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Table of Contents

Index of Figures

Index of Tables

List of Abbreviations and Terms

CAPEX	CAPital EXpenditure
CEP	Clean Energy Partnership
CHIC	Clean Hydrogen in European Cities, project co-funded by the FCH JU under the 7th Framework Programme
DIS	Draft International Standard
EU	European Union
FC	Fuel Cell
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FP	Framework Programme
H_2	Hydrogen
HRS	Hydrogen Refuelling Station(s)
HyFLEET:CUTE	Hydrogen for Clean Urban Transport in Europe, project co-funded by the EU under the 6th Framework Programme
ISO	International Organization for Standardization
LHV	Lower Heating Value (also called Net Calorific Value / NCV). The LHV denotes the chemical energy content of a fuel that can be converted into mechanical energy; LHV of hydrogen: 3 kWh/Nm^3 or 33.33 kWh/kg.
NCV	Net Calorific Value; see LHV
Nm^3	Normal cubic metre (1 m^3 of dry gas at 1.013 bar absolute and 0°C)
OIML	Organisation Internationale de Métrologie Légale (International Organization of Legal Metrology)
OPEX	OPerational EXpenditure
PEM	Proton Exchange Membrane *or* Polymer Electrolyte Membrane
SAE	Society of Automotive Engineers
TRL	Technology Readiness Level(s)

0 Executive Summary

The objective of this document is to offer guidance to participants in future fuel cell bus demonstration projects regarding hydrogen refuelling infrastructure. It is a concise document that focusses on key messages in order to establish an initial orientation to fundamental topics and issues. References to further information sources with more details are provided.

The introduction presents a set of basic facts regarding hydrogen as a fuel and hydrogen refuelling stations in comparison with diesel. It also discusses the concept of rating the maturity of innovative technology by means of Technology Readiness Levels.

Lessons and recommendations that result from planning, procurement, obtaining approvals, and operation of the hydrogen stations in the CHIC project are summarised. In addition to organisational and technical matters, the lessons and recommendations extend to the importance of interaction with various parties all the way through a demonstration project, and in particular during its early stages. A key learning has been that an inclusive approach at the outset pays major dividends.

Equally important, it turned out that the system of Technology Readiness Levels is too generic to rate the performance of a hydrogen refuelling station appropriately. A Technology Readiness Level rating can only give a rough indication of the level of performance. This might lead to a mismatch of expectations, as encountered at some of the CHIC sites, in particular because there is no universal set of requirements across all operators. Instead, they can be more appropriately determined by local circumstances, i.e. the way a bus depot is organised.

In order to help avoiding a mismatch of expectations in future projects and to make new players aware of likely challenges:

- A set of qualitative performance criteria was developed for adequately characterising hydrogen refuelling stations for fuel cell bus fleets, and
- Ranges of quantitative performance targets regarding these criteria were suggested for future commercial stations.

The main criteria discussed are:

- Availability and factors impacting on it (overall availability on a 24/7 basis, availability during a dedicated refuelling window, dependable service, and waiting time for repairs and spare parts)
- Duration of refuelling
- Staff qualifications and labour effort.

These criteria relate to topics that received particular attention in the course of the internal debate within CHIC. Additional issues are:

- Length of a teething period
- Scalability
- Accuracy of hydrogen metering
- Hydrogen quality requirements and quality monitoring
- Footprint.

Reduced expectations with respect to pre-commercial stations were also covered, insofar as what lower performance targets might be satisfactory relative to fully commercial stations. An example could be accepting reduced availability.

In conclusion, it can be stated that the current generation of hydrogen stations is by far more reliable than the previous ones. Nonetheless, significant challenges still lie ahead on the way to fully commercial refuelling infrastructure suitable to supply an entire bus depot with hydrogen fuel.

These challenges are well understood and can be expressed in terms of the performance criteria as described in this document.

The challenges are being tackled. An ongoing project called NewBusFuel is expected to publish its results by the end of this year, suggesting first solutions for hydrogen stations capable of refuelling up to around 250 fuel cell buses per day.

1 Objective and Structure of the Report

The objective of this document is to offer guidance regarding hydrogen refuelling infrastructure to participants in future fuel cell bus demonstration projects.

To this end, Chapter 2 presents some basic information regarding hydrogen as a fuel and hydrogen refuelling stations (in comparison with diesel). It also discusses the concept of rating the maturity of innovative technology by means of Technology Readiness Levels.

In Chapter 3, a summary of lessons and recommendations is provided. These have resulted from planning, procurement, obtaining approvals, and operation of the hydrogen stations in the CHIC project.

Chapter 4 documents the outcomes of a debate about the technical performance of the hydrogen stations in CHIC, focussing on adequate criteria and target levels for performance rating. The idea is to help avoid a mismatch of expectations of stations in future projects, as was encountered at some of the CHIC sites, and to make new players aware of likely challenges. Simply referring to Technology Readiness Levels, which are frequently used for categorising the status of innovative technology, is not sufficient.

Chapter 5 gives a summary and conclusions.

This report is a concise document that focusses on key messages, in order to get an initial orientation to fundamental topics and issues. It does not attempt to be a comprehensive guidebook, which might deter interested parties from taking up the information offered due to its bulkiness. Instead, reference is made throughout the text to documents containing further information.

Sources of reference include other public reports generated within CHIC which are project deliverables to the co-funding body Fuel Cells and Hydrogen Joint Undertaking (FCH JU). They can be downloaded from the project's website http://chic-project.eu/.

2 Introduction

2.1 Basics of hydrogen as a fuel and of hydrogen refuelling stations

There are some facts important to bear in mind in the context of using hydrogen as a vehicle fuel, in order to understand its potential and the challenges involved, especially in comparison with diesel.

2.1.1 Energy density

Gaseous fuels such as hydrogen have a considerably lower energy density per unit of volume than liquid fuels such as diesel, even though gaseous fuels are usually pressurised. The rated pressure of on-board bus tanks for hydrogen is 350 bar. At this pressure level, the energy density of hydrogen amounts to about 0.85 kWh per litre, which is less than one-tenth of that of diesel at ambient conditions (Table 2-1).

Therefore, storage of hydrogen – on the site of the station, and on board the buses – requires significantly more volume than storage of diesel. This needs to be considered when planning a refuelling facility.

Hydrogen can also be liquefied, but this requires very low temperatures and, therefore, is energy intensive. Moreover, the effective gain in energy density compared with compressed gas is not as high as suggested by the figures in Table 2-1 because vessels for storing liquid hydrogen must be highly insulated to prevent boil-off as much as possible. This requires volume in addition to that occupied by the fuel.

Table 2-1: Volumetric energy density of diesel and hydrogen.
Based on [H2 Data 2016]. See text for further details. All figures here and in the following refer to the lower heating value (LHV), which denotes the chemical energy content of a fuel that can be converted into mechanical energy.

Fuel	Temperature	Pressure	Energy density
Diesel	ambient	ambient	approx. 10 kWh/litre
Hydrogen (gaseous, compressed)	ambient	350 bar	approx. 0.85 kWh/litre
Hydrogen (liquefied)	-253°C	up to about 10 bar	approx. 2.36 kWh/litre

While on-site storage of liquid hydrogen fuel in stations has been implemented in a number of projects, on-board storage of liquid hydrogen is not practiced in the bus sector.

2.1.2 Fuel supply to the station

Both diesel and hydrogen (compressed and liquefied) are delivered by tanker lorry throughout the world. However, due to hydrogen's lower energy density and because pressure vessels for gaseous fuels are heavy and hence reduce the payload, the amount of energy per delivery is much smaller than would be the case with diesel.

Accordingly, the delivery of hydrogen fuel to the station requires a higher logistical effort compared with diesel. This is exemplified by the following rough estimate: In order *to deliver the same amount of energy* as 1 forty-tonne tanker lorry carrying 30.000 litres of diesel, about 10 forty-tonne trucks transporting pressurised hydrogen at 500 bar are required or more than 2 forty-tonne trucks that carry liquefied hydrogen. However, fuel cell buses operate more efficiently than diesel buses. The 12 m buses in CHIC need about 25% less energy per kilometre compared with their diesel equivalents [Lozanovski et al. 2016]. Considering this, only about 7.5 forty-tonne trucks with pressurised hydrogen at 500 bar or less than 2 forty-tonne trucks with liquefied hydrogen are required *to facilitate the same mileage as with a diesel bus*.

Hydrogen can also be carried by pipeline. However, this is only economically viable at high throughputs, as in the natural gas grid. The natural gas grid covers large areas of Europe and in many regions reaches bulk and retail customers, including filling stations.

Only a few pipeline networks for hydrogen exist, which connect industrial producers and consumers in a particular region, but to date supply very few filling stations. The option of feeding hydrogen into the natural gas grid, transporting it in a "piggy-back" way and subsequently separating it from the natural gas is not currently mature.

2.1.3 Dispensing

Dispensing usually takes place by overflow filling, i.e. resulting from a pressure differential between the storage of the station (at e.g. 450 or 500 bar) and the bus tank. A top-off routine using a "booster compressor" to speed up the complete filling is in place at some sites.

Due to the lower energy density of hydrogen relative to diesel, hydrogen needs to be dispensed at a higher flow rate in order to refuel the same amount of energy in the same time frame, i.e. to refuel the bus as fast as with diesel[1]. However, restrictions on the bus tank temperature apply, depending on its type (materials used).

The faster the fill rate, the greater the temperature increase in the hydrogen gas and the tank. Therefore, the hydrogen flow needs to be controlled to manage the temperature increase in the tank. The temperature increase will also depend on other factors such as the ambient temperature.

In the CHIC project, typically less than 10 minutes have been required to refuel a bus after a full day of line service [CHIC 2016], which is significantly faster than with the previous generation of stations.

Figure 2-1 shows a generalised schematic of the hydrogen refuelling stations (HRS) in this project. All sites possess a Station Unit for hydrogen storage and dispensing. Several sites also employ a Production Unit for on-site hydrogen generation through water electrolysis, which splits water into hydrogen and oxygen using electrical energy. Some sites rely on a mix of on-site fuel generation and external delivery (of gaseous hydrogen), while others have employed external delivery only as a backup option[2].

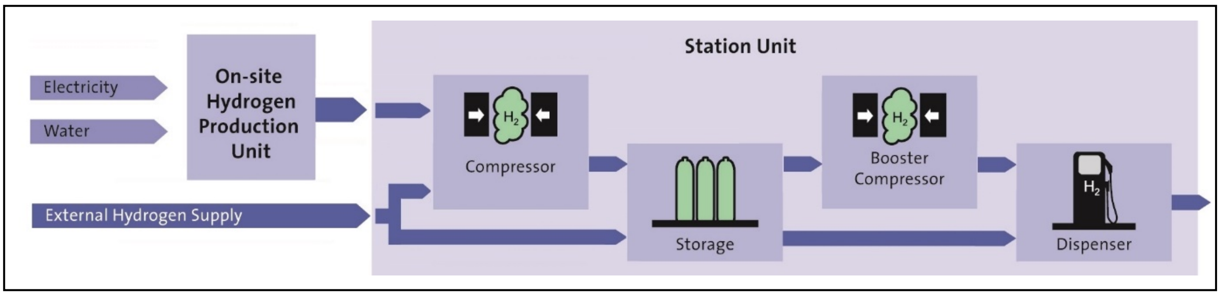

Figure 2-1: Generalised schematic of the HRS in CHIC.
Source: HyFLEET:CUTE project (2006 – 2009), modified for CHIC.

2.1.4 Fuel quality

A specific requirement for hydrogen used to power road vehicles is the absence of hydrocarbons and a number of other substances, in order to prevent terminal damage to the fuel cells, a reduction of its performance, or of its lifetime. Since lubricants for

[1] However, because the fuel cell drivetrain is more efficient than the diesel drivetrain, as exemplified above, less energy needs to be refuelled for the same vehicle range.

[2] The specifics of some of the installations vary from the schematic in Figure 2 1. Details can be found in [Stolzenburg et al. 2014].

mechanical devices and in particular compressors typically consist of or include hydrocarbons, special attention has to be taken as to avoid their transfer into the hydrogen on its way from delivery or on-site generation up to the dispensing nozzle.

Different hydrogen production methods can also introduce substances that will impair the performance of the fuel cells and these also need to be carefully monitored.

2.1.5 Redundancy

A lesson from previous fuel cell bus demonstration projects has been to allow for the failure of key components of the hydrogen stations, in order to ensure the timely refuelling of the vehicles. That relates to problems with hydrogen compression in particular. Accordingly, a spare compressor unit was installed at most sites, but also – depending on the local concept – extra storage capacity, an extra electrolyser, or an extra dispenser. Drawbacks of this approach are higher investment costs, and a lower rate of utilisation relative to the increased nominal daily capacity of the station.

For example, since current fuel cell bus fleets are rather small, one compressor unit per station would usually be sufficient in terms of capacity. Therefore, the need to add another for redundancy makes a significant impact. In the future, when hydrogen stations supply an entire bus depot with fuel, several compressor units will have to be installed in parallel anyway, so under these circumstances adding a spare unit is going to be less significant[3].

2.1.6 Green hydrogen

Hydrogen can be produced almost without carbon dioxide emissions when it is derived from water electrolysis using power from renewable sources. This is the most common way of generating “green” hydrogen today and it typically takes place on site at the station.

Hydrogen delivered by truck typically is produced from fossil fuels today, e.g. in large-scale methane steam reforming plants, or it comes as a by-product from chemical processes such as chlor-alkali electrolysis.

[3] On-site compression can be avoided when hydrogen is delivered to the site at high pressure, as this will allow refuelling by pressure differential from the trailer without compression.

An increasing percentage of hydrogen fuel from green sources is important to address concerns of environmental groups and gain their support. They often fear that hydrogen will only serve to shift emissions from the tailpipe to the place of fuel generation, instead of ensuring low-carbon mobility along the entire chain of hydrogen supply and use. These groups wish to see hydrogen as a low emission technology along the complete life cycle. [Whitehouse/Whitehouse 2013, Whitehouse/Whitehouse 2015]

An assessment of the sustainability of the fuel cell buses and related infrastructure in CHIC is currently underway [Lozanovski et al. 2016].

2.2 Technology readiness

Stations for refuelling hydrogen-powered buses are not currently as technologically mature as stations for diesel, so they do not always meet bus operators' expectations. Also, HRS suitable for supplying large bus fleets are only in a concept stage of development.

The concept of Technology Readiness Levels (TRL) can help to determine where an innovative concept currently is on its way from basic research (TRL 1; see Table 2-2) to a fully commercial product (TRL 9). However, the definitions of the individual TRL are general, so that specific stakeholders or groups of stakeholders may have differing opinions on where a technology is currently to be located on the TRL ladder. Moreover, various definitions of the TRL steps exist, which are often specific to certain technology sectors (such as space, oil and gas, or military). Differences can extend just to wording, but also systems that range from 0 to 9 as well as from 0 to 7 are in place[4]. To illustrate this, Table 2-2 lists, in addition to the definitions used by the FCH JU, another set with alternative descriptions from a European Commission source. In some cases, the alternative EC set of definitions seem more practical.

A supplier and an operator of an HRS may have different views as to what standard of performance is to be expected from a piece of equipment. Given the generic nature of the TRL definitions, relying only on them is not necessarily sufficient for reaching a common understanding. When an HRS is referred to as having reached TRL 7 for

4 [Wikipedia 2016] provides an overview and historical account plus comprehensive references.

example, i.e. being mature for "System prototype demonstration in operational environment", it is clear that it cannot be a fully mature product. However, merely based on a TRL 7 status[5] it is not clear what exactly can be expected regarding its availability (uptime/downtime), the length of a teething period at the beginning of operation, its average time to repair, or the regular servicing effort per day or month.

Table 2-2: Definitions of Technology Readiness Levels.
As used by the FCH JU in their Multi-Annual Work Plan 2014 - 2020 [FCH JU 2014] and, in square brackets, according to a European Commission source [Schild 2013].

TRL	Definition
9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies) [Full commercial application, technology available for consumers]
8	System complete and qualified [First of a kind commercial system. Manufacturing issues solved]
7	System prototype demonstration in operational environment [Demonstration system operating in operational environment at pre-commercial scale]
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies) [Prototype system tested in intended environment close to expected performance]
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies) [Large scale prototype tested in intended environment]
4	Technology validated in lab [Small scale prototype built in a laboratory environment ("ugly prototype")]
3	Experimental proof of concept [Applied research. First laboratory tests; proof of concept]
2	Technology concept formulated [Technology formulation. Concept and application have been formulated]
1	Basic principles observed [Basic research. Principles postulated and observed but no experimental proof available]

[5] In its 2016 Work Plan, the FCH JU requires with respect to the "Large scale validation of fuel cell bus fleets" a TRL of 7 for stations to service fleets of 20 or more buses [FCH JU 2015].

In order to develop a common understanding of adequate performance criteria for HRS, the matter was debated among the members of the CHIC consortium. In particular, the features required of future fully commercial hydrogen stations for buses were clarified (see chapter 4)

3 Lessons and Recommendations

The purpose of this chapter is to provide a concise overview of lessons and recommendations from the project based on experiences with applying hydrogen refuelling technology on a day-to-day basis.

Sections 3.1 to 3.3 on planning, tendering, and obtaining approvals mainly summarise findings of an earlier CHIC public report [Stolzenburg et al. 2014]. Additional information on these subjects can be found there. Learnings from operation (section 3.4) were collected for this document and in the context of discussing technology readiness and expectations of infrastructure performance (chapter 4).

There is no doubt that significant challenges lie ahead on the way to refuelling infrastructure suitable to supply an entire bus depot with hydrogen fuel. Nonetheless, it is worthwhile pointing out the considerable progress that has been made over the last 10 to 15 years in a series of demonstration projects. The current generation of HRS is much more reliable than the previous ones, particularly in terms of availability and of ensuring a complete fill in a reasonably short period. Approval processes are clearer, and experience reports and guidelines exist.

3.1 General issues and initial planning

On-site generation of hydrogen was favoured and implemented by the majority of sites because it facilitates low-carbon fuel based on green electricity. However, on-site generation was also a matter of debate, because when the HRS is located in the bus depot hydrogen production requires additional space, which always seems to be scarce in depots.

- Bear in mind the complexity of hydrogen refuelling infrastructure in comparison with that for diesel.
- Bear in mind the importance of securing hydrogen supply at all times.
- Consider carefully the exact location of the HRS for long-term practical reasons and for safety reasons.
- A modular design of the facility is important, since it should always be possible to extend or reduce the refuelling capacity as required.

- Sufficient space (footprint) must be available, and limitations should not be set before planning has reached a certain level of detail and finality.
- Be prepared for unknown challenges and delays and extra costs. That can include issues as diverse as oil spills underground from previous usage of the area, or unexploded wartime items. Consider the location of the broadband, gas, water and electricity lines etc.
- Hold regular progress meetings with all parties involved, both within your organisation and local partnership.
- Include the local permitting authorities in the planning process from the very beginning. Consider them as partners. Familiarise them with relevant national and international standards and best practice examples, in order to avoid delays in permitting process due to safety concerns (see also section 3.3).
- Keep your neighbourhood, the general public, decision makers etc. informed from the very early stages of a hydrogen project.

As part of the HyFLEET:CUTE project that preceded CHIC, guidelines for local community engagement when implementing hydrogen-powered transport were compiled [Rouvroy et al. 2008].

The factors that influence the acceptance process of fuel cell and hydrogen technologies in public transport among various groups of players were researched in an extensive public study as part of the CHIC project [Hölzinger/Lüdi-Geoffroy 2013]. The report presents the diverse opinions and concerns of the people involved, both directly in the orbit of the project, and also in the broader regional political processes that took place, in order to demonstrate hydrogen buses in public transport. A concise summary is available as well [Hölzinger/Lüdi-Geoffroy 2014].

3.2 Tendering

Suppliers recognise that tender callers cannot know all technological details. However, a clear idea of what the tender caller wants is very important. The tender caller should have investigated his needs, the market options, and their costs.

- In particular, it must be clear whether the tender caller wants to operate the HRS or just buy the hydrogen that is dispensed and leave operation to the tenderer, or to a third party.
- Be aware of the importance of clearly and fully defining responsibilities between local partners early and certainly before putting the station out to a competitive tender.
- Tender processes are time consuming and can cause delays. They can have unforeseen results and issues. Sourcing external expertise may be necessary.
- Nonetheless, public tendering can help reducing the price significantly. It can also ensure a strong contractual position vis-à-vis the successful bidder.
- Be specific in the preparation of the tender documents. This will pay during installation, commissioning, and operation, and limit costs.
- Specify outputs and not inputs. Define scopes and interfaces clearly.
- A turn-key solution provided by a single supplier can help prevent or reduce interface and responsibility problems.
- Tender with clear performance quality criteria (not only the price) to be matched; this will simplify following up on issues with the supplier during operation.
- Suppliers point out that a tender should specify realistic requirements (particularly regarding on-site production and refuelling) instead of worst-case scenarios. Operators stress their need to be assured that extremes can be catered for.
- Suppliers with standard products or alternative solutions may not be able to bid their most economical options if the station specifications are too strict.
- Including multi-year warranties and maintenance arrangements will enhance affordability of the technical solution supplied.
- Penalty clauses will ensure best efforts from the supplier. Penalties could apply to delivery delays, to not meeting the required availability of the facility (and possibly of some major components), to not meeting the refuelling capacity, to failing to meet minimum/maximum reaction times in the case of failure etc.

Both sides agree that flexible options are needed (e.g. stating ranges instead of exact capacity requirements), including back-up solutions. They also consider important a reasonable level of standardization with respect to volume, footprint, storage, on site production and quality. It will help to reduce costs.

- Operators will want only one supplier to be responsible for the hardware. Suppliers recommend separating different roles (e.g. overall coordination of planning, approval processes, hardware and installation, operation, and maintenance).
- However, if the supplier is expected to be responsible for operation, it is advisable to request hardware and operation in a single tender.

3.3 Obtaining approvals

Permitting continues to be a laborious and time-consuming element of implementing an HRS. The authorities were often interested in the new technology and supportive. However, factors such as lack of experience, or particular requirements at the local administration can still slow down the pace of obtaining the required approvals.

- An inclusive approach at the outset pays: It is important to involve the relevant authorities, including the fire department, from the beginning and develop a collaborative working relationship.
- Spend time and energy helping the regulators understand the technology, issues, and solution options. The need to “educate your regulator” must be expected to continue into the future, even though representatives from sites with experiences before CHIC stress the progress that had been made with respect to dealing with authorities over the past decade.
- It is important to be thorough in preparing for approvals and understand that the applicant retains responsibility. Permitting authorities do not audit documents but make it clear that you must get it right in creating a complete concept.
- Previous experiences with natural gas or biomethane (biogas) as a vehicle fuel can be of help.
- Sometimes, there can be a difference of opinion between safety consultants on requirements in/around a hydrogen station, for example when assessing the risk and consequences of a pipe or vent breach.

Several CHIC partners stress the need for specific documents that support both the operator who has to obtain approvals, and the authorities considering granting them.

This could lead to a mandatory EU description of safety requirements on/around hydrogen infrastructure, such as a recognised European standard. Some partners even favour a binding EU Directive.

However, the prevailing experience is that individual local authorities follow their own procedures within an overarching framework. Therefore, even an EU Directive would not necessarily solve all major issues with regard to infrastructure licensing, since such a document cannot substitute individual and organisational experiences on local/regional level.

A detailed account of the authorisation procedures for hydrogen infrastructures and buses at the CHIC sites has been compiled [Seriatou/Reijalt 2013].

The National Organisation for Hydrogen and Fuel Cell Technology in Germany has developed guidelines that gather the experiences with approval processes [NOW 2016].

3.4 Operation

For a *rough* assessment of HRS performance, operators were asked how they rate their stations in terms of the Technology Readiness Levels (Table 2-2) today and at the beginning of operation. The approximate average is TRL 7 (“System prototype demonstration in operational environment”), both for the early stages of operation and now.

Some stations with significant problems in the beginning have improved from TRL 5 or TRL 6 to TRL 7 according to their operators. However, one moved from TRL 7 down to TRL 6 due to repeated problems with its hydrogen compressors. Two stations started with TRL 8 (“System complete and qualified”) and have kept this level of performance throughout.

A TRL 7 rating seems appropriate for a demonstration project. However, it also implies that considerable challenges remain. Operators’ comments in relation to experiences centred around a lack of robustness of equipment and procedures, as well as significant involvement of own staff being required. Items include:

- Serious “teething problems” occurred during a long start-up phase. These included interface issues, no thorough failure handling by the supplier, and a flat learning curve. Errors occurred repeatedly, without standard solutions/procedures in place.
- Shorter response times to problems or failure situations are needed. Sometimes, no person with technical skills seemed to be available through phone or e-mail. A need for 24/7 service was pointed out.
- Long downtime periods have been encountered due to waiting for spare parts (such as compressor heads, valves, sensors, etc.).
- Time to fill can be variable and longer than anticipated.
- Complete fuelling of all buses in a row (“back-to-back refuelling”) is not always possible at some sites.
- At one site, the connection between nozzle and receptacle seems to be a bit loose. When not properly connected, the station may read this as a leakage and shut down. Consequently, refuelling had to be restricted to just a handful of additionally trained personnel, rather than all drivers qualified to operate the FC buses.
- At another site, the feeling was that they have to pay for resolving technical problems despite having operated the HRS exactly according to the manufacturer specifications.

It was recommended to:

- Have clear documented arrangements as to responsibilities from the beginning;
- Get a good service level agreement for any breakdown;
- Create a good working relationship with the station operator and fuel supplier;
- Request in the tender/contract a minimum package of spare parts do be delivered with the station and stored at the local facility.
- Ensure that the scheduling is robust if hydrogen is delivered to the site from an external source.

With respect to staff requirements, it was pointed out that:

- Enthusiastic staff who take care of the station on top of their regular duties are still key to ensure a high level of availability;
- Future HRS should be less staff demanding; in particular, un-supervised refuelling must be possible.

4 Expectations as to the Performance of Future Commercial Hydrogen Refuelling Stations for Bus Fleets

While there was an overall good level of performance with the quantitative project targets being met or mostly met, some of the operators were not satisfied with their hydrogen station, as outlined in the final section of the preceding chapter. After overcoming a sometimes cumbersome teething period, a mismatch remained between performance expectations and what the HRS could actual achieve in day-to-day service. This was partly because the challenges were not always clear at the outset, despite experience reports from previous projects being available.

In order to tackle this issue and make the challenges more transparent to future new players in the field, it was decided to specify, based on the work in this project, the most relevant performance criteria for an HRS and, as far as possible, to attach quantitative targets to them.

The views of operators and technology suppliers naturally are not the same. Generally, the perspective of the operators is based on the requirements to be met to operate the bus depot as with diesel buses, with as few restrictions or adjustments as possible. The suppliers' perspective is based on what is feasible today and what is likely to become feasible in the future with a reasonable level of development effort and investment costs.

It also became clear that there is no universal set of expectations among the CHIC demonstration sites. Instead, local circumstances, the way a bus depot is organised, can have an important impact, e.g. concerning the expected speed of refuelling. This resulted in ranges of quantitative expectations in relation to individual performance criteria.

The majority of the operators in CHIC claimed that only HRS designed for a capacity to supply an entire bus depot comprising 100 or more FC vehicles can reach a TRL 9 status. The HRS is part of an overall system that has to facilitate the operation and servicing of the buses (maintenance, repair, fuelling and cleaning). Hence, it has to fit into this fine-tuned, interdependent system with local characteristics, as mentioned above. The depot's function is to ensure reliable transport for the public. This operational environment (TRL 9 is defined as "Actual system proven in operational environment") constitutes a fundamental difference from HRS for cars.

FC bus fleets today typically comprise less than 10 vehicles, and the rated capacities of the HRS are accordingly small. Designs for full-depot stations are at an early concept stage. A dedicated project named NewBusFuel is underway to make progress in this respect. By end of 2016, engineering studies will be produced for 12 locations, each defining the optimal design, hydrogen supply route, commercial arrangements and the practicalities for hydrogen stations capable of providing fuel to fleets of 75 to 260 FC buses. Public reports with aggregated results will be made available. [NewBusFuel 2016]

Given that the coming generations of HRS with increased capacity, in line with growing FC bus fleets[6], will have demonstration/prototype character at first (roughly equivalent to TRL 7, as with the current generation), there was agreement that significant challenges are likely to be encountered in the future.

In the context of all the above points, the outcomes of the internal debate are presented below:

- A set of qualitative criteria is presented that is considered adequate for characterising HRS for FC bus fleets, and
- Ranges of quantitative expectations regarding these criteria are suggested for future commercial stations (TRL 9).

The performance criteria are grouped under four headings:

- Availability and factors impacting on it (section 4.1)
- Duration of refuelling (section 4.2)
- Staff qualifications and labour effort (section 4.3)
- Additional issues (section 4.4).

In total, these can be considered the components of an overall measure of reliability.

The additional issues are topics that received less attention in the course of the internal debate, though in general they may be considered equally important.

Quantitative expectations of HRS with TRL 8 or TRL 7 ratings are discussed in terms of possible concessions on requirements for TRL 9 stations (section 4.5).

[6] See e.g. footnote 4 on page 11.

4.1 Availability of the HRS and factors impacting on it

The availability target for the HRS in CHIC is "better than 98%" on a 24/7 basis. Under this prerequisite, the maximum number of allowed downtime hours is 175 per year (2% of 8,760 hours), equivalent to about 7 days annually or about 15 hours per month. The majority of the CHIC stations meet this target but not all of them.

Downtime means that refuelling is not possible during a certain period. The reasons for downtime range from internal causes such as maintenance, failures and repair work, or lack of fuel due to problems with on-site hydrogen generation, to external reasons such as power outages or lack of fuel due to delays in fuel delivery from a remote source. Component failure, such as breakdown of one or all compressors, does not lead to downtime as long as there is enough hydrogen at the right pressure in the on-site storage to refuel a bus.

4.1.1 Overall availability

Expectations with respect to availability of a TRL 9 station range from "better than 98%" to "close to 100%" or "availability should be no concern anymore". It was also suggested that a high level of availability should be accompanied by a lower requirement for redundancy compared with a TRL 8 station (see section 4.5). That could mean, for example, that on-site storage capacity amounts to one day of fuel demand instead of two or three, or that only one spare compressor or dispenser is installed instead of two.

A modular design of the stations is expected, which increases flexibility, so that e.g. maintenance work does not lead to downtime. Instead, individual sections of the facility can be serviced while the rest remains available and buses could be refuelled without restrictions.

At one of the CHIC stations, downtime for annual maintenance takes more than four days, such as Monday morning to Friday afternoon, which is a substantial share of the "allowed" seven days off per year.

4.1.2 Availability during a dedicated refuelling window

Apart from a 24/7 perspective on availability, it was stressed that a station must be available 100% during a certain window of time, usually during the night, to ensure that refuelling does not disrupt the routine of preparing the buses for the next day of line service. Depending on the operator, this window is expected to last from 4 to 12 hours.

Apart from the length of such a period, the number of buses needs to be taken into account. It will make a significant difference whether 50 or 100 buses have to be refuelled within 4 hours.

4.1.3 Dependable service

There was agreement that apart from availability numbers and resulting requirements, planning reliability for the bus/station operator is important, in particular for situations where problems occur. Therefore, apart from requiring a reasonable level of (technical) availability, operators should ask potential suppliers for a concept for scheduled preventive maintenance that affects operation as little as possible and for a concept for how to respond to the different possible failures of the HRS ("what if" approach) and required response times.

That should include backup strategies for situations where a breakdown lasting longer than half a day or one day occurs. These strategies could include external delivery from a remote source if on-site production fails, or refuelling from high-pressure tube trailers in the event of problems with compression or dispensing. This would ensure availability by *organisational* measures to compensate for *technical* problems.

Contractual arrangements for such situations need to be supported by penalty clauses.

As pointed out in section 3.4, operators want a 24/7 service in terms of a qualified contact that can act as a "first responder" e.g. by phone.

The operators are aware that a high level of technical and organisational availability (and reliability in general) comes at a price[7]. However, that is likely to be outweighed by the consequences of a major disruption of bus service, which would result in lost revenue and business confidence.

[7] The investment costs for the fuel cell bus workshops and hydrogen refuelling stations in CHIC are analysed in [Lozanovski et al. 2015].

4.1.4 Waiting time for repairs and spare parts

Compared with the previous generation of HRS, the *number* of problems has reduced. "Problems" here stands for failures causing downtime, but also for problems with components that do not interrupt the service, often because of redundancy of devices installed in parallel, such as compressors.

However, it often still takes a long time until a problem is fixed, because a particular spare part with a long lead-time is required. That is annoying for both the operators and the station manufacturers, as well as the service company in charge of maintenance and repairs. It highlights the current immaturity of the supply chains.

Manufacturers and service providers depend on their component suppliers. Since the number of HRS built and operated is currently small, components suppliers are reluctant to keep "exotic" spare parts for these installations in stock, and their manufacturers will not produce them ahead of being required. Components designed for natural gas stations often cannot be used due, for example, to issues such as different flow rates or different materials required.

This constitutes another "chicken and egg" problem, in addition to the broader situation that HRS will not be built unless there are FC vehicles on the roads, but FC vehicles will only be built and sold if hydrogen fuel is easily available. Solving this will require joint efforts by all stakeholder groups involved.

One site recommended giving the supplier of the station a long-term service contract, so that both sides have a secure perspective in this respect, and the operator has a higher degree of certainty that a high-quality, reliable product is provided.

4.2 Duration of refuelling

With respect to the time needed for refuelling (time to fill), the expectation is often expressed as "same as for diesel buses", i.e. not quantified. When quantified, the range is from "3 minutes" to "5 to 10 minutes" and "up to 10 minutes". The requirement depends on the servicing regime at the particular depot: Sometimes the buses are cleaned while being refuelled. In this case, the duration of filling is not critical as long as it does not take longer than the cleaning. When refuelling and cleaning are consecutive work items, the requirements on the time to fill are usually more demanding.

The dispensing equipment for 350 bar bus refuelling is designed for a flow rate of up to 120 g per second (see e.g. [WEH 2014]), which is equivalent to 7.2 kg per minute. This *seems* to imply that about 21 kg can be refuelled within 3 minutes. However, 120 g/sec is the *maximum* flow rate that is allowed. Given that refuelling is based on a pressure differential between on-site storage and bus tank, the *average* flow rate will be smaller than the allowed maximum. In CHIC, typically less than 4 kg/min are achieved[8]. The process is influenced by factors such as the ambient temperature and the temperature in the bus tank, and, in particular, whether or not the control system of the station receives pressure and temperature readings from the bus tank. There is no standard refuelling protocol for buses yet, unlike for cars.

The tank capacities in CHIC range from about 30 to more than 50 kg hydrogen [CHIC 2016]. Assuming a bus with 35 kg tank capacity and 10 kg left in the tank, it is clear from the above, that refuelling within 3 minutes is not possible (8.3 kg/min required). Also achieving a 5 minute refuelling time is rather ambitious (5 kg/min required).

The time to fill is expected to be the same for the first and the last bus, i.e. no slowing down due to less hydrogen remaining in the on-site storage. A waiting time between refuelling two buses, as still encountered at a few of the CHIC stations today, is not considered acceptable for the future.

4.3 Staff qualifications and labour effort

There was agreement that a certain level of education is mandatory for staff dealing with hydrogen and fuel cell equipment. Over time, this is expected to become "normal", as it is a commonplace today to know how to refuel and handle a car.

Operators expect that refuelling can be carried out by any member of staff after a briefing and that complex training is not required. They demand robust equipment and robust procedures (see section 3.4). Station manufacturers point out that for the time being they must live with what the components suppliers offer, given the "chicken and egg" situation.

[8] The energy content of 1 kg hydrogen is roughly equivalent to that of 3.3 litres diesel. Therefore, 4 kg/min corresponds to about 13 litres/min in terms of energy. (Note that the specific energy consumption of a fuel cell bus per 100 km travelled is lower than that of a diesel bus of the same size.)

Operators also expect that unmanned refuelling is possible. This means that the person starting the refuelling of the first bus does not have stand next to the dispenser while the filling takes place, but can proceed to the next bus/dispenser or do something else, and return when the filling process is complete.

Unmanned operation is the solution desired by the operators, with supervision via remote control. Daily checks should no longer be necessary, except for fulfilling possible legal obligations, as exist in Italy.

It should be possible to carry out any routine checks and service by personnel from the bus depot who have received dedicated training. External specialists would be only needed for scheduled preventive maintenance via a service contract as outlined above.

4.4 Additional issues

4.4.1 Length of a teething period

Most of the HRS in CHIC (and in previous demonstration project) have encountered a teething period, during which many issues occurred and there was a rather low level of availability. They lasted up to a year for one “first of a kind” installation. For a TRL 9 station, ranges from 30 working days up to three months were stated as acceptable for a ramp-up phase.

4.4.2 Scalability

A bus operator is unlikely to convert an entire fleet or depot to hydrogen within a short period, such as a year, but primarily based on the end-of-life schedule of the existing diesel vehicles. A TRL 9 station therefore needs to be scalable (modular and flexible), in line with the FC bus fleet growth, in order to avoid a huge initial investment followed by massive underutilisation for a long time.

Scalability should go hand in hand with reduced customisation and complexity.

4.4.3 Accuracy of hydrogen metering

Bus operators point out the importance of precise measurements of hydrogen refuelled (hydrogen purchased), because fuel is a major cost factor for them.

Metering hydrogen at high pressures with sufficient precision is a long-standing issue. A study on the refuelling of cars by a working group of the Clean Energy Partnership (CEP) in Germany revealed tolerances of sometimes greater than ± 9% (see e.g. [Arxer Ribas et al. 2013]).

According to an expert report by the International Organization of Legal Metrology [OIML 2007], the maximum permissible relative errors on mass indications should be ± 1.5% of the measured quantity for the complete measuring system (± 1% for the meter alone). For natural gas refuelling, weights and measures authorities allow ± 2% mass deviation [Arxer Ribas et al. 2013].

4.4.4 Hydrogen quality requirements and quality monitoring

The current standard for hydrogen fuel quality (ISO/DIS 14687-2 “Hydrogen fuel - Product specification” that stipulates the same tolerances as SAE 2719 “Hydrogen Fuel Quality for Fuel Cell Vehicles”) is considered too conservative and increases the fuel price. For example, there are very few laboratories globally that can measure all the listed sub-stances at the stipulated accuracy. A more practical fuel standard is needed.

Contamination of hydrogen has rarely occurred in CHIC. Water and nitrogen were found in hydrogen once each, and oil in hydrogen twice, causing major downtime of the buses. These incidents were the results of component failure (e.g. membrane fissure in a compressor) in combination with the absence or the inadequacy of a dedicated device for the detection of such a failure (e.g. response time too long).

Unlike some years ago, online monitoring of fuel quality close to the nozzle, and therefore downstream from all possible components that could cause contamination, is no longer favoured by technology providers. The effort in terms of technology and costs would be immense, and suitable solutions that would work outside a laboratory environment are not in sight.

Regular offline checks of samples taken from or close to the nozzle appear to be more appropriate. The CEP recommends tests once a year, for example.

4.4.5 Footprint

Footprint is scarce in virtually every depot. Bus operators therefore hope for solutions equivalent, in terms of space requirements, to a diesel system for the same number of buses. As pointed out in chapter 2.1, however, hydrogen storage requires more specific volume than storage of diesel.

Suppliers pointed out that solutions for underground storage or for “going up” exist or are under development.

For hydrogen generation on site, PEM water electrolysers promise more compact designs than traditional alkaline water electrolysers (PEM = Proton Exchange Membrane or Polymer Electrolyte Membrane).

New insights into this topic are expected from the ongoing NewBusFuel project.

4.5 Reductions on requirements for future pre-commercial HRS

Operators were asked what reductions on the level of performance they would be prepared to accept for an HRS rated TRL 8 or TRL 7, apart from the fact that it would possibly not have the capacity to supply an entire bus depot. The concessions suggested again depend on the local conditions:

- A lower availability than required for a TRL 9 station, such as 98% or 96% availability on a 24/7 basis.
- A smaller daily window with 100% availability.
- Supervision of refuelling necessary, but otherwise unmanned operation.
- A slower speed of refuelling.
- A longer teething period.
- More redundancy to achieve e.g. 99% availability, such as an additional spare compressor or dispenser compared with a TRL 9 station, or more on-site storage. A larger storage could also ease the schedule for hydrogen delivery when the fuel is trucked in from a remote source.

5 Summary and Conclusions

With respect to the basics of hydrogen as a fuel and of hydrogen refuelling stations in comparison with diesel, it is important to bear in mind that:

- Storage of hydrogen requires more volume.
- Delivery of hydrogen fuel to the station from a remote source requires a higher logistical effort.
- Refuelling takes longer.
- The transfer of any contaminants into the hydrogen must be avoided in order to protect the fuel cells on board the buses from damage.

An increasing percentage of hydrogen fuel from green sources, up to total green hydrogen supply, will be important to ensure low-carbon mobility along the entire chain of fuel supply and use. This will address concerns of environmental groups and gain their support, and counter views that hydrogen may only serve to shift emissions away from the tailpipe.

Lessons and recommendations derived from infrastructure planning, procurement, permitting, and operation in CHIC project are summarised in this report. Apart from organisational and technical matters, the interaction with various parties all the way through a demonstration project, and in particular during its early stages is of key importance. Recommendations in this respect include:

- Hold regular progress meetings with all parties involved, both within your organisation and with your local partners.
- Keep your neighbourhood, the general public, decision makers etc. well informed.
- Involve the relevant authorities from the beginning and develop a collaborative working relationship. An inclusive approach at the outset pays major dividends.

Further information and guidelines regarding these and other topics are available in separate reports that are referred to throughout this document.

As regards tendering, operators and technology suppliers agree that flexible options are needed. This should include stating ranges instead of exact capacity requirements, and back-up solutions. They also consider a reasonable level of standardization to be important, as a way to reduce costs.

With respect to staff requirements in day-to-day service, operators point out that enthusiastic staff still are key to ensuring a high level of availability. Future hydrogen stations need to place less demands on staff. In particular, un-supervised refuelling must always be possible.

The system of Technology Readiness Levels is too generic to rate the performance of a hydrogen refuelling station appropriately. It can only give an approximate indication of the level of performance. Moreover, there is no universal set of quantitative expectations across all operators. Instead, quantitative requirements with respect to qualitative criteria can be significantly determined by local circumstances, e.g. the way a bus depot is organised.

As the result of these issues and following internal debate:

- A set of qualitative criteria was developed for adequately characterising hydrogen refuelling stations for fuel cell bus fleets, and
- Ranges of quantitative performance targets regarding these criteria were suggested for future commercial stations (Technology Readiness Level 9).

The main criteria discussed are:

- Availability
    - Overall availability on a 24/7 basis
    - Availability during a dedicated refuelling window
    - Dependable service
    - Waiting time for repairs and spare parts
- Duration of refuelling
- Staff qualifications and labour effort.

These criteria relate to topics that received particular attention in the course of the internal debate. Additional issues are:

- Length of a teething period
- Scalability
- Accuracy of hydrogen metering
- Hydrogen quality requirements and quality monitoring
- Footprint.

Reduced expectations with respect to pre-commercial stations (Technology Readiness Level 7 or 8) were also covered, insofar as acceptable reductions on requirements relative to fully commercial stations. An example is a lower percentage of availability.

Conclusions and Outlook

The current generation of hydrogen stations is far more reliable than the previous ones. Significant challenges still lie ahead on the way to fully commercial refuelling infrastructure suitable to supply an entire bus depot with hydrogen fuel.

These challenges are well understood and can be expressed in terms of the performance criteria as described in this document.

The challenges are being tackled. The ongoing NewBusFuel project is expected to publish its results by the end of this year, suggesting first solutions for hydrogen stations capable of refuelling up to around 250 fuel cell buses per day.

Even though hydrogen may initially appear awkward to somebody new to this field of technology, it is simply a different fuel relatively new to the mobility sector.

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