Clean Hydrogen In European Cities

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Public Executive Summary of the **Report on Hydrogen Infrastructure Operation and Performance**

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RE – Restricted to a group specified by the consortium,
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0 Publishable Executive Summary

This report evaluates the performance of the hydrogen refuelling infrastructures in the CHIC project. In particular, their performance is benchmarked against the target figures for a number of Key Performance Indicators (KPIs). These targets were stated in the 2009 Call for Proposals of the Fuel Cells and Hydrogen Joint Undertaking (FCH JU).

The assessment is based on the operating data collected from the start of demonstration at the individual sites, up to 30 June 2016, half a year before the completion of the project. The assessment is carried out using a set of performance indicators defined in the project's Assessment Framework. The KPIs are a subset of these indicators. This summary focusses on the four quantitative KPIs related to infrastructure operation.

Figure 0-1 shows a generalised schematic of the hydrogen infrastructure facilities in the project. All nine sites possessed a Station Unit for hydrogen storage and dispensing. Most of the sites also employed a Production Unit for on-site hydrogen generation through water electrolysis.

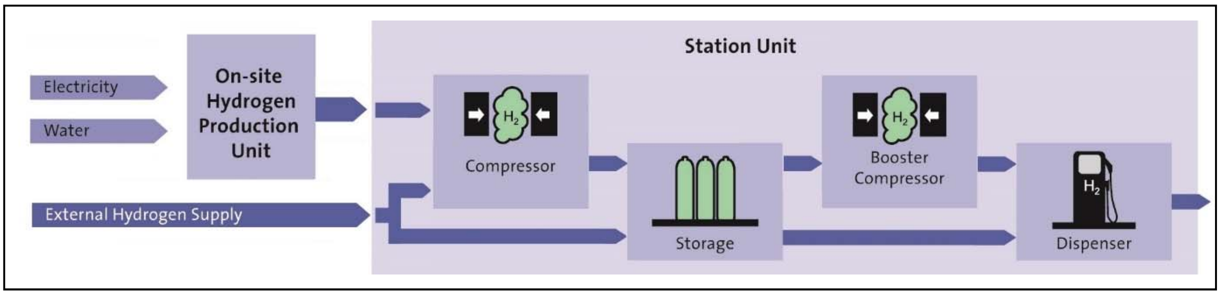

Figure 0-1: Generalised schematic of the CHIC refuelling infrastructures.

The majority of sites with a Production Unit had enough daily generation capacity (second column of Table 0-1) to cover the daily refuelling capacity of the Station Unit as specified when the facility was ordered (fourth column of Table 0-1). The only exceptions were Aargau and Hamburg where a mix of on-site generation and regular external delivery had been foreseen. In practice, however, supplemental external supply was hardly needed, amongst other things because of the excellent fuel economy of the buses (see section 0.1).

Table 0-1 distinguishes between Phase 1 sites and Phase 0 sites. The former received co-funding from the FCH JU. Most of them had not had previous experience with hydrogen-powered transport. The latter were co-funded from national sources. They already had expertise in hydrogen-powered transport at the start of CHIC.

Table 0-1: Outline of the hydrogen supply pathways and bus fleet sizes in CHIC.
* Buses from a former project with hydrogen internal combustion engines.
**Second set of two buses in operation from May 2014.

Site	On-site electrolysis: daily capacity [kg H_2]	Regular external H_2 delivery	Refuelling: daily capacity [kg H_2]	Number of FC buses	Supplementary information
Phase 1 Sites					
Aargau	130	Yes	300	5	
Bolzano	390	No	260	5	Additional dispenser for cars (700 bar)
London	No	Yes	320	8	Transport by liquid H_2 tanker to site and high-pressure gaseous H_2 delivery to Station Unit up to autumn 2014; gaseous high-pressure transport and delivery since then
Milan	215	No	200	3	
Oslo	260	No	250	5	
Phase 0 Sites					
Berlin	No	Yes	200	4 *	Additional dispenser for cars (350 and 700 bar)
Cologne	No	Yes	120	2 + 2 **	
Hamburg	280	Yes	700	4	Additional dispenser for cars (350 and 700 bar)
Whistler	No	Yes	1’000	20	Liquid delivery and storage

The target values for the four quantitative KPIs and the actual level of performance as of June 2016 are presented in Table 0-2. They are discussed in the following subsections.

Table 0-2: The Key Performance Indicators, their target values according to the 2009 Call for Proposals of the FCH JU, and the actual level of performance.
* Excluding Berlin (see footnote 2 on page 7).

Key Performance Indicator	Target value	Actual level of performance
Efficiency of hydrogen production on site (ratio of AC electricity consumed to hydrogen produced, based on the net calorific value of hydrogen, at the outlet of the electrolyser at 10 bar or 30 bar)	> 50%	> 54% at all sites
Availability of the station (100% = station available 24 hours a day)	> 98%	> 98% at three sites > 94% at all sites 97% across all sites*
Diesel fuel replaced (based on the local fuel consumption of diesel buses, ideally operating on the same line)	> 500’000 litres	> 1.5 million litres across the Phase 1 sites > 4.3 million litres across all sites
Specific operational expenditure (OPEX) along the on-site chain of hydrogen production and dispensing, excluding VAT - at the start of the project - during the project	< 10 €/kg < 5 €/kg	> 13 €/kg at all sites

0.1 Efficiency

At all sites with local fuel generation, the average efficiency of hydrogen production surpassed the target of 50%. This means that, on average, less than 66.7 kWh electrical energy were required to produce 1 kg hydrogen.

During periods with capacity factors[1] lower than 10% to 15%, however, stand-by losses adversely affected performance, sometimes resulting in monthly efficiency values less than 50%. The reason for this under-utilisation was the building in of over-capacities to allow for redundancy in the case of equipment failure or to consider a future enlargement of fleet size. Moreover, the fuel economy of the buses improved greatly, which reduced the daily hydrogen demand. It was not clear at the beginning of the project that the specific fuel consumption per kilometre travelled would be more than halved compared with previous trials.

The electrolysers integrated into buildings seemed to perform some 2% to 4% better on average than those installed in containers (see Figure 0-2). This can be explained

[1] The capacity factor is a measure of the rate of utilisation of a system. If a unit were to be operated 24 hours per day at rated capacity during its lifetime, its capacity factor would be 100%.

by the fact that containerised units usually receive all energy via one single power plug, including e.g. for heating, which is not part of the production process but results in reduced efficiency values. This is in effect a measurement artefact and needs to be considered when comparing and assessing numbers from various sites.

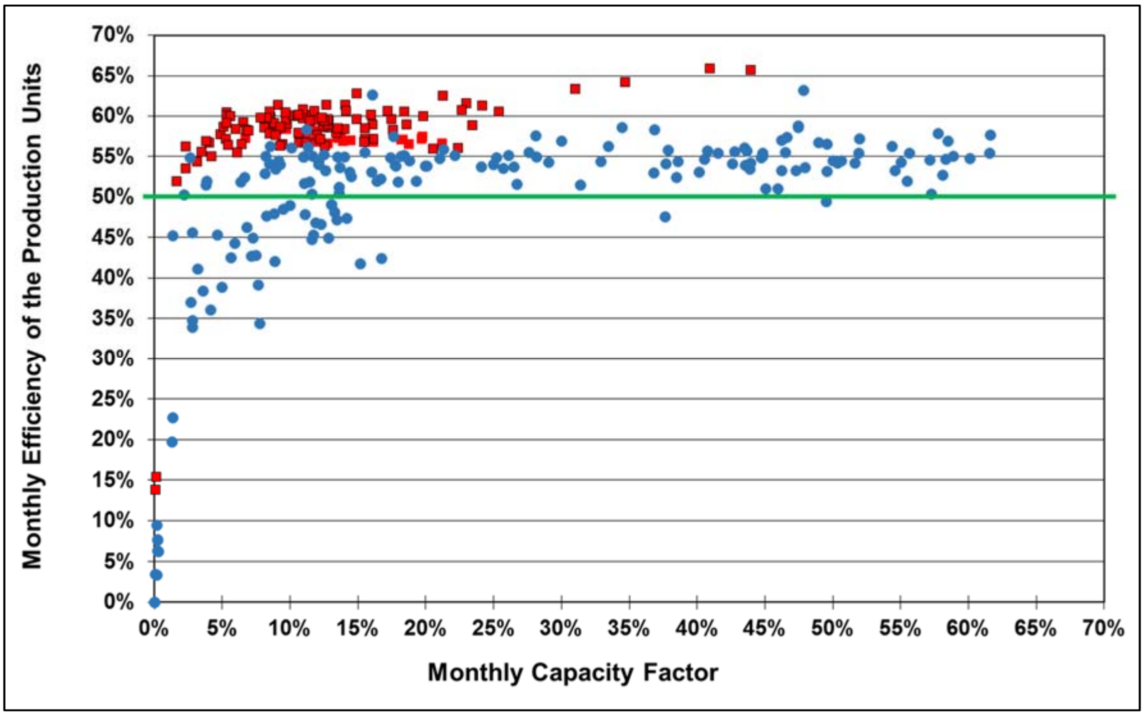

Figure 0-2: Monthly efficiencies of the electrolysers as a function of the capacity factor. The red squares are based on data from building-integrated electrolysers and the blue circles on data from containerised units. The green line represents the 50% efficiency target for hydrogen production. See text for discussion.

In addition to the KPI "Efficiency of hydrogen production on site", the efficiency of the complete on-site hydrogen chains, i.e. from generation to up to dispensing was studied, thus including power consumption for compression from 10 bar or 30 bar to above 350 bar.

It turned out that the efficiency figures for complete on-site hydrogen supply chains were approximately 3% lower than those for hydrogen generation only. Even with the added energy consumption of the Station Unit, the on-site supply chains exceeded the 50% threshold (assuming reasonable capacity factors), which originally was defined for the Production Units alone.

0.2 Availability

Three Station Units surpassed the 98% target (up to 99.8%). Another one was close to meeting it (97.8%). A fifth station had a difficult start during the first year of operation but accomplished 98.7% on average since June 2013. All sites scored more than 94% (see the blue bars in Figure 0-3). Therefore, the level of availability of the refuelling stations was not a matter of concern overall in CHIC.

The project average availability across the Station Units was 97%[2]. This is a much better level of performance than in the preceding project HyFLEET:CUTE when only close to 90% could be achieved[3].

As in previous trials, the most prominent reason for downtime were failures of hydrogen compressors (see Figure 0-4). This happened even though most sites had built in redundancy with two units installed in parallel, while the capacity of one unit would have been sufficient to supply the daily fuel demand.

If there had been no downtime caused by hydrogen compressors, all sites would have achieved 97.7% average availability at least, which is very close to the CHIC target of 98% (see the red bars in Figure 0-3). Difficulties with compressors were avoided at one of the sites by external hydrogen delivery at high pressure, above the rated tank pressure of the buses, so that filling of the buses could be achieved without compression at the station being required.

Downtime for maintenance was negligible at some sites. Elsewhere, up to 1.5% availability were lost for a week of annual maintenance or for regular monthly maintenance (even though monthly maintenance never affected refuelling thanks to appropriate scheduling). Therefore, a good maintenance concept, in line with a fully modular design of a station, can have a positive impact on availability.

External downtime causes included thunderstorms, power surges, by-passers pushing an emergency shutdown button, and external hydrogen delivery being delayed.

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2 Berlin is not included in this sub-section, because the facility there belonged to an earlier generation of stations. It was commissioned in 2006 as part of the project HyFLEET:CUTE. Therefore, it did not represent state-of-the-art technology to be assessed here.

3 In this context, it can be noted that the target of more than 98% availability was ambitious: Only eight hours of downtime per month, e.g. for maintenance, reduce availability by more than 1%. Availability calculation is based on 24 hours a day and 7 days a week.

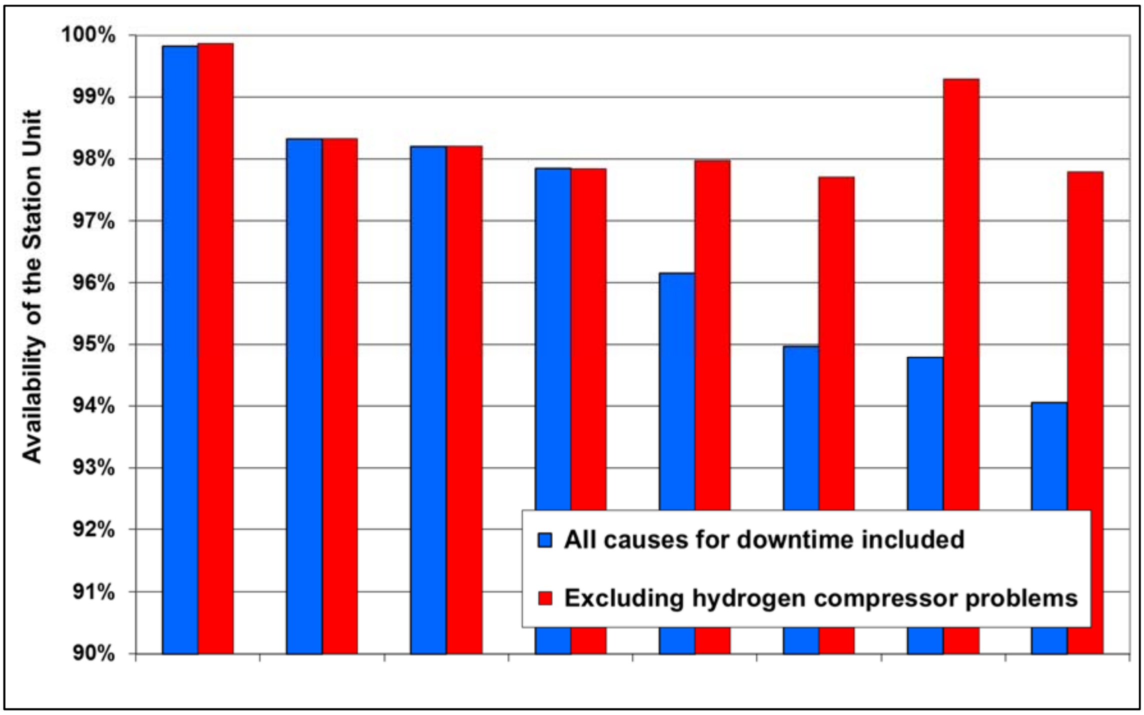

Figure 0-3: Impact of compressor problems on the availability of Station Units.
The sites are sorted by their average availability with all causes for downtime included (blue bars). The red bars show the level of availability that would have been achieved if there had been no downtime due to problems with hydrogen compressors.
Note that the y-axis intersects the x-axis at 90% availability. Excluding Berlin (see footnote 2 on the preceding page).

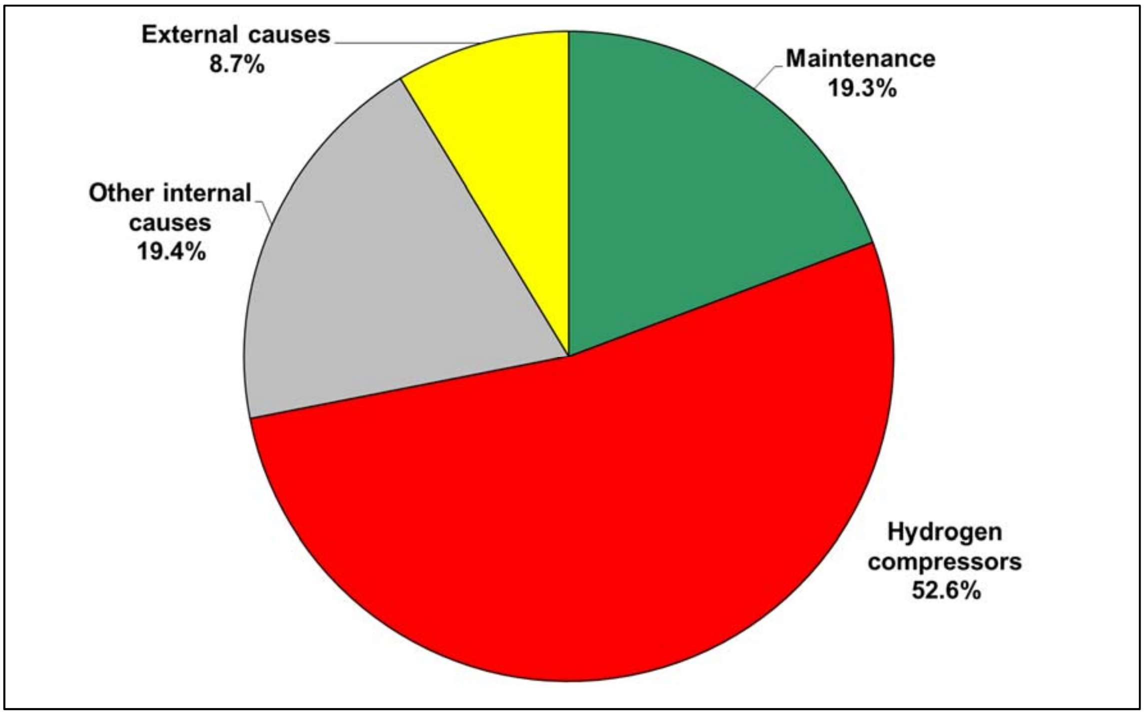

Figure 0-4: Distribution of causes for downtime of the Station Units across the sites.
See text for discussion.

Figure 0-5 and Figure 0-6 show that neither the amount of hydrogen refuelled per year nor the length of the period since commissioning seem to have had a clearly diminishing effect on average availability during the trial.

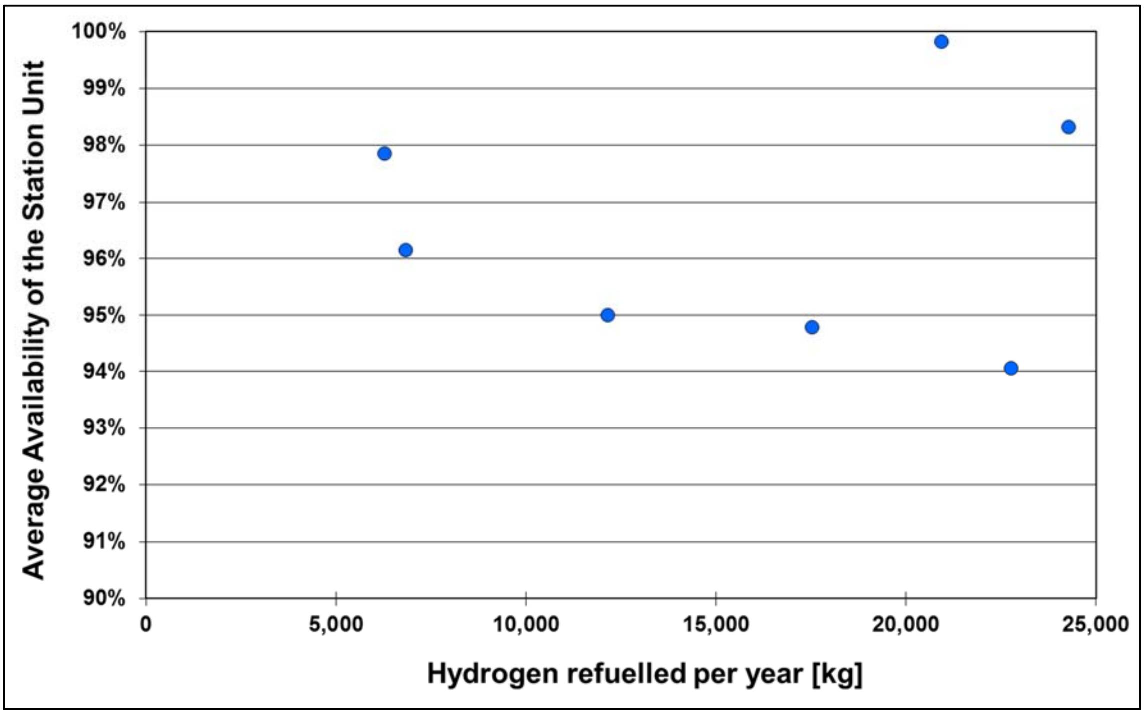

Figure 0-5: Availability of the Station Units at the individual sites as a function of the annual amount of hydrogen dispensed.
Note that the y-axis intersects the x-axis at 90% availability.

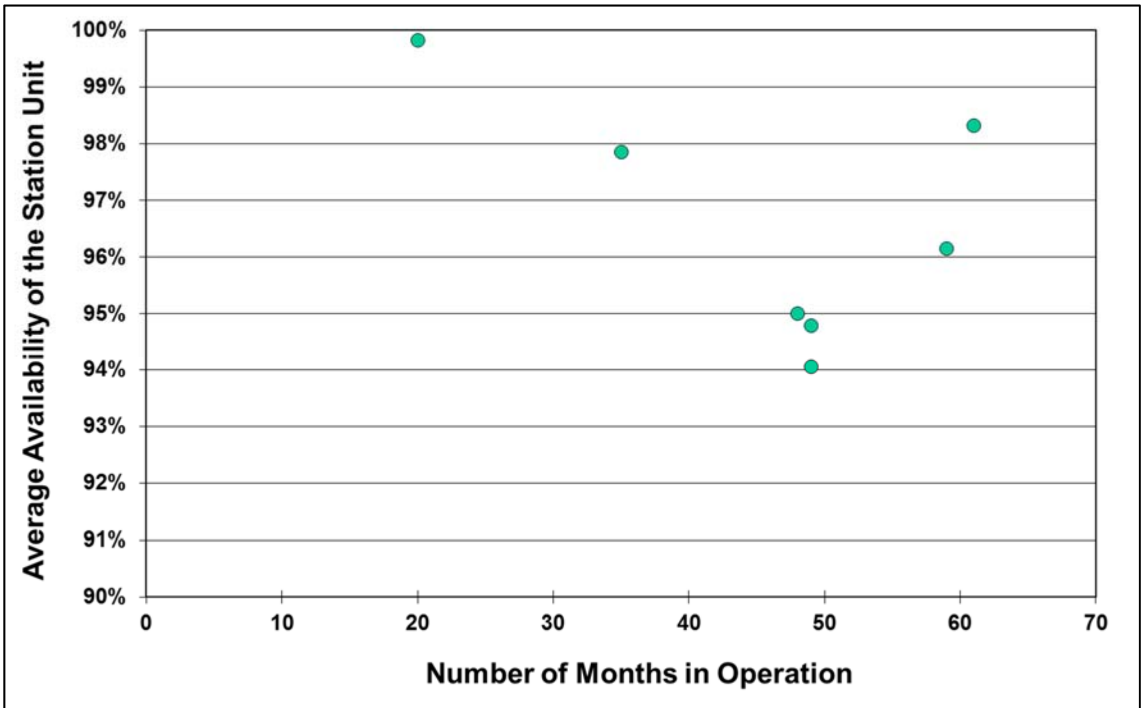

Figure 0-6: Availability of the Station Units at the individual sites as a function of its number of months in operation.
Note that the y-axis intersects the x-axis at 90% availability.

0.3 Diesel Fuel Replaced

The amount of diesel fuel replaced at the five Phase 1 sites was more than 1.5 million litres, thereby passing the target of 0.5 million litres by a factor of three.

When including the four Phase 0 sites, the use of more than 4.3 million litres diesel was saved.

0.4 Operational Expenditure

The targets with respect to the specific operational expenditure (OPEX) along the entire on-site supply chain of hydrogen production and dispensing were not met by any of the sites. Instead of less than 10 €/kg hydrogen dispensed at the start of the demonstration phase and less than 5 €/kg during or towards the end of the project, OPEX of up to 20 €/kg were encountered. The reasons include high prices for power and the low capacity factors of the facilities.

As part of an interim report on hydrogen infrastructure performance, a parameter study was carried out to further investigate the impact of various cost factors on the overall level of OPEX. It revealed that, in order to meet the initial 10 €/kg OPEX target, the capacity factor of the stations would have to be significantly higher than 50%. Moreover, power prices, including grid charges, energy taxes, sustainable energy surcharge etc., would have to be in the range of 0.10 € per kWh (or even lower at lower capacity factors). However, the actual capacity factors in the CHIC stations were smaller than 25% on average and power prices ranged from 0.12 to 0.17 €/kWh.

According to the parameter study, it is feasible that future larger, well-utilised, and more efficient facilities designed for servicing a fuel cell bus fleet of around 120 vehicles can accomplish the even more challenging 5 €/kg OPEX target. The key prerequisite to achieving this target is an average power price of about 0.08 €/kWh. Such a price range will require relief from at least some of the abovementioned cost elements, e.g. renewable energy surcharges.

0.5 Speed of Dispensing

The speed of dispensing is not a KPI but important to bus operations and worth being included here.

The dispensing equipment allowed a maximum gas flow rate of 120 g H_2 per second. This corresponds to 7.2 kgH_2/min. However, the actual momentary and average flow rate depends on the constantly changing pressure differential between station storage and bus tank. It is also influenced by the refuelling protocol that the manufacturer applies, by the capacity of the station storage (including the size and number of benches it has) and of the bus tank, by temperature, and by whether or not the station receives information on the status of the bus tank. While the maximum flow rate of 7.2 kgH_2/min may be reached at some point during a fill, the average across a complete filling event will be much smaller than this figure.

At the European CHIC sites, the average speed of dispensing derived from the operating data ranged from 2.1 kg/min to 2.8 kg/min. The average amount refuelled was 17 kg per filling. Accordingly, the typical fill time after a normal day of bus line service lasted about 6 to 8 minutes, therefore usually less than the targeted 10 minutes. This is another achievement compared with previous projects when refuelling took much longer.

0.6 Quality and Safety

During the course of the project, incidents relevant to quality and safety were reported internally and to the European Hydrogen Incident and Accident Database (HIAD), using a standardised template. Review of these reports supports two conclusions:

- The safety systems designed to prevent accidents operated successfully. Measures included shutdown of non-explosion proof equipment, forced ventilation in closed rooms, etc.
- Equipment redundancy was the key to keep the stations available at or close to the target level. Under these conditions, compressor or dispenser failure becomes a major problem only when both redundant components are out of order. Without contingency arrangements, the availability of some of the CHIC stations would have been significantly lower than actually achieved.

0.7 Summary, Lessons and Recommendations

In summary, operation of the hydrogen refuelling infrastructures was a success. In particular, the higher levels of availability and the shorter times to refuel, compared with the first generation of 350 bar refuelling facilities engineered a decade ago, represent a significant improvement in technology.

With regard to lessons and recommendations for future activities, the results of the analysis reveal how the underutilised operation of hydrogen refuelling infrastructure can reduce energy efficiency and increase specific costs. Under-utilisation undermines the economic feasibility of hydrogen as a fuel and of fuel cell bus operation. It must therefore be avoided as much as possible in subsequent demonstration activities to pave the way to commercialisation.

Appropriate infrastructure solutions will require reasoned and insightful design of facilities that enables flexible, step-by-step increases in production capacity, if applicable, and in dispensing capacity, to go hand-in-hand with the build-up of fuel cell bus fleets.

The problems with compressors at some CHIC sites again highlight the need for robustness of equipment, contingency arrangements or – where compatible with the local refuelling concept – elimination of the need for critical components. Any built-in redundancy must be balanced with the economic operation of the facilities, i.e. ensuring the security of fuel supply to the buses whilst minimising costs.

Despite the technical progress in refuelling infrastructure deployed in the CHIC project, next generation hydrogen refuelling operations should still expect that implementing a new hydrogen facility is unlikely to be completely trouble free.

Further details on operators' experiences with respect to planning, procurement, obtaining approvals, and operation of the hydrogen stations can be found in the public CHIC report "Recommendations for Hydrogen Infrastructure in Subsequent Projects". It also includes the outcomes of a debate among the CHIC partners on the requirements that future stations suitable for refuelling a complete depot with 100 and more fuel cell buses will have to meet. Whilst there was an agreement on qualitative criteria. The quantitative expectations associated with some of these criteria were not universal. This includes different expectations on matters such as regarding the required speed of dispensing or the length of a dedicated daily "refuelling window" with 100%

station availability. The expectations depend on the size of the individual depot and on how the routine of preparing the buses for the next day of service is organised.