Technical performance of HRS under high utilisation and recommendations (WP5)

Deliverable 5.38	Technical performance of HRS under high utilisation and recommendations – Executive Summary (March 2024)
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Frequently used abbreviations

DE	Germany
DK	Denmark
EU	European Union
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FR	France
GTC	Green Tomato Cars
HDV	Heavy-Duty Vehicle
HRS	Hydrogen Refuelling Station
H2	Hydrogen
H2ME	Hydrogen Mobility Europe (project)
ICE	Internal Combustion Engine
KPI	Key Performance Indicator
LDV	Light-Duty Vehicle
MDV	Medium-Duty Vehicle
MPS	Metropolitan Police Service
NL	The Netherlands
NREL	National Energy Research Laboratory
OEM	Original Equipment Manufacturer
UK	The United Kingdom
ZEFER	Zero Emission Fleet Vehicles for European Roll-out

Glossary 2/2

Definitions

Availability	Percentage of time a HRS is fully operational and able to dispense fuel, excluding planned maintenance.
Capacity	Amount of hydrogen that the HRS can dispense daily.
Downtime	Period when the HRS is not available for refuelling a vehicle.
Flexibility Services	Range of solutions that electricity system users can provide to help balance demand and supply in the electricity network and support its efficient use.
Performance indicator	Event-based indicator that looks at the percentage of refuelling that were successful on the first try.
Range anxiety	Concern that the vehicle has insufficient range to reach its destination.
Redundancy	Mitigation measure implemented within the design of a station by including extra components to reduce the risk of station issues caused by the failure of said components or process line within the HRS, thus alleviating downtime.
Single point of failure	Disrupted operation of HRS due to a single malfunctioning component/process.
Teething phase	Period after HRS commissioning during which the dispensing amounts are still low. During this period, HRS usually experience initial parts failures, software malfunctions and other issues.
Throughput	Amount of hydrogen that the HRS dispenses. This value is dependent on the prevalence of low-pressure onsite storage or onsite generation.
Uptime	Period when the HRS is available for refuelling vehicles.
Utilisation (utilisation rate)	Metric representing the percentage of the total station capacity effectively used. It is calculated by dividing the average daily demand for hydrogen by the total daily capacity of the station.

An extensive and reliable Hydrogen Refuelling station (HRS) network is a key enabler to the uptake of hydrogen in transport

Context of this report

- Governments across Europe have committed to limit global warming by targeting 'net zero' carbon emissions by 2050. As part of this endeavour, there is a focus on reducing emissions in the transport sector which is estimated to be responsible for **over 20% of Europe's greenhouse gas emissions in 2020**[1].
- **Road transport accounts for the largest share of emissions withing the transport sector** with all European countries still heavily reliant on petrol and diesel vehicles. Transitioning to **zero-emission alternatives** such as battery-electric (BEV) and fuel cell electric vehicles (FCEV) is therefore vital in achieving Europe's climate targets.
- FCEVs have the potential to play a significant role in the future transport sector as they can provide **similar operational flexibility to that of petrol and diesel vehicles,** with long ranges and quick refuelling times. Moreover, the hydrogen used to power the vehicle can be **produced through zero- or low-carbon production methods** (e.g., electrolysis)**.**
  - Hydrogen mobility, although not fully commercialised, has developed recently. Currently, Europe has approximately 5,100* operational light FCEVs (passenger cars and vans) and over 400* heavy-duty vehicles (HDVs) and buses. These vehicles rely on a network of around 150 hydrogen refuelling stations (HRS)[2]. Most deployments received support from funded demonstration projects to overcome initial market barriers. However, additional advancements in technology and market conditions are needed for widespread commercial adoption and further scaling.
  - One key area requiring improvement is hydrogen refuelling infrastructure. An **extensive network of hydrogen refuelling stations** will be required to meet the growing demand for hydrogen within European road transport sector. For hydrogen mobility to become a more widespread reality, **improvements in the performance and availability of HRS** need to be achieved to ensure that infrastructure is well-equipped for increasing demand and can satisfy the needs of end users with limited additional effort or compromise.

1 - EEA (2020) Greenhouse gas emissions from transport in Europe. https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases-7/assessment
2 - 700-bar and 350-bar HRS publicly available stations for cars (https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/distribution-and-storage/hydrogen-refuelling-stations)
**https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/end-use/hydrogen-fuel-cell-electric-vehicles*

H2ME lays the foundations for the first truly pan-European network of hydrogen refuelling stations and key learnings have been gathered

Hydrogen Mobility Europe

Hydrogen Mobility Europe

- The Hydrogen Mobility Europe (H2ME) initiative has been an **important step in increasing the deployment of FCEVs and developing a pan-European network of HRSs**.
- Consisting of two projects – H2ME and H2ME 2 – the initiative provided funding to **deploy over 1,400 FCEV (cars and vans)** and **49 HRSs**, to test the feasibility of the technology and confirm its readiness for commercial roll-out.

Introduction to the Report

- Previous H2ME reports have identified a variety of barriers for roll-out, but a **consistent challenge has been the deployment and operation of the HRS networks**. The aim of this report is to give an **overview of the performance, availability, and utilisation levels of HRSs** in the H2ME project as well as **challenges encountered**, focusing specifically on **stations which experienced the highest high utilisation rates** over the course of the project.
  - The H2ME-2 initiative aspired to deploy HRS which would be rigorously tested under high levels of utilisation. The levels of utilisation were expected to reach an average around 20% by the end of the trial, with several individual stations exceeding 50%. Nevertheless, only a **few stations are reaching that level of 20% described as high utilisation** as FCEV deployment in Europe has not developed as fast as forecasted when the project was commissioned. This slower development has reduced the sample size of sites which can be examined.
  - The report therefore aims to outline some of the **key performance and utilisation trends** seen across the project, as well as examine case studies of **few key stations that have achieved moderate to high levels of utilisation** (**>20% utilisation** relative to the station capacity). For most of these stations, the deployment of high-mileage fleets in the area was the main contributor to bigger amounts of hydrogen been dispensed.
- This report is the executive summary of a series of four reports produced on this topic throughout the H2ME project. For further detailed analysis, please see published interim reports *Technical performance of HRS under high utilisation and recommendations* (Publications | Hydrogen Mobility Europe (h2me.eu)).

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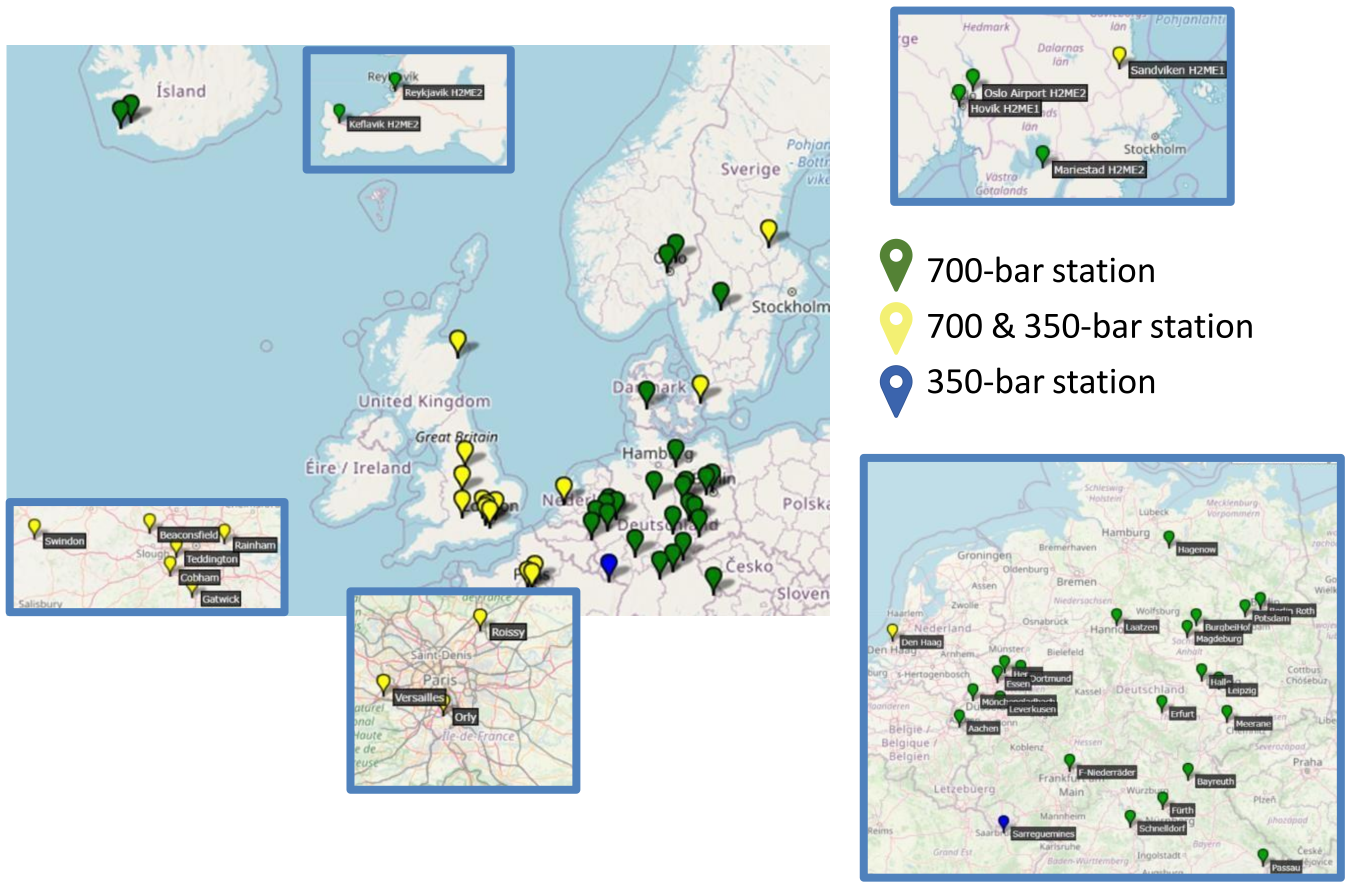
The extensive data for this study has been gathered from 43 HRS from 9 suppliers

Hydrogen Mobility Europe

- **At the time of writing, 43 HRSs have been installed** as part of the project, supplied by Air Liquide, ITM Power, Linde (including its subsidiaries AGA and BOC), McPhy, NEL Hydrogen Fueling, Resato, and Elogen.
- Over the course of the project some stations have unfortunately had to close while new ones are still expected to be deployed. Overall, 45+ stations will be operational by the end of the project.
- Detailed **data has been gathered from a majority of these stations*,** with some datasets stretching from 2016 to Q1 2023.



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Source: H2ME2, D5.33 – Six monthly Summary Technical Report – Presenting Project Data to June 2022, Cenex
** Some stations are no longer providing data as they are currently operating beyond their stipulated period for data provision (mainly H2ME stations).*

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H2ME data evidences high average availability of HRS, but not yet consistently above targeted levels of 98% and technical issues and teething issues have led to poor performance at certain stations

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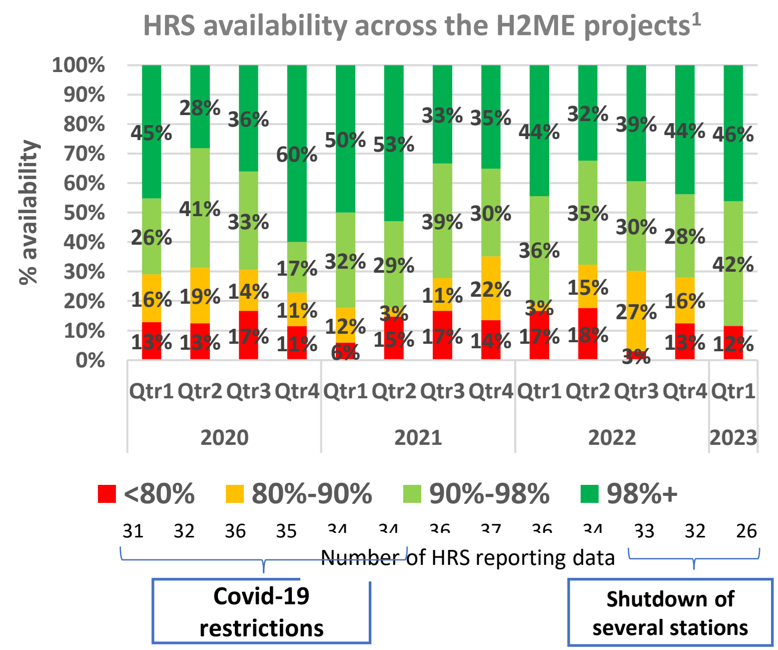
HRS Availability in H2ME

- HRS availability is defined as the **percentage of time a HRS is fully operational and able to dispense fuel, excluding planned maintenance.**
- As of March 2023, 26 HRSs* were reporting availability data to the H2ME projects, but only 23 had availability levels above 80%. **The average availability** (**excluding one off incidents,** i.e., HRS with availability levels below 80%) **in Q1 2023 was of 97.1% across project HRSs.** When considering all stations, is of 90.7%. The project's availability target is set at 98%.
- Despite this strong performance, **variable availability levels of HRS across the project have been observed, with some stations only achieving ~20% availability in Q2 and Q3 2021.** This can mainly be explained by the 'teething phase' experienced by newer stations and some consequences from the Covid-crisis.
- This has improved and stabilised since Q4 2021, with lowest value at 45-50%. In Q1 2023, the range of availability stretched again with stations achieving levels slightly above 25%.
- In order to have FCEV deployment thrive against the internal combustion engine (ICE) vehicles, **availability levels close to 100% will be required** to match that of a petrol/diesel station and to mitigate the risk of fewer stations being accessible.
- The following slides provide an insight into the **main challenges facing vehicle operators in achieving high availability** and the **key learnings** taken from the project.
    1. Stations often experience teething issues shortly after being commissioned, which can be enhanced when the levels of demand are low.
    2. Key components such as compressors and dispensers have been identified as components experiencing high failure rate.



1 – *Internal project data, Cenex (data up to Q1 2023).*
**Out of the 43 stations previously mentioned, several have stopped operations during the project's lifetime hence the 26 HRS reporting availability data.*

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Teething phases were observed in the H2ME project during which the availability levels often are unstable until more hydrogen is dispensed

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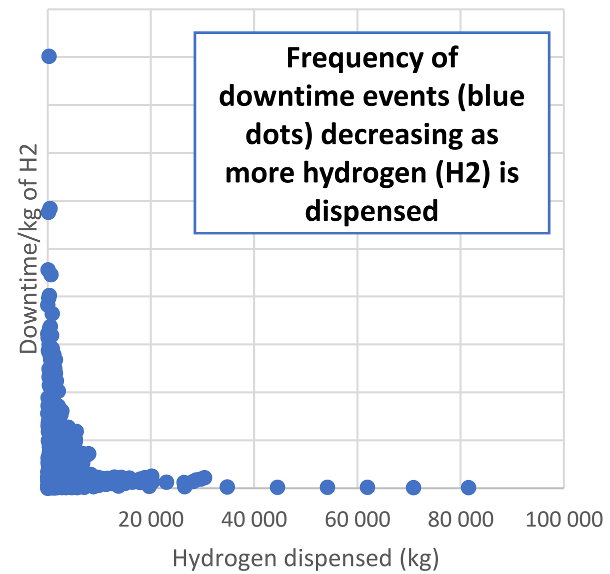
Causes of HRS downtime

- **HRS typically have lower availability in the early months after commissioning** when the cumulative hydrogen dispensed is low. This is also known as the **'teething phase'** when issues with the equipment, such as sensor failures, software malfunctions or equipment breaks, are frequent. This is also a period during which users will need to get acquainted with manipulating the equipment.
- Utilisation of a station is noted to have an impact on the availability of the HRS. **As more hydrogen is dispensed, the number of failures often decreases** as initial problems are addressed and learnings are implemented into the station design, operation and maintenance strategies.
    - Operators have highlighted that some components have been designed for semi-continuous operation meaning that the start and stop operation when utilisation is low can increase wear and reduce the lifetime of the component.
- Data from the H2ME projects has indicated that **above a threshold of 100 kg dispensed, the number of downtime events per kilogram reduces dramatically.** This is commonly illustrated in a 'bathtub curve' (graph on the right) whereby the **frequency of downtime decreases as greater volumes of hydrogen are dispensed .**

Downtime per kg of hydrogen dispensed for H2ME HRS[1]



- Issues with the teething phase are increasingly being recognised by the sector and actions are being put in place to reduce instances of downtime. For example, HRS operators are now **undertaking more testing on HRS** before finalising commissioning and opening an HRS to the public.
- Additionally, to **support in highlighting possible issues with HRS to end users ahead of time,** availability apps such as H2.LIVE have been developed**.** These apps show the locations of HRS with information on their availability status, whether there is maintenance ongoing, and expected (re)start date.

1 – Internal project data, Cenex (data up to Q1 2023).

Compressors, dispensers and chillers have been identified as ‘high-risk’ components, responsible for 63% of downtime across the project

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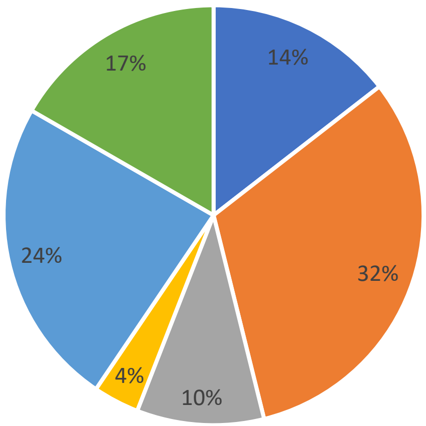
Causes of HRS downtime

- Data has been collected on the key causes of downtime for HRS in the H2ME project and is summarised in the chart to the right. Note that electrolyser downtime is not included as not all station designs used an on-site hydrogen production system.
- Many **downtime events within the H2ME project can be associated with a failure with one piece of equipment**. Many stations are susceptible to a single point of failure meaning that one malfunctioning component can cause the HRS to stop operating.
- Data from HRS providers identify compressors, chiller/precooling and fuelling dispensers as the largest cause of HRS downtime, accounting for 63% of total HRS downtime in the project.
- A targeted improvement in these equipment types is therefore important to improve HRS availability and will require:
  - **Research and development** into compressors, dispensers and chillers to improve reliability and durability. This can also go through standardising designs to make maintenance and repairs more efficient.
  - **Robust supply chains** for equipment, including local reserves to reduce the period of downtime in case of unexpected failures.
  - **Building redundancy** into HRS (n+1 philosophy) to mitigate the failure rate of high-risk components. This will have an associated CAPEX impact which is likely more justifiable for HRS with high utilisation, high availability and high revenues.

H2ME and ZEFER[1] HRS Downtime by category [2]



1 – Zero Emission Fleet Vehicles for European Roll-out ; 2 - Internal project data, Cenex (data up to Q1 2023).
Source: H2ME, D6.10/D6.18, Commercial advancements in the hydrogen fuel retailing – final / Recommendations for harmonising the hydrogen refuelling business in Europe – final, Element Energy

Over the course of the project, key drivers for improvement of the overall availability levels have been identified. However, unforeseen events have also brought additional challenges

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Causes of HRS downtime

- H2ME has led to significant improvements in HRS availability, setting new ‘state-of-the-art’ records for performance in comparison to previous demonstration projects. Key improvements can be attributed to:
    - **Deployment of ‘state-of-the-art’ technology** – H2ME has helped trigger the deployment of a new generation of HRS, using equipment that has been rigorously tested and developed over multiple prototypes and deployments.
    - **Improvements in station design** (e.g., reviewing the placement of HRS sensors on equipment to reduce instances of faulty readings or end user damage).
    - **Improved management of the station to reduce response times**, e.g., training local staff, storing spare parts near or at the HRS, increasing remote monitoring and introducing preventive maintenance.
    - **Sharing of HRS operator experiences**, including the requirement for preventative scheduled maintenance.
    - **Maturing of the HRS supply chain**, ensured thanks to scaling up of the sector.
- It is, however, necessary to highlight that **progress is still required to reach the level needed to see hydrogen mobility develop further.**
- Additionally, unexpected external events, such as the Covid-19 crisis, have impacted critical aspects of the development of the industry (e.g., supply chain and availability of raw materials[1]).
    - The **impact of the Covid-19 pandemic on the availability level** of the project’s stations has not been **homogeneous** across locations.
    - On the one hand, anecdotical evidence from partners strongly suggested that there was, for some stations, a **correlation between the Covid-19 crisis and the lower station availability** due to two main factors: the lack of maintenance personnel and lack of parts because of the global supply chain disruption for key components and materials.
    - On the other hand, not all station experienced the same Covid-19 impact on their availability. This was the case with the German HRS network. This may be due to a **scaling effect of the network** combined with a **well-established value chain at the national level**.

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The strategies implemented regarding HRS deployments and the utilisation levels varied from one region to another

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Utilisation across the project

- The utilisation, or loading, of a station is a function of the **average daily demand for hydrogen against the total daily dispensing capacity of a station**. It therefore provides a standard figure for usage across stations of different capacities.
- Across the H2ME project, utilisation of HRS varies dramatically from <2% at stations which have no 'linked demand' (e.g., motorway services between cities), up to 82% in Q1 2023. High levels of utilisation (i.e., >30%) are observed in locations where high mileage captive fleets have been introduced to provide 'anchor demands' at stations. This concerns 4 stations in Q1 2023.
- When considering all stations within the project, **average utilisation was approximately 11.62% in Q1 2023**. Whilst this remains low, it is important to note that:
  - Many stations have been **designed with higher capacities than originally required to support future deployments**; many are currently capable of dispensing 200kg of hydrogen per day, equivalent to over 40 full FCEV refuels from empty*.
  - The **uptake of FCEVs outside the H2ME project has been slower than expected**. Most HRS have yet to cater to significant demands from FCEV deployments outside of the H2ME project.
  - **Utilisation of the stations has been influenced by early national roll-out strategies for hydrogen** (see table (right) for more detail).
  - Load levels are **expected to grow** as some of the stations start **accommodating for other types of vehicles** (i.e., HDVs).
  - The overall load levels have increased over the past years.

Region	Strategy for HRS network development[1]
Germany	Extensive national coverage with major cities as 'hubs'. Unconditional plans to deploy 100 HRS by 2021, irrespective of the number of vehicles or demand in the area.
France	Local/regional clusters of HRS linked to FCEV demand (captive fleet approach) to guarantee station utilisation and de-risk early HRS investments.
UK	Regional (south-east) focus to build 'H2 hubs' around emerging demand hotspots in, and around, London.
Nordic region	Network to allow long distance mobility across the region. Deployments linked to vehicles sales which leads to a city focus.

Based on a standard FCEV tank size of 5kg

1 – Hydrogen mobility strategies, 2020, H2ME (1) Deliverable 5.13. Element Energy

Despite low levels of utilisation across the HRS in the project, improvements have been observed, especially as sites recovered from the Covid-19 period

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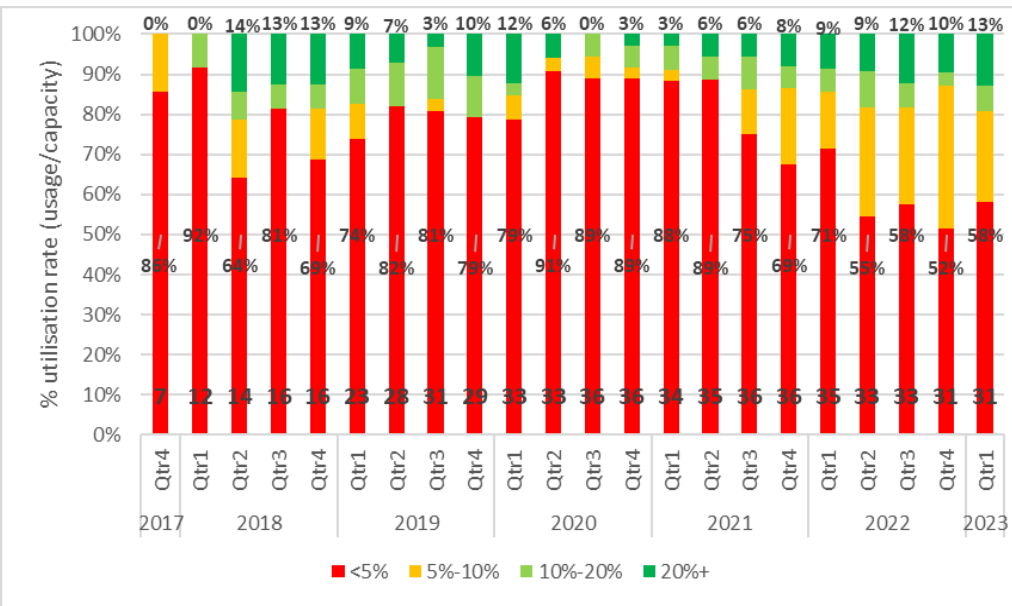
Evolution of HRS utilisation

- Overall, the utilisation of the stations remains lower than expected. Most stations remain at a utilisation well **below 20%**. In **Q1 2023**, only **13%** of the H2ME and H2ME-2 stations had utilisation **above 20%** (the expected end objective for all stations in the project)**.** This is primarily due to the slow rollout of vehicles.
  - There was also a significant impact due to the **COVID-19 crisis**, which substantially reduced the operation of some fleets.
- Since the end of COVID-19 restriction, there has been a steady increase in station utilisation, which **seems to confirm that vehicle deployment is being supported by a better-established network of stations**.
- The deployment of fleets of vehicles has had a **significant impact on the volume of hydrogen dispensed** across HRS in H2ME (see next slide).

H2ME HRS utilisation rate[1]



Higher level of HRS with utilisation rates above 20% as there were fewer HRS overall and the two Paris stations and the two London ones formed a much larger portion of the H2ME total

Covid-19 pandemic

Post-Covid: Steady increase in the number of HRS with utilisation rates above 10% and decrease in the stations below 5%

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1- Internal project data, Cenex (data up to Q1 2023).

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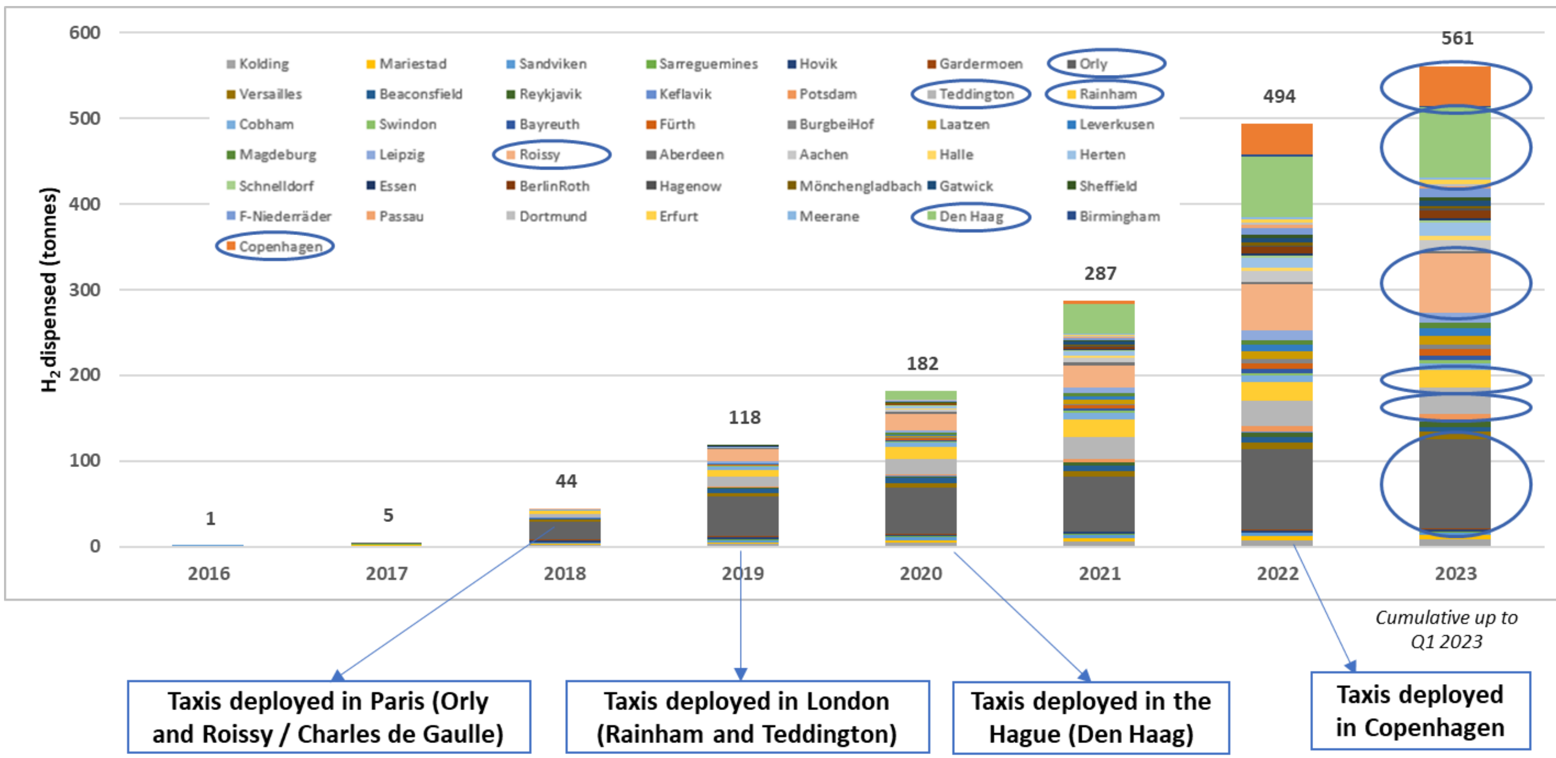
The hydrogen dispensed across the H2ME HRS has significantly increased since the start of the project, driven mainly by 6 stations

Cases of higher utilised stations

- Of the 561,000 kg of hydrogen dispensed as of March 2023, **more than 60% has been distributed by 6 stations** which are frequently used by the fleets: **Orly (Paris, FR), Rainham (London, UK), Teddington (London, UK), Roissy/Charles de Gaulle (Paris, FR), Den Haag (NL), Copenhagen (DK)**

H2ME HRS cumulative hydrogen dispensed



Source: Internal project data, Cenex (data up to Q1 2023).
** Exception for the Hague HRS.*

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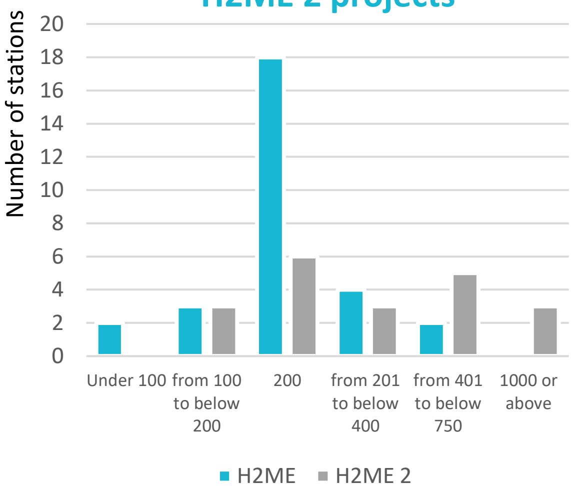
Additionally, while HRS utilisation in the project remain low, trends in the project show improvements and positive utilisation cases

Trends in HRS deployment strategies

- **Despite the low utilisation of HRS, the project data shows interesting trends** which indicate the evolution of operators' strategies to maximise utilisation, including targeting fleet operators and planning for multi-use or heavy-duty focused deployments.

Station capacity (kg/day) by project

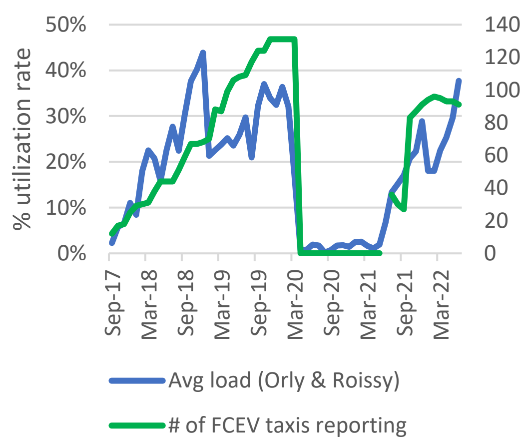
Evolution between H2ME 1 and H2ME 2 projects



The **daily capacity of stations has increased** over time. This reflects the increase in multi-use stations (**co-location of different vehicles types**) and fleet deployments

Utilisation of HRS near taxi fleets

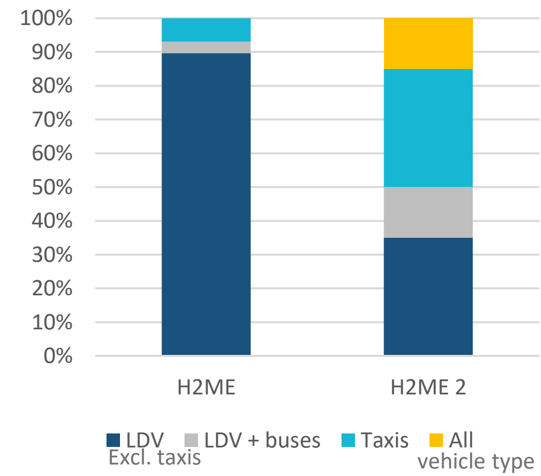
France: Orly and Roissy HRS usage example



The stations with higher levels of utilisation and H2 dispensed are those **located where FCEV taxis are deployed**. Many new HRS are centred around a main 'anchor load' fleet demand

Type of vehicle using the HRSs

Main vehicle type using or planned for H2ME 1 and H2ME 2 HRS



Taxis have become the main vehicle type to use stations deployed in H2ME. There is a shift for station providers to plan for multimodal stations including bus or HDV offtake.

Source: H2ME Emerging Conclusions 2020 (reviewed March 2021), Element Energy; Internal project data, Cenex (data up to Q2 2022)

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Since the start of the H2ME projects, the average HRS utilisation level has increased, driven by stations with a common characteristic of the presence of high mileage light duty vehicle fleets

Demand at high utilisation stations

- The overall utilisation levels observed throughout the project have been **below expectations. This is mainly explained by the lower uptake of FCEVs compared to the forecasts at the beginning of H2ME and H2ME-2.** Nevertheless, **improvements in the average utilisation levels** have been observed and several stations have proven the possibility for HRS to **target the correct demand pool to reach moderate to high levels of utilisation**.
- In **Q1 2023**, the average utilisation level was of **11.62%**. This was the highest average observed since the start of the projects.
- 5 stations (Herten, Copenhagen, Den Hague, Roissy, and Orly) reached levels of utilisation above 20% during Q1 2023 and 9 HRS reached levels close to 20% over the course of the project. Only 2 stations across the project reached utilisation levels above 50% (Paris Orly and Paris Roissy), with one station, The Hague getting very close to 50% in Q1 2023.
  - The majority of these stations share the common point that they are **in areas where high mileage light duty vehicles fleets,** such as taxis or vehicles for hire, **are deployed**.
- Among these stations which have been able to reach moderate to high levels of utilisation during the project, several have been in operation since 2017/2018 and are part of the legacy stations deployed in the project:
  - In Paris, the **Orly and Roissy Charles de Gaulle HRS have responded well to increased utilisation, primarily from the deployment of Hype taxis.** The Orly HRS experienced some of the highest average utilisation levels seen across passenger car HRS in Europe (>82% in Q1 2023). This has led to **high driver confidence in the technology** evidenced through project survey results. Newer stations operated by HysetCo (some outside the H2ME project) have recently opened (between 2021 and 2023). They are situated closer to the city centre and activity areas of the taxis leading to high utilisation. Additionally, the Porte de Saint Cloud station has been designed specifically for high utilisation with a capacity of 1t/day.
  - In London, 4 of the H2ME stations experienced utilisation levels close or higher than 20% since the start of the project. Two sites in particular, Teddington and Rainham, experienced very high loads, with days reaching >80%. The sites relied significantly on the deployment of the Green Tomato Cars (GTC) and of the Metropolitan Police Service (MPS). The sites proved their ability to adapt to increased demand and to implement the lessons learned in early stages of commissioning to reduce downtime. Nevertheless, the decommissioning of the Green Tomato Car between April and October 2022 and the change of strategy of ITM Power and Motivefuels announced in spring 2023 led to the eventual shutdown of the stations.

More recently commissioned stations at The Hague and Copenhagen have also experienced strong utilisation, thanks to the deployment of large FCEV fleets

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Demand at high utilisation stations

- More recently commissioned stations and hydrogen mobility hubs have been developing since 2020 at the Hague and Copenhagen. These two sites also have the characteristic of having large fleets of high mileage vehicles deployed in their vicinity.
  - In The Hague, **utilisation steadily increased to >49% daily average at the end of Q1 2023**. The **deployment of high mileage taxi vehicles (Noot taxis) has played a key role**. This situation has caused a steep learning curve for the HRS equipment supplier, enabling them to implement their lessons learned into the next generation of their equipment. This increase in daily average load combined with the increase in the average refuelling amount per refuelling event reflects the confidence that users have in fuel cell technology for their vehicles and day-to-day use.
    - However, in 2021, news regarding the ban / discouragement for hydrogen fuelled vehicles to be accepted in the next zero-emission tenders for 'target group transport' in the city showed that having all the favourable conditions gathered to have a high performing HRS alone is insufficient without willingness from local authorities to encourage the deployment of FCEVs.
  - In Copenhagen, the utilisation steadily increased to **37% in Q1 2023**. This followed the **increase in the number of FCEV taxis put in operation**. The station is, as with other high utilisation stations, **strategically situated** close to the city centre. Additionally, the growing fleet of DRIVR taxis provides the station with a baseload demand. The Danish government also has ambitions for all taxis be zero-emission by 2030 (and all new taxis to be zero-emission by 2025).
    - However, Everfuel experienced issues that led to the closure of the site and pause of operation in the second half of 2023. First, issues were identified with the trailer fleet which had to be grounded for safety reasons. Secondly, accessibility of hydrogen was limited with hydrogen sourced from Germany and impacted the economic case for the station. During Everfuel's Q2 2023 Earnings Presentation, the company presented its strategy realignment: a reviewed focus on scaling green hydrogen production and on prioritising the development of a hydrogen refuelling network for HDVs. In line with this announcement, the operations of several station were discontinued or paused.

Considering the lower-than-expected level of deployment of light duty vehicles, several HRS operators foresee the heavy-duty segment as the new main source of demand for their stations

Demand at high utilisation stations

- **Most of the clusters developed their HRS network strategy based on (expected) demand of FCEVs**. As previously mentioned, despite having enabled important increases in utilisation at some sites, the light duty FCEV deployments outside of the project were lower than anticipated. The technology to accommodate high amounts of hydrogen distribution is available but must be supplemented by demand to be economically viable for HRS suppliers and operators.
- Therefore, many operators today are increasingly looking to the **heavy-duty segment** to increase in amounts of hydrogen dispensed per station.
  - In **Germany**, the operator (Hydrogen Mobility Deutschland) which focused in a first stage on having a nationwide coverage with no particular focus on concentrated demand areas is now moving to the next phase of its strategy: **increasing the capacities of stations implemented in strategic locations and deploying new stations in areas where the level of hydrogen demand is high**. This high demand is expected to be mainly driven by **trucks and buses** which have larger capacity tanks and therefore refuel larger quantities at each station visit. Whereas previously the stations were primarily 700-bar stations established to cater for LDVs, the new stations will have 350-bar refuelling capabilities to ensure accessibility for HDVs.
- **Accommodating a station for several types of vehicles** to refuel is also key to ensure **diversified** demand. This entails securing sufficient hydrogen, having an adequate storage system, delivering hydrogen at the correct pressure for different vehicle types to refuel, etc. Indeed, relying on only one source of demand / one client can expose the HRS to unstable demand patterns.
- Nevertheless, **not all operators plan on developing stations aimed at accommodating HDVs**. For instance, HYPEAsset and HysetCo's strategies are focused on delivering a global light duty mobility service which includes the demand side (vehicles) and the supply side (the development of the infrastructure). This provides the companies with an understanding of their utilisation and enables them to develop stations with a primary focus on delivering sufficient hydrogen to their own taxi fleets.

Overall, a key lesson from the projects is the **importance of demand in the development of stable and highly-utilised HRS** networks. It must be **strong** (high-levels of hydrogen required – e.g., with heavy-duty vehicles)**, stable** (regular refuelling activities) **and diversified** (to ensure that in the event of an unforeseen stop of activity of one source (e.g., a taxi fleet), the station will still have demand).

In addition to securing demand, the success of high utilisation stations will depend on their capacity to meet high levels of availability and performance

Hydrogen Mobility Europe

Availability and performance of high utilisation stations

- Over the course of the project (until Q1 2023), the **average availability of the stations was of 93.7**% (below the project target of >98%). High utilisation stations must demonstrate high availability to provide the necessary level of service to customers.
- **HRS availability has been evidenced to improve with increasing utilisation** across the project. Increased utilisation can be evidenced to have both a **short- and long-term impact on HRS availability**.
  - On a short timescale, HRS experience a '**teething phase**' when the station is newly commissioned, and the hydrogen dispensed is low and during which availability levels are often low. Following the teething phase, the availability levels of HRS tend to increase as initial parts failures and software malfunctions are addressed by the operator and learnings are factored into station design and operation.
  - Cumulative hydrogen dispensed over a longer period is also seen to have a positive impact on station availability and this is attributed to a) individual **components performing better with regular use** and b) **more service support** and attention being given to better utilised (and hence higher revenue) stations. HRS now not only need to be **high performing but also be a productive business for the operator**.
- However, the stations within the project have experienced issues which contributed to their lower levels of availability. Common reasons for downtime identified in the project include **failures with compressors, chillers/precooling and fuelling dispensers in Q1 2023. These accounted for 63% of the downtimes registered**. Whilst these parts undergo further technical development, many HRS operators have classed them as 'high-risk' components and stock spare parts at, or local to, the HRS to mitigate downtime.
- Beyond availability, the **performance** (indicator - seen as the percentage of successful refuels) of high utilisation stations **must be high as well**. FCEVs (all vehicles included) have a greater range compared to BEVs, making them better suited to some specific use cases. However, this advantage may be negated if the HRS are unable to provide fuel refuels in one event to the vehicles.
- Through the different case studies of the most utilised stations across the project, several key lessons learned around designing HRS to minimise downtime and to ensure high availability under high utilisation have been gathered. These are described in the following pages.

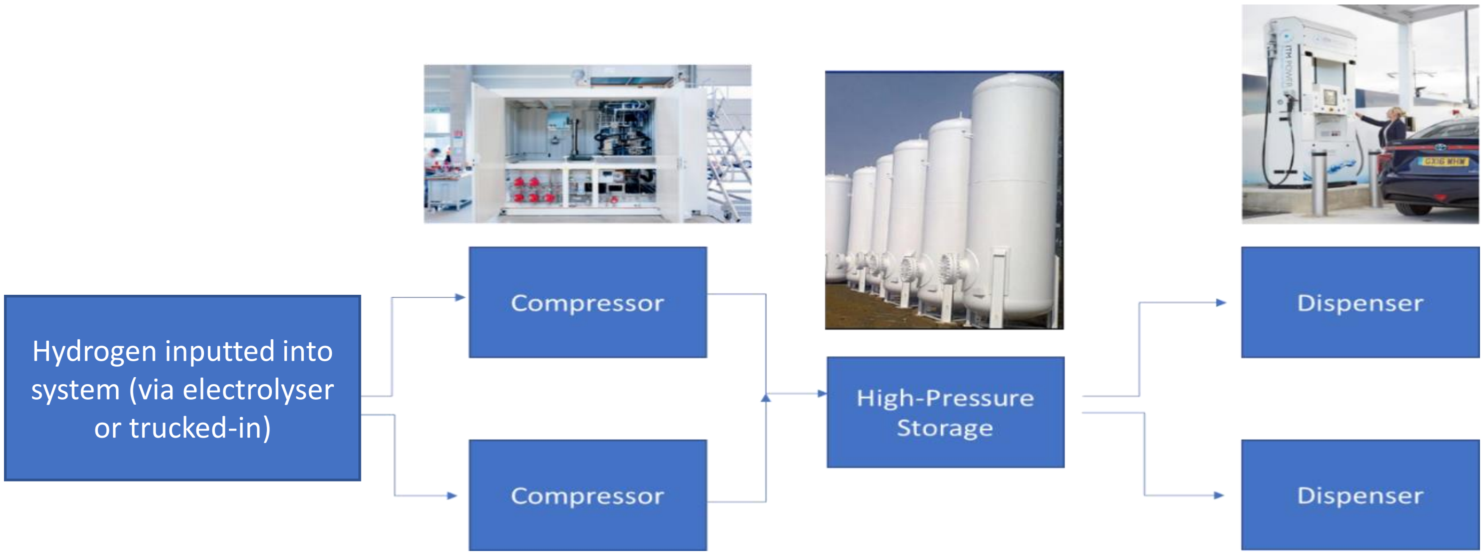
Design and Technical improvements were identified to reduce downtime and improve availability

Hydrogen Mobility Europe

Reducing downtime

Design and technical improvements – System redundancy

- Future HRS designs should **include redundancy into process systems** (i.e., dual modules) to withstand isolated failures or maintenance without downtime.
    - Many HRS within H2ME are designed with a single process line so **a single failure will cause downtime** of the station.
    - The example of the Copenhagen station is a good illustration that H2ME2 HRS have learned from past projects and observations and are implementing this approach to good effect. Despite both modules having varying availability, the overall station availability was greater than 98%.
    - However, implementing redundancy does increase costs and can make the economic case for a station more challenging.



Simplified example of station designed with n+1 redundancy

Design and Technical improvements were identified to reduce downtime and improve availability (contd.)

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Reducing downtime

Design and technical improvements – On-site storage and compressor capacity

- **Upgrading the station to increase the capacity of onsite high-pressure storage tanks can reduce downtime** and help adapt to increasing demand. On-site storage is often **limited to a day's supply**, meaning that any failures or maintenance beyond this time result in station downtime. **Increasing the volume of high-pressure storage available on-site is therefore often viewed as an effective way to reduce downtime** caused by production (if on-site electrolyser) or delivery (if hydrogen is trucked-in).
  - However, increasing the volume of on-site hydrogen storage does pose challenges and its feasibility will depend on:
    - **The generation of the asset –** if the station is a first-generation design, it may be cost effective to decommission it and rebuild a new one designed to dispense larger amounts of hydrogen.
    - **The size of the site –** hydrogen at HRS is often stored in large metal or composite tanks or tubes. These can be designed to minimise the footprint of storage on the HRS (i.e., placed vertically, rather than horizontally) but will still require significant space at the station (especially when safety distances are included).
    - **Relevant safety distances –** due to the pressure at which hydrogen is stored, tanks or tubes often require a significant distance to mitigate the impact of damage if an incident/failure occurred with the station (i.e., gas release, gas explosion, fire, etc.). Safety distances are determined by codes and standards which vary between countries, but these are often based on standards defined by the International Organisation for Standardization (ISO 19880-1), the European Industrial Gases Association and the National Fire Protection Association.
    - **Approval from local authorities –** increasing hydrogen storage on-site may require approval from local authorities. This can often be a long process as local authorities are often inexperienced in dealing with hydrogen and therefore must be convinced of the safety of the technology.
    - **Approval from landlords –** HRS operators must seek landlord approval for the installation of additional high-pressure storage on-site. This can be a long process and hard to secure.
  - High pressure hydrogen storage also comes at a **significant cost to HRS operators, but this can be mitigated by consistently** high utilisation to allow revenues to cover the cost premium.

Design and Technical improvements were identified to reduce downtime and improve availability (cont'd)

Hydrogen Mobility Europe

Reducing downtime

Design and technical improvements – back-to-back refuelling, back-up supply, standardisation, lower-pressure stations

- The **back-to-back refuelling performance of the station** is a key technical consideration as the demand grows. It is important for the operators/suppliers to understand the target vehicle type for back-to-back refuelling as the setup and requirements for HRS will differ.
- A **back-up hydrogen supply chain** is essential in securing high availability of stations. This prepares the site in case of onsite production malfunctions or failed delivery.
  - Due to the **lack of maturity of the hydrogen supply chain**, many HRS operators **do not have significant back-up hydrogen production facilities**. This often means extended HRS downtime.
  - Common approaches of HRS operators today include:
    - **Hydrogen produced for local industrial purposes can be trucked to the station** as an emergency back-up.
    - HRS operators with large on-site electrolysers can use surplus capacity to potentially provide emergency back-up. However, the hydrogen is not often transported to the HRS experiencing downtime due to high costs and logistical difficulty of the process.
  - Overall, **these back-up solutions can entail increased CAPEX and/or OPEX**. This is why HRS operators agree that it is essential to reach and maintain high levels of utilisation and of reliability of the stations to ensure that such downtime issues are avoided. However, in the meantime, securing back-up solutions remain a key factor for ensuring higher station availability.
- **Standardised, modular designs for HRS** could lead to improved availability as best practices can be employed for installing and operating the station. Efficiencies can also be achieved in HRS management as spares could be easily sourced and technicians could be trained to maintain a network of HRS to reduce response times.
- Over the various trial phases, some operators have observed that **700-bar systems were more prone to technical issues** (due to the higher-pressure requirements). Operators such as H2MDE are therefore moving towards 350-bar **HRS with a 700-bar booster.**

Station Operational Management improvements were also identified to reduce downtime and improve availability

Reducing downtime

Management improvements

- **Ensure local (in-country) availability of spare parts for 'high-risk' components.** This is essential to avoid extended downtimes stemming from supply chain issues rather than technical repair difficulties.
- **Train technicians** (in-house or in-country) to address issues at the HRS. This ensures that most technical issues can be addressed rapidly (remotely or by the local maintenance staff) to avoid long station downtime.
- **Conduct rigorous off-site and on-site testing of stations**. This could include third party testing of the HRS before commissioning.
- **Ensure robust, centralised, and constant data monitoring systems** are in place with dedicated employees for analysis of data.
- Establish formalised maintenance procedures and contracts with defined responsibilities and timescales which reflect targeted availability (>98%).
- Ensure that **all safety measures are in place prior to the commissioning of the station**.

User confidence in the technology and customer experience will play a central role for hydrogen mobility to be adopted more widely

Hydrogen Mobility Europe

Customer experience of high utilisation stations

- As previously shown, **demand** is critical to enable high utilisation. Additionally, the stations catering for this demand must **provide high availability and performance** to support the development of hydrogen as one of the pillars of zero tailpipe emission mobility.
- **In addition, user-friendliness and trustworthiness of the station** are also essential for high utilisation stations. Trustworthiness assesses the number of days the station operated without any issues and helps quantify customer satisfaction.
- Improvements to customer satisfaction and confidence can be enabled by:
  - **Using data** (cross-checking downtime with video surveillance) **and/or customer feedback to improve user-friendliness** of stations to help decrease user error as a cause of downtime.
  - **Good communication with the customers on the availability status of the station.** This can be done through the implementation of an easy access to the live availability status of stations (e.g., H2Live or Whatsapp groups).
  - **Implementing 24/7 customer helplines** at HRS can also help ensure that any technical issues are identified quickly.
- Customer confidence in a station's capability to meet their needs can also be observed through the **average amount of hydrogen dispensed per refuelling**. Low confidence may translate into **top-ups** rather than using tank range to a greater extent before refuelling.

Conclusions : ensure high availability under high utilisation

High utilisation of stations depends on mainly 2 factors

	DEMAND	AVAILABILITY
Status in project	The **deployment of FCEV beyond the project has been slower than anticipated**, hence restricting the demand pool of established HRS and limiting the possibility for some stations to be highly utilised.	Most of the stations deployed in the project were **first-generation demonstration HRS**. **Technical issues** have been reported to the projects which in turn **affected the overall availability** of the station and the ability for users to refuel their vehicles.
Next steps	Most station operators within the project have announced their willingness to **focus on the development of their HRS network to cater for Heavy Duty Vehicles**. Only in specific cases (i.e., Paris) is the operator's strategy to continue focusing on Light Duty Vehicles as the key source of demand. In the case of Paris, the fleet owner is also the HRS operator with visibility on demand from its drivers and is confident in the continued stability of this demand.	The **technology is expected to mature** as manufacturers gain experience and apply the lessons learned in these early demonstration projects. HRS operators have also been able to gather **key learnings which will support the development of strategies to mitigate technical issues of their stations to maintain high levels of availability**.

Contents

Despite low average levels of utilisation, several stations and networks of HRS have achieved medium to high levels of utilisation and were therefore studied to draw key learnings

Hydrogen Mobility Europe

Overview of case studies

- The majority of HRS deployed through the H2ME project have not achieved high utilisation rates. Therefore, in order to extract useful learnings from the program, interim reports* on the topic of *HRS performance under high utilisation* have focused on the case studies for stations which have achieved utilisation rates greater than 20% of the installed station capacity or networks that are preparing their station for higher levels of utilisation. The reports cover:
  1. Which **factors helped the stations achieve moderate/high levels of utilisation** and which **factors affected utilisation** throughout the project.
  2. The links between **high utilisation and HRS availability**.
  3. Key **lessons learned** and **recommendations** for future HRS to ensure the success of high utilisation stations.

- Most of the stations which began experiencing moderate to high levels of utilisation were deployed next to or in parallel of a fuel cell electric vehicle fleet. Thanks to their high mileage, FCEV fleets can consume large quantities of hydrogen and can operate effectively using a small cluster of stations due to their predictable operating patterns. The use case can therefore provide a significant anchor demand for HRS and can help stabilise the business case for the operators.

- The case studies focused on the following sites / networks:
  - German HRS network
  - The Hague, NL
  - Paris HRS network, FR
  - London HRS network (Teddington, Rainham), UK
  - Copenhagen, DK

The following slides concisely present the different sites / networks studied and highlight the general insights identified from the focus on these stations.

Links to the reports: https://h2me.eu/publications/technical-performance-of-hrs-under-high-utilisation-and-recommendations/

Each station / network has its specificities; however, a common point can be identified for most of these HRS: a high-mileage fleet of FCEV was deployed nearby, providing a source of demand for hydrogen

Hydrogen Mobility Europe

Overview of case studies (1/3)

The Hague, NL

- *Station Operator*: Kerkhof – Orange gas
- Utilisation in Q1 2023: **49%**

Specificity: A fleet of 40 FCEV fleet is deployed in the proximity of the station under the taxi company Noot, therefore supplying the HRS with a steady demand for hydrogen. 17 of these vehicles were deployed under the H2ME-2 project.

The Hague's HRS is Resato's first public HRS and has therefore enabled the supplier to gain immense knowledge into optimising the setup and overall management of such projects while aiming to continue offering HRS capable of answering to high levels of utilisation. The Hague HRS managed to maintain high levels of availability and performance (c. 98% for both at the end of 2022).

In November 2021, the Municipality of the Hague published the new taxi tender which stated that given that hydrogen was not 'green' enough, FCEV would be banned/discouraged from the next zero-emission tenders for 'target group transport'. This ban does not affect the current fleet of FCEV taxis in operation but brings uncertainty regarding the evolution of the hydrogen demand landscape in the area, especially as no HDVs nor buses are yet deployed. This highlights the importance of securing the support from local authorities to ensure the long-term success of an HRS.

Paris, FR (Roissy, Orly, Porte de la Chapelle)

- *Station Operator*: HysetCo
- Utilisation in Q1 2023: **38%** average utilisation of the Roissy and Orly HRS. Porte de la Chapelle – utilisation peak in Q4 2022: **61%.** The levels for these historical stations reached levels above 90% before the inauguration of the Porte de Saint Cloud (1t/day capacity HRS).

Specificity: A fleet of over 340 Hype fuel cell taxis is deployed in Paris. This fleet is expected to continue growing in the upcoming years. Additionally, independent taxi drivers operating hydrogen fuel cell vehicles leased by HysetCo form a growing share of the FCEV drivers in Paris and users of the HRS (c. 150 in July 2023). With regards to HRS, both Hype and HysetCo plan to continue deploying and operating stations (26 by the end of 2025 and 12 by the end of 2024 respectively) to answer to the growing needs from their fleets.

Despite some successful deployments of HRS with high demands for hydrogen thanks to the presence of high mileage vehicle fleets, the business strategy of the operators has also evolved since the start of the trial

Overview of case studies (2/3)

London, UK (Teddington & Rainham)

- *Station Operator*: ITM Power / Motive Fuels
- Utilisation peak in Q4 2021: **33%** (average utilisation for both stations)

Specificity: Two main sources of hydrogen demand used to be deployed in the London area: the Green Tomato Car private car hire fleet, which represent more than 50 vehicles, and the Metropolitan Police Service vehicles.

Status to date: All the stations operated by ITM Power (and then Motive Fuels) in London (i.e., 5 out of the 6 stations in the project) are now all closed since spring 2023. This followed a review of the assets which led to the conclusion that some of the strategies adopted in the early years were no longer suited to market needs and the current and foreseeable demand levels made the economic case for continuing operations challenging.

Motive Fuels has therefore decided to focus its future developments on stations dedicated to heavy-duty vehicles.

Copenhagen, DK

- *Station Operator*: Everfuel
- Utilisation in Q1 2023: **37%**

Specificity: A fleet of approximately 100 fuel cell taxis (DRIVR) is deployed in the proximity of the station, therefore supplying it with a steady demand for hydrogen. The setup of the Copenhagen station (2 modules and 3 dispensers) has enabled the HRS to achieve high levels of availability throughout the period of operation.

Status to date: Currently, the station is not dispensing hydrogen. Everfuel experienced constraints that led to the closure of the site and pause of operation in the second half of 2023. First, issues were identified with the trailer fleet which had to be grounded for safety reasons. Secondly, accessibility of hydrogen was limited with hydrogen sourced from Germany and impacted the economic case for the station. During Everfuel's Q2 2023 Earnings Presentation, the company presented its strategy realignment: a reviewed focus on scaling green hydrogen production and on prioritising the development of a hydrogen refuelling network for HDVs. In line with this announcement, the operations of several station were discontinued or paused.

Beyond the H2ME-2 site specific analysis, the German HRS network offers an insightful view into the strategy and management of a network preparing itself to answer to an increase in utilisation through a focus on HDVs and buses

Overview of case studies (3/3)

German HRS network
• *Station Operator*: Hydrogen Mobility Deutschland • Average network utilisation in Q1 2023: **5.5%.** Stations ranging from <1% to 22.8%. **Specificity**: The current levels of utilisation remain low. This is explained as the network was developed following a strategy of national coverage. As this phase has been completed, the next step in the operator's strategy is to focus on deploying 350-bar stations to cater for HDVs and buses, hence increasing the utilisation of the concerned stations and of the network overall. To successfully achieve these deployments, the stations must provide high levels of availability and performance. Specific areas of focus have also been identified by the operator as critical to establish a reliable and sustainable network of high utilisation stations: the hydrogen supply (storage and source) and communication with station users.

Beyond the site / network analysis, new indicators have also been developed to assess the customer experience at stations, critical for high utilisation stations

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Availability and trustworthiness indicators

- As the technology develops to meet a wider range of customers, it will be increasingly important to focus on the **customer perspective** for whom it could be argued a station is available when they are able to refuel. To support the preparation for a wider rollout, Toyota Motor Europe have developed two KPIs to understand **availability as experienced by customers**. These are the **Availability and Trustworthiness indicators.**

<u>Availability</u>

- In this availability KPI, **station shutdown due to maintenance is included** as it impacts the customers' capacity to refuel their vehicles.
- Downtime caused by the lack of hydrogen supply is also taken into consideration.
- The availability indicator looks only at the station's operational status.

TOYOTA

<u>Trustworthiness</u>

- This indicator **reflects the expected level of satisfaction of the customer for a specific site.**
- This is assessed by monitoring the number of days the station operated <u>without any issues.</u>
- The types of issues considered do not necessarily have an impact on the availability KPI. They can be of various nature: station unit or non-station unit related such as issues with the payment system or with hydrogen supply.

- The aggregation of data and a first level analysis have already allowed greater understanding on the refuelling experiences of customers at the sites. There are several cases of **high station availability but low trustworthiness.** This may **indicate a poorer customer experience.**
  - Such cases can reflect **issues beyond the functionality of the station unit itself** (e.g., the payment system down, insufficient hydrogen supply, etc.). However, these are currently difficult to track.
  - In other cases, this situation can also highlight a **very efficient response from the operator** in dealing with station unit issues which does not impact the overall availability as there is no overall station shutdown. Despite these efforts and the responsiveness of the operator, the low level of trustworthiness highlights that the recurring issues and inconveniences at the station impact the overall customer experience (and at times their ability to refuel at an "available" station.

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Hydrogen Mobility Europe

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