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Four years of operational data for five hydrogen refueling stations

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Abstract. Worldwide about 550 hydrogen refueling stations (HRS) were in operation in 2021, of which 38%. were in Europe. With their number expected to grow even further, the collection and investigation of real-world station operative data are fundamental to tracking their activity in terms of safety issues, performances, costs, maintenance, reliability, and energy use. This paper shows and analyses the parameters that characterize the refueling of 350 bar fuel cell buses in four HRS within the 3Emotion project. The HRS are characterized by different refueling capacities, hydrogen supply schemes, storage volumes and pressures, and operational strategies. From data logs provided by the operators, a dataset of three years of operation has been created. In particular total hydrogen quantity, the fill amount dispensed to each bus, the refueling duration, the average mass flow rate, the number of refueling events and the daily number of refills, the daily profile, the utilization factor, and the availability are investigated. The results show similar hydrogen amount per fill distribution, but quite different refueling times among the stations. The average daily mass per bus is around 12.95 kg, the most frequent value 15 kg, the standard deviation 7.46. About 50% of the total amount of hydrogen is dispensed overnight and the refueling events per bus are typically every 24 hours. Finally, the station utilization is below 30% for all sites.

1 Introduction

Supported by regulators, investors, and consumers, hydrogen is strongly emerging as one of the principal protagonists among the actors for the global shift towards a decarbonized road transportation system. The European Union has identified in its Hydrogen Strategy three phases to develop a mature hydrogen market by 2050 [1]. Instead, the United States Department of Energy has launched Hydrogen at Scale, an initiative that promotes R&D projects aiming at affordable hydrogen production, transport, storage, and utilization [2]. At the same time, China has listed hydrogen among the energy sources for the first time in its latest Energy Law [3]. Jointly, Japan and Korea have set aside substantial funds for hydrogen technology [4,5].

As of 2020, the number of fuel cell electric vehicles on the road were 35 800, with Korea becoming the leading country reaching more than 10 000 vehicles in circulation [6]. Complementarily, a sufficient hydrogen infrastructure has been established. Currently, there are around 550 Hydrogen Refueling Stations (HRS) worldwide. Of these 275 are located in Asia, around 200 HRS are in Europe – of which just a little less than half are in Germany – and 75 HRS are sited in the United States, mainly in California [7]. In the majority of the HRS the hydrogen is stored as a compressed gas at pressures up to 700 bar [8] and then delivered into the onboard vehicle tanks. To charge the pressurized storages, the stations are generally equipped with a compression system. An alternative solution is to store the hydrogen in liquified form. Although studies show that this configuration reduces the stations' footprint, capital and operating costs, the lack of a global assessment over the entire liquefaction chain and the poor performance of existing pumps slow down its application [9,10]. The compressed gas delivery is conducted either by tube trailers, in which the hydrogen is generally stored at a pressure of 200 bar or is transported from the point of production until the distribution point through pipelines at pressures between 30 and 80 bar [11,12]. Otherwise, the hydrogen can be produced locally via steam methane reforming or water electrolysis. In this case, along with the compressors, the stations include buffers, filters, and a purification system [13].

Over the last years, the body of literature on hydrogen infrastructure was expanded notably, among these [11,14–19]. Nevertheless, a study that shows the HRS operational performance in terms of hydrogen quantity delivered to the vehicle, refueling duration and station utilization applied to real-world stations has been less investigated. The study of Samuelsen et al. [20] presents the performance metrics of the 180 kg/day 700 bar University of California, Irvine HRS. The data collected are compared with the National Renewable Energy

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Laboratory (NREL) dataset for all HRS in the United States [21].

This paper illustrates and analyses the operational performances of five HRS involved within the European 3Emotion project [22] during three years of activity. The project plans for the deployment of 29 articulated fuel cell buses in four cities in the UK (London), the Netherlands (Rotterdam and Province of South Holland), France (Versailles, Pau), and Denmark (city of Aalborg). The stations are characterized by different refueling capacities (kg_{H2}/day), hydrogen supply schemes (in-situ production or delivery), storage volumes and pressures, and operational strategies. The ultimate aim is to provide a

global outlook of the actual functioning of small/medium size hydrogen stations, investigating their availability, capacity utilization and technical performance and benchmarking their status.

2 Case study: the 3Emotion project

The 3Emotion Project, which stands for Environmentally friendly Efficient Electric Motion, envisages the establishment of a pan-European consortium for the deployment of 26 new buses in addition to 8 existing buses and the realization of 3 new HRS. The buses and the HRS operate in 5 leading cities: Aalborg (DK), London (UK), Pau (FR), Rotterdam (NL), Versailles (FR). By considering the lesson learned from past fuel cell bus projects, 3Emotion aims to enhance the number of operators involved paving the way to commercialization.

The sites were selected so that the most effective commercialization impact is reached, ensuring the implementation of the hydrogen refueling stations with a different supply (hydrogen is provided via pipeline in Rotterdam, by trailers in London and Versailles, and is produced locally via electrolysis in Pau and Aalborg). In addition, the HRS refuel buses of different size fleets (3 to 10 buses) that are used in different environmental conditions (urban and extra-urban roads). The design capacity is smaller for the on-site stations, 100 kg/day in Aalborg and 174 kg/day in Pau. Rotterdam and Versailles sites have both a capacity of 200 kg/day. The largest station is London, capable of dispensing 400 kg/day. All the stations are equipped with a dispenser to refuel the bus at 350 bar, whilst the Dutch and Versailles sites are the only ones that were realized with the possibility to refuel cars at 700 bar. The project aims to reach the following objectives concerning the stations' performance:

- Bus capacity 16 kg_{H2}/refueling once a day
- Refueling time 10-15 minutes
- Refueling station capacity 200-350 kg_{H2}/day
- Availability of the station 98%
- Station production efficiency >70%

3 Methods

Except for Versailles, the operational data on which this study is based have been taken from excel logbooks spreadsheets that monitor the bus refueling. The site operators fill the logbooks manually, later sharing the information to be analyzed. The spreadsheets provide qualitative and quantitative data with daily frequency and, when possible, divided by bus number. In particular, the refueling data include: date (dd:mm:yy), hour (minutes), hydrogen dispensed per fueling event (kg), refueling duration (minutes). Although, this last data cannot be obtained in the Rotterdam site. For the Aalborg station, the data on the electrolyzer operation (hydrogen produced, electricity and water consumption) were also collected and investigated. The HRS data for the Versailles come from quarterly reports provided by AirLiquide in which a preliminary aggregated analysis about the charging distribution over the day, the total and per filling quantity dispensed, the duration, and the availability divided into months are presented.

Due to slight but still relevant unevenness between the data and the activity period, further elaboration in Microsoft PowerBI was required. Indeed, London and Rotterdam were the first stations to start the operations, and their data are available from 2018. At the end of 2019 also the data collection in Versailles was put in place. The Aalborg HRS was delivered in December 2019, but it is not until March 2020 that it became fully operational. Finally, in Pau, the HRS was installed during summer 2019. However, due to the COVID pandemic, the HRS was on stand-by mode until August 2020, when its regular activity began. Albeit, it is not before summer 2021 that the HRS data transfer was set up. All the stations are currently running, except London, which has reached the demonstration goal in March 2020 and took the buses out of service.

The outcome is a complete and rich data set of four years of the real-world performance of hydrogen stations. In particular total hydrogen quantity, the fill amount dispensed to each bus, the refueling duration, the average mass flow rate, the number of refueling events and the daily number of refills, the daily profile, the utilization factor, and the availability are obtained and elaborated in Matlab, PowerBI and RStudio software.

4 Results

Fig. 1 shows the total quantity of hydrogen dispensed for each site. The longer period of operation allowed to build up a greater experience and the bigger bus fleet of London is the reason for the prevailing quantity dispensed, i.e., 67 209.9 kg, with respect to the other sites. Although, on

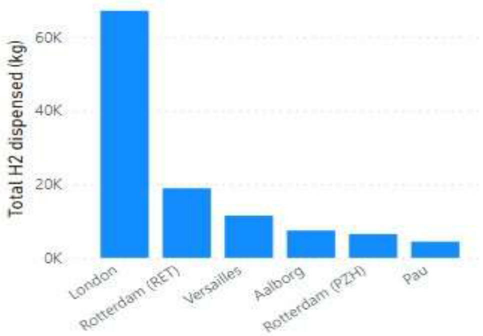

Fig. 1. Total quantity of hydrogen dispensed for each site.

Table 1. Total hydrogen amount dispended per site and relative specific values.

Site	Total H2 quantity (kg)	Bus fleet (#)	Specific H2 dispensed (kg/bus)
London	67 209.90	10	6 720.99
Rotterdam (RET)	18 917.23	2	9 458.61
Rotterdam (PZH)	6 446.12	4	1 611.53
Versailles	11 470	7	1 638.57
Aalborg	7 421.62	3	2 473.87
Pau	4 396.77	8	549.59

specific terms (hydrogen dispensed per bus), the highest amount of hydrogen was dispensed by the transport operator RET in Rotterdam. At the same time, the results for the buses of the Province of South Holland (PZH) and Aalborg are nearly balanced (Table 1). The underperformance of the Pau site is because of the smallest period of available data.

Fig. 2 shows all the daily dispensed hydrogen per site and the relative rolling 30-day average. London HRS (Fig. 2a) is characterized by a reasonably stable quantity dispensed since the beginning of the operation in 2018. The drop observed from February 2020 is related to the progressive decommissioning of the station. The HRS has a maximum capacity of up to 400 kg/day, while the estimated bus demand is approximately 160 kg/day, leading to a lower utilization rate equal to 40% in nominal operating conditions. Furthermore, the data shows that the actual demand is substantially lower. In fact, the maximum total hydrogen mass refueled is 187.92 kg/day, with a mean value of 81.86 kg/day. As a consequence, the station capacity utilization achieves 26% at best.

With respect to the initial period of operation, the quantity of hydrogen dispensed in Aalborg (Fig. 2b) has gradually increased until the beginning of 2021. Subsequently, a component breaking in the dispenser that caused zero refueling events in January 2021, in addition to COVID-19, which strongly impacted the public transportation sector, led to a reduction of the station performance. The Aalborg HRS has a maximum capacity of up to 100 kg/day, while the estimated bus demand is approximately 90 kg/day. The data shows that the maximum total hydrogen mass refueled is 67.97 kg/day, with a mean value of 16.85 kg/day. Therefore, the station capacity utilization is, on average, just 18%.

In Rotterdam (Fig. 2c), several zero refueling strong affect the moving average, oscillating around 17 kg/day. Nevertheless, an improvement of the station performance is noticed from January 2021, after implementing the buses of a second operator and the total bus circulation recovery. The total HRS capacity is 200 kg/day, while the data shows that the maximum total hydrogen refueled is 103.58 kg/day. With respect to the average amount, the aggregate utilization rate is about 9%.

Finally, for what concerns the Pau site (Fig. 2d), the data related to just three months of operation show an increase of the mass dispensed at the beginning of September 2021, followed by a stable trend. The station is designed to provide 174 kg/day, in contrast the maximum total hydrogen refueled observed is more than 170 kg/day, the mean value is 72 kg/day, leading to a station utilization of about 41%.

In Fig. 3a), is plotted the probability density function of the hydrogen amount dispensed by refueling. The buses of PZH in Rotterdam are characterized by the highest mass quantity dispended, with the majority of the refuelings above 18 kg/fill. Conversely, Aalborg, Versailles, and London HRS distributions feature a pick in correspondence of around 16 kg/fill. On average the lowest fueling amount is provided to the buses of RET. Only 26% of the total refueling events are below 10 kg/fill. Fig 3b) shows the density function of the refueling

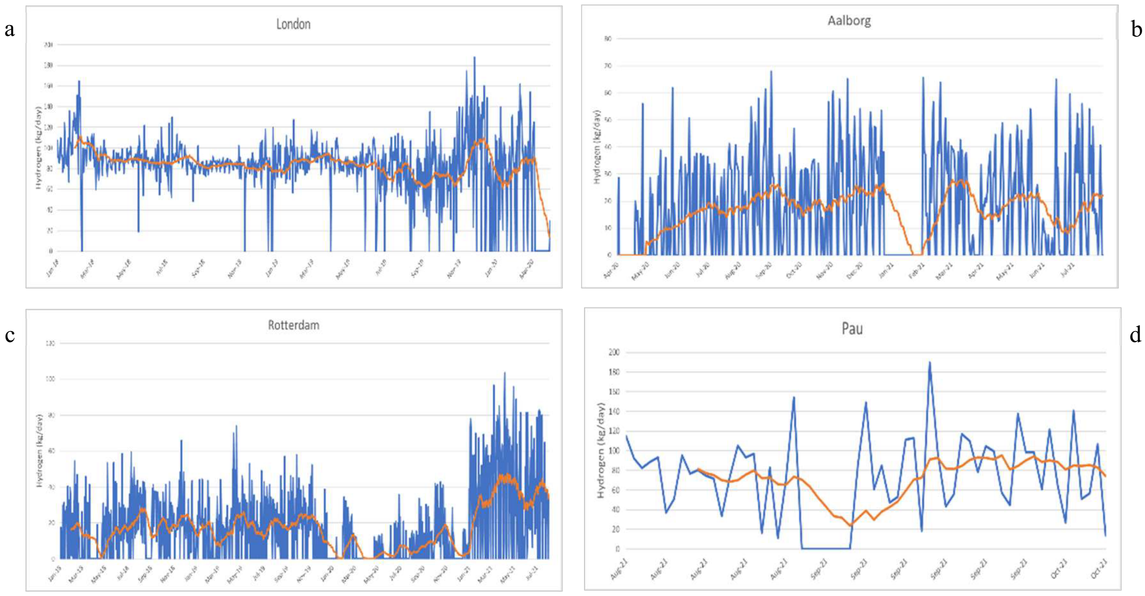

Fig. 2. Daily dispensed hydrogen and rolling 30-day average in the sites of London a), Aalborg b), Rotterdam c), and Pau d).

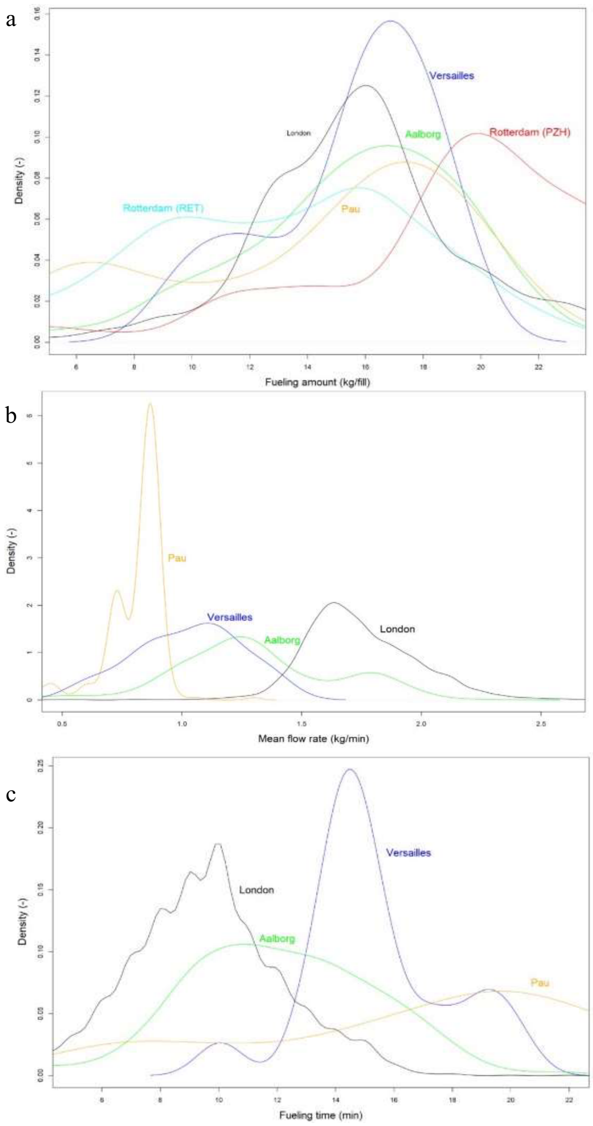

Fig. 3. Probability density function of the hydrogen quantities dispensed per fill a), duration b), and mean flow rates c).

duration. If the curve is shifted towards refueling above 15 minutes for Versailles and Pau, in Aalborg and London, the average oscillates around 11 minutes. Fig 3c) illustrates the mean mass flow rate distribution. The mean fueling rate in London is 1.74 kg/min, in Aalborg is 1.19 kg/min, in Pau is 0.80 kg/min, lastly in Versailles is 1.03 kg/min. No more than 7% of flow rates are greater than 2 kg/min, whilst the maximum value detected is 3.6 kg/min. The results are aligned with the protocol SAE J2601/2 requirements, which prescribes a maximum flow rate of 3.6 kg/min for heavy-duty vehicles [23]. More detailed information on the mean, mode, standard deviation and the 50th percentile for the three parameters analyzed above are reported in Table 2.

Fig 4 shows the correlation between the refueling time and the mass dispensed per fill during the years. In 2018 and 2019 only the stations of London and the buses of RET were running. In that period, recurrent zones are noticed in correspondence of 15 to 18 kg/fill and around 10 minutes. With the implementation of the other stations, the results show a concentration of the number of refills

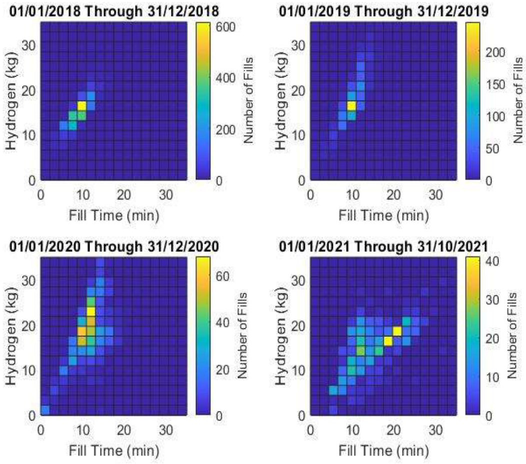

Fig. 4. Correlation of the hydrogen amount per fill vs. refueling duration during the years of operation.

between 15 to 25 kg/fill and 10 to 20 minutes, which means that the buses are refueled mainly by half-tank.

The daily load dispensing profiles with a one-hour resolution for the different sites is shown in Fig. 5. In London, Rotterdam (RET) e Pau, the buses are refueled overnight to secure capacity and availability. In particular, the majority of the refueling events are focused from 8 pm to 1 am, coinciding with about 50% of the total amount dispensed. Peaks of the refuelings are observed at 8 pm (6 248.36 kg_{H2}), 11 pm (8 364.63 kg_{H2}) and at midnight (7 326.77 kg_{H2}). Aalborg HRS mainly operates in the early morning and evening hours, especially between 3 am-5 am (1 915.18 kg_{H2}) and from 8 pm-10 pm (1 805.66 kg_{H2}). Contrarily, in Rotterdam (PZH), the refuellings are centralized in the morning, with peaks occurring at 7 am (2 225.28 kg_{H2}), and 9 am (1 784.17 kg_{H2}). In general, all the sites execute top-up refuelings throughout the day.

Finally, Fig. 6 shows the density function of the time between refuelings per site. Except for Aalborg, 50% of the fills per bus occur with a distance of 24 hours from the last refueling event. The data also shows recurrent zones in correspondence of 48 hours, thus the buses are frequently refueled two days apart. In Aalborg, the 50th percentile is 11.3 hours since it is referred not to single bus refilling but to all the events occurring at the station.

5 Conclusions

In this study, the operational performances of five hydrogen refueling stations within the 3Emotion project are presented. The analysis covers a total period of four years, even though differences within the stations' activity timeframe subsist. The results show a similar hydrogen amount per fill distribution, but quite different refueling times among the stations. The average daily mass per bus is around 14.43 kg, the most frequent value 15 kg, the standard deviation 5.05, the 50th percentile is 14.85 kg. Conversely, the average refueling time is 10.28 minutes, the mode is 10 minutes, the standard deviation is 3.26, the 50th percentile is 10 min. The average flow rate is around

Table 2. Mean, mode and standard deviation of the filled mass, refueling time and flow rate for all the sites.

Site	Mean			Mode			St deviation			50th percentile		
	Mass (kg)	**Time (min)**	**Flow (kg/min)**	**Mass (kg)**	**Time (min)**	**Flow (kg/min)**	**Mass (kg)**	**Time (min)**	**Flow (kg/min)**	**Mass (kg)**	**Time (min)**	**Flow (kg/min)**
London	12.58	9.55	1.74	15	10	1.66	8.39	5.03	0.82	15.95	10	1.71
Rotterdam (RET)	12.60	-	-	15	-	-	5.45	-	-	13.36	-	-
Rotterdam (PZH)	18.73	-	-	19	-	-	5.68	-	-	19.76	-	-
Versailles	15.53	15.34	1.02	15.8	14	1.13	2.88	2.43	0.22	15.8	14.57	1.09
Aalborg	14.23	11.77	1.19	15	11	1.32	6.03	6.26	0.48	15.84	12	1.25
Pau	14.08	16.77	0.80	17.03	21	0.88	5.75	6.59	0.14	15.83	18	0.85

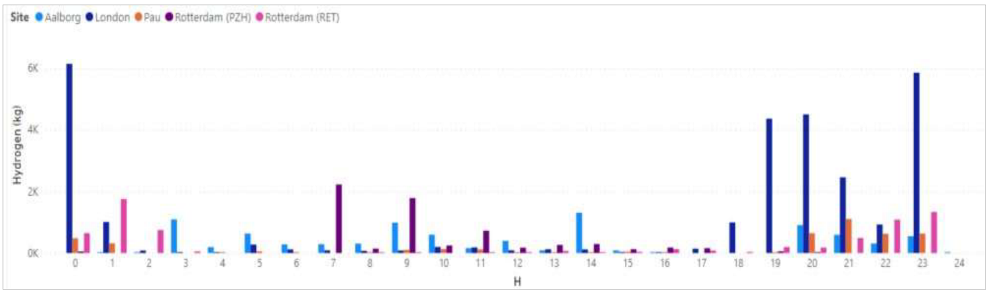

Fig. 5. Daily resampling of the hydrogen refueled amount in hourly resolution

1.68 kg/min, which is compatible with the limitations of the SAE J2601-2 maximum value of 3.6 kg/min for slow filling. The hourly dispensing profiles show that, in general, the majority of the refueling are performed overnight from 8 pm to 3 am to secure capacity and availability. Still, all the sites execute top-up fills throughout the day. Typically, the buses are refueled every 24 hours. From the investigation of the station capacity utilization, the actual demand is substantially lower than the planned maximum capacity. Indeed, the station utilization is below 30% for all the sites. Therefore, this study illustrates the HRS capability to sustain larger fleets than the current, ensuring future hydrogen bus fleets ramping up potentiality.

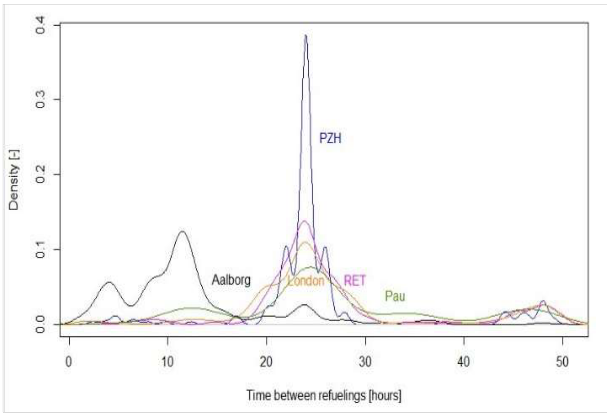

Fig. 6. Probability density function of time between refuelings.

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