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Hydrogen Mobility Europe (H2ME)

Fuel Cell Electric Vehicles as Taxis

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Executive Summary

Hydrogen Mobility Europe (H2ME, 2015-23) is the largest Clean Hydrogen Partnership-funded light vehicle and infrastructure demonstration project which aims to deploy 49 HRS and around 1 200 hydrogen cars and vans in several European clusters. Since 2015, project vehicles have driven over 27 million km and the 43 HRS that have reported data to the project have dispensed over 400 tonnes of hydrogen. This paper provides a case study on the use of fuel cell vehicles as taxis in Paris, where the zero tailpipe emissions of FCEVs have a compelling advantage over conventional vehicles, and their long range and short refuelling time offer potential advantages over battery electric equivalents. The effect of intensive usage of FCEVs on HRS usage is also explored.

Keywords: demonstration, deployment, driver feedback, fuel cell vehicle, infrastructure.

1 Introduction

The European Commission's hydrogen strategy for a climate-neutral Europe [1] has identified hydrogen as a key energy vector for renewable energy storage, with a share of the European Union energy mix reaching up to 14% by 2050. In transport, the strategy highlights the potential for early adoption of hydrogen in hard to electrify segments, including taxi fleets. The strategy notes the role of the Horizon 2020 Fuel Cells and Hydrogen Joint Undertaking projects (FCH-JU, now the Clean Hydrogen Partnership) such as Hydrogen Mobility Europe (H2ME) in developing lead markets for hydrogen transport solutions and accelerating technology development in Europe.

This paper provides a summary of the results of this landmark fuel cell electric vehicle (FCEV) and hydrogen refuelling station (HRS) demonstration project, with a focus on case studies of taxi deployments in urban environments.

1.1 Hydrogen Mobility Europe (H2ME)

H2ME (2015-2023) is the largest passenger vehicle and hydrogen refuelling station demonstration initiative co-funded by the Clean Hydrogen Partnership (CHP). H2ME (www.h2me.eu) is formed of the two separate CHP-co-sponsored projects listed below:

- H2ME-1 (2015-2020), which deployed 300 FCEVs and fuel cell range-extended electric vehicles (FC REEVs) and 29 HRS.
- H2ME-2 (2016-2023), which aims to deploy around 900 FCEVs and FC REEVs and 20 HRS.

H2ME brings together Europe's leading national initiatives on hydrogen mobility to begin to achieve a critical mass of European hydrogen vehicle deployment and help initiate the roll-out of a European hydrogen network. The project's aims are summarised in Fig 1 [2].

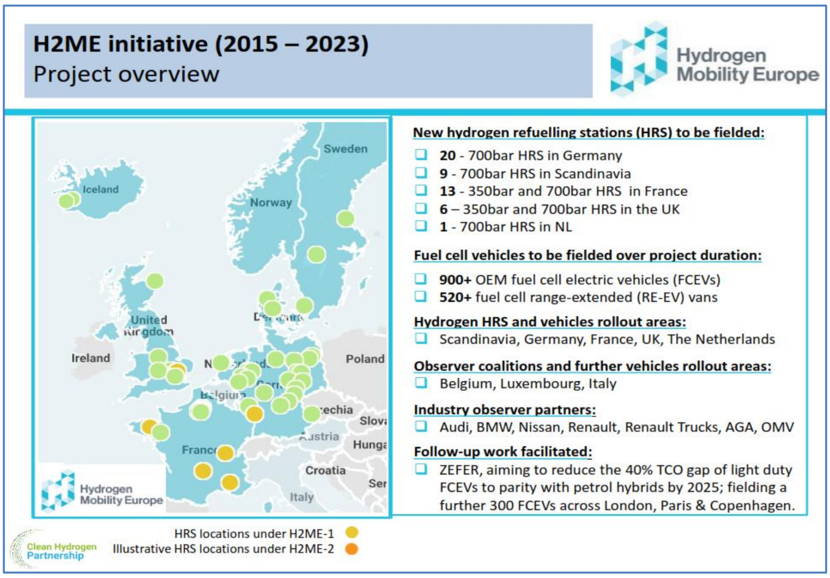

Figure 1. H2ME summary

The vehicle and HRS demonstration activities of H2ME aim to prove that fuel cell vehicles and HRS can substitute for conventional vehicles in a number of test cases such as passenger car deployments with individual users, van deployments with working fleets, etc. This paper focuses on the use of FCEVs as taxis in urban centres.

2 H2ME Overall Results

2.1 Vehicles

Vehicles (FCEVs, FCEV/plug in hybrid EVs, FCEV/PHEV, and fuel cell range extended EVs, FC REEVs) deployed by H2ME are summarised in Fig 2.

	Daimler B-Class F-CELL FCEV	Daimler GLC F-CELL FCEV/PHEV	Honda Clarity FCEV	Hyundai ix35 FCEV	Hyundai Nexo FCEV	Toyota Mirai FCEV	Symbio ZE H2 FC REEV
							
Project and dates reporting data	H2ME-1 2015-2018 (retired)	H2ME-1 & 2 2019-	H2ME-2 2017-	H2ME-2 2017-	H2ME-2 2019-	H2ME-1 & 2 2017-	H2ME-1 & 2 2015-
H2ME use-cases	Passenger and fleet car	Passenger and fleet car	Passenger and fleet car	Passenger and fleet car, taxi	Passenger and fleet car	Passenger and fleet car, police car, taxi	Light van in company fleets
NEDC range	380 km	478 km	650 km	590 km	756 km	605 km (Gen 1)	300 km
H_2 tank capacity and pressure	3.7 kg (700 bar)	4.4 kg (700 bar)	5.5 kg (700 bar)	5.6 kg (700 bar)	6.3 kg (700 bar)	5.0 kg (Gen 1) 5.6 kg (Gen 2) (700 bar)	1.8 kg (350 bar version)
Battery capacity	1.4 kWh	13.5 kWh (9.3kWh usable)	1.7 kWh	0.95 kWh	1.6 kWh	1.6 kWh (Gen 1) 1.2 kWh (Gen 2)	22 kWh

Figure 2. H2ME vehicles

The vehicles have operated in a variety of use cases in the different H2ME deployments, including:

- Company fleet vehicles in all countries
- Police response vehicles in London (Toyota Mirai Generation 1)
- Taxis in Copenhagen, Oslo, London, Paris and the Hague (Toyota Mirai Generation 1 and 2, Hyundai Nexo).

Overall, since 2015, vehicles supported by H2ME have driven over 27 million km. The FCEVs have generally been very reliable and have proven that they can fulfil drivers' needs in all applications.

2.2 HRS

The 43 hydrogen refuelling stations that have reported data to H2ME have dispensed almost 420 tonnes of hydrogen since the first station was opened in 2016. 61% of the H2 dispensed by these stations comes from six HRS in locations where H2ME has deployed taxis, showing the importance of these relatively intensely used vehicles in promoting the HRS business case. This is discussed further in the next section.

2.2.1 HRS availability

The average reported availability (considered here as the percentage of opening time, excluding planned maintenance or upgrades, where the station were available for the user to refuel) of H2ME HRS has varied between 94% and 98% since 2019. In the fourth quarter of 2022 the average was 95.8% (June 2022 value: 95.0%) [3]. As Fig 3 shows, 47% (June 2022 value: 32%) of the HRS exceeded the H2ME-2 availability target of 98%.

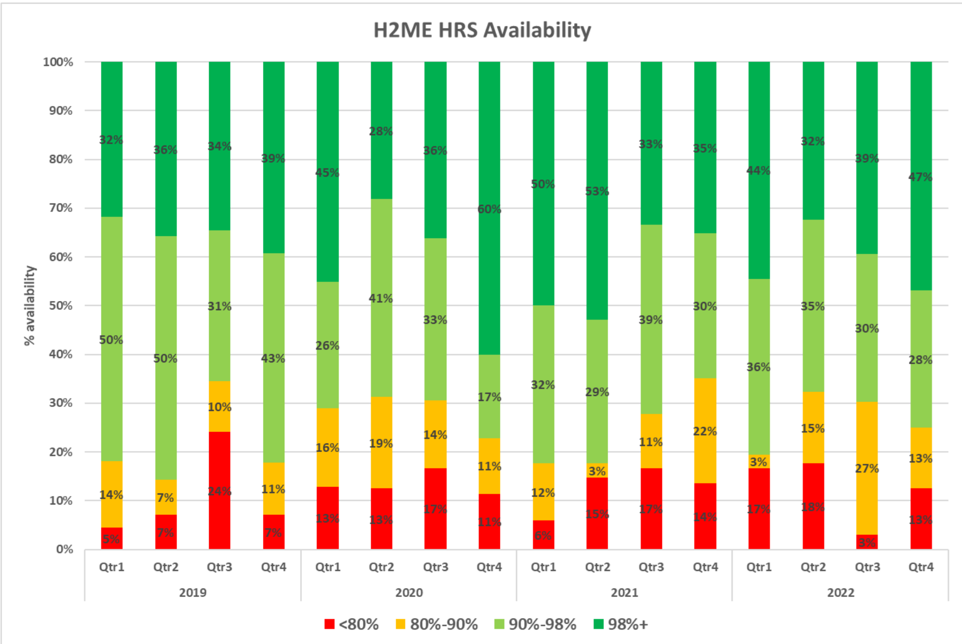

Figure 3. H2ME HRS availability 2019-present

One of the factors in the variation of HRS availability shown in Fig 3 is that the project has continued to introduce additional stations in new locations to serve vehicle deployments. Fig 4 shows that reliability of newly introduced project HRS improves and reaches a steady state after initial teething problems are resolved, demonstrating the well-known reliability engineering phenomenon of the bathtub curve. This is in line with the findings US DOE Fuel Cell Technologies Office Learning Demonstration [4].

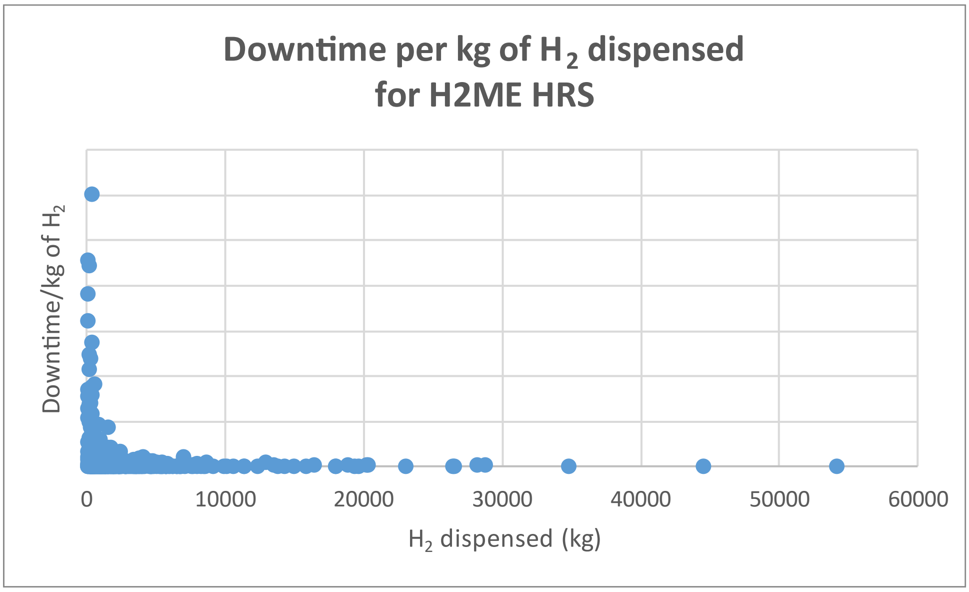

Figure 4. H2ME HRS downtime per kg H_2 dispensed (bathtub curve)

2.2.2 HRS reasons for downtime

Fig 5 shows the reasons for HRS downtime reported by station operators, demonstrating that fuelling dispensers, chillers, and compressors dominate the downtime incidents that were given a specific attributed cause by the operators. These results are also similar to those of the US DOE Fuel Cell Technologies Office Learning Demonstration [4].

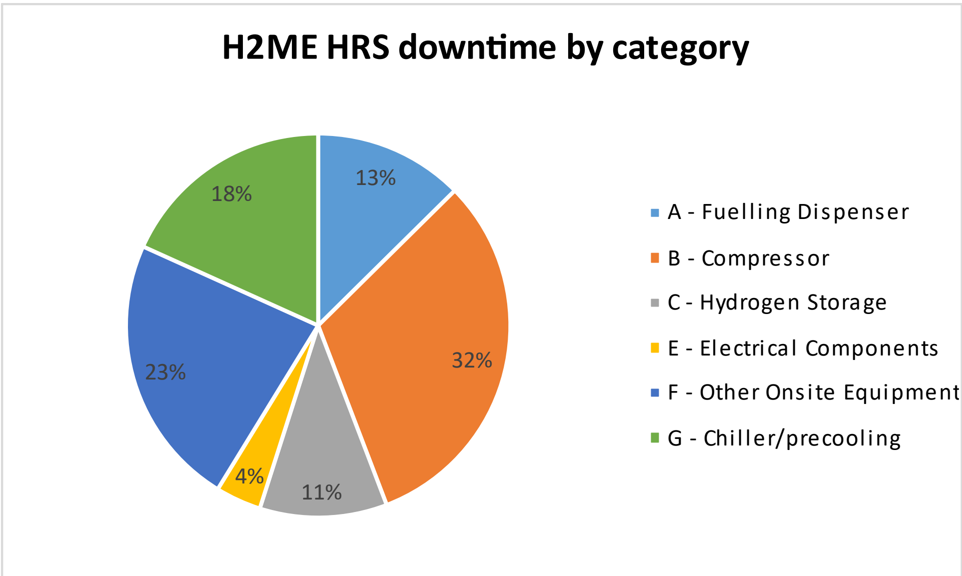

Figure 5. H2ME HRS downtime by category

3 FCEVs as Taxis – Case study of H2ME Taxis Operated by Hype in Paris

As noted above, taxis provide the most intense operational test case for passenger FCEV demonstrations as many operate 24/7 on dual-shift systems. The zero tailpipe emissions of FCEVs have a compelling advantage over conventional vehicles, and their long range and short refuelling time and offer potential advantages over battery electric equivalents.

3.1 Vehicle duties

Hype (https://hype.taxi/) began operating Toyota Mirai Generation 1 FCEVs supported by H2ME as taxis in Paris in 2017. The vehicles have averaged around 45 000 km/year an accumulated a total of almost 6 million km driven (Hype Mirais supported by the CHP project ZEFER have covered over 3 million km in addition).

3.2 Fuel consumption and range

Toyota Mirai Generation 1 FCEVs operating as taxis in Paris have averaged a fuel consumption of between 1.06 and 1.18 kgH_2/100 km since 2017. This gives the vehicles a range of over 400 km on a full 5 kg tank, making them comfortably capable of fulfilling their average daily duty of less than 200 km per day on a single tank.

3.3 Vehicle operation and refuelling locations

Fig 6 presents a heatmap of the FCEV taxi operation and refuelling in 2021 and 2022. The FCEVs primarily operate in and around the central area of Paris bounded by the Périphérique ring road. The Paris refuelling network has developed since the first vehicles were deployed and, by the end of 2022, four HRS were used by the taxis. Two HRS on the edge of the city at Orly and Roissy/CdG airports act as destination fuellers as drivers can refuel while dropping off or picking up passengers as part of their daily duties. The third HRS at Porte de la Chapelle is on the ring road, and the location is also a taxi parking depot. This combination of a convenient central location and its ability to refuel vehicles at the start and end of their shifts means that the Porte de la Chapelle HRS, opened in 2021, is now the most used by the vehicles. The fourth HRS at Versailles is not as conveniently located for the taxis and is rarely used.

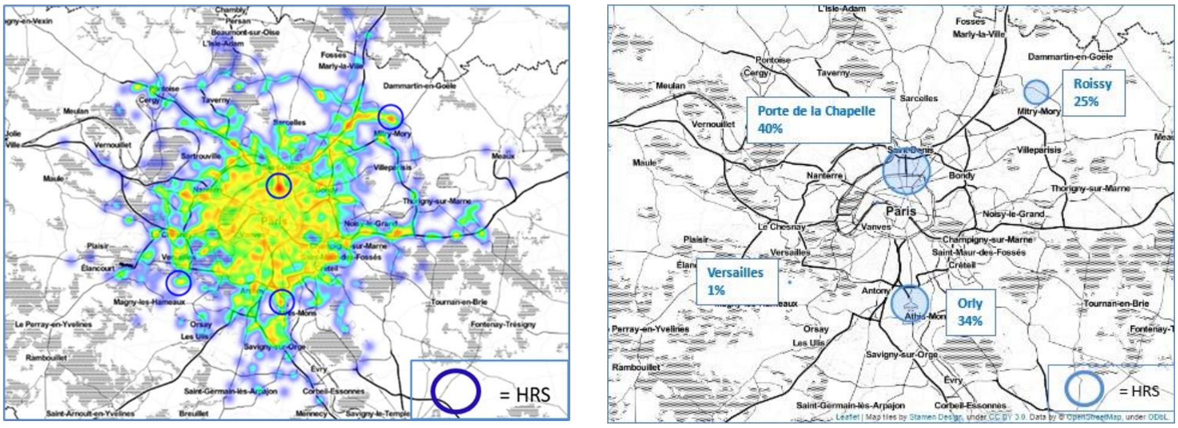

Figure 6. H2ME FCEV taxi operation and refuelling in Paris in 2021 and 2022

3.4 FCEV taxi usage compared to a BEV

Hype does not operate battery electric (BEV) taxis. The data collected during H2ME allows comparison of how a potential BEV option would compare to the FCEV taxi, as discussed below.

3.4.1 Refuelling time

The Hype drivers are contractually obliged to refuel their FCEV at least once per day. Analysis of telemetry data provided by Hype summarised in Fig 7 shows that the average time spent at the dispenser during each refuelling event is under five minutes, and that 95% of refuels involve the vehicle being stopped at the refuelling point for less than ten minutes. This can be compared to the 50 kW recharge time of around 90 minutes for a 59 kWh Nissan LEAF e+ [5] showing that the relatively rapid FCEV fuelling time offers potential operational advantage compared to the BEV.

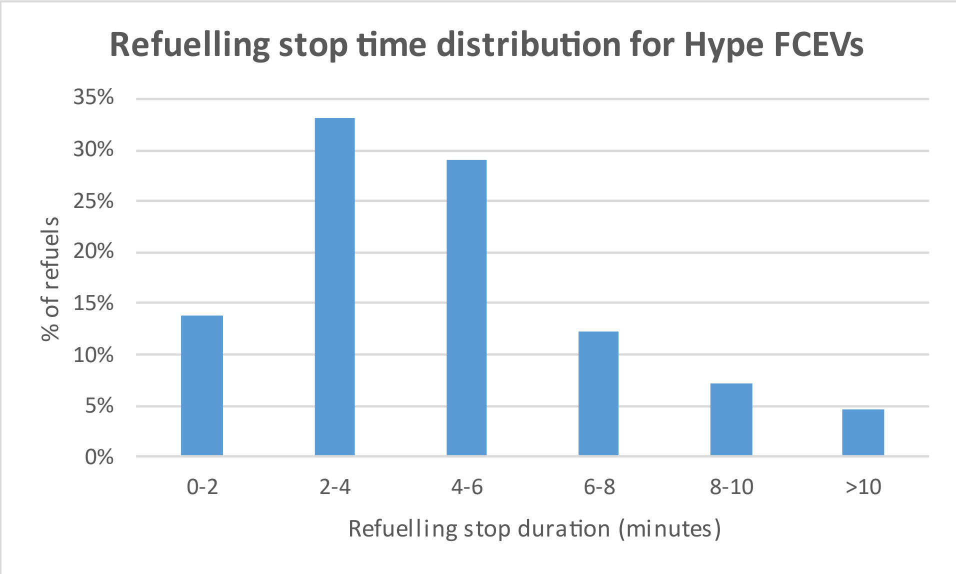

Figure 7. Refuelling stop time distribution for Hype taxis in Paris

3.4.2 Range

Detailed analysis of the daily mileage of individual FCEV taxis summarised in Fig 8 reveals that, for the fleet as a whole, around 93% of days could be fulfilled by a 62 kWh BEV on a single charge with an assumed 310 km real word range from full charge to 10% state of charge. An 85 kWh BEV could complete almost 99% of the daily mileage of individual vehicles on a single charge.

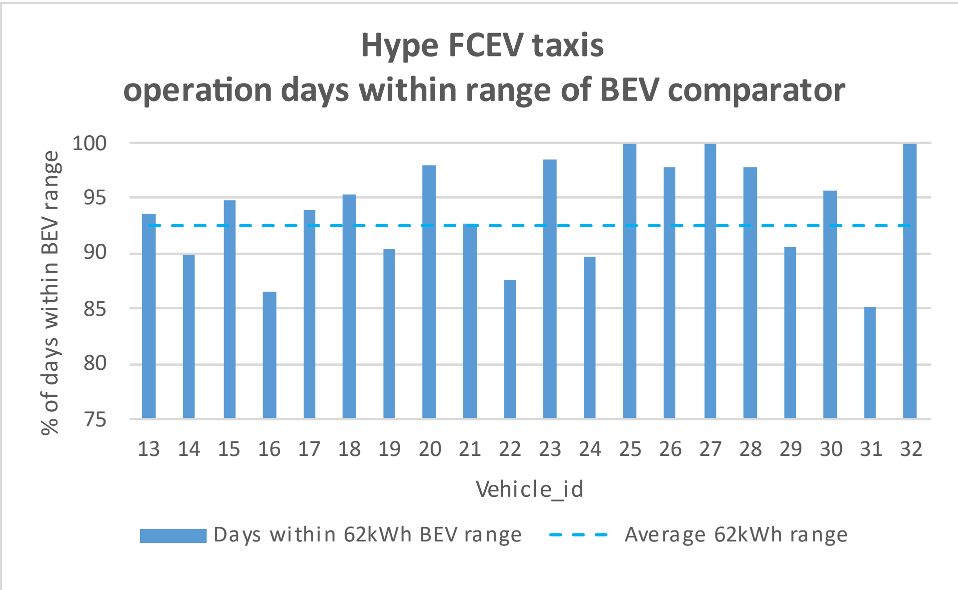

Figure 8. Estimated days within 62 kWh BEV range for individual FCEV taxis

3.4.3 Average and long days

The previous discussion on range indicated that, in the vast majority of cases, a modern BEV could perform the same daily duties as the FCEV on a single charge, assuming that time could be found during the day's operation to recharge the vehicle. Further detailed analysis of individual days reveals what happens on days when the daily driving falls outside the predicted BEV range.

Fig 9 shows how the energy usage by the FCEV and a modelled 62 kWh comparator BEV varies during a representative day of operation, during which the vehicle covered 189 km; green markers indicate a full energy store; yellow around half empty and red less than 25% full. For both the FCEV and the modelled BEV, the day's driving is comfortably within the range of the vehicle without refuelling/recharging.

Figure 9. FCEV and BEV energy usage comparison on an average day

Fig 10 shows a similar comparison for a relatively long day of operation covering 370 km. In this case the FCEV chose to refuel at the Roissy CDG refueller at the end of the day's operation, but the day's operation is still possible on a single tank of fuel. The day's driving exceeds the range of the BEV, as shown by the red dots on the map where the battery's energy store is exhausted and meaning that the BEV comparator would need to be recharged during the day to fulfil its driving duties.

Figure 10. FCEV and BEV energy usage comparison on a long day

3.4.4 Conclusions

The zero tailpipe emissions of FCEV and BEV taxis operating in urban environments offer compelling advantages over conventionally fuelled equivalents. Both types of zero emission vehicle can support the average daily duty cycle of taxis in Paris. FCEVs offer two potential operational advantages over BEV taxis in this case study:

- Speed of refuelling, which means that drivers and companies who are accustomed to using and fuelling conventional taxis can transition to FCEV equivalents without operational adjustment,
- Single charge range, which gives FCEV taxis operational flexibility over BEV equivalents.

4 Learnings from H2ME

Since the start of H2ME in 2015 there has been substantial progress in hydrogen mobility, including:

- The wider rollout of FCEVs and HRS supported by projects such as ZEFER (www.zefer.eu) and organisations such as the CHP.
- The deployment of FCEVs with larger onboard hydrogen storage capacities: Fig 2 shows that the Daimler B-Class FCEVs deployed by H2ME in 2015 had a tank capacity of 3.7 kg. The H2ME-

supported Hyundai Nexos that are used taxis in The Hague have tank capacities of 6.3 kg.

- The start of the rollout of hydrogen medium duty vehicles (MDVs) such as buses and refuse collection vehicles, and the anticipated deployment of hydrogen heavy duty vehicles (HDVs).

These changes have been reflected in the findings of H2ME, and in the deployments of hardware by the project, in areas including:

4.1 HRS capacities

The rollout of increasing numbers of FCEVs and FC MDVs means that HRS need higher capacities. Fig. 11 shows that the capacities of HRS deployed by H2ME reflect this, with newer stations installed under H2ME-2 generally being capable of dispensing much more than the ~200 kg/day norm of H2ME-1 HRS. Also, since most current MDVs and HGVs refuel at 350 bar, the newer HRS offer dual 350/700 bar dispensing. H2ME participants such as H2MOBILITY in Germany are in the process of upgrading many of their existing HRS to offer dual 350/700 bar fuelling.

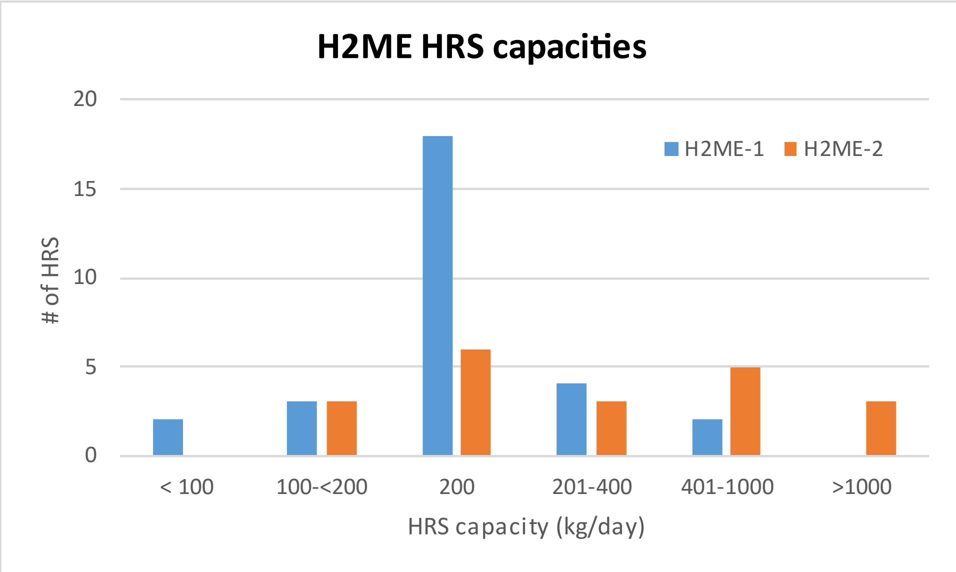

Figure 11. H2ME HRS daily refuelling capabilities

4.2 HRS performance

Increased HRS utilisation resulting from the deployment of additional vehicles has implications for two aspects of HRS performance:

- Daily throughput (amount of hydrogen that can be dispensed in a day), governed by the amount of onsite hydrogen storage and/or onsite generation.
- Back-to-back (B2B) refuelling capability (number of consecutive refuels within ten minutes of a previous fuelling), dependent on the amount of high pressure storage and capabilities of the onsite compression and precooling.

4.2.1 Load

Fig. 12 demonstrates the essentially linear relationship between vehicle deployment and station load (defined as daily amount refuelled as a percentage of the daily capacity) for the two airport HRS in the Paris refuelling network. When the taxis were taken off the road between April 2020 and June 2021 during the COVID-19 pandemic, station utilisation dropped to negligible levels.

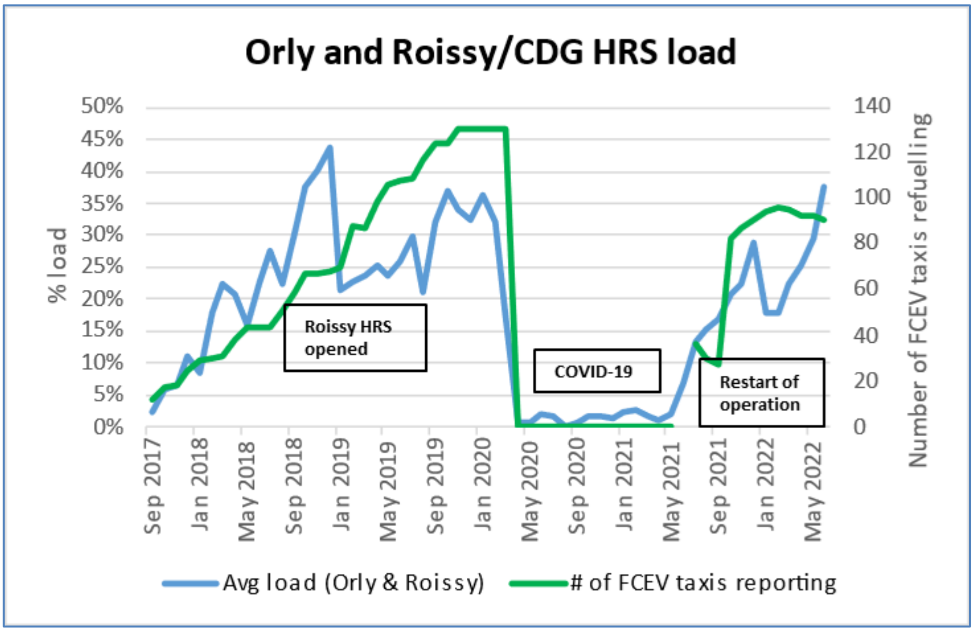

Figure 12. HRS load and FCEV taxi deployments in Paris

4.2.2 B2B performance

Fig. 13 shows that the Orly HRS has a daily refuelling pattern that bears reasonably close resemblance to that of a typical liquid refuelling station (the Chevron Demand Profile used by NREL to benchmark the operation of HRS that it monitors against conventional stations [7]), with the main usage between 7am and 5pm, but continuing with some non-zero level of usage throughout the period reflecting the 24/7 usage of the Paris FCEV taxis.

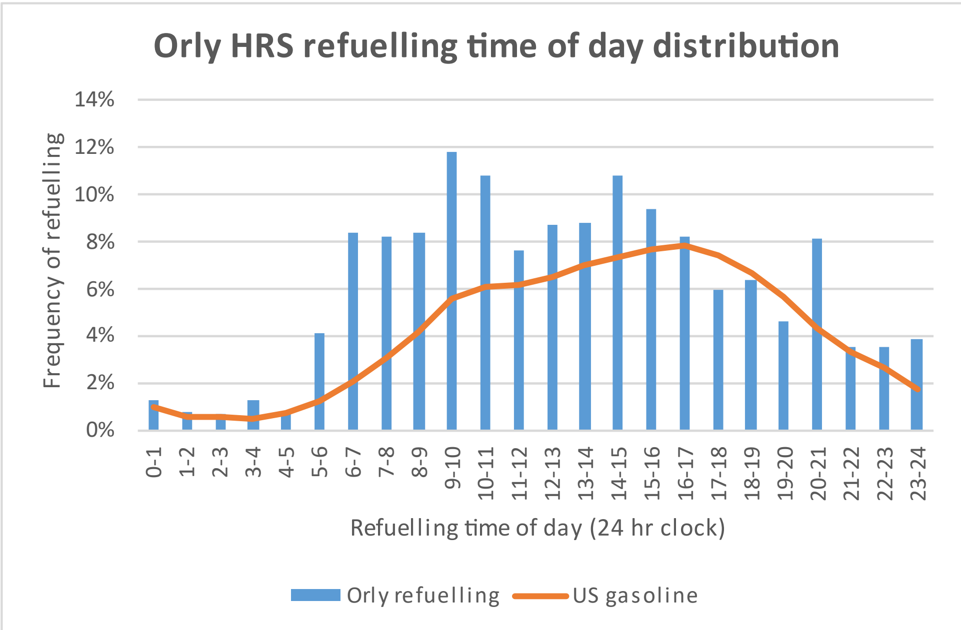

Figure 13. Orly HRS refuelling profile compared to a conventional station

In 2022, the Orly HRS delivered an average of 78 kg per day on 31 refuels with a B2B refuelling probability over the entire day of 27%.

If B2B refuelling capability is exceeded regularly, it is likely that issues such a lack of sufficient hydrogen availability at the HRS for immediate refuelling, and therefore increased waiting time for vehicles to refuel, will being to emerge. To understand how the back-to-back performance of the HRS will evolve with increased load, a Monte Carlo simulation was carried out on a model HRS with the Orly refuelling profile as shown in Fig. 14.

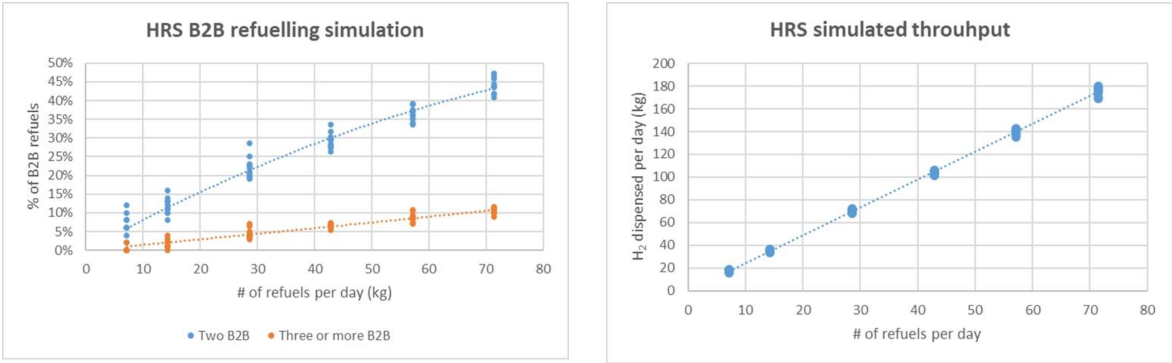

Figure 14. Monte Carlo simulation of HRS B2B refuelling and throughput

For a station with a 200 kg/day capacity, which was the design specification of a typical H2ME-1 HRS such as Orly, the simulation shows that around 70 refuels per day appears to be an upper limit, as at this point:

- The probability of three B2B refuels reaches 10%, a level which may cause issues in terms of the availability of hydrogen for immediate refuelling to subsequent vehicles, and
- The station approaches its daily design throughput limit of 200 kg/day

Based on typical H2ME usage patterns observed during the project for Generation 1 Toyota Mirais with a tank capacity of 5kg of H_2, this usage level corresponds to a fleet of around 100 taxis or 300 passenger cars using the HRS.

4.3 State of art HRS implementation

The Everfuel HRS in Copenhagen, which supports a fleet over 100 Mirai taxis, is the one of the latest HRS deployed by H2ME and shows the lessons learned during the project which have advanced the state of art. The station has two 700 bar dispensers, which have independent precooling, dispensing, compression, plus medium and high pressure storage and share common low pressure (supply) storage. This set up mitigates issues with availability and B2B performance by essentially operating two independent HRS side by side.

4.4 Customer perceptions

Drivers of FCEVs in H2ME are required to answer questionnaires before and during their time with the vehicles [6]. The questions address their expectations of, and experience with FCEVs and HRS. Overall, 90% of taxi drivers in the H2ME and ZEFER projects reported ‘positive’ or ‘very positive’ experiences. With HRS however, the picture was somewhat different, as shown in the results of surveys taken during vehicle operation in the H2ME and ZEFER projects shown in Fig. 12. Fewer than 80% of drivers in France reported ‘positive’ or ‘very positive’ experiences, and 10% gave a ‘negative’ or ‘very negative rating’. The percentage of negative ratings dropped in 2022 compared to 2021, perhaps due to the addition of the newest and most central HRS to the Paris network at Porte de la Chapelle discussed in Section 3.

5 Conclusions

Hydrogen Mobility Europe (H2ME) is the CHP’s largest light vehicle and infrastructure demonstration project. H2ME has accumulated the largest European dataset on how real customers are using vehicles and stations. Amongst the main findings are:

- OEM FCEVs have proven reliable and popular with end users. They are driven in the same way as conventional vehicles regarding daily usage patterns.

- FCEVs have demonstrated that they can replace conventional vehicles in high-intensity applications such as taxis operating in urban environments. Their short refuelling time and long single-refuel range gives them potential advantages over BEVs in these applications.
- 47% of H2ME HRS exceeded the project availability target of 98%. Compressors, dispensers, and chillers are the main sources of downtime.
- Increased utilisation of HRS from the wider deployment of FCEVs means that their reliability, and capabilities in terms of daily throughput and back-to-back refuelling performance will become increasingly important.
- Hydrogen mobility is safe, and there have been no H2ME vehicle or HRS safety incidents reported that involved the release of hydrogen.

The data gathered by H2ME forms a crucial evidence base for policy makers, manufacturers, and consumers towards the wider rollout European rollout of hydrogen vehicles and infrastructure.

Acknowledgments

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Presenter Biography

Robert Evans has been CEO at Cenex, the UK's first Centre of Excellence for Low Carbon and Fuel Cell Technologies, since 2005. Since 2011, Robert has been SRO for projects involving analysis work on the real-world trialling of hydrogen vehicles and refuelling stations in large-scale projects, including the CHP-funded HyTEC (2011-15) and H2ME (2015-23) projects. Robert has a BSc in Chemistry from Kings College London and a Masters from Imperial College London.