HRS, with particular attention to hydrogen leak detection, emergency shutdown and safety interlocks, and fire and explosion protection.

4.1 Key Protective Functions

Hydrogen refueling stations (HRS) require a combination of preventive, monitoring, and protective measures to control the hazards associated with hydrogen handling and high-pressure refueling operations. Hydrogen's high flammability, low ignition energy, and high diffusivity make early detection of abnormal conditions and rapid intervention essential for safe station operation. Consequently, HRS safety relies on multiple complementary layers, including hydrogen leak detection, pressure and flow monitoring, ventilation and dispersion control, fire and explosion protection, safety interlocks, and emergency shutdown systems. These functions should not operate as isolated measures; rather, they should be coordinated to detect abnormal conditions, prevent escalation, and place the station or affected equipment in a safe state. (Gao et al., 2026)

In an automated HRS, protective functions are closely integrated with sensing, control, and supervisory systems. Sensors provide continuous information on hydrogen concentration, pressure, temperature, flow, and equipment status, while control and safety systems use this information to initiate predefined protective actions when operating conditions exceed specified limits. Depending on the detected event, these actions may include generating an alarm, isolating a section of the hydrogen system, stopping hydrogen flow, shutting down compressors or dispensers, activating ventilation, or initiating an emergency shutdown. Such an integrated approach can reduce dependence on manual intervention and shorten the time between detection of a hazardous condition and the corresponding protective response. (Genovese et al., 2024)

The principal protective functions considered in this study are therefore hydrogen leak detection, emergency shutdown and safety interlocks, ventilation and dispersion control, and fire and explosion protection. Their effectiveness depends not only on individual devices but also on their integration into a coherent safety architecture. The following sections examine these functions, with particular emphasis on their contribution to automated monitoring, rapid response, and reliable HRS operation.

4.2 Hydrogen Leakage Detection

Hydrogen leakage is one of the most important initiating hazards at hydrogen refueling stations (HRS), since an uncontrolled release can rapidly develop into a flammable or explosive atmosphere. The detection of hydrogen leakage is therefore a fundamental safety function and an essential input to automated protective actions. Recent reviews of hydrogen leakage at HRS emphasize that the behavior of a release depends strongly on leak characteristics, hydrogen dispersion, and the geometry and ventilation conditions of the surrounding environment (Hu et al., 2024). Consequently, effective leak detection cannot be reduced to the presence of a hydrogen sensor alone; sensor type, location, response time, detection range, and integration with the station control and safety system all influence the effectiveness of the overall protection strategy.

Several sensor technologies have been developed for hydrogen leakage detection, including ultrasonic, electrochemical, metal-oxide (MOX), catalytic, and fiber Bragg grating (FBG) sensors. Each technology offers specific advantages and limitations depending on the required sensitivity, response characteristics, environmental conditions, and application. Menon et al. (2025) reviewed these technologies and highlighted, among other characteristics, the explosion resistance and durability of fiber-optic sensors, the potential of ultrasonic sensors for leak detection, and the sensitivity and manufacturing advantages of MOX sensors, while also identifying limitations such as cross-sensitivity and response time. The authors further note that ultrasonic detection has so far seen limited commercial application in hydrogen environments.

Fiber-optic approaches are of particular interest for hydrogen applications because they can provide inherent safety advantages in hazardous environments and are largely insensitive to electromagnetic interference. Among these approaches, palladium-coated fiber-optic sensors exploit the interaction between palladium and hydrogen to produce measurable optical changes, while FBG-based configurations offer the potential for distributed or multipoint sensing (Alkhabet et al., 2025).

For automated HRS, the spatial distribution of sensors is as important as the sensing technology itself. Hydrogen leakage does not necessarily produce a uniform concentration field, and hydrogen dispersion is influenced by the release rate, release location, enclosure geometry, ventilation, and surrounding equipment. Sensor placement must therefore be considered as part of the overall safety design rather than as an independent instrumentation problem. Quantitative risk assessments of HRS have identified hydrogen detection sensors as an important mitigation measure, particularly in combination with emergency shutdown functions and other engineering safeguards (Yuan et al., 2024). More recent research has also emphasized the need to relate leakage characteristics and hydrogen dispersion to the location and configuration of detection systems (Hu et al., 2024).

The main advantage of automated leak detection is therefore not merely the ability to detect hydrogen, but the ability to transform detection into a coordinated protective response. A detected increase in hydrogen concentration can be used to generate an alarm, verify the abnormal condition through redundant measurements, isolate the affected section, stop hydrogen transfer, initiate ventilation, or activate an emergency shutdown. The resulting sequence can be expressed as: detection → evaluation → protective action → safe state. Such integration reduces dependence on manual intervention and can shorten the time between the onset of a leak and the initiation of appropriate protective measures.

Recent research also points toward the use of data-driven methods for improving hydrogen leak detection and localization. Hu et al. (2024) note that the integration of multiple sensor data points with artificial intelligence could improve the identification of leakage location and severity. This approach is particularly relevant to automated HRS because distributed sensors can provide spatial and temporal information that may be combined with process data, ventilation conditions, and equipment status. However, AI-based detection should be regarded as a complementary diagnostic layer rather than a replacement for dedicated safety instrumentation and deterministic emergency protection functions.

4.3 Emergency Shutdown and Safety Interlocks

Emergency shutdown (ESD) systems provide a critical protective layer in hydrogen refueling stations by interrupting hazardous operations when predefined abnormal conditions are detected. Unlike ordinary process-control functions, an emergency shutdown function is intended to bring the affected part of the station to a safe state and to take precedence over normal operating commands. ISO 19880-1 addresses ESD functionality within the instrumentation and control system of gaseous hydrogen fueling stations, specifying requirements for hydrogen leak detection, manually actuated emergency stop devices, and the functional linkage between detection systems and ESD/isolation actions so that detected hazardous conditions initiate appropriate protective measures (ISO, 2020)

In an automated HRS, an emergency shutdown can be initiated by different safety-related signals, depending on the station design and risk assessment. These may include detection of hydrogen leakage, abnormal pressure or flow, failure of ventilation, hose or breakaway-device activation, or a manually operated emergency stop. The resulting protective actions may include closing automatic isolation valves, stopping hydrogen transfer, shutting down compressors or dispensers, and preventing further fueling until the hazardous condition has been assessed and the system has been safely restored. Quantitative risk assessment of a liquid hydrogen refueling station has shown that measures including hydrogen detection sensors and automatic and manual emergency shutdown devices can contribute substantially to risk reduction. (Yuan et al., 2024)

Safety interlocks complement emergency shutdown systems by preventing specific operations from being performed when the required safety conditions are not satisfied. Rather than responding only after a hazardous event has developed, an interlock can prevent or interrupt an operation when a permissive condition is lost. In this way, interlocks can be used to coordinate equipment such as compressors, valves, dispensers, ventilation systems, and hydrogen detection systems. The resulting logic can be implemented as a sequence of predefined safety functions in which sensor signals are evaluated by the control or safety system and appropriate final elements are activated to maintain or restore a safe state. ISO 19880-1 identifies safety functions and safety-instrumented systems in terms of sensors, logic solvers, and final elements, providing an appropriate conceptual framework for this type of protection. (ISO, 2020)

The effectiveness of automated protective actions depends on the reliability and appropriate design of the complete safety chain rather than on any individual component. Detection, decision logic, communication, actuation, and isolation must operate with sufficient reliability to ensure that a hazardous condition does not escalate. For this reason, safety-related functions should be defined through risk assessment and validated according to applicable safety requirements rather than being treated simply as extensions of conventional process automation. In an automated HRS, the objective is therefore not merely to detect an abnormal condition, but to ensure a rapid, coordinated, and reliable transition from normal operation to a predefined safe state.

4.4 Fire and Explosion Protection

Fire and explosion protection at hydrogen refueling stations requires several complementary layers of prevention and mitigation. The primary objective is to prevent the formation and ignition of a hazardous hydrogen-air mixture and, if ignition nevertheless occurs, to limit fire development and its consequences. Accordingly, fire and explosion protection begins with measures incorporated into the station design, including appropriate separation distances, control of ignition sources, hazardous-area classification, suitable equipment selection, pressure protection, and ventilation. These measures reduce the probability that hydrogen release will develop into a fire or explosion and provide the basis for subsequent active protection systems. (Gao et al., 2026)

Conventional fire protection systems provide an additional layer of protection when prevention measures are insufficient. Depending on the station configuration and applicable requirements, these measures may include fire detection and alarm systems, portable fire extinguishers, water-based systems such as water spray or deluge systems, and other fixed fire-protection equipment. Physical barriers and appropriate separation can also limit the consequences of a fire or explosion by reducing the exposure of personnel, vehicles, equipment, and adjacent facilities. The selection of a particular protection system should be based on the hydrogen storage and dispensing configuration, the identified hazards, and applicable codes and standards rather than on a single universal solution. (Jabatan Bomba dan Penyelamat Malaysia, 2025; Jiang et al., 2025)

Automation significantly increases the effectiveness of these protective measures by connecting detection, decision-making, and actuation. Fire detection, hydrogen concentration monitoring, pressure monitoring, and equipment-status signals can be integrated with the station safety system so that the detection of a hazardous condition initiates predefined action. Depending on the event and system design, these actions may include stopping hydrogen flow, isolating affected equipment, activating alarms, initiating emergency shutdown, and controlling ventilation. Fire alarm activation can also be linked to the shutdown of gas flow in dispensing areas, illustrating how fire protection and process safety can be integrated into a coordinated automated response. (Technical Committee on Hydrogen Technologies, 2019)

More advanced protection strategies build on this conventional safety architecture by combining distributed sensing, automated fire and leak detection, real-time process information, and coordinated protective actions (Deshmukh et al., 2026). Such integration can improve situational awareness and reduce the time required to respond to developing hazards. Recent reviews emphasize that active engineering safety devices and emergency response should be considered together with inherently safer design and preventive measures, rather than as independent protection layers (Gao et al., 2026)

5 INTELLIGENT SYSTEMS AND UNDERLYING TECHNOLOGY

Implementing HRS requires advanced technologies and intelligent systems to optimize operations, enable real-time monitoring, and synchronize with renewable energy sources.

5.1 SCADA and PLC-Based Control

Supervisory control and data acquisition (SCADA) systems and programmable logic controllers (PLCs) form an important part of the automation architecture of hydrogen refueling stations. PLCs provide local process control by receiving signals from sensors, executing programmed control and interlock logic, and sending commands to actuators such as valves, compressors, cooling equipment, and dispensing systems. SCADA systems operate at a supervisory level, collecting process data from distributed equipment and providing operators with visualization, alarms, historical data, and higher-level monitoring functions. In this configuration, PLCs and safety-related controllers are responsible for fast local control and protective actions, while SCADA provides a broader view of station operation and supports supervisory decision-making.

The relevance of this architecture to HRS arises from the need to coordinate several interdependent processes, including hydrogen storage, compression, cooling, dispensing, pressure regulation, and safety monitoring. Process variables such as pressure, temperature, hydrogen flow, storage status, and equipment condition can be acquired continuously and used by the control system to regulate station operation. For example, process-control strategies can adjust compressor operation and cascade-storage management according to refueling demand and pressure conditions. Experimental and modelling work on HRS has demonstrated that optimized control strategies can improve refueling performance, reduce energy consumption, and increase the effective daily fueling capacity of a station (Xu et al., 2022).

SCADA also provides an interface between the physical station and the operator. Real-time process visualization, alarm management, event recording, and historical data acquisition allow abnormal operating conditions to be identified and investigated. In a connected HRS, the supervisory layer can also exchange information with higher-level data-processing and management systems. However, safety-critical functions should not depend exclusively on supervisory or remote communication layers. Local PLC and safety-system logic must remain capable of executing predefined protective actions when communication with higher-level systems is interrupted. This separation between local control and supervisory functions is particularly important for hydrogen infrastructure, where rapid response to abnormal pressure, leakage, or equipment conditions may be required.

The resulting architecture can therefore be viewed as a hierarchy in which sensors and field devices provide measurements at the process level, PLCs and safety controllers perform local control and protection, and SCADA systems provide supervisory monitoring and data management. This architecture forms the technological foundation for subsequent integration of IoT devices, advanced analytics, predictive maintenance, and edge–cloud computing. The transition from conventional SCADA toward intelligent HRS does not eliminate the basic control hierarchy; rather, it extends it with additional sensing, communication, and data-processing capabilities.

5.2 IoT and Intelligent Monitoring

The integration of Internet of Things (IoT) technologies extends the monitoring capabilities of conventional HRS automation by connecting distributed sensors, equipment, and data-processing systems. While traditional control architectures primarily focus on local process control and supervisory operation, IoT-based monitoring enables data from compressors, storage systems, dispensers, cooling units, and other critical components to be collected and analyzed as part of an integrated information environment. This provides greater visibility of station conditions and enables continuous monitoring of parameters such as pressure, temperature, flow rate, hydrogen concentration, and equipment status.

An IoT-enabled HRS can therefore combine distributed sensing with centralized or remote monitoring. Sensors on individual components transmit measurements through communication networks to a data-collection or analysis platform, where the information can be visualized, evaluated, and stored. A recently proposed HRS monitoring architecture, for example, uses IoT sensors installed on station components together with a data-collection device and an analysis server to assess component condition and calculate risk levels from sensor measurements. Such architecture illustrates how IoT can extend station monitoring beyond the physical control room and support remote assessment of equipment condition. (Oh et al., 2024)

The value of intelligent monitoring, however, lies not simply in increasing the number of connected sensors. The collected data must be transformed into information that can support operational and maintenance decisions. Continuous data acquisition makes it possible to identify deviations from normal operating conditions, detect recurring abnormal patterns, and establish condition indicators for critical equipment. In this context, IoT monitoring provides an important foundation for predictive maintenance and anomaly detection, while also supporting the integration of historical and real-time operational data. Recent work on hydrogen infrastructure has demonstrated the use of connected sensing, data collection, and analysis for risk assessment and prognostics of individual HRS components. (Oh et al., 2024)

IoT technologies can also provide a link between individual stations and higher-level monitoring platforms. This is particularly relevant when hydrogen infrastructure consists of multiple geographically distributed stations. Centralized data environments can provide operators with a common view of equipment condition and operational performance, while local control systems continue to perform time-critical process and safety functions. Such a division preserves the local control hierarchy described in Section 5.1 while allowing station data to be aggregated for fleet-level monitoring, maintenance planning, and performance analysis.

Consequently, IoT should be regarded as an enabling layer rather than a replacement for conventional HRS automation. Its principal contribution is to increase connectivity, data availability, and visibility across the station infrastructure. Combined with advanced analytics, IoT data can support anomaly detection, predictive maintenance, digital twins, and optimization. The following sections cover these capabilities.

Table 3. *IoT-enabled Functions in Hydrogen Refueling Stations*

IoT-enabled function	Role in HRS	Contribution to intelligent automation
Sensor integration and data acquisition	Collection of pressure, temperature, flow, hydrogen concentration, and equipment-status data from distributed sensors	Provides continuous information about station conditions and operating parameters
Remote monitoring	Transmission and visualization of operational data from station equipment	Enables remote assessment of station status and reduces dependence on continuous on-site observation
Equipment condition monitoring	Monitoring of compressors, valves, dispensers, storage systems, and other critical components	Supports identification of abnormal operating patterns and equipment degradation
Predictive maintenance	Collection and analysis of historical and real-time equipment data	Provides a basis for anomaly detection, condition assessment, and maintenance planning
Data integration	Combining data from multiple sensors and station subsystems	Creates a common information layer for subsequent analytics and decision support

As summarized in Table 3, IoT-enabled functions provide the data foundation for more advanced analytical approaches, including anomaly detection, artificial intelligence, digital twins, and predictive maintenance, discussed in the following section.

5.3 AI, Digital Twins, and Predictive Maintenance

The continuous collection of operational data in automated HRS creates opportunities for advanced analytical methods that extend conventional monitoring and control. Machine learning (ML) has already been investigated for hydrogen refueling processes. Wang and Decès-Petit (2020), using data from three hydrogen refueling stations, applied multi-task machine learning to classify fueling events and predict the state of charge (SOC). The classification accuracy exceeded 85%, while the models also demonstrated the ability to predict SOC, indicating that operational HRS data can be used to support prediction of the fueling process.

Machine learning can also be applied to safety-related prediction. Li et al. (2024) developed a deep probabilistic learning model for real-time prediction of hydrogen release and dispersion at HRS. The proposed model predicted spatial hydrogen plume concentration with an R^2 value of 0.97 and an inference time of 3.32 s, while also providing uncertainty information. The authors proposed the approach as a potential basis for a digital twin for emergency management of hydrogen refueling stations. (Li, et al., 2024)

Digital twin technology provides another approach to integrating operational data, system models, and analytical methods. An et al. (2024) developed a digital-twin-based safety model for an HRS using real-time data, including temperature, pressure, and state of charge, collected from an actual station. Nine machine-learning and deep-learning algorithms were evaluated for risk prediction; the CNN model achieved the highest reported performance, with an F1 score of 0.993 and a prediction time of 68 ms. The digital twin was used to visualize predicted risk situations and support rapid identification of potentially unsafe conditions. (An et al., 2024)

Predictive maintenance represents a further application of data-driven methods in HRS. Kim et al. (2024) analyzed operational data from hydrogen storage pressure vessels at a refueling station in South Korea and proposed a predictive reinspection methodology based on fatigue analysis and Rainflow counting. The study demonstrates how operational data can be used to support maintenance and reinspection planning for critical HRS components, although the authors emphasize that broader data collection is required before the results can be generalized to other stations. (Kim et al., 2024)

Recent work published in 2026 further explores the combination of digital twins, real-time monitoring, predictive risk assessment, and predictive maintenance for hydrogen refueling infrastructure. Hasulyó (2026) developed a dynamic digital-twin framework incorporating hydrogen refueling processes, sensor data, and safety-related modelling. The reported results include real-time leak detection, automated alarms, and mass-flow measurement, while the study identifies predictive maintenance and optimized energy consumption as potential applications of the digital-twin approach.

These studies indicate that the role of intelligent systems in HRS is evolving from data acquisition and monitoring toward prediction, risk assessment, and maintenance planning. However, the available studies differ considerably in their data sources, modelling approaches, and validation methods. Their results should therefore be interpreted as evidence of the potential of AI and digital-twin technologies rather than as proof that such methods can universally replace conventional control or safety systems. In an automated HRS, AI-based methods are better regarded as an additional analytical and decision-support layer, while deterministic control, interlocks, and emergency shutdown functions remain responsible for time-critical protective actions.

5.4 Edge and Cloud Computing

The increasing volume of data generated by automated and IoT-enabled HRS raises the question of where data processing should take place. Edge and cloud computing provide complementary approaches to this problem. Edge computing performs data processing close to the physical equipment and data sources, thereby reducing communication latency and allowing selected functions to remain operational locally. Cloud computing, in contrast, provides centralized computational and storage resources suitable for historical data analysis, large-scale optimization, and coordination of multiple stations.

For HRS, the distinction between edge and cloud processing is particularly important because different functions have different response-time and reliability requirements. Local control and safety functions should remain within the station's control and safety architecture, where they can operate independently of external communication. Edge computing can complement this architecture by processing selected monitoring and analytical tasks close to the station, while cloud platforms can be used for computationally intensive analysis, long-term data storage, fleet-level monitoring, and optimization.

A practical example of this approach was demonstrated at the AuxHYGen hydrogen refueling station in France, where a hybrid Edge–Cloud energy management system was implemented for an industrial-scale green hydrogen refueling station. The architecture used cloud-based energy management to coordinate hydrogen production sites while maintaining local capabilities for station operation. The study included real-time digital-model assessment of the system and demonstrated the practical application of a hybrid Edge–Cloud architecture in a hydrogen refueling environment (Nguyen et al., 2024)

The hybrid approach is also relevant to intelligent HRS monitoring. Data generated by local sensors and control systems can be processed at the edge for applications requiring rapid feedback, while selected information can be transmitted to cloud systems for more extensive analysis. This can reduce unnecessary data transmission and allow computational resources to be allocated according to the requirements of individual applications. Recent research on intelligent HRS platforms similarly identifies edge computing as a means of performing low-latency data processing near the source, while cloud-based systems support broader coordination and data exchange. (Huo, et al., 2026)

The resulting architecture can therefore be understood as a layered computing environment. Local PLC and safety systems remain responsible for deterministic control and protective actions; edge computing provides additional local data-processing and analytical capabilities; and cloud computing supports centralized analysis, storage, optimization, and coordination. This arrangement allows the benefits of connected and intelligent HRS to be realized without transferring time-critical safety functions to remote computing resources.

5.5 Communication Architecture and Cybersecurity

The increasing automation and digital integration of HRS require reliable communication between sensors, controllers, safety systems, station equipment, supervisory platforms, and hydrogen vehicles. Communication architecture therefore represents an important part of the overall automation system. It must support the exchange of operational data while providing appropriate timing, reliability, and interoperability for different station functions.

At the station level, communication networks connect equipment such as compressors, storage tanks, dispensers, valves, sensors, and control systems. Recent research has investigated the application of IEC 61850 to hydrogen refueling stations as an alternative to communication approaches traditionally used in HRS. Lee and Hwang (2025) developed IEC 61850 data models for major HRS components and implemented a prototype using the libIEC61850 library and Raspberry Pi hardware. Their experiments showed that communication delay and its variability depend on the selected data-collection method, demonstrating the importance of communication architecture for real-time HRS monitoring and control. (Lee & Hwang, 2025)

Communication is also required at the vehicle–station interface. SAE J2799 specifies communication hardware and software requirements for fueling hydrogen surface vehicles and provides a basis for harmonized implementation of the hydrogen fueling interface. The standard is intended to be used together with SAE J2601 fueling protocols, SAE J2600 connection requirements, and ISO 17628. The current SAE J2799 revision was published in March 2026, providing a recent standardization reference for vehicle-to-station communication. (SAE International, 2026)

The increasing connectivity of HRS, however, introduces cybersecurity requirements in addition to conventional functional safety requirements. Communication networks that connect sensors, controllers, supervisory systems, remote platforms, and vehicle interfaces can create additional attack surfaces if they are not appropriately protected. Cybersecurity should therefore be considered as an integral part of HRS resilience rather than as a separate information-technology issue. In particular, unauthorized access, manipulation of sensor data, disruption of communication, or compromise of control systems could affect the availability or integrity of automated station operation.

This distinction is important because cybersecurity and functional safety address different, although related, types of risk. Functional safety seeks to ensure that the system responds correctly to hazardous conditions, whereas cybersecurity seeks to protect the system against intentional or unauthorized actions that could compromise its confidentiality, integrity, or availability. In an automated HRS, these two domains increasingly overlap because safety functions depend on sensors, communication networks, controllers, and digital supervisory systems.

Consequently, a resilient HRS communication architecture should combine reliable communication protocols, appropriate network segmentation and access control, secure data exchange, monitoring of abnormal network activity, and mechanisms for maintaining safe operation in the event of communication failure or cyberattack. Recent work on hydrogen fueling infrastructure has identified SAE J2799, IEC 61850, and related communication and security standards as relevant references for the development of connected hydrogen fueling systems. (Hatic et al., 2025)

From the perspective of the overall architecture proposed in this paper, communication should therefore be regarded as the connecting layer between physical HRS equipment, local automation, intelligent analytical systems, and external information systems. Its design must preserve the independence and reliability of time-critical safety functions while enabling the connectivity required for monitoring, prediction, optimization, and future integration of hydrogen infrastructure into wider energy and transportation systems.

6 KEY ELEMENTS OF AUTOMATED HYDROGEN STATIONS

6.1 Hydrogen Purification Unit

FCVs require hydrogen of higher purity than that used by internal combustion engines (ICEs), as contaminants such as carbon monoxide (CO) and sulfur species can poison catalysts, reduce efficiency, or lead to system failure (Čekerevac & Čekerevac, 2025). The purification processes may involve pressure swing adsorption (PSA), membrane technologies, and, depending on the hydrogen production and supply configuration, cryogenic separation processes. These technologies can remove contaminants such as nitrogen (N_2), methane (CH_4), water, and other impurities to achieve the required hydrogen quality (Ruthven et al., 1994; Ockwig & Nenoff, 2007; Smith, 2005).

Automation can support hydrogen quality control through real-time purity monitoring using dedicated sensors. Online hydrogen quality analyzers have been demonstrated for continuous monitoring of impurities including O_2, N_2, H_2O, CO, CO_2, and CH_4, providing real-time information on hydrogen quality and potential deviations from specified limits (Kim et al., 2025). Advances in hydrogen sensing have also enabled wireless real-time monitoring and integration with IoT and machine-learning systems, providing opportunities for automated quality assessment and remote monitoring (Zhu et al., 2025; Pandey et al., 2026). These measurements can be integrated with control systems to maintain required hydrogen quality and support safe, reliable station operation.

6.2 Storage Tanks

Hydrogen can be stored in different forms, including compressed gaseous hydrogen (CGH_2), liquid hydrogen (LH_2), cryo-compressed hydrogen (CcH_2), and material-based hydrogen storage systems (Čekerevac & Čekerevac, 2025). The selected storage technology determines the required operating conditions, transfer and conditioning technologies, instrumentation, and control strategy. Consequently, the associated hazards and protection requirements also vary with the storage configuration. In CGH_2 systems, hydrogen is stored and distributed at high pressure, with 700 bar (70 MPa) being widely used for vehicle refueling. CcH_2 combines cryogenic cooling with high-pressure storage and can operate at approximately 350 bar (35 MPa). These configurations therefore require different approaches to monitoring pressure, temperature, leaks, and transfers (Cekerevac et al., 2025; Čekerevac & Čekerevac, 2025).

Automation supports safe, efficient operation of hydrogen storage systems by continuously monitoring pressure, temperature, hydrogen concentration, and equipment status, while coordinating valves and hydrogen transfer processes. Key automation features include the following:

- *Pressure and temperature control***.** Sensors continuously monitor storage pressure and temperature, and deviations from predefined operating limits can initiate alarms, isolation, or other protective actions. High-pressure gaseous storage may involve pressures up to 70 MPa, depending on the station configuration and application (International Organization for Standardization, 2025; Cekerevac et al., 2025).
- *Leak detection systems***.** Hydrogen detectors provide continuous monitoring around storage equipment and can initiate predefined protective actions when a leak is detected. Integration with control and safety systems enables rapid isolation of affected equipment and helps reduce the potential consequences of uncontrolled release (International Organization for Standardization, 2025; Li et al., 2024).
- *Storage capacity management.* Control systems can coordinate hydrogen storage and transfer according to refueling demand and pressure conditions, supporting efficient use of available storage capacity and improving station operation (Xu et al., 2022).
- *Automated filling and transfer.* Control systems can regulate hydrogen transfer to and from storage vessels, coordinating valves and operating conditions while minimizing manual intervention.
- *Safety and alarm systems***.** Automated systems detect abnormal pressure, temperature, hydrogen concentration, or equipment conditions, generate alarms, and initiate predefined protective actions when specified limits are exceeded (International Organization for Standardization, 2025).
- *Remote monitoring and data analysis***.** Real-time storage data can be transmitted to

supervisory systems for visualization, analysis, event recording, and condition monitoring. This allows operators to assess storage-system status remotely while local control and safety functions remain responsible for time-critical protective actions (Oh et al., 2024).

In addition to ISO 19880-1, component-level requirements for valves, piping, and associated equipment are addressed by ISO 19880-3, including requirements related to materials, pressure ratings, and safety testing (ISO, 2020). These requirements support the structural integrity and safe operation of high-pressure hydrogen storage and associated equipment.

6.3 Compressor Station

Compressors are core components of hydrogen refueling stations because they provide the pressure required for hydrogen storage and vehicle refueling. For 70 MPa storage systems, compressor outlet pressure may reach approximately 82 MPa (820 bar), as demonstrated in studies of high-pressure fast-filling systems (Li et al., 2021). Compressor performance directly affects refueling speed, energy consumption, equipment reliability, and overall station efficiency. The appropriate compressor technology depends on the required pressure, flow rate, duty cycle, hydrogen purity requirements, and station configuration. Several compressor technologies are therefore relevant to HRS, as summarized in Table 4.

Table 4. *Hydrogen Compressor Technologies Relevant to HRS*

Compressor type	Operating principle	Main advantages	Main limitations / considerations	Source
Diaphragm compressor	Hydraulic actuation deforms a diaphragm, separating the hydrogen from the hydraulic oil and mechanical drive.	High hydrogen purity; effective gas sealing; suitable for high-pressure compression.	Diaphragm fatigue, hydraulic-oil effects on volumetric efficiency, thermal management, and relatively high discharge temperatures.	Xu, et al. (2025); Ren, et al. (2024)
Hydraulically driven piston compressor	Hydraulic pressure drives a free piston that compresses hydrogen reciprocally.	High-pressure capability; relatively simple reciprocating mechanism; suitable for high-pressure applications.	Piston/sealing wear, vibration, hydrogen embrittlement, and maintenance requirements.	Xu, et al. (2025)
Ionic liquid compressor	An ionic liquid acts as a liquid piston and seal while a hydraulic system drives the free piston.	High sealing performance, low hydrogen contamination risk, good thermal management potential, and high-pressure capability.	Gas–liquid two-phase-flow control, thermal management, material compatibility, corrosion, and long-term reliability.	Xu, et al. (2025); Li et al. (2023)
Reciprocating piston compressor (oil-free)	Mechanical piston reciprocates directly to compress hydrogen without oil in the compression chamber.	Established compression principle; potential for high flow rates without oil contamination of hydrogen.	Sealing and leakage, component wear, and hydrogen-related material degradation require careful management.	Xu, et al. (2025); Li et al. (2023)

Other compression technologies, including centrifugal and electrochemical compressors, are also being investigated for hydrogen infrastructure (Fuel Cells Works, 2026; Marciuš, 2024). Their applicability depends strongly on required flow rate, pressure ratio, station configuration, and technology maturity; therefore, this section does not discuss them as primary HRS compressor configurations.

Regardless of the selected compressor technology, automation provides an important means of maintaining stable operating conditions, detecting developing faults, optimizing energy use, and coordinating compressor operation with storage and dispensing systems (Xu et al., 2022; Lv et al., 2025; Kim et al., 2024). Key automation functions include:

- *Predictive maintenance.* Sensors and data-driven methods can monitor compressor temperature, pressure, vibration, leakage, and other condition indicators to identify abnormal behavior and support maintenance planning before failures occur.

- *Energy-efficiency optimization.* Control systems can adjust compressor operation according to hydrogen demand and pressure conditions, helping to reduce unnecessary energy consumption while maintaining the required operating conditions.
- *Safety and protective shutdown.* Automated monitoring can detect conditions such as overpressure, excessive temperature, abnormal vibration, or leakage and initiate predefined protective actions, including compressor shutdown when required.
- *Continuous condition monitoring.* Digital systems provide real-time information on compressor performance and operating conditions, allowing deviations and developing faults to be identified and supporting long-term performance assessment.
- *Integration with storage and dispensing.* Compressor operation can be coordinated with storage systems, valves, cooling equipment, and dispensing systems to maintain the conditions required for efficient and controlled vehicle refueling.
- *Automated startup, shutdown, and parameter control.* Automation can execute predefined operating sequences and control parameters during compressor startup, normal operation, and shutdown, reducing dependence on manual intervention and the associated potential for operator error.

6.4 Hydrogen Dispensing Units

Hydrogen dispensing units form the interface between the hydrogen refueling station and the vehicle and therefore combine process control, communication, monitoring, and user-interface functions. Dispenser automation coordinates vehicle connection, hydrogen flow, pressure and temperature control, safety monitoring, and fueling-status information.

Key automation functions include:

- *Vehicle connection and safe flow control.* Sensors and control systems verify the appropriate vehicle–dispenser connection and regulate hydrogen flow during fueling, helping to prevent unsafe conditions and unintended hydrogen release.
- *Pressure and temperature control.* The dispensing system continuously monitors fueling pressure and gas temperature and adjusts or terminates hydrogen delivery when predefined limits or fueling conditions are reached. SAE J2601 defines fueling protocols for 35 MPa and 70 MPa vehicle systems and includes fuel delivery temperature categories of −40 °C, −30 °C, and −20 °C.
- *Real-time fueling information and user interface.* The dispenser provides the user with information such as fueling status, delivered hydrogen quantity, pressure, and estimated completion status, while presenting warnings or instructions when required.
- *Leak detection and protective response.* Hydrogen detection and other safety signals can be integrated with the dispenser control system to interrupt fueling and initiate predefined protective actions when a hazardous condition is detected.
- *Data acquisition and analytics.* Fueling data can be recorded and transmitted to supervisory systems for operational analysis, performance assessment, troubleshooting, and maintenance planning.
- *Vehicle–station communication and compatibility.* Communication between the vehicle and station enables the exchange of information required for automated fueling and supports implementation of the applicable fueling protocol. SAE J2799 provides the communication hardware and software framework used together with SAE J2601 for communicating fueling.
- *Vehicle–station communication and fueling protocols* are an important part of automated hydrogen dispensing. SAE J2601 defines the fueling protocols and process limits for light-duty gaseous hydrogen vehicles, including fuel delivery temperature, maximum fuel flow rate, pressure increase rate, and end-of-fill pressure. The standard covers 35 MPa and 70 MPa fueling systems and defines fuel delivery temperature categories of −40 °C, −30 °C, and −20 °C. For fueling with communications, SAE J2601 is used together with SAE J2799, which specifies the communications hardware and software requirements and the communication protocol between the hydrogen surface vehicle and the fueling

station (SAE International, 2020; SAE International, 2026).

- *Payment and transaction processing.* Where applicable, automated payment and billing systems can be integrated with dispenser operation to support user authentication, transaction processing, and recording of fueling transactions.
- *Error reduction and operational consistency.* Automation reduces dependence on manual intervention during connection, fueling, and transaction procedures and supports consistent execution of predefined operating sequences.

The safety and operational requirements of hydrogen fueling facilities are addressed by ISO 19880-1 and, particularly for installations subject to the U.S. fire and building code framework, NFPA 2, Hydrogen Technologies Code. NFPA 2 contains dedicated requirements for gaseous hydrogen systems and vehicle fueling facilities, including separate provisions for GH_2 and LH_2 fueling installations. (ISO, 2020; National Fire Protection Association, 2026)

Dispenser hoses and hose assemblies are addressed by ISO 19880-5. The current edition, ISO 19880-5:2025, specifies requirements for hydrogen dispenser hoses and hose assemblies up to 70 MPa nominal working pressure and replaces the 2019 edition (ISO/TC 197, 2025).

Table 5 summarizes selected reference specifications for key parameters of hydrogen refueling stations, with particular emphasis on the dispensing process. These values provide reference points for the design and automated control of hydrogen dispensing systems; actual operating parameters may vary depending on station configuration, vehicle application, fueling protocol, and applicable standards and regulations.

Table 5. *Selected Reference Specifications for Hydrogen Dispensing*

Parameter	Typical value / range	Standard / source
Nominal dispensing pressure	35 MPa; 70 MPa	SAE J2601; ISO 19880-1
Fuel delivery temperature category	T40 (−40 °C), T30 (−30 °C), T20 (−20 °C)	SAE J2601
Fueling time	≈3 min under SAE J2601 reference conditions	SAE J2601
Vehicle–station communication	Communication hardware, software, and protocol requirements	SAE J2799_202603
Fueling connection device	—	SAE J2600_201510

7 PERFORMANCE OUTCOMES OF AUTOMATION

Multiple factors determine the performance of a hydrogen refueling station (HRS), from the development and performance of individual system components to the design and implementation of the station as an integrated system. Consequently, it is not always straightforward to separate the effects of individual factors, including automation, from the overall change in station performance. This is particularly important when evaluating automation because improvements in HRS performance may occur simultaneously with advances in compressors, cooling systems, storage technologies, sensors, fueling protocols, control strategies, and hydrogen production technologies.

Performance outcomes should therefore be evaluated using clearly defined indicators and interpreted with regard to the station configuration and the conditions under which the measurements were obtained. Automation may influence energy consumption, fueling performance, operational availability, equipment reliability, safety, hydrogen losses, and operating costs, but the magnitude of these effects depends on the functions automated, the level of automation, the station architecture, and how performance is measured. A change observed in a particular performance indicator should therefore not automatically be attributed entirely to automation unless the available evidence allows its contribution to be distinguished from other technological or operational changes.

7.1 Performance Indicators

The performance of an HRS can be evaluated from several complementary perspectives. Energy performance indicates the resources required to operate the station and dispense hydrogen, while fueling performance describes the station's ability to complete refueling within specified operating conditions. Availability and reliability characterize the continuity of station operation and the frequency of equipment failures, while safety indicators describe the system's ability to detect and respond to abnormal conditions. Hydrogen losses and economic indicators provide additional information on process efficiency and operating costs.

In this study, *energy consumption per kilogram of hydrogen* refers to the energy required to dispense one kilogram of hydrogen from the HRS, expressed in kWh/kg H_2. The reported value depends on the system boundary and may include the energy consumed by compression, cooling, storage, dispensing, and other station functions. Therefore, comparisons between reported values require consideration of the system boundaries and operating conditions used in each study.

In this study, *fueling performance* refers to the ability of an HRS to deliver the required amount of hydrogen within the specified fueling time and operating conditions. It can be characterized by parameters such as fueling time, dispensed hydrogen mass, mass-flow rate, and compliance with the specified pressure, temperature, and communication requirements. These parameters describe different aspects of the fueling process and should therefore not be treated as interchangeable measures. Fueling time, for example, indicates how long the refueling process takes, whereas mass-flow rate describes the rate at which hydrogen is delivered. Fueling-cycle compliance indicates whether the completed fueling process remained within the applicable operating and communication requirements.

Availability and utilization are sometimes used interchangeably in literature, although they describe different aspects of HRS operation. In this study, availability refers to the proportion of time the station can perform its intended function, whereas utilization refers to the extent to which the available station capacity is used. Downtime represents periods during which the station or a critical subsystem is unavailable. This distinction is important because a station may have high availability while operating at relatively low utilization.

Reliability and maintenance performance can be assessed using indicators such as mean time between failures (MTBF), failure frequency, maintenance frequency, and downtime associated with equipment failures. In this study, MTBF refers to the average operating time between successive failures of the considered HRS or system component. For hydrogen refueling stations, MTBF can be expressed in days of operation and provides an indicator of how long the station or considered equipment can operate before a failure occurs (Clean Hydrogen Partnership, 2021). Failure frequency provides complementary information on how often failures occur, while failure-related downtime describes their operational consequences. Maintenance data provide additional information on the type and frequency of interventions required to maintain station equipment in operation. These indicators are particularly relevant to HRS because failures of components such as compressors, dispensers, and chillers can directly affect station availability and lead to unscheduled maintenance and missed fueling opportunities (Kurtz et al., 2020; Kurtz et al., 2024). Data-driven prognostics and health monitoring can further support maintenance decisions by estimating the remaining useful life of critical components and reducing unexpected downtime. Because the definition of failure may differ between studies, MTBF values should be compared only when the equipment or system boundary, operating conditions, and failure criteria are sufficiently consistent.

Safety performance can be evaluated using indicators related to the detection of abnormal or hazardous conditions and the response of the HRS to such conditions. In this study, *leak-detection latency* refers to the time between the occurrence of a hydrogen leak and the generation of the corresponding detection signal. Detection speed is an important characteristic of hydrogen leak-detection systems because the time available for protective action depends on how quickly a leak can be detected. Performance criteria for hydrogen detection systems may include response time, detection limit, detector location, and other characteristics relevant to the specific application (H2Tools, n.d.). Alarm response time provides a related measure of detection-system performance and may be specified for individual hydrogen sensors or detection systems. These indicators describe different stages of the safety-response process and should therefore not be treated as interchangeable measures. A response time specified for an individual sensor, for example, does not necessarily represent the response time of the complete HRS safety system, because signal processing, alarm logic, communication, and the execution of protective actions may introduce additional delays. Hydrogen leak-detection systems are typically integrated with control systems to initiate actions such as automatic isolation of the hydrogen source, shutdown of process equipment, and activation of audible or visual alarms (H2Tools, n.d.; Kirillov, 2019). Other potentially relevant indicators include safety-related shutdown frequency and the rate of defined safety events per fueling cycle. Safety-related shutdown frequency describes how often the HRS enters a predefined shutdown or emergency shutdown state in response to an abnormal or potentially hazardous condition. However, the frequency of shutdowns should not be interpreted independently of the conditions that triggered them, because a higher frequency may reflect either more frequent abnormal conditions or more sensitive detection and more conservative protective logic. Similarly, interpreting safety-event rates requires clearly specified event definitions and system boundaries. Consequently, safety-performance indicators from different studies should be compared only when the underlying event definitions, measurement procedures, and system boundaries are sufficiently consistent.

Hydrogen losses provide an additional measure of process performance. In this study, hydrogen losses refer to the difference between the hydrogen entering the defined HRS system boundary and the hydrogen accounted for within the system and dispensed to vehicles over a specified period. The hydrogen mass balance can be used to identify or estimate losses associated with venting, purging, measurement discrepancies, and other unaccounted hydrogen. The interpretation of this indicator depends strongly on the selected system boundary, measurement accuracy, and operating conditions, particularly changes in the amount of hydrogen stored within the station. Improved instrumentation and automated monitoring can make deviations from the expected mass balance more visible and support the identification of abnormal losses. However, an observed reduction in hydrogen losses should not be attributed to automation alone unless the relevant study separates its contribution from changes in equipment, operating procedures, measurement methods, or station configuration.

Economic performance can be evaluated using indicators such as operating expenditure (OPEX) per kilogram of dispensed hydrogen, maintenance costs, and labor requirements, where sufficient data are available. In this study, OPEX per kilogram refers to the operating cost associated with dispensing one kilogram of hydrogen from the HRS, expressed per kilogram. This indicator directly measures the operating cost of hydrogen dispensing, but its interpretation depends on the defined cost boundary and may include energy, maintenance, labor, and other operating expenses. Automation can affect these costs by changing equipment operation, maintenance requirements, downtime, and labor requirements. However, the economic effect of automation cannot be assessed independently of station utilization, energy prices, equipment configuration, maintenance practices, and the initial cost of automation infrastructure.

Taken together, these indicators provide a framework for assessing HRS performance from complementary operational, energy, reliability, safety, and economic perspectives. They also provide a basis for distinguishing improvements in individual automated functions from changes in overall station performance. This distinction matters when comparing results across studies because measured outcomes may reflect different system configurations, operating conditions, system boundaries, performance definitions, and levels of automation. Consequently, interpret the indicators in the context of the conditions and measurement methods under which they were obtained, rather than treating them as universally comparable values.

7.2 Comparative Results

The performance indicators defined in the previous section provide a basis for comparing reported HRS performance under different technological and operational configurations. The available evidence covers energy consumption, fueling performance, reliability and maintenance, safety, hydrogen losses, and economic performance, although the amount and quality of data vary considerably among these areas. The following comparison therefore focuses on results reported in the literature and considers the conditions under which they were obtained.

Because HRS configurations, operating conditions, measurement boundaries, and definitions of performance indicators differ among studies, the reported values cannot always be compared directly. In particular, an observed improvement in a performance indicator does not necessarily represent an isolated effect of automation. Changes in compressor and cooling technologies, storage configurations, fueling protocols, sensors, control strategies, station utilization, and other system characteristics may contribute to the observed result. The comparison therefore distinguishes, where the available evidence permits, between measured performance improvements and effects that can reasonably be associated with automation.

The results are presented by performance domain, beginning with energy performance and continuing with fueling performance, reliability and maintenance, safety, hydrogen losses, and economic performance. This structure makes it possible to examine both the reported magnitude of performance changes and the conditions that may influence their interpretation.

7.2.1 Energy Performance

Energy performance is one of the most relevant indicators for evaluating hydrogen refueling station operation because compression, cooling, storage management, and dispensing require significant energy input. However, reported energy consumption cannot be interpreted independently of the station configuration, storage technology, refueling strategy, throughput, and system boundary used in each study. Differences in these parameters may produce substantial changes in energy consumption even when the level of automation remains unchanged.

The effect of station configuration is illustrated by the analysis of cascade fueling systems by Rothuizen and Rokni (2014). Their dynamic simulation of a complete refueling cycle showed that the compressor accounts for approximately 50% of station energy consumption. Increasing the number of cascade tanks from one to three reduced the calculated energy consumption by approximately 30%, while adding more than four tanks provided less than 4% additional savings per tank. The study therefore identified three or four tanks as an energy-optimal range for the analyzed cascade configuration (Rothuizen & Rokni, 2014).

Process optimization can provide additional energy savings without necessarily involving a change in the overall automation architecture. For example, optimization of the auxiliary cooling system has been reported to reduce energy consumption per fueling event by approximately 2.9% to 9.4%, depending on the operating conditions and station throughput. Similarly, optimization of the pressure-switch difference values (PSDVs) in a cascade HRS has been shown to reduce energy consumption while maintaining the required refueling performance, with a maximum reported reduction of 10.76% in the analyzed scenarios (Chen et al., 2024). The latter study used an HRS simulation model, a proxy model, and multi-objective optimization to select refueling strategies that balance energy consumption and refueling demand.

Automation and advanced control offer another pathway for energy optimization by allowing station operation to respond dynamically to hydrogen demand and system conditions. Model Predictive Control (MPC), for example, has been applied to on-site green HRS to perform online optimization while considering plant dynamics, operating constraints, and predicted disturbances. Cardona et al. (2023) demonstrated the applicability of MPC to an integrated HRS comprising renewable energy sources, an electrolyzer, buffer storage, compressors, and batteries, and reported performance advantages over rule-based operation in the analyzed simulations.

More recent optimization studies combine automated control, demand prediction, and pressure-management strategies to reduce energy consumption under variable refueling demand. Reported reductions reach approximately 10.76% for optimized PSDV control and, in some simulation and control studies, substantially higher values under specific demand and system configurations. These results indicate that automated control can measurably improve energy performance, but the magnitude of the effect depends strongly on the process configuration, control objective, demand profile, and assumptions used in the analysis.

Taken together, the available evidence indicates that HRS energy performance depends on the combined effects of equipment configuration, storage architecture, cooling strategy, refueling protocol, station utilization, and control strategy. Automation can provide an important mechanism for exploiting these factors through real-time monitoring, demand prediction, and dynamic optimization. However, improvements reported for automated or optimized systems should not be interpreted as a universal percentage reduction attributable to automation alone. Controlled comparisons are required to separate the contribution of automation from that of changes in station design, process configuration, and operating conditions.

7.2.2 Fueling Performance

Fueling performance is determined by the ability of an HRS to deliver the required amount of hydrogen within the specified pressure, temperature, and time constraints. For a 70 MPa fueling system, the final state of charge (SOC), vehicle-tank pressure and temperature, and fueling time provide complementary measures of dispensing performance. Real-world operation is affected by variations in initial tank conditions, ambient temperature, hydrogen supply conditions, and other factors that are not fully represented by static fueling tables.

Researchers have investigated data-driven methods as an alternative or complement to conventional table-based and model-based fueling control. Wang and Decès-Petit (2020) used operational data from three hydrogen refueling stations to classify fueling events as non-dispensing, normal, or undershot dispensing events and to predict future SOC using multi-task machine learning. The classification accuracy exceeded 85% for the three stations, while SOC predictions for future time steps were accurate on two stations with larger datasets. The authors proposed integrating the machine-learning models into the HRS controller to support alternative fueling strategies (Wang & Decès-Petit, 2020).

A subsequent study by Wang, Wang, and Decès-Petit (2022) extended this approach using robust regression and real operational data from four HRS. The models predicted final SOC, temperature, and pressure while accounting for noise and outliers in actual fueling data. For H70-T40 dispensing, the study considered a final SOC of 95–100%, a vehicle-tank pressure below 70 MPa, and a temperature below 85 °C as key fueling constraints. The desired fueling time was within 3 minutes. The robust regression approach performed better than LASSO and Gaussian process regression for three of the four stations, demonstrating the potential of data-driven prediction to support more consistent fueling-process control under variable operating conditions (Wang et al., 2022).

Experimental studies also demonstrate that refueling performance depends strongly on station configuration and refueling strategy. Genovese et al. (2024) experimentally compared direct-pressurized and cascade refueling at the Hydrogen Research and Fueling Facility at California State University, Los Angeles. The cascade configuration reduced hydrogen-chiller energy consumption by 12–20% and reduced nozzle outlet temperature by approximately 8 °C over the tested pressure range. However, the cascade configuration did not achieve the required pressure target in the reported experiments, illustrating that improvements in one performance measure may be accompanied by limitations in another (Genovese et al., 2023).

Taken together, these results indicate that automation and data-driven control can support fueling performance by using real-time measurements and early-stage operating conditions to predict fueling outcomes and adjust the control strategy accordingly. The available evidence, however, does not support a single universal improvement factor for fueling time or fueling success. Reported performance depends on the fueling protocol, station configuration, initial conditions, ambient temperature, control strategy, and definition of a successful fueling event. Consequently, improvements in fueling performance should be interpreted in conjunction with the pressure, temperature, SOC, and time constraints used in the corresponding study.

7.2.3 Reliability and Maintenance Performance

Reliability and maintenance performance are particularly important for HRS because failures of critical components can directly reduce station availability and interrupt vehicle fueling. Field data indicate that reliability has been a significant operational limitation of hydrogen refueling infrastructure. Kurtz et al. (2020) analyzed more than 180,000 hydrogen fills and over 5,000 maintenance events from retail hydrogen stations to characterize failure and maintenance behavior under real-world operating conditions. Dispensers and compressors were among the leading maintenance categories, with the dispenser identified as a particularly failure-prone subsystem (Kurtz et al., 2020).

The same body of field data provides a useful reliability measure in terms of mean fills between failures (MFBF), rather than calendar-based MTBF. For the leading maintenance category, the dispenser system, MFBF was below 500 fills. Based on the reported fueling trends, this corresponded approximately to one failure every 15 days. The use of fills rather than calendar time is particularly relevant for HRS because station utilization varies substantially and calendar-based measures can therefore describe different levels of equipment loading. (Kurtz et al., 2024; Kurtz et al., 2020)

The reported reliability data also show why improvements in HRS reliability should not automatically be attributed to automation. As hydrogen infrastructure develops, component technology, preventive maintenance, station design, operating conditions, and control strategies may change simultaneously. Consequently, an improvement observed between older and newer station data does not by itself establish the contribution of automated monitoring or control.

Data-driven prognostics and health monitoring provide a more direct connection between automation and maintenance decision-making. Kurtz, Bradley, and Gilleon (2024) developed a hydrogen station prognostics and health monitoring (H2S PHM) model using operation and maintenance data from 34 U.S. retail hydrogen stations. The dataset included more than 465,000 hydrogen fills and recorded fueling, maintenance, and station availability information. The model considered dispensers, compressors, and chillers and used remaining useful life estimates to support decisions on whether maintenance should be performed in view of predicted component condition and expected future station use. (Kurtz et al., 2024).

The PHM approach therefore provides a mechanism through which automation can affect maintenance performance without directly changing the mechanical reliability of the equipment. Continuous condition monitoring, data analysis, failure prediction, and maintenance decision support can be used to identify developing problems and reduce the likelihood or duration of unexpected downtime. The 2024 study specifically presents the H2S PHM framework as a means of reducing unexpected downtime and improving station availability. (Kurtz et al., 2024; Kurtz et al., 2020)

Taken together, the available evidence indicates that reliability and maintenance performance should be considered through several complementary measures, including MFBF, failure frequency, maintenance frequency, downtime, availability, and remaining useful life. These measures describe different aspects of station performance and should not be treated as interchangeable. Moreover, improvements in reliability attributable to automation can be established only when the relevant study distinguishes the effect of monitoring, control, or predictive maintenance from changes in equipment technology, maintenance practice, station utilization, and other operating conditions.

7.2.4 Safety Performance

Safety performance can be evaluated through indicators describing the detection of hazardous conditions and the subsequent response of the HRS safety system. For hydrogen refueling stations, leak detection is particularly important because the time available for protective action depends on how rapidly an abnormal condition is detected and how effectively the detection system is connected to the station control and shutdown functions. Detection latency, alarm-response time, and shutdown time therefore describe different stages of the safety-response process and should not be treated as interchangeable measures.

Recent studies demonstrate the potential of automated data processing to reduce the computational component of safety response. An et al. (2024) developed a digital-twin-based safety model using real-time temperature, pressure, and state-of-charge data collected from an operational HRS in Samcheok, Republic of Korea. Among the evaluated machine-learning and deep-learning methods, the CNN model achieved a risk-prediction time of 68 ms, with safety decisions evaluated at 1-s intervals. This result demonstrates the potential for rapid automated assessment of abnormal operating conditions; however, the reported 68-ms value represents model prediction time rather than the complete response time of the HRS safety system (An et al., 2024).

Component-level engineering specifications provide a further reference for the physical execution stage of the safety-response chain. For hydrogen-service emergency shutdown (ESD) valves, Valve and Flow Control Specialists reports that conventional ESD arrangements traditionally had closing times of approximately 1–2 s, while newer systems have achieved closing times below 200 ms for valves up to 80 NB. The reported value includes mechanical and electrical actuation and controller delays and therefore provides an engineering benchmark for fast ESD valve operation rather than a measured response time for a complete HRS safety system (Valve and Flow Control Specialists, n.d.).

Other industrial valve and actuator specifications similarly demonstrate that sub-second ESD actuation is technically achievable. Habonim reports approximately 0.2 s closing times for compact quarter-turn actuator configurations, while fast-exhaust arrangements for larger valves can provide closing times below 1 s. These values further illustrate the range of physical actuation performance achievable with dedicated ESD architectures, but they remain component-level specifications and should not be interpreted as complete HRS response times (Habonim, 2021).

The response of hydrogen flame-detection systems provides another example of the distinction between component response and complete system response. The manufacturer specification for the MSA FL500-H_2 UV/IR flame detector reports a typical alarm activation response time of 2.1 s at a distance of 60 ft for hydrogen flames under the specified test conditions. This value describes detector alarm activation and does not represent the time required for complete station shutdown, which would additionally depend on the subsequent safety logic and physical actuation of protective equipment (MSA Safety, n.d.).

Real-world incident data provide a complementary perspective on the effectiveness of safety barriers. Tzioutzios et al. (2025) analyzed 193 hydrogen refueling station accident records from the Japanese KHK database. An emergency shutdown system was reported as triggered in 42.5% of the cases, while manual shutdown procedures were reported in 47.2% and automatic activation by installed safety systems in 40.4% of cases. In 4.1% of the reported accidents, the alarm system was operating but did not trigger in response to the leakage. The study also found that fixed and portable detectors were important detection mechanisms, while approximately one in seven reported leakage events relied on human detection. These results describe safety-barrier performance in reported accidents and should not be interpreted as probabilities of successful automated protection during normal HRS operation (Tzioutzios et al., 2025).

Taken together, the available evidence indicates that automation can strengthen safety performance by integrating continuous sensing, rapid computational assessment, alarm logic, and automated protective actions. The evidence nevertheless does not support a single universal value for HRS safety-response time. Model prediction time, detector response time, alarm-response time, valve actuation time, and complete station shutdown time represent different quantities and should be reported separately. Similarly, accident-based activation frequencies cannot be directly compared with component-level response specifications. Meaningful comparison therefore requires clearly defined response stages, measurement procedures, system configurations, and safety-event definitions.

7.2.5 Hydrogen Losses

Hydrogen losses provide an additional indicator of HRS process performance because they reveal discrepancies between the amount of hydrogen supplied to a station and the amount accounted for within the system and dispensed to vehicles. Field studies indicate that these discrepancies can be considerably larger than idealized process models would suggest and that interpreting them requires detailed examination of station operation, measurement procedures, and maintenance activities.

Genovese et al. (2020) demonstrated this issue through a detailed hydrogen-accounting study at the Cal State Los Angeles Hydrogen Research and Fueling Facility. During the earlier stage of the investigation, the average monthly loss was approximately 30–35%. After a more detailed analysis of station operation and identification of critical points, reported losses for most analyzed months fell to approximately 2–10%. The remaining discrepancy included effects associated with buffer-tank defueling, dispenser rebooting, line venting, the uncertainty of the dispenser mass-flow meter (approximately ±5%), and the uncertainty associated with estimating hydrogen production from Faraday's law. Maintenance activities were identified as particularly important because they could produce significant discrepancies in hydrogen accounting.

The same study also illustrates why hydrogen accounting should not be interpreted simply as a direct measure of fugitive leakage. In a broader assessment of nine stations, the authors reported specific hydrogen losses ranging from 7% to 46%, with the causes including compressor-related contamination, metering problems, purging and venting, background leakage, and, for some configurations, prolonged downtime and boil-off. The results therefore demonstrate that the quantity identified as a hydrogen loss may represent a combination of physical releases, operational consumption, storage effects, and measurement discrepancies rather than atmospheric leakage alone. (Genovese et al., 2020)

More recent work has demonstrated that hydrogen mass balance can also be monitored continuously during normal station operation. Zhang, L. et al. (2025) developed the Holistic Idle Periodic Evaluation (HIPE) method and applied it to real-time operational data from two commercial HRSs with off-site hydrogen supply. The resulting average mass balances were 94.2% and 83.6%, corresponding to apparent discrepancies of approximately 5.8% and 16.4%, respectively. The method was designed for online monitoring and was able to identify normal and anomalous operating conditions without interrupting station operation. Importantly, the approach required only one mass-flow meter installed at the dispenser, illustrating the potential of automated data acquisition for continuous hydrogen accounting.

Metering accuracy represents another important limitation when hydrogen losses are evaluated from station-level mass balances. Full-scale experimental investigations of HRS metering have shown that the accuracy of the pressure-volume-temperature (PVT) method is strongly affected by ambient temperature variation and by differences in the thermal response of hydrogen storage vessels and piping. Differences in the sensitivity and accuracy of pressure and temperature measurements can therefore produce apparent hydrogen losses even when no corresponding physical leakage is present. The study further demonstrated that improved temperature insulation and more accurate instrumentation can reduce these metering errors and improve the reliability of hydrogen-loss calculations. (Zhao et al., 2024)

These findings establish an important distinction between hydrogen accounting losses and physical hydrogen leakage. A discrepancy in the mass balance should first be treated as an indication that requires investigation rather than as direct evidence of a leak. Automated measurement, continuous data acquisition, and online mass-balance analysis can improve the visibility of such discrepancies and help distinguish abnormal station operation from measurement-related effects. In this respect, automation may contribute to loss reduction both indirectly, through improved monitoring and identification of operational causes, and directly, where automated control reduces unnecessary venting, purging, or other sources of hydrogen consumption.

Overall, the available evidence indicates that hydrogen losses are a meaningful but highly configuration-dependent HRS performance indicator. Reported values range from relatively small discrepancies of a few percent to substantially higher values under particular operating, maintenance, storage, or measurement conditions. These results cannot therefore be reduced to a universal percentage attributable to automation. Instead, the main contribution of automation is the ability to establish a continuous and traceable mass-balance framework in which abnormal losses can be detected, investigated, and, where their operational causes are identified, progressively reduced.

7.2.6 Economic Performance

Economic performance provides a different perspective on HRS automation because the economic consequences of automation extend beyond the direct cost of control and monitoring equipment. Capital expenditure, operating expenditure, maintenance, labor, energy consumption, station utilization, and hydrogen supply costs all contribute to an HRS's economic performance. Their relative importance varies substantially with station capacity, hydrogen supply configuration, utilization, and the boundaries of the economic analysis.

Capital expenditure represents a major barrier to HRS deployment. Techno-economic studies show that the cost structure is strongly influenced by the high-pressure compression and storage equipment. In one analysis of different HRS configurations, the compressor represented approximately 29–49% of total capital expenditure in configurations based on hydrogen production from alternative feedstocks, illustrating the importance of compression technology in the overall cost structure. Such values are configuration-specific and should not be interpreted as a universal share of HRS capital cost. (Perna et al., 2022)

Operating expenditure is similarly dependent on the way the station is configured and operated. Electricity consumption, hydrogen supply, maintenance, and other operating requirements contribute to the cost of hydrogen delivery. The economic effect of station utilization is particularly important because many HRS costs are incurred independently of the quantity of hydrogen dispensed. Consequently, an increase in utilization can reduce the cost per kilogram even when the absolute operating expenditure remains unchanged. Techno-economic analysis of large-scale HRS applications, for example, has reported LCOH values in the range of approximately €4–7/kg under the specific system boundaries and operating assumptions considered in the study (Caponi et al., 2022).

Maintenance represents another important component of HRS operating cost. Field data from retail hydrogen stations indicate that maintenance requirements can be substantial and that failures may significantly affect station availability and the amount of hydrogen that can be dispensed. Kurtz et al. (2024), using operational and maintenance data from 34 U.S. retail hydrogen stations, analyzed mean fills between failures and station availability and demonstrated the importance of reliability and maintenance to the economic performance of hydrogen infrastructure. These findings indicate that maintenance costs should be considered together with station utilization and availability when evaluating OPEX per kilogram.

Automation can influence these economic parameters through several mechanisms. Automated monitoring and control can reduce unnecessary equipment operation, improve energy management, support condition-based or predictive maintenance, and reduce the need for routine manual intervention. The economic value of these effects depends, however, on the initial investment required for automation and the extent to which the resulting savings are realized under actual station operating conditions.

Recent optimization studies illustrate the magnitude of the economic effects that can be obtained when automated or algorithmic control is considered together with station configuration and energy management. A real-project-based study of a renewable hydrogen production–refueling station in China used operational data to validate an HRS model and subsequently optimized system capacity, renewable generation, hydrogen storage, and operation. Depending on the optimization objective and configuration, the study reported reductions in initial investment of up to 29.31%, reductions in annual operating cost of up to 100%, and reductions in LCOH of up to 44.19%. Peak grid load was reduced by up to 43.80%. These results demonstrate the economic potential of integrated optimization and automated energy management, but they should not be interpreted as isolated effects of automation because the optimization simultaneously changes system capacity, renewable generation, storage capacity, and operating strategy. (Zhang et al., 2025)

The same distinction is important when evaluating payback. An automated control system may generate economic benefits through lower energy consumption, reduced downtime, fewer maintenance interventions, or lower labor requirements, but the investment required for sensors, controllers, communication infrastructure, software, and integration must also be included. The resulting payback period therefore depends on the relationship between the incremental cost of automation and the recurring savings achieved under the station's actual utilization and operating conditions.

External economic factors can further influence the results. Electricity prices, hydrogen supply costs, utilization, financing conditions, and public capital support may substantially change the economic attractiveness of an HRS. When the objective is to determine the contribution of automated control and monitoring to economic performance, these factors should be separated from the effects of automation. In particular, subsidies that reduce the effective capital burden may improve project economics without representing an efficiency gain attributable to automation.

Taken together, the available evidence indicates that automation can contribute to improved HRS economic performance, but its effect is mediated through energy consumption, reliability, maintenance, utilization, and system configuration. OPEX per kilogram and LCOH are therefore useful indicators, but neither should be interpreted as a direct measure of automation efficiency. A meaningful assessment requires the incremental cost of automation to be considered together with the operational savings that can be demonstrated under comparable station configurations and utilization levels.

Table 6 summarizes the reported results for the HRS performance indicators considered in this study and shows how the corresponding automation functions are related to these results. It also indicates the type of evidence on which each result is based and the main factors that limit direct attribution to automation.

Table 6. *Comparative Evidence on HRS Performance Indicators and the Role of Automation*

Performance indicator	Reported results	Automation-related mechanism	Evidence type	Limitation for attribution	Source
Energy consumption	10.76% reduction with optimized PSDV; approximately 30% reduction with a three-bank cascade configuration	Adaptive control of compression and storage operation; optimization of pressure-switch thresholds and operating schedules	Simulation/model and controlled comparison	Results also depend on process configuration, storage arrangement, operating strategy, and station utilization	Chen et al. (2024); Rothuizen and Rokni (2014)
Fueling performance	Normal dispensing defined by a final SOC of 95–100%; data-driven models predict final fueling outcomes from early-stage operating data.	Real-time prediction of fueling behavior and dynamic adjustment of the fueling process based on early-stage operating data	Real-world operational data and data-driven modeling	Results depend on vehicle conditions, ambient temperature, initial state, fueling protocol, and station configuration	Wang & Decès-Petit (2020); Wang et al. (2022)
Reliability and maintenance performanc	More than 180,000 fueling events and more than 5,000 maintenance events analyzed; PHM model developed from O&M data from 34 U.S. retail HRSs	Continuous condition monitoring, failure prediction, remaining-useful-life estimation, and maintenance decision support	Real-world operational and maintenance data	Availability and reliability also depend on component reliability, maintenance practices, spare-parts availability, and operating conditions	Kurtz et al. (2020); Kurtz et al. (2024)

Performance indicator	Reported results	Automation-related mechanism	Evidence type	Limitation for attribution	Source
Safety performance	68 ms prediction time; approximately 2.1 s detector alarm activation; ESD valve closure benchmark below 200 ms	Automated detection, risk assessment, alarm generation, and initiation of protective or emergency shutdown actions	Mixed evidence: operational-data-based modeling and engineering benchmarks	Reported times describe different stages of the safety-response chain and should not be interpreted as a single HRS-level response time	An et al. (2024); H2Tools (n.d.); Valve and Flow Control Specialists (n.d.); Habonim (2021)
Hydrogen losses	Apparent mass-balance discrepancies of 5.8% and 16.4% at two commercial HRSs	Continuous mass-balance monitoring, automated anomaly detection, and identification of abnormal hydrogen losses	Real-world operational data and field measurements	Mass-balance discrepancies may reflect measurement uncertainty, venting, purging, maintenance, or accounting procedures and do not necessarily represent physical leakage	Genovese et al. (2020); Zhang, L. et al. (2025); Zhao et al. (2024)
Economic performance	Up to 44.19% reduction in LCOH and up to 43.80% reduction in peak grid load in an integrated optimization study	Automated energy management, process optimization, and coordination of equipment operation with demand and energy availability	Model-based techno-economic optimization validated with operational data	Results also reflect system configuration, capacity, renewable generation, storage, energy prices, and operating strategy; they are not automation-only effects	Zhang, Y. et al. (2025)

This is particularly important because the reported values may also be influenced by station configuration, operating conditions, utilization, maintenance practices, and other technological or operational factors. The comparison therefore provides an overview of the available evidence while avoiding the assumption that the reported values represent directly comparable or automation-specific improvements.

7.2.7 Cross-Study Comparison and Interpretation

The comparison of the performance indicators considered in this study shows that automation can affect several aspects of HRS operation, but the magnitude of the observed effects depends strongly on system configuration, operating conditions, station utilization, and the definition of the performance indicator. Real-world operational studies demonstrate substantial differences among stations in capacity, hydrogen supply, storage configuration, operating strategy, utilization, and refueling behavior, even when the stations serve similar applications. (Caponi et al., 2023; Samuelsen et al., 2020) The available evidence therefore does not support a single quantitative estimate of the overall improvement produced by automation. Instead, automation should be understood as a set of interconnected functions involving sensing, monitoring, process control, prediction, maintenance decision support, and operational optimization.

The strongest evidence for an automation-related improvement is obtained when the automated function is closely connected to the measured indicator. Automated control can directly influence compressor operation, storage management, cooling, and fueling parameters, making its effect on energy or fueling performance comparatively easier to evaluate. The interpretation becomes more difficult for reliability, safety, hydrogen losses, and economic performance because these outcomes depend on several interacting components and operating conditions. HRS infrastructure studies have identified reliability, throughput, and operation and maintenance costs as closely related challenges, while real-world station data show that utilization and operating strategies can differ substantially between sites. (Kurtz et al., 2019; Caponi et al., 2023) For example, improved availability may result from predictive maintenance, improved component reliability, changes in maintenance practice, or increased utilization rather than automation alone.

The comparison also reveals an important distinction between reported improvement and automation-attributable improvement. A reported improvement describes a change in a measured performance indicator between two conditions or configurations. An automation-attributable improvement requires evidence that the observed change can reasonably be attributed to the automated function rather than to simultaneous changes in equipment, operating conditions, utilization, maintenance strategy, or system configuration. This distinction matters because many HRS studies evaluate several technological or operational changes simultaneously. Reviews of HRS equipment and process optimization show that equipment configuration, storage arrangement, compressor configuration, and process optimization can substantially affect both operating performance and cost. (Tian et al., 2022)

The strength of the evidence also depends on the study type. Long-term operational datasets provide valuable information about actual station behavior but contain uncontrolled variables. Controlled experiments can isolate individual process effects more effectively but usually cover a limited range of operating conditions. Simulation and optimization studies allow researchers to investigate a broader range of configurations, but their results still depend on model assumptions and boundary conditions. This distinction is particularly relevant to HRS research, where operational studies increasingly use data collected from functioning stations while simulation and optimization remain important tools for evaluating alternative configurations and control strategies. (Caponi et al., 2022)

The same limitation applies when comparing the numerical values reported for different performance domains. Energy savings associated with a change in cascade configuration, for example, cannot be directly compared with a reduction in detection latency or an improvement in reliability. These indicators describe different physical and operational phenomena, use different measurement bases, and respond differently to changes in station configuration and utilization. Meaningful comparison therefore requires the KPI definition, system boundary, operating conditions, measurement method, and level of automation to be considered together.

Taken together, the evidence indicates that automation should not be regarded as a single intervention with a uniform performance effect. Its contribution is better understood as an enabling layer within the HRS control and operational architecture. Continuous sensing and data acquisition improve the visibility of station conditions; automated control allows operation to respond to changing conditions; predictive methods support decisions before failures or abnormal events occur; and integrated supervisory systems can coordinate equipment operation according to demand, energy availability, and safety constraints.

The evidence reviewed in this study therefore supports a cautious but positive conclusion. Automation has clear potential to improve HRS performance where continuous monitoring, adaptive control, predictive analysis, and coordinated operation address identifiable sources of inefficiency, unreliability, or operational risk. However, the available literature does not provide sufficient evidence to assign a universal percentage improvement to automation across all HRS performance dimensions. The magnitude of improvement depends on the technology, station configuration, operating conditions, utilization, and measurement methodology used to implement the automation.

8 THE FUTURE OF HRS

Based on this study's findings, several directions can be identified for the future development of hydrogen refueling stations. Rather than considering automation as a collection of isolated functions, future HRS are likely to evolve toward increasingly integrated and autonomous operation. As hydrogen stations become more closely connected with hydrogen production, storage, compression, cooling, dispensing, renewable electricity, and energy management, the number of interacting processes and operating variables will increase. This will create a greater need for coordinated control, continuous monitoring, predictive diagnostics, and data-driven optimization. Future HRS automation will therefore depend not only on improving the control of individual components, but also on the ability to coordinate these interconnected processes within a common control architecture.

One important direction is the integration of HRS with renewable electricity generation and on-site hydrogen production. Such configurations can allow hydrogen production, storage, compression, and dispensing to be coordinated according to electricity availability and refueling demand. Advanced control systems can use information about renewable generation, storage levels, station demand, and equipment condition to adjust operating schedules and energy flows in real time. The resulting architecture can move the HRS from a station that primarily responds to refueling demand toward an integrated energy system in which production, storage, and dispensing are coordinated as parts of a common operating strategy.

Another important direction is developing predictive and increasingly autonomous station operation. Continuous data acquisition from compressors, storage systems, dispensers, cooling equipment, and safety-related sensors can provide the basis for detecting abnormal operating conditions before they result in equipment failure or unplanned shutdowns. Prognostics and health monitoring can progressively move HRS operation from predominantly reactive maintenance toward condition-based and predictive maintenance (Kurtz et al., 2024). Digital twins and advanced data-processing methods may further support this transition by combining real-time measurements with virtual representations of station components and processes (An et al., 2024). As these capabilities mature, increasingly autonomous operation may become possible, while local control and safety functions remain independent of higher-level communication and supervisory systems.

Energy integration is another area in which future HRS development can extend beyond the conventional boundaries of hydrogen production and dispensing. In general, heat generated during hydrogen production, compression, and cooling processes can potentially be recovered and used for space heating or other local thermal demands. When these processes are integrated within an HRS, such recovery can become part of the station's overall energy-management strategy (Decormis et al., 2026; Liu et al., 2025). Such integration can improve overall energy utilization within the station and create additional value from processes that would otherwise require heat rejection. Future control systems will therefore need to coordinate not only hydrogen flows and electrical consumption, but also thermal energy flows and energy-recovery equipment. As these functions become more integrated, energy management could become an integral part of HRS automation rather than a separate auxiliary function.

As HRS become more integrated, the complexity of their automation architecture is also expected to increase. Integrating hydrogen production, storage, compression, cooling, dispensing, energy management, and additional process functions will require coordinated monitoring and control of a growing number of interacting variables. This may require more advanced sensing, communication, data processing, and control strategies, while maintaining clear separation between supervisory functions and safety-critical local control. Future development will therefore depend not only on adding new automated functions, but on improving the overall control architecture's ability to coordinate them reliably. In this context, the long-term objective is not necessarily full autonomy, but a more adaptive, predictive, and resilient HRS capable of responding to changing demand, energy availability, equipment condition, and safety requirements.

9 CONCLUSION

This study examined the role of automation in hydrogen refueling stations (HRS), with particular emphasis on how automated monitoring, control, communication, predictive analytics, and safety functions influence station performance. The analysis shows that automation should not be considered as a single technological intervention, but as an integrated set of functions that affects several aspects of HRS operation. Its contribution is therefore better understood through a combination of operational, energy, reliability, safety, and economic performance indicators.

The reviewed evidence indicates that the most consistent benefits of automation are associated with operational control, fueling performance, reliability, maintenance, and safety. Continuous monitoring, automated control, predictive diagnostics, and faster response to abnormal conditions can improve the ability of an HRS to maintain stable operation and respond to changing demand or equipment conditions. Automation can also support more coordinated operation of compression, storage, cooling, and dispensing processes. These capabilities are particularly relevant for maintaining station availability and reducing the effects of equipment failures and abnormal operating conditions.

The effects of automation on energy and economic performance are less straightforward. Improvements in energy consumption, operating costs, and overall efficiency depend not only on the level of automation but also on station configuration, equipment selection, utilization, energy prices, operating procedures, and control strategy. Comparing results from different studies therefore requires caution. Reported improvements cannot automatically be attributed to automation when other aspects of the station or operating conditions have changed at the same time. This is particularly important when comparing performance indicators reported using different system boundaries, measurement methods, and definitions.

The analysis also shows that HRS is likely to move toward increasingly integrated, predictive, and adaptive operation. Renewable electricity, on-site hydrogen production, storage, compression, dispensing, energy management, and predictive maintenance can increasingly be coordinated within a common control architecture. As these functions become more interconnected, automation will have to manage more interacting variables while maintaining reliable local safety functions. The long-term development of HRS may therefore depend less on automating individual components and more on the overall system's ability to coordinate them effectively.

Overall, automation is an important enabling technology for developing safer, more reliable, and more responsive HRS. Its value does not arise from automation alone, but from its ability to connect sensing, control, diagnostics, communication, and decision-making into a coordinated operating framework. Further development and validation of HRS automation will require longer-term operational data, consistent performance definitions, and more systematic separation of automation effects from changes in equipment, configuration, and operating conditions. This approach would provide a stronger basis for evaluating automation's contribution to performance and the future development of hydrogen refueling infrastructure.

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