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List of abbreviations

ATEX	EU directives describing equipment in explosive atmosphere
CHIC	Clean Hydrogen in European Cities
D	Day
FC bus	Fuel cell bus
FCH JU	Fuel Cell and Hydrogen Joint Undertaking
h	Hour
H_2	Hydrogen
HPTT	High Pressure Tube Trailer
HRS	Hydrogen refuelling station
HV	High Voltage
IC	Ionic compressor
LEL	Lower Explosion Limit
Nm^3	normal cubic metre (0.0899 kg H_2 = 1 Nm^3)
Vol%	Volume percent

1 Executive summary

When it comes to applying hydrogen (H_2) as a fuel in the field of public mobility, recurring questions regarding the necessary infrastructure and its investment cost arise. All fuel cell vehicles are powered by H_2, so a H_2 refuelling station (HRS) is essential for their deployment. Maintenance workshops differ from workshops for conventional diesel buses, as H_2 and the adjacent high voltage (HV) technology in fuel cell buses (FC bus) require different installations and safety precautions. Furthermore, differing national and local requirements need to be taken into account. The relevant authorities should be approached at an early stage of planning in order to consider the respective regulatory obligations.

This summary intends to give a first indication of investment cost for FC bus workshops and HRS based on the actual costs within the CHIC project. The figures are rounded and are of indicative nature only. More specific cost information can only be sourced by means of quotations based on the specific boundary conditions of an individual operator. The figures will vary among different countries, depending on exchange rates, local labour costs and local building regulations. However, the figures indicated in this report will provide interested parties to get an idea of the order of magnitude for the necessary investment cost.

FC bus workshops

Table 1 gives an overview of the relevant investment cost for FC bus workshops. The investment cost mentioned are for retrofitting an existing workshop or in the case of a new build workshop, the H_2 related incremental investment cost. The first row of Table 1 is about the investment cost for equipment like H_2 sensors, explosion proof lights, ventilation and so on[1]. Case A) in the first row is an ideal scenario as some cities used a washing hall or a paint shop as the basis for their FC bus workshop. Hence, components like ventilation were already there, resulting in lower incremental investment cost. Ventilation or windows at the highest part of the roof are essential components of a dedicated workshop for FC buses, a, as H_2 is lighter than air and therefore rises. This can be done by changes to the workshop resulting in extra cost.

[1] According to ATEX directive

The need to work on the roof of the FC bus is due to the fact that FC buses have equipment such as H_2 tanks and high voltage (HV) components mounted on the roof. This is not only FC bus specific as diesel hybrid buses also have roof mounted components. In both cases, facilities for rooftop working are necessary. As the FC system contains water, the buses need an overnight power supply for freezing prevention (power outlet).

Table 1: Summary of the investment cost analysis of the FC bus workshop

Part	Investment cost [€]
H_2 specific incremental investment cost for workshop equipment per bay: A) Retrofitting under ideal conditions (some existing components like existing ventilation and/or ATEX electricity)	30,000 to 60,000
B) H_2 specific investment cost for the workshop under normal conditions (applying H_2 sensors, ATEX lights and ventilation, emergency venting etc.) for 12m standard bus bay	75,000 to 100,000
C) H_2 specific investment cost for the workshop under normal conditions (applying H_2 sensors, ATEX lights and ventilation, emergency venting etc.) for 18m articulated bus bay	190,000 to 230,000
Changes to the workshop structure Extra windows or fire protective doors	5,000 to 15,000
Rooftop working: A) Simple mobile working platform for rooftop working	5,000 to 15,000
B) Technically sophisticated solution for rooftop working covering whole length of the bus and moving hydraulically around the bus	90,000 to 150,000
Power outlet for overnight power supply at parking space	1,000 to 1,500 per power outlet

Hydrogen refuelling stations

All HRS in the CHIC project are unique and the investment cost differs widely. Nevertheless, the HRS can be sorted into three groups, and ranges of the specific investment cost (excluding buildings and foundation) per rated refuelling capacity per day[2] can be identified:

[2] 30 kg per bus per day can be assumed for calculating the number of buses.

- HRS getting hydrogen delivered without on-site production (stations 1 and 2 in Table 2). They comprise storage, usually a compressor and a dispenser. The specific investment figures in this group are 5,300 and 7,100 €/(kg/d).
- Then there are HRS with a mix of on-site production via electrolysis and external H_2 delivery. These stations have storage, one or more electrolysers, one or more compressors (typically with a spare unit for the event that one fails) and one or more dispensers. The specific investment cost, including the on-site production unit, for station 3 and 4 in Table 2, with a rated on-site production capacity that can cover about 40% of the rated refuelling capacity, are about 8,000 €/(kg/d).
- Another type of HRS similar to the second group but with a larger unit for hydrogen production so that all fuel can be generated on site. The specific investment cost, including the on-site production unit, range from 13,000 to almost 19,000 €/(kg/d).

Table 2: Summary of technical equipment and investment cost of HRS

	External H_2 delivery		On-site production and external H_2 delivery		On-site production		
	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7
H_2 supply - On-site generation [Nm³/h]	No	No	Electrolyser (1 * 60)	Electrolyser (2 * 65)	Electrolyser (2 * 50)	Electrolyser (2 * 60)	Electrolyser (3 * 60)
H_2 supply - On-site generation [kg/d]			129	280	215	258	388
H_2 supply - Regular external delivery	Yes	Yes	Yes	Yes	No	No	No
Compression capacity [Nm³/h]	1 * 300	None	2 * 60	2 * 400	2 * 150	2 * 60	2 * 180 + 3 * booster
Storage capacity [kg]	420	1200	450	650	250	340	300
Dispensers (350 bar)	1	2	1	1	1	1	2
Dispensers (700 bar)	0	0	0	1 (twin dispenser)	0	0	1
Rated refuelling capacity [kg H_2/day]	120	320	300	700	200	250	360
Investment cost without building & foundation [million €]	0.8	1.7	2.4	5.8	2.6	4.7	5.2
Investment cost per rated refuelling capacity [€/(kg/d)]	7,100	5,300	7,900	8,200	13,000	18,900	14,500

2 Objective(s) of the report and Introduction

The assessment intends to give a first indication of the investment cost for FC bus workshops and HRS based on the actual investment cost paid in the CHIC project.

In chapter 3 maintenance workshops suitable for FC buses are investigated from the point of view of investment cost. To serve as a baseline, an evaluation of the additional technical features required for FC buses were determined. These were then used to provide the basis for investment cost for retrofitting a workshop or, in the case of a new build workshop, for the incremental FC bus related investment cost.

Chapter 4 provides an overview of the investment cost for a HRS. As the technical specifications of the HRS in CHIC vary, a closer look is taken at the specific cost for components such as storage. Generally the total investment cost for an HRS are shown with reference to the technical specifications but without considering buildings and foundation.

Due to confidentiality reasons in some instances, not all details can be disclosed.

If the cost occurred in a different currency, the official exchange rate by the European Central Bank for the year the station was built is used for the respective Euro amount (European Central Bank 2014).

3 Results of investment cost analysis of bus workshops

In the first instance, this chapter gives a brief introduction into dealing with hydrogen safety in workshops. The differences between normal workshops and H_2 specific workshops are explained. Following this, the incremental investment cost for H_2 workshops are detailed. Further technical information on the workshops used in CHIC can be found in the Annex. Generally the workshop equipment varies a lot mostly depending on local safety regulations. The number of H_2 sensors per working bay is in between 1 sensor and more than 4 sensors for example.

3.1 Differences between H_2 bus maintenance workshops and typical diesel bus workshops

3.1.1 Basic information on hydrogen safety requirements in workshops

In contrast to conventional diesel bus workshops special requirements concerning “danger of explosion” while handling H_2 have to be fulfilled. This chapter gives a brief overview of the most important requirements. As is evident from the CHIC project the requirements are different in most country. Local fire departments and local governments need to be consulted for further regulations.

The following section on H_2 safety in workshops is mainly based on the publication “Hydrogen Safety in Workshops, 2009[3]” and on the information collected while the cities were in the process of building their workshops.

Intentionally or accidently released H_2 spreads, diffuses and rises very quickly. Under unfavourable architectural conditions and ventilation, the gas could collect below the roof and reach the lower explosion limit. The lower explosion limit is 4 Vol%, the upper explosion limit is 77 Vol%, while the detonation limits are narrower ranging between 18 and 59 Vol%. Therefore the H_2 must be removed quickly and not exposed to any ignition source.

As H_2 cannot be detected by human senses the workshop must be equipped with H_2 sensors as a primary protective measure. These sensors need to be located at the ceiling area of the workshop and warn visually and audibly. The warning system must

[3] Translated from German title: „Wasserstoffsicherheit in Werkstätten“ (Hydrogen Safety in Workshops 2009)

be coupled with a ventilation or gas extraction system. The ventilation system and the vent openings shall be located at the highest points of the roof area. In the case of danger, the electrical equipment is switched off with the exception of the explosion-proof installations and emergency lighting. As the ventilation is part of the "Emergency system" it cannot be switched off. The ventilation sucks a hydrogen-air mixture, so the design must be explosion-proof. In small workshops, the supply of fresh air must be monitored.

There might be the risk of an electrostatic discharge from the buses to the environment. Hence, either the workshop has to have a dissipative floor or grounding by wire must be provided.

3.1.2 Rooftop Working and Power Outlet for overnight heating

Depending on the layout, FC buses might have roof-mounted components such as hydrogen tanks, FC system, batteries or a high voltage (HV) system. This is similar for diesel hybrid buses which usually are equipped with a HV battery and other components such as inverters etc. mounted on the roof. Hence, a facility for working safely on the roof is needed.

As the FC system can contain unreleased water, the majority of the currently deployed FC buses need a power outlet at their parking spot to prevent the FC system from freezing at low temperatures.

3.2 FC bus maintenance workshop investment cost analysis

Table 3 gives a summary of the incremental investment cost for bus workshops. Please note that in the case of newly built workshops, this includes only the incremental investment cost directly related to H_2 specific components.

Table 3: Investment cost analysis FC bus workshops

Part	Investment cost [€]
1. H_2 specific incremental investment cost for workshop equipment per bay: A) Retrofitting under ideal conditions (some existing components like existing ventilation for example)	30,000 to 60,000
B) H_2 specific investment cost for the workshop under normal conditions (applying H_2 sensors, ATEX lights and ventilation, emergency venting etc.) for 12m standard bus bay	75,000 to 100,000
C) H_2 specific investment cost for the workshop under normal conditions (applying H_2 sensors, ATEX lights and ventilation, emergency venting etc.) for 18m articulated bus bay	190,000 to 230,000
2. Changes to the workshop structure Extra windows or fire protective doors	5,000 to 15,000
3. Rooftop working: A) Simple mobile working platform for rooftop working	5,000 to 15,000
B) Technically sophisticated solution for rooftop working covering whole length of the bus and moving hydraulically around the bus	90,000 to 150,000
4. Power outlet for overnight power supply at parking space	1,000 to 1,500 per power outlet

3.2.1 Workshop equipment

Some of the retrofitted workshops were originally a paint shop or wash hall. This has several advantages, such as an already existing ventilation system or being separated from the rest of the workshop which makes potentially required changes to the electric installations easier. The investment cost for retrofitting an existing workshop under ideal conditions with already existing ventilation and only applying H_2 sensors, circuit breakers and ATEX lights can be as low as 30,000 € ranging up to 60.000 € depending on the existing equipment. In order to respect confidentiality further detail on the existing equipment can't be provided at this time.

However, those ideal conditions are rarely in place. Most of the cities had to invest more efforts by applying H_2 sensors and flame sensors, changing parts of the electrical system, applying ATEX lights, ATEX ventilation and an emergency venting system. If there are no existing components, the total investment cost are between

75,000 € to 100,000 € for a 12 m standard bus bay. For an 18 m articulated bus bay the investment are between 190,000 € to 230,000 €.

Figure 1 shows examples of an H_2 detection system with the control panel indicating the H_2 concentration in the left part of the picture. On the right side H_2 sensors (round disc in the middle of the picture), ventilation (fan in the square in the upper part of the picture) and ATEX lights are visible.

Figure 1: Example of H_2 detection system, H_2 sensors, ventilation and ATEX lights

Source: (Transport for London 2014)

3.2.2 Changes to the workshop structure

Structural adaptation of the workshop, such as additional windows for ventilation, fire prevention doors or walls may also be required. Extra windows or fire protective doors can come at investment cost of 5,000 € to 15,000 €.

Figure 2: Example of a fire protective door

Source: (Azienda Trasporti Milanesi S.p.A. 2014)

3.2.3 Working platform

As mentioned before, a facility for safely working on the roof of the buses is needed. This can be a simple mobile working platform for 5,000 € to 15,000 €. Other operators installed a bridge crane and a technically sophisticated solution of a permanently installed working platform, which covers the whole length of the bus on both sides and moves hydraulically around the bus. These more sophisticated systems are obviously more comfortable for working but they are also more costly, ranging from 90,000 € to 150,000 € for one maintenance bay, depending on the local circumstances and the length of the bus (standard 12m bus or 18 m articulated).

Figure 3 shows an example of a mobile working platform next to a FC bus in London. This kind of platform is the simplest way for roof top working.

Figure 3: Example of a mobile working platform used in London

Source: (Transport for London 2014)

3.2.4 Power outlet at overnight parking

The investment cost for the power outlet at the parking place varies depending on the local circumstances, for example distance between the parking spot and the next power connection. These were around 1,000 € to 1,500 € per power outlet. Figure 4 shows examples of power outlets. In this case these are connectors at the pillars which are connected to the buses by wire.

Figure 4: Examples of power outlets at overnight parking

Source: (BC Transit Corporation 2014)

4 Results of investment cost analysis of filling stations

This chapter is divided into two main sections: The first one covers the detailed component investment cost, for electrolysers and storage for example. The second section analyses the investment cost for a complete HRS.

All data, unless otherwise stated, is based on the information given by the CHIC partners. Table 4 shows a template with the items that were requested. For the analysis presented in this chapter, generally the data was anonymised using at least 3 data points. If less than 3 data points were available, no details are provided in the following.

Table 4: Data collection template

Data collection template		
Building and Foundation	Investment cost of Building	
	Investment cost of Foundation	
Electrolyser	Investment cost of electrolyser	
	Number of electrolyser units	
	Capacity per unit	
Compressor	Investment cost of compressors	
	Number of compressors	
	Capacity per unit	
Storage Tank	Investment cost of Storage Tanks	
	Number of bundles and capacity	
	Capacity per unit	
Dispenser and other	Investment cost of 350 bar Dispenser	
	Investment cost of Installation	
	Engineering	
	Other investment cost	
Total	Total investment cost of the HRS	

4.1 HRS component investment cost analysis

All HRS differ in their layout, size, capacity, H_2 supply (on-site production or external delivery), whether they have redundancies, and regarding other aspects. The difference in the investment cost between a simple and a technically complex station can be significant. In order to overcome these differences, this part of the investigation focusses on the components of an HRS, such as storage, compressors, and dispensers. Table 5 shows an overview of the investment cost of the main component. Please note that all figures include the costs for installation.

Table 5: Summary of the ´component investment cost of HRS

Component	Investment Cost
Electrolyser	9,600 to 13,300 €/(Nm³/h)
Compressors	See Text
Gaseous H_2 storage	1,300 to 1,700 €/kg
350 bar dispenser	120,000 to 220,000 €
Engineering / Project Management / Start Up	300,000 to 1.4 million €
Civil Engineering A) Simple foundation and fence around B) Protective walls (site specific) C) Normal building without control room and offices (but including protective walls and foundation) D) Multi-store building with control room, offices and/or meeting rooms (including the protective walls and foundation)	>150,000 € Low to medium six digit Euro amount Ca. 1 million € Up to 5 million €

4.1.1 On-site H_2 production via water electrolysis

All electrolysers within the project are alkaline water electrolysers with a rated production of 50 to 65 Nm³/h per unit and an outlet pressure of 10 to 30 bars. The investment cost varied between 9,600 and 13,300 Euro per Nm³/h including transformers and rectifiers. The total investment cost of one electrolyser unit varied between 580,000 € to 800,000 €.

4.1.2 Compression

There are 3 different compressor types applied in the CHIC filling stations: membrane, ionic and piston compressors. Some are used for storage filling, some for storage filling and booster operation, some only as booster. Not all cities were able to provide the detailed investment cost for the compressors. Investment cost are available for 1 membrane, 1 piston and 2 ionic compressors, which vary widely. Hence, it is not possible to provide anonymised figures.

4.1.3 Storage

The investment cost for gaseous H_2 storage varies between 1,300 and 1,700 Euro per kg storage capacity. The storage capacity of the stations ranges between 250 to 1,200 kg H_2 storage. Again not all cities were able to provide detailed investment cost. It is expected that especially HRS with higher storage capacity have smaller specific investment cost, resulting in lower costs per available capacity.

4.1.4 Dispensers

The investment cost for a 350 bar dispenser range from 120,000 to 220,000 Euro. Not all cities were able to provide the investment cost for a dispenser. One possible explanation for this range is that the lower end does not have Infrared communication between filling station and the bus. The dispensers at the upper end are equipped with Infrared communication which can enable faster filling.

4.1.5 Engineering / Project Management / Start Up

The investment cost for the engineering, project management and start-up were between 300,000 to 1,400,000 €. They depend on the local labour cost, which can easily differ by a factor of two or more among different countries in Europe. Secondly some cities involved external companies in the planning phase which was more expensive and it was not possible to separate out the internal vs. external costs. Thirdly, the cost figures stated sometimes included the start-up phase and this cost element could not be singled out.

4.1.6 Civil Engineering

The investment cost for foundation and buildings vary widely. They differ by a factor of more than 30. When taking a closer look at the different buildings in Figure 14 to Figure 22 the reason becomes obvious. Some of the HRS do not have a building but only have a simple foundation, maybe a concrete wall and a fence around it. The investment cost for a simple foundation and fence was around 150,000 Euro. Some components of the station are containerized (for example compressors and electrolysers).

Some cities had to install protective walls due to local circumstances and regulations, which ranged between a low and a medium six digit Euro amount per HRS.

The investment cost for a normal building including foundation and protective walls HRS was about one million €.

Other cities opted for a more advanced building, with features such as an illumination by night or a dedicated control room, offices or even meeting rooms. Such a sophisticated station with a multi-storey building can come at an investment cost as much as 5 million Euro.

4.2 Investment cost for a complete HRS

The investment cost of the HRS are presented individually, sorted by the type of hydrogen supply path. Table 6 at the end of this section gives an overview of the main technical features of each HRS and its total investment cost. These investment cost are those for technical equipment. Investment cost for buildings and foundations are not included.

Some of the cities did not purchase the entire refuelling station, but leased individual components. Using this approach, the actual amount paid can be less than the full station investment cost. However, this section, including Table 6, states investment cost as if all equipment had been bought.

One restriction regarding the figures of chapter 4.1 detailed component investment cost is that, as already explained, not all of the cities were able to provide the full level of detail requested regarding all of the components. For this reason, it is not necessarily possible to derive the total investment cost of a specific station in Table 6 from the component costs in Table 5.

4.2.1 Stations with external H_2 supply

Station 1 is an example of simple HRS getting hydrogen delivered, with a small storage on-site and having one compressor (no redundancy). The station is located close to a hydrogen supplier which enables delivery just in time. Hence, the storage can be smaller than for other stations getting H_2 delivered from a more remote source. The technical equipment of this station has investment cost of 0.8 million € excluding a building (not required) and foundation. Assuming a demand of 30 kg H_2 per bus per day, this station has the capacity to fuel 4 buses per day, while being capable of filling 2 buses in a row (followed by 60 minutes waiting time). This station with its single train design (without redundancy) and its location close to the H_2 source makes it the HRS in CHIC with the lowest investment cost.

Another example of a HRS with hydrogen delivery is station 2. H_2 is delivered at 500 bar by a High Pressure Tube Trailer (HPTT). The HPTT is connected to the on-site fuelling system, making the delivery vehicle an integrated part of the station. The station has no compressors as the large high pressure storage is sufficient to fill the buses directly. Having two dispensers and being designed for 10 buses (no waiting time between the buses), the investment cost are around 1.7 million €.

4.2.2 Stations with on-site production and H_2 delivery

These stations have a mix of on-site production and external H_2 delivery. In both cases the on-site production capacity amounts to about 40% of the rated refuelling capacity.

Station 3 features 1 electrolyser with the possibility of receiving regular external supply for the purpose of either increasing the refuelling capacity, or as a redundancy. Two compressors (one for redundancy) are installed together with one dispenser. Being designed for five buses (no waiting time between the buses) this station has investment cost of 2.4 million €. Having only one electrolyser, this station features the lowest cost within the CHIC project among the stations with on-site H_2 production. excluding building and foundation?

Station 4 has two electrolysers and the possibility of getting H_2 delivered (for capacity increase and/or redundancy), two compressors (one redundant), one bus dispenser and one dual dispenser for cars and buses. It has additional equipment to be able to fuel 700 bar FC passenger cars besides the FC buses. It is technically more complex and capable of fuelling around 23 buses per day assuming 30 kg H_2 per bus per day (3 buses per hour). This station has investment cost of 5.8 million € excluding building and foundation.

4.2.3 Stations with on-site H_2 production

Stations 5, 6 and 7 depend on on-site production via electrolyser solely.

Station 5 has two electrolysers, two compressors (one for redundancy) installed with one 350 bar dispenser. Assuming 30 kg H_2 per bus per day this station has the capacity of refuelling around 6 buses per day. The investment cost are 2.6 million € which makes it the station with on-site production solely with the lowest investment cost.

Station 7 has the highest investment cost among the stations with on-site production. It comprises 3 electrolysers and 5 compressors (3 of which are boosters). There are two 350 bar dispensers and a 700 bar dispenser including the equipment needed to fuel passenger car vehicles. This station is capable of fuelling 12 buses per day (assuming 30 kg H_2 per bus per day). The investment cost are around 5.2 million €.

4.2.4 Overview on the specific investment cost per rated refuelling capacity

Figure 5 shows an overview of the specific investment cost per kilogram rated refuelling capacity (see also the last row Table 6). The two stations depending on external H_2 delivery are in the same range between 5,300 and 7,100 €/(kg/d). The lowest specific investment cost belongs to station 2 with the larger rated refuelling capacity. The difference may partly be explained by the absence of compressors and economies of scale.

The specific investment cost of stations with a mix of on-site production (covering 40% of the rated refuelling capacity) and H_2 delivery range between 7,900 to 8,200 €/(kg/d) (Station 3 and 4). Given that station 4 has more than twice the rated refuelling capacity and also two electrolysers instead of one the specific investment cost are similar.

Station 5, 6 and 7 which have on-site production solely have the highest specific investment cost which is plausible as more production capacity is needed relative to the rated dispensing capacity. They range in between 13,000 to 18,900 €/(kg/d). This means that specific investment cost vary by a factor of about 1.5. Reasons for this can be assumed to be differences in local labour cost and extra equipment for fuelling FC cars to 700 bar.

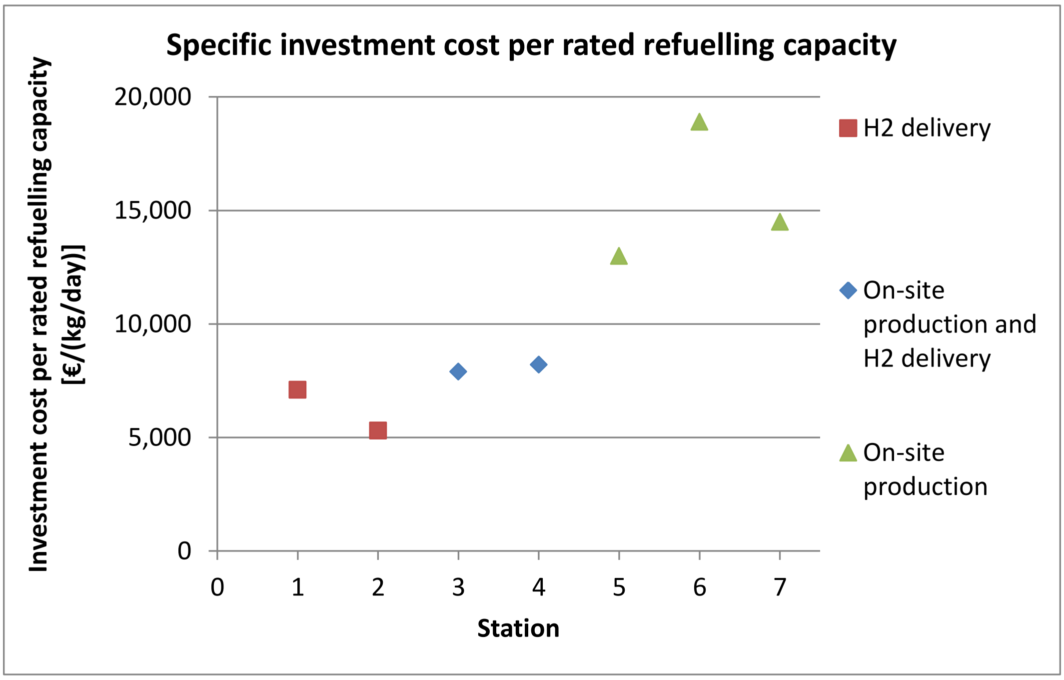

Figure 5: Specific investment cost per kilogram rated refuelling capacity

Table 6: Overview of the technical equipment and investment cost of HRS within the CHIC project

	External H_2 delivery		On-site production and H_2 external delivery		On-site production		
	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7
H_2 supply - On-site generation [Nm³/h]	No	No	Electrolyser (1 * 60)	Electrolyser (2 * 65)	Electrolyser (2 * 50)	Electrolyser (2 * 60)	Electrolyser (3 * 60)
H_2 supply - On-site generation [kg/d]			129	280	215	258	388
H_2 supply - Regular external delivery	Yes	Yes	Yes	Yes	No	No	No
Compression capacity [Nm³/h]	1 * 300	None	2 * 60	2 * 400	2 * 150	2 * 60	2 * 180 + 3 * booster
Storage capacity [kg]	420	1200	450	650	250	340	300
Dispensers (350 bar)	1	2	1	1	1	1	2
Dispensers (700 bar)	0	0	0	1 (twin dispenser)	0	0	1
Rated refuelling capacity [kg H_2/day]	120	320	300	700	200	250	360
Investment cost without building & foundation [million €]	0.8	1.7	2.4	5.8	2.6	4.7	5.2
Investment cost per rated refuelling capacity [€/(kg/d)]	7,100	5,300	7,900	8,200	13,000	18,900	14,500

5 Summary and Outlook

When a city or a region is interested in introducing H_2 mobility, there is no simple answer as yet when it comes to the investment cost for infrastructure. The investment cost in CHIC showed wide ranges, both with respect to the workshop and the HRS. This can be partly explained by different technical equipment, but also by local circumstances such as the cost of labour.

Hydrogen Vehicles Maintenance Workshops

At several of the CHIC sites, a washing hall or former paint shop was retrofitted, which had some of the necessary equipment already installed. For small FC bus fleets that require only one workshop bay, this is an ideal case in terms of investment cost. In other cities a new workshop was built. Three different scenarios for H_2 workshops were identified and their H_2 related incremental investment cost calculated:

A. Retrofitting under ideal conditions (with some existing components like ventilation) → 30,000 to 60,000 €
B. H_2 specific investment cost for the workshop under normal conditions (installing H_2 sensors, ATEX lights and ventilation, emergency venting etc.) for a 12m standard bus bay → 75,000 to 100,000 €
C. H_2 specific investment cost for the workshop under normal conditions (installing H_2 sensors, ATEX lights and ventilation, emergency venting etc.) for an 18m articulated bus bay → 190,000 to 230,000 €.

Additionally, there are investment cost necessary for a bus rooftop working device and possibly a power outlet for overnight parking supply at a parking space. The power outlet is around 1,000 to 1,500 €/bus. The cost for a rooftop working device depend on which solution is chosen; a simple mobile platform ranges between 5,000 to 15,000 €, while a platform moving hydraulically around the bus can cost between 90,000 to 150,000 €.

Depending on the local circumstances, changes to the workshop structure might be necessary too. Changes like extra windows or fire protective doors can range between 5,000 to 15,000.

Hydrogen Refuelling Stations

If someone wants to install an HRS for FC buses, important questions are related to:

- The rated refuelling capacity - How many buses should the facility be designed for?
- Hydrogen supply choice - Is external H_2 delivery favoured or should the HRS be based on on-site production, possibly from renewable energy?
- Should refuelling of FC passenger cars be foreseen in addition?
- What are the local labour costs and safety demands?

There is no simple answer on the investment cost of an HRS that could be derived from the stations in CHIC, because they differ widely in their technical characteristics as well as in their H_2 supply arrangements. Nonetheless, three main types of stations can be distinguished: Those with external H_2 delivery exclusively, those with a mix of on-site production and delivered H_2, and those with solely on-site produced H_2.

HRS with external H_2 delivery only

The HRS with external H_2 delivery have the lowest investment cost overall, both in absolute and relative terms. There are two HRS of this type in CHIC with gaseous H_2 delivery, one with a rated refuelling capacity of 120 kg/d and investment cost of 0.8 million €, the other one with 320 kg/d and 1.7 million € investment cost. The specific investment cost per kilogram refuelling capacity are 7,100 and 5,300 €/(kg/d), respectively, which are in a similar range and can be used as an indicator for an HRS of this type.

HRS with on-site production and external H_2 delivery

Two HRS combine external H_2 delivery with on-site production, the capacity of the latter amounting about 40% of the rated refuelling capacity. The rated refuelling capacity ranges from 300 kg/d to 700 kg/d, with investment cost of 2.4 million€ and 5.8 million€ respectively. The specific investment cost per rated capacity are 7,900 to 8,200 €/(kg d).

HRS with on-site production only

There are 3 stations of this type within CHIC with rated refuelling capacity ranging from 200 to 360 kg/d. They have at least two electrolysers and two or more compressors.

The specific investment cost per kilogram rated refuelling capacity is in a range of 13,000 to 18,900 €/(kg/d). The variation in this range can be explained by local differences in labour costs and different technical equipment as, for example, some HRS are capable of fuelling cars (700 bar) in addition to buses (350 bar).

Future Stations

The investment cost of future hydrogen filling stations are expected to be lower than at present. One indicator is the volume production by a major manufacturer which started in 2014. These stations are built in small-series production with a potential capacity of 50 stations per year. The technical equipment is accommodated within a 14 feet container including the high pressure storage, and an additional storage for gaseous or liquid hydrogen next to the container. On-site production is not foreseen in this concept (Linde AG (2014)).

Based on an industry survey it can be assumed that the equipment in the container and the storage is included in the investment cost (Mayer 2014). These stations are for passenger cars with a maximum of 4 kg/H_2 per filling with investment cost of about 1 million € per station (excluding civil engineering). There is no official figure for the daily refueling capacity. However, the compressor that is used in these stations has a throughput of around 180 Nm³/h. This indicates a max. refuelling capacity of about 360 kg H_2 per day. The would result in specific investment cost of about 2,800 €/(kg/d) rated refuelling capacity, which is about half the CHIC figures for this type of station.

The investment cost for a station suitable for bus filling could be roughly the same if just the 700 bar dispenser had to be replaced by a 350 bar dispenser. However, the storage capacity of common car filling stations would probably not suffice for refuelling several buses within a short period of time (up to 30 kg per filling). Thus, for bus refuelling the investment cost are likely to increase, due to – for example – extra storage, depending on the exact requirements. Therefore, the investment cost of an

HRS of about 360 kg H_2 rated refuelling capacity per day will probably remain higher than 3,000 €(kg/d).

6 References

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7 Annexes

7.1 Overview on the technical specifications of the different workshops in CHIC

Table 7 gives a brief overview of the different workshops in CHIC. Additionally the workshops are shown in the following pictures (Azienda Trasporti Milanesi S.p.A. 2014; BC Transit Corporation 2014; Berliner Verkehrsbetriebe 2014; Fahrzeugwerkstätten Falkenried GmbH 2014; HyCologne e.V. 2014; Ruter As 2014; Transport for London 2014; Südtiroler Transportstrukturen AG 2014).

Table 7: Overview of technical specifications of FC bus workshops in CHIC

	Berlin	Bolzano	Cologne[4]	Hamburg	London	Milan	Oslo	Whistler
Work area [m²]	221	200	203	200	252	180	160	900
Type of workshop	New	Retrofitted	Retrofitted	New	New	Retrofitted	Retrofitted	New
Bays for standard 12m buses	1	2		-	2	1	1	6
Bays for articulated buses	1	[5])	1	1	0	1		0
No. of buses	4	5	4	4	8	3	5	20
No. of H_2 sensors	4	3		4	9	5		7 (includes 1 in washbay)
No. of flame sensors	2	in the planning		-	-	-		4
ATEX lights	4 (luminous tapes)	32		16	18	36		no

[4] No information available on H_2 specific components in Cologne

[5] The two bays are in a row, so one articulated bus would also fit

	Berlin	Bolzano	Cologne	Hamburg	London	Milan	Oslo	Whistler
ATEX ventilation	yes	yes		yes	yes, at 40%LEL hydrogen venting occurs.	yes	yes	fixed ventilation (no H_2 extraction fan), pneumatically controlled dampers
ATEX electricity	yes	not necessary		yes (bridge crane, phone, lights)		yes (bridge crane; speakers, emergency exit panels, fire alarm button, door panel, antennas)		no
Circuit Breaker	no	yes		yes		light system managed from outside the bay - emergency circuit breaker inside the bay for the bridge crane		
Emergency power supply (UPS)	yes	yes		no	yes	no	yes	Standby diesel generator
Acoustic alarm	yes	yes		yes	yes	yes		yes
Flashlight alarm	yes	Yes		yes	yes	no		yes
Fire protection	yes	in the planning		4 fire extinguisher s		2 flame arrester doors; fume extraction system	fire protective doors	4 flame detectors, building fire system (sprinklers)
Venting hose for H_2 discharge	yes	see ventilation		yes	yes	yes		2 per bay
Crane	fork lift	no (roof maintenance is done at EvoBus Service Center)		yes	yes (mechanical hoist)	yes	yes	yes (bridge crane)

7.2 Pictures of the workshops in the CHIC cities

Aargau

As PostAuto has a full service contract with EvoBus Switzerland PostAuto does not have an own workshop, there is a retrofitted workshop in Kloten (Kt. Zürich).

Berlin

A new workshop was built with one bay for 12 m buses and one for articulated buses.

Figure 6: Workshop in Berlin

Source: (Berliner Verkehrsbetriebe 2014)

Bolzano

An existing paint shop was converted, containing one bay (max two buses in line). The maintenance regarding FC and HV components is done at the suppliers Service Center in Brixen, 40 km of distance from the operator’s regular bus depot in Bolzano.

Figure 7: Workshop in Bolzano

Source: (Südtiroler Transportstrukturen AG 2014)

Cologne

An existing paint shop was rebuilt to be suitable as a workshop.

Figure 8: Workshop in Cologne

Source: (HyCologne e.V. 2014)

Hamburg

A completely new workshop was built.

Figure 9: Workshop in Hamburg

Source: (hySOLUTIONS GmbH 2014)

London

A new facility was built with two maintenance bays.

Figure 10: Workshop in London

Source: (Transport for London 2014)

Milan

A small area of an existing diesel maintenance depot was converted to suite hydrogen safety demands.

Figure 11: Workshop in Milan

Source: (Azienda Trasporti Milanesi S.p.A. 2014)

Oslo

A former wash hall was converted into a single bay workshop.

Figure 12: Workshop in Oslo

Source: (Ruter As 2014)

Whistler

A new depot was built having six maintenance bays with two vent lines per bay which are hooked up to the H_2 tanks when the buses are brought in for maintenance.

Figure 13: Workshop in Whistler

Source: (BC Transit Corporation 2014)

7.3 *Pictures of the filling stations in the CHIC cities*

Aargau

Aargau has a filling station at the bus depot without building. The concrete wall is partly for safety reasons.

Figure 14: Aargau filling station

Source: (PostAuto Schweiz AG 2014)

Berlin

The Berlin station was a partly public filling station, with one part of the station inside the bus depot and another part outside the depot.

Figure 15: Berlin filling station

Source: (Berliner Verkehrsbetriebe 2014)

Bolzano

The Bolzano filling station is located at the H_2 center of the Institute for innovative technologies. The location is close to a highway as part of the Brenner axis from Munich to Modena. Figure 16 shows the dispensers, the rest of the station is in a building not visible on the picture.

Figure 16: Bolzano filling station

Source: (Institut für Innovative Technologien Bozen 2014)

Cologne

The Cologne station has no building only a protective wall and a fence around.

Figure 17: Cologne filling station

Source: (HyCologne e.V. 2014)

Hamburg

The Hamburg station is a representative public filling station located in the so-called HafenCity which is a central area in Hamburg. Figure 18 shows mainly the filling area. The technical equipment of the station is located in the building at the left end of the picture.

Figure 18: Hamburg filling station

Source: (Vattenfall Europe Innovation GmbH 2014)

London

The London filling station is located at the Lea Interchange Bus depot where the FC buses are located and where the workshop was built. Figure 19 shows the dispenser while the equipment is in the area behind without a building, just a fence around.

Figure 19: London filling station

Source: (Transport for London 2014)

Milan

The Milan station is built at the bus depot in San Donato especially for the FC buses located there. Figure 20 shows the technical part of the station while the dispenser is close by.

Figure 20: Milan filling station

Source: (Azienda Trasporti Milanesi S.p.A. 2014)

Oslo

The Oslo filling station is at the bus depot, where the FC buses are located and the workshop was built. It has some nice illumination at night as visible on Figure 21.

Figure 21: Oslo filling station

Source: (Ruter As 2014)

Whistler

The Whistler station is located at the Bus depot, where also the workshop was built.

Figure 22: Whistler filling station

Source: (BC Transit Corporation 2014)