New Bus ReFuelling for European Hydrogen Bus Depots

High-Level Techno-Economic Project Summary Report

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

NewBusFuel

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High-Level Techno-Economic Project Summary Report

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Disclaimer

Partners

Project coordinators

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Abbreviations

a	year
bar	pressure unit
CAPEX	capital expenditure
Cent	one-hundredth subdivision of one Euro
CHC	cryogenic hydrogen compressor
CHIC	fuel cell bus project by the FCH JU (Clean Hydrogen in European Cities)
CUTE	hydrogen fuel cell bus project (Clean Urban Transport for Europe)
d	day
ECTOS	fuel cell bus project by the INE (Icelandic New Energy)
EEX	European Energy Exchange
EPEX	European Power Exchange
EU	European Union
€	Euro
FC	fuel cell
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
g	gram
GH_2	gaseous hydrogen
GWh	gigawatt-hour
h	hour
H_2	hydrogen
HRS	hydrogen refuelling station
HyFLEET:CUTE	successor project of CUTE
ISO	international organization for standardization
kg	kilogram
km	kilometre
kV	kilovolt
kWh	kilowatt-hour
LH_2	liquid hydrogen
LPG	liquefied petroleum gas
m	metre
m^2	square metre
M€	million Euros
min	minute
MW	megawatt
MWh	megawatt-hour
NBF	New Bus reFuelling for European hydrogen bus depots project
NewBusFuel	New Bus reFuelling for European hydrogen bus depots project
Nm^3	normal cubic metre (1 m^3 of dry gas at 1,013 bar absolute and 0°C)
NOx	mono-nitrogen oxides, i.e. nitric oxide and nitrogen dioxide
OPEX	operational expenditure
PEM	proton membrane exchange
PM	particulate matter
RCS	regulations, codes and standards
RFT	request for tenders
SAE	society of automotive engineers
SMR	steam methane reformer
s	second
t	ton
Wh	watt-hour
WP	work package
°C	degree Celsius

Introduction

About the NewBusFuel Project

Introduction

About the NewBusFuel Project

Hydrogen buses are recognised as one of very few routes to the full decarbonisation of public transport in cities. This project aims to fill a major gap in the existing knowledge base around the refuelling of hydrogen at a bus depot scale. Existing hydrogen refuelling stations (HRS) have been designed and operated with maximum fuelling capacities in the 100s of kg/day supplying up to 15 buses. For hydrogen to be a viable fuel for bus operators in the medium term, solutions are required which can provide fuel for 100's of buses. This implies fuelling requirements of 1,500 kg/day and above.

Providing fuel at this scale creates new challenges which have only been tackled theoretically by the hydrogen industry. Until now there is a considerable knowledge gap around the designs, processes and safety implications of providing hydrogen refuelling on this scale. A large pan-European consortium has assembled to develop solutions to these challenges. The consortium carried out engineering studies for 13 different large scale hydrogen fuelling station designs at 12 different sites in seven European countries.

There are four main project objectives, which can be prioritised in the order below:

- Produce 13 engineering studies which define the optimal designs, hydrogen supply routes, commercial/ownership arrangements and the practicalities involved in refuelling very high volumes of hydrogen at a variety of busy bus depots across Europe.
- Prepare a range of publicly accessible, design guideline reports based on analysis by the engineering studies which are carried out. The diversity and the number of studies carried out will allow a comprehensive engineering data set to be assembled. A comprehensive program of evaluation of the engineering dataset will allow the production of valuable learning for the European bus sector.
- Kick start the large scale bus deployment projects which are required for the next stage of the commercialisation process. The study sites have been selected to be located in Europe's most proactive hydrogen bus deployment regions. In each region, the study will enable the operators and their industrial partners to make steps towards their next wave of hydrogen bus deployment.
- Disseminate the results to a wider audience in order to ensure that the challenge of hydrogen fuelling for buses is not seen as a credible reason to delay engagement with the technology.

1. Objectives and structure

This report describes the HRS solutions developed, it presents the key insights, summarises the most important lessons learned and provides recommendations.

1. Objective and Structure

The basis of this summary report are the HRS design solutions that were developed for the 13 case studies within the NewBusFuel project. For these, bus operators and suppliers cooperated and jointly optimized the HRS design as well as the organizational framework of the HRS, e.g. the business model for its operation. In doing so, valuable knowledge and insights were created, especially with respect to improving the techno-economic performance of the solutions developed, which in this report refers to the concept of optimising the technical solutions as well as the costs of the project.

This summary report describes in an anonymized form the HRS solutions developed and presents the key insights to interested stakeholders, it summarises the most important lessons learned and provides recommendations to the relevant stakeholder groups. Three stakeholder groups have been identified as the main target audience:

- **Bus operators and transport agencies**
- **Policy makers**
- **H_2 infrastructure suppliers and the overall H_2 community**

More detailed advice for the HRS design including quantitative technical estimates and recommendations for a possible project framework for setting up an HRS can be found in the Guidance Document on Large Scale Hydrogen Bus Refuelling which was also developed as a key output of the NewBusFuel project [NBF – D4.2].

After explaining the objective and the structure of this techno-economic summary report, **Section 2** provides a short introduction into the relevant HRS technologies and the main HRS modules. **Section 3** summarises the requirements of the individual HRS case studies conducted within NewBusFuel and analyses their techno-economic performance.

Section 4 contains the lessons learned and provides recommendations for techno-economic improvements. This section is divided into three parts and addresses the three main stakeholder groups.

Section 5 summarizes aspects that will require additional consideration in the future in order to enable the successful commercialization of fuel cell buses and the related infrastructure. Finally, **Section 6** provides a summary.

2. Introduction to relevant HRS technologies

This section gives a brief introduction into the overall concepts for refuelling hydrogen fuel cell buses in an HRS, the main modules and the most commonly deployed technologies.

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2. Introduction to relevant HRS technologies

This section gives a brief introduction into the overall concepts for refuelling hydrogen fuel cell buses in an HRS, the main modules and the most commonly deployed technologies. More detailed explanations on applicable concepts and technologies can be found in the *Guidance Document on Large Scale Hydrogen Bus Refuelling*, which is another deliverable of the NewBusFuel project [NBF – D4.2]. The explanations contained in this section support the understanding of the analyses and the recommendations that are provided within the later sections.

All HRS concepts that were developed within the NewBusFuel project are intended for refuelling a fleet of fuel cell buses. Hydrogen powered fuel cell buses offer a range of potential advantages such as the complete avoidance of local pollutants, e.g. nitric oxide and nitrogen dioxide (NOx) as well as particulate matter (PM). Further, the greenhouse gas emissions that are caused by the operation of a hydrogen bus can be reduced almost completely if the hydrogen is produced from renewable sources.

Because numerous sources can be used for the production of hydrogen, the use of fuel cell buses increases the energy flexibility compared with conventional diesel buses.

Hydrogen can also be used within internal combustion engines. However, the hydrogen consumption of this technology is significantly higher [CHIC – brochure], and so current developments focus on the more efficient fuel cell powertrains.

A large variety of HRS concepts exists. The following paragraphs explain the most important ones. **Figure 1** shows a scheme of a typical HRS concepts in which four different modules can be differentiated. These are the H_2 production or delivery unit (for external supply), the compression unit, the hydrogen storage and the dispensing unit. Since compression and storage are strongly related to each other, they are illustrated together within **Figure 1** and will be addressed together within this section.

H_2 production or delivery

An essential differentiation of HRS concepts is the origin of the hydrogen. If the required hydrogen is produced directly at the HRS, this is called **on-site production**. In contrast, some HRS only refuel the hydrogen to the vehicles and use hydrogen that is delivered from a different facility. This could be a specialised facility for large-scale hydrogen production, or one that produces hydrogen as a by-product. Both cases are examples of the **off-site production** of hydrogen. If the production of hydrogen does not take place at the HRS but close to it, this is called **near-site production** and a truck trailer delivery or pipeline is usually used for the transport of the hydrogen to the HRS.

If the HRS uses hydrogen from offsite production, two different forms of delivered hydrogen need to be differentiated: **gaseous and liquid hydrogen (GH_2 and LH_2)**. The liquefaction of hydrogen consumes a considerable amount of energy. With current technology about one third of the hydrogen energy content is required for the liquefaction process but approaches are investigated to reduce the current energy demand by almost 50 % in the future [Cardella]. However, a significantly larger amount of liquid hydrogen can be transported in one shipment, which is usually done in truck trailers, compared with the delivery of gaseous hydrogen. For this reason, the transport costs per kilogram are usually smaller for LH_2 than for GH_2 and may compensate for the higher production effort of liquid hydrogen. If transported in gaseous form, H_2 is compressed to 200 bar or more due to its low density under ambient conditions.

On-site hydrogen production generally uses one of the two following technologies: **electrolysis** or **steam reforming**. An electrolyser uses electricity to split water into hydrogen and oxygen. A steam reformer uses methane and water vapour and produces hydrogen by way of a catalytic reaction.

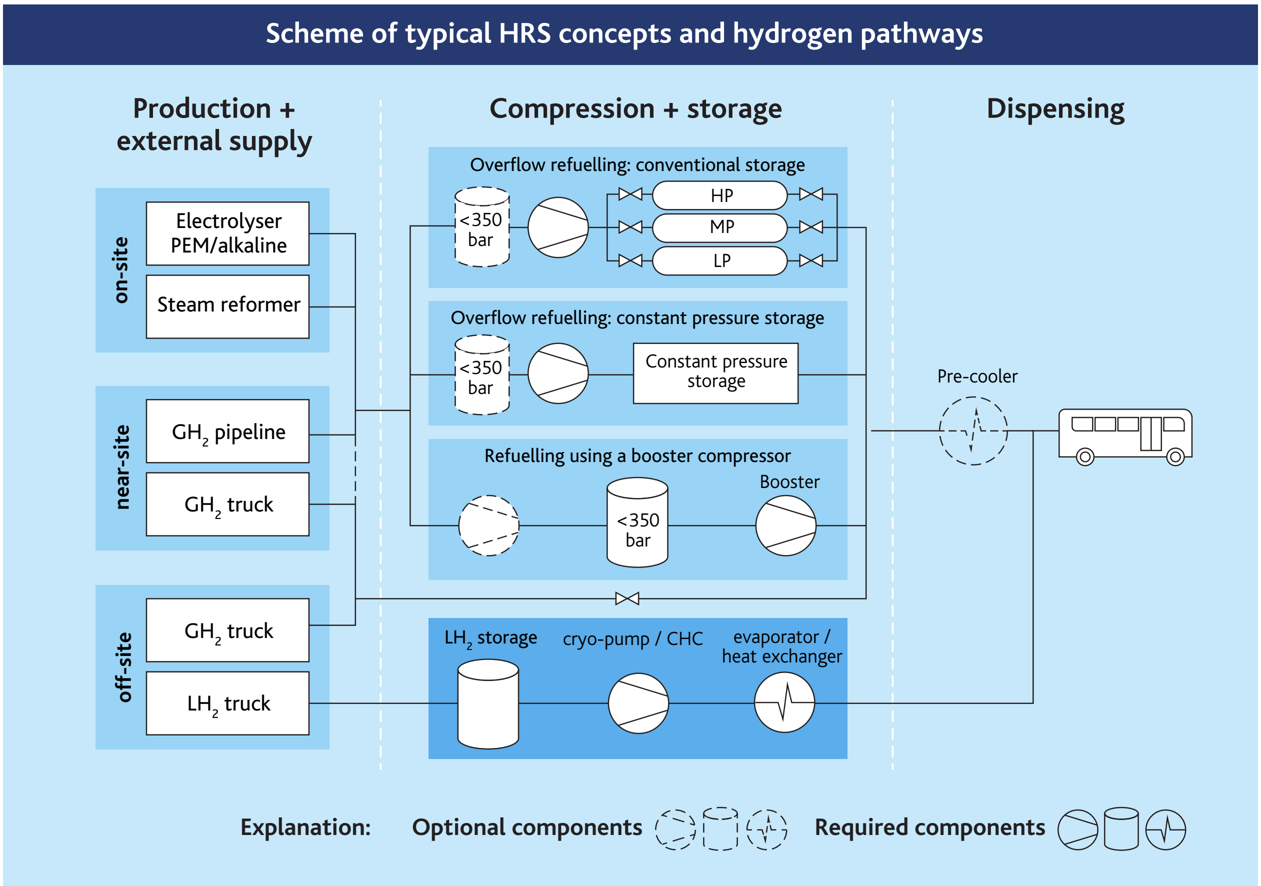

Figure 1: Scheme of typical HRS concepts and hydrogen pathways

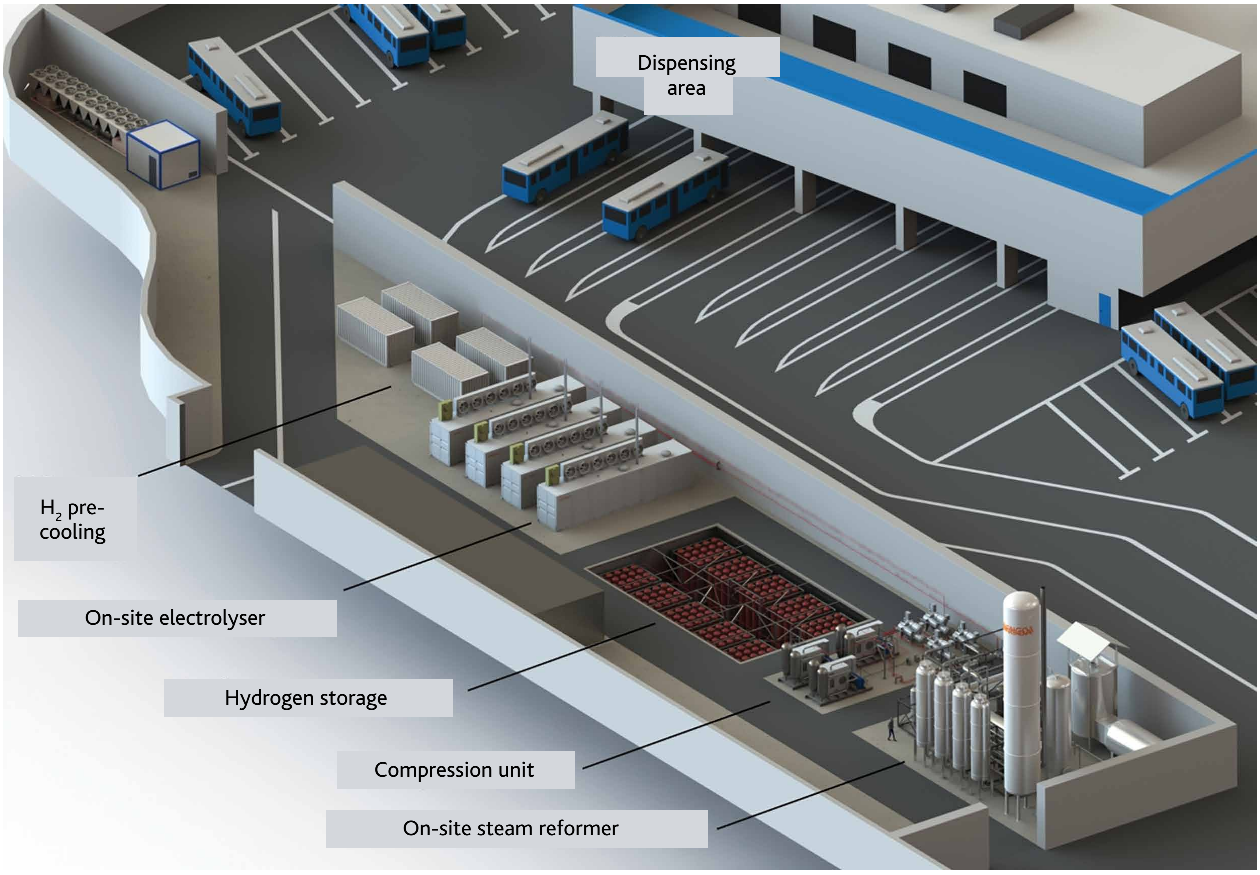

Figure 2: Example of an HRS with on-site electrolysis and steam reforming, Source: Abengoa Innovación

Compression and storage

The compression unit and the hydrogen storage are strongly interrelated with each other. Two basic concepts for the handling of GH_2 need to be differentiated: The first one (see the two paths indicated at the top of **Figure 1**) uses a high pressure storage, with a pressure level above the target pressure in the bus tank. Due to this pressure difference, the refuelling process can take place by **overflow filling** without the need of a compressor during the actual refuelling process. A relatively young technology is the so-called **constant pressure storage**. It uses a hydraulic unit to maintain the desired pressure level in the hydrogen storage during refuelling.

The second concept (see the third path under compression + storage in **Figure 1**) uses a lower pressure level in the storage and a **booster compressor** which transfers the hydrogen from the storage into the bus tank when refuelling the bus.

By increasing the storage pressure, more gaseous hydrogen can be stored in a certain volume and on a certain footprint. On the other hand, higher pressure levels require higher strength storage tanks and most likely higher investment costs.

Liquid hydrogen, that has a boiling temperature of about -253°C at ambient pressure, has to be stored in highly insulated storage tanks to avoid the warming of the LH_2 and hence the boil off (evaporation) as gaseous hydrogen (see bottom H_2 path in **Figure 1**). Instead of compressors, cryo-pumps or cryogenic hydrogen compressors (CHC) can be used for moving the hydrogen from the storage tank to the dispenser unit. When passing through a combined evaporator/heat exchanger unit, the hydrogen

Figure 3: Example of an HRS with LH_2 delivery, Source: Linde

is conditioned to appropriate pressure and temperature levels to allow for standard 350 bar refuelling of gaseous hydrogen at the dispenser.

Note that the pressure level for bus tanks is currently 350 bar, whereas a pressure level of 700 bar is commonly required for refuelling passenger vehicles, making bus HRS less complex and hence cheaper.

It is also important to note the critical role of compressors within an HRS design. Within the CHIC project and its predecessor projects CUTE, ECTOS and HyFLEET:CUTE, the majority of the HRS downtime was caused by problems with the hydrogen compressors (see [CHIC – brochure]). The importance of this HRS module must not be underestimated.

Dispensing unit

The buses are connected to the HRS using the dispensing unit. Different standards and protocols exist for the refuelling of different vehicles, such as passenger vehicles, buses or forklifts. An important parameter is the refuelling speed which can be considered in three clusters: slow-fuelling (up to 30 g/s or 1.8 kg/min), normal-fuelling (up to 60 g/s or 3.6 kg/min), and fast-fuelling (up to 120 g/s or 7.2 kg/min). These figures indicate the maximum refuelling speed, and the average during an entire refuelling process may be well below these limits.

Depending on the refuelling protocol, pre-cooling of hydrogen may be required, e.g. when using fast-fuelling especially for passenger vehicles due to the higher pressure (700 bar), leading to additional installations and higher dispensing cost.

3. Techno-economic analysis

The requirements and the techno-economic performance of the solutions developed for the case studies within the project are summarised and analysed to understand the main influencing factors regarding design and operation of an HRS.

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3. Techno-economic analysis

Within the NewBusFuel project, 13 case studies were developed for 12 different cities in seven European countries (see **Figure 4** next page). Eight of the participating cities, have gained experience with hydrogen buses in previous projects, whereas four, namely Birmingham, Potsdam, Riga, and Wuppertal, have not been active in earlier projects of the Fuel Cell and Hydrogen Joint Undertaking (FCH JU). In projects such as CHIC or HyTransit bus operators have been testing a small number of fuel cell buses, generally in the range of 4 – 10 buses, together with the related refuelling infrastructure.

In each case study of NewBusFuel, bus operators or transport agencies cooperated with partners from the hydrogen industry and with equipment suppliers, jointly developing customized solutions for the individual circumstances of each of the case studies. Their individual requirements and the techno-economic performance of the solutions developed are summarised and analysed in a generalised form within this section to better understand what the main influencing factors are regarding the design and operation of an HRS.

Figure 4: - Partnership overview of the NewBusFuel project

Requirement variation across the case studies conducted within the NewBusFuel project

Parameter	Typical range within NewBusFuel	Min/Max
Assumed H_2 consumption of a 12m bus[1]	9 – 10 kg H_2/100 km	8.5 / 12.0 kg H_2/100 km
Assumed H_2 consumption of a 18m bus	12 – 15 kg H_2/100 km	11.5 / 15.6 kg H_2/100 km
Required daily operating range of a fuel cell bus	200 – 300 km	155 / 450 km
Operating days of one bus per year	250 - 350	240 / 365
Number of buses in initial fleet size	10 - 20	3 / 50
Number of buses in final fleet size	50 - 250	40 / 275
Amount of hydrogen required per day (for final fleet size)	1,000 – 6,000 kg H_2	700 / 6,000 kg H_2
Duration of the refuelling window	4 - 6 h	2 / 8 h
Required storage autonomy	1 day - 3 days	0.5 / 4.5 days
Refuelling availability	98 % - 100 %	98 % / 100 %
H_2 cost target	4 – 6 €/kg H_2	4 / 8 €/kg H_2

Table 1 - Requirement variation across the case studies conducted within the NewBusFuel project

[1] Note that the consumption values are expected to decrease in the future. The Multi-Annual Work Plan 2014 - 2020 of the Fuel Cell and Hydrogen Joint Undertaking assumes a gradual reduction of the hydrogen consumption to 7.6 kg H2/100km in 2023 [FCH JU – MAWP]. Further information on current hydrogen consumption of FC buses can be found in the final brochure of the CHIC project [CHIC - final brochure]

Requirements from bus operators

The fact that suitable solutions were developed for all 13 case studies using components and technologies that are available today represents a remarkable achievement of the NewBusFuel project. Each of these solutions takes into account all project specific requirements, such as the bus fleet operation, H_2 demand, refuelling operations, and requirements to comply with local regulations, codes and standards (RCS). The range of the most important key requirements and their variations across the case studies within NewBusFuel is summarised in **Table 1**. The indicated H_2 target cost is assessed at nozzle, which includes all CAPEX and OPEX costs that need to be incurred by the bus operator.

Technical characteristics of the solutions developed within NewBusFuel

The case studies developed include all the sources of hydrogen that were described in **Section 2**, and some studies involve multiple sources as well as back-up options. Some preference is given to on-site production by electrolysis, which is chosen by eight studies, with on-site steam reforming used in three cases. Off-site production and the delivery of gaseous hydrogen are considered for two and the delivery of liquid hydrogen for three studies.

Different concepts are considered for the compression and storage modules. For most HRS concepts that handle gaseous hydrogen, overflow filling is selected using a high pressure storage, which is usually subdivided into three storage banks with different pressure levels (low, medium, high pressure) and that fills a bus in a cascading manner using the pressure difference between vehicle tank and storage tank. The combination of a medium pressure storage and a booster compressor is also applied in a few cases.

Several studies consider the use of constant pressure storages in order to make better use of H_2 stored in the storage tanks and to reduce the number of pressure cycles for the storage tank significantly, thereby extending the lifetime of the storage tanks.

Surprisingly the required storage autonomy was reduced in the course of the NewBusFuel project. Initially the studies considered individual storage autonomies with an average of about three days. This was reduced for many case studies, commonly to reduce costs, resulting in an average of about two days in the final engineering designs.

The characteristics of the refuelling patterns also vary widely. This includes the duration of the refuelling window (see **Table 1**) as well as the number of buses that need to be refuelled at the same time. For example, with a back-to-back refuelling time of 12 minutes per bus (assuming an average speed of 2.5 kg H_2/min to refuel 25 kg H_2 plus 2 minutes for manoeuvring and setup time) 4 dispenser points are required to work in parallel to refuel of a fleet of 100 buses within 5 hours. Most studies aim for normal-refuelling speed (see **Section 2**), but also fast-refuelling and slow-refuelling of a large number of buses in parallel are considered within the case studies. A refuelling option for fuel cell passenger cars in addition to the one for buses, was integrated within only one study.

It should be noted that the technology selection within the NewBusFuel project was sometimes influenced by the product portfolio of the industry partners involved, or by certain pre-decisions taken by the bus operator. For this reason, the final designs do not necessarily reflect the optimum HRS design.

Analysis of HRS footprint and utility requirements

Since bus depots are often located within urban areas and surrounded by commercial or residential areas, the constraints on the HRS footprint are usually very strict and challenging.

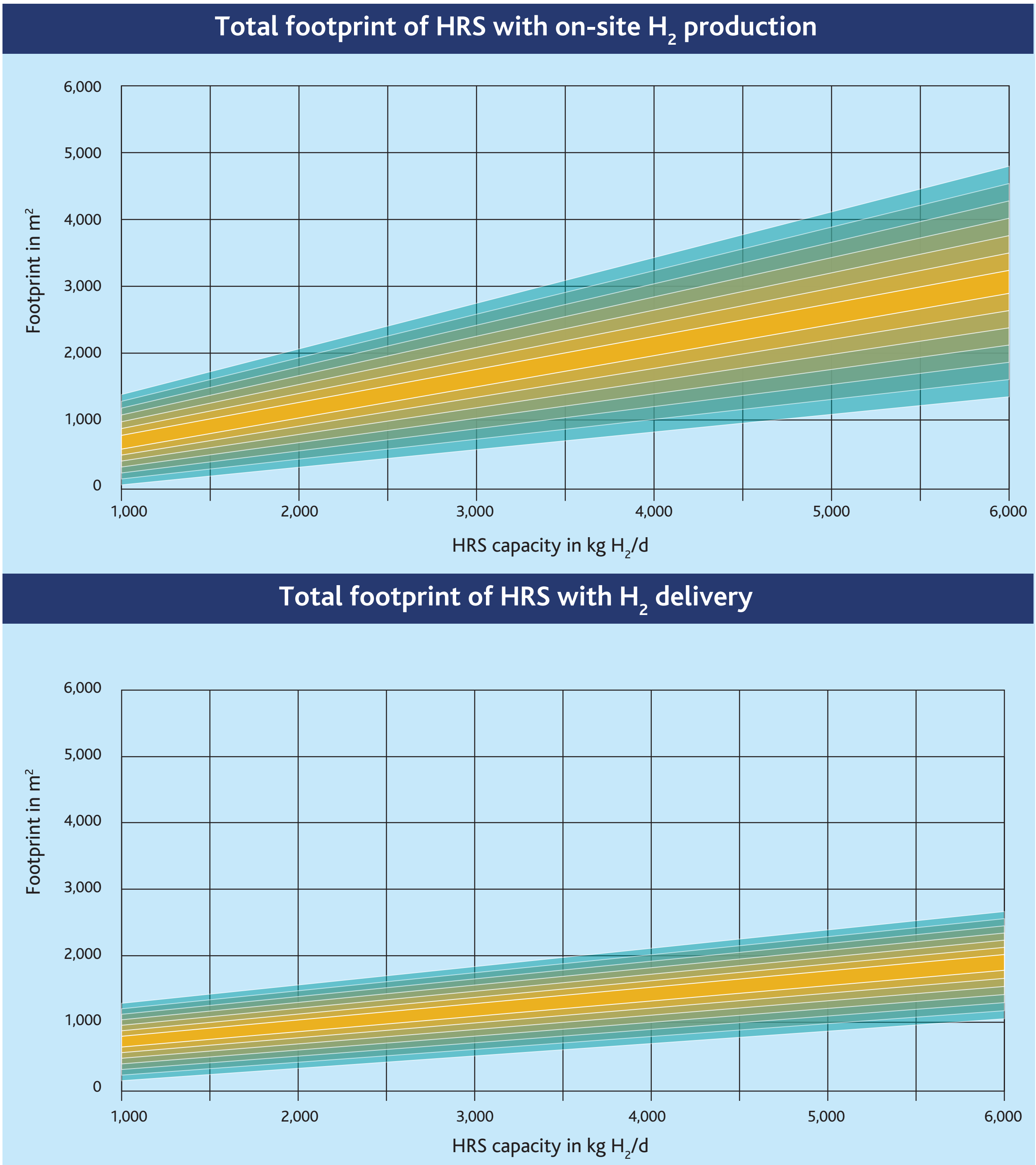

Fig 5 - Approximate overall footprint of an HRS with on-site H_2 production (top) and with H_2 delivery (bottom)

Figure 5 shows the correlation between HRS footprint and the daily H_2 refuelling capacity. As might be expected, an HRS with on-site production (see **Figure 5 – top**) requires more space than an HRS with H_2 delivery (see **Figure 5 – bottom**). Some HRS concepts aim for a reduction of the footprint by increasing the height of the facilities, e.g. by stacking components on top of each other for instance in double storey buildings. However, all components need to be accessible for maintenance, and potential height restrictions need to be respected, e.g. due to the development plan, passing high-voltage overhead lines, or possible proximity to an airport. Note that all these height limitations are actual examples taken from the case studies of the NewBusFuel project.

Depending on the technology used for on-site hydrogen production, the required utility supplies need to be available at the HRS site. An electrolyser with a production capacity of 1,000 kg H_2/day requires an electric power connection of about 2.5 MW. Other components also have a significant power demand, e.g. the compressors. An HRS with on-site electrolysis is likely to have a substantial electric power demand and may require a connection at higher voltages such as 110 kV, which is already used for longer distance transmission, if the power demand exceeds the capacity limits of the current distribution network connection. Obviously, on-site steam reforming requires sufficient supply of natural gas. As a rule of thumb, for the production of 1,000 kg of hydrogen 5,000 Nm³ of natural gas are needed. Water is needed for all forms of on-site hydrogen production, which is usually purified on-site according to the individual water purity requirements.

For off-site hydrogen production, the number of trailer deliveries required per day and the related logistics is important. High-pressure tube trailers carry different quantities of hydrogen, depending on the pressure level in the trailer. Established trailers with 200 bar contain about 350 kg and the more recently developed trailers with 500 bar carry more than 1,000 kg H_2 [DeliverHy], whereas a LH_2 trailer contains more than 3,000 kg H_2. Depending on the hydrogen demand, the daily effort for delivering and exchanging the trailers at the HRS may be significant.

Economic analysis of hydrogen fuel costs to bus operators

As indicated previously in Table 1, the typical target cost range within NewBusFuel is at 4 - 6 €/kg H_2 and generally aims at achieving fuel cost parity between hydrogen and diesel buses[2]. This target cost range was reached by three studies within NewBusFuel with different HRS concepts, while three other studies achieved final hydrogen costs in the range of 6 - 8 €/kg H_2. The H_2 cost of the remaining seven studies exceeds 8 €/kg H_2. The average H_2 cost across all studies within the NewBusFuel projects is approximately 8.00 €/kg H_2, which represents a substantial reduction of H_2 costs compared with the actual H_2 costs paid within the CHIC project of 13 – 20 €/kg H_2 [CHIC – D1.5]. This cost improvement is mainly caused by the larger HRS capacities within the NewBusFuel project and the related economies of scale. However, given that over half of the studies do not achieve the set hydrogen target cost, further efforts are required by all stakeholders (see **Section 4** for recommendations).

The hydrogen costs that can be achieved by deploying HRS with on-site steam reforming are generally below those achieved by HRS with on-site electrolysis. For the latter, the disadvantage is mainly caused by the high price for electricity compared with the cost of natural gas. The hydrogen cost of HRS with hydrogen delivery can be cost competitive to that from on-site hydrogen production, independently from whether GH_2 or LH_2 is delivered to the HRS. Nevertheless, a large number of aspects, e.g. the amount of hydrogen purchased per delivery, the delivery frequency, the delivery distance, the duration of the contract, the conditions of contract cancellation, penalties for non-fulfilment, and many other contractual aspects determine the final cost of delivered hydrogen which is highly location specific.

[2] Note that the cost parity between fuel cell and diesel buses is influenced by the respective fuel consumption. A lower hydrogen consumption, i.e. higher energy efficiency of the FC bus, allows a higher hydrogen cost (ceteris paribus) for achieving cost parity with diesel.

HRS with on-site electrolysis

The capital and the operational expenditure (CAPEX and OPEX) are assessed separately below, including the contribution of each to the costs of the main HRS modules. The cost estimates and contributions are illustrated using a generic example of an HRS with on-site electrolysis and a capacity of 3,000 kg H_2/d, which is sufficient to refuel more than 100 buses depending on their individual hydrogen consumption per day. The generic technical and financial assumptions are given in **Table 2**. More background information on cost estimates of each of the HRS components is provided by the NewBusFuel Guidance Document on Large Scale Hydrogen Bus Refuelling [NBF – D4.2].

For the four main modules, the generic HRS requires an initial investment of 23.5 M€, which equates to a CAPEX of 1.54 €/kg H_2 over the indicated depreciation periods. Including other costs such as additional civil works, financing costs and project management costs, this amount is increased to 28.2 M€ or 1.76 €/kg H_2. The maintenance, which is assumed to account for 3 % of the overall CAPEX for the H_2 equipment each year, totals about 700,000 € per year which increases the hydrogen cost by 0.64 €/kg H_2.

Technical and financial assumptions of an HRS with on-site electrolysis

H_2 production unit	
Daily H_2 production capactiy	3,000 kg H_2/d
Investment for the H_2 production unit	10.5 M€
Technical lifetime and depreciation period of the H_2 production unit	10 years
Electricity consumption of the H_2 production unit	58 kWh/kg H_2
Operating days per year	365 days
Compression + Storage Unit	
Investment for the compression unit + storage	12.0 M€
Technical lifetime and depreciation period of compression unit + storage	20 years
Electricity consumption in the compression unit (storage pressure bus: 350 bar)	4 kWh/kg H_2
Dispensing unit	
Investment for the dispensing unit (5 dispensers)	1.0 M€
Technical lifetime and depreciation period of the dispensing unit	20 years
Other costs	
Other investment costs, e.g. additional civil works, financing costs, project management	4.7 M€
Depreciation period	20 years
Maintenance (for H_2-related technologies)	3% of CAPEX p.a.

Table 2 - Technical and financial assumptions of an HRS with on-site electrolysis H_2 production unit

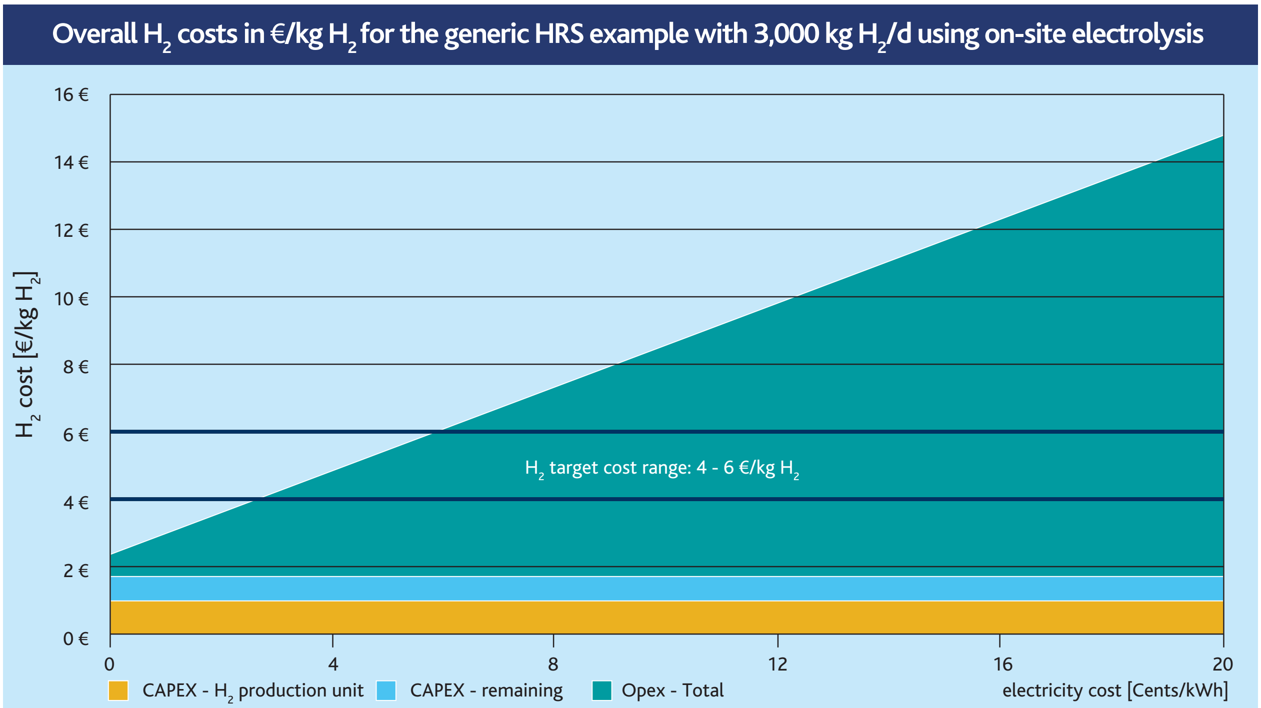

Fig 6 - Overall H_2 costs in €/kg H_2 for the generic HRS example with 3,000 kg H_2/d using on-site electrolysis

The total electricity consumed by the HRS amounts to 62 kWh/kg H_2 (58 kWh/kg H_2 for the H_2 production and 4 kWh/kg H_2 for the compression). Using these assumptions, **Figure 6** illustrates the total hydrogen cost as a function of the electricity cost. The figure shows that for the majority of the electricity cost range considered, the OPEX is significantly higher than the CAPEX. In order to achieve a hydrogen cost at nozzle within the desired cost target range, i.e. below 6 €/kg H_2, the electricity price needs to be less than 6 Cents/kWh for this generic HRS with its underlying assumptions (see **Table 2**).

Figure 7 shows the wide variation of the electricity price across European countries according to Eurostat with an average electricity price of about 12 Cents/kWh (including taxes and levies) for industrial consumers. It is important, however, to mention that these statistics are valid for a yearly electricity consumption between 500 and 2,000 MW, whereas the generic HRS with on-site electrolysis requires about 70,000 MWh per year.

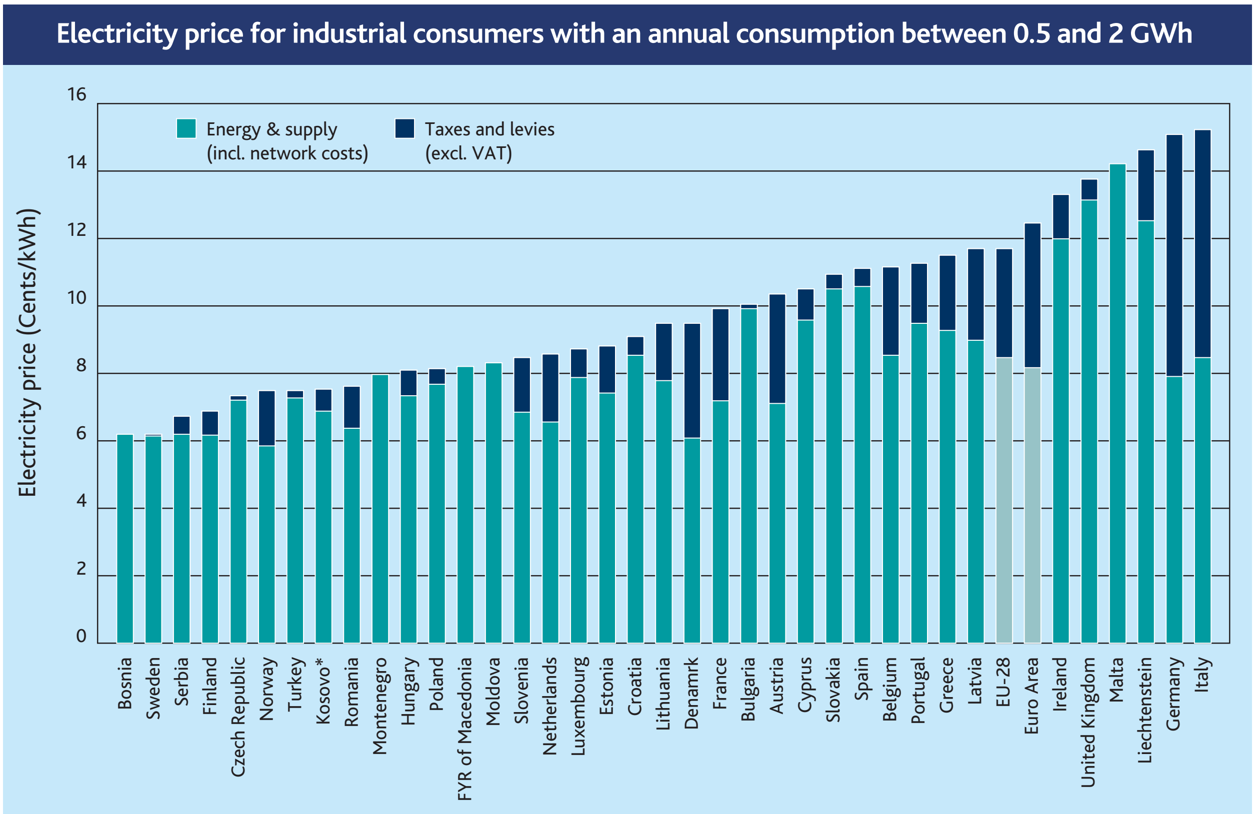

Fig 7 - Electricity price for industrial consumers with an annual consumption between 0.5 and 2 GWh [Eurostat 2016, electricity prices]

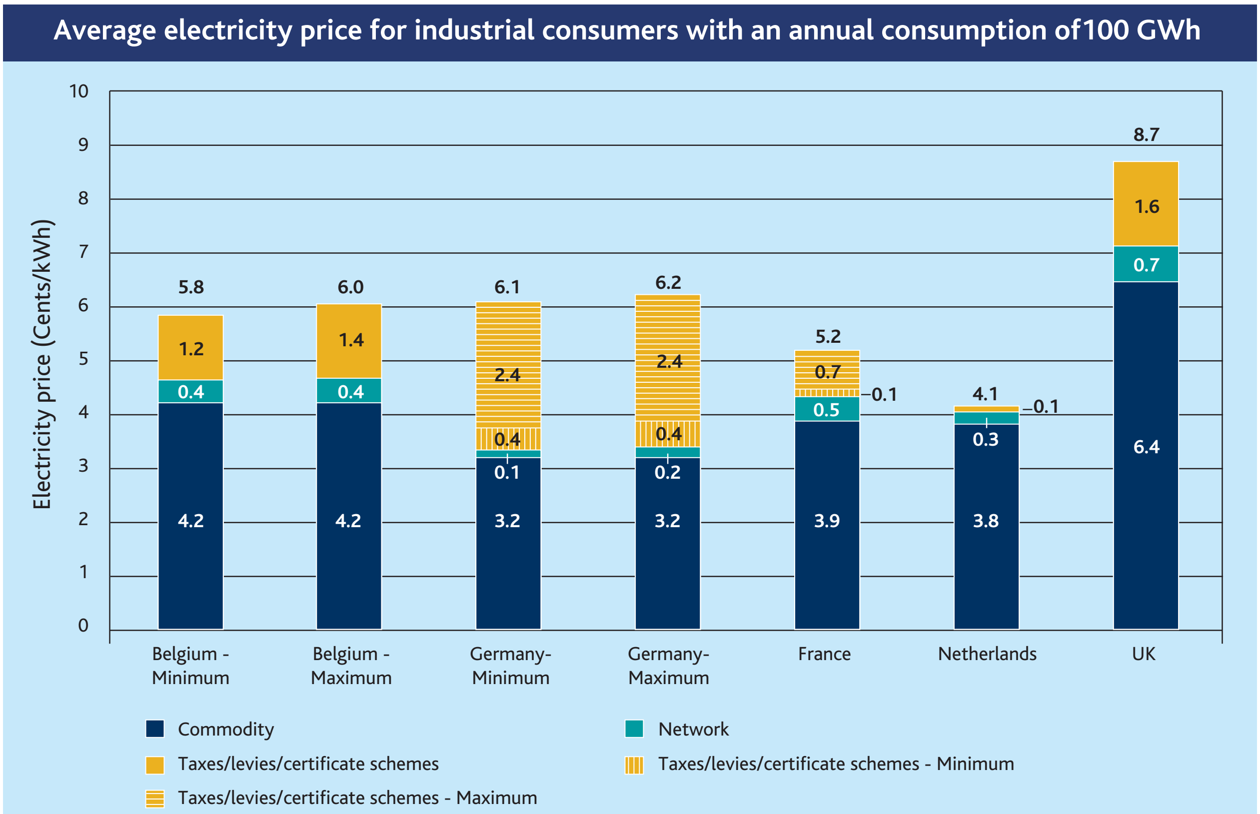

Fig 8 - Average electricity price for industrial consumers with an annual consumption of100 GWh [CREG 2016]

Figure 8 shows the electricity prices for industrial consumers in some European markets with an annual electricity consumption of 100 GWh according to [CREG 2016]. The price of electricity, traded as commodity on the electricity market (e.g. at the EEX or the EPEX), is below 4 Cents/kWh in several countries. Even including the taxes and levies, the electricity price for large industrial consumers in European countries can be in the range of 6 Cents/kWh or even lower.

It is important to note that the electricity price situation is very specific to individual European countries and their regulations on taxes and fees. In some countries, such as Germany and Italy, the overall electricity price can include a high share of taxes and levies (see **Figure 7** and **Figure 8**). For industrial consumers with an annual consumption of 70 - 150 GWh the average electricity price in Germany is reported to 9.76 Cents/kWh for the year 2015 with the considered non-refundable taxes and levies amounting to 4.21 Cents/kWh, which represents more than 40 % [bdew 2016]. This high share of taxes and levies is of significant influence on the achievable hydrogen cost. Especially in the case of Germany, the current regulatory framework for the existing electricity taxes and levies in Germany is highly complex and numerous regulations for exemptions exist [bdew 2016]. For this reason, the applicable electricity price depends on a range of legal and organisational aspects. **Table 3** illustrates the effect of purchasing electricity at different electricity prices including or excluding the non-refundable taxes and levies.

Variation of the total hydrogen cost depending on the electricty price for large industrial consumers in Germany

Assumed cost of electricity (Cents/kWh)	Resulting final H_2 cost for the generic HRS example (€/kg H_2)
5.55 Cents/kWh (excluding non-refundable taxes and levies)	5.84 €/kg H_2 Electricity contribution: 3.44 €/kg H_2
9.76 Cents/kWh (including non-refundable taxes and levies)	8.45 €/kg H_2 Electricity contribution: 6.05 €/kg H_2

Table 3 - Variation of the total hydrogen cost depending on the electricity price for large industrial consumers in Germany

For the generic HRS example discussed here, an electricity price of 9.76 Cents/kWh leads to a hydrogen cost below 8.50 €/kg H_2, whereas the electricity price without taxes and levies leads to a hydrogen cost of below 6 €/kg H_2, reaching the desired hydrogen target cost range of 4 - 6 €/kg H_2.

The NewBusFuel project addressed different commercialisation models for the use of electrolysers. The strong influence of the electricity price regulations and its (potentially negative) effect on the business models chosen within the NewBusFuel project is discussed within [NBF – D3.4][3].

HRS with on-site steam reforming

Also for HRS with on-site steam reforming, the contribution of the OPEX towards the final H_2 cost is usually larger than the contribution of the CAPEX. As a rule of thumb, about 4.5 – 5.5 Nm³ of natural gas are required for the production of 1 kg H_2. Assuming a consumption of 5 Nm³, an energy density of 10 kWh/Nm³ (with respect to the lower heating value), the annual natural gas demand of the generic HRS example is at about 55 GWh/a. At the average price of natural gas for industrial consumers within Europe of 2.75 Cents/kWh (see **Figure 9** and **Figure 10**), the natural gas related OPEX accounts for 1.38 €/k g H_2.

Other contributions to the OPEX are caused by the electricity consumption of the steam reformer, the electricity for the hydrogen compression and the maintenance cost. The lower cost per energy of natural gas compared with electricity (see **Figure 7** to **Figure 10**) means that the cost of hydrogen produced from steam reforming is therefore usually below the cost of hydrogen from electrolysis.

In accordance with other literature sources (see for example [H2A – Production studies], [NOW]), the figures reported within NewBusFuel show that the necessary CAPEX can be considered lower for a steam reformer than for an electrolyser, nevertheless the difference is less significant than for the OPEX difference.

HRS with delivered hydrogen

Since HRS receiving delivered hydrogen do not require deployment of any H_2 production technologies, this type of HRS usually requires the lowest capital investment. However, as mentioned earlier, the cost of the delivered hydrogen varies significantly depending on a number of technical but also contractual parameters. It may be higher or lower than that of hydrogen produced on-site.

[3] For more information sources from the NewBusFuel project, see the list of references in the Annex

Natural gas price for industrial consumers with an annual natural gas consumption of 2.8 – 27.8 GWh

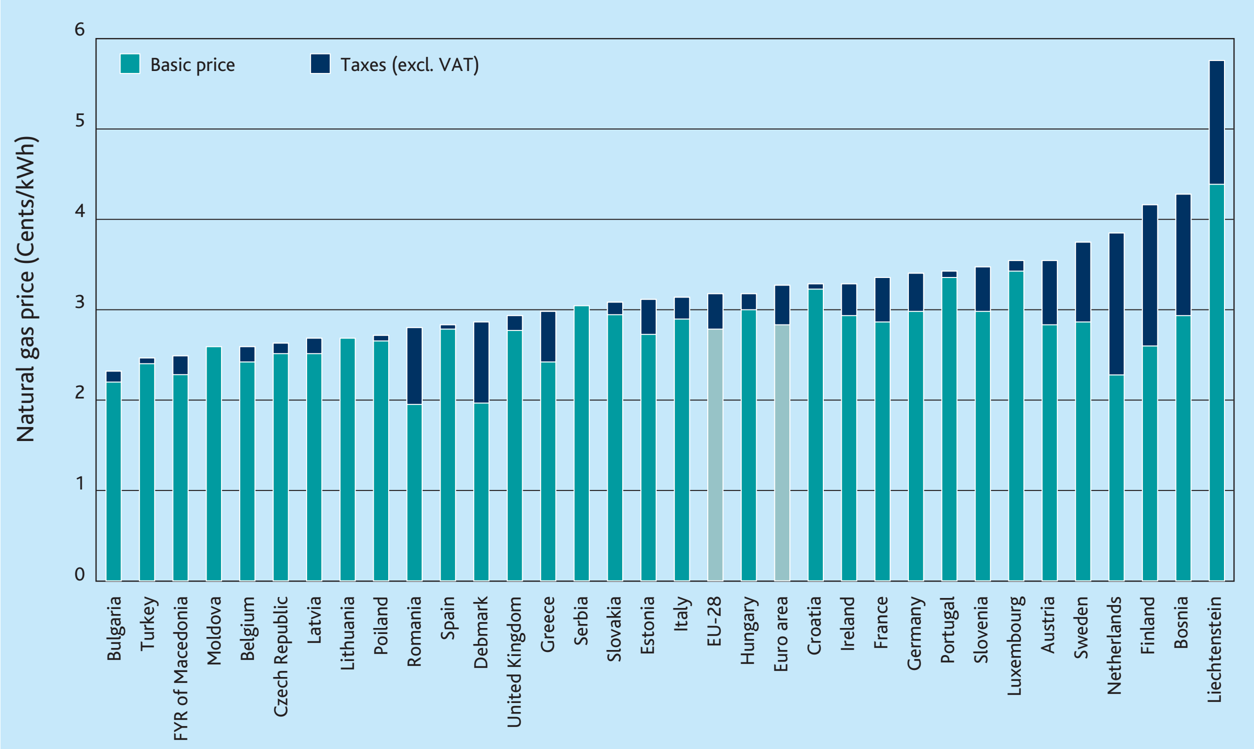

Fig 9 - Natural gas price for industrial consumers with an annual natural gas consumption of 2.8 – 27.8 GWh [Eurostat 2016, natural gas prices]

Summary conclusion on the techno-economic analysis

As described in this section, the suitable technical solutions for an HRS, especially with respect to the final hydrogen cost is highly individual and depends on a number of aspects, such as the local electricity and natural gas supply, the availability of H_2 sources and the potential use of H_2 delivery, the local legislation and effects through taxes and levies, and many more. Within NewBusFuel these individual differences were levelled out to a certain degree by taking into account the characteristics of multiple HRS designs developed within the project. Some of the derived mean values are provided within this and other publications. Nevertheless, for a particular HRS project the assessment of the entire range of technological possibilities needs to be assessed in detail by the bus operator in close cooperation with the HRS or hydrogen suppliers in order to tailor a suitable HRS design that suits the specific requirements based on the individual circumstances [NBF - D4.2].

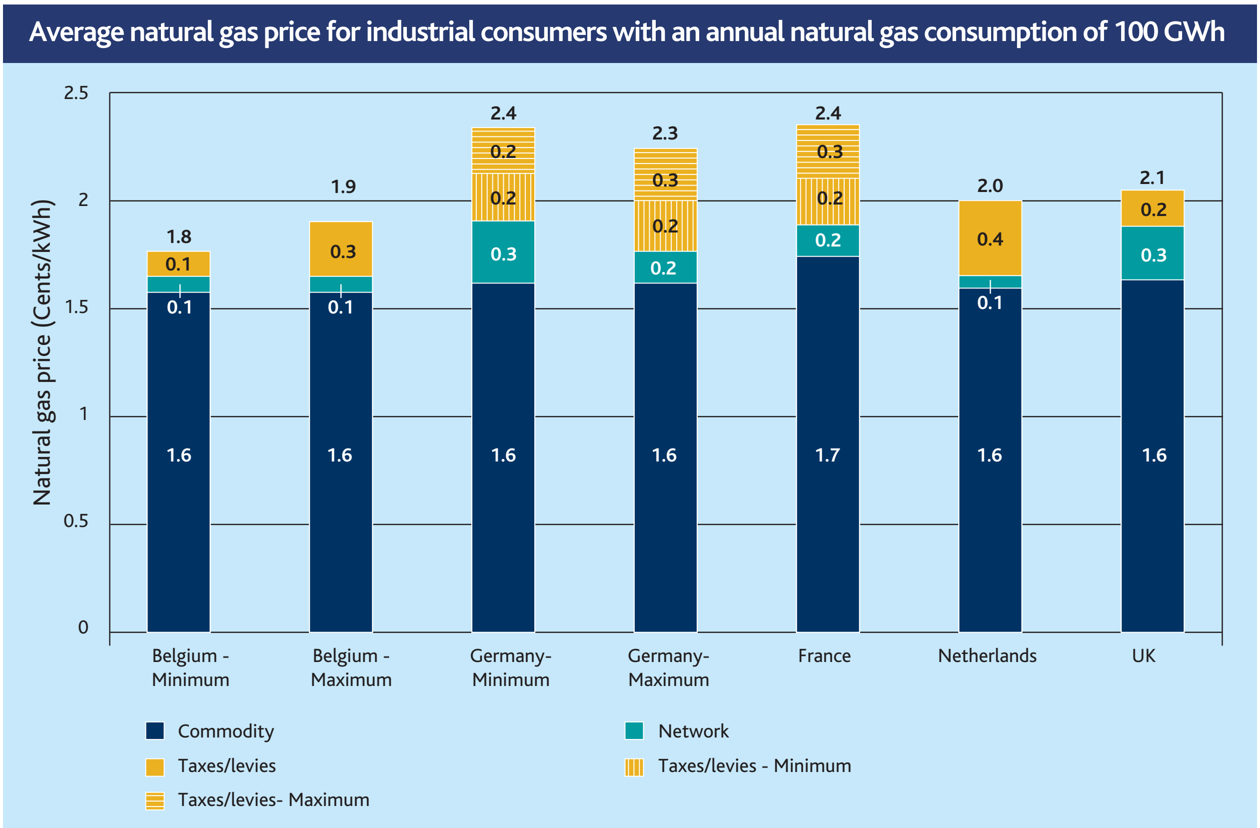

Fig 10 - Average natural gas price for industrial consumers with an annual natural gas consumption of 100 GWh [CREG 2016]

4. Lessons and Recommendations

Lessons and recommendations for bus operators and transport agencies, for policy makers as well as for H_2 infrastructure suppliers and the overall H_2 community.

4

4. Lessons and Recommendations

The exchange of requirements and the cooperation between bus operators, HRS suppliers and other stakeholders, such as permitting bodies, to develop ideas and concepts on how to fulfil the requirements, created a wealth of valuable insights and knowledge for all partners involved in the NewBusFuel project. These insights certainly influenced the approach for determining the most suitable HRS design.

The most important insights are summarised in the following three subsections. The first contains issues that should be considered by bus operators and transport agencies, while the second details recommendations for policy makers. The third subsection comprises tasks that need to be addressed by the suppliers and the H_2 community. Together, these three sets of recommendations outline the actions needed to support the delivery of large deployments of fuel cell bus fleets and associated refuelling infrastructure.

4.1 Recommendations for decision-makers at bus operators and transport agencies

Take into account the differences between H_2 and diesel refuelling

There are significant differences between refuelling hydrogen into fuel cell buses and the well-known handling of diesel. Some of these are not immediately apparent, but they strongly influence the HRS solution that will meet the specific needs of the individual bus operator. The specific characteristics of hydrogen refuelling need to be taken into account when considering the range of options and selecting the most suitable HRS solution. Influence from previous diesel-based practices need to be set aside and a new 'mind set' brought to play.

One of the key differences is the state of the fuel and the pressure level necessary for refuelling. This is a crucial parameter for the refuelling of hydrogen and there are a variety of possible approaches: The appropriate pressure level can be reached by using on-site equipment or the hydrogen can be delivered at the required pressure level. The states of delivered hydrogen (liquid and gaseous hydrogen) and the technologies for on-site compression, such as conventional compressors and booster compressors combined with different storage concepts, further increase the complexity of options. The solution must also be easily adaptable to increases in the bus fleet size.

The importance of the hydrogen pressure and the selection of the appropriate approach for compression is just one example of the differences between refuelling hydrogen or diesel. Other differences call for further individual solutions and an open mind helps to find innovative approaches for all of them.

Establish an appropriate initial fleet size

Hydrogen infrastructure is expensive and its contribution to the final hydrogen cost can be significant. This is especially the case for a small hydrogen throughput servicing a small initial fuel cell bus fleet. To minimise hydrogen costs at this initial stage it is important to maximise infrastructure utilisation. This can be achieved by implementing the first stage of refuelling and fleet infrastructure so that the amount of hydrogen produced and required are matched, and the quantity of hydrogen produced is not too small. This requires a larger investment for the infrastructure but leads to a lower cost per amount of hydrogen refuelled.

A rule of thumb for the critical bus fleet size to achieve this throughput estimated by the participants of the NewBusFuel project is in the range of 10 – 20 fuel cell buses depending on their individual hydrogen demand.

If smaller hydrogen bus fleets are planned for the beginning of the scale-up process, less cost-intensive alternatives should be assessed such as the use of an existing hydrogen refuelling station or installing a small

HRS without on-site hydrogen production, using delivered hydrogen instead.

Ensure infrastructure sizing and procurement is adequately linked to growing bus fleet

As the bus fleet is increased, unused overcapacities need to be avoided as they will increase the costs. The bus fleet size needs to be coordinated with the HRS extension. **Figure 11** (next page) shows two examples for different bus procurement strategies.

A continuous ramp-up of the fuel cell bus fleet (see **Figure 11** - top), common with diesel bus fleets with regular annual replacement of a constant number of vehicles, leads to significant unused overcapacities and higher hydrogen cost during most of the ramp-up period. The step-wise procurement strategy (see **Figure 11** - bottom) leads to a better, though still not ideal, utilisation of the infrastructure, with a reduced hydrogen cost.

The fact that many of the NewBusFuel case studies which planned a continuous ramp-up of the hydrogen bus fleet at the beginning of the project changed to a step-wise procurement strategy emphasises the importance of this issue. An early coordination strategy of the bus procurement and the extensions of the HRS infrastructure is important for increasing the utilisation of the HRS and for reducing the cost contributions from the infrastructure related CAPEX.

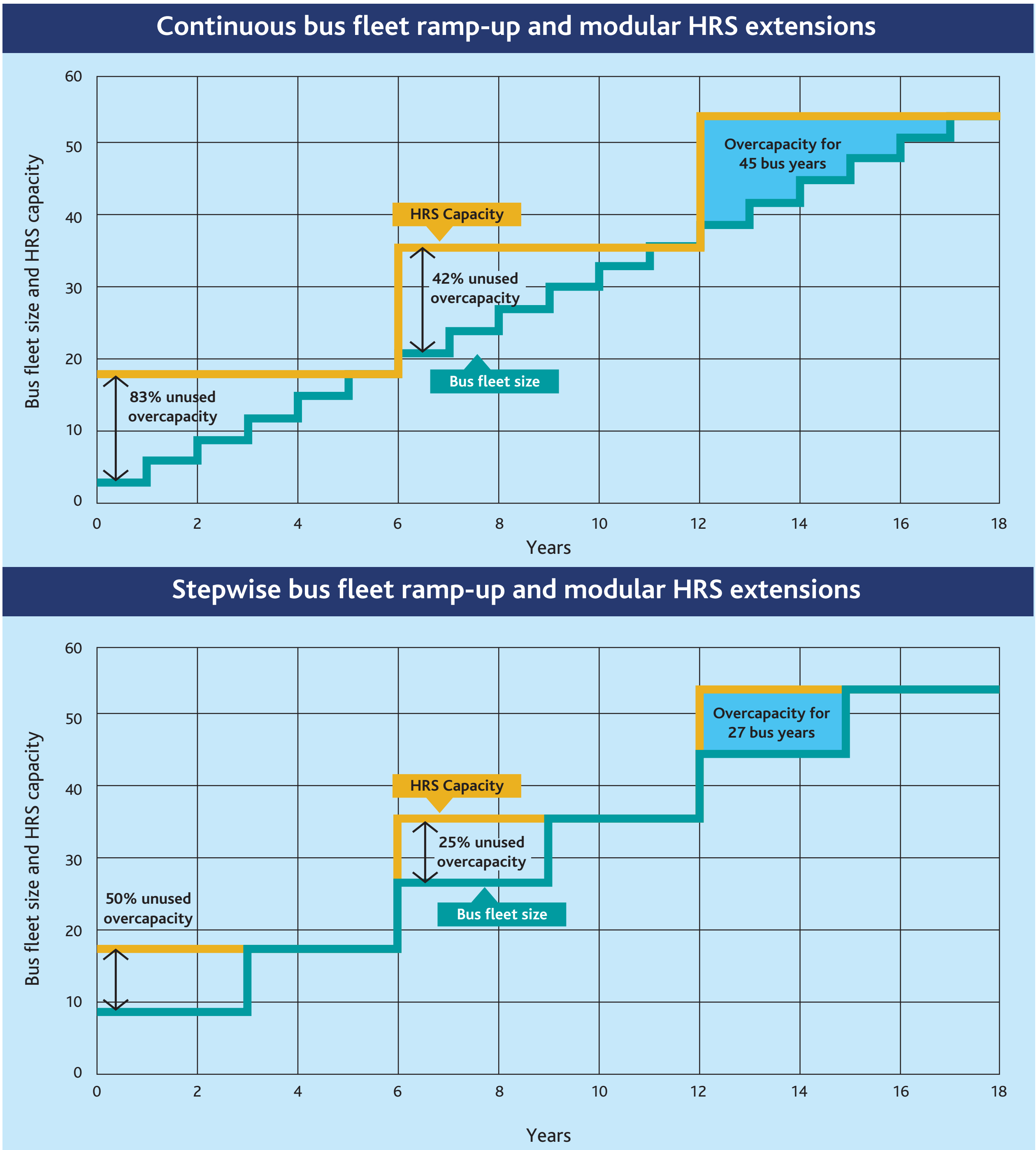

Figure 11: Overcapacities depending on the bus procurement strategy. Top: Continuously 3 buses per year. Bottom: Stepwise 9 buses every 3 years

Chose a modular HRS design

Modular HRS designs have several important advantages. An HRS containing multiple independent modules, ideally units in parallel, is only partially affected in case of a component failure. This helps to avoid complete HRS downtime.

A modular design also allows better scaling and matching of the HRS infrastructure during bus fleet ramp-up. Also units purchased later may have a lower price and better performance due to advances in the technology.

The integration of a redundant component causes a smaller cost increase for an HRS with small modules, compared with an HRS requiring larger elements.

These benefits, however, need to be weighed against some disadvantages. A modular design is likely to have higher CAPEX, OPEX (due to lower efficiency) and a larger HRS footprint.

Find the appropriate balance between reliability and cost

Reliability can be increased by incorporating redundant components and increased storage which can back up operations in the event of failures. But this strategy comes at a cost especially in CAPEX and increases the necessary footprint.

Most studies reduced the desired storage capacity over the course of the project. Whereas the average storage autonomy was about three days at the beginning, this figure decreased to about two days at the end of the project. Assuming a storage cost of 1,200 €/kg H_2 [NBF - D4.2], for an HRS with a daily refuelling capacity of 3,000 kg H_2/d such a correction of the storage autonomy results in a cost reduction of 3.6 million €.

The cost increase from redundant components is especially significant for small HRS. It is advisable not to set too ambitious reliability targets, especially if only a small number of hydrogen buses are operated. It may be economically more reasonable to use conventional diesel buses as back-up instead of demanding very high reliability levels and therefore accept a large investment cost for the HRS. For larger systems, however, redundancies can be integrated more economically, especially if the HRS features a modular design.

The NewBusFuel case studies also consider a variety of other potentially more cost-effective means to ensure high refuelling reliability. Attention to logistic arrangements can be very effective. These could include stocking critical spare parts with long delivery times at the HRS site, and requiring quick response of trained maintenance staff. These measures are especially cost-effective if they are implemented for a number of HRS within a certain region. Enforcement of the availability and reliability via a suitable contractual framework between bus operator and HRS operator is recommended. The standardisation of HRS designs and technologies can also help to reduce the effort related to maintenance and repairs.

Provide flexibility for the HRS design and its operation

Preconceived ideas derived from experience with diesel or other conventional fuels and vehicles can be misleading and counterproductive when implementing a hydrogen HRS system. It is important that the full range of existing options are included in the considerations and that innovative and unconventional solutions are able to be developed. Proposals, and most probably costs, will benefit from allowing technology suppliers sufficient flexibility to suggest the full range of options provided by their product portfolio.

It is of particular importance to maintain sufficient flexibility for the development of the HRS design and its operation including the organisational framework as well as with regard to the extension strategy, instead of specifying technical and financial parameters that are too rigid.

Put effort into reducing the OPEX

OPEX generally dominates the overall hydrogen costs at nozzle. Reductions in this area can be very effective in reducing overall costs.

For on-site electrolysis, a low electricity price is the key for a low OPEX. Taxes and levies are frequently a large component in electricity prices, but they are commonly determined at the Government level. Bilateral cooperation with utilities to get access to cheap electricity is an approach that was addressed within the NewBusFuel project (see Section 3 and [NBF – D3.4]). This might include direct production and use of electricity at the power plant instead of using the electricity grid.

Although natural gas is currently cheaper than electricity per energy content, the price is subject to volatility. Long term contracts reduce the risk of sudden price increases but also restrict the access to potentially decreasing prices.

If hydrogen from off-site production is delivered to the HRS, the contractual conditions have a critical influence on the final hydrogen cost. The amount of regularly purchased hydrogen, the duration of the contract and the distance of delivery have significant influence on the hydrogen price as well as other contractual conditions, e.g. price adjustment mechanisms, termination rights, penalties for non-fulfilment etc.

Try to collaborate with other bus operators for the joint procurement of buses and of HRS infrastructure

The bundling of the demands of multiple bus operators for the procurement of equipment increases the tender size, which might attract more bidders and lead to reduced costs. This can be applied not only to the procurement of hydrogen fuel cell buses (see also [EE – joint procurement]) but also to the purchasing of the necessary hydrogen refuelling infrastructure. Clusters of bus operators that have similar demand can be an effective platform for joint procurement activities.

Confirm the pathways of the procurement process

Some participants within the NewBusFuel project were unclear about the extent to which local and European regulatory frameworks allows a detailed exchange of information between the bus operators and infrastructure suppliers prior to a request for tenders (RFT). The communication between bus operators and suppliers is considered to be essential for a successful project. Engaging an independent engineering office as neutral third party to anonymise the communication process between bus operators and suppliers was suggested as a possible precautionary measure for ensuring the impartiality during the RFT. Advice should be sought from appropriate experts on whether or not such a measure is really necessary. In any case, a standardised specification sheet supports the procurement process significantly.

4.2. Recommendations for policy makers

Reduce the taxes and levies for electricity used for hydrogen production

The electricity price is critical to the final cost of hydrogen produced in electrolysis. The contribution of taxes and levies on electricity in some European countries can account for a significant share of the final electricity price and be a major contributor to the hydrogen cost.

For the cost of hydrogen in transport to reduce sufficiently so hydrogen powered fuel cell public transport can be cost competitive with diesel and other fuels, the regulations have to be reviewed so that the total cost of ownership is reduced.

Ideally, this reduction should occur in a harmonised way across Europe so that tax and charge differences do not

harm the opportunities for any region to benefit from clean public transport.

Set a regulatory framework that allows hydrogen to participate in grid balancing services

Hydrogen has the potential to play an important role in the whole energy system, not just in transport.

This is particularly the case with electricity production from renewable sources where hydrogen can be used as an energy storage medium. Electrolysers can act as flexible loads, enabling them to provide balancing services to the grid, e.g. frequency control in the primary reserve market. This may lead to additional investment, e.g. through increased storage capacity, that needs to be assessed in detail together with potential income for the individual market.

However, the regulatory framework in many European markets is based on regular auctions of short term contracts, for example of one week duration. This is suitable for incumbent technologies and systems, but is an obstacle for the large investments necessary for any new system such as a hydrogen based system. Introducing longer contractual periods would provide increased certainty to industry and increases the security of investment. More information on using electrolysers for providing grid services can be found in the literature [E4tech & EE].

Harmonise RCS across European countries

Large variations of the relevant RCS applying to HRS for buses exist across Europe. These differences significantly increase costs by requiring particular HRS concepts to be modified to meet the different situations. For example, the building for housing the compression and storage equipment required by Italian regulations increases the HRS investment costs by about 500,000 €. The RCS related cost increases were investigated in depth within task 3.2 of the NewBusFuel project [NBF – D3.3].

The harmonisation of RCS among European countries would reduce investment obstacles in Europe significantly.

Extend local air quality regulations and support bus operators during the transition

Imposing and enforcing stricter local air quality regulations for key air pollutants, particularly NOx and PM, in urban areas is a key policy driver for the advancement of clean urban public transport. This creates the need to use fuel cell, battery electric or other zero or very low emission buses in the operator's fleet to comply with such regulations and avoid financial penalties. Taking this approach across Europe would create a favourable policy and financial environment for zero emission bus technologies within a consistent framework. Introduction of a suitable regulatory framework should be strongly pursued at all political levels. At the same time, the bus operators can be supported during the required transitions, e.g. through financial and organisational resources.

4.3 Recommendations for H_2 infrastructure suppliers and the overall H_2 community

Improve current technologies and develop new solutions

Some of the components used in an HRS for refuelling hydrogen buses have not been tested under conditions where large fleets of buses have to be refuelled with appropriate quality hydrogen to meet operational needs of the bus operator. A number of the approaches and

components are based on relatively new technologies which are often produced in rather small volumes. This offers potential for (a) further improving the technical performance and (b) significantly reducing costs through higher production volumes.

Higher reliability and durability of individual HRS components, as well as the whole HRS is essential for bus operators to have confidence to move forward with this technology. Especially for the first large scale HRS that are implemented, it is essential to fully satisfy the bus operators' requirements on reliability and availability.

Similarly important is obtaining efficiency gains in all HRS components to achieve reductions of the OPEX, e.g. through reduced cost for electricity or natural gas.

Another relevant field of development are novel powertrain technologies that can be used in buses. One option is the combination of a high capacity high-voltage battery and the use of a fuel cell as range extender that allows the typical daily ranges that are required by bus operators [NBF – D3.2].

Develop suitable business models and contractual frameworks

The roll-out of a fuel cell bus fleet and the related installation and operation of an HRS is a complex business venture, usually involving multiple entities. All of them have individual interests and constraints that need to be considered in the chosen business model.

A number of commercial ownership models for electrolysers were investigated [NBF – D3.4]. Different owner and operator partnerships and joint ventures were developed as the participants improved their understanding of the local regulatory framework, especially with respect to the electricity price. In many instances these frameworks would otherwise not have been the first choice of the various parties.

Most bus operators were not willing to own and operate an HRS with on-site hydrogen production, and preferred a business partner or a newly created company to be responsible for this task. However operating an HRS which did not have on-site production, i.e. with delivered H_2, was a feasible option for many bus operators. The roles and responsibilities as well as the interfaces between the partners need to be defined clearly to avoid potential conflicts, or even gaps between responsibilities.

Mechanisms to ensure a fair risk and reward sharing are essential and need to be negotiated and integrated into the in the contractual framework. Also, partners making substantial investments need a satisfactory level of commercial protection by appropriate contract length and cancellation conditions. The development of promising business models is ongoing, especially as the regulatory framework for operating hydrogen facilities is still evolving. For this reason, more innovative business and commercialisation models need to be developed and tested in the future.

Review H_2 quality requirements for fuel cell buses

The commonly used specifications for the required hydrogen purity are challenging and require significant cost and effort to fulfil. There is no practical method of on-line sampling at the nozzle, and there are very few laboratories that are able to conduct an analysis of all the impurities to the specified tolerance, such as in SAE J2719.

Reducing this specifications would reduce the hydrogen cost. Some stakeholders consider the purity levels to be overly restrictive [eMobil BW], and are recommending a revision of the requirements. The task is to find an appropriate balance between protecting the fuel cells from impurities and excessive hydrogen purity and costs.

Commit to 350 bar technology

Some bus manufacturers have suggested possible benefits from using hydrogen at a pressure of 700 bar in fuel cell buses. It has been proposed that this would

provide benefits through mass production of the same components for both fuel cell passenger vehicles and buses, as well as for both types of HRS.

However, the NewBusFuel project as well as previous and on-going fuel cell bus projects such as CHIC, HyTransit or High V.LO-City demonstrated that the existing 350 bar technology already provides sufficient range for most bus routes today. Also the space constraints for H2 on-board storage in buses are less restrictive than for cars.

For a bus tank to be refuelled to a pressure of 700 bar, compressors with a higher capacity would need to be installed at the HRS along with pre-cooling. This would mean a higher energy demand and more importantly would increase the complexity of the HRS configuration which may diminish reliability.

This would increase the overall CAPEX and OPEX components of the overall hydrogen cost. Since low fuel cost is essential for the operation of high mileage vehicles, such as buses in public transport, the use of the 350 bar technology seems to be the more promising path for the roll out of fuel cell buses.

It is important for fuel cell buses to take the lead in the development of hydrogen infrastructure and to push the hydrogen fuel cell technology. Any uncertainty about the future pressure level in fuel cell buses is a barrier for the development of, and investment in, the technology and should be avoided. For this reason, it is strongly recommended that all efforts need to focus on the 350 bar technology in hydrogen fuel cell buses.

5. Further aspects supporting the commercialisation of hydrogen fuel cell buses

Additional issues that were identified within the NewBusFuel project which should receive further attention for improving the prospects of commercialisation of hydrogen fuel cell technologies in the future.

5

5. Further aspects supporting the commercialisation of hydrogen fuel cell buses

Some issues were identified within the NewBusFuel project which should receive further attention as they will likely improve the prospects of commercialisation of hydrogen fuel cell technologies in the future. One example is the current technical and procedural requirements for **measuring the H_2 quality and quantity during the refuelling process** [NBF – D4.2], [e-mobil BW].

Suitable and appropriate business models are essential for the deployment of hydrogen refuelling infrastructure. These need to be developed and investigated further beyond the scope of the NewBusFuel project. What are the **optimal contractual elements** that allow a fair sharing of risks, costs and revenues among all parties involved? What contractual framework supports the enforcement of the HRS operator to ensure a high refuelling availability?

These question deserve further investigation considering all different HRS concepts.

6. Summary

6

6. Summary

Within the NewBusFuel project 13 case studies were conducted for 12 different locations that had to take into account the individual boundary conditions and constraints of the individual projects. These comprise numerous challenges with respect to local conditions such as topography and climate, the situation of the bus operator, e.g. the existing bus depots, or the national regulatory framework. Despite the large variation of requirements, suitable HRS solutions could be developed for all case studies within NewBusFuel. This was achieved by **close cooperation between the bus operators and infrastructure suppliers** and represents the most important success of the NewBusFuel project. All solutions consider components and technologies that are available already today, which proves that there are no insurmountable technological limits related to hydrogen infrastructure.

Further, the economic performance of the hydrogen infrastructure could be improved significantly within the NewBusFuel project compared to earlier projects. Three case studies following different HRS technology concepts achieved the **hydrogen target cost** range of 4 – 6 €/kg H_2. For those case studies missing the target cost range, the most relevant reasons and obstacles were identified.

This document summarises the techno-economic characteristics of the developed case studies and derives lessons and recommendations from the experiences and insights that were generated among the project participants. They address the three main stakeholder groups and aim for further technical and economic improvements of the HRS technologies, and consequentially for improving the cost-competitiveness of operating hydrogen fuel cell buses.

The recommendations for **bus operators and transport agencies** are:

- Take into account the fundamental differences between H_2 and diesel refuelling
- Establish an appropriate initial fleet size
- Ensure infrastructure sizing and procurement is adequately linked to growing bus fleet
- Chose a modular HRS design
- Find the appropriate balance between reliability and cost
- Provide flexibility for the HRS design and its operation
- Put effort into reducing the OPEX
- Try to collaborate with other bus operators for the joint procurement of buses and HRS infrastructure
- Confirm the pathways of the procurement process

The recommendations for **policy makers** are:

- Reduce taxes and levies for electricity used for hydrogen production
- Set a regulatory framework that allows hydrogen to participate in grid balancing services
- Harmonise the RCS within the EU
- Extend local air quality regulations and support bus operators during the transition

The recommendations for **H_2 infrastructure supplier and the overall H_2 community** are:

- Improve current technologies and develop new solutions
- Develop suitable business models and contractual frameworks
- Review the H_2 quality requirements for fuel cell buses
- Commit to the 350 bar technology

The fact that the first NewBusFuel participants have completed the tendering process leading to the installation of an HRS underlines that the use of hydrogen buses and the related HRS infrastructure are viable for many locations and boundary conditions already today. Within the recently started MEHRLIN project seven HRS are installed for the refuelling of FC bus fleets in different locations across Europe and their technical, environmental, economic and regulatory performance is assessed. The next steps of action are clear and they are expected to lead to further improvements not only with respect to the techno-economic performance but also to the legal and regulatory framework. This will support H_2 buses to be competitive with conventional and other zero-emission bus technologies which will lead to less polluting and less carbon intense public transport in the future.

Illustration of a HRS with on-site electrolysis and a maximum daily capacity of about 6 t H_2/d, Source: WSW/Hydrogenics

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