Hydrogen Refuelling Station Dependability: Learnings from Industry

November 2025

ZERO EMISSION

JIVEs / MEHRLIN projects

@fuelcellbus www.fuelcellbuses.eu

Clean Hydrogen Partnership

Co-funded by the European Union

Main author(s): David Hart (ERM), Lewechi Nkata (ERM), Gianluca Galeazzi (ERM), Nicole Whitehouse (Sphera), Simon Whitehouse (Sphera)

Contributor(s):

Aberdeen City Council, Brighton & Hove and Metrobus, Daimler Truck, Everfuel, Guoufu Hee, Hydrogen Europe, Hydrogen Fuel Cell Partnership, HTECOV Bureau Gronignen Drenthe, PLANET GbR, Resato Hydrogen Technology, RVK Cologne, Ryze hydrogen, Toyota Motor Europe, Transport For London, Tyczka Hydrogen

Dissemination status: Final

Dissemination level: Public

Deliverable number: D2.6

Approval process

Steps	Status
Work Package Leader	Approved
Coordinator	Approved
Clean Hydrogen Partnership	Pending/approved

Disclaimer

Table of Contents

Glossary

ACRONYM	DEFINITION
AFIR	Alternative Fuels Infrastructure Regulation
CHP	Clean Hydrogen Partnership
CORGI	CORGI technical services
EMEA	Europe, Middle East and Africa
FCB / FCEB	Fuel Cell Bus / Fuel Cell Electric Bus
HE	Hydrogen Europe
HFC	Hydrogen Fuel Cell
HRS	Hydrogen Refuelling Station
IP	Intellectual Property
KOGAS	Korea Gas Corporation
OEM	Original Equipment Manufacturer
PTO	Public Transport Operator
PTA	Public Transport Authority
TEN-T	Trans-European Transport Network
TUV	Technischer Überwachungsverein (Technical Inspection Association – German certification body)
VDMA	Verband Deutscher Maschinen- und Anlagenbau (German Engineering Federation)

1. INTRODUCTION

1.1. Importance of HRS Dependability

Hydrogen powered transport remains one of few options for achieving zero emissions from road transport, supporting both decarbonisation and air quality goals. The sector is in a developmental stage, with vehicle fleets operating in a limited number of locations globally. In Europe, the publicly-funded JIVE 1 and2 and MEHRLIN projects have aimed to demonstrate the feasibility of hydrogen powered public transport through supporting hydrogen fuel cell (HFC) bus fleets along with hydrogen refuelling stations (HRS) in 16 European cities. More than 290 fuel cell electric buses (FCEBs) have been deployed across Europe, from 2017 to 2025. Within the wider HRS network developed, 17 stations have received funding assistance through these projects. Passenger cars, light and heavy trucks are also operating, using the same or additional HRS infrastructure.

The projects above have showcased the use of FCEBs as an effective zero emission solution for passenger transport. They – and other global initiatives – have also highlighted barriers that need to be overcome to scale up the deployment of hydrogen mobility. One important factor is increasing the level of confidence in the reliability of fuelling infrastructure to support fully commercial hydrogen vehicle operations, whether in public transport bus fleets or more broadly.

HRS need to be able to dependably refuel vehicles to the required specifications as and when needed. The HRS need to be available to operate and provide a successful fill as and when needed. Unfortunately, this standard is not currently consistently met, which results in customers not being able to depend on the stations.

This report examines why, in many cases, station availability (uptime of the station) and reliability (ability to provide full refuelling) are below what is required to allow commercial vehicle operation. It then proffers recommendations to improve the stations' 'dependability'[1]. To this end, three guiding questions have been used to consider this issue:

- What is going wrong?
- Why is it not being fixed?
- What will make sure it gets fixed?

Hydrogen mobility systems have been operated with many different vehicle types in several regions globally over more than three decades. Despite the experience gained, the dependability of hydrogen refuelling infrastructure has not yet become good enough to give existing and future customers confidence to expand fully commercial vehicle fleets.

To understand the underlying reasons why HRS dependability has not met the needs of the vehicle operators, stakeholders across different geographies were interviewed to understand what has worked or not worked, and to gather suggestions for how to

[1] In this study, dependability is used to encompass the ability of a station to deliver fuel as needed and when needed – a combination of performance, reliability and availability.

improve HRS availability and performance. These interviews have been used as inputs to the recommendations in this report.

1.2. Global experiences of HRS Dependability

1.2.1. Overview

Globally, more than 1,300 HRS were deployed across 44 countries by the end of 2024. This is more than double the roughly 550 stations reported to be operational in 2020[2].

The deployments are geographically concentrated, with over 90% of the HRS in just 13 countries. Asia Pacific leads, with most stations in China, South Korea and Japan. The EMEA (Europe, Middle East and Africa) region has over 400 HRS deployed, with France and Germany accounting for over 60% of these stations. Across the Americas, the US has over 80 stations, most of which are in California. Canada has a small but growing network.

HRS dependability does not currently meet commercial needs. Although certain stations have achieved >99% availability, the overall average performance of the stations has been lower and varies significantly. The inconsistency over longer periods of time and across different sites has decreased customer confidence and slowed development of the hydrogen mobility sector. Costs, especially operational costs, of the stations have not reduced as much as anticipated, in part due to the high level of maintenance needed.

This study has focused on HRS dependability in the most developed regions for hydrogen mobility: East Asia, Europe and North America.

1.2.2. East Asia

Asia leads the deployment of HRS, with 748 deployed across the continent at the end of 2024[2]. Japan initially led the build-up of infrastructure. The Tokyo government had aimed for 6,000 fuel cell vehicles and 35 accompanying HRS in the city by 2020, and 3,500 'small trucks', 1,000 'large trucks' and 50 additional accompanying HRS by 2030[3]. Across Japan, only 160 HRS were deployed by 2020, reaching 181 by May 2023. The national target is 1,000 HRS by 2030. The deployment was affected by dependability issues, persistently high costs and slower than anticipated uptake of hydrogen vehicles. Significant scale up in station roll-out is needed to meet the 2030 goal[3].

Though it started after Japan, China leads the global deployment of hydrogen refuelling infrastructure with 384 stations in operation[2]. The country targets 1,200 HRS to be built by 2025. While achieving this is unlikely, the region has a significant focus on hydrogen mobility in China's hydrogen strategy[4] and is progressing quickly.. Stakeholder interviews for this project suggest that existing stations in China have generally been dependable with minimal downtime, partly achieved through the presence of permanent on-site maintenance staff.

---

[2] H2Stations.org by LBST

[3] The Mainichi, 2024, Tokyo bets big on hydrogen with moves to boost commercial fuel cell vehicles

[4] Hydrogen Industry Development Plan (2021-2035) – Policies - IEA

In South Korea, there has been a strong push for hydrogen mobility. It has been included as one of the key components of the national energy strategy and the national hydrogen economy roadmap, with the goal of having 1,200 HRS by 2040[5]. Some 250 were operational by the end of 2024, with roughly 50 being added each year since 2021[6].

South Korea's state-owned gas company KOGAS has reported significant downtime for the stations between 2022 and 2024, attributed to breakdown of compressors, issues with refrigeration equipment and charger malfunctions[7]. There were also issues with maintaining a reliable spare parts supply chain for the stations, as they use a mix of products (including valves and heat exchangers) from South Korea and Japan. However, stakeholder interviews suggest that these conditions may have improved as some stations are experiencing less frequent and shorter-lived downtime.

1.2.3. Europe

Europe has placed hydrogen mobility as a central component of its strategy for decarbonisation of the transport sector. The European Alternative Fuels Infrastructure Regulation (AFIR)[8] has set a target to construct an HRS every 200km along the Trans-European Transport Network (TEN-T) network by the end of 2030. Different policy frameworks are being put in place by member states to achieve this target. The network of HRS has started to take shape, with around 400 HRS installed.

Across these stations, there have been mixed experiences of dependability. For example, while several stations deployed in the JIVE projects have reported high dependability, many stations have faced persistent challenges that have restricted stations from being used[9].

1.2.4. North America

Of just over 80 HRS across the United States, 65 are in California[10]. The State had previously targeted 200 stations to be deployed by the end of 2025, but rollout suffered from funding, technology and hydrogen delivery issues. In recent years, the pace of new deployments has slowed, and the California Air Resources Board also reports that existing stations are encountering disruptions in the supply of gaseous

---

[5] South Korea | Green Hydrogen Organisation

[6] South Korea: hydrogen refueling stations 2024| Statista

[7] Hydrogen insight, 2024, 'Inconvenience' | About half of all hydrogen refuelling stations in South Korea have broken down since start of 2022

[8] Regulation - 2023/1804 - EN - EUR-Lex

[9] These issues were highlighted within an open letter to Hydrogen Europe from representatives of the JIVE, JIVE 2 and MEHRLIN project consortia.

[10] Alternative Fuels Data Center: Alternative Fueling Station Counts by State

hydrogen, stemming either from limited hydrogen availability or challenges in its delivery by truck[11].

Across Canada, 11 HRS are in operation, mainly in British Columbia. Canada has some supportive policies in place and regional initiatives to increase the use of hydrogen in transport[12].

1.3. The study

While the experiences of HRS dependability vary across geographies, many stations face similar issues that affect their ability to operate. To develop a comprehensive set of recommendations for addressing these issues, a series of interviews with stakeholders across these regions was conducted. These interviews included over 15 organisations globally, encompassing Europe, North America and China, and spanned the value chain of HRS. The interviewees included hydrogen suppliers, HRS and equipment OEMs, HRS operators as well as various hydrogen industry associations.

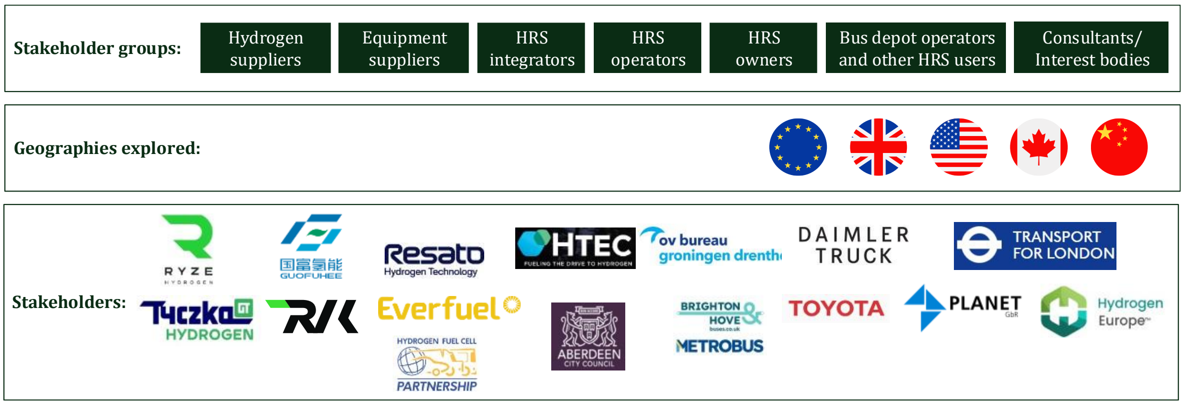

Figure 1: Overview of stakeholders interviewed for this study

The objective of these interviews was to explore the issues experienced and ways to enhance HRS dependability, drawing on the insights and experiences of each stakeholder in the hydrogen mobility sector. To achieve this, the interviews centred on the following guiding questions:

- What issues have you encountered that result in downtime at HRS?
- Do these persist, and if so, why?
- What measures can be taken to ensure these issues get resolved?

These discussions were used to generate a set of recommendations for future projects based on lessons learned to date.

This report synthesises the responses to these questions gathered through stakeholder engagement as well as findings from public reports on HRS availability.

[11] 2024 Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development

[12] Fuel Cell Works, 2022, Canada: Connecting East to West With Hydrogen Refuelling Stations

2. WHAT IS AFFECTING HRS DEPENDABILITY?

HRS dependability is affected by multiple issues, many of which are quite specific. On the technical front, studies have repeatedly found that the most common causes of downtime include faults with hydrogen storage, dispensing equipment, hydrogen compression, and safety devices[13,14]. Additionally, stations are affected by the availability of trained HRS service technicians as well as the security of the hydrogen supply. When these issues arise, the time taken to rectify them often contributes significantly to the overall station downtime.

However, the underlying reasons for these issues are seldom purely technical. Instead, they usually stem from a handful of broader categories:

- Hydrogen mobility system-wide maturity
- HRS planning and ‘fit for purpose’ design
- Equipment and supply chain reliability
- Inadequate maintenance arrangements
- Hydrogen supply and delivery
- Contractual issues

The causes of the underlying issues can be unbundled to identify potential solutions. For example, problems caused by inadequate maintenance might be addressed through alternative component selection, better training, or faster response times, or a combination of these measures.

To enhance the dependability of HRS, the potential problem causes need to be foreseen and the right incentive structures established to minimise them. Since the causes and solutions to problems are often multifaceted and interdependent, improving the dependability of stations will likely require the implementation of multiple, interacting actions.

The following sections set out these categories in detail, outlining the key contributing factors and possible solutions for each.

2.1. Hydrogen Mobility System Wide Maturity

2.1.1. *Problem:* The hydrogen mobility system is at a relatively small scale

The hydrogen refuelling system needs to have substantial operational scale to succeed. In many geographies, the system has not matured to provide consistent and reliable hydrogen supply and refuelling capability, and so scaling is expensive and risky. This applies throughout the production and supply chain up to and including the HRS and refuelling capability.

The challenges with maturity and scale of the hydrogen mobility system interact with the other categories of issues explored in this report in several ways, resulting in:

---

[13] Kim et al, 2024, Failure analysis and maintenance of hydrogen refueling stations

[14] Hoseyni et al, 2024, Mitigating risks in hydrogen-powered transportation

- Low replication of HRS designs so that refuelling cannot always be undertaken at an alternative location if a particular HRS is not operational
- Insufficient quantities of hydrogen production and supply to where it is needed
- Intermittent or unreliable component supply chain delivery to HRS
- Low availability of spare parts and skilled technicians
- Limited numbers of companies operating throughout the supply chain so that competition and innovation are constrained
- Uncertain profitability of investment

2.1.2. Potential solutions to failure causes

Many, if not most, of these issues are intrinsic to the fact that the hydrogen mobility sector is a relatively small market. There are not many actors in any of the logistic segments, and, in many cases, those that are present are relatively small companies, and new to the sector.

Increasing the size of the market is a clear possible solution and is regularly referred to by stakeholders including the European Commission, national Governments, various industry groups, and some NGOs. Increasing the demand for hydrogen, the number and range of vehicles, refuelling capabilities and various other aspects should lead to significant reduction in costs, and dependable performance throughout the system. There are several initiatives working to this end, including the JIVE projects.

2.2. HRS Planning and "fit for purpose" Design

2.2.1. *Problem:* The design of the station may lead to problems in operation

The station design can cause operational issues when:

- The design specification is not properly informed by the state of the art or the use case to be addressed;
- The design is not based on a good understanding of the available technology or its best operation modes;
- The available equipment does not perfectly match the design specification;
- Implementing the ideal design at an HRS site may not be possible because of space or infrastructure constraints

For example, stakeholders interviewed reported instances where their stations included either design elements or, in some cases, components that have been found to be inappropriate or failed in previous stations. In at least one instance, an HRS supplier incorporated station design and equipment such as valves that they had previously installed at a different station and had failed. There appeared to have been little, if any, internal communication or learning by the supplier from its own experiences. Learnings gathered from the design and operation of previous projects may also not be considered.

Problematic station design can also arise from rigid tendering requirements. For instance, HRS suppliers interviewed gave examples of Public Transport Authorities (PTAs) or Public Transport Organisations (PTOs) insisting on specific design elements and components which, in the opinion of the HRS supplier, were either inappropriate or not needed. The HRS supplier believed that the customer's needs could have been met with a simpler, cheaper design, believed to provide greater reliability.

As a result of some of the competing constraints of station operators and suppliers, HRS can be designed to meet unnecessarily onerous conditions, or incorporate unnecessary componentry, to meet some perceived requirement of the client. In practice, options such as depot logistic flexibility (which can adjust the requirements that the HRS needs to fulfil) might be available but not explored. The need for simplifying station componentry was observed by several interviewees.

As suggested by interviews conducted, dialogue alone between HRS developers and vehicle operators may result in a unique HRS design each time. This consistently bespoke approach would go against the benefits of standardisation, and result in increased costs and likely ongoing performance issues. Ideally, HRS suppliers will develop a suite of modular solutions. Deploying them at different scales can aid with:

- Cost – repeat purchasing and identical installations simplify procedures
- Speed – installing the same modules repeatedly enables optimisation of approach
- Redundancy – having several compressors, dispensers etc allows for maintenance downtime
- Training – teaching installers and maintenance staff is quicker and more effective with a limited set of equipment

Station design will need to account for constraints from both the end users and the technology suppliers

FC bus operators' constraints include:

- Buses refuelled and available to operate and service the public 100% of the time
- Existing refuelling logistic arrangements (including staff availability) and specific refuelling windows that may need to align with existing diesel refuelling
- Relatively small percentage of FCBs in their overall fleet, so the HRS may experience long periods of inactivity

HRS Suppliers have constraints including:

- Limited experience in real-world hydrogen vehicle refuelling
- Bus operators over-specifying performance or componentry with negative impacts on cost, dependability, project timelines.
- Restricted budgets of both the HRS supplier and the bus operator, leading to significant tensions between reducing costs versus increased dependability.
- Lack of a full suite of standardised and tested components to be used in vehicle HRS.

Informed dialogue and requirement-setting could be significantly enhanced by strong transfer of lessons learnt across different use cases and jurisdictions. While HRS projects have been running for several decades, with extensive reporting on challenges and possible solutions, communication is not wide enough and many of the same mistakes are still being made.

These challenges can mostly be addressed by enabling or incentivising the parties involved in the HRS tendering process to take on board existing knowledge on both technical and non-technical constraints of the full system, through structured information provision and dialogue.

2.2.2. Potential solutions to failure causes

The most appropriate station design is likely to result from:

- A dialogue between HRS supplier and operator to identify the usage requirements and trade-offs
- Up-to-date information on available technology and any performance issues
- Experienced designers and contractors
- Recognised and standardised testing methods, both pre- and post-installation

2.3. Equipment and Supply Chain Reliability

2.3.1. *Problem:* The reliability or performance of components may not match those stated or what is needed for HRS functionality

Numerous component failures and inadequate reliability have been identified in previous reports as well as through these interviews. They include:

- Specific components with high failure rates such as sensors, compressors or valves
- Gas leaks from poor installation or equipment failure
- Replacement parts not being available due to bespoke design, or supply chain issues
- Cooling equipment inadequate for the required service cases, leading to increased waiting times or knock-on performance reduction
- Software integration poorly implemented, as different suppliers may have different approaches or systems. This can lead to components within the HRS failing to communicate properly with each other, to a failure of communication between HRS and vehicle, or a failure of the payment system

Several interviewees commented that compressor breakdown is more likely to occur when they are constantly stopping and starting. This is almost always the current situation given the relatively small number of vehicles accessing each HRS. As noted in the recent JIVE Performance Assessment Reports, there appears to be little improvement in compressor performance for vehicle HRS in the past 20 years[1].

The HRS sector is small, with few integrators as well as limited equipment choice. Most equipment was originally intended for a different purpose or use case and not designed for integration with other components in HRS use. What equipment there is may not be available in all regions or have limited production runs. There is also a limited choice of component options for the HRS designers and suppliers to choose from.

Replacement part availability has often been an issue with few spares being available, or not immediately on hand. In some cases, the bespoke design of particular HRS has meant that the item must be re-ordered and manufactured from a particular supplier, resulting in very long lead times. The small number of HRS across Europe means that a lot of equipment suppliers appear not to have a large stockpile of spare parts and these are kept at their manufacturing site and not dispersed geographically.

While some of this is normal in a developing sector, the limited progress in some regions has been disappointing. Europe and North American HRS performance has frequently been below expectations, with some exceptions, though in South Korea and particularly China it has improved year-on-year.

The limited market size means that equally limited resource is available for bespoke component designs, but it should still be possible to optimise component and equipment configurations, improve training and communication, and ensure appropriate acceptance and performance testing. Until the prize is big enough to provide market incentives for full competition, this may need to be done partly though incentives linked to funding support.

2.3.2. Potential solutions to failure causes

Addressing the challenges requires improvement in the following:

- Ensuring designers and developers know the full range of components, equipment and suppliers that are available
- Creating incentives for supply chain resilience including localised parts availability and short replacement schedules
- Enabling developers and designers to understand how to match performance needs with available equipment
- Producing standard or semi-standardised testing and benchmarking to allow like-for-like comparisons across components and the whole HRS
- Standardisation of components with a resulting increase in availability and reduction in cost

2.4. Inadequate Maintenance arrangements

2.4.1. *Problem:* There are delays to the maintenance of HRS

The downtime that results from equipment failures that have been highlighted is often accentuated by further failures in the maintenance arrangements of the HRS. There are three main types of failures that occur in relation to maintenance:

- A shortage of trained maintenance staff means that maintenance may be poor, or may not happen
- Unclear contractual allocation of maintenance responsibilities means that either maintenance is not carried out, or becomes an additional cost to the current service provision
- Spare parts may not be available to replace faulty equipment, leading to delays in resolution

For instance, interviewees noted that the limited number of HRS suppliers, as well as their component suppliers, coupled with an absence of standardised training programmes results in a shortage of trained HRS maintenance technicians.

The maintenance provider base, usually the OEM of the station, is sometimes located far from the station. Many OEMs are responsible for stations spread across extensive regions, in some cases spanning across Europe. This geographic spread causes those technicians to undertake long journeys to get to their work site. According to some interviewees, it can therefore take several days for staff to attend to a station after a fault is reported.

Interviewees also noted that knowledge sharing across maintenance providers is limited, so that some staff are not fully equipped to deal with some failures. This can cause further downtime even though the technician is on site.

The absence of government endorsed standards and certification for HRS maintenance technicians limits the supply of any generic technician. While organisations such as H2Mobility in Germany have developed internal certification for engineers operating at their sites, it is likely to have limited portability.

OEMs have also expressed reservations to training more HRS technician numbers given the uncertain future demand for HRS in Europe and beyond. There have been mixed market signals in the past years, with some regions rapidly increasing demand for hydrogen vehicles, and others slowing down their plans for infrastructure development.

Some station operators interviewed highlighted an increase in downtime from failures leading from unclear contractual agreements regarding maintenance responsibilities. This unclear ownership of tasks has led to delays in resolution of even routine failures that could otherwise have been dealt with quickly. Some equipment supply contracts failed to clearly outline who would be responsible for maintenance of failing parts – the OEM or the station operator.

Stations often integrate components from multiple suppliers, and interviewees highlighted cases where the warranties for different parts vary in duration. In such cases, a central warranty covering the entire station was not secured, meaning that when some equipment failed outside of its warranty, the station operator had to arrange for maintenance themselves. This is in part caused by the lack of station providers on the market, meaning that often an HRS operator needs to rely on multiple suppliers to complete the station, increasing the likelihood of maintenance issues.

Finally, a shortage of spare parts often further increases downtime associated with maintenance activities when responding to equipment failure. The small number of HRS across Europe (and other geographies other than some Asian markets) means that a lot of equipment suppliers cannot justify producing a large stockpile of spare parts and therefore only have limited replacements available at their manufacturing site. As the OEMs producing the equipment could be geographically distant, the delivery of spare parts can have long lead times which result in extended station downtime.

Some interviewees noted that a lack of equipment standardisation across stations (in Europe as well as with other geographies) means that in some cases suppliers need to manufacture bespoke spare parts for different stations. These more bespoke parts typically have limited spare or alternative parts; hence replacements need to be manufactured when a fault arises, resulting in increased downtime.

2.4.2. Potential solutions to failure causes

Improving the maintenance arrangements will require actions across the industry, involving not only station operators and maintenance providers, but also standards development, and certification organisations, such as CORGI, VDMA, TÜV. The standards and certification organisations may need to lead this initiative.

Addressing these challenges will require:

- Standardised components from OEMs as far as practicable, to enable generically trained maintenance providers to easily service the equipment
- Increased adoption of telematics or predictive maintenance to allow scheduling of remote maintenance calls
- Specific training courses and certification as part of existing training for support technicians/engineers
- Shared learning on likely problems arising at HRS and their associated resolutions, in a manner that avoids blame and protects the OEM's intellectual property
- Contracts that clearly define responsibilities, incentivise timely resolution of problems and are enforced.

2.5. Hydrogen supply and delivery

2.5.1. *Problem*: Supply of hydrogen to the HRS is curtailed or quality is low

HRS dependability also hinges on hydrogen being available at the required quantity and quality for its customer demands. This is not always the case:

- The supply of hydrogen may be inconsistent or even cease entirely
- Lack of system standardisation may mean that delivery can only be done with a specific connector or pressure range
- The hydrogen delivered may have impurities that cause problems with vehicle operation, or may become contaminated within the system

Hydrogen supply to individual HRS may depend on a single supply route, and disruption has caused some extended periods of downtime. While some of this is due to wider system and market issues which are addressed below, some is linked to specific suppliers, and some to station design limitations.

Interviewees noted that there is frequently an insufficient number of hydrogen suppliers available for a given HRS or HRS network, or an insufficient quantity of hydrogen to supply all HRS. A station operator wishing to source hydrogen from an alternative supplier can face very high prices or may be contractually restricted from doing so.

In such cases where the specified supplier is unable to deliver on their contractual agreement, many contracts have included penalties for missed supply. However, this has not always been an effective method to reach resolution. In many cases, the penalties paid from the missed hydrogen supply are insufficient to cover the cost of alternative hydrogen sourcing.

In some instances, lack of equipment standardisation has caused shortage of hydrogen supply. Some interviewees noted that tube trailers delivering the hydrogen have been unable to dispense the fuel due to a mismatch in connectors between the trailer and the compressor or storage tank.

2.5.2. Potential solutions to failure causes

Hydrogen storage on site can mitigate the impacts of missed hydrogen supply. However, in most geographies, the amount of hydrogen that can be stored at the HRS is limited. In most European jurisdictions, detailed permits and safety assessments are needed to store more than 2 tonnes of hydrogen, and this capacity can be less than the required supply for large fleets[15]. This additional permitting requirement adds cost to the HRS build, with an uncertain payback.

On site hydrogen production can also be an option to ensure consistency of supply. However, if there is no redundancy in the hydrogen supply arrangements, such as emergency trucked in supply, the downtime of the hydrogen production unit will also hinder the station's dependability.

Overall, to improve station dependability through its hydrogen supply, the following elements could be adopted:

- Multiple suppliers and pre-negotiated prices
- Bundled demand between HRS, with options to share if one station is short
- A variety of client types, some of whom have flexible refuelling schedules, to conserve supplies if required
- Appropriate contract design, with inclusion of several alternate plans to cover different circumstances, along with realistic and implementable performance obligations and penalties.

2.6. Contractual issues

2.6.1. *Problem*: Contracts are not always written with clear responsibilities and accountabilities, so that problems are not always speedily resolved.

Several elements contribute to this problem:

- In the hydrogen refuelling system value chain, the involvement of numerous actors and suppliers can lead to ambiguity in contracts regarding responsibility for a problem, especially when problems arise that involve multiple components or stages.
- Some companies are relatively new or small, making it hard to ensure continued support in the event of their failure.
- Some problems may be hard to anticipate and so may not be covered by a contract.
- Penalty clauses may not be sufficient to motivate action.

While bus operators and public transport authorities are experienced in establishing contracts for the acquisition and operation of existing infrastructure and services, the new technology involved with building HRS, hydrogen supply, FC Buses and their maintenance are frequently outside their usual experience.

The unclear specification of responsibilities can include:

- Which party has responsibility for maintaining hydrogen supply?
- At what point does the hydrogen become the responsibility of the PTA/PTO?
- Which entity is responsible for specific equipment performance, maintenance and replacement?
- What are the performance KPIs and how are they measured?

[15] 12-meter long buses can have a hydrogen storage capacity of 25-36 kg. Source: Hexagon Purus

Interviewees suggest that these and other issues have not always been determined and documented, leading to contracts which leave important areas open for disagreement, and therefore delay remedies.

In some cases, there has not been an overall warranty for the HRS, and individual component suppliers have implemented their own warranty conditions. Some HRS users have had to negotiate with multiple suppliers, each with their own terms of business and warranty, and arrange for individual component maintenance themselves.

At the same time, the contractual remedies and penalties have either been absent, insufficient, or inappropriate to achieve the outcome of putting the HRS back into service. Stakeholders have reported instances where the HRS supplier has been prepared to suffer a financial penalty rather than remedy the situation. It is essential that contractual penalties can be implemented to achieve the desired outcomes, but penalties that are too high will either result in few bidders for a contract, or would be unsustainable for a small business, so are often not able to be activated to achieve a useful outcome.

2.6.2. Potential solutions to failure causes

The approach to solving these problems can build on a combination of high-quality legal expertise, standard templates for contracts based on previous experience (but modifiable for specific situations and regions), and a pragmatic balance between sufficiently strong penalties that can drive action and those that are so strong that they cannot be signed up to.

2.7. Summary of factors affecting HRS dependability

As originally suggested, the apparently diverse issues described above have common threads. This means that it is possible to address them simultaneously through a structured approach to HRS roll-out. The common threads highlighted by the interviewees can be summarised as:

- A need for much better internal and external communication and rapid learning
- Ensuring incentives are aligned from hydrogen supplier, through HRS installer and operator, to vehicle operator, to local or national authority and are ultimately measured by uptime of the hydrogen vehicles
- A focus on standardisation, scale and modularity

These are not new issues, and neither are the proposed solutions. The challenge is to propose ways to ensure more of the solutions are implemented.

Section 3 explores targeted measures, presented as recommendations, that will help lead to dependable HRS. It also identifies the key stakeholders that could be responsible for implementing these initiatives.

3. RECOMMENDATIONS TO IMPROVE HRS DEPENDABILITY

Section 2 outlined the major groups of issues that continue to constrain HRS dependability. There are common linkages between them, and many of the detailed sub-problems affect more than one of the dependability issues. Accordingly, while the recommendations below are linked to issues, they should be considered and implemented in the context of the entire hydrogen refuelling system. Several suggested actions will interact.

The Guiding Principles and Recommendations for each category are written as an ‘action plan’. This section proposes responsibilities for each recommendation and a suggested ‘ideal’ timeframe to implement them.

3.1 HRS Planning and ‘Fit for Purpose’ Design.

The infrastructure must be designed to meet the needs of the customers using the station for it to be ‘fit for purpose’. The process to achieve this should be based on some Guiding Principles which lay the groundwork for the success of the project.

3.1.1. Guiding Principles

As noted in section 2.2, several priorities need to be balanced in designing an HRS. The actions taken need to incorporate dialogue between the technology and overall station suppliers, the intended operator for the station and its customers. During tendering and design, the HRS supplier and buyer must understand the objectives and constraints of both parties. Tenders that clearly list customer needs separate from optional requirements give technology providers the freedom to use their knowledge to adapt the design and make sure the station meets its intended use.

Additionally, station design should emphasise reliability and redundancy. Where possible, components with demonstrated performance should be used. While innovative technologies may improve performance in the long run, they should not be tested in commercial stations. Such testing should only occur when there are well-defined, documented arrangements in place for any necessary remediation in the event of unacceptable performance. Furthermore, station design should incorporate redundancy of components and, where feasible, be in a network of HRS to provide further layers of redundancy.

3.1.2. Recommendations

Recommendation #1: Develop and publish generic HRS designs, including incorporating redundancy of key components

While these should not be overly prescriptive, template designs can be useful for new entrants developing new HRS to ensure they do not repeat previously noted mistakes.

Owner: Funding organisations such as the Clean Hydrogen Partnership could commission a project to undertake this and publish the designs.

Timeline: Complete within two years

Recommendation #2: Establish an open-source databank of best practice for HRS designs, including performance objectives and criteria

These best practice guides, already published by initiatives like JIVE, offer valuable insights into project and stakeholder experiences that can be relevant across various geographies. They can also do so without disclosing any IP-sensitive performance criteria.

Owner: Funding organisations such as the Clean Hydrogen Partnership could commission a project to undertake and publish this.

Timeline: Immediate

Recommendation #3: Establish a bank of contract templates for acquisition and operation of HRS, including performance objectives and criteria

Owner: Funding organisations such as the Clean Hydrogen Partnership could commission a project to undertake this and publish.

Timeline: Within two years

Recommendation #4: Establish a list of HRS operators prepared to share information and learnings that are not IP-sensitive with interested parties

Sharing information, such as technical learnings, from HRS design and operation can benefit current and future HRS operators. Having a list of HRS operators that are willing to share their generated knowledge can be useful for organising visits and connections from interested parties. If data are also shared they can be aggregated from these stations, anonymised and centrally managed to prevent sharing sensitive IP.

Owner: Organisations such as Hydrogen Europe, Hydrogen Council, or the Clean Hydrogen Partnership could lead this compilation. Funding bodies like national funding organisations or the Clean Hydrogen Partnership could solicit for willing station operators through the network of stations that have received or are receiving funding support. Bodies such as Hydrogen Europe could explore the stations owned or operated by their members.

Timeline: Within two years

Recommendation #5: Require all project receiving public funds to participate in learning sessions on HRS designs and performance, and undertake visits to two operating HRS

Owner: All Public Funding agencies, including the JU, to include this as a requirement in all future HRS funding grant contracts

Timeline: Immediate

Recommendation #6: Establish a framework, including commercial principles, to facilitate the sharing of HRS and hydrogen supplies between multiple users

Owner: Commercial arrangement structures need to be developed and shared from HRS operators, but the standardisation of the equipment needs to be coordinated with standardisation bodies.

Timeline: Within two years

3.2. Equipment performance and supply chain reliability

3.2.1. Guiding Principles

Although stations may be designed appropriately for their use case, as discussed in Section 3.1, equipment failures can still be a significant cause of HRS downtime. Equipment used in HRS to date has been unstandardised, sometimes unavailable and in cases shown poor performance. To ensure this is not repeated in future stations, the recommendations here focus on improving these three key elements. These recommendations will increase the use of available components that meet recognised performance standards. They will support resilience in the supply chain, by increasing stocks, availability and replacement schedules. HRS operators should have the certainty that the equipment they use is reliable, and readily replaceable in the event of any expected or unplanned failures, and these recommendations offer a pathway to achieve this.

3.2.2. Recommendations

Recommendation #7: Establish a data bank of components currently in use in HRS, and their performance specifications

This could be a data bank of components and available suppliers that is continuously updated. This can either be a global database, or a set based on regional availability, to be owned by relevant local bodies, though ideally should be co-ordinated to avoid duplication.

Owner: Database can be commissioned by bodies such as Clean Hydrogen Partnership

Timeline: Complete and publish in the next two years

Recommendation #8: Establish and publish standard tests that can be applied to key non-standard or unique HRS components

This can be developed together with station operators and OEMs that have used such equipment previously to draw on their experience of integrating such components.

Owner: Testing certification organisations, such as CORGI, TÜV, DNV

Timeline: Within two years

Recommendation #9: Develop a contract framework of incentives and penalties for component performance that encourage and reward reliability

Owner: This can be done as part of the compilation in Recommendation #3.

Timeline: Within two years

3.3. Inadequate maintenance arrangements

3.3.1. Guiding Principles

To ensure the effective maintenance of hydrogen refuelling stations, it is essential to establish a framework built on clear and measurable principles. First, performance indicators must be both realistic and quantifiable, enabling consistent monitoring and evaluation of maintenance outcomes. Responsibilities and accountabilities should be explicitly defined not only for individual components but also for the overall HRS infrastructure, with associated timelines to ensure timely interventions.

A balanced system of financial incentives and penalties should be implemented to drive performance, rewarding high standards while discouraging neglect. Additionally, the availability of trained technicians must be guaranteed within a specified response time to minimise operational disruptions. Similarly, spare parts should be readily accessible within a defined timeframe to support rapid repairs and reduce downtime.

3.3.2. Recommendations

Recommendation #10: Establish a data bank of maintenance contract templates
These should include a clear definition of responsibilities by all parties involved in the HRS.

Owner: This can be done as part of the compilation in Recommendations #3 and #9

Timeline: Within two years

Recommendation #11: Develop a skill and competency profile for a generic HRS maintenance technician, a training course plan, and skill standards that are recognised by Government and Industry across jurisdictions
Maintain an updated list of existing certification bodies, courses and programmes across geographies that can be used alongside these resources. Include reference to the standard HRS designs and components mentioned in previous recommendations.

Owner: Government training bodies, Certification bodies such as TÜV and DNV.

Timeline: Within two years

Recommendation #12: Increase the use of standardized components so that spare part stores can be accessed by a range of HRS
Develop centralised spare part storage sites in areas where HRS have been clustered as part of a network, to facilitate rapid access.

Owner: component OEMs in collaboration with maintenance providers

Timeline: Within five years

3.4. Hydrogen Supply and Delivery

3.4.1. Guiding Principles

Reliable hydrogen supply is fundamental to the successful operation of hydrogen refuelling stations. It is critical that hydrogen is consistently available at the required locations and at the times it is needed to meet operational demands. To mitigate risks associated with supply disruptions, a sufficient level of redundancy among hydrogen suppliers should be established to ensure continuity even in the event of individual supplier issues.

Once delivered to site, hydrogen must be dispensed effectively and in a timely manner. This requires robust infrastructure and operational procedures that support seamless transfer from delivery to end use, maintaining both safety and efficiency throughout the process.

3.4.2. Recommendations

Recommendation #13: Establish hydrogen user 'hubs' with multiple hydrogen providers supplying multiple HRS within a region, with each HRS able to access more than one supplier.
Include, from a contractual stage, the option to secure hydrogen from alternative suppliers and supply sites, to reduce the likelihood of HRS downtime from lack of fuel.

Owner: Local, regional and national transport and energy authorities

Timeline: Within five years

Recommendation #14: Cluster HRS within reasonable proximity so that users have the option to refuel at more than one HRS
Encourage the creation of local networks of HRS to give users confidence in refuelling. This may also promote semi-localised hydrogen production facilities at large scales, able to supply multiple stations.

Owner: Local, regional and national transport and energy authorities

Timeline: Within two years

3.5. Contractual issues

3.5.1. Guiding Principles

Robust contractual arrangements are essential to ensuring the long-term performance and reliability of hydrogen refuelling stations. Contracts should include performance KPIs that are both realistic and measurable, providing a clear basis for assessing delivery against expectations. Responsibilities and accountabilities must be explicitly defined, covering not only the overall performance of the HRS but also warranties and, where appropriate, individual component performance and warranties.

Crucially, incentives should be aligned through the supply chain and reward uninterrupted operation of both vehicles and station. If rewards can be structured around dependability and throughput, this should help vehicle owners maximise use, and station owners maximise uptime.

To drive consistent performance, contractual frameworks should incorporate a balanced system of financial incentives and penalties. These mechanisms should be designed to encourage suppliers to meet or exceed performance standards, while also providing financial consequences for underperformance, thereby aligning commercial interests with operational reliability.

3.5.2. Recommendations

Recommendation #15: Establish a data bank of HRS acquisition contract templates and legal advisers with previous experience in HRS contracts
These can be separate data banks. However, it will be beneficial to provide examples of legal advisers who can aid in the delivering of said contracts. Lists will need to be kept updated as the sector evolves.

Owner: Include with template contracts in recommendations #3 and #10

Timeline: Within two years

Recommendation #16: Increase weighting of the track record of HRS suppliers during tendering

This can help mitigate the risk of insufficient technical experience leading to station faults.

Owner: HRS tenderers

Timeline: Immediate

4 CONCLUSION

Refuelling of hydrogen powered vehicles must be simple and dependable for the hydrogen mobility sector to be able to have a significant role in the broader transport sector. Refuelling needs to be at least as convenient and dependable as refuelling with petrol, diesel or natural gas.

The current dependability of HRS and the accompanying hydrogen supply chain is, at best, inconsistent. In general, the current status of the system has not improved significantly over the last few decades. While refuelling at some sites for some time periods is highly dependable, the same stations may be unavailable for long periods in between periods of high availability. Where station performance is good or improving, this seems to be linked to greater competition, created by a growing market.

Stakeholder comments reported in this study are remarkably and depressingly similar to those recorded in multiple studies over the last 2 or 3 decades. These include unavailable spare parts, compressor breakdowns, unreliable maintenance and HRS suppliers seemingly uninterested in developing improved performance and displaying a lack of learning from past practices.

The recommendations in this report seek to remedy this. However, it is essential that the organisations listed take responsibility for taking action and are held accountable for the outcomes. Continued proactive action is the only remedy for the challenges being faced in hydrogen refuelling.

Project coordination:

ERM

Project dissemination:

Hydrogen Europe

The **JIVE and JIVE2 projects** have received funding from the Clean Hydrogen Partnership (formerly known as FCH JU) under Grant Agreement No 735582 and 779563.

This Joint Undertaking receives support from the **European Union's Horizon 2020** research and innovation programme, Hydrogen Europe and Hydrogen Europe Research.

The **MEHRLIN project** is co-financed by the **European Union's Connecting Europe Facility.**

@fuelcellbus
www.fuelcellbuses.eu

Clean Hydrogen Partnership

Co-funded by the European Union