Technical performance of HRS under high utilisation and recommendations (WP5, Task 5.2)

Deliverable 5.36	Technical performance of HRS under high utilisation and recommendations - Interim 3
Authors	Element Energy: Alex Stewart, Lisa Ruf, Magali Senaux Cenex: Peter Speers
Document Status	Final (March 2023)
Dissemination Level	Public

A project co-funded by
under the Grant Agreement n.671438

Co-funded by the European Union

Report produced by elementenergy an ERM Group company

Contents

If hydrogen is expected to play a significant role in transport, extensive and reliable networks of hydrogen refuelling stations are required

Context of this report

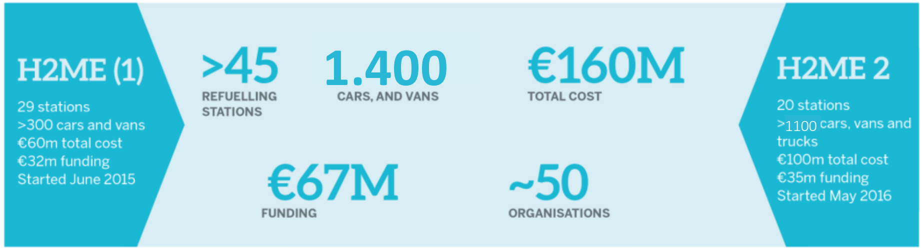
- Numerous governments across Europe have committed to limiting increases in global temperatures by achieving net zero carbon emissions by 2050. As part of this, there is a focus on reducing emissions in the transport sector which is estimated to be responsible for **over 20% of Europe's greenhouse gas emissions**[1].
- **Road transport is the largest emitter** in 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.
- There is a growing consensus that FCEVs will play a significant role in the future transport sector as they can provide **similar operational flexibility to petrol and diesel vehicles,** with long ranges and quick refuelling times. The hydrogen used to power the vehicle can also be **produced in large volumes through zero or low carbon production methods.** When electrolysis is used, local or national energy systems can also benefit as hydrogen can be used to **provide flexibility services for energy markets** struggling with the variability of renewable energy supply.
- However, hydrogen mobility is not yet fully commercialised. To date, around **3,700 light FCEV (passenger cars and vans) are operational** on roads in Europe. There is an increase in the number of heavy-duty vehicles and buses as well: currently more than 300. These vehicles utilize a limited network of around **200 hydrogen refuelling stations*** (HRS). Most deployments have required support from funded demonstration projects to overcome initial market barriers. This has helped evidence the readiness of the technology for further scale-up, but further technology and market improvements are required before wide-scale commercial roll-out.
- One key area requiring improvement is hydrogen refuelling infrastructure. An **extensive network of hydrogen refuelling stations (HRS)** will be required to allow unfettered movement of vehicles across Europe, and **improvements in the performance of HRS** need to be achieved to ensure 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
** 700 bar and 350 bar HRS for cars*

H2ME lays the foundations for the first truly pan-European network of hydrogen refuelling stations

Hydrogen Mobility Europe

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



Clean Hydrogen Partnership

Co-funded by the European Union

- The project collates a **vast array of qualitative and quantitative data** from vehicles, hydrogen refuelling stations, public/private stakeholders and end users. This allows the consortium to analyse the performance of the technology, investigate areas for improvements, discuss barriers to uptake and propose recommendations on how to scale up the future roll-out of FCEVs and HRS.
- Previous H2ME reports have identified a variety of barriers to roll-out, but a **consistent challenge has been the deployment and operation of the HRS networks**. This has led to project calls for:
  - Increased **rate of deployment** of new HRS across Europe.
  - Improved **availability and performance** of existing and future HRS.

This report provides an update on the technical performance of HRS, with case studies on stations experiencing higher than average demands

Hydrogen Mobility Europe

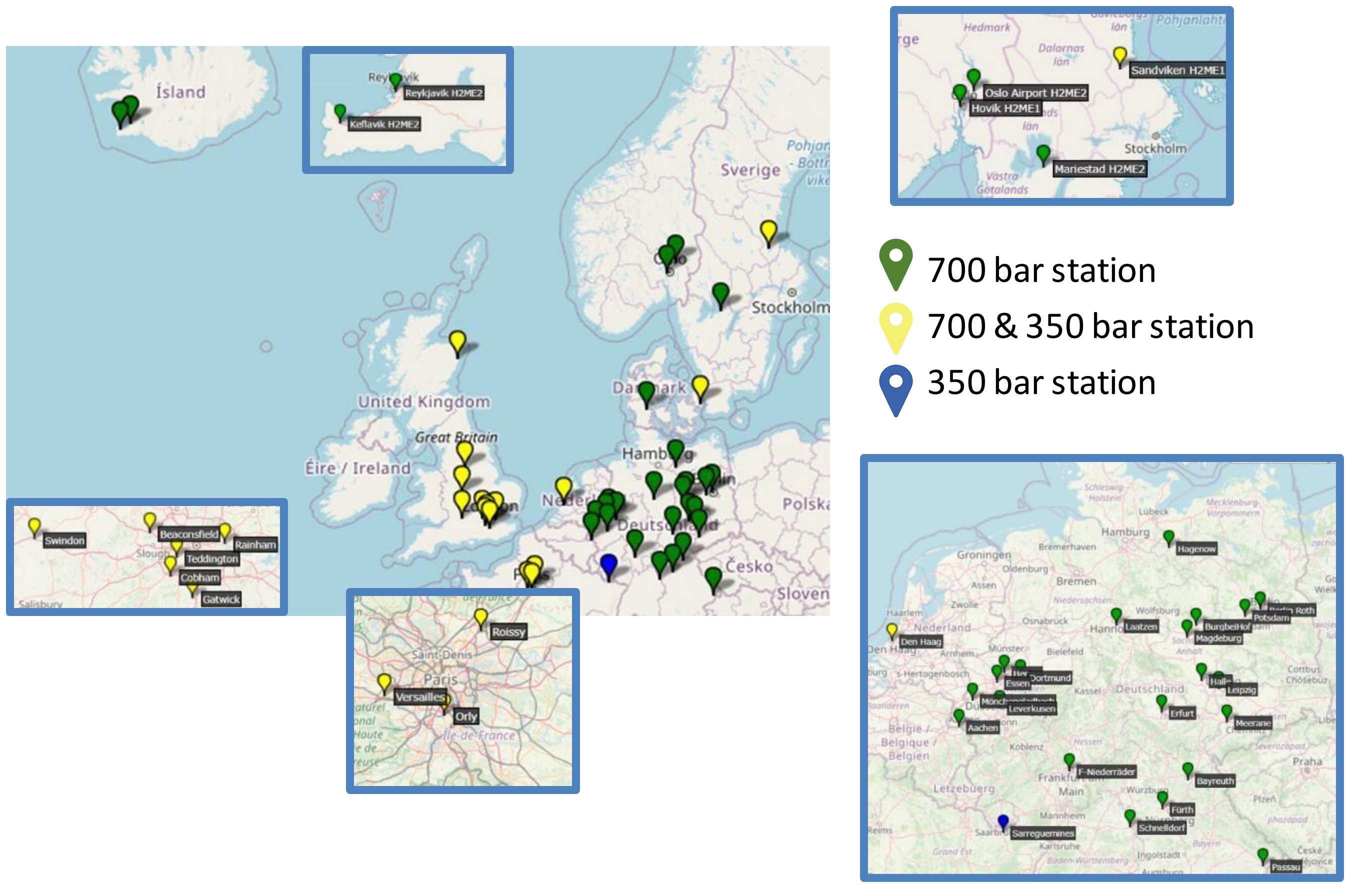
Overview of this report

- This report aims to give an **overview of the performance and utilisation of HRS** in the H2ME project, providing insights into the specific challenges stations are facing with increasing demand.
- Within the H2ME project, **few stations are experiencing high utilisation** as FCEV deployment in Europe has not developed as fast as forecasted when the project was commissioned. Most stations are therefore relying on hydrogen demand created by the FCEVs deployed directly by H2ME, or other similar European or national projects.
- This report is therefore **not able to undertake a detailed analysis** on the performance of stations under high utilisation **for a large sample of sites** , or to anonymise commercially sensitive data from HRS operators. The analysis in this report will however contribute to **draw preliminary conclusions on the relationship between utilisation and station performance**.
- To achieve this, the report will outline some of the **key performance and utilisation trends** seen across the project. Case studies will also be presented on cities where HRS have begun to encounter **moderate levels of utilisation (~20% to 40% of station capacity) due to the deployment of high-mileage fleet applications. Interviews with the associated stations operators will be used to outline some of the common issues faced** when utilisation at a station is increased and key learnings will be used to form **recommendations on the design and management of future HRS** for high-utilisation.
- This is the **third iteration** of this report. It provides an update up to Q2 2022 (and Q3 2022 for some specific case studies). A fourth and final report will be published in 2023. This report will investigate **approaches to improve the performance and the readiness of the technology for commercial roll-out**.

Contents

Data is collected from 43 HRS, supplied by 9 different HRS suppliers

- **43 hydrogen refuelling stations (HRS) 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.
- Detailed **data has been gathered from a majority of these stations*,** with some datasets stretching from 2015 to December 2021.
- The following slides will provide a **summary of key performance trends (availability and utilisation)** derived from project data.



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 have been operating for quite some time and no longer have the obligation to provide data (mainly H2ME stations).*

Contents

There are different concepts and definitions to be considered for the analysis of availability of HRS

Hydrogen Mobility Europe

- There are different definitions of availability.
- **The analysis on availability to date in the H2ME project is based on the H2ME project definition.**

H2ME project definition

- An HRS will be categorised as **available when the dispenser is open and available for users to refuel** their vehicles. Station availability **excludes planned maintenance.**
- If there are multiple dispensers, the HRS will be shown as available if at least one of the nozzles is working (as in the HyLights definition).
- In the H2ME project, experience has shown that for a large dataset of HRS operating under a wide range of circumstances, a number of HRS will have one off issues leading to low availability levels, typically below 80% for a given month or period.
- As this is not representative of HRS operating under expected circumstances, data excluding these HRS is also provided.

HyLights definition

- The availability of the stations is **calculated on a 24/7 basis.** For a 98% availability, no more than 175.2 downtime hours may occur per year.
- Periods during which the station is not in service due to **scheduled preventive maintenance do not count as downtime.**
- Downtime happens when the station is not available for refuelling a vehicle. If several dispensers or nozzles are in place and the vehicle can refuel, downtime occurs when none of them is available for refuelling. Otherwise an outage of one of several nozzles/dispenser merely results in a reduced dispensing capacity if the station is designed to operate them in parallel.

Other indicators

- Beyond the commonly used availability indicator, operators have increasingly been looking at **other indicators** to evaluate the progress of their HRS network performance such as **an Availability Performance Index.**
- The performance indicator is an event-based indicator that looks at the **percentage of refuelling that were successful on the first try** and differentiate between:
  - High availability - the station has a higher up-time
  - High performance - more customers are able to get a full tank on the first try

Source: H2ME D4.1, Data Collection and Storage Protocol, Cenex
https://www.fch.europa.eu/sites/default/files/HyLights_D3_3_MAF-Handbook-II_Final%20%28ID%202875010%29.pdf

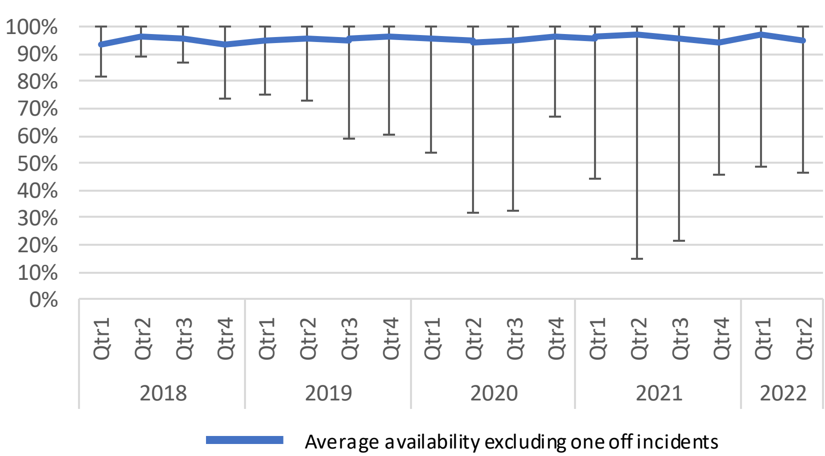
H2ME data evidences high average availability of HRS, but one-off failures and teething issues have led to poor performance at certain stations

Hydrogen Mobility Europe

HRS availability in H2ME projects

- HRS availability is defined as the **percentage of time a HRS is fully operational and able to dispense fuel, excluding planned maintenance**. In order to facilitate commercial roll-out of FCEVs, high HRS availability is essential to foster confidence in the technology and ensure that customers can operate FCEVs without compromise.
- Previous deployment projects have demonstrated high availability for small clusters of HRS. However, the **H2ME initiative aims to achieve availability improvements across a pan-European network, targeting an average HRS availability of over 98% by 2023** across all HRS in the project.
- As of June 2022, 33 HRSs were reporting availability data to the H2ME projects, but only 27 had availability levels above 80%. The **average availability (excluding one off incidents) was of 95% across project HRSs** (as shown by the **blue line** in the figure below*). In Q1 2022, this average reached 97.5%.
- The availability level in Q2 2022 experienced a slight decrease. In order to have FCEV deployment thrive against the internal combustion engine 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.
- Range bars on the graph (right) also highlight the **variable performance of HRS across the project, 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%.**

HRS availability across the H2ME projects[1]



- The following slides provide an insight into the **main issues operators have faced in achieving high availability** and the **key learnings** taken from the project.

Clean Hydrogen Partnership

1 – Cenex analysis of data reported by refuelling stations across H2ME and H2ME2 projects up to end of June 2022.
**Note HRS average availability excludes HRS with availability <80% in one quarter, as this is generally due to one off issues.*

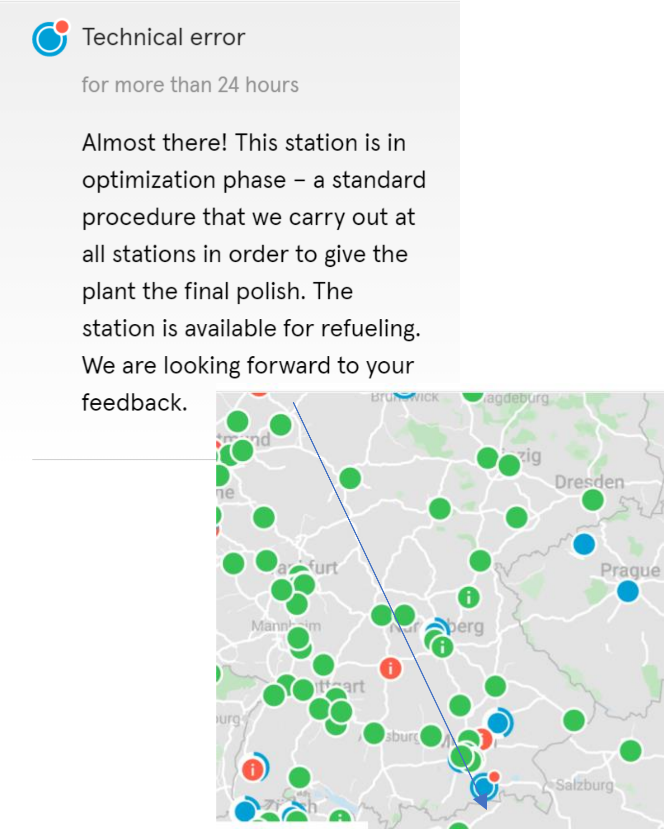
elementenergy
an ERM Group company

‘Teething issues’ shortly after the commissioning of a station are a common cause of low availability

Utilisation and availability

- It is well known that **HRS have lower availability in the early weeks/months after commissioning** when the cumulative hydrogen dispensed is low. This is also known as the **‘teething period’** when issues with the equipment, such as sensor failures, software malfunctions or equipment breaks, are frequent.
- **As more hydrogen is dispensed, the number of failures often decreases** as initial problems are addressed and learnings are implemented into the station design or operation.
- Data from the H2ME projects has indicated that **above a threshold of 100 kg dispensed, the number of downtime events per kilogram reduces dramatically.** After which, fewer critical failures are reported and less technician intervention is required.
- 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 HRS to the public.
- Availability apps such as H2.LIVE are also **highlighting possible issues with the HRS to end users ahead of time to manage expectations**, noting when HRS are in an ‘optimisation phase’ for a short period after the stations are commissioned and when the cumulative volume of hydrogen dispensed is low.

Presentation of HRS in the ‘optimisation phase’ on H2.LIVE[1]



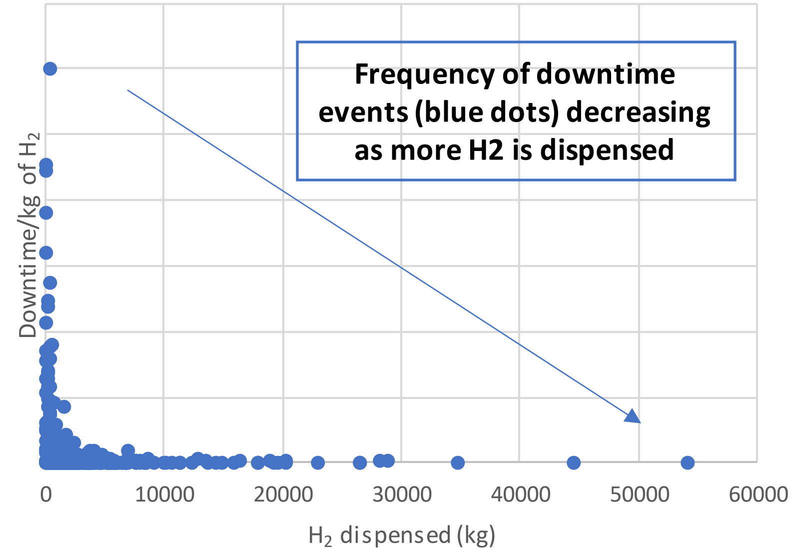
1 – H2.Live (https://h2.live/en/tankstellen)

High throughput of hydrogen at HRS reduces downtime at stations

Utilisation and availability

- Due to the early stage of market development, many **HRS commissioned as part of H2ME have relatively low levels of utilisation**, supporting small numbers of FCEVs with limited daily demands.
- Utilisation of a station is noted to have an impact on the availability of the HRS. This is commonly illustrated in a 'bathtub curve' whereby the **frequency of downtime decreases as greater volumes of hydrogen are dispensed by an HRS.** The graph (right) illustrates this trend by plotting downtime days (adjusted for total dispensed hydrogen) against the total hydrogen dispensed by HRS across the H2ME project.
- Key reasons for **reduced downtime vary between HRS in the project**. However, many operators have noted the value of equipment being regularly used, highlighting that **many components within an HRS operate more reliably with regular operation**. Some of the components have been designed for semi-continuous operation. Hence, start and stop in low usage stations increases wear and reduced component life (e.g., of compressors or dispenser nozzles).
- However, reductions in downtime may also be the result of the **management approach of HRS operators** as highly utilised stations will likely be fixed as a priority. This is because these stations generate more revenue for the operator and will likely impact more customers when out of service.

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



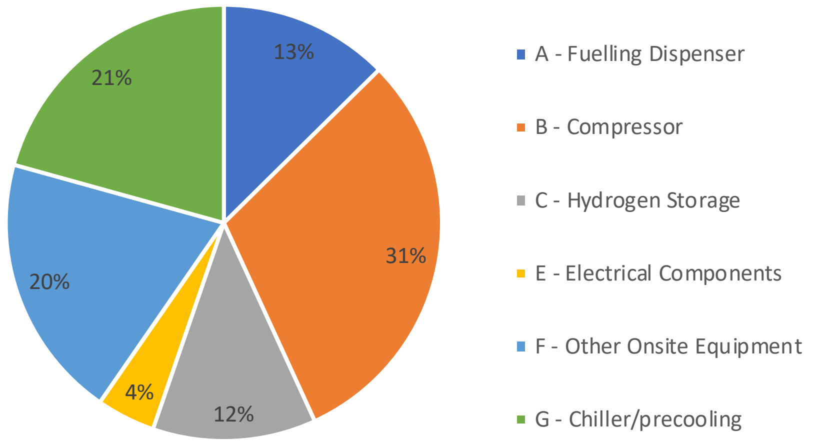
1 – Internal project data, Cenex (data up to Q2 2022).

Compressors, dispensers and chillers have been identified as 'high-risk' components, responsible for 65% of downtime across the project

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 to preserve the anonymity of HRS suppliers in the project.
- Many **downtime events within the H2ME project can be associated with a failure with one piece of equipment**. This is because many stations are built with one process line meaning that if one component fails, the whole station is forced out of operation.
- Moreover, problems can also vary by vehicle type. For instance, larger tanks are more prone to issues related to temperature regulation during refuelling. However, the data shown here is only for LDV with tanks between 4.4 kg and 6.3 kg.

H2ME and ZEFER HRS Downtime by category [1]



- Data from HRS providers identify **compressors, chiller/precooling and fuelling dispensers** as the largest cause of HRS downtime, accounting for 65% 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.
  - **Better 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 allow high risk components to fail without causing downtime to the station (this will require higher capacity, better utilised stations which can bear the higher capital cost of an n+1 redundant solution).

1 – Internal project data, Cenex (data up to Q2 2022).

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

Availability statistics in H2ME have shown a significant improvement as a result of technical and managerial developments

Hydrogen Mobility Europe

Recent progress on availability issues

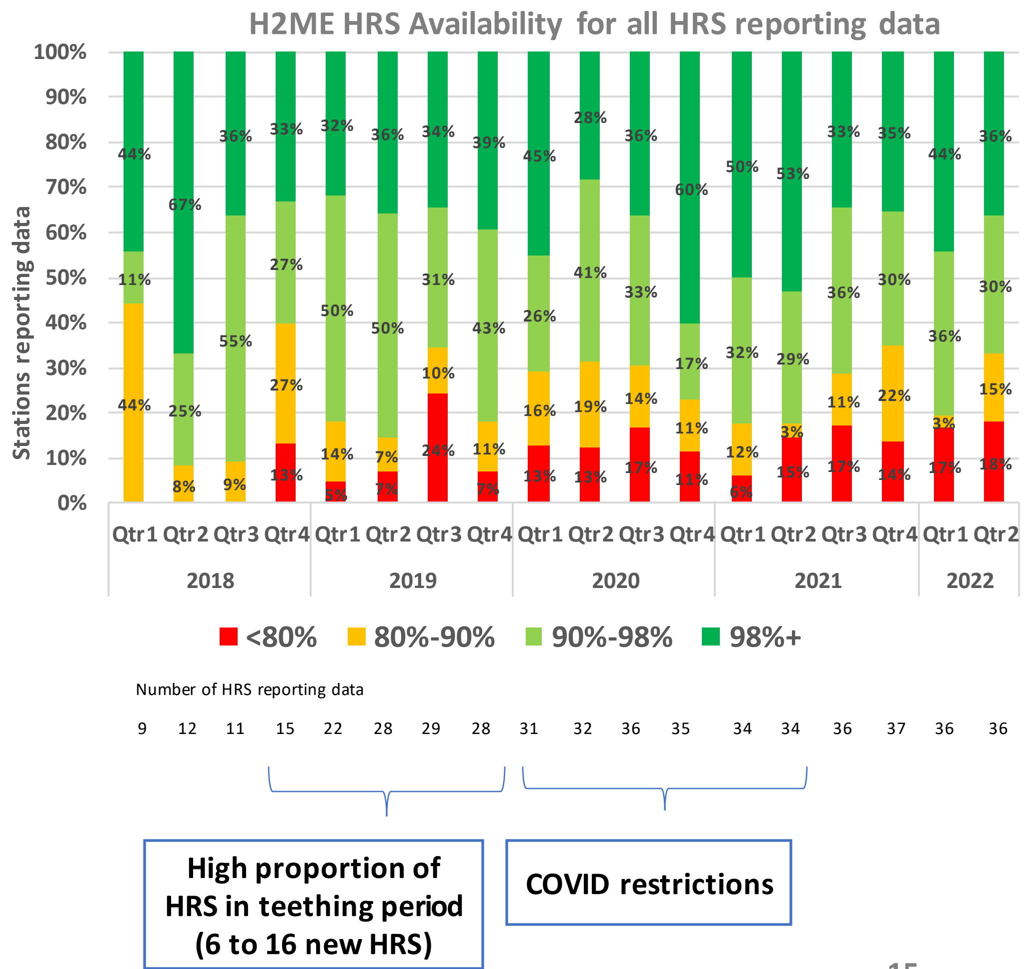
- H2ME has led to significant improvements in HRS availability, setting new 'state-of-the-art' records for performance in comparison to previous demonstration projects. Key improvements can be attributed to:
  - **Deployment of 'state-of-the-art' technology** – H2ME has helped to trigger the deployment of a new generation of HRS, using equipment that has been rigorously tested and developed over multiple prototypes and deployments.
  - **Improvements in station design** – HRS operators have made improvements to the design of stations to avoid high risk components, materials and software. For example, many operators have changed 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** – HRS operators have been able to reduce the response time to emergency maintenance calls by:
    - **Training local staff** to maintain the HRS and quickly respond to unexpected failures.
    - **Storing spare parts** at, or near, refuelling stations to avoid delays in the supply chain.
    - Introducing preventative maintenance protocols which trigger **upgrades of equipment/technology which is identified as 'high-risk'.**
    - **Increased remote monitoring of HRS performance** to allow quick identification of issues.
  - **Sharing of HRS operator experiences** – HRS operators share best practices and lessons learnt from operating and maintaining stations to avoid the repetition of preventable technical or management issues.
  - **Maturing of the HRS supply chain** – H2ME has led to a significant scale-up in HRS demand and has matured the supply market to make the access to parts less complicated, costly and time consuming. The project has also facilitated suppliers in scaling up their operations. For example, Nel Hydrogen opened a large-scale production facility in 2018 which can produce up to 300 HRS per year.

The current average availability rate is of 95%; some quarters experience lower averages due to the introduction of new HRSs and other factors

Hydrogen Mobility Europe

Overall progress on HRS availability

- The definition of availability is focused on the user – an **HRS will be categorised as available when the dispenser is open and available for users** to refuel their vehicles. Station availability **excludes (planned) maintenance.**
- In Q2 2022, 36% of the project HRS exceeded 98% availability. The **average of all HRS** in Q2 2022 (excluding those with availability levels <80%) was **95%**. The average when including all the HRSs reporting data drops to 89.7%.
- The lower availability levels observed during some quarters can be explained by the introduction of new HRSs in their "teething phase" in operation for 9 months or less. It is also expected that Covid restrictions have impacted availability (see next slide). Other factors may contribute to the availability level experienced, such as low utilisation level leading to components degradation, aging stations and reduced maintenance support.
- In Q2 2022, the average availability rate slightly dropped. Indeed, there was a fall in the number of HRS in the 90-98% category and a corresponding increase in the 80-90% category. Availability increased again in Q3 2022.



Clean Hydrogen Partnership

Source: Internal project data, Cenex (data up to Q2 2022).

elementenergy
an ERM Group company

Covid-19 has had some impact on HRS availability for some sites

Covid-19 and HRS availability

- **The Covid-19 crisis** has had some **impact on HRS availability**, leading to unusually low availability levels in the more recent project periods, with unusual low levels (less than 80%) reached at the time of lockdown and travel restrictions.
  - **Lack of available maintenance staff**: given the restrictions for international travel, some sites were unable to receive the necessary maintenance required to maintain the availability level of their station. This type of issue was detected for instance in the HRSs in Iceland which require the technical support of teams based in Denmark who was not able to travel to the site.
  - **Lack of parts** due to global supply chain disruption and **problems with the supply of specific materials**.
- The analysis of the factors leading to low availability levels experienced is complex and while there are some indications that the Covid-19 pandemic has impacted HRS availability, it is likely other factors have also played a role. However, anecdotical evidences from partners strongly suggest there was a correlation between the Covid-19 crisis and lower station availaiblity in a high number of cases. This observation was particularly visible for stations which had critical components coming from other countries and which relied on the maintenance expertise of staff located in another country.
- It is worth noting that this has **not been the case for all sites**. For example, there was no correlation found between the change in demand or lower than usual availability of staff due to the Covid-19 pandemic and the level of availability and performance of HRSs in Germany. This may be the results of the scaling effect of the network combined with a well established value chain at the national level.
  - Germany has adopted a **national coverage strategy** and is among the most advanced European countries in terms of HRS network deployment. The HRS are primarily operated by one entity (H2Mobility Deutschland), which has developed in house expertise and was able to increase the rapidity of responses to events.
  - Moreover, compared to what has been mentioned above, the German HRS network's value chain is mainly contained within its borders, hence mitigating the supply chain issues that can arise in times of crisis.
- However, the Covid-19 period has also been, for some HRS operators, the opportunity to do some additional maintenance given the lower utilisation rates and hence increase knowledge to support the increase of availability (e.g., Air Liquide).

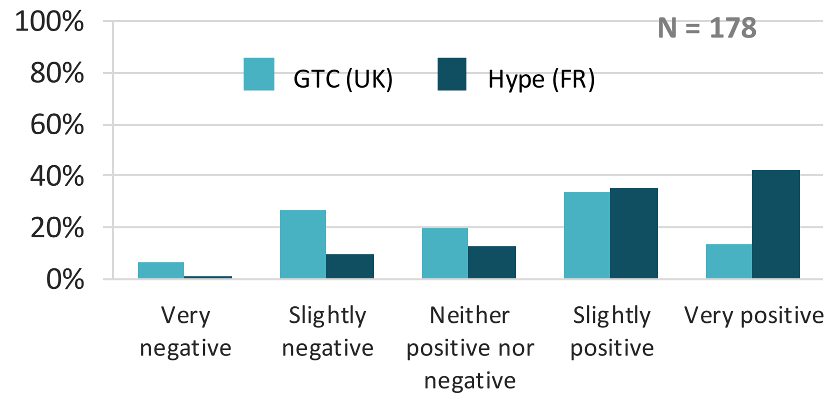
Additional improvements to HRS availability are required to satisfy end user expectations and to facilitate further roll-out

Hydrogen Mobility Europe

Customer perceptions of HRS

- Drivers of FCEVs funded by the H2ME projects are required to answer pre- and during-operation questionnaires on their expectations and experiences using FCEVs and the supporting refuelling infrastructure.
- The data collected and presented here results from the during-operation survey. Only answers from the Hype (FR) and GTC (UK) drivers are shown in the graphs as the other fleets have just begun operations.
- Overall, 90% of the drivers have had a "positive" or "very positive" experience with the FCEVS.
- However, the picture is more mixed when it comes to the drivers experience with the refuelling stations (see graph left). Indeed, 33% of the UK drivers reported a "very negative" or "negative" experience vs. only 10% in France.

Overall, how would you describe your experience with hydrogen refuelling stations?[1]



- It is worth noting that, compared to a previous survey, the satisfaction of Hype drivers with regards to the Paris HRS network improved as the dissatisfaction rate was previously approx. 12.5% (in the first half of 2021)
- Two issues continue to be pointed out as needing improvements:
  1. **More HRS are needed** on major roads for long distance journeys and in operators local areas – the former was especially pointed out by van operators.
  2. **Improvements in HRS reliability** are required to be more suitable for drivers.
- Driver experience satisfaction for FCEVs and HRSs was **very high in areas where large FCEV taxi fleets were deployed** (for instance, in France with the Hype taxi fleet in Paris) **alongside a network of HRS.** This shows that the deployment of vehicles in areas where there is a high concentration of existing HRS (in strategic locations) is clearly a strategy to support positive customer experience.

1- *ZEFER, D4.7 - Summary of customer value proposition of FCEV/HRS in the ZEFER project, June 2022, Element Energy*

Contents

Hydrogen Mobility Europe

Daily hydrogen demand seen at refuelling stations varies with the types of vehicles using the HRS

Hydrogen Mobility Europe

Demand characteristics for FCEV applications currently deployed in Europe

Taxis

- Hydrogen demand of up to 1.7kg/day per vehicle (based on average mileage of 150km/day observed in Hype fleet).
- Usually requires 700 bar refuelling.

Cars for private users

- Hydrogen demand of ~ 1kg/day (based on average mileage of 96km/day as observed in GLC fleet).
- Usually requires 700 bar refuelling.

Buses

- Hydrogen demand of ~ 15 - 20kg/day (based on an average mileage of 200km/day).
- 350 bar refuelling.
- Refuels at set times in the morning and evening.

Range extended vans

- Hydrogen demand of ~ 0.1 kg/day (based on average mileage of 54km/day as observed in Symbio fleet).
- Either 350 bar or 700 bar refuelling.

Heavy duty vehicles

- Hydrogen demand of ~ 18 – 32 kg/day.
- Either 350 bar or 700 bar refuelling.

Note that daily demand per vehicle, and time of refuelling varies significantly between specific applications.

Assumptions behind demand estimates are provided in the Appendix

Demand at light duty HRS is expected to be low based on the limited number of FCEV deployments to date

Hydrogen Mobility Europe

Estimated hydrogen demand at HRS by country

- The "average" utilisation of HRS for light vehicles in Germany, France, the UK and Scandinavia can be estimated based on the **number and type of fuel cell cars and vans deployed and the number of HRS in each country.** Further details and key assumptions can be found in the Appendix.
- **Estimates for the daily demand of hydrogen per HRS across the 5 H2ME countries** can be found below.

UK

FCEV light vehicles: 254

HRS: 9

Estimated hydrogen demand per HRS:

55 kg/day

France

FCEV light vehicles: 669

HRS: 41

Estimated hydrogen demand per HRS:

20 kg/day

Denmark

FCEV light vehicles: 228

HRS: 7

Estimated hydrogen demand per HRS:

65 kg/day

The Netherlands

FCEV light vehicles: 593

HRS: 22

Estimated hydrogen demand per HRS:

53 kg/day

Germany

FCEV light vehicles: 1,256

HRS: 101

Estimated hydrogen demand per HRS:

24 kg/day

Source: H2ME-2, D6.13 – Overarching progress beyond the current state of the art and gaps preventing full commercialisation – Interim 3, Element Energy

Utilisation levels vary significantly between HRS in the project but the project average remains low

Hydrogen Mobility Europe

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 45% pre-Covid in locations where high mileage captive fleets have been introduced to provide 'anchor demands' at stations. This pre-Covid level was reached again at one of the sites in Q2 2022.
- When considering all stations within the project, **average utilisation was approximately 7.4% in Q2 2022**. Whilst this is 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).

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*

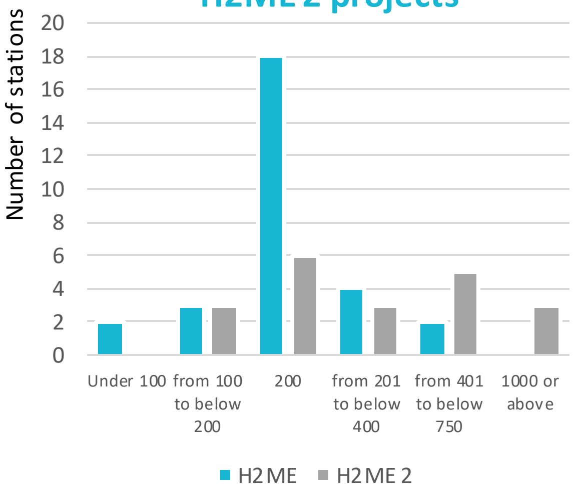
1 – Hydrogen mobility strategies, 2020, H2ME (1) Deliverable 5.13. Element Energy

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

- Overall, the utilisation of the stations remains lower than expected. The majority of stations remain at a utilisation rate well **below 20%**. In **Q2 2022**, only **9%** of the H2ME and H2ME-2 stations had utilisation rates **above 20%.**
- **However, interesting trends and evolutions** have been observed across the HRS deployed in the project which indicate operators' strategies to maximise utilisation are evolving based on insights from the market.

Station capacity (kg/day) by project

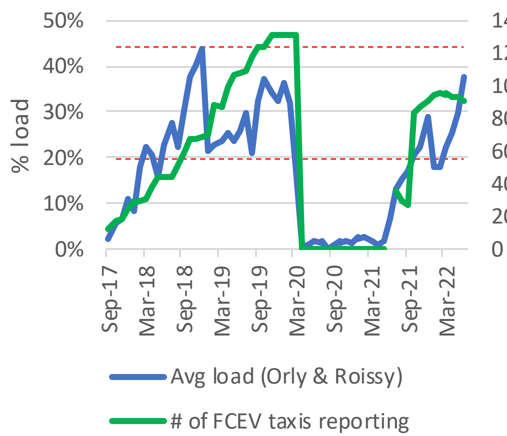
Evolution between H2ME 1 and H2ME 2 projects



The **daily capacity of stations has increased** over time. This reflects the increase in multi-use stations (**co-location of different vehicles types** benefitting from economies of scale

Utilisation of HRS near taxi fleets

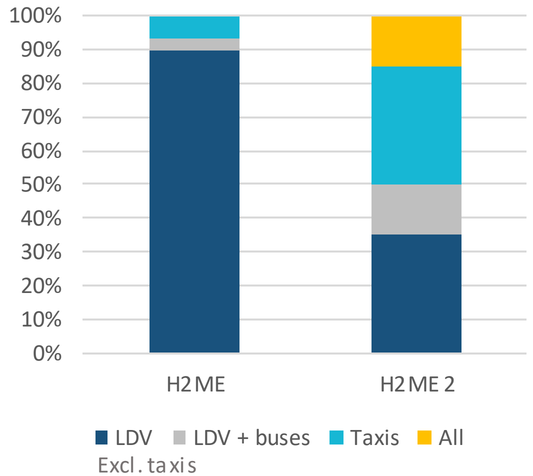
France: Orly and Roissy HRS usage example



The stations with higher levels of utilisation and H2 dispensed are those **located where FCEV taxis are deployed**: Orly (FR), Roissy (FR), The Hague (NL) or Copenhagen (DK)

Type of vehicle using the HRSs

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



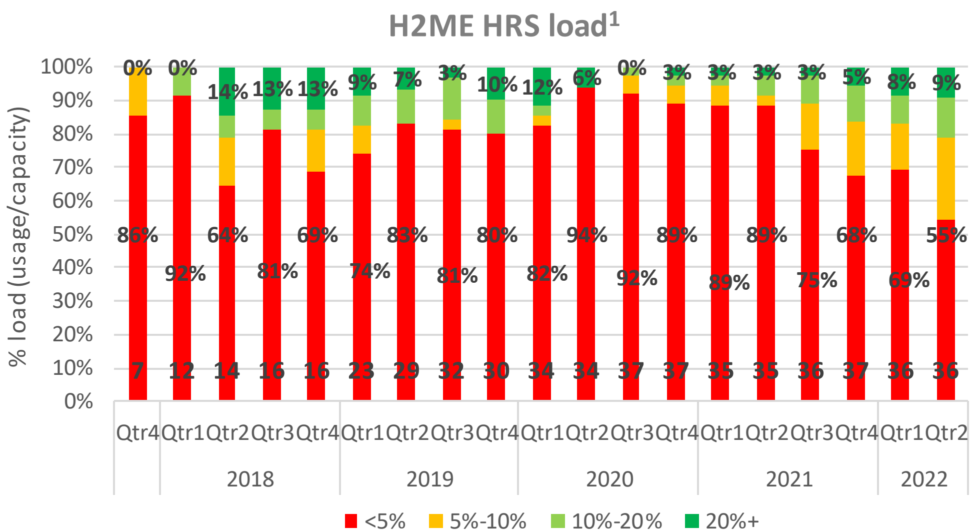
Taxis have become or are expected to become the main vehicle type to use stations deployed in H2ME 2

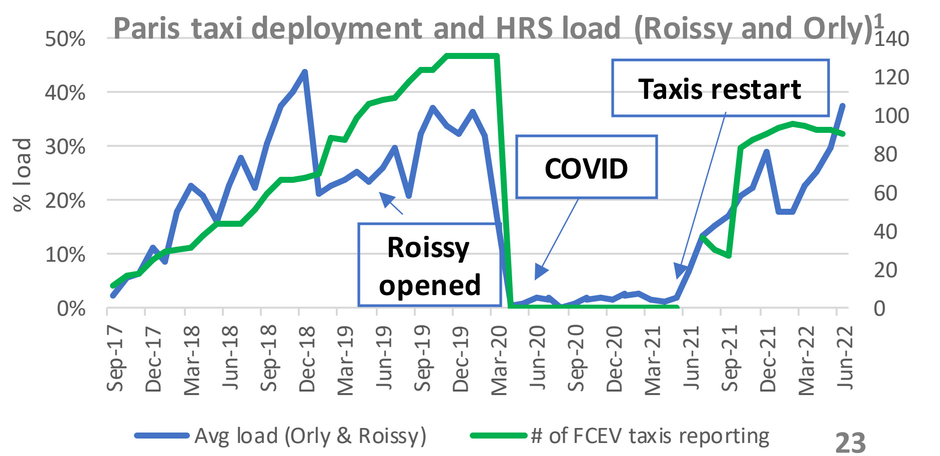
Source: H2ME Emerging Conclusions 2020 (reviewed March 2021), Element Energy; Internal project data, Cenex (data up to Q2 2022)

The Covid-19 crisis has had an impact on the HRS loads; but the various sites are recovering

Covid-19 and HRS loads

- Due to the various **restrictions and lockdowns** that were enacted in several countries involved in the H2ME project, **taxi activities were drastically cut down** and **private FCEV owners had reduced needs to use their vehicles due to restrictions on travelling**.
- The impact of this was clearly observed in the two **Parisian HRSs**, Roissy and Orly, as shown on the bottom right graph. These two sites were further impacted by the **reduction in airport traffic**. From the end of Q1 2020 to the end of Q1 2021, taxi activities were stopped, leading to the HRS load fluctuating around 0% and 3%.
- **London's HRSs** were also affected as the GTC fleet reduced operations in March 2020 by approx. 50%.
- Nevertheless, with the **increasing level of normality** being restored, the number of FCEVs (and mainly taxis) back on the roads rose again, leading **HRS loads to slowly follow an upward trend**. This was observed in the Parisian HRSs, with the taxi restart in Q2 2021, enabling the station to recover load levels in Q4 2021 similar to those when the Roissy HRS opened (Q1 2019). Load levels are gradually reaching pre-Covid levels.





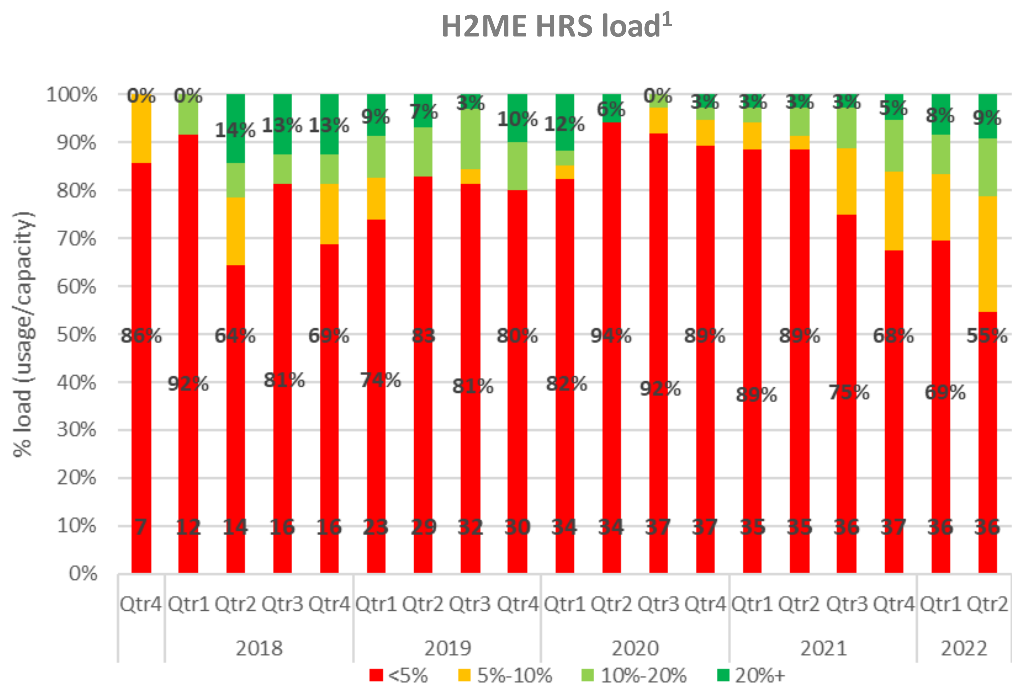
1- *Internal project data, Cenex (data up to Q2 2022).*

A successful recovery from the Covid-19 period and benefits of the efforts to encourage deployment of vehicles can be observed through the increasing number of stations with utilisation rates above 10%

Hydrogen Mobility Europe

Evolution of the HRS loads

- In **Q2 2022, three stations** (9% of the stations with loads above 0%) had **utilisation rates above 20%** (and even above 30%). These stations represent those **located next to FCEV high mileage fleets** (i.e., taxis).
- **During that quarter, the number of stations with a level of utilisation above 10% utilisation rate also increased (21%).** Such levels had been experienced only at the very start of the HRS deployment (Q2 2018) when only 14 stations were operational, hence highlighting an improvement and increase in the utilisation of the stations. **The steady increase in station utilisation seems to confirm that vehicle deployment is being supported by a well-established network of stations.**
- The majority of stations still have low loads (55% below the 5% load rate). However, this is the lowest level ever reached by the H2ME HRS. Moreover, it is interesting to note that a vast majority of the stations (~74%) have managed to achieve their highest load levels post-Covid (i.e., since H2 2021).
- It is important to note as well that some of the 43 stations ceased operations before or during the Covid-19 crisis period.



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 proportion of the H2ME total

Covid-19 pandemic

Post-Covid: Steady increase in the number of HRS with utilisation rates above 10% and 20%

Clean Hydrogen Partnership

1- Internal project data, Cenex (data up to Q2 2022).

elementenergy
an ERM Group company

A subset of stations have encountered high demands as a result of the deployment of high mileage fleet applications

Hydrogen Mobility Europe

Fleet deployment and HRS utilisation

- Although average utilisation across the H2ME regions is low, some stations are beginning to see **moderate levels of utilisation as a result of fleet demands.**
- Fleet applications, such as taxi, private hire and emergency services, are increasingly being recognised as an early opportunity for commercial operation of FCEVs as the use case requires **high range vehicles** and **quick refuelling times** which cannot yet be fully satisfied by battery-electric vehicles.
- Due to their **high daily mileages,** FCEV fleets can consume **large quantities of hydrogen** and can operate effectively using only a **small cluster of stations** due to their predictable patterns of operations. The use case can therefore provide a significant anchor demand at HRS and can help stabilise the business case for HRS operators.
- Four fleets can be identified in Europe, with operations centring on major cities and clusters of HRS:

London, UK – Green Tomato Cars is a green private hire service, operating a variety of low emission vehicles. 50 FCEVs were deployed in the company's 'zero-emission' service in collaboration with H2ME's successor project ZEFER. An additional 14 vehicles were deployed in H2ME in 2021. All vehicles were taken off the road since October 2022 as they reached the end of their leasing contract.

Paris, France – Hype has deployed a fleet of over 160 FCEVs to become the largest fuel cell taxi fleet in the world. Plans are on-going to scale up deployments to over 600 vehicles. Hype plans to deploy 26 HRS in the Paris greater area by the end of 2025. These would be able to refuel up to 10,000 FCEV taxis. For this plan, Hype has therefore concluded strategic partnerships with HRS and McPhy, two French equipment suppliers.

The Hague, The Netherlands – 17 H2ME-2 FCEVs were deployed in NOOT taxi fleet in The Hague. The overall NOOT taxi fleet comprises a total of 40 FCEVs.

Copenhagen, Denmark – 100 Toyota Mirai hydrogen taxis have been deployed in Copenhagen in the app-based taxi company DRIVR. These additional vehicles will complement the already existing low-emission vehicles the fleet has (hybrid and battery electric vehicles).

The hydrogen dispensed across the H2ME HRS has significantly increased, driven mainly by 6 stations located near FCEV high mileage fleets

Hydrogen Mobility Europe

Cases of higher utilised stations

- The deployment of high mileage fleets have had a **significant impact on the volume of hydrogen dispensed** across HRS in H2ME.
- The graph on the following slide shows the cumulative hydrogen dispensed across the 43 stations installed in the project (33 of which were still reporting data as of June 2022).
- Of the 375,684 kg of hydrogen dispensed as of June 2022, **more than 60% has been distributed by 6 stations** which are frequently used by the fleets:
  - **Orly (Paris, FR)**
  - **Roissy/Charles de Gaulle (Paris, FR)**
  - **Rainham (London, UK)**
  - **Teddington (London, UK)**
  - **Den Haag (NL)**
  - **Copenhagen (DK)**
- The utilisation of these stations are therefore some of the highest seen in the project, with **maximum utilisation reaching nearly 45% at Orly pre-Covid and close to 47% in Teddington in Q4 2021.** These are stations which have, since the Covid-19 crisis, been able to reach load rates above 30%*.
- The following sections will provide an insight into the utilisation trends across HRS networks in Copenhagen, The Hague, London, and Paris (and the overall German network).

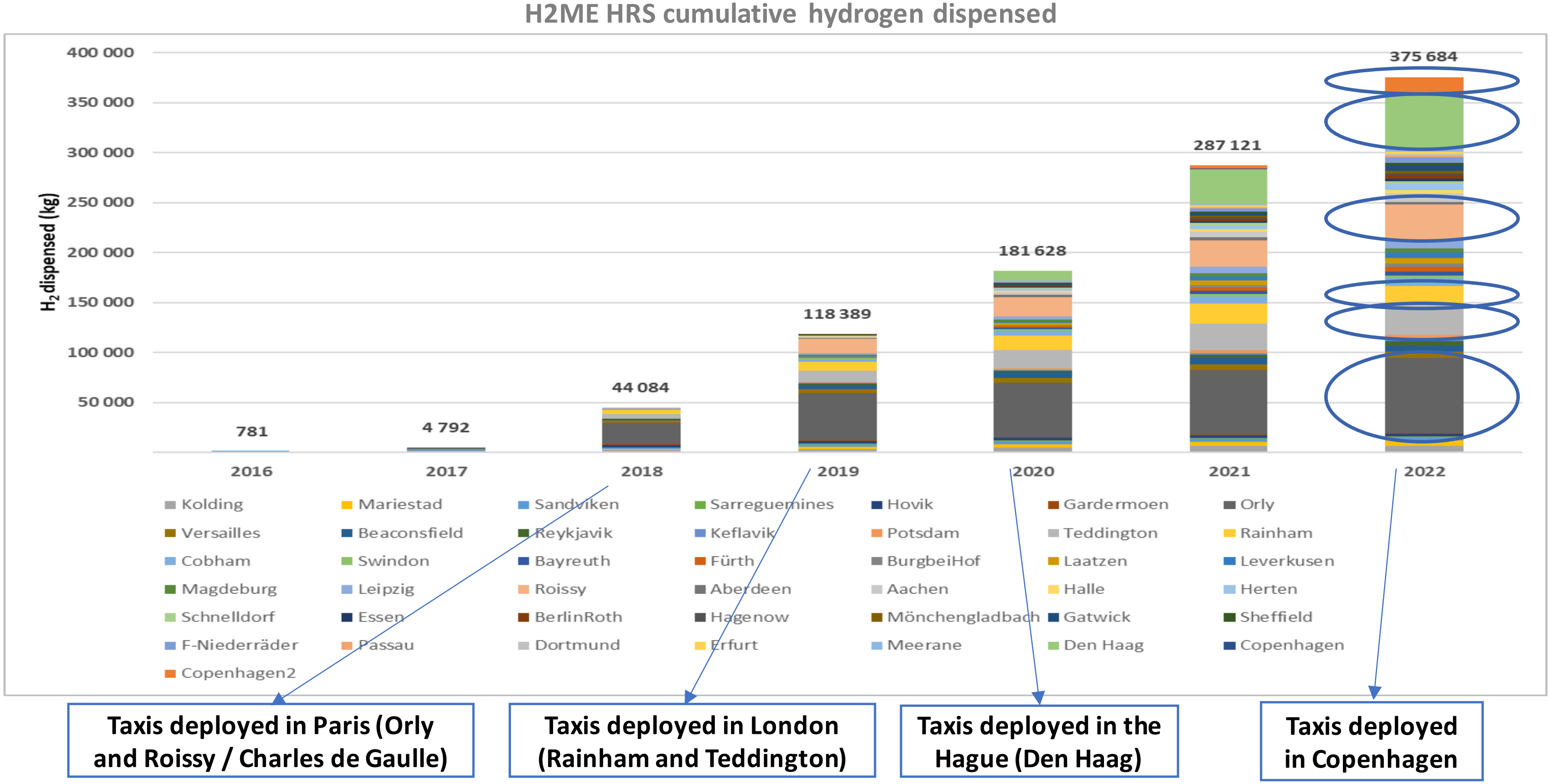
Source: Internal project data, Cenex (data up to Q2 2022).

** Exception for the Hague HRS.*

The hydrogen dispensed across the H2ME HRS has significantly increased, driven mainly by 6 stations located near FCEV high mileage fleets

Hydrogen Mobility Europe

Cases of higher utilised stations



Clean Hydrogen Partnership

Source: Internal project data, Cenex (data up to Q2 2022).
** Exception for the Hague HRS.*

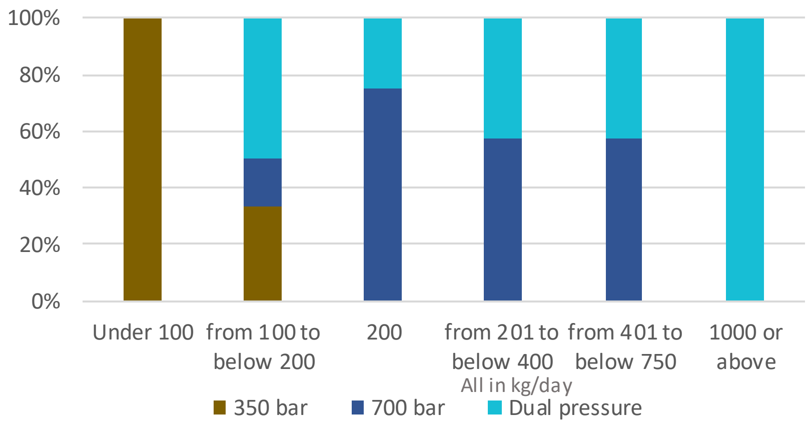
elementenergy
an ERM Group company

Planning utilisation to increase performance of HRS

Factors affecting HRS performances

- Utilisation profile can impact the performance of HRS due to two main factors:
  - **Daily throughput** – this determines the amount of hydrogen a HRS can dispense per day and is dependent on the low-pressure onsite storage or onsite generation.
  - **Back-to-back (B2B) refuelling capacity** – this determines the number of consecutive refuelling events (within 10 minutes) a station can handle and is dependent on the high-pressure storage / compressor capacity at the site.
- These two factors can impact the ability of users to refuel or refuel a full tank on the first attempt.
- The large majority of the HRS in the projects provide or will provide refuelling at 700 bar or both at 700 bar and 350 bar. The 350 bar HRSs deployed have been in France to support the Symbio fleet which operates on 350 bar. At these HRSs, refuelling of 700 bar vehicles is possible but not for a full tank.
- The large majority of the HRSs (84%) have daily dispensing capacity ≥200kg/day.
- Several HRSs with capacity <200kg/day were designed to cater for the Symbio fleet. HRSs with higher daily capacity are typically designed as multi-use stations that will cater for different vehicles types (currently: buses, refuse trucks, etc.). Most of the H2ME HRS operators and suppliers are considering upgrading HRS to increase the capacity to at the site and accommodate various types of vehicles to ensure their viability.

Dispensing characteristics of HRS in H2ME project – station daily refuelling capacity based on dispensing pressure



Sources: H2ME 2, D5.17 – Yearly Vehicle and Infrastructure Performance Report 4 (2015-2021), Cenex; European Hydrogen Week 2021 Emerging conclusions (2021), Element Energy.

The Monte Carlo Simulation of Increased HRS Load: understanding the back-to-back refuelling probabilities

Hydrogen Mobility Europe

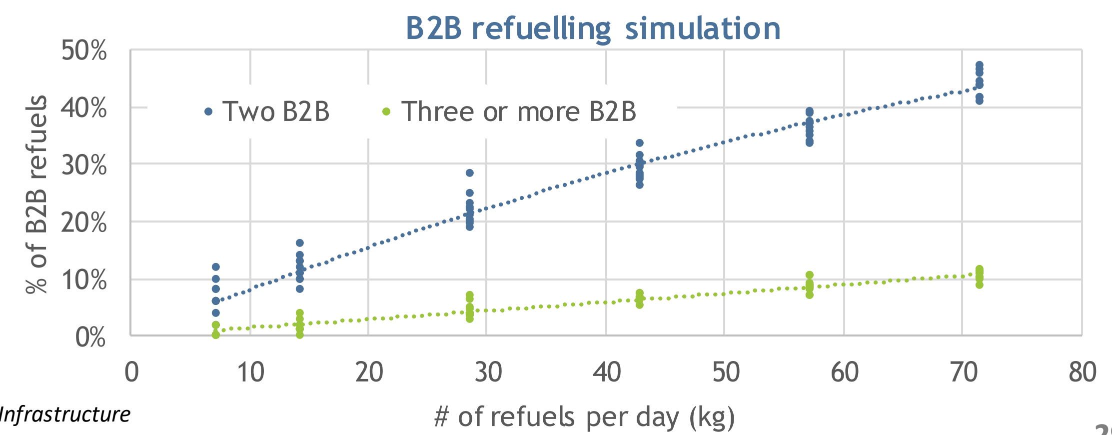
Cases of higher utilised stations and back-to-back (B2B) refuelling

Objectives of the simulation

- Definition of **B2B refuelling**: refuelling event that occurs **within 10 minutes of a previous event**.
- HRS back-to-back (B2B) refuelling capability as the number of vehicles deployed and the station load increases is one of the **key learning aims of H2ME projects.**
- The simulation aims to **understand the usage point at which HRS operational issues may become problematic**.
- B2B refuelling events are **not yet common** (e.g.: only 9% at Teddington).

The results

- The simulation has shown that beyond 70 refuels per day, there is a 40% probability of two B2B refuels and 10% probability of three B2B refuels.
- Hence, the **lower the station load, the lower the probability of having B2B refuelling and vice versa.**
- This has an **impact on the design of HRSs.**
  - There is a need to **precisely understand the refuelling needs of the HRS end users** to have a good estimation of the B2B refuelling probability.
  - The **daily station throughput limit** (typically 200kg/day) will be **reached** the same time that the **probability of three B2B refuels reaches 10%,** a level which is likely to **cause issues** (incl. lack of sufficient hydrogen available for immediate refuelling and therefore increased waiting time). This usage level is reached when 100 taxis or 300 cars use the station daily.



Source: H2ME 2, D5.17 – Yearly Vehicle and Infrastructure Performance Report 4 (2015-2021), Cenex; European Hydrogen Week 2021

Contents

Hydrogen Mobility Europe

A new HRS started operation in Q4 2021 and accommodates the refuelling of a 100 FCEV taxi fleet in the centre of Copenhagen in Denmark

The Copenhagen HRS

Copenhagen Prags HRS in Denmark

Station	Operator	Capacity
Copenhagen	Everfuel	376 kg/day

- The Copenhagen Prags HRS was **commissioned in Q4 2021**.
- The HRS is situated at the heart of the city of Copenhagen. There will soon be >**100 FCEVs** in operation in the area as part of the DRIVR taxi fleet (>100 Toyota Mirais under the H2ME-2 and ZEFER projects).
- The Danish government has set targets for all taxis be zero-emission (at the tailpipe) by 2030. DRIVR, with Toyota and Everfuel, have announced intention to increase the number of FECV taxis in the city to over 500 by 2025.
- The station is open to the public and disposes of a **daily capacity of 376 kg**. It is equipped with **3 dispensers**: two 700 bar and one 350 bar. The dispensers have independent precooling, dispensing, compression and medium and high pressure storage (and a common low pressure supply storage). With this configuration, **the station is capable of refuelling 18 vehicles back-to-back.**
- The HRS dispenses **green hydrogen** which is supplied via tube trailer. Everfuel has the ambition to build a large scale 20 MW central electrolyser.
- Another station exists in Copenhagen, also operated by Everfuel. It is situated around 5km from the Prags HRS. The Copenhagen metropolitan area is spread over 1,767 sq km, while the urban area of Copenhagen is spread over 292 sq km).

Everfuel and Nel have built a station which aimed to cater demand for different types of vehicles and to be ready to answer to high demands for hydrogen

Hydrogen Mobility Europe

The Copenhagen HRS

- The station in Copenhagen is equipped by Nel and operated by Everfuel. It is the first station co-built by both companies and is also the first station in Denmark with the capacity to refuel both passenger cars and heavy-duty vehicles (trucks and buses).
- **Nel ASA** is a Norwegian company providing production, storage and distribution solutions for hydrogen using renewable energy sources.
  - Nel supplied the station with its H2Station™, a station equipped with next generation 700 bar refuelling for FCEV. The module enables flexible scaling of capacities to meet the growing demand. For cars, this capacity can go up to 500 kg per day and up to 1,500 kg per day for buses and trucks. The in-house compressor technology in place was developed to provide optimal and dynamic refuellings, enabling multiple back-to-back refuellings without compromising on half full tanks.
  - Nel has been part of several early demonstration projects in Europe (HyTEC, HyFIVE, etc.) and also has an significant presence in other geographies where hydrogen mobility is experiencing faster growth compared to Europe (i.e, South Korea, the USA (California)) enabling the company to gather significant knowledge on the technology.
- **Everfuel**, a Danish hydrogen operator, is the company operating the station.
  - Everfuel is a growing player in the European market, with intense activities in the North-West regions (Norway, Sweden, Denmark, the Netherlands, and Belgium). Their ambition is to continue growing and expanding beyond those countries in Europe.
  - In January 2022, Everfuel, DRIVR and Toyota established a partnership aiming for a symbiotic development of the market for FCEV in Copenhagen.

Clean Hydrogen Partnership

Sources: https://nelhydrogen.com/; https://www.everfuel.com/, ZEFER, D4.7 – Summary of customer value proposition of FCEV/HRS in the ZEFER project, Element Energy

elementenergy
an ERM Group company

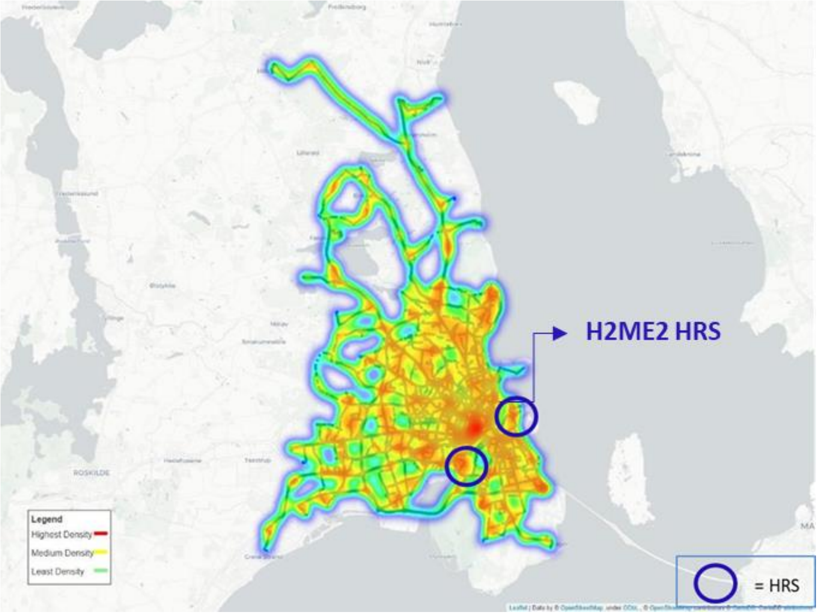
The taxis deployed in Copenhagen operate mainly close to the city centre (and hence to the HRS) but still accumulate high levels of kilometres

Hydrogen Mobility Europe

Demand pattern around the HRS

- The first FCEV taxis in the DRIVR fleet were deployed in Q3 2021.
- The heatmap (right) shows the driving pattern of one of the DRIVR taxis. It can be highlighted that the vast majority the **taxi's operation is within or near the centre** of Copenhagen.
- The network of Copenhagen is composed of 2 stations: an H2ME-2 and a non-H2ME station, both of which are strategically located and around which there is an important taxi activity.
- As of Q2 2022, 62 DRIVR taxis were reporting data to the H2ME-2 project; these vehicle reached a cumulated distance travelled of more than 2M km. The taxis in the fleet can drive on **average between 113 km and 228 km per day**. As a comparison, the average Hype taxi travels ~190 km per day.
- The DRIVR taxis can reach **peaks of daily distance travelled up to more than 470 km**.

Heatmap showing FCEV taxi activity in Copenhagen between June and October 2022



- The fleet of DRIVR taxis is composed of Toyota Mirais, the majority being Gen 1, the rest being Gen 2. These second generation vehicles seem to have better fuel efficiency than their predecessor; however, the driving style is still determinant to define the actual fuel efficiency. This improved fuel efficiency seems to be reflected in the increased kilometres driven by the vehicles.
- The fact that 2 HRS exist in Copenhagen (one large dual HRS and a smaller one) ensures redundancy for the vehicles in operation in the event that one of the stations is unavailable.

Source: Internal project data, Cenex (up to October 2022)

Given the particular setup of the station, overall the cumulative availability reaches more than 98%

Copenhagen HRS availability

- The Copenhagen HRS, operated by Everfuel and equipped by Nel, is based **on 2 modules and 3 dispensers.** The first module has two dispensers (one 700 bar and one 350 bar – Prags 1,2) and the second one is equipped with an additional 700 bar dispenser (Prags 3).
- This setup enables the station to continue refuelling FCEV even if one of the modules is down or under maintenance.
- The dispensers set on the different modules have varying availability levels. Nevertheless, when taking the station as a whole, the HRS reaches an availability level >98%. This is the very reason for having redundancy at the site.

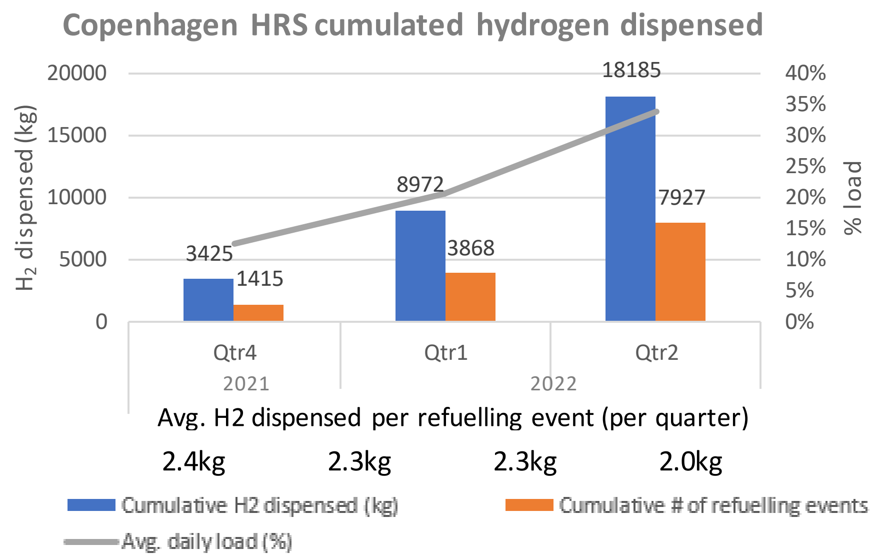
Source: Internal project data, Cenex

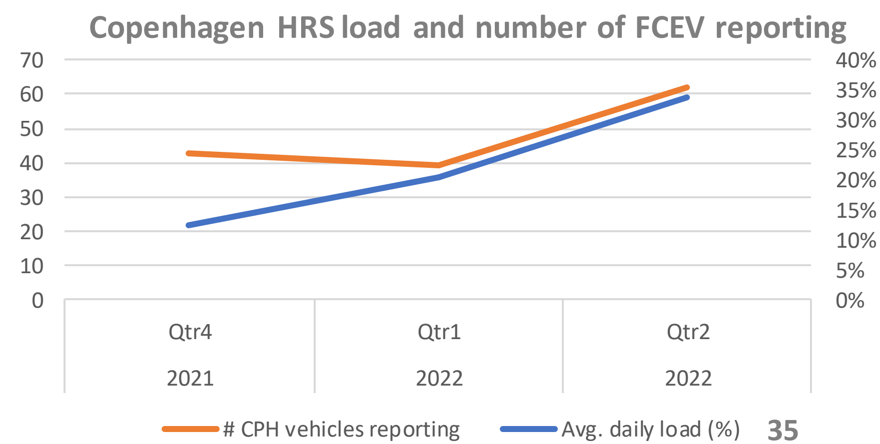
Up until Q2 2022, the load at the Copenhagen HRS has not ceased to increase, quickly exceeding H2ME-2 load averages. This growth is linked to the taxi fleet deployment

Hydrogen Mobility Europe

Impact of fleet deployment on HRS utilisation

- As of Q2 2022, the Copenhagen H2ME-2 station dispensed **more than 18,000 kg of hydrogen** and **more than 7,900 refuels up to date**.
- The average daily load gradually increased, achieving a peak of **34% in Q2 2022**. Since the start of operation of the station, the load has always been above 10%.
- The increase in utilisation of the station followed the expansion of the H2ME-2 and ZEFER taxi fleet and hence in the number of vehicles reporting data (bottom right).
- As of Q2 2022, around **41 refuellings took place per day**. It can be expected that this number increases if the other HRS in Copenhagen has an issue and needs to be closed. This could hence bring the amount of hydrogen dispensed daily up and increase as well the probability of B2B refuellings. Thus the station needs to be well equipped and ready to meet these potential requirements.





Clean Hydrogen Partnership

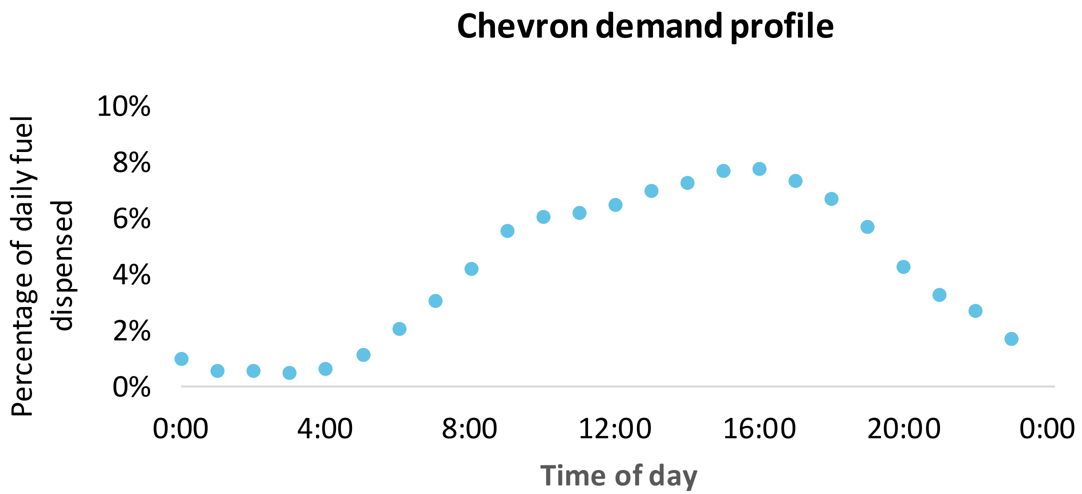
Source: Internal project data, Cenex (data up to Q2 2022).

elementenergy
an ERM Group company

Demand also varies on a hourly basis depending on the schedules of drivers

Daily utilisation profile

- **Fuel demand at a HRS also varies over the course of a day** depending on the schedules of drivers and opening times for the station. This variance needs to be carefully considered by HRS operators and integrated into station design and technical performance specifications.
- The National Energy Research Laboratory (NREL) compiled the '**Chevron demand profile**' below which represents the typical demand profile of a 24-hour US petrol/diesel station[1]. Data shows a **peak of ~8% daily fuel demand** between 16:00 and 17:00 when drivers commute home from work. Much lower utilisation is then seen during the night time, between midnight and 04:00.
- The chart is commonly used to inform benchmarks for HRS designs. This will be explored in more detail in the next chapter of this report. However, the following slides will focus on comparing demand profiles at the London HRS to the Chevron profile.



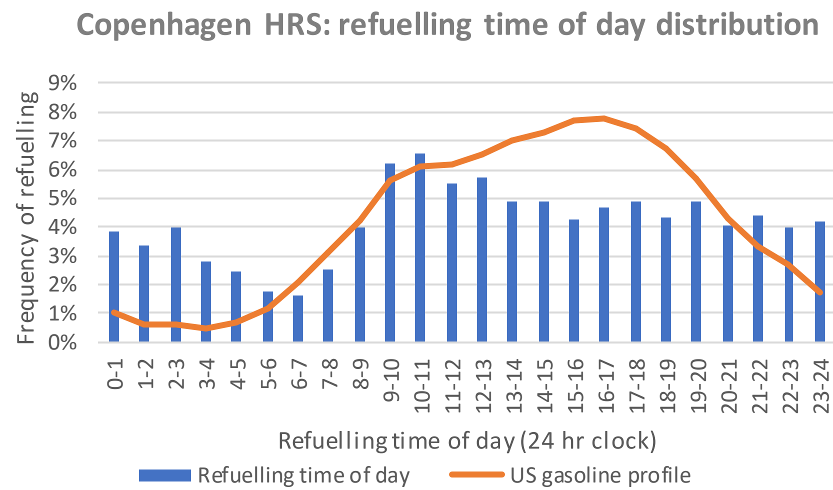
Source: H2FIRST Reference Station Design Task, p11. Sandia National Laboratories, National Renewable Energy Laboratory & Argonne National Laboratory, 2015

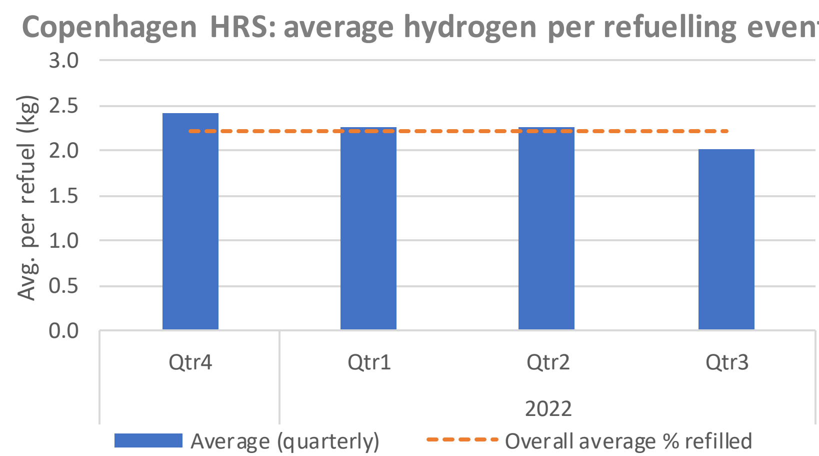
The day distribution for refuellings at the Copenhagen station are quite smoothed out throughout the day with a slight peak mid-morning

Hydrogen Mobility Europe

Daily utilisation profiles

- The Copenhagen HRS has the specificity of having quite a **consistent level of activity throughout the day and night** compared to the utilisation profile of other stations across the project. From 8am to 12pm, the frequency refuelling is around 5%.
- Indeed, compared to other stations which see their peaks in the early hours of the morning, this is actually the period during which the demand at the HRS is the lowest.
- The **DRIVR taxis have the specificity of being available for customers 24/7** and all year long. Therefore, refuelling patterns may change depending on the type of trips. Drivers may hence need to refuel at different times depending on the day.
- Over time, the **average hydrogen dispensed per refuelling event decreased**. The average since the start of operation is **2.2 kg**. This trend is unlike what has been observed at other sites where average refills tended to increase overtime. This may be explained by the additional vehicles that have been more recently deployed with new drivers. As a fleet is growing, there is typically a phase during which the new drivers need to **become accustomed to the vehicle's refuelling needs** in relation to their daily operations and gradually **gain confidence in the reliability of the HRS**. This is confirmed by an initial poll conducted with drivers employed by DRIVR who has confirmed they expect the FCEV to have a much shorter driving range than a conventional vehicle. Moreover, opportunistic refuelling when passing near the station could help explain the lower refuelling levels.





Clean Hydrogen Partnership

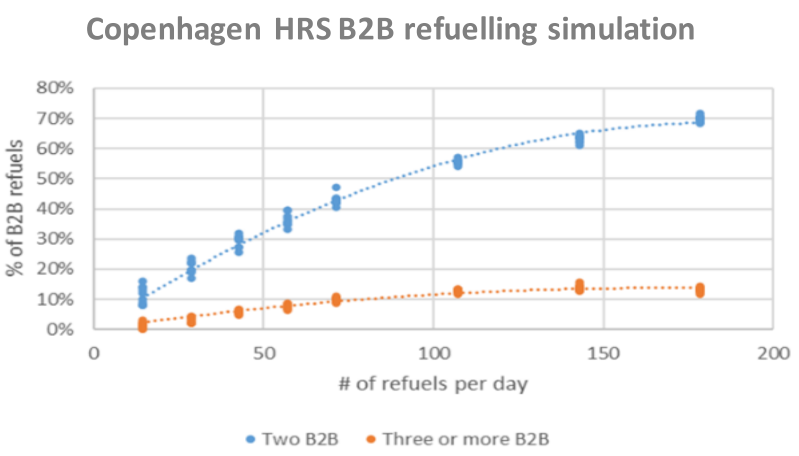
Source: Internal project data, Cenex (data up to Q3 2022).

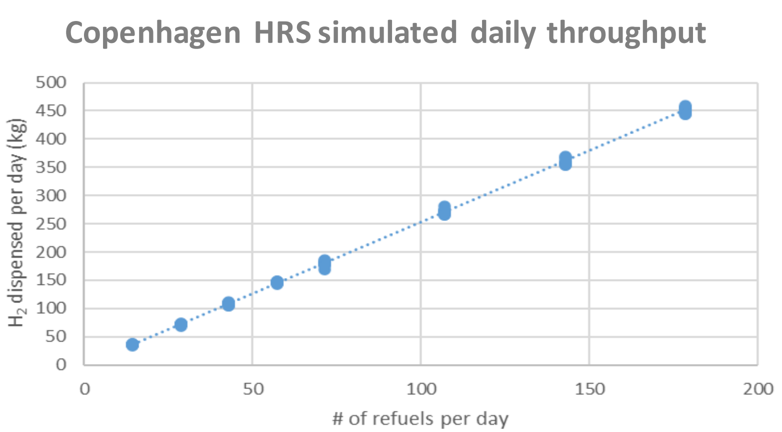
elementenergy
an ERM Group company

31% of the refuels at the Copenhagen station are B2B refuellings

Simulation of B2B refuellings at the HRS

- As an overall system, the Copenhagen has **31% of its refuels which are B2B**. If the **Prags 1,2** module is taken separately, the **B2B rate is 20%.**
- A Monte Carlo simulation, using data from the Copenhagen station, was developed by Cenex for the H2ME2 project.
- Taking into consideration the current setup of the station, with ~150 refuellings per day, the HRS average daily load approaches the station's capacity (i.e., 376 kg). In Q2 2022, the average number of daily refuelling was around 41 (approx. 3.65 times less than the amount taken into account for the simulation).
- Nevertheless, once again, given the setup of the Copenhagen hydrogen refuelling station (i.e., twin dispensers), at current levels of utilisation of the station, the B2B probability and throughput per dispenser remains quite low. Even considering daily refuellings of 150, the probability for 3 or more B2B refuellings remains relatively low.





Source: Internal project data, Cenex

Two Nel station locations provide two very different experiences in terms of utilisation

Scandinavian HRS status

- Within the H2ME-2 project, other stations, equipped and operated by Nel, have been established in Scandinavia.

Sweden	Iceland	Denmark
Mariestad	Reykjavik and Keflavik	Copenhagen, Herning and Aarhus*

- However, despite the similar equipment, the experiences at the station differ on various topics, including the utilisation.
- **Example of the Icelandic HRS**:
  - In Iceland, approximately **25 FCEVs were deployed** under the H2ME-2 project. This represents a relatively small fleet, especially for 2 stations.
  - The 2 stations were part of the first wave of stations installed by Nel in the project and entered in operation in 2018. They are small capacity stations (200 kg per day) both delivering green hydrogen with **utilisation levels around 1.08% and 2.37%** for Keflavik and Reykjavik respectively in Q2 2022.
  - The stations have faced quite **significant issues** in the first years of operation. These were **not related to the equipment**, but to the ongoing discussion on the approach to take with regards to the operation of the station. Moreover, the **Covid-19 crisis and lockdowns** did not help with the situation in Iceland. Indeed, much of the **maintenance relied on teams from Denmark** going to the site which was made impossible with the travel restrictions that were introduced. Lastly, the incident in Kjorbo, Norway, also impacted the availability of the station as the Icelandic stations had to be closed down.
  - Following these events, the strategy was revised and **increased training of local technicians** was provided and a **back up of spare parts** was constituted to prevent major downtime at the stations. This has led to more reliable stations in Iceland.
- Lower levels of utilisation can be detrimental to the success of the station. The lower levels are not always directly linked to the equipment and parts. Indeed, the performance of a same OEM station can vary drastically from one location to another. Possible reasons can be the remote **location** of the station and the overall **commercial strategy**.

*7 FCEVs are in operation in Aarhus

Ensuring that the station is located in a high demand location and with a setup to thwart risks of long downtimes is essential

Hydrogen Mobility Europe

Key learnings for HRS with high utilisation

- **High utilisation is key for a station's viability** (especially financial). Such high load levels can be achieved if the station is **strategically located** next to a large fleet of high mileage professional FCEVs. Ensuring that such fleets exist or are planned is therefore key. Everfuel has demonstrated this perfectly by setting up the station close to the city centre of Copenhagen and by signing a collaboration with DRIVR and Toyota to get the station to a level which brings confidence on the reliability of FC vehicles as a complement to other low/zero tailpipe emission vehicles.
- However, in the future, the **utilisation of a station will also highly depend on the deployment of heavy-duty vehicles** (buses and trucks).
  - A challenge however currently remains regarding the fuel cell trucks: there are no homogeneous standards across the industry on what the future truck will need in terms of specific HRS requirements. This makes the development of adapted and future-proof stations challenging for HRS suppliers.
- The **setup and design of a high utilisation station** is key to ensure that the level of availability remains high. The **two independent module system** of the Copenhagen station shows this well, as if ever one of the modules is down or needs maintenance, FCEV drivers (and especially the DRIVR fleet) can continue refuelling their vehicles. High availability is key to ensure that confidence around the technology rises and therefore to see a growth in the number of FCEV deployed in an area.
  - Moreover, such a system also reinforce the stations' capability to face high levels of back-to-back refuellings.

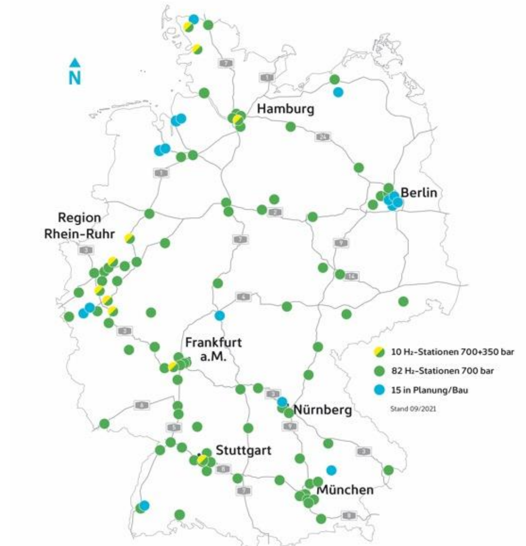
Contents

Hydrogen Mobility Europe

Out of the c. 100 HRS in the German network, 20 HRS deployed are reporting data to the H2ME projects

H2ME funded HRS part of the German Network

H2ME HRS (left)



Overall Hydrogen mobility Deutschland HRS network (left)

- In Germany, **twenty HRS are deployed across the territory under the H2ME project.** This reflects the German strategy of having an **extensive coverage** with major cities as “hubs”. The deployment of the stations was done irrespective to the number of vehicles or demand in the area to create a minimum viable network in. This contrasts with the tactical approach of the previous case studies, where HRS deployments are focused in cities where high-mileage fleets are located.
- All the HRS are operated by H2 Mobility Deutschland (H2MDE), a company founded by the shareholders Air Liquide, Daimler, Linde, OMV, Shell and TotalEnergies. Overall, H2MDE operates over 90 HRS across Germany and Austria.
- The HRS equipment is provided by two different suppliers: Air Liquide and Linde.
- Most of the H2ME H2MDE stations are 700 bar, refuelling mainly passenger vehicles. Two stations across the network are 350 bar and refuel dedicated fuel cell bus (FCB) fleets. Across the entire network, 10 are dual pressure, 82 700 bar and 15 in planning at the end of 2021.

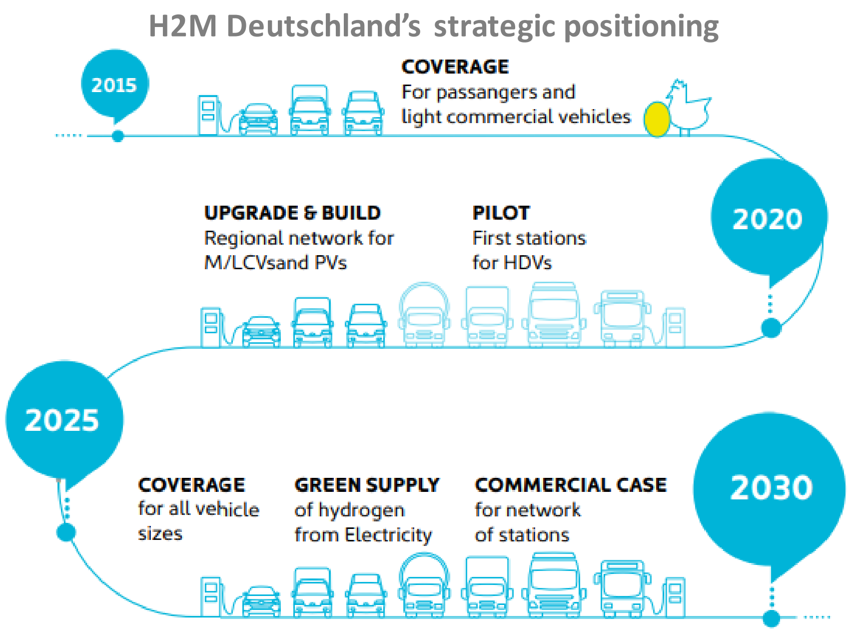
Sources: Maps: https://h2me.eu/ and H2 Mobility Deutschland, Annual Report 2021

National coverage has been achieved for 700 bar refuelling, but it is now necessary to upgrade the network for heavy duty vehicles, without neglecting performance and availability

Hydrogen Mobility Europe

H2 Mobility Deutschland HRS network

- The **first step** to building the H2MDE HRS network was to **focus on passenger and light-duty vehicles**, hence the building of approximately 100 700 bar HRS across Germany.
- Nevertheless, to ensure the energy transition within the transport sector, **350 bar HRS will need to be established to accommodate heavy duty vehicles**. Stations which will be / have been upgraded are located in **strategic locations** where such vehicles are deployed / are expected to be deployed. This follows the trend shown in the graph on the previous slide: buses, medium duty (3.5t – 15t) and heavy duty vehicles (>15t) will account for 83% and 88% of the total hydrogen demand in mobility by 2025 and 2030 respectively. In 2030, HDV are expected to represent 80% of the total demand. **As these vehicles have bigger sized tanks** (>30 kg vs. average 4 kg for passenger vehicles), the **load factor will hence increase**, bringing these stations into the category of HRS under high utilisation.



- Moreover, now that the coverage has been achieved, another priority will be to **guarantee supply of hydrogen**.
  - This will be implemented through the development of **clusters**. These clusters are situated in areas where there is already a dense network of stations. **Additional high-performance HRS** will therefore be established.
  - To guarantee this supply, there needs to be **continuous efforts to get rid of the causes of HRS deficiency**. Such efforts have already been implemented, including technical optimisations and a reviewed approach to maintenance and overall HRS safety and quality checks.
  - All in all, new hydrogen stations will need to be well-utilised and large scale to be able to justify the capital investment. A station with such capacities often have an offtake of >1T/day, i.e., 1,000 passenger FCEV or c. 50 FDVs.

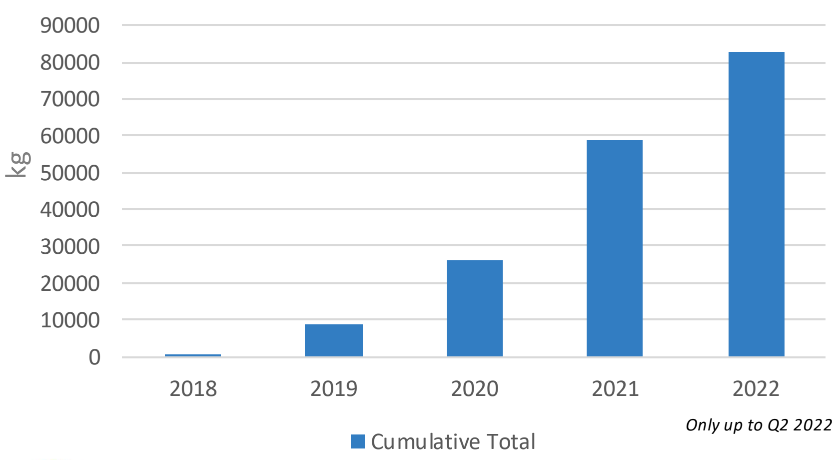
Source: H2 Mobility Deutschland, Annual Report 2021

The 20 HRS in the H2ME projects mainly refuel passenger vehicles and light commercial vehicles and have relatively low capacities (majority at 200 kg per day)

Demand patterns across the network

- The HRS across the German H2ME network dispensed **82,638 kg of hydrogen as of June 2022**. This represents quite low levels of hydrogen dispensed per HRS. The site with the largest amount of hydrogen dispensed as of Q2 2022 delivered around 9,100kg since 2019. In Q2 2022, the average load rate of the H2ME HRS network was of **4.18%** (excluding HRS with no load). The load levels **ranged from 1.21% to 11.67%.**
- These HRS refuel mainly **passenger and light commercial vehicles**. This is in line with the FCEV type distribution in Germany for 2021 (bottom right graph).
- Regarding HRS availability, across the entire H2 Mobility Deutschland network, the level was of **93.2%** for 2022.

H2ME German HRS cumulative hydrogen dispensed[1]



FCEV and hydrogen demand development through 2030[2]

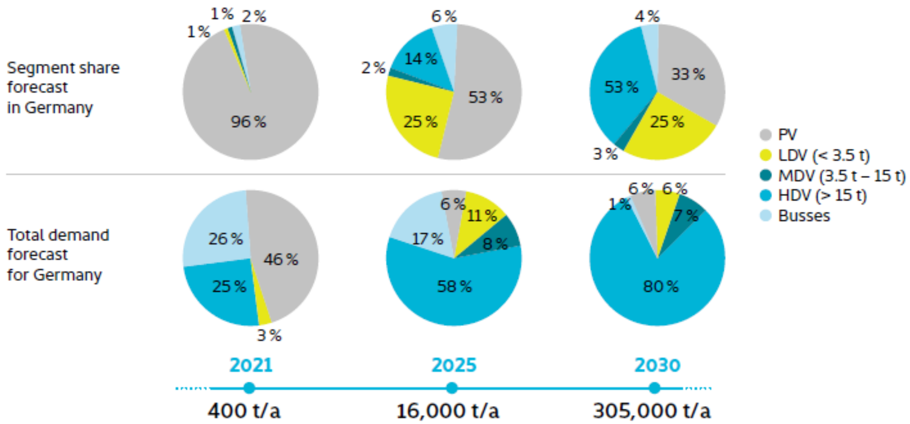


Figure 4 – FCEV and hydrogen demand development through 2030 (Source: McKinsey (2021) & H2 MOBILITY)

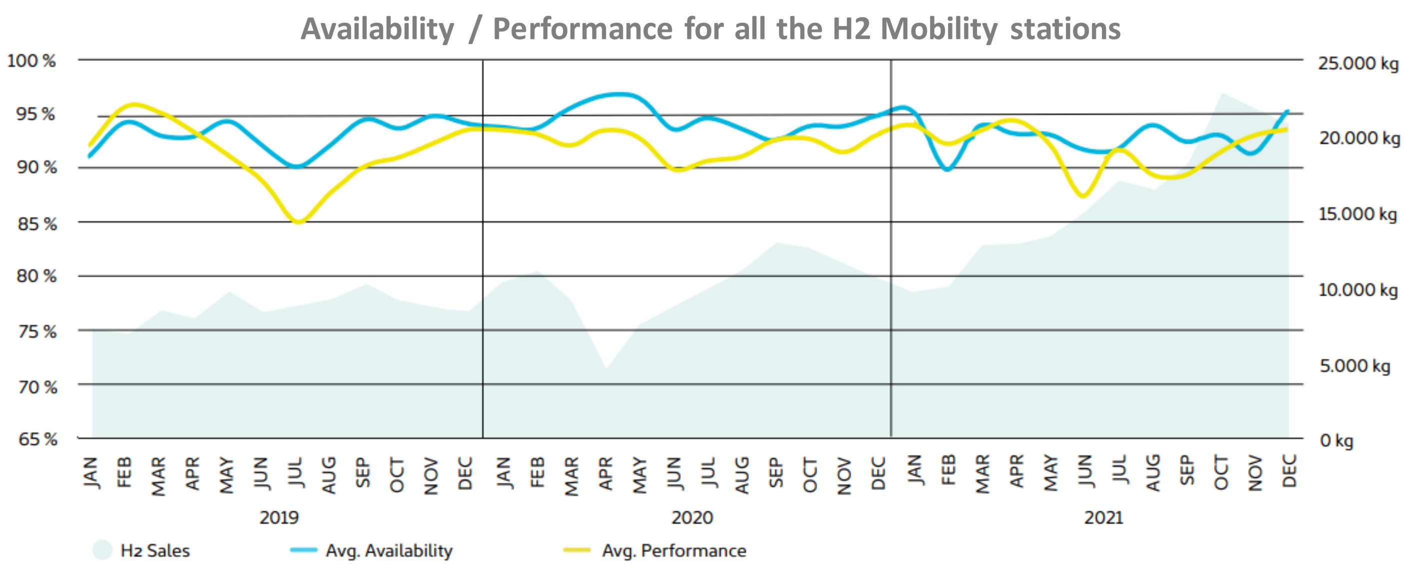
1 – Internal project data, Cenex (data up to Q2 2022)

2 – H2Mobility (August 2021), "Overview: Hydrogen Refuelling for Heavy Duty Vehicles".

Despite low load levels, the H2 Mobility network is able to maintain high levels of performance and availability across its stations

Demand patterns across the network

- **Availability and performance are two key aspects for a successful HRS.** Both of these indicators are quite **closely linked**.
  - **High availability** reflects the fact that the stations have **higher up-times.**
  - **High performance** highlights the **ability of the station to dispense full tanks of hydrogen to the customers on the first try** (i.e., 100% SOC).
- It can be observed that the H2 Mobility Deutschland HRS network (H2ME and non-H2ME stations included) has maintained relatively high levels of availability and performance over time, with only several drops below 90% for the availability indicator. Overall, the **average for the performance was 91.7%** and **92.9%** for **availability in 2021 and of 91.8% and 93.2% in 2022** respectively**.**
- This high level of both performance and availability was maintained even as the level of hydrogen dispensed increased and despite the Covid-19 crisis which affected many of the H2ME stations.



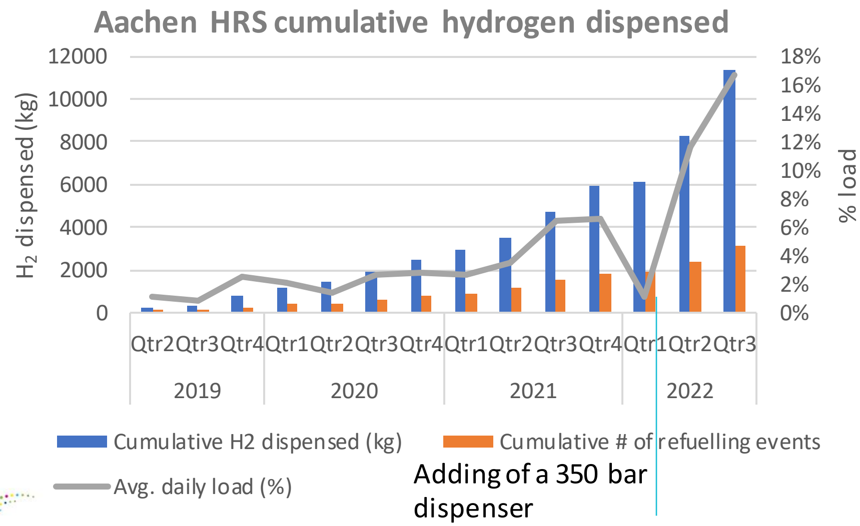
Source: H2 Mobility Deutschland, Annual Report 2021

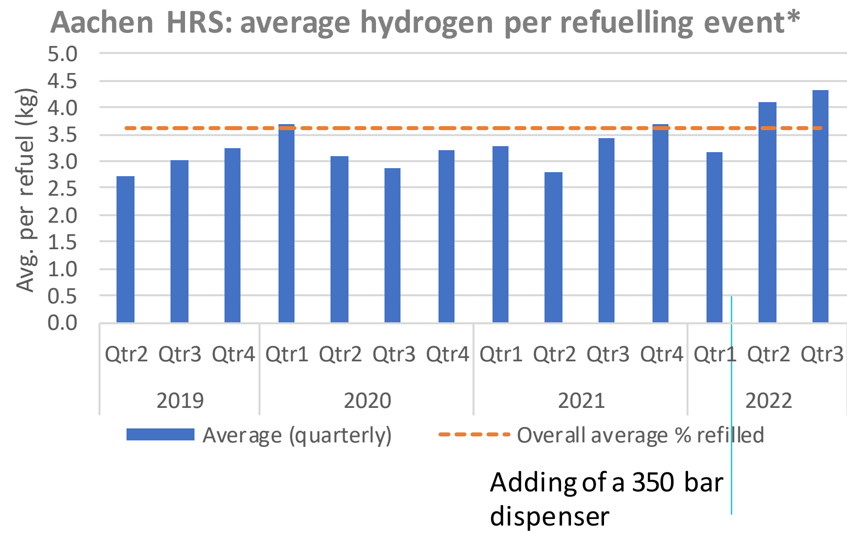
Among the German H2ME stations, the HRS of Aachen has shown the highest load rate thanks to an upgrade now enabling buses to refuel via a 350 bar dispenser

Hydrogen Mobility Europe

Demand patterns across at the HRS

- The Aachen station opened in **May 2019**. It is a 200 kg/day station built first of all with only 700 bar refuelling capabilities. During its first year of operation, the amounts of refuelling events and H2 dispensed remained quite low. **Load levels also stayed well below 5%**.
- Gradually, and especially since mid-2021, more hydrogen was dispensed at the station. A significant change occurred in **Q1 2022 when a 350 bar refuelling dispenser was added to the station**, now enabling buses to refuel. This pushed up the amount of hydrogen dispensed and thus the load rate, reaching **17% in Q3 2022**.
- With regards to **availability**, in 2022, the average rate was of **94.9%**.
- The average hydrogen dispensed per refuelling was quite irregular from quarter to quarter. Following the upgrade of the station, the amounts per refuelling increased and should be expected to stabilise over the next quarters.
- It is worth noting that the H2 dispensed per refuelling event is higher at German sites than for many other H2ME stations given that H2MDE look at the number of cars rather than the number of refuellings when determining those amounts.





Clean Hydrogen Partnership

Source: Internal project data, Cenex (data up to Q3 2022).

**The averages following Q1 2022 now include tank sizes for buses (around 15-20kg per refuel for a bus)*

elementenergy an ERM Group company

Given that no high mileage fleets are deployed around the HRS, refuelling "peak" times follow mainly the business rhythms of drivers. Special refuelling patterns can be observed for HRS accommodating HDV and buses

Demand patterns across the network

- Across the H2 Mobility Deutschland network, specific **trends regarding refuelling times and amounts** have been identified. On the day the network reached 1.5t of hydrogen dispensed, the following characteristics were observed.
  - Peak refuelling moments:
    - Around 9am: start of business
    - Around 1pm: post-lunch
    - Around 6pm: end of working day
  - Ratio of hydrogen dispensed:
    - In the mornings, the amount of kg refuelled is often quite low (top up refuelling to ensure that people get through the day).
    - In the evenings, drivers are often on their regular drives back home and therefore the amounts can be quite heterogeneous.
    - Midnight refuellings: this is an off-peak time for refuelling. However, the types of vehicle that tend to refuel at this time of day are buses. Therefore, the amount of hydrogen dispensed during this time window is often much higher than in other moments of the day.
- Given the refuelling patterns and load levels across the network, **B2B refuellings are quite rare**. However, the technology on most of the recent stations should enable several B2B refuellings. The issue may arise with older stations which do not have good levels of performance (i.e. good levels of SOC) and have other technical issues (e.g., with the precooling system).

With increasing number of HDV deployed in Germany in the coming years, load levels are expected to increase. High availability and performance rates will be necessary

Hydrogen Mobility Europe

Utilising key learnings for planning future HRS with high utilisation and high availability

- The German case study is quite particular as the current **levels of utilisation remain low** (well below 5% for a majority of stations). This is explained by the **strategic approach taken by Germany which aimed to reach national coverage compared that of other countries.**
- However, this strategy based on territory coverage is now moving on to the **next phase which is to cater for the higher hydrogen demanding vehicles**: MDV, HDV and buses. The stations which have the sufficient performance and availability levels, which are strategically located and can be upgraded will be equipped with 350 bar. This should therefore, in the upcoming years, increase the load factor of the concerned stations and hence of the network overall.
- For older generation stations, it can be difficult to keep improving the availability levels, especially if these are stations which have had several issues. It is therefore necessary for network HRS operators to discuss the strategy to be adopted regarding these stations. Decommissioning of these HRS may be the approach to consider in order to develop and establish higher performing stations enable to withstand higher levels of utilisation.
    - For the German network, various criteria are looked at to determine a suitable location for a station:
        - Initial utilisation levels: the station must be capable of reaching 20% utilisation rate in the 1st year of operation.
        - Load potential: the location should show load potential of up to 60% - 70%.
        - Opex: the station's activity should be able to cover operating costs by the 3rd year of operation.
- The HRS network has been able to **maintain high levels of both availability and performance**. These features will be key for successful high utilisation stations which are expected to be deployed in the upcoming years.
- It is quite important for a station / a network of stations to be able to **rely on a diversified customer base**. Indeed, HRS which are located in the proximity of high mileage FCEV fleets (e.g., taxis) and which therefore have high levels of utilisation can be at risk, in the case of an unpredicted collapse from that single customer base, to be out of business. This has been observed for several stations across the project during the Covid-19 crisis and lockdowns.

Contents

A new HRS opened in 2020 and accommodates the refuelling of 19 H2ME-2 FCEVs in the centre of the Hague, in the Netherlands

The Hague HRS

The Hague HRS in the Netherlands

Station	Operator	Capacity
The Hague	Kerkhof – Orange gas	480 kg/day

- The Hague's HRS was **commissioned in January 2020**. All the 19 FCEVs planned under H2ME-2 are operational: **17 were deployed in Noot's taxi fleet** in the Hague between October and December 2020 and **Jan-Paul Kerkhof and Orange gas own one FCEV each.** As of May 2022, the FCEVs have driven approximately **839,000 km**. The taxis that refuel at the station run to other cities within a radius of approximately 50km.
- The HRS is located just outside the inner city of the Hague, near the busy business district and near the Dutch ministries. It is integrated into a BP petrol station forecourt using Resato's HRS technology. Around 100 FCEVs are active in the area and the location is very convenient for taxi companies.
- The HRS has a **capacity of 480 kg/day with 300 kg of onsite storage and this first Resato HRS was designed to cope with 3 full tank back-to-back refuelling events.**
- The HRS uses green hydrogen supplied by Air Liquide in Antwerp which is CertifHy-certified. The hydrogen is produced with green electricity via electrolysis of a sodium chloride solution which results in chlorine and hydrogen. Future supply will come from Oosterwolde green hydrogen production electrolyser which uses renewable energy.
- In the Netherlands, new HRS, some relatively close to the Hague, have also opened. Overall, around 590 FC LDV are in operation.

Source: Map: h2stations.org/stations-map

The Hague's HRS is Resato's 1st public HRS to be deployed: a benchmark for its future strategy

Hydrogen Mobility Europe

The Hague HRS

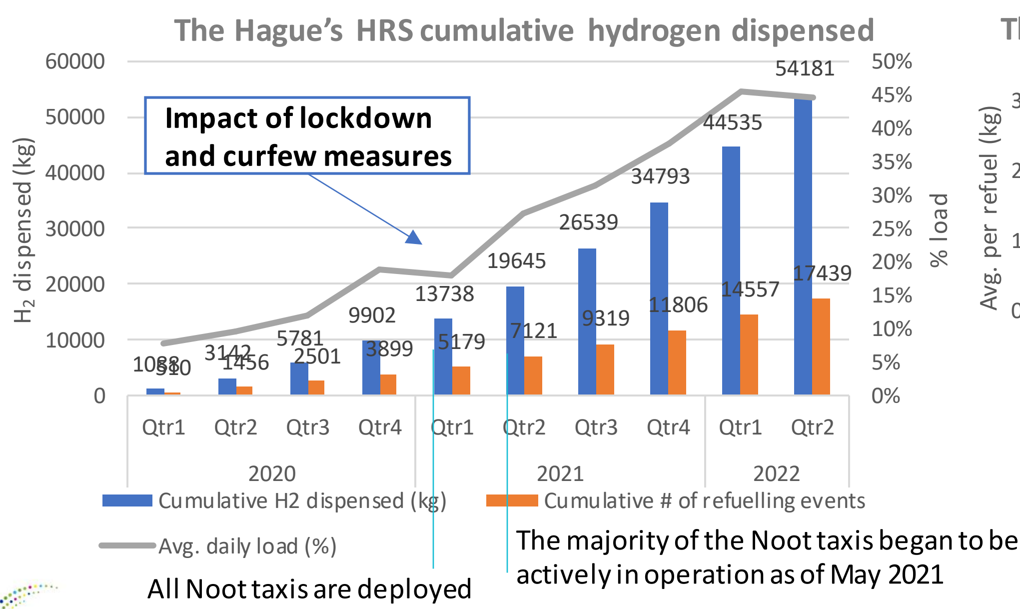
- Resato is the **supplier and technology owner of the HRS** used at the refuelling station in the Hague, the 1st of its public refuelling station FSS series (FSS1.0) to be deployed. Deployment of its successor FSS2.0 series has already started.
- Resato aims to **be in the top 3 hydrogen refuelling technology players worldwide** and will be pursuing this mission by **deploying more public and fleet owner HRS** across Europe and later worldwide.
- The **HRS in the Hague is the busiest in Europe to date**, making it a perfect case study for a HRS under high utilisation.
  - The amount of daily users refuelling at the station has been superior to what had originally been anticipated, with between 30 and 50 vehicles per day. This led Resato to experience a very **steep learning curve in 2019 and 2020.** Indeed, quick reactivity was required when the station faced downtime, availability and performance issues, especially at the beginning of the deployment, to ensure the operator and the customers were satisfied and confident about the capability of the infrastructure to meet their expectations.
  - Resato was able to fix the initial start-up issues accordingly and implement continuous improvements and innovations to its station in the Hague and to its new HRS, through, for instance, software updates and a better supply chain overall. (*Further lessons learned can be found on slide 52).*
  - Despite the higher than expected level of traffic at the station, no safety incidents have occurred.
  - Today, the **HRS has reached a high and stable level of availability which reflect the progress the supplier has made in managing its station in the context of being highly used**.
- Beyond ensuring high levels of availability and performance of its stations, Resato aims to make its HRSs **attractive business tools for operators**. This is a key element in its strategy to offer successful high utilisation HRSs. This vision entails:
  - A flawless user experience.
  - Large hydrogen capacities to meet the required daily throughput.
  - The ability to meet high demand for back-to-back refuelling.
  - An optimised supply chain with a good "Well-to-wheel" knowledge.

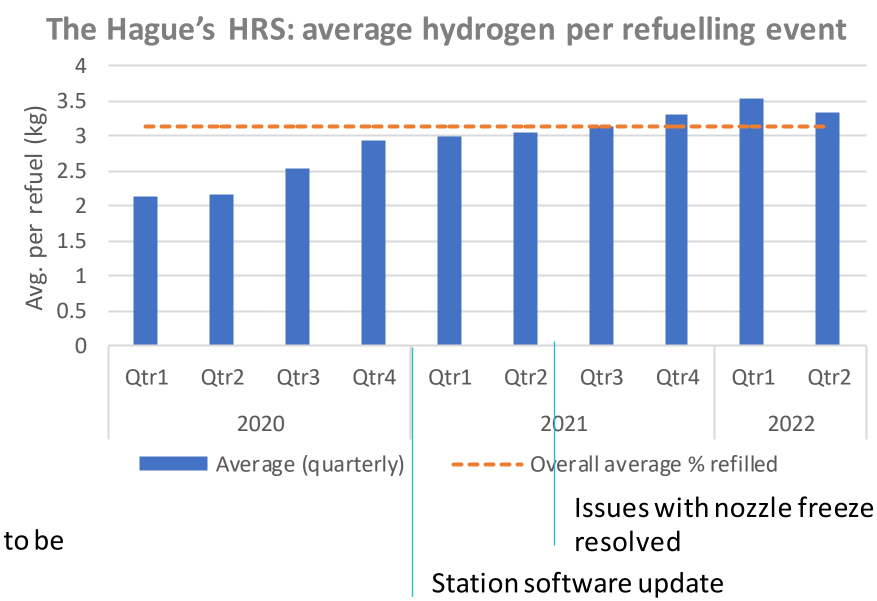
Source: Resato

The Hague's HRS reached levels of utilisation of 46% and average hydrogen dispensed per refuelling event of 3.5 kg reflecting improved confidence in the station

Demand patterns across at the HRS

- The HRS of the Hague dispensed **61,917 kg of hydrogen as of September 2022**. The HRS is SAE J2601 compliant which should guarantee a fill time of approximately 1kg per minute at 700 bar.
- The number of refuelling events gradually increased, as did the average hydrogen amount per refuelling. For **Q2 2022**, the average hydrogen per refuelling event was of **3.35 kg** and the overall average for the station since the opening was of **3.11 kg**. The progressive increase in refuelling efficiencies is understood to reflect the growing confidence of drivers towards the stations availability and the improved station software ensuring more successful full tank refuellings.
- The **average daily load** as of June 2022 was of **45%.** Periods of relatively low utilisation in 2020 and 2021 can be in part explained by the Covid-19 pandemic.





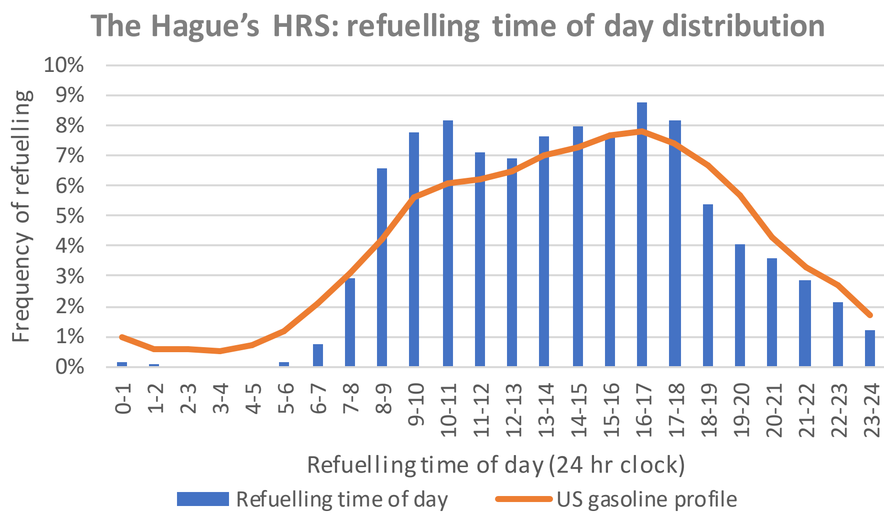
Source: Internal project data, Cenex (data up to Q2/Q3 2022).

The demand in the Hague is concentrated between 9am and 5pm, generating a higher chance of B2B refuelling

Hydrogen Mobility Europe

Daily utilisation profiles

- The graph (right) shows the average daily utilisation of the Hague's HRS, which supports the refuelling of approximately 60 Mirais (1st & 2nd gen) and Nexos (mainly taxis).
- The HRS is closed between midnight and 5:00 AM. Therefore, **refuellings are compressed into a smaller timeframe** and the peak is longer than what can be observed in other locations (e.g., in Roissy).
- Findings from the Monte Carlo simulation conducted show that the smaller the refuelling window, the **higher the chance of back-to-back refuelling**. For the station, this **probability is of 20%.** This seems to confirm that the station is performing well even with relatively frequent back-to-back events.



- In Q3 2022, 2,358 refuelling events occurred, which gives an **average of 25 refuelling per day**. As most refuellings are done during the week, the average between Monday and Friday is above 35.
- However, **this number can increase quite significantly (x2) if the nearest station (i.e., Rotterdam) is unavailable**. Indeed, drivers which would ordinarily refuel in Rotterdam would need to drive to the HRS in the Hague (~40km) hence increasing the traffic at the station.
- Users of the refuelling station can get **access to HRS availability information** through the public **H2Live application** or via the **private Dutch Whatsapp group**. This enables users to be aware of issues at the different stations and therefore the consequences this may have on waiting times to enable them to plan for their day and trips accordingly.
- Currently, the station at the Hague can allow **for 3 full back-to-back refuelling** and **maximum 8 back-to-back refuelling if the tanks are not fully refuelled** thanks to the 350 bar 2nd dispenser. (The use of the 350 bar dispenser to carry out additional back-to-back refuelling is mainly applied when other stations are down).

Source: Internal project data, Cenex (data up to Q3 2022).

The strategic location of the HRS and the continuous learning process are enabling the station to experience growth in its utilisation rate

Hydrogen Mobility Europe

Key learnings for HRS with high utilisation

- Lessons learned on the strategy behind the location and deployment of the HRS
  - The HRS is in a **very central location** in the Hague, close to very busy districts. Thanks to the presence of the HRS, the **number of non-H2ME cars in the area has increased.**
  - However, the car deployment (especially of taxis) and the realisation of the HRS could have been more aligned.
  - In the future, the stations which will experience the highest utilisation rates will be those located in areas where HDV are deployed. Modular stations will be the best prepared for this situation.
- Reliability and efficiency key learnings and best practices
  - The **HRS had some initial start-up problems.** This is the first full-size HRS to be commissioned and operated for both BP Kerkhof and Resato. It is therefore a **continuous learning process** to make the HRS more stable and develop innovations to make the station more reliable.
  - Problems faced at the start of the project included equipment-related issues (I.e., software issues, cooling, and fuelling-nozzle). Initially, communication with the suppliers to resolve these issues was intermittent. However, as the suppliers and Resato learned to work together and as the station began to see its utilisation rate increase, the **communication with the suppliers improved consequently leading to better overall performance of the HRS**.
  - As the number of vehicles using the station increased, measures were implemented to mitigate the risk of high waiting times at the station during peak periods. A **software** was installed in mid-2021 to give drivers the **option between refuelling a full tank of hydrogen** (and having to wait) or **only half a tank** (and having little to no waiting). This followed a previous HRS upgrade which led to the **improvement of communication between the vehicles and the stations to optimise the overall refuelling process.** The refuelling time was fine tuned thanks to this enhanced communication, supporting the improvement of the state-of-charge and consequently the overall hydrogen dispensed at the station. These software updates aim to continue reducing the time required for a successful full tank refuelling.

Successful high levels of utilisation are enabled by applying technical and managerial lessons learned and by ensuring the long-term support of local authorities

Hydrogen Mobility Europe

Key learnings for HRS with high utilisation

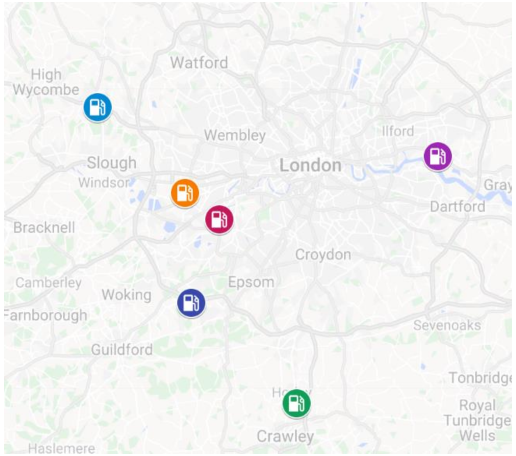
- Reliability and efficiency key learnings and best practices (continued)
  - The Resato lessons learned from the **FSS1.0 series have been implemented into the successor FSS2.0 series** (e.g., increased capacity allowing for continuous **back-to-back for H70 refuelling** to meet today's fuelling requirements combined with better adaptation towards HDV H35 high fuelling demands).
  - **How drivers use the equipment impacts the reliability of the station**. **Improving the performance and the user experience** of a HRS will consequently reduce the risk of drivers damaging the equipment due to abrupt handling of the material.
  - **Aftersales** of HRS are a key element for high-utilisation stations. This is ensured by **preventive maintenance** which enables to avoid unexpected downtimes caused by unforeseen technical problems, **cooperation with large local service partners** and thorough **HRS maintenance training** (of employees and in collaboration with schools).
- Lessons learned on the importance of the support from local authorities in the ensuring the long-term success of a HRS
  - As of today, the Hague's HRS can be categorised as a **high utilisation HRS** and is performing very well with high levels of availability and a continuously increasing number of refuels. However, with the recent announcement from the Hague's municipality regarding the **ban of FCEV in the next zero-emission tenders for target group transport,** questions arise on the **future hydrogen demand landscape for the station** as taxis currently represent the majority of the demand. Therefore, **liaising with local authorities early on to inform them on the various benefits hydrogen-fuelled passenger vehicles bring is key to ensure a stable and growing long-term utilisation of the HRS**.

Contents

Following a change in strategy, only 2 HRS are still refuelling FCEV in the London area. These stations are the ones which had the highest utilisation rate

Hydrogen Mobility Europe

The London network



Station	Operator	Capacity	Status
Hatton Cross/Heathrow	Air Products	80 kg/day	Open
Teddington	Motive	80 kg/day	Open
Rainham	Motive	80 kg/day	Open
Cobham	Motive	80 kg/day	Closed
Beaconsfield	Motive	80 kg/day	Closed
Gatwick	Motive	80 kg/day	Closed

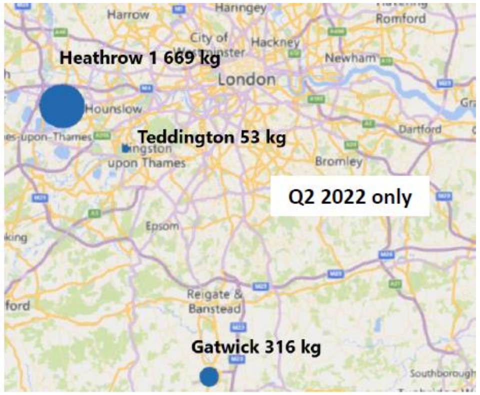
- In London, **six HRS used to support the operation of over 70 vehicles** in fleet applications. However, now only three are still in operation since (*further explanations in the next slides).*
- The HRS are owned and operated by Motive* (excluding Hatton Cross) and use on-site electrolysis to produce hydrogen for the vehicles. The remaining operational HRS are **focused in the East and West linked to major roads** in, and out, of the city.
- Utilisation of the London stations increased dramatically from 2018 as a result of large fleet services being deployed by:
  - **Green Tomato Cars (GTC)** – 50 FCEVs deployed in private hire services as part of H2ME's successor project 'ZEFER'. Vehicles average **over 44,000km per annum** and have **consumed 33,800 kg of hydrogen** between April 2018 and September 2021 (latest data available). Since October 2022, no FCEV are operational within the GTC fleet.
  - **The Metropolitan Police Service (MPS)** – 21 FCEVs deployed in emergency service applications. 11 vehicles are used as emergency response (H2ME) and 10 are placed in 'general purpose' services (ZEFER)**. Mileage depends on service calls and, as such, annual mileages can vary dramatically. Overall, the fleet has **amassed over 780,000km** and **consumed over 11,500kg of hydrogen** cumulatively.

**Motive is a joint-venture established in March 2022 between ITM Motive and Vitol. Motive owns all the UK HRS constructed by ITM Power. In the following report, ITM Power will be used when referring to the equipment and Motive for all topics related to the ownership and operation of the station.*
***First 11 vehicles entered operation in April 2018, followed by the ZEFER (11) vehicles in February 2019*

With the evolution of the hydrogen mobility market since the first demonstration projects, strategic investment decisions for HRS are now focusing on long term viability

- ITM Power is one of the longest-running providers of HRS solutions. They deployed first series products in a number of early demonstration projects enabling them to gain expertise on the market and improve their technology to fulfil customer requirements while supporting the development of the market.
- In recent years, dedicated operators taking over operation of HRS from equipment suppliers have started to appear as the market developed. In the case of London, the operation of HRS built by ITM Power was transferred to Motive Fuels. A review of these assets concluded that **some of the strategies adopted in the early years were no longer well suited to the needs of the current market**, hence leading to a **decision to close some of the early sites**.
  - Vehicle deployments from the light duty segment remains limited in the UK and London. The location of sites initially selected is not well suited to fleet operation in central London and these sites cannot be upgraded to deliver hydrogen to the heavy duty segment. Because of this, low demand levels are expected at these sites for the foreseeable future, which makes the **economic case for continuing operation challenging.**
  - Moreover, the equipment of these **first generation stations is no longer efficient compared to the new technologies** developed in recent years and can be expensive to maintain or repair. On the other hand, fleet operators naturally have high expectations on availability of the network. The GTC vehicles in London have been gradually taken off the road. Of the 50 vehicles deployed under ZEFER, 25 were de-fleeted in April 2022 and the remaining 25 retired in October 2022 as they reach the end of the leasing contract and this despite positive feedback regarding the vehicles themselves from the drivers. A key factor in this decision was the limited number of HRS and concerns around availability.
  - As a result, 3 out of 6 HRS were closed in London in the summer of **2022**. The remaining HRS provide sufficient capacity to support the remaining users in London. Future sites will need to be developed in collaboration with identified users to ensure that the location and specifications of the HRS fully meet the demand of users.

Volume of hydrogen (kg) dispensed across the London HRS network to GTC FCEVs (for Q2 2022)



The following slides review the experience acquired over the past years across the London network and specifically look at utilisation patterns at Teddington and Rainham as these stations provide the best insights on operation under 'high' utilisation.

1: ZEFER, D3.4 - Bi-Annual Technical Report on Vehicle and Refuelling Station Operation, 2022, Cenex.

The GTC trial showed that stations which are more centrally located are more highly utilised by fleet drivers in London

Hydrogen Mobility Europe

Demand patterns across the London network

- Before the deployment of the GTC and MPS fleet, utilisation of the HRS in the London network was low. However, as a result of fleet deployment, hydrogen demand has increased dramatically so that between April 2018 (when the vehicles were deployed) and June 2022 **over 68,000 kg of hydrogen was dispensed across the London network**.
- The map (right) shows the cumulative volume of hydrogen dispensed across the stations in the network to GTC FCEVs. Note that some stations have not been open for the full period and hence have lower dispensed volumes (e.g., Q4 2019 for Gatwick).
- **Over the course of the whole trial, Teddington and Rainham have received the most demand to date**, responsible for around 70% of the hydrogen dispensed across the London network. Concentration of demand at these stations is likely due to their **proximity to the city centre**, offering the shortest distance travel for drivers to refuel. The map shows that since the beginning of the trial, these are the two preferred stations for refuelling for GTC drivers. The MPS vehicles have also tended to refuel mostly at the Teddington station (69% of hydrogen dispensed to MPS vehicles).
- **Reducing the distance travelled to refuel is critical to the business case of fleet operation**, especially taxi and private hire services, where revenues are determined by the availability of the vehicle for customer service. Reducing 'wasted mileage' is also important for the **economic efficiency of the service** as any fuel used to commute to a station impacts the 'profits' taken from daily services.

Volume of hydrogen (kg) dispensed across the London HRS network only to GTC FCEVs (as of June 2022)[1].

- Outer-city HRS such as Beaconsfield, Cobham and Gatwick are used less frequently by drivers in London. However, **Beaconsfield and Cobham still attract ~10% demand** each as a result of GTC recruiting drivers who live in, or around, the Western cluster of HRS. The Heathrow Air Products station, opened since 2012, has also been dispensing increasing amount of hydrogen to taxis.

Clean Hydrogen Partnership

1: ZEFER, D3.4 - Bi-Annual Technical Report on Vehicle and Refuelling Station Operation, 2022, Cenex.

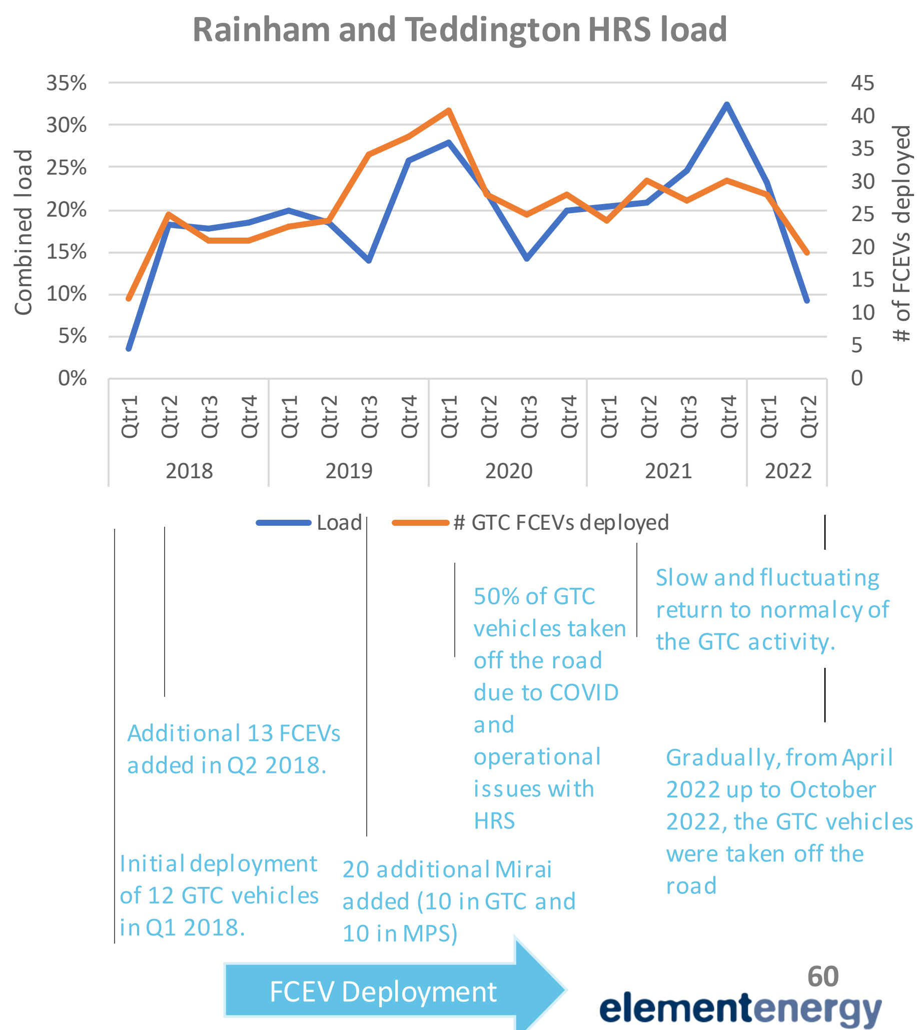
elementenergy an ERM Group company

Fleet deployment has increased utilisation of stations in central London to an average of 20% during the GTC trial

Hydrogen Mobility Europe

Impact of fleet deployments on the utilisation of HRS in central London

- The graph (right) illustrates how utilisation at Teddington and Rainham changes over time in response to FCEV deployment.
- Before the launch of FCEV fleet activities in London, the HRS network was used by private users who refuelled infrequently and in small volumes. This led to a **utilisation levels of less than 4%** at Teddington and Rainham.
- As vehicles began to be deployed by GTC and MPS, the **utilisation of the stations increased**.
- **Clear increases in utilisation can be seen in response to GTC's deployment** (graph), with station utilisation increasing by nearly 15 percentage points when 25 vehicles were introduced. A similar pattern was seen in Q3/Q4 2019 when the second batch of private hire vehicles were introduced.
- The **introduction of the MPS fleet had a less pronounced impact on utilisation** likely due to the lower daily mileage of the fleet and availability issues encountered during their launch into operation (see next slide).
- Other than in Q3 2019 and Q4 2021, there has been a relatively clear correlation between FCEV deployment and HRS utilisation. This can be used to evidence that the **HRS have responded well to increases in utilisation,** with few periods of downtime encountered**.**
- Despite the slightly fluctuating number of GTC vehicles between Q3 2020 and Q3 2021, the HRS load steadily followed an upward trend until the last quarter of 2021 and first quarters of 2022 due to the decommissioning of the GTC vehicles and issues at the Rainham station.



Clean Hydrogen Partnership

Source: Internal project data, Cenex (data up to Q2 2022).

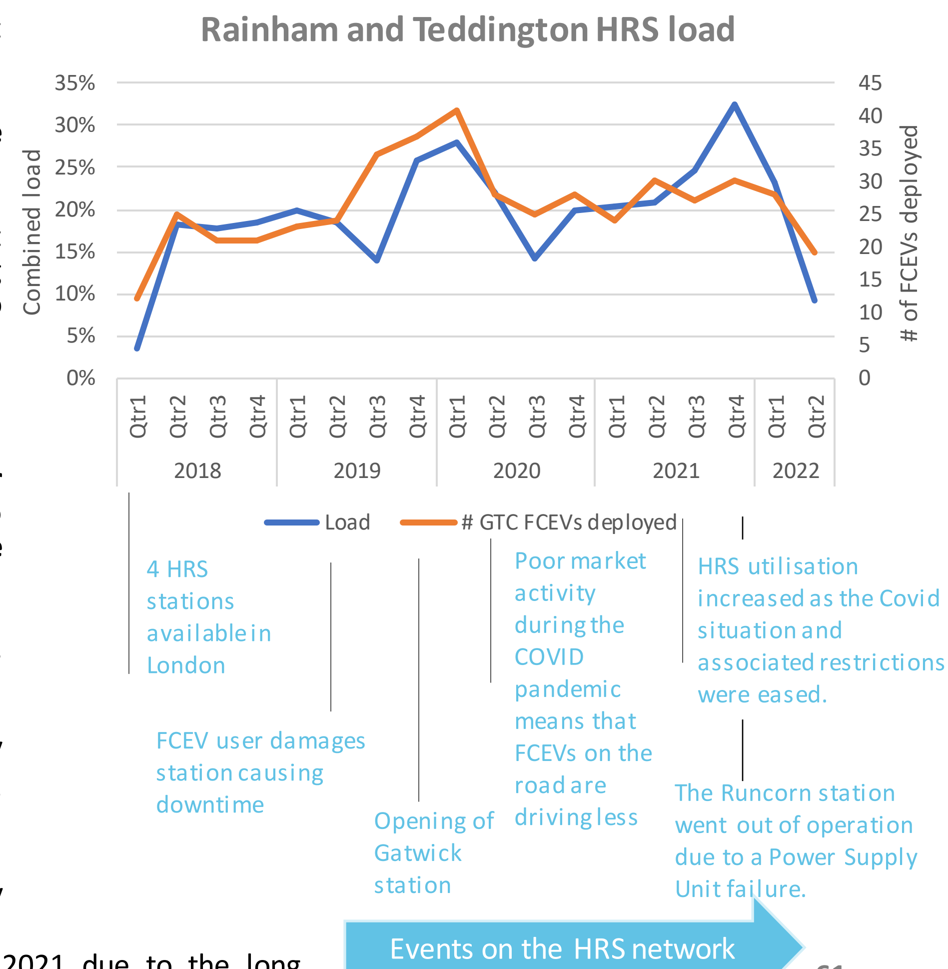
elementenergy
an ERM Group company

Isolated periods of HRS downtime and the impact of the COVID pandemic has led to sharp decreases in average network utilisation

Hydrogen Mobility Europe

Impact of fleet deployments on the utilisation of HRS in central London

- Although the graph (right) shows a relatively consistent correlation between FCEV deployment and HRS utilisation, there have been periods of divergence.
- Notably in **Q3 2019, utilisation decreased by 6 percentage points** across the Teddington and Rainham stations despite the addition of 20 FCEVs throughout the year.
- This drop came shortly after the introduction of the MPS fleet and was caused by a **period of downtime** at one station**.** During this time, no FCEV could refuel at the station and drivers **had to use other HRSs in the network to refuel** (for which data is not included in the graph)**.**
- In this instance, downtime was caused by **user damage** to the station. This is a frequent trend seen at HRSs when new drivers are introduced to fleets as station **equipment is mishandled or dropped** (e.g. dispenser nozzles, etc.). This often leads to extended periods of **downtime until a replacement part can be sourced**.
- A sharp decrease in utilisation was also seen in utilisation from **Q2 2020 onward as a result of the COVID pandemic** and its impact on the taxi market (50% of vehicles were taken off the road and fewer services were carried out by those remaining in service). Governmental restrictions also **limited ITM Power / Motive's ability to attend maintenance call outs** at the stations which has also led to periods of downtime at the stations and thus reduced utilisation.
- As restrictions were eased, the HRS utilisation steadily increased, reaching pre Covid levels in Q4 2021.
- However, the combined load reduced post Q4 2021 due to the long downtime experienced at the Rainham station.



Source: Internal project data, Cenex (data up to Q2 2022).

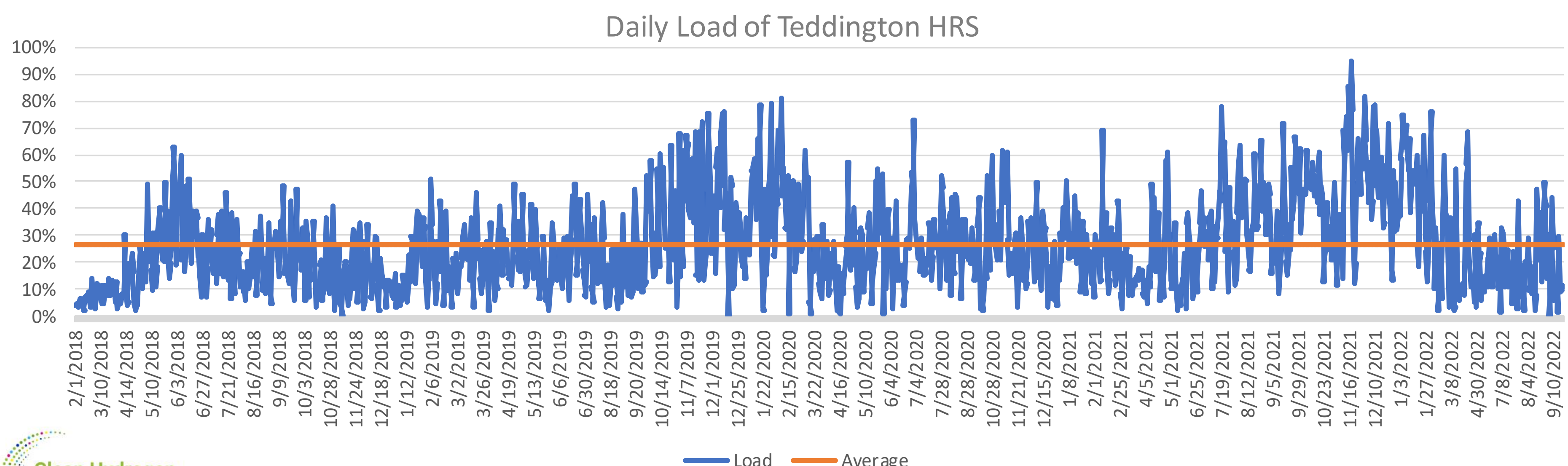
Clean Hydrogen Partnership

element energy an ERM Group company

Despite moderate average levels of utilisation, Teddington has encountered high one-off daily loads of over 90%

Daily utilisation/loading at Teddington

- **Fuel demand varies on a daily basis** depending on when and where drivers are operating their vehicles and require a refuel. This causes significant peaks and troughs in the utilisation of a station.
- The graph below shows the **daily utilisation of the Teddington station** between February 2018 and September 2022, excluding periods of station downtime.
- Although the **station average is 26%** (see orange line), there are a significant number of days when utilisation is markedly above this level. For example, when all GTC and MPS vehicles were on the road in Q4 2019 and Q1 2020, the station encountered a number of days when the **dispensed volume of hydrogen was over 70% of the station capacity**. The same observation can be done at the **end of Q4 2021 up until the end of Q1 2022 when the load also reached more than 90%** on certain days. This highlights that stations are **capable of coping with high demands and significant variances in the hydrogen dispensed on a daily basis**.
- A decrease in the daily load can be seen from Q2 2022 as the GTC vehicles began being taken off the road.

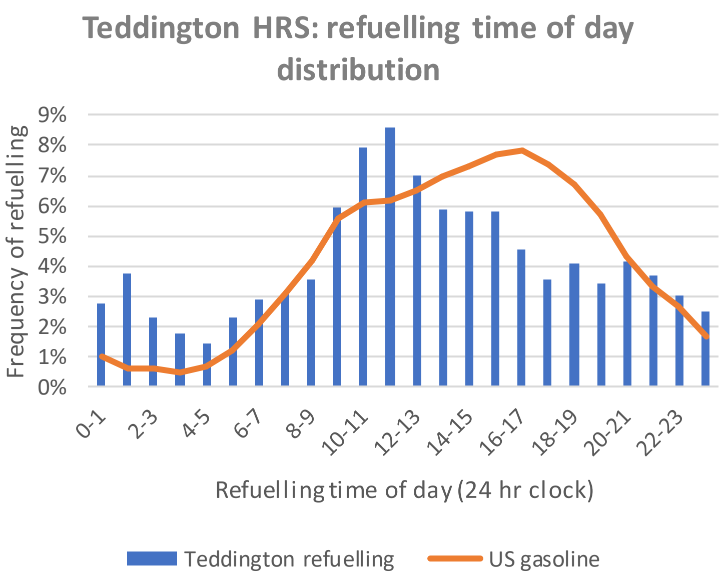


Source: Internal project data, Cenex (data up to Q3 2022).

Demands at Teddington loosely correlate with the Chevron demand but peak demands are focussed in the early and late morning hours

Daily utilisation profile - Teddington

- The hourly demand at Teddington is displayed in the graph (right) in comparison to the Chevron demand profile (orange line).
- Demands are loosely correlated with the Chevron curve. However, **peak demands are experienced in the morning** (between 10am to 12pm) instead of the late afternoon. This is likely because GTC drivers are beginning their shifts, entering the city from their homes further out in the suburbs.
- Late morning refuelling is also expected to be attractive to GTC drivers as **less congestion is expected on the roads outside of key commuting times.** This highlights again the importance of minimising wasted time/mileage for the business case of private hire operations.
- A **small peak in refuelling is seen in the early hours of the morning** between 1am to 2am when GTC drivers are finishing their night shifts.
- Utilisation patterns and correlations with GTC daily consumption figures indicates that **GTC drivers aim to refuel their vehicles at least once a day.**



- **Peak utilisation levels are slightly higher than NREL demands at nearly 9% of total capacity** of the station, equivalent to ~3 cars per hour*. To accommodate this, ITM Power have installed 42kg of variable high-pressure storage on-site which can allow several back-to-back refuels.
- Whilst the volume of high-pressure storage is over-specified for the existing demand at the station, it ensures that **drivers do not encounter waiting time** at the station (often caused by the time needed to compress hydrogen) and that **temporary disruptions to hydrogen production (~24 hours) would not impact the ability of drivers to refuel**.
  - High volumes of storage have been noted as **critical by ITM Power to reduce the risk of downtime at stations.** This is because the operator needs to account for periods of electrolyser maintenance and failure which can temporarily pause the production of hydrogen at the station.

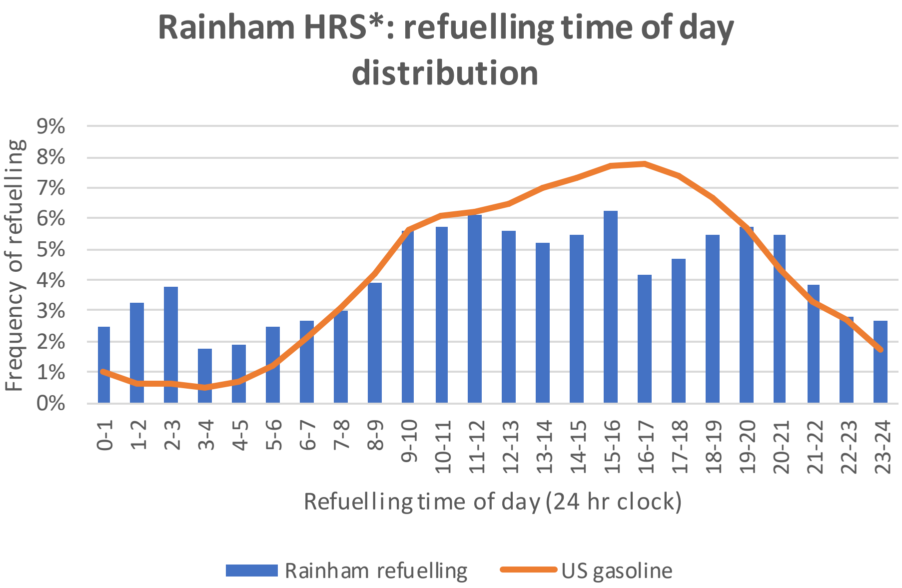
**Based on GTC's average refuelling amount of 2.2kg*
Source: Internal project data, Cenex (data up to Q4 2021).

Demand at Rainham has a flatter profile, with refuels taking place throughout the day and night

Hydrogen Mobility Europe

Daily utilisation profile - Rainham

- The Rainham station has had a flatter profile than Teddington, with **minimum demands of ~2%** during the early hours of the morning (3am to 7am) and **maximum demands of ~6%** at 3pm to 4pm.
- Peaks in demand in the early morning (1am to 3pm) are likely to be **GTC drivers doing night shifts** and refuelling before returning home.
- Demand throughout the day is relatively stable, with **~4 to 5 kg refuelled per hour**. Based on an average refuelling amount for GTC of 2.2kg, this is likely to be **two separate refuels**.
- The reasoning behind the flat demand profile at Rainham is unclear. However, it is expected to be **linked to driver tendencies to avoid travelling to the HRS during 'rush hour'** when traffic is bad and customer services are in high demand. Trips throughout the day to the station are therefore likely to be preferable to **reduce wasted time/mileage and to maximise the economic efficiency** of the FCEV operations.
- The flatter profile could also indicate **confidence in the station,** with drivers willing to refuel at any time of day without any additional concern about its availability.



Source: Internal project data, Cenex (data up to Q4 2021).
**NB: the stations was closed from November 2021 to end of year 2022; hence this refuelling pattern reflects the situation before the stop in operations.*

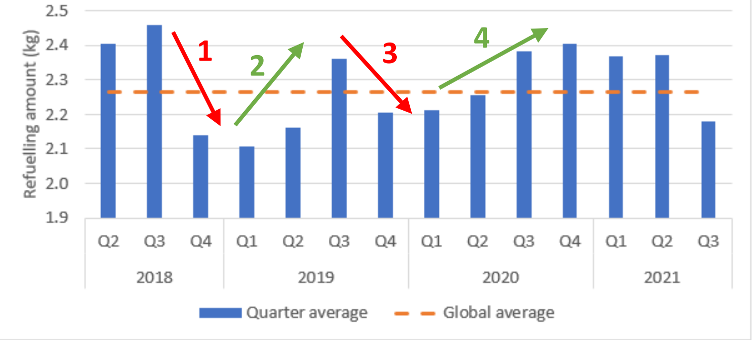
Periods of low HRS availability have caused 'range anxiety' in GTC drivers which can impact refuelling behaviour

Hydrogen Mobility Europe

Impact of HRS availability on driving/refuelling patterns

- The graph (right) shows the average amount GTC drivers have refuelled over the course of the project.
- Data shows that the **average refuel for the GTC fleet is slightly below 2.3kg,** representing only 46% of tank capacity of 5 kg. Drivers tend to drive 240km on average between refuels.
- **Periods of reduced availability in London have been seen to change utilisation patterns** at HRSs as drivers experience increased **'range anxiety'.** This often results in drivers refuelling their FCEVs more frequently than required to mitigate the risk of the HRS not being available and having to travel to the next nearest station (which is often far away). This can be evidenced in HRS refuelling data as **drivers frequently refuel small volumes** to 'top-up' their tank when they reach ~50% of their stated range (see Arrow 1).

Average volume of hydrogen refuelled by GTC drivers (kg)



Please note that the vertical axis does not start at zero.

Source: Internal ZEFER project data up to Q3 2021, Cenex.

- **Increases in refuelling amounts correlate closely with periods of improved HRS performance**. This can be seen in 2019 (see arrow 2) when a period of high and stable HRS availability increased the average refuelling amount by GTC drivers by nearly 25%.
  - Improvements in refuelling amounts are also linked to the **introduction of the ITM Availability App** which allowed drivers to check the live status of stations during their shifts. This provided **greater visibility of the network** and allowed drivers to **plan more effectively their routes and refuels**.
- Other variables (such as the introduction of new drivers or Covid) may influence the refuelling behaviours and patterns of FCEV drivers hence increasing or decreasing the refuelling efficiencies (Arrow 3 and 4).
- HRS performance can therefore have a significant impact on the utilisation patterns seen at HRS. **As confidence increases, HRS operators will have to prepare for larger peaks in daily/hourly utilisation as drivers are willing to deplete their tank capacity to lower levels and will thus require more hydrogen when they refuel.**

London HRS have responded well to high utilisation, but downtime is common when new FCEV fleets are introduced due to user error

Impact of utilisation on HRS performance

- Overall, the London network has responded well to increased utilisation, but there have been some incidents of lower availability when new FCEVs are deployed. Common reasons for this include:
  - **User error and equipment breakages** are frequent due to customer handling and false triggering of safety alarms. The picture (right) shows damage to a refuelling nozzle after just 6 weeks of commissioning.
  - High utilisation provides a significant **stress test on equipment**. In many cases, downtime has been caused by the replacement of a part which was nearing the end of its useful lifetime.
- As HRS are exposed to higher utilisation and drivers gain experience and knowledge of using HRS, availability has been seen to increase. ITM Power have also taken action to mitigate against common risks by:
  - **Storing 'high-risk' components** which are prone to user damage or technical failure at, or nearby, the HRS. This aims to avoid delays in the supply chain and ensure that parts can be quickly replaced as, and when, required.
  - ITM Power have discussed **design improvements for parts prone to user damage** with suppliers. For example, ITM Power are providing Linde with inputs into designs for a more robust refuelling nozzle.
  - **Increasing remote monitoring of stations** and improving **technician response times** to undertake emergency maintenance work.
  - **Undertaking more preventative maintenance** at stations to replace parts before they fail in order to avoid downtime.

Picture of a HRS dispenser nozzle damaged by users (Credit: ITM Power)

For future high utilisation stations, ITM Power/Motive would recommend new station designs to ensure higher HRS performance

Hydrogen Mobility Europe

Key learnings for HRS with high utilisation

- It is important to note that the London HRS have also encountered technical difficulties, with critical components failing more frequently than expected causing periods of downtime. This has led to a series of learnings to take forward into the design of highly utilised stations, including:
  - **Accounting for more redundancy in HRS designs (n+1 philosophy),** with separate process lines between the electrolyser and dispenser to ensure that one component failure does not lead to full station downtime. An increase in the number of dispensers was noted as very important to avoid repeating issues with user damage.
  - **Increased volumes of high-pressure storage** to support high peak demands and to act as a back-up in case of a system failure. It is expected that new station designs involving on-site production need to account for between two to three days average demand in order to support periods where electrolyser maintenance is required or downtime is encountered.

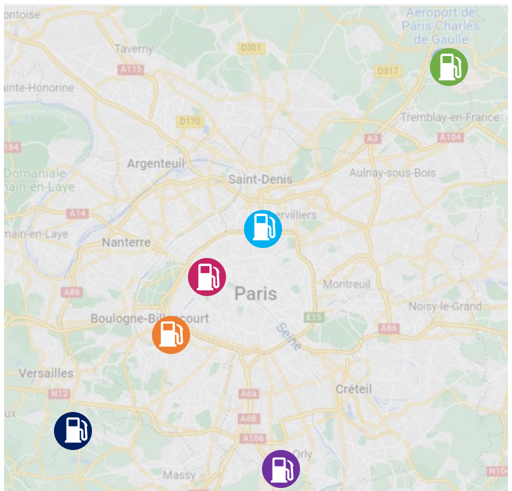
- Aside from the technical design, ITM Power / Motive have also noted the value of improved management of HRS for higher utilisation. This has led to the a series of learnings, including:
  - **Clear communication with end users** regarding the availability of stations helps manage expectations. This led ITM Power to devise a live availability app which gives the status of stations and notifies drivers if any are unavailable due to maintenance or downtime.
  - **24/7 customer support is required** to ensure that any failures or incidents are quickly addressed and to increase the value of remote monitoring.
  - **Remote monitoring and maintenance** of the station is essential. There have been many instances where drivers have triggered false alarms which can be quickly addressed by resetting the system software.
  - **Personnel and companies in charge of HRS operation need to be separated from suppliers**. This ensures that sufficient resource is appointed to the HRS operation and customer response.

Contents

6 HRS have been deployed in conjunction with FCEV taxis in Paris, France

Hydrogen Mobility Europe

The Paris Network



Station	Operator	Capacity	Status
Alma	Air Liquide	40 kg/day	Reopening Q2 2023
Orly	Hysetco	200 kg/day	Open
Versailles	Air Liquide	200 kg/day	Open
Porte de la Chapelle	Hysetco	250 kg/day	Open
Charles de Gaulle	Hysetco	150kg/day	Open
Porte de St Cloud	Hysetco	1,000kg/day	Soft opening Q4 2022

- Paris hosts one of the largest fleets of FCEV taxi fleets in the world, with **over 160 vehicles operated by HYPE or Hysetco each driving an average of 75,000km per year**. Small fleets of Symbio range-extender vans are also in operation in the city, but their demand is comparatively small.
- Taxi operations are supported by **5 (soon to be 6) key stations which are placed strategically in the city**, either close to major airports (Orly and Charles de Gaulle) or in the city centre (Porte de St Cloud, Alma*and Porte de la Chapelle**). This aligns well with business models for HYPE or Hysetco's taxi operations which rely on identifying demand in the street (i.e. customer hailing).
- Most stations in the city (excluding Alma and Les Loges) are **operated by HysetCo** and utilise trucked-in low carbon hydrogen. The stations were previously operated by Air Liquide. Air Liquide remains in charge of the maintenance from level 2 onwards of these sites.

** The HRS in Alma was set in operation for the COP21 and is currently out of operation. Reopening expected in Q2 2023.*
***HRS outside of the H2ME project.*

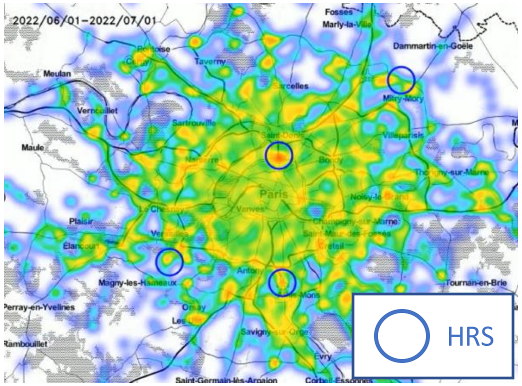
Hydrogen demand has largely been centred on HRS at airport locations where the FCEV taxis operate: Orly and Roissy Charles de Gaulle

Hydrogen Mobility Europe

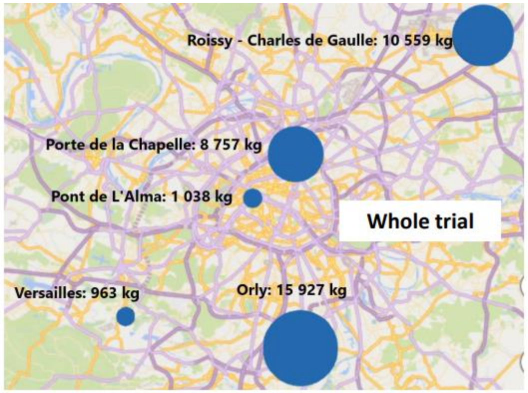
Demand patterns across network

- The vehicle heatmap (top graph on the right) is a monthly summary heatmap for the month of June 2022 showing the area in Paris where FCEV taxis are most active. Red areas highlight intense activity of FCEVs, reducing to few activities in blue. The map shows that the **majority of FCEV taxi operations are focused within the A86** (the Super-Périphérique (ring road) of Paris) and that frequent trips are made to the three H2ME HRS at Orly, Charles de Gaulle and to the most central HRS, Porte de la Chapelle.
- This is also reflected in the level of demands seen at the HRS (see bottom right), with the three stations dispensing over **94% of the hydrogen dispensed to Hype fuel cell vehicles** across the Paris network.
- As of June 2022, the Roissy and Orly HRSs have dispensed 34,755 kg and 75,031 kg of hydrogen overall respectively since beginning operation (between Q3 2017 and Q4 2018).
- Orly is of specific interest as the station has become one of the **most utilised light-duty HRS in the project**, and across Europe more generally, with **average utilisation of 36**% (pre-COVID) and **above 27% since Q3 2021** (i.e., post-Covid) with continued improvement expected. Data from the station indicates that an average of **36 refuels are completed at the station per day** (prior to COVID-19), with the average amount dispensed being 2.1kg (42% of the tank capacity (5kg)). The average number of refuels per day is slowly increasing post-Covid with approx. 23 refuels per day.

Heatmap showing FCEV activity in Paris in June 2022[1].



Map showing the volumes of H2 dispensed per station (to ZEFER vehicle) during the whole trial (i.e., since Q2 2018)[2].



1: Cenex (2020) Internal project data.
2: ZEFER D3.4 - Bi-Annual Technical Report on Vehicle and Refuelling Station Operation, 2022, Cenex.

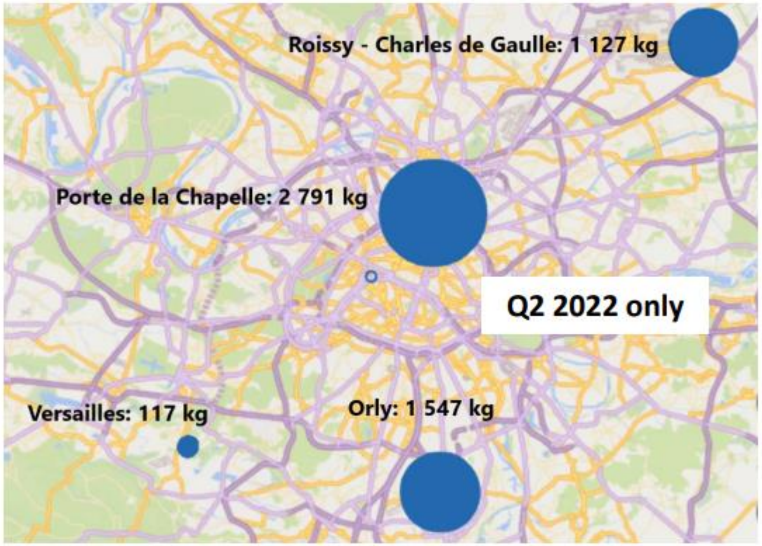
However, the pattern is slowly changing as the HRS at Porte de la Chapelle conveniently located closer to the center is dispensing increasing amount of hydrogen to FCEV

Hydrogen Mobility Europe

Changes in the demand patterns across network

- As of Q2 2022, **Porte de la Chapelle represented 50% of the total hydrogen dispensed** to the **Hype fuel cell vehicles** across the Paris network.
- The Porte de la Chapelle station, operated by Hysetco, was inaugurated in July 2021. It has the biggest capacity amongst all the stations in the Paris area and a newer and more standardised designed compared to the earlier commissioned stations. This enables the HRS to have a more efficient operation and optimised utilisation.
- This particular station has become increasingly popular since Q3 2021 as many taxis have their depot/base at the same site. Moreover, this site is the more centrally located site in Paris at the moment and convenient for operation in central Paris.
- The Porte de la Chapelle station is not a permanent station as the land is leased by Hysteco and is therefore dependent on the owner's decision to extend or not the lease. If it is not extended, the station will be relocated.

Map showing the volumes of H2 dispensed per station (to ZEFER vehicle) during the Q2 2022 [1].



- The **Versailles station is not used frequently by the taxis** (as mostly destined for the buses in the area) **but is used as back-up** when the Orly station is down.
- The **Roissy and Orly stations** are part of the older generation stations. They continue to dispense important amounts of hydrogen to the taxis fleet. However, upgrades in Orly to enable more hydrogen to be dispensed (and to other vehicles) are challenging due to space constraints. The Roissy station could be upgraded to add more capacity or to add another compressor for increased reliability. However, such improvements would be less valuable than the potential a new station, with a scalable design, could bring (e.g., Porte de la Chapelle).

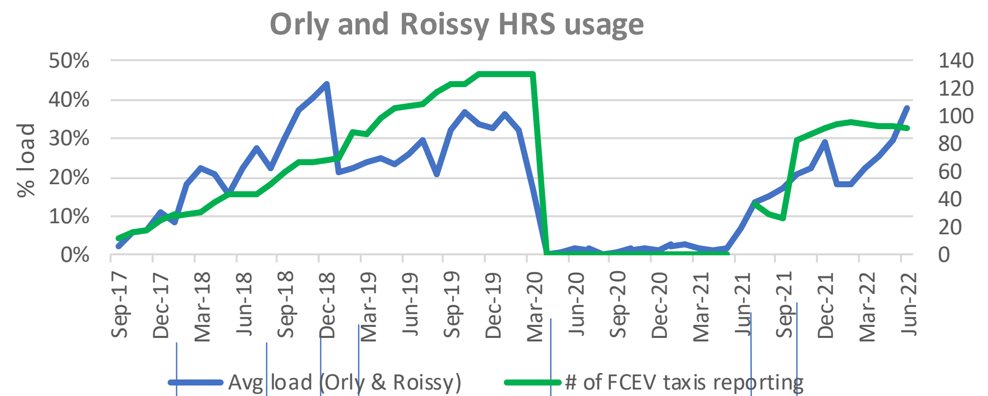
1: ZEFER D3.4 - Bi-Annual Technical Report on Vehicle and Refuelling Station Operation, 2022, Cenex.

HRS have responded well to sharp increases in demand as new FCEV fleets are introduced and began recovering from the impactful Covid-19 period

Hydrogen Mobility Europe

Impact of fleet deployments on HRS utilisation

- The graph (right) shows how the load of the HRS (i.e., utilisation) has increased as more FCEVs have been deployed into operation.
- Sharp increases in utilisation can be seen throughout 2018, with **peak demands of nearly 45% reached in December 2018** (before Charles de Gaulle was commissioned).
- Significant peaks in demand prior to December 2018 highlight that Orly **can respond to sudden increases in utilisation** without encountering significant technical issues. Short periods of downtime were encountered, but once remedial works were complete, the station was able to **cater to high demands immediately**.
- The **Charles de Gaulle station has also responded well after its commissioning**, with utilisation steadily increasing from 12% in January 2018 to 30% in January 2020 with no significant periods of downtime.
- The Covid period between Q1 2020 and Q2 2021 significantly affected the HRS load. After Q2 2021, the FCEV taxis and HRS activities restarted, enabling the number of FCEVs back on the road and reporting data to reach 91 as of Q2 2022 and bringing the average HRS load back up to 38%, reaching pre-Covid levels.



12 FCEV in operation

30 FCEVs in operation

60 FCEVs in operation

Commissioning of Charles de Gaulle HRS – lower utilisation of new station brings down average

131 FCEVs in operation. All vehicles taken off the road in March 2020 as a result of the pandemic.

Covid situation and restrictions eased. FCEVs gradually are put back into operation

In Q3 2021, some of the HYPE vehicles were defleeted. In Q4 2021, the number increased again to plateau at 91.

Source: Internal project data, Cenex (data up to Q2 2022).

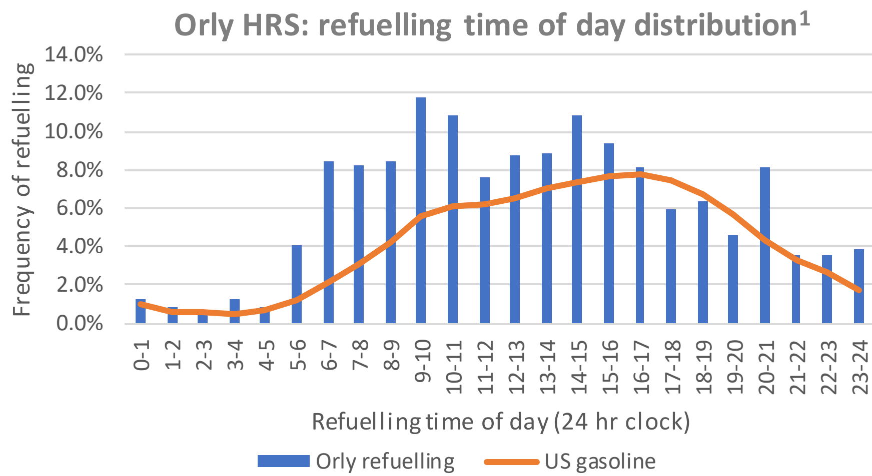
Clean Hydrogen Partnership

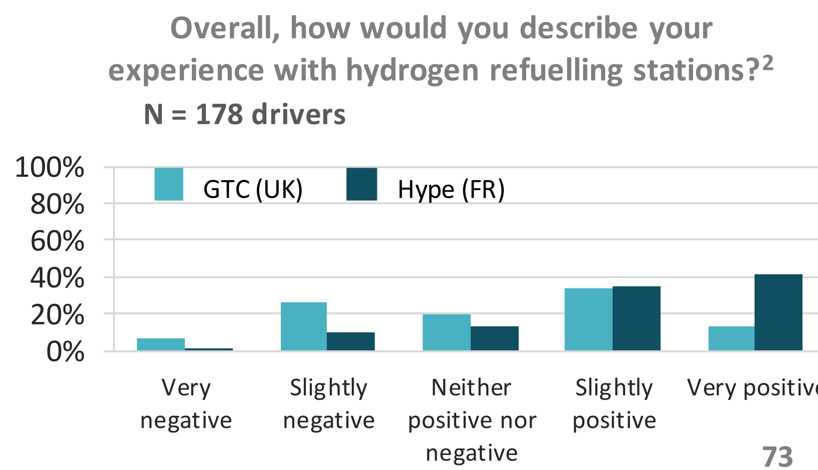
elementenergy
an ERM Group company

Daily refuelling profiles at Orly indicate that drivers are quite confident that they can refuel at any time of the day

Daily utilisation profiles – Orly

- The graphs (right) show the average daily utilisation of the Orly HRS, located close to the city airport.
- Orly shows a **more important demand for refuelling in the morning (with a peak end of morning between 9am and 11am) and at the end of the day around 8pm**. A peak is also observed after the lunch period. Throughout the rest of the day, the frequency remains quite stable at about 8%.
- This **closely mirrors the times the airport is busy** and thus when customers are likely to need taxi transport in/out of Paris. Refuelling during driver shifts could be a result of the proximity of the HRS to the airport. However, this is also thought to be a **reflection of driver confidence** in the technology, with few having concerns about their ability to refuel at any given time. This is reflected in survey results where French drivers overwhelmingly **described their experience of HRS as 'positive' or 'very positive'**.
- Good perceptions of HRS may be linked to the archetype of stations in Paris, with all Air Liquide models based on hydrogen delivered to site. This often means that there are **fewer instances of downtime due to the production chain** (in comparison to on-site electrolyser production) and **high volumes of hydrogen stored on site.**



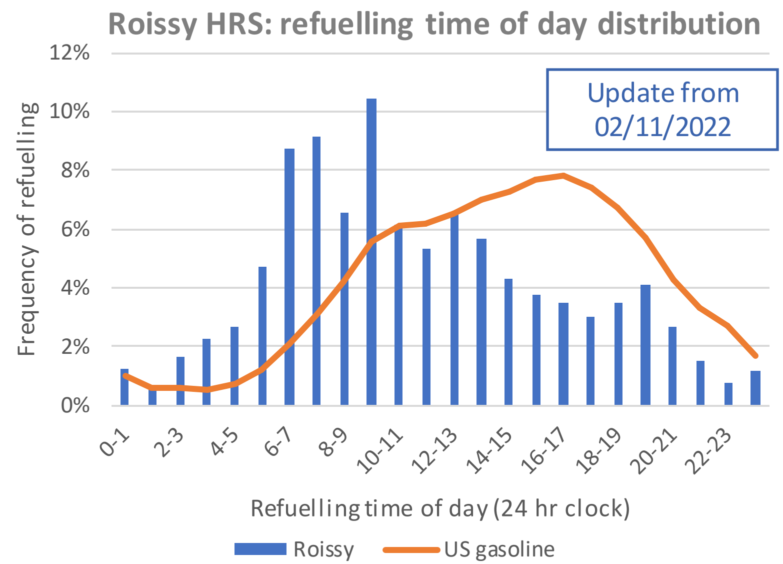


1: Internal project data, Cenex (data up to Q2 2022).
2: ZEFER D4.7 – Summary of customer value proposition of FCEV/HRS in the ZEFER project, June 2022, Element Energy

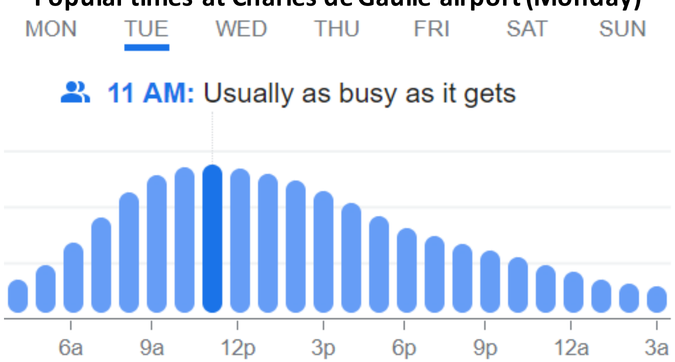
Peak demands at Charles de Gaulle closely mirrors customer demand at the nearby airport, with many drivers refuelling before their shift to reduce wasted mileage/time

Daily utilisation profiles – Roissy Charles de Gaulle

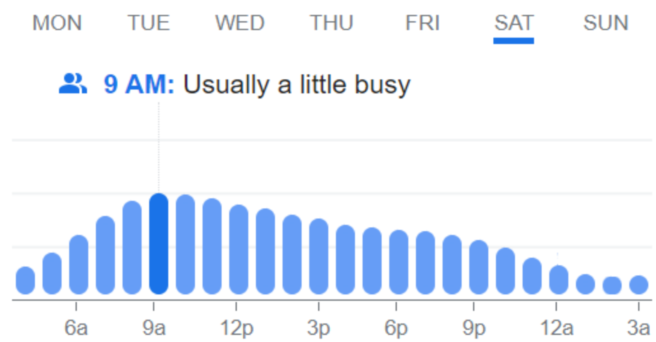
- Demand at the Charles de Gaulle HRS is quite similar to Orly, with utilisation increasing rapidly from 5am onwards. After 10am, the frequency of refuelling slowing decreases for the rest of the day.
- The demand at the station follows closely the most popular times at Charles de Gaulle airport (see below). Drivers therefore likely **refuel before starting their "airport shuttle" shifts** into/out of Paris.
- However, relatively steady demands throughout the day indicate that drivers are **willing to refuel during their shift**. This is likely because the station is close to the airport, meaning that drivers do not have to travel out of their way to refuel. However, this could also reflect the operational model of FCEV taxis, with the business focussing on shuttle services throughout the day.



Popular times at Charles de Gaulle airport (Monday)



Popular times at Charles de Gaulle airport (Saturday)



Source: Internal project data, Cenex (data up to Q2 2022).

Air Liquide are already implementing learnings from the project into future station design

Hydrogen Mobility Europe

Key learnings for HRS with high utilisation

- Whilst the HRS in Paris have responded well to increasing utilisation, Air Liquide has noted a series of design improvements which will be implemented into the new stations, including:
  - **Building redundancy into the system** – going forward, Air Liquide will install at least 2 to 3 dispensers in highly utilised stations. This will allow one process line to fail without the full station being forced into downtime. Redundancy can also facilitate better management of the station as maintenance can be isolated to a certain process line or dispenser, without impacting the ability of drivers to refuel.
  - **Improving the supply chain** – as Air Liquide use trucked-in hydrogen to supply their stations, a key concern is the security of the supply to the site. To improve this, Air Liquide are working on the optimisation of the logistics chain in the city, replacing conventional tube trailers with larger capacity ones. This will allow higher volumes of hydrogen to be transported into the city in one go to optimise the logistics costs and reduce the greenhouse gas emissions per kilogram of hydrogen. The approach also aims to improve the performance of the station, with the higher inlet pressure of the hydrogen reducing the compression ratio required for cascade filling. The time taken to compress the hydrogen is therefore reduced, meaning more back-to-back refuelling can be accommodated.
  - **Increasing the hydrogen storage on-site** – by increasing the capacity of tube trailers, Air Liquide are also increasing the volume of hydrogen stored on site as the equipment can be used as 'temporary storage'. This can provide the station with greater autonomy, especially on weekends when large trucks are forbidden on the roads. Air Liquide are also investigating increasing the volume of high pressure hydrogen stored on-site at new stations to cater to the higher number of dispensers and to improve back-to-back performance of the station.
  - **Improving temperature regulations** – this reduces the probability of a refuelling event being prematurely terminated
  - **Onsite stock of key component spare parts** – downtimes due to technical issues at the station can significantly impact the operation of the station and behaviour of drivers who might as a result have less confidence in the stations' capacity to deliver hydrogen when needed. Air Liquide highlighted the importance to keep spare parts onsite for key components of the station to avoid as much as possible long downtimes, amplified by issues with the overall supply chain of these parts.

Air Liquide highlights the importance of the management of the station for it to be successful and the fact that future stations will need to be able to accommodate heavy duty vehicles to further increase their load rates

Hydrogen Mobility Europe

Key learnings for HRS with high utilisation

- Improvements in the management of the station were also noted as critical to a positive experience with the HRS. To facilitate this, Air Liquide has **increased their communication with drivers** using apps such as FillnDrive and launching a 24/7 support line. Response times to failures have also been a key area of improvement, with Air Liquide introducing a graded system for faults, with maximum response times enforced.
- **Heavy duty vehicles and buses are expected to become a key focus** for Air Liquide and for their HRS. Due to their heavier weights and often higher expected average daily range, their tanks have more capacity. This entails that **such vehicles would bring the amount hydrogen dispensed by a station up**. It is therefore necessary for HRS to be designed (or upgraded) to accommodate such vehicles through increased capacity, storage and number of dispensers to ensure they are future proof.

Contents

High-pressure hydrogen storage tanks can be used to reduce downtime

Designing HRS to minimise downtime

- During HRS operation, pieces of **equipment upstream from the high pressure storage**, such as the electrolyser or compressor, **may break down** and require maintenance.
- During the time this equipment is being fixed, **hydrogen can still be dispensed from the high pressure storage**. This helps the station to serve customers even during equipment break downs.
- However, often the volume of high-pressure hydrogen stored on site is **limited to a day's supply**, meaning that any failures or maintenance work that stretch beyond this time period will result in station downtime.
- **Increasing the volume of high-pressure storage available on-site is therefore often viewed as a simple way to reduce downtime** caused by production (if on-site electrolyser are used) or delivery (if hydrogen is trucked-in to the station) and to ensure that end user demands can be met.

ITM Power Shell Hydrogen Station. Credit: ITM Power

Achieving approvals for upgrading high pressure storage on-site could pose a challenge to operators

Hydrogen Mobility Europe

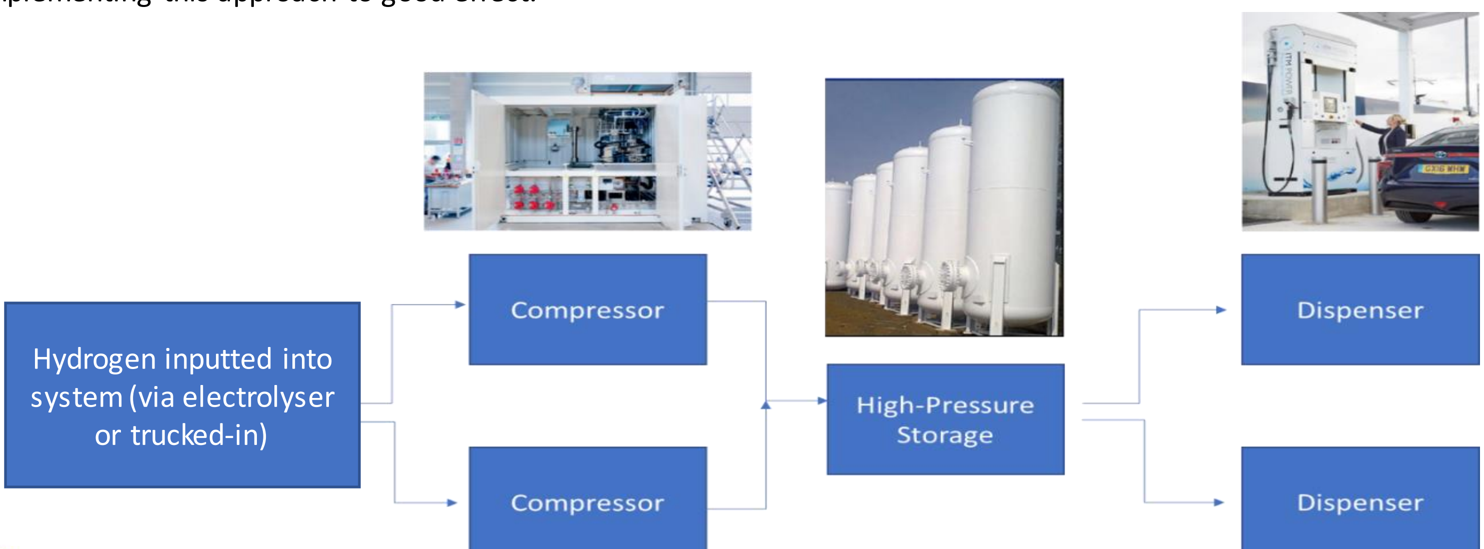
Designing HRS to minimise downtime

- Increasing the volume of hydrogen stored on-site does however often pose a challenge to operators and its feasibility will depend on:
  - **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. standing 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 surrounding them 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 may 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 have to be convinced of the safety of the technology.
  - **Approval from landlords –** HRS operators will need to seek landlord approval for the installation of additional high-pressure storage on-site. This can be a long process and can be hard to secure.
- High pressure hydrogen storage also comes at a **significant cost to HRS operators**. In order to justify this, high and consistent utilisation will need to be encountered at the station to allow revenues to cover the cost premium.

Introducing redundancy into the system is key to improve performance with increasing utilisation

Designing HRS to minimise downtime

- As noted in the availability section, many of the HRS within H2ME are designed with one process line meaning that **any failure in the system will cause downtime** of the station.
- A key learning from the project has been to **design HRS with an ‘n+1’ philosophy** whereby all equipment (especially high-risk components) has a back-up on a separate process line. This means that if a failure is encountered, the station can remain open just with fewer dispensers.
- Redundancy is also important in helping HRS operators **minimise disruption caused by maintenance** as one process line can be ‘switched off’ to allow isolated technical works. The other system can remain operational and open to the public to reduce the impact on station availability.
- 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.



Simplified example of station designed with n+1 redundancy

Ensuring back-up hydrogen supply chains are in place is a key mitigation strategy

Designing HRS to minimise downtime

- In order to minimise downtime, HRS operators need to prepare for disruptions to hydrogen production caused by **electrolyser malfunctions/maintenance** or **failed deliveries** to site.
- Due to the immaturity of the hydrogen market at current, many HRS operators do not have significant 'back-up' hydrogen production facilities. This often means that the **downtime of a HRS is extended until equipment can be fixed or supply chains can be re-established**.
- Ensuring that there is a back-up supply of hydrogen is therefore a good approach to minimise downtime at the station. 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, this is often **not transported to the HRS experiencing downtime** due to high costs and logistical difficulty of the process. Drivers are instead diverted to the station directly.
- Overall, these back-solutions come at a price. 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.

Air Liquide hydrogen tube trailer.

Contents

Clean Hydrogen Partnership

elementenergy
an ERM Group company

HRS within H2ME have performed well, but improvements will be required to reach commercialisation

- Overall, hydrogen refuelling stations within the H2ME project are performing well, with **average availability of 94.1% across 43 HRS**. **HRS performance has been evidenced to improve with increasing utilisation** across the project as all stations have encountered fewer periods of downtime as the cumulative volume of hydrogen dispensed increases.
- Increased utilisation can be evidenced to have both a **short- and long-term impact on HRS performance**. For example, on a short timescale, it is commonly known that HRS experience a '**teething period**' when the station is newly commissioned and the hydrogen dispensed is low (<100kg). After this milestone is reached, the availability of HRS is often seen 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 time period is also seen to have an impact and this is attributed to a) individual components performing better in regular use and b) more service support and attention being given to better utilised (and hence higher revenue) stations. HRS now need to not only be high performing but also be interesting business tools for the operator.
- Common reasons for downtime can be identified in the project, with **74% of the downtime which has been experienced due to failures with compressors, chillers/precooling and fuelling dispensers**. Whilst these parts undergo further technical development, many HRS operators have marked them as 'high-risk' components and keep stores of spare parts at, or local to, the HRS in case of failure and to reduce the downtime encountered.
- Despite the significant improvements made in HRS performance in H2ME, end user feedback highlights that **increases in the number of HRS available and improvement in the reliability of stations** are critical to achieving the commercialisation of FCEVs.

Some HRS within the project are beginning to experience 'moderate' levels of utilisation as a result of high mileage fleet deployments

- Due to the lower uptake of FCEVs than forecasted at the beginning of H2ME, many HRS within the H2ME project experience **low levels of utilisation**. This leads to a low project average of ~7.4% utilisation.
- However, due to the deployment of high-mileage fleets, some **HRS in London, Paris and the Hague are beginning to experience 'moderate' levels of utilisation**.
- In London, case studies on the most utilised station have highlighted that **HRS are capable of coping with significant increases in average demand**. This is emphasised by an analysis of the peak daily loading at the station, with many daily instances of >80% utilisation encountered with no significant impact on the availability of the station.
- Utilisation patterns seen at the London stations showed **loose correlation with the Chevron demand profile**, with drivers refuelling throughout the day. However, the volume of hydrogen drivers refuel per station visit is lower than expected and can be linked to driver 'anxiety' surrounding a period of poor HRS performance which would mean that they would not be able to refuel and hence drive their vehicles during that period.
- HRS performance can have a clear impact on usage patterns of FCEVs. In the UK, a **period of high availability led drivers to travel greater distances between refuels** and deplete their hydrogen tanks to lower levels due to higher confidence in the stations being available as, and when, required. This can be seen by the average amount refuelled per station visit increasing over time.
- In Paris, **HRS have responded very well to increased utilisation** even as the Orly HRS experienced some of the highest average loading seen across passenger car HRS in Europe. This has led to **high driver confidence in the technology** which can be evidence through project survey results and refuelling patterns which closely mirror the Chevron demand profile.

Some HRS within the project are beginning to experience 'moderate' levels of utilisation as a result of high mileage fleet deployments

- At the Hague's HRS, the utilisation level has been higher than expected and gradually increased to reach 38% daily average load at the end of 2021. The deployment of high mileage taxi vehicles has played a key role. This situation has given the opportunity the HRS equipment supplier to experience a **very steep learning curve** 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 event reflects the **growth in confidence drivers** have in the FC technology for their vehicles and day-to-day use.
- However, recent news regarding future taxi tenders in the city has shown that having all the favourable conditions gathered to have a high performing HRS is not sufficient if there is not a strong willingness from local authorities to encourage the deployment of FCEVs.

Design and technical improvements to HRS need to be a priority for HRS operators in order to increase driver confidence in the technology and commercialise the sector

Hydrogen Mobility Europe

Designing HRS to minimise downtime

Design and technical improvements

- Future HRS designs should **include redundancy into process systems (i.e., dual modules)** to allow isolated failures to occur without the HRS experiencing downtime.
- Sufficient **high-pressure hydrogen storage should be installed on site to account for at least one full day of hydrogen demand from the fleets using the station** should there be disruption to hydrogen supply (e.g. electrolyser failure or transport disruption). As the scale of demand increases at HRS sites, many HRS operators are increasing storage capacities to account for 2 to 3 days of hydrogen demand.
- The **B2B refuelling performance of the station is also a key technical aspect to consider**.
- A **back-up hydrogen supply chain** is essential in securing high availability of stations. This can be a centralised production plant or using local on-site electrolysers at nearby HRS to support temporary periods of supply disruption.
- **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 the management of stations as spare parts could be easily sourced and technicians could be trained to maintain a network of HRS to reduce response times.

Management improvements

- Ensure local (in-country) **availability of replacement parts** for ‘high-risk’ components and **train local technicians** to address a range of issues at the HRS.
- Conduct **rigorous testing of stations** off-site and on-site. 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.
- Provide **training to ensure that common technical issues can be addressed remotely or by local maintenance staff**.
- Establish **formalised maintenance procedures and contracts** with clearly defined responsibilities and timescales which reflect targeted availability (>98%).
- Use 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.
- Ensure that end users can **access the live availability status of stations** and that **24/7 customer helplines are available** at HRS (this can help ensure that any technical issues are identified quickly).

To improve performance, HRS should be designed with high utilisation in mind and mitigation measures need to be put in place to reduce the impact of periods of downtime

- As highlighted above, many HRS operators are advising that **HRS are specially designed for high utilisation use cases** to ensure that the technology can meet the high demands and expectations of customers.
- Designing a HRS for high utilisation needs to take into account **average, daily and hourly demand profiles** which are often complex to model, especially when considering private FCEV users.
- The ability of a HRS to meet daily demand fluctuations will depend on the **installed compressor capacity on-site** and the **volume of high-pressure storage available**. The approach taken by HRS operators will depend on the size of the site and careful consideration of the costs of upgrading each equipment piece.
- Meeting hourly demand variations will depend on the **back-to-back refuelling specification** of the station and the **waiting time required to refill high-pressure buffer storage**. **Increasing compressor capacity allows for an increase in back-to-back refuelling events and would facilitate shorter wait times in comparison to upgrades in high-pressure storage** (as the compressors work faster to refill the high-pressure storage). Currently, B2B refuellings are not frequent within the observed H2ME HRS. However, the Monte Carlo simulation study showed that with increased loads, the probability of B2B refuellings also rises. The throughput limit of many HRS today (200kg/day) will be reached when around 100 taxis or 300 passenger cars refuel daily at such sites. At that point, back to back refuelling performances of HRS will become increasingly important.
- Another key option to prepare HRS for high utilisation is to **instigate mitigations measures that can reduce downtime**. Three key strategies have been recommended by HRS operators including: **increasing high-pressure storage on site, introducing redundancy into process lines at stations** and ensuring a **back-up supply of hydrogen is in place** in case of production failures. However, as previously mentioned, these come at a high cost, hence the importance of scaling.
- A **good user experience** at the stations is also essential to ensure the success of a high demand HRS. This passes through an adapted design of the station and **good communication with the customers** who are going to refuel their vehicles at the station to provide them with the latest information regarding the station. This can be achieved through the use of dedicated apps, 24/7 support lines, or dedicated Whatsapp groups.
- **Availability, performance and user experience** are critical aspects that need to be given particular attention when designing a HRS which will be highly utilised.

HRS utilisation rates will in the future highly depend on fuel cell HDV refuellings. To ensure success for these stations, performance and availability will need to be high

- Beyond the importance of the availability level of a high utilisation station, it is key that its **level of performance** (i.e., percentage of refuels which are successful, meaning that the refuelling did not stop before the tank was full) **be high as well**. Indeed, fuel cell electric vehicles have for main advantage, compared to battery electric vehicles, to have a higher range, enabling them to respond better to some specific use cases. However, if the stations which refuel the vehicles are not able to provide 100% SOC, this advantage can be put in question.
- As the utilisation levels of stations increasingly grow a question that can be asked is: **how to adapt**?
  - **Upgrade** the station to increase its capacity
    - This will depend on whether the station is an ageing asset or not. If the station is already quite old and part of the first / last generation stations, it may be more coherent to decide to decommission the station to rebuild a new one which will be originally designed to dispense larger amounts of hydrogen.
    - If the station is quite recent with however a small installed capacity, an upgrade of the station can be a viable solution (if the scaling up of the station is not hindered by other aspects, e.g., space available, policy and regulations, etc.).
  - **Deploy another station** in the area
    - If demand increased in the location where the HRS is situated, another option could be to open up another station in another strategic location of the city/region to start creating a network. In an area where fleets of taxis are deployed, such an approach could be highly valued by the drivers who would then have various options to refuel their vehicles. The Parisian network seems to have well addressed this, and even more so with the opening of the more central station of Porte de la Chapelle.
- Today's stations considered as high utilisation still have quite low levels (below 50%). The **high utilisation stations of the future** will be stations which will not only cater for high-mileage light duty vehicles but also for **heavy duty vehicles** (e.g., trucks and buses). Stations with daily throughput of 200 kg will not be viable and are already seen today as uncompetitive assets in some cases.
  - The increase in the hydrogen amount will hence also depend on the countries / cities and OEMs' strategies with regards to these types of H2 mobility. Some stations will need to be upgraded to respond effectively to this increase.
  - Lastly, to secure high levels of utilisation, the supply of hydrogen must be guaranteed.

Contents

Appendix

Hydrogen Mobility Europe

Assumptions behind average daily demand figures for different vehicles (slide 9)

These assumptions are informed by data from the H2ME project, unless otherwise specified.

Metric	Toyota Mirai in Hype fleet	GLC, private users	Symbio Range-Extended Vans	Buses	Heavy duty vehicles
Average daily distance (km)	150	96[1]	54	200[2]	200 – 600[5]
% of mileage operated in 'hydrogen mode'	100	85	50	100	100
Average daily distance driven in 'hydrogen mode' (km)	150	82	27	200	200 - 600
Efficiency (km/kg H2)	86	80[3]	Confidential	11[4]	13[6]
Average daily demand (kg)	**1.7**	**1**	**0.1**	**18**	**15-46**

[1] H2ME Annual Technical Report 4. The daily average of the GTC fleet is 96km which is above the average daily distance for petrol/diesel vehicles estimated in the Motor Vehicle Use and Travel Behaviour in Germany, http://www.diw.de/documents/publikationen/73/diw_01.c.44461.de/dp602.pdf

[2] Based on "typical" routes for fuel cell buses. Note that average daily distance can vary significantly between operators.

[3] Estimated efficiency (actual figure is confidential)

[4] 8-9kg per 100km: https://www.hydrogeneurope.eu/hydrogen-buses

[5] Distance varies depending on the use case of the truck: varies between 100km to 800km. A mean range was taken: 200 – 600km. https://s3.production.france-hydrogene.org/uploads/sites/4/2022/02/France-Hydrogene-Mobilite_Livre-blanc-Camion-H2_web-final.pdf

[6] 7-8kg per 100km: https://s3.production.france-hydrogene.org/uploads/sites/4/2022/02/France-Hydrogene-Mobilite_Livre-blanc-Camion-H2_web-final.pdf

Deployment figures have been used to estimate the average daily hydrogen demand per station

Estimated hydrogen demand in Europe for light vehicles

- The "average" utilisation of HRS for light vehicles in Germany, France, the UK and Scandinavia can be estimated based on the **number and type of fuel cell cars and vans deployed and the number of HRS deployed in each country.**
- Based on this methodology, **estimates for the daily demand of hydrogen per HRS** can be found below. Note that these estimates are likely to be high, as the assumed demand is based on typical demand from highly utilised fleets.
- With most stations within H2ME having a capacity of between 80kg/day to 200kg/day, utilisation levels are expected to only reach a maximum of 40% utilisation.

Region	Germany	France	UK	Denmark	The Netherlands
Number of FCEV cars	1,240	396	247	226	579
Assumed demand per FCEV car (kg/day)	2.0	2.0	2.0	2.0	2.0
Number of FCEV vans	16	273	7	2	14
Assumed demand per FCEV van (kg/day)	0.1	0.1	0.1	0.1	0.1
Total demand per day (kg)	2,481.60	819.30	494.70	452.20	1,159.40
# of HRS for cars and vans	101	41	9	7	22
Average daily demand per HRS (kg)	**24.57**	**19.98**	**54.97**	**64.60**	**52.70**