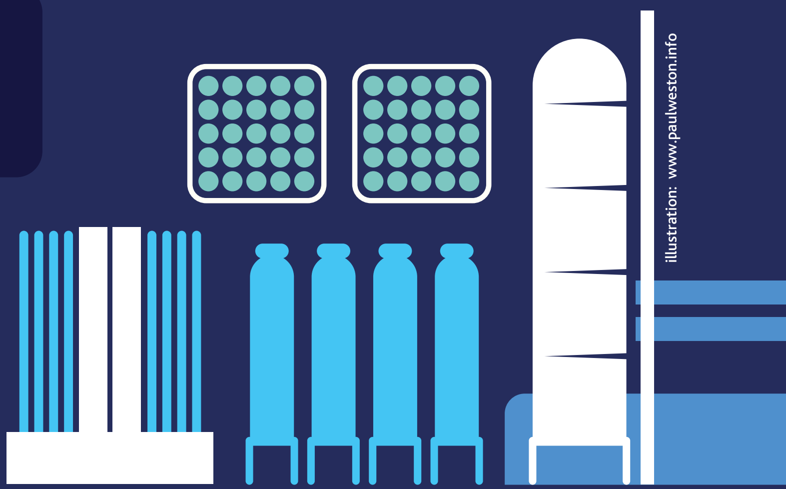
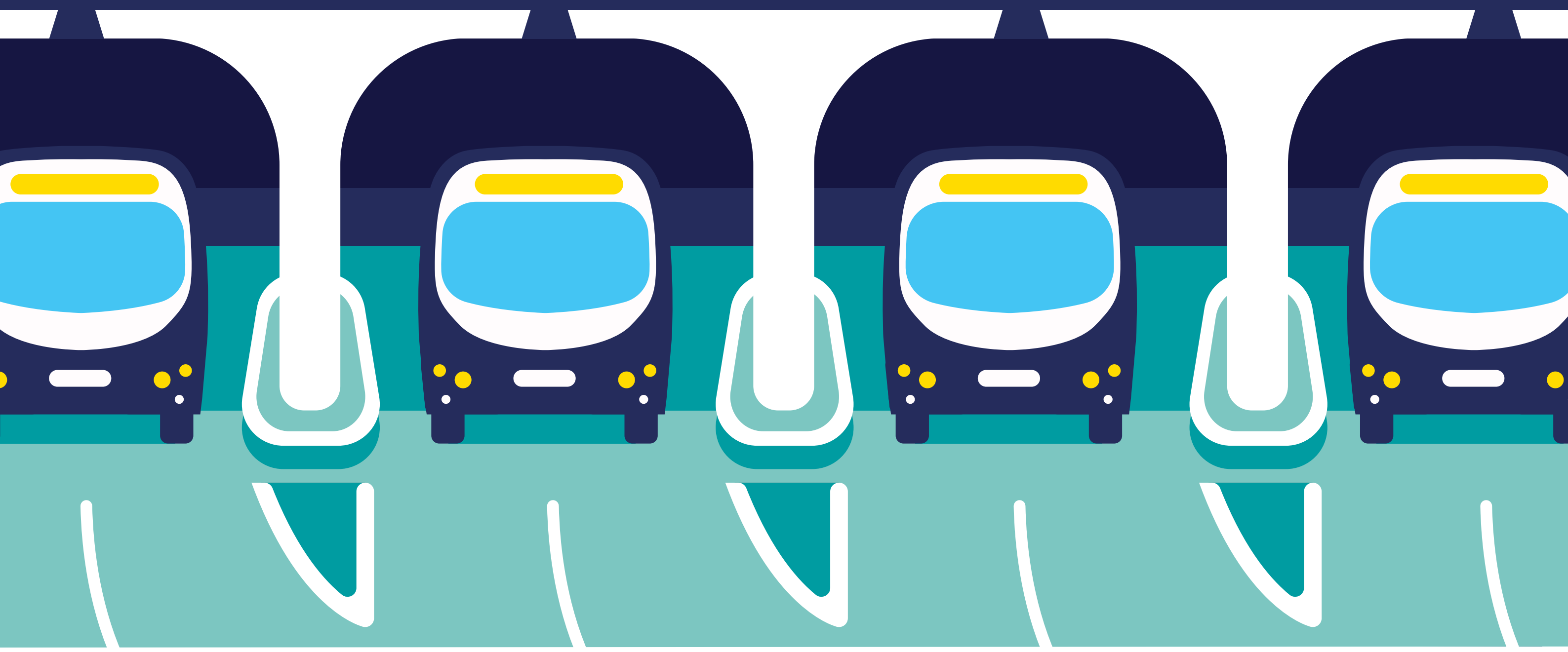
New Bus ReFuelling for European Hydrogen Bus Depots

Guidance Document on Large Scale Hydrogen Bus Refuelling





FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

NewBusFuel

New Bus ReFuelling for European Hydrogen Bus Depots

Guidance Document on Large Scale Hydrogen Bus Refuelling

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Authors

Dr. Benjamin Reuter
Dr. Michael Faltenbacher
Dr. Oliver Schuller
Nicole Whitehouse
Simon Whitehouse

Author printed in bold is the contact person for this document.

Phone: +49 – 711 – 341817 – 0

benjamin.reuter@thinkstep.com

thinkstep

thinkstep AG,
Hauptstr. 111-113,
70771 Leinfelden-Echterdingen,
Germany

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Abbreviations

a	year
bar	pressure unit
BEV	battery electric vehicle
CAPEX	capital expenditure
Cent	one-hundredth subdivision of one Euro
CHC	cryogenic hydrogen compressor
CHIC	fuel cell bus project co-funded by the FCH JU, 2010-2016 (Clean Hydrogen in European Cities)
CO	carbon monoxide
CO_2	carbon dioxide
CUTE	hydrogen fuel cell bus project co-funded by the EU, 2001 - 2006 (Clean Urban Transport for Europe)
d	day
€	Euro
ECTOS	fuel cell bus project by the INE (Icelandic New Energy)
EU	European Union
FC	fuel cells
FCH JU	Fuel Cell and Hydrogen Joint Undertaking
FMEA	failure mode and effect analysis
g	gram
GH2	gaseous hydrogen
GHG	greenhouse gas
GWh	gigawatt-hour
GWP	global warming potential
h	hour
H_2	hydrogen
H2O	water
HAZOP	hazard and operability study
HAZID	hazard identification study
HP	high pressure
HRS	hydrogen refuelling station
HyFLEET:CUTE	successor project of CUTE, co-funded by the EU, 2006 – 2009
ICE	internal combustion engine
ISO	international organization for standardization
kg	kilogram
km	kilometre
kV	kilovolt
kWh	kilowatt-hour
LCA	life cycle assessment
LH2	liquid hydrogen
LP	low pressure
LPG	liquefied petroleum gas
m	metre
m^2	metre square
MJ	megajoule
MP	medium pressure
MW	megawatt
MWh	megawatt-hour
NBF	New Bus reFuelling for European hydrogen bus depots project
NDA	non-disclosure-agreement
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)
non-ren.	non-renewable
NOx	mono-nitrogen oxides, i.e. nitric oxide and nitrogen dioxide
OPEX	operational expenditure
PED	primary energy demand
PEM	proton exchange membrane
PM	particulate matter
PSA	pressure swing adsorption
RCS	regulations, codes and standards
REX	range extender / range-extended
RFI	request for information
RFT	request for tenders
s	second
SAE	society of automotive engineers
SME	small and medium enterprises
SMR	steam methane reformer
STEP	hydrogen fuel cell bus project, 2001 – 2005 (sustainable transport energies for Perth)
t	ton

About the NewBusFuel Project

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 in the most theoretical fashion 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. Introduction

1

1. Introduction

1.1 Purpose of this document

The use of hydrogen fuel cell buses is a very promising approach to make public transportation more sustainable. Hydrogen fuel cell buses avoid the emission of local pollutants such as nitrogen oxides (NOx), i.e. nitric oxide and nitrogen dioxide, and particulate matter (PM), which are a cause for concern in urban areas for health and air quality impact. The buses also can reduce noise pollution and provide more flexibility with respect to the energy source used for fuel production. Depending on the chosen source, the total amount of greenhouse gas (GHG) emissions on a full life cycle basis caused by public transport can be reduced significantly. Because of these and other benefits, combined with their operational effectiveness, several activities have addressed the use of hydrogen buses, e.g. STEP (2001 – 2005), ECTOS (2001-2005), CUTE (2001-2006), HyFLEET:CUTE (2006-2009), CHIC (2010 – 2016).

The NewBusFuel project (2015-2017) is focussing on large scale hydrogen refuelling stations (HRS) that will be necessary for deploying a large number of fuel cell buses in a public bus fleet. The production of the hydrogen and the implementation of refuelling infrastructure are crucial points for the economic and reliable operation of H_2 buses.

This guidance document is created for project managers, in particular employees of a bus operator or transport agency, and diverse project management teams that are tasked with initiating the engineering design and implementation of an HRS for refuelling a hydrogen bus fleet. Since the development of an HRS is a complex task with numerous design options that pose several technical and organisational challenges, and since the ideal HRS is influenced by the goals, requirements and priorities of various stakeholders, support and guidance is needed for a successful implementation of H_2 powered FC buses. This is especially the case for entities that have little experience in the field of hydrogen bus and infrastructure technologies.

The intention of this guidance document is to make use of the knowledge and the experience created within the 13 case studies carried out within the NewBusFuel project, and disseminate it to other interested stakeholders. Besides the quantitative techno-economic information about particular components and complete HRS solutions, the document provides an organisational framework for effective project management that has been developed based on the experience of the NewBusFuel consortium.

In summary, this guidance document:

- Indicates key information on the technologies that can be used in an HRS
- Proposes a framework for initiating plans and implementing an HRS for a hydrogen bus fleet
- Provides advice for the stakeholder dialogue process and the related definition of the HRS specifications
- Helps to determine the goals, requirements and constraints imposed by the variety of stakeholders
- Helps to determine basic techno-economic and environmental parameters of the required HRS
- Contains suggestions for the dialogue process with suppliers and the related engineering design process
- Provides guidance on issuing an official request for tenders (RFT)

A further document, the ***High-Level Techno-Economic Project Summary Report*** [NBF – D4.3], contains an aggregated analysis of the case studies carried out within the NewBusFuel project with respect to technical and economic results. The aggregated analysis was used to develop the main recommendations, and to identify obstacles for the roll-out of hydrogen buses. The Summary Report details the necessary actions for different stakeholder groups to cost-effectively deploy a fuel cell bus fleet and related infrastructure across Europe.

1.2 Structure of this document

Section 2 of this guidance document describes all relevant modules of an HRS and explains the commonly used technologies for the necessary components of each module. Section 3 provides the proposed project framework for setting up an HRS, which was developed using the experience of the participants of the NewBusFuel project.

The subsequent sections follow the structure suggested by the proposed project framework: Section 4 addresses important preparations for the HRS project, such as an initial definition of the project goals and priorities.

Section 5 contains a variety of quantitative and qualitative information that helps in the determination of basic parameters of the HRS. The design studies that were carried out within the NewBusFuel project as well as other information sources are the basis of the provided techno-economic and environmental findings, such as the footprint of components or their cost.

Section 6 concentrates on the engagement with relevant stakeholders, which must be maintained throughout the entire HRS project. Section 7 addresses the definition of the HRS project in more detail including the goals, priorities and constraints of the project. The conversion of these into a functional specification sheet is discussed within Section 8. These specifications serve as a starting point for the dialogue with suppliers that is addressed in Section 9. The preparation of a request for tenders (RFT) is the topic of Section 10.

The list of references contains additional valuable sources of information and the various Annexes provide more detailed insights.

1.3 Other relevant sources of information

In addition to the main objectives of the NewBusFuel project, a number of other challenges relating to the deployment of a large-scale HRS have been addressed. These include:

- Constraints and requirements for bus operators
- European landscape of regulations, codes and standards (RCS)
- Electrolyser ownership and commercialisation models
- Strategies for demand growth and expansions
- Availability of the HRS and mechanisms for enforcement as well as strategies to ensure the required reliability of the refuelling infrastructure

A list of the public reports from the NewBusFuel project addressing these issues can be found in the list of references (see Section 12).

Useful information has been published by a number of other projects. These include trials of hydrogen buses and refuelling infrastructure in CHIC, HyFLEET:CUTE, CUTE, and ECTOS. Many hydrogen projects in Europe have been funded by the Fuel Cell and Hydrogen Joint Undertaking (FCH JU). A selection of relevant deliverables from these projects is also included in the list of references.

Further interesting documents and publications include the Multi-Annual Work Plan of the FCH JU [FCH JU – MAWP], the Study on development of water electrolysis in the EU [E4tech & EE], the study on fuel cell electric buses conducted by Roland Berger [RB – FC buses], the study on urban buses com-piled earlier by McKinsey & Company [McK – Urban buses], or the study about using hydrogen in the German railway service [NOW-A]. There are numerous of other interesting publications but the ones mentioned here serve as a good starting point for further literature research.

2. Background information on hydrogen refuelling stations (HRS) for buses

2

2. Background information on hydrogen refuelling stations (HRS) for buses

2.1 General information on HRS

Hydrogen refuelling stations (HRS) are used for transferring hydrogen from stationary H_2 storages to on-board vehicle storage tanks to be used as a fuel either in fuel cells (FC) or in internal combustion engines (ICE) for vehicle propulsion. Today, the use of fuel cells is the dominant technology in the hydrogen mobility sector, since their efficiency is significantly higher than that of ICEs, and hence the hydrogen consumption per kilometre is considerable lower [CHIC – Final brochure]. However, the requirements for dispensing hydrogen to a vehicle are similar for both powertrain technologies. Furthermore, the use of gaseous hydrogen dominates the bus sector.

During the refuelling process, gaseous hydrogen is dispensed to the vehicle storage tank until a maximum pressure is reached. This pressure threshold is defined by the vehicle storage tank and influenced by the ambient temperature and the temperature of the hydrogen contained in the vehicle tank. Depending on its volume, a storage tank can carry a certain amount of hydrogen, which determines the maximum range of the vehicle together with the efficiencies of the fuel cell and the total powertrain including all auxiliary systems. As the hydrogen is consumed in the fuel cell to produce electricity and water (H_2O), the pressure in the H_2 storage tank decreases.

Although hydrogen is the most abundant element in the universe, it is only present on earth within molecular compounds. Hence, it does not occur as an exploitable natural resource, unlike coal, crude oil or other fossil fuels, and no deposits exist from which hydrogen could be extracted. It needs to be produced in technical facilities before it can be used.

The hydrogen required for operating a bus fleet can be produced directly at the HRS where it is later dispensed to the vehicles. This is called **on-site production of H_2**. Other components of HRS are for storage, compression and dispensing hydrogen.

Hydrogen can also be delivered to the refuelling station from a production facility, which might be a large-scale hydrogen production plant, or a facility where hydrogen is produced as a by-product. Both cases are examples for **off-site production**.

If the production of hydrogen does not take place at the HRS but close to it, this is called **near-site production**.

2.1.1 (Technical) difference between HRS for cars and buses

The design and construction of hydrogen refuelling stations is not a completely new challenge since a growing number of HRS already exist in Europe and globally and some have been in operation for sev-eral years. Most of these HRS provide hydrogen to a relatively small number of passenger vehicles and/or buses. However, if an HRS is intended to fuel a bus fleet with a significant number of FC buses such as a full depot, this will require some special HRS design specifications.

Refuelling a large number of buses, typically with storage tank sizes of 30 – 50 kg of H_2 [CHIC – Final brochure], requires significantly more hydrogen than refuelling passenger vehicles that usually carry about 5 kg of H_2 [e-mobil BW]. Another important difference is the capability of buses to carry more weight and greater volumes. This means that the on-board hydrogen storage for buses commonly operates on a lower pressure level than the common pressure level for passenger cars. Two standard dispensing pressures have been adopted globally, 350 bar for buses and 700 bar for cars.

The lower pressure level (350 bar) provides several advantages. Firstly, it allows the use of lower specification and, in some cases less complex, components both for the bus and the HRS infrastructure. This reduces cost and increases overall reliability of the technology. Secondly, the hydrogen compression up to 350 bar requires less energy than the compression up to 700 bar. Furthermore, the available standards for hydrogen refuelling of passenger vehicles (SAE J2601) prescribes the precooling of hydrogen to -40°C when being refuelled above a certain fuelling speed to a 700 bar storage. This precooling, which requires additional equipment and energy, is not necessary for the refuelling of H_2 at 350 bar level.

The comparison described above reflects only the current situation. In future, potential mass production of fuel cell passengers vehicles equipped with 700 bar tanks could reduce the technical and economic advantages of 350 bar storage for buses [e-mobil BW]. However, 350 bar is the current state-of-the-art for H_2 buses and will be for the foreseeable future [NBF – D4.3].

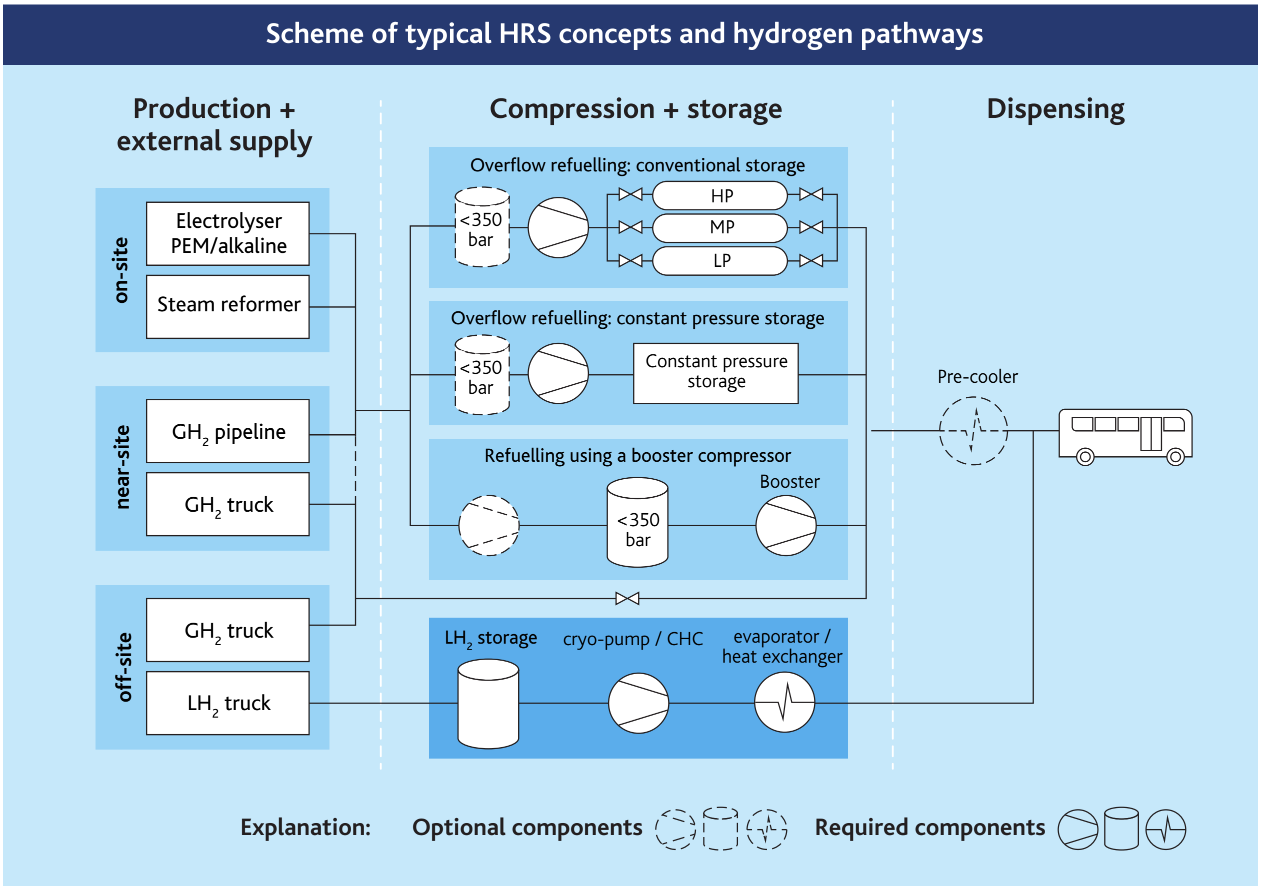


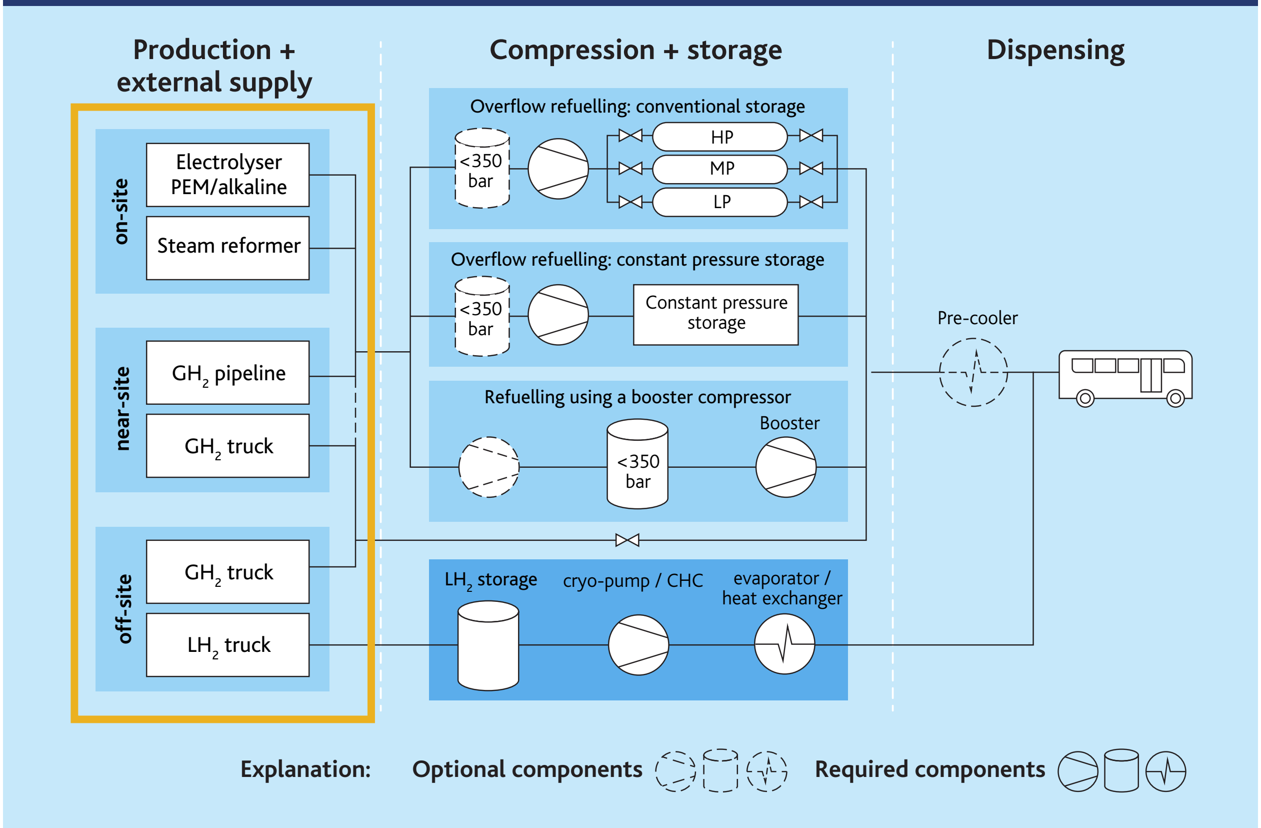
Figure 1 - Scheme of typical HRS concepts and hydrogen pathways

2.2 Modules of an HRS for buses

There are a range of different concepts available that are suitable for the overall HRS design, and various technologies to choose from that can be used for each of the necessary components. Providing detailed explanations for all of them is beyond the scope of this guidance document. Nevertheless, the four main modules that exist for all HRS systems will be described in more detail within the following subsections.

1. Hydrogen supply: on-site production of hydrogen or off-site production including H_2 delivery to the HRS
2. Compression: to reach the pressure level necessary for the vehicles
3. Storage: contains the hydrogen buffered at the HRS site
4. Dispensing: connection between the HRS and the buses to transfer hydrogen to the vehicles

Scheme of typical HRS concepts and hydrogen pathways



2.3 Description of all HRS modules

2.3.1 H_2 supply

As mentioned earlier, hydrogen is not a naturally occurring resource and needs to be produced in an appropriate form, quality and quantity before it can be refuelled and used in buses or other applications. Several technologies exist for the production of hydrogen. This can either take place on-site at the HRS or off-site.

On-site production

On-site hydrogen production generally uses either **electrolysis** or **steam reforming**. An electrolyser uses electricity and separates water into hydrogen and oxygen. In contrast, a steam reformer uses hydrocarbons, predominantly methane, and water vapour and produces hydrogen within a catalytic reaction (steam methane reformer – SMR).

Two different technologies are commonly used for the electrolysis of water: **alkaline electrolysers** and **proton membrane exchange (PEM) electrolysers**. Whereas the former is a proven technology with a long history, the latter has been developed to market maturity relatively recently. Both technologies have advantages for future infrastructure and both have been considered in the NewBusFuel studies.

Figure 2 - Illustration of a PEM electrolyser stack (left) [Siemens] and an alkaline electrolyser stack (right) Source: McPhy Energy

For hydrogen production to have a low carbon intensity or even be carbon-neutral, electricity from renewable sources needs to be used for electrolysis, or methane from biogas for steam reforming.

An important technological characteristic of the electrolysers, in contrast to a steam reformer, is their suitability to adjust quickly to load changes. This makes them suitable for additional uses, such as frequency control and other ancillary services for the electricity grid, which could introduce new revenue streams for the electrolyser owner/operator (see [E4tech & EE]). Furthermore, the efficiency of an electrolyser is higher at partial load due to the lower electric currents and lower resistive losses. Critical aspects such as energy efficiency and hydrogen production cost, are addressed in more detail in Section 5.

All types of on-site hydrogen production require certain connections and supplies. Since the electrolysis of water consumes a large amount of electricity, the grid connection needs to provide sufficient electric power, which, depending on the required H_2 capacity, will require a dedicated connection to the electric grid at minimum medium voltage level (e.g. 10 kV) (see Section 5.1.4 for more details). The methane that is converted in steam reformers is often taken from the natural gas grid or other hydrocarbon sources are used that are suitable for steam reforming, e.g. Liquefied Petroleum Gas – LPG. Both electrolysis and steam reforming require water that usually needs to be purified in a pre-treatment unit to meet the required water quality specifications.

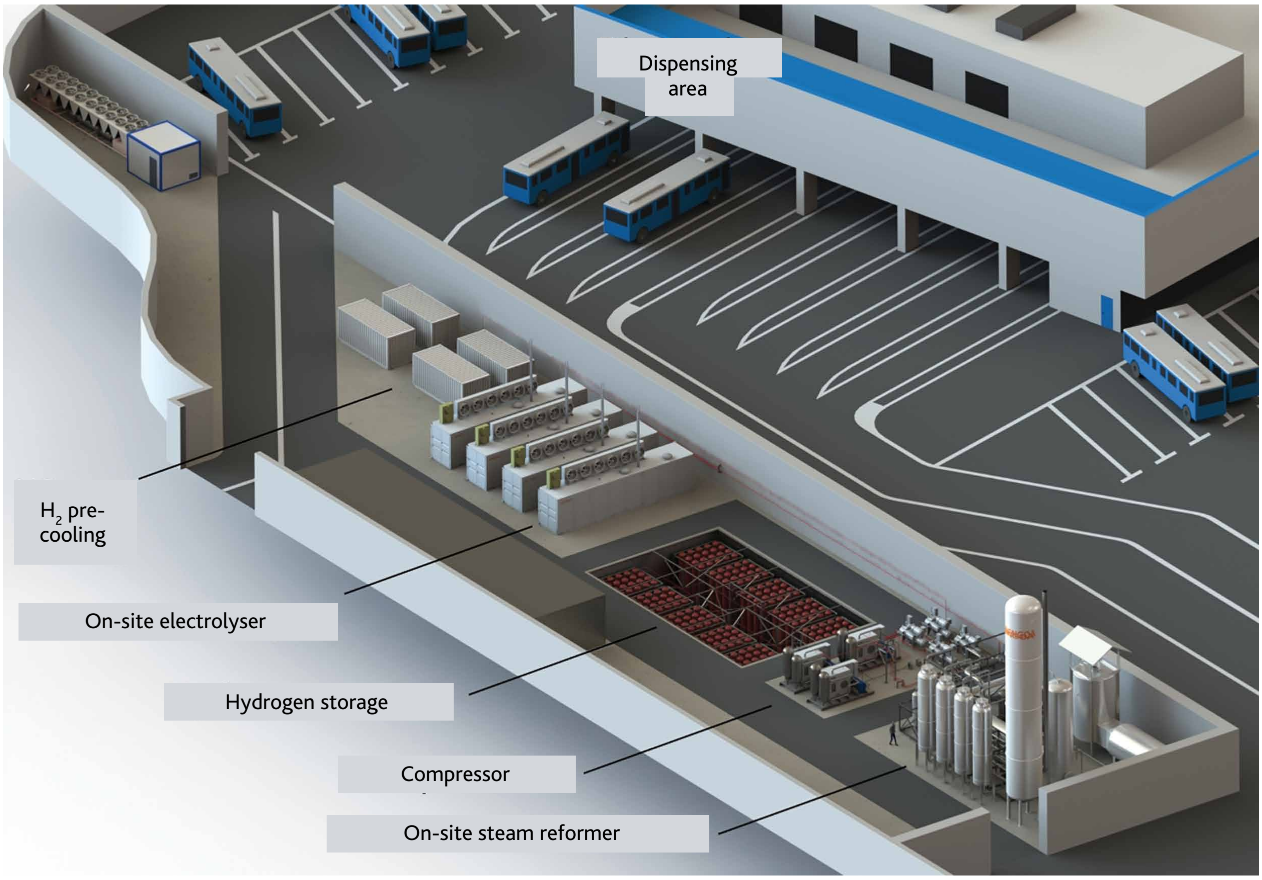


Figure 3 - Illustration of an HRS with both on-site electrolyser and on-site steam reformer (Source: Abengoa In-novación)

Off-site production and hydrogen delivery

Large-scale production facilities can also use either of these two production technologies. Usually, the efficiency of the hydrogen generation in large and centralized production facilities is higher than in decentralised on-site production, due to, for example, smaller energy consumption of auxiliary systems per hydrogen output.

Hydrogen can also be a by-product in industrial processes. A frequent example is the chlor-alkali process, which is used for chlorine production and which produces hydrogen as a by-product. Another common source is the partial oxidation or thermal cracking of hydrocarbons contained in crude oil which takes place in refineries.

Figure 4 - Industrial steam reformer, Source: BASF SE

There are other production methods currently being developed but they are not yet mature technologies, e.g. high temperature electrolysers and gasification processes or biological hydrogen production using algae. They will not be addressed within this document since they are not relevant for HRS designs today or in the near future.

Depending on the origin of hydrogen and the sources of the electricity, methane, and other feedstocks, the cost and the environmental performance of the hydrogen may vary significantly.

Hydrogen delivery

If the hydrogen is produced off-site, it needs to be delivered to the HRS. Delivery usually occurs via pipeline or via truck transport, depending on the distance between H_2 production site and HRS, and the amount of hydrogen to be delivered. A pipeline can carry high volumes of hydrogen but construction is very expensive, especially in urban areas. Hydrogen delivered by truck needs to be differentiated further into gaseous hydrogen delivery and liquid hydrogen delivery.

Gaseous hydrogen (GH_2)) is transported in tube trailers which can contain hydrogen at different pressure levels. The higher the pressure of the hydrogen, the more hydrogen can be delivered in each load (see Table 1). Common pressure levels for tube trailers that are currently used range between 200 bar and 500 bar containing several hundred kg and up to 1000 kg of hydrogen respectively. Tube trailers with higher pressure levels may be advantageous but no such solutions are on the market yet.

Hydrogen requires even less space if it is transported as **liquid hydrogen (LH_2)** which increases the amount of hydrogen that can be transported in one trailer. In order to reach the liquid state, hydrogen needs to be cooled down to or below its boiling point (-253°C at ambient pressure) and this consumes a significant amount of energy. With current technology this is about a third of the hydrogen's energy content, approximately 11 kWh/kg H_2 (see also [e-mobil BW], [US DoE H2A A], [FCH JU – MAWP]). Several technologies are currently being investigated for reducing the energy demand to a target of 6 kWh/kg H_2 [Cardella]. Highly insulated trailer tanks are used to deliver the LH_2 from a hydrogen liquefaction plant to the HRS. Currently only a few liquefaction plants exist in Europe, but more plants are expected to be built if the demand for LH_2 increases in future. Due to the higher density of liquid hydrogen (see Table 1) more than 3 tonnes of H_2 can be transported in one truck trailer. If the LH_2 warms up and reaches its boiling temperature, it evaporates and the gaseous hydrogen increases the pressure inside the storage tank. If the pressure exceeds the maximum pressure of the container, the gaseous hydrogen needs to be vented (boil-off losses). However, since highly insulated trailers are used, boil-off losses are minimised during LH_2 delivery. Depending on the local RCS, the use of LH_2 may require larger safety distances compared to handling GH_2.

Figure 5 - High pressure tube trailer for GH2 (left) [Air Products] and LH2 trailer (right) [Tamhankar]

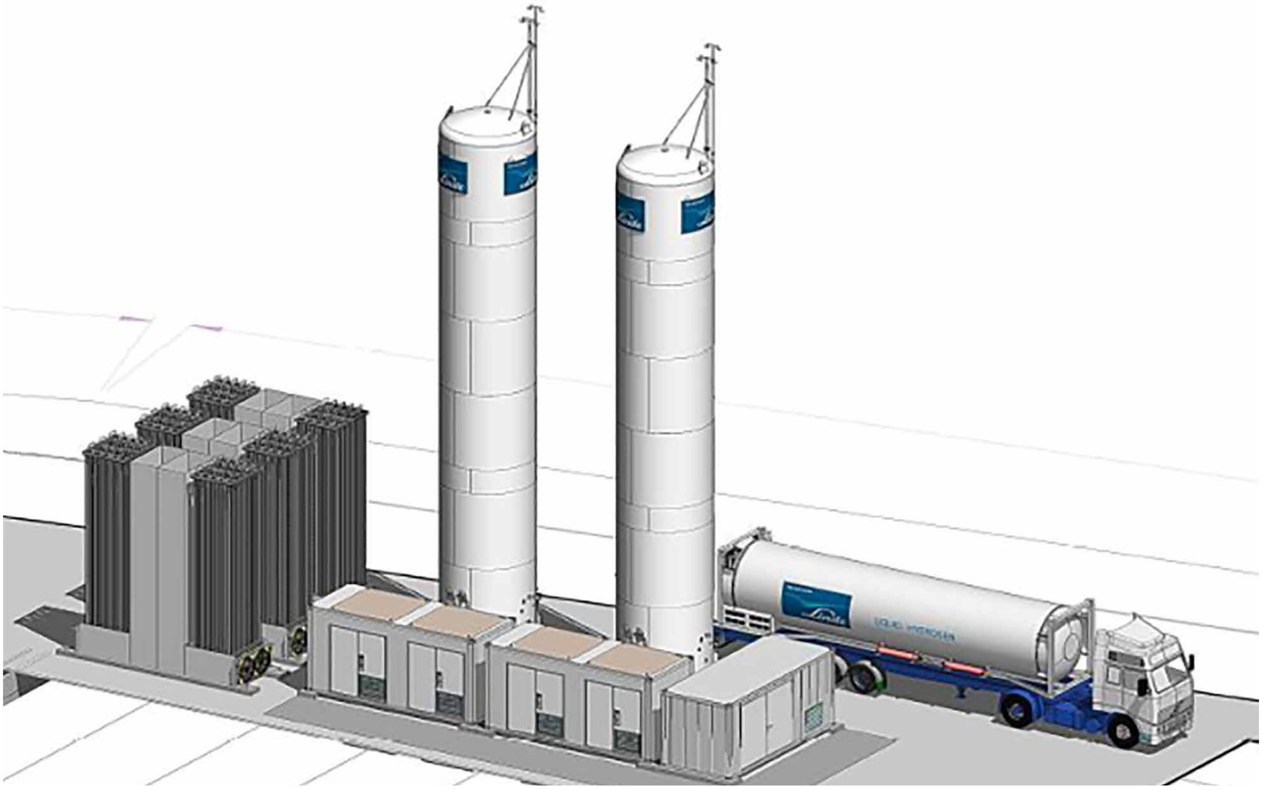


Figure 6 - 3D illustration of an HRS with LH2 delivery without dispensing area (daily capacity of 2.25 t H_2/d), Source: Linde

Mass of hydrogen and energy per m³

Pressure level	Mass contained in 1m³	Energy contained in 1m³
1 bar (0.1 MPa), 25°C	0.081 kg H_2	10 MJ (2.7 kWh)
100 bar, 25°C	7.67 kg H_2	922 MJ (256 kWh)
300 bar, 25°C	20.54 kg H_2	2,469 MJ (686 kWh)
500 bar, 25°C	30.81 kg H_2	3,704 MJ (1,029 kWh)
Liquid hydrogen (at boiling point)	70.8 kg H_2	8,501 MJ (2,361 kWh)

Table 1 - Mass of hydrogen and energy per m³ according to [US DoE]

Since more hydrogen can be delivered in one LH2 trailer, the delivery cost of LH2 is usually below the delivery cost of GH2. Nevertheless, the production cost of LH2 is above that of GH2 due to the liquefaction step. For this reason, the production and delivery of gaseous hydrogen is economically more reasonable only up to a certain delivery distance, whereas the production and delivery of LH2 is economically advantageous beyond this threshold. Generally, hydrogen delivery via pipeline is only feasible for short distances.

For a small depot size, the study ***Urban buses: alternative powertrains for Europe*** [McK – Urban buses] determines LH2 delivery to be economically beneficial for distances above 275 km according to the individual assumptions and taking into account cost effects on the HRS investment. The study reports that using a pipeline for the delivery leads to lower distribution costs only for short distances below 5 km.

Impurities and H_2 quality

Hydrogen from any of the available production processes will include some impurities which originate from either the source inputs, or the production processes. These can be separated in three groups [e mobil BW]:

1. Substances which do not affect the lifetime of the fuel cell but only reduce the short-term performance temporarily, such as nitrogen, water vapour, and noble gases.
2. Catalyst poisoning substances, e.g. carbon monoxide (CO) and ammonia, which lead to premature performance reduction of the fuel cell.
3. Substances which induce membrane damages, e.g. sulphur containing compounds and acids that lead to fuel cell failure and the need to replace the fuel cell stack. More information on the fuel cell technology and its subcomponents can be found in different sources.

Hydrogen produced by a PEM electrolyser contains only water vapour and maybe oxygen as impuri-ties, the gas produced in an alkaline electrolyser may also contain potassium hydroxide (caustic pot-ash – KOH) and possibly nitrogen from rinsing processes. Hydrogen from the reforming of natural gas might be accompanied by CO, CO_2, and sulphur-containing compounds [e mobil BW].

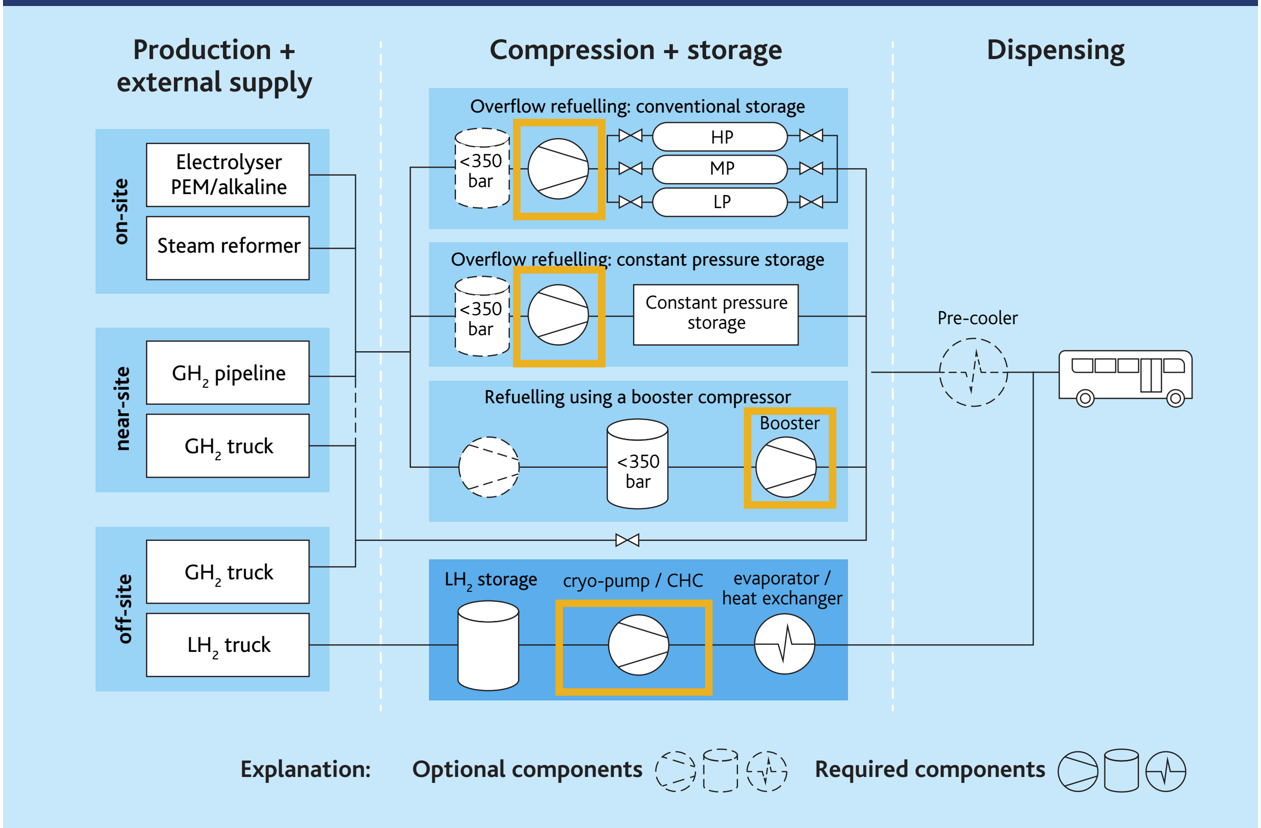
In general, the manufacturers of fuel cell hydrogen buses specify a particular purity level for the hy-drogen.

Several concepts for specifying H_2 purity exist, e.g. both the **ISO 14687-2** and the **SAE J2719** specify hydrogen fuel. The latter sets maximum concentrations for several substances, e.g. 5 ppm water, 2 ppm CHx, 2 ppm CO_2, 0.2 ppm CO [e-mobil BW]. Some concentration thresholds specified in the SAE J2719 are considered to be too low for measurement which makes a monitoring of the H_2 quality at the HRS according to this quality level almost impossible and also very costly.

Another common concept for specifying H_2 purity exists. "**Hydrogen 5.0**" designates hydrogen with a purity of 99.999 %, whereas "Hydrogen 3.0" has a lower purity of 99.9 % and "Hydrogen 6.0" is characterized by a purity of 99.9999 %. Besides the overall purity, thresholds exist for certain substances: the sum of CO and CO_2 in Hydrogen 3.0 for example shall not exceed 2 vol. ppm and the hydrocarbons in Hydrogen 5.0 are below 0.5 vol ppm.

Due to their negative effects, impurity concentrations need to be reduced below the levels required by the fuel cell system using purification equipment. Oxygen and water vapour are removed in DeOxo-Dryers which convert oxygen to water vapour in a first step, and then remove the vapour in a subsequent step. If the hydrogen is produced in a steam reformer, usually pressure swing adsorption (PSA) is used to remove any impurities from the hydrogen stream.

Scheme of typical HRS concepts and hydrogen pathways



2.3.2 Compression

A compression unit is required for almost all HRS designs. If the hydrogen is produced on-site in an electrolyser or steam reformer, its pressure needs to be increased in order to be refuelled into the buses' storage tanks. If GH2 is delivered at a high pressure level which is above the pressure in the HRS storage, **overflow filling** induced by the pressure difference can be used without a compressor for transferring H_2 from the truck trailer into the storage tanks of the HRS. However, hydrogen can only overflow until the pressure level in the receiving storage tank is similar to the pressure in the releasing storage tank. For further emptying, e.g. of a tube trailer and for transferring more hydrogen into a stationary HRS storage or into the vehicle tanks, a compressor is required.

If the HRS receives hydrogen in trailers at pressures above the target pressure within the bus tanks, the delivered tube trailers can be connected to the buses directly, which makes the use of an on-site compressor unnecessary if certain storage overcapacities are accepted (see the concept of overflow filling from a cascade storage in Section 2.3.3).

In general, two different types of compressors and their related operations can be differentiated: common compressors and booster compressors. **Common compressors** run continuously, whereas **booster compressors** are used only on demand, i.e. during the refuelling of vehicles.

Besides these two types, a number of different compressor technologies exist: **Reciprocating compressors** use a piston which is moved by a hydraulic oil or compressed air. They usually accept increased wear and tear of the seals and do not use lubricants in order to avoid impurities in the hydrogen. **Diaphragm compressors** use a membrane which separates the hydrogen from all mechanical parts to avoid problems with the sealing wear.

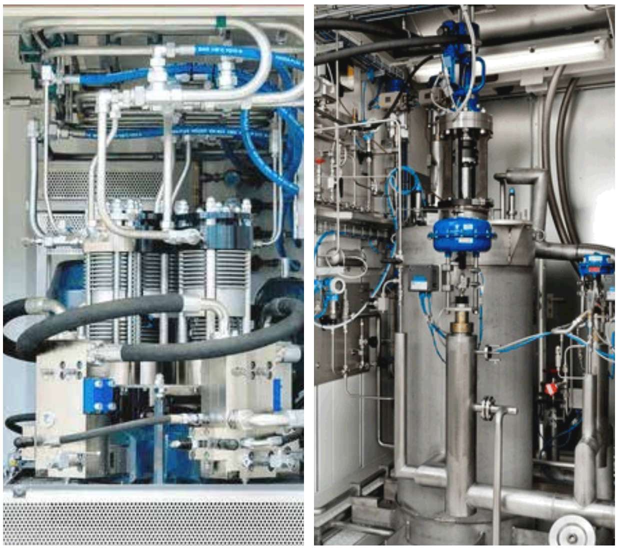


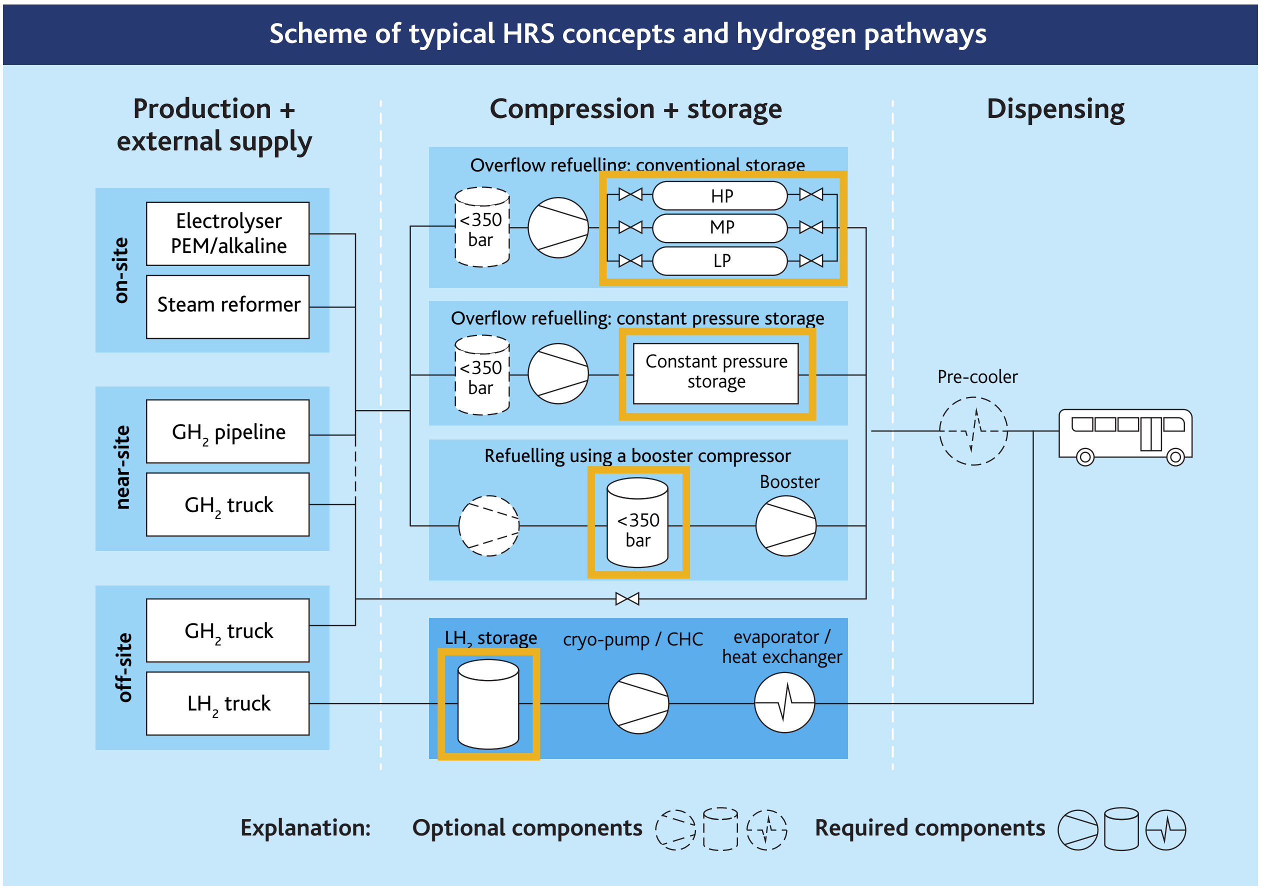
Figure 7 - Ionic compressor (left) and cryo-pump (right), Source: Linde

The use of an **ionic liquid piston compresso**r, which uses an ionic liquid that is insoluble in hydrogen, allows the removal of further seals, bearings and other moving parts with the aim of minimising the risk of hydrogen contamination, increasing the service life and reducing maintenance and energy costs [e-mobil BW].

If the hydrogen is used in liquid state, **cryo-pumps** or **cryogenic hydrogen compressors (CHC)** are used for increasing the hydrogen pressure (see Figure 7 (right) and Figure 8). These are usually more compact due to a larger hydrogen throughput at comparable size and work more efficiently than compressors for gaseous hydrogen. They also allow for direct refuelling of the hydrogen without the need of a medium and high pressure storage. In case a CHC is used, a certain share of gaseous hydrogen (e.g. from boil-off effects) can be included in the LH2 stream without causing problems in the compression unit [e-mobil BW].

Figure 8 - Cryogenic hydrogen compressor (CHC), Source: Air Products

Since compressors are very expensive components of an HRS, several new technologies, such as electrochemical compressors, are under development. However, they are in an early stage of development and not yet ready to be used in an HRS as they have not been considered within the studies of the NewBusFuel project.



2.3.3 Hydrogen storage

Hydrogen storage is necessary to balance the hydrogen supply, both from on-site or off-site production, and the hydrogen demand. The amount of stored hydrogen depends on a variety of parameters, such as the requirements for refuelling reliability and the redundancy concept.

As with hydrogen tube trailers, the size of a storage decreases as gaseous hydrogen is stored at higher pressure levels. Usually, four different types of hydrogen tanks are differentiated (Type I – IV) that are made from different materials - pure metal, metal overwrapped with fibre material, fibre-metal composite, and fibre-plastic composite. Each type can withstand different pressure levels and consequently different costs exist which generally increase with the pressure level and the use of a lighter material from Type I to IV.

Often, multiple storages are used within a HRS, as indicated in the figure above, including any optional storage tanks. Since they are often operated at different pressure levels, they are differentiated according to those pressure levels, e.g. low, medium, and high pressure (LP, MP, HP). These must not be confused with different pressure banks within one storage unit (especially within cascade storages, see below). Also note that depending on whether the HRS is used for fuelling cars or buses, the term "high pressure" might indicate a different pressure level, since the pressure level in passenger vehicles is higher than that of buses (700 bar vs. 350 bar, see Section 2.1.1).

Many HRS use their gaseous hydrogen storage as a **cascade storage** which uses overflow filling from different **pressure banks** for refuelling the buses. This concept requires that the hydrogen is stored at a pressure level above the final pressure in the vehicle (i.e. 350 bars for buses) at least in the high pressure bank of the storage. This means that the hydrogen can be transferred from the stationary storage tank into the bus storage tank by the simple opening of a valve until the final pressure in the bus is reached by overflow and without using a compressor.

As mentioned, **one such storage system** is subdivided into **several storage banks** with different pressure levels (see Figure 9). An empty bus storage tank is first refuelled from the LP storage bank until the flow of hydrogen starts to slow due to a decreasing pressure difference between LP storage bank and bus storage tank. By switching valves the MP storage bank is connected to the bus tank and continues the refuelling process which is completed by the HP bank. This consecutive use of multiple storage banks with (potentially) different pressure levels is the reason why this practice is called **cascade refuelling**.

It is important to keep in mind that for overflow filling not all H_2 contained in the storage banks can be used, since the pressure, at least in the HP storage bank, needs to be above the final pressure in the vehicle at all times of the refuelling process. Hence, a certain amount of hydrogen will remain in the HP bank, and usually also in the MP and LP banks, in order to keep the storage pressure above the necessary pressure levels. Due to this hydrogen, which cannot be used for refuelling, the installed and the useable hydrogen capacity need to be differentiated when this storage and refuelling concept is chosen.

Scheme of a cascade storage with three pressure banks (HP, MP, LP)

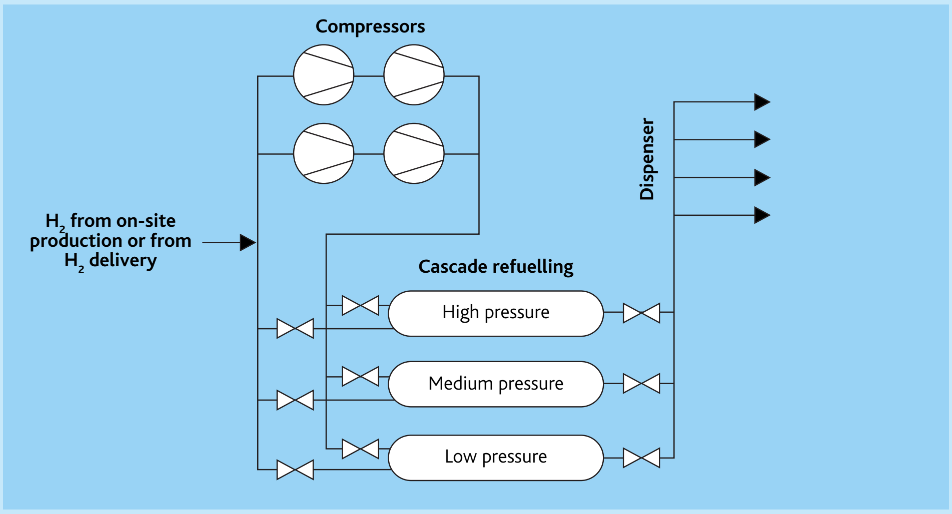


Figure 9 - Scheme of a cascade storage with three pressure banks (HP, MP, LP) and compressors to restore the requried pressure levels in each bank

Further, the lifetime of a storage tank is limited by a maximum number of pressure load changes. For increasing the lifetime of the hydrogen storage, additional overcapacities may be installed in order to reduce the pressure load variation within the storage.

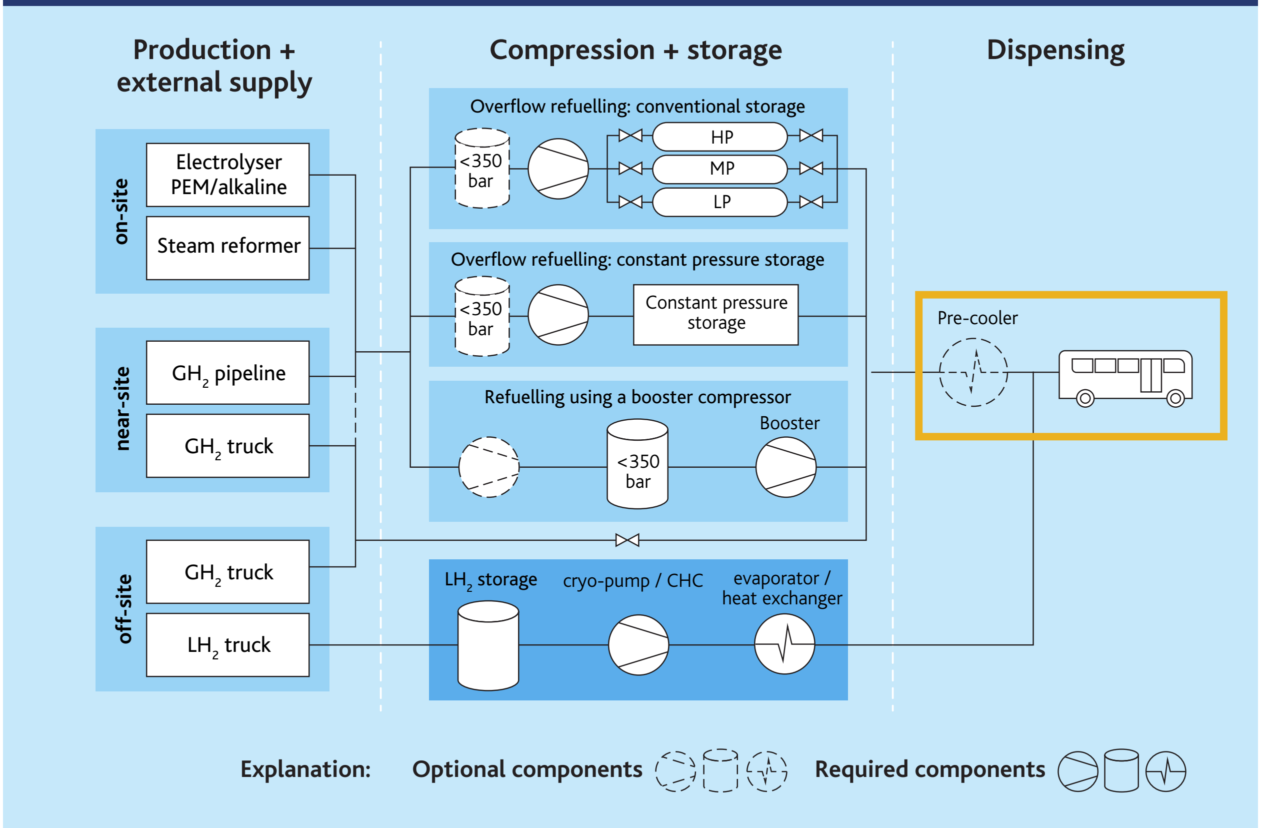
Another gaseous hydrogen storage concept that has been developed recently, is the so-called **constant pressure storage**. This storage combines a gaseous hydrogen storage and a hydraulic unit for providing hydrogen at a constant pressure level that is suitable for overflow refuelling. Such a technology can use almost the entire amount of hydrogen in the storage and only very small storage overcapacities are necessary, which usually leads to considerable reductions in the necessary footprint. Nevertheless, the hydraulic unit requires some additional space and consumes electricity to constantly provide the hydrogen at the desired pressure level.

In contrast to overflow refuelling, the pressure level in the HRS storage can be below the pressure level in the buses, if a **booster compressor** is used for the refuelling process. Since a booster compressor is usually only used during the refuelling process, it needs to achieve higher mass flows than a (nearly) continuously running common compressor.

If LH2 is delivered to the HRS, the hydrogen needs to be stored in a highly insulated **LH2 storage tank** to maintain the required low temperature. Since the heat flow into the storage cannot be avoided completely, a small proportion of the liquid hydrogen in the storage may eventually reach its boiling point and become gaseous hydrogen. Literature values give estimates in the range of 0.5% of the H_2 contained in the storage per day (see [e-mobil BW], [NOW-A]), which can be expected to be even lower for the large hydrogen throughput at an HRS for the refuelling of bus fleets. Gaseous hydrogen from boil-off and liquid hydrogen are kept in the same LH2 storage tank up to a certain maximum pressure. If the pressure exceeds this limit, the gaseous hydrogen needs to be removed from the LH2 storage tank. It may be used for energy production on-site or it can be stored in a separate storage tank for gaseous hydrogen and later added to the LH2 stream for refuelling the vehicles in case a CHC is used. If the GH2 is vented into the atmosphere, the hydrogen is lost as boil-off. By using an appropriate design and operation strategy for the HRS, actual boil-off losses can be avoided completely.

To make use of the pressure level of GH2 in tube trailers, especially when stored at pressures above 300 bar, the parked tube trailer is usually integrated into the overall storage system of the HRS. If the hydrogen is delivered as LH2 it is usually just connected for refilling the stationary LH2 storage tank. The transfer of the complete LH2 trailer with 3 – 3.5 t H_2 requires a few hours.

Scheme of typical HRS concepts and hydrogen pathways



2.3.4 Dispenser

The international standard ISO 17268:2012 (as well as SAE J2600) defines the **connection device** for the refuelling of hydrogen land vehicles. It applies to different working pressures and includes the high flow refuelling of commercial vehicles at 350 bar.

Besides the dispensing connector, the **refuelling process** is also standardised. SAE J2601 addresses the refuelling of light duty vehicles, **SAE J2601-2** refers to heavy duty vehicles (amount of refuelled hydrogen above 10 kg) and SAE J2601-3 addresses fork lifts. The protocol for passenger vehicles comprises refuelling with and without communication between the dispenser and the vehicle tank and it sets different maximum fuelling speeds depending on a potential pre-cooling strategy. SAE J2601-2 recommends SAE J2799 as the communication protocol. It differentiates between slow-, normal-, and fast-fuelling, the latter being limited to 120 g/s (7.2 kg/min). Some companies have also developed their own refuelling protocols to provide a safe and fast refuelling process.

If LH2 is delivered and stored at the HRS, it has to pass through a combined evaporator/heat exchanger before reaching the dispenser. The hydrogen changes from the liquid into gaseous hydrogen state and is warmed up in the evaporator/heat exchanger to a temperature that complies with the refuelling protocol. The combined evaporator/heat exchanger unit can be a passive or active component, i.e. using active fans or heating devices to support the heating process. Since the hydrogen is conditioned with respect to temperature but also pressure, this element is often associated with the compression section of an HRS.

If, in contrast, pre-cooling is necessary before refuelling, e.g. due to a high pressure level and the desired refuelling speed as applied for passenger vehicles, the hydrogen needs to be cooled down before reaching the dispenser. This usually causes additional energy consumption during the refuelling process and adds complexity to the HRS.

Figure 10 - Refuelling a fuel cell bus [RVK, CHIC – Final brochure]

Measuring the hydrogen mass flow with high accuracy is currently still challenging and has been addressed in various previous R&D activities. A discussion on different technologies for measuring the hydrogen flow, and the current regulations in Europe are discussed in Deliverable 1.2 of the CHIC Project [CHIC – D1.2]. However, in contrast to business-to-consumer activities such as the refuelling of passenger vehicles, this issue may be of less relevance for business to business relations depending on the chosen business model. For hydrogen delivered to the HRS, for instance, the mass of the delivered H_2 can be determined by weighing the delivery truck as a whole.

2.4 Differences from diesel refuelling stations

TAs the previous sections already indicated, there are several fundamental differences between refuelling diesel or hydrogen to buses. The infrastructure of an HRS is significantly more complex and more expensive than that of a diesel refuelling station. The space required by the compression unit and the storage of an HRS may be significant, which unlike diesel is usually not located underground due to safety and accessibility reasons. There is also the difference between the handling requirements of the liquid diesel and gaseous hydrogen.

Furthermore, hydrogen does not occur as a natural resource and its supply structure is not as developed as for diesel and other petroleum products. For this reason, either it needs to be delivered from an established supplier of GH2 or as LH2, or it needs to be produced on-site or near-site.

Based on all these differences, the approach for planning and setting up an HRS is different from that for a diesel refuelling station. In many aspects, the planning of the HRS requires a way of thinking that is different from that which has been used for diesel. The fact that most technologies for HRS components are still maturing developments and will remain so at least within the near future, requires some caution. However these issues are manageable by applying proper HRS designs and project planning and management processes.

The following sections detail the experiences and insights generated within the NewBusFuel project and provide the basis to facilitate an efficient approach to and successful realisation of the HRS project.

3. Proposed framework for an HRS project

3

3. Proposed framework for an HRS project

Many hydrogen bus projects have been conducted worldwide, ranging from activities in Canada and the United States, Iceland and the countries of the European Union, to the operation of hydrogen buses in Asia and Australia. Although the intentions of these projects might be similar, individual operation of hydrogen buses, hydrogen supply and design of the refuelling infrastructure vary significantly. This can be related to different climate and topography among the locations as well as specific operational regimes, and the size of the fleet that needs to be regularly refuelled.

Further important influencing factors are the availability requirements for the HRS and the achievable costs of H_2 which depend largely on the local price of energy and local conditions such as the distance to nearby H_2 sources. From an environmental perspective, access to cheap renewable energy is especially important. The individual regulatory circumstances, locally active industries, different levels of political and financial support as well as different levels of experience with hydrogen technologies increase the possible variations among hydrogen projects.

Due to these individual particularities, there is no "ideal procedure" that should be applied for initiating a project to deploy an HRS for bus refuelling. However, as this guidance document aims to provide as much support as possible for the start of an HRS project, a proposed framework was developed, refined and confirmed by the NewBusFuel consortium.

Deploying an HRS will require a project management team due to the wide range of skills and tasks involved. Special external technical and/or legal advice may also be integrated into the project team and that this seemed appropriate to many of the project participants within NewBusFuel.

Figure 11 illustrates the proposed framework developed for initiating an HRS project. Each box represents a different set of tasks, which may be interrelated.

Before starting with the actual project, some preparations have to be conducted which are represented in box I. After these, the basic parameters need to be determined for the HRS (box II). Even though some stakeholders might have been integrated in the project at this stage already, others such as the city council or neighbours might still have to be integrated or consulted for discussing the results of the basic parameters related to the HRS design.

Maintaining a stakeholder dialogue is a continuous process throughout a project, therefore box III is relevant to the entire project implementation. Based on the basic parameters, the HRS project needs to be defined further with all relevant stakeholders. This addresses the overall goals of the project, but also includes setting priorities between potentially conflicting targets, such as low cost versus green hydrogen. Other constraints also need to be identified such as the maximum HRS footprint due to space constraints (box IV).

Based on the project definition, a functional specification sheet can be compiled (box V) that includes all relevant and critical aspects, such as the security of supply, environmental characteristics, constraints of the HRS footprint due to space limitations at the depot,
maximum costs and alike. Such a specification sheet is an ideal starting point for the dialogue with potential suppliers (box VI), since it contains all relevant information about the project. The suppliers might be invited through
a request for information (RFI) and can propose customized solutions. These can be assessed among all stakeholders and further refined and optimized together with the suppliers.

If the suppliers cannot provide a satisfactory solution, the requirements and specifications may need to be revised by the project consortium (back to box IV), but always without compromising on safety related aspects. In contrast, if promising solutions are found, the final specifications can be defined and a binding request for tenders can be issued (box VII).

All the tasks of the proposed project framework are addressed and described in detail within the following sections of this document.

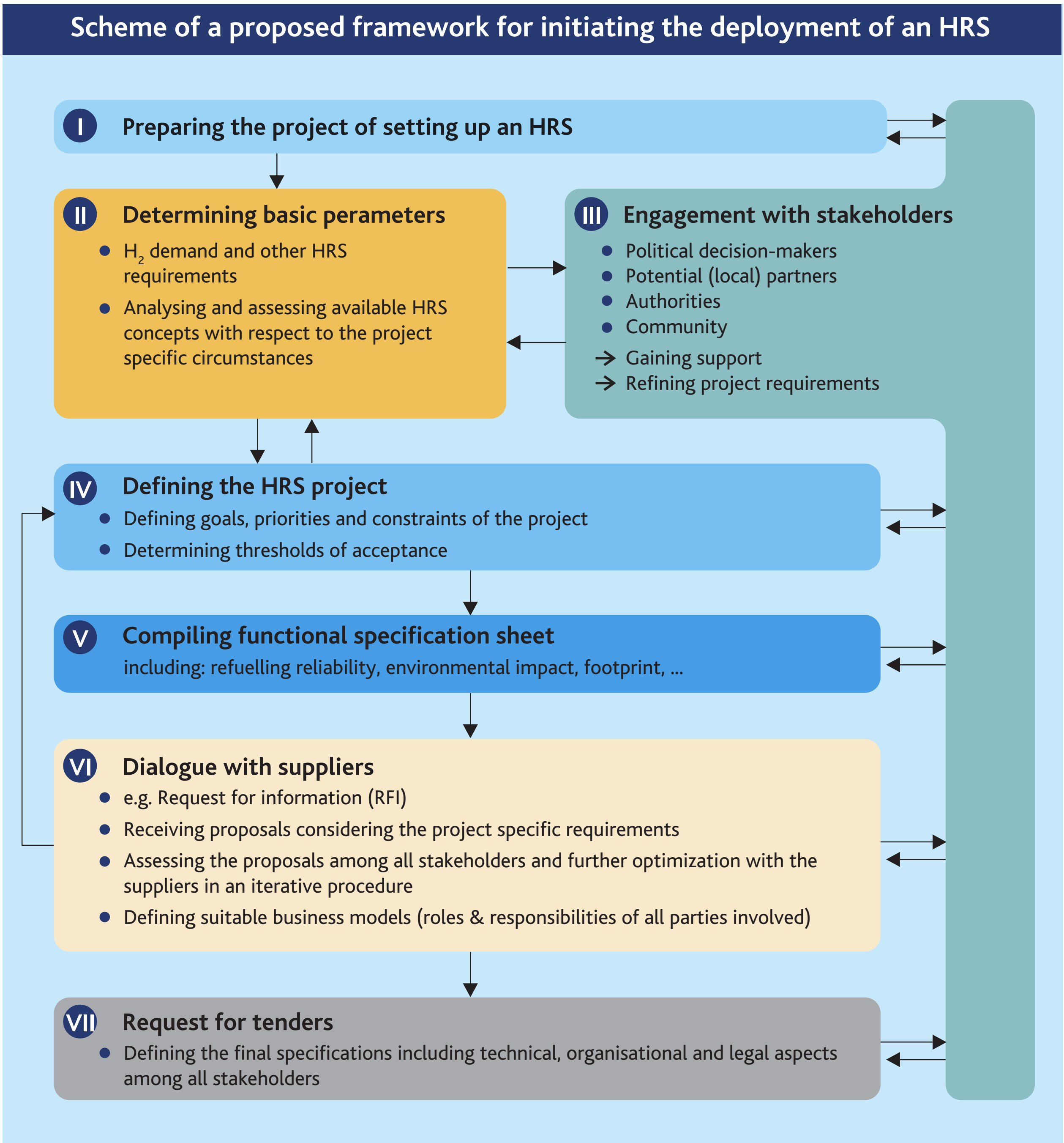


Figure 11 - Scheme of a proposed framework for initiating the deployment of an HRS

4. Preparation for setting up an HRS

Box I in the proposed project framework, see Figure 11 on page 43

4

4. Preparation for setting up an HRS

A prerequisite for developing a hydrogen bus fleet and the related considerations about the HRS design is a sound knowledge of the available hydrogen bus technologies and the related advantages and disadvantages. This has been assessed in various previous and ongoing projects, e.g. CHIC, High V.LO-City, and since several hydrogen bus models from different manufacturers are currently on the market, this will not be addressed within this guidance document. However, it is important that the advantages, for example, zero tailpipe emissions, are attractive attributes for potential operators and that the disadvantages, especially the currently high cost compared with diesel buses, are within the limits of acceptance. Information on these differences between conventional diesel buses and H_2 buses can be found in the literature mentioned in Section 1.

Defining clear **project goals and priorities** is essential to any successful HRS deployment. The definitions can provide a useful guideline for any issues that arise, and to support decisions that need to be made throughout the project. It also represents a point of orientation for all stakeholders involved in the project, since it summarises a common understanding that ideally all stakeholders have agreed upon. For this reason, the definition of the project goals and priorities **needs to be reassessed regularly** during the course of the project, for example when new stakeholders are introduced into the project. The goals and priorities also need to be revised when the boundary conditions change and new aspects become relevant, or when the objectives of the stakeholders change. The definition of the project goals and priorities may also facilitate the later engineering design of the HRS, since it can help suppliers to understand the specific customer's needs.

Aspects to be addressed include:

- What are the positive (e.g. environmental, financial) effects of an HRS and the intended expansion of a H_2 bus fleet?
- Are these goals, such as the provision of an environmentally friendly public transport system by deploying a zero emission urban bus system, valid for the city and the particular context, with respect to local pollution, topography, or other factors?
- Can you identify additional positive side effects related to the HRS and the H_2 buses, such as local employment effects?
- Are some goals conflicting with each other and if they do, which ones are more important than others?

Based on the overall goals, more specific requirements can be derived for the HRS. These may comprise technical, economic, and environmental aspects, the requirement to integrate the HRS at a particular existing bus depot, and many more. It is important to collect as many aspects as possible that are known and relevant at that point of the project development. It is highly likely that some of the goals will conflict, especially a goal of low cost. If so, it is essential to assess the relative importance of each of these aspects and consider this when taking the appropriate decisions.

Usually, not all relevant stakeholders are known at the beginning of the project but they may be identified and integrated during the course of the project. However, an early assessment of the goals and priorities that considers the current stakeholders at this early stage of the project and their respective demands is important. It helps to answer important questions early in the project.

Different **tools and approaches** exist that can be used for undertaking this process. One example is to list all identified requirements for the HRS and to sort them according to their importance. Another approach is to list the conflicting goals and to distribute a certain number of points among the conflicting issues (see Table 2). Assessing the relative importance within comparison pairs of conflicting requirements can also be used for determining the overall priority of the requirements.

Assessing the willingness-to-pay for certain aspects, such as for a high refuelling reliability or for a low environmental impact of the hydrogen, is more difficult but it introduces specific financial thresholds against which a potential HRS design can be benchmarked.

Exercise for determining the relative importance of conflicting requirements	
Refuelling reliability of the HRS design	
Low hydrogen cost refuelled at the HRS	
Low environmental impact of the hydrogen provided at the HRS	
...	
Sum	∑: 100 points

Table 2 - Exercise for determining the relative importance of conflicting requirements

Depending on the progress of the project and the number of stakeholders involved, the list of defined requirements might become longer and the most suitable tool for determining the HRS requirements and their relative importance among all involved stakeholders may change.

5. Determination of basic parameters of the HRS

Box II in the proposed project framework, see Figure 11 on page 43

5

5. Determination of basic parameters of the HRS

In this section, the basic parameters related to the design and operation of an HRS are addressed. It contains a list of questions that need to be asked by the responsible project manager or the management team initiating an HRS project. It further provides some rules of thumb derived mainly from the design studies carried out within the NewBusFuel project and input from the project partners. These will help to develop some first estimates at this early stage of the project for the techno-economic or environmental characteristics of the future HRS.

This information is important for developing a common understanding among the stakeholders, also for new partners, such as political decision-makers, and funding bodies. The estimates can also be used for concentrating on certain technical options or operation patterns. However, caution needs to be exercised in discarding alternatives from future considerations based on approximations during an early stage of the project, since these options might result to be advantageous at a later stage.

The following three subsections (5.1 to 5.3) address technical, economic, and environmental parameters describing the performance of the HRS. In Section 5.4 the key issues that need to be considered for the design of an HRS are summarised. Figure 13 illustrates the required components for the available hydrogen pathways at an HRS.

5.1 Basic technical parameters

This section provides assistance for the determination of basic technical parameters, e.g. related to the hydrogen demand and to the requirements of the HRS. Since numerous interdependencies exist between these parameters, they cannot be determined separately but they should rather be considered in relation with one another. For this reason, an iterative procedure may be appropriate. For the purpose of this document, this section addresses the relevant aspects following the typical hydrogen flow in the HRS, starting with the H_2 production and finishing with the dispensing.

5.1.1 Determination of the hydrogen demand (including ramp-up strategies and additional hydrogen demand)

The relevance of the daily hydrogen demand

The first parameter on which all considerations related to an HRS are based is the daily required amount of hydrogen. Within the NewBusFuel project, all developed HRS are dedicated bus refuelling stations and car refuelling was only considered in one study. Although synergies with other hydrogen consumers might be relevant for the techno-economic performance of the planned HRS, this document focusses only on the use of hydrogen for refuelling bus fleets. More information on this can be found in other sources, e.g. [NextHyLights].

The hydrogen consumption of a future bus fleet should be determined with as much accuracy as possible, ideally as averages as well as maximum amounts during the year. If the amount estimated is too high, overcapacities of the HRS will result and the costs of the HRS and of the hydrogen increase unnecessarily. In contrast, if the consumption is estimated too low, not all buses will be able to be refuelled as intended which would potentially affect the operating regime of the buses that was originally envisaged.

Daily hydrogen consumption per bus

In a first step, the hydrogen consumption needs to be assessed. For this, the type (e.g. 12 m / 18 m bus) of FC buses in the future fleet is an important parameter as their hydrogen consumption differs significantly: in the NewBusFuel project the consumption of a 12 m bus is assessed in the range of 9 -10 kg H_2/100 km and that of an 18 m articulated bus typically within the range of 12 - 15 kg H_2/100km (see Table 3). To calculate the daily H_2 demand per bus this hydrogen consumption needs to be multiplied with the intended daily operating range of a FC bus, which can differ significantly depending on the individual route planning. Within the NewBusFuel project, the average daily operating distances range from less than 200 km to more than 400 km due to different operating regimes such as urban and extra-urban bus routes. However, the operating range of most studies is in the range of 200 – 300 km per day, which corresponds with a typical hydrogen consumption of 20 -30 kg H_2/day per bus. More information on the bus operators' requirements can be found in [NBF – D3.2].

Parameters determining the amount of required hydrogen per FC bus

Parameter	Typical range	Min/Max values
Assumed consumption of a 12m bus	9 – 10 kg H_2/100 km	8.5 / 12 kg H_2/100 km
Assumed hydrogen consumption of a 18m articulated 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
Typical range of daily hydrogen consumption per bus	20 – 30 kg H_2	15 / 36 kg H_2

Table 3 - Parameters determining the amount of required hydrogen per FC bus

It needs to be considered that the hydrogen consumption of fuel cell buses depends on a number of aspects. The circumstances, in which they are operated, including the topography, the average traveling speed, and their occupancy influence the fuel consumption. The climate conditions in which the H_2 buses are operated can also have a significant impact on the fuel demand, since heating in winter and air-conditioning in summer require considerable amounts of energy and hence increase the hydrogen consumption. For a 12 m bus this additional fuel consumption is in the range of 1 – 2 kg H_2/100 km in cold conditions. In hot conditions the energy demand for air conditioning may even be higher.

It must also be noted that the values used for the hydrogen consumption of fuel cell buses reflects the current and near-future technologies. With future developments, however, the hydrogen consumption is expected to decrease further. According to the Multi-Annual Work Plan of the FCH JU [FCH JU – MAWP] the H_2 consumption of a 12 m bus is expected to decrease to 7.6 kg H_2/100 km by the year 2023.

Also, buses that use hydrogen fuel cells as a secondary energy source, e.g. trolley buses that usually use overhead power lines or range extended (REX) battery electric vehicle (BEV) buses, require significantly less hydrogen per distance driven, which reduces the needed amount of hydrogen per bus and as a consequence the overall daily hydrogen demand of the bus fleet.

Fleet consumption and ramp-up scenarios

The next major parameter for the determination of the hydrogen demand is obviously the number of FC buses in the fleet and the planned ramp-up of the fleet size over time. Most NewBusFuel studies assume an initial fleet size of 10 - 20 buses (see Table 4) and a target fleet size ranging typically from 50 to 200 FC buses and beyond. Accordingly, the daily hydrogen demand is expected to be typically in the range of 200 – 600 kg H_2/day for the initial fleet size and between 1,000 - 6,000 kg H_2/day for the final fleet size within the NewBusFuel project.

As with diesel buses, usually not all H_2 buses will be on the road at the same time. While a few studies intend to use their FC buses during the entire year except for a small number of public holidays, most of the studies assume 250 – 350 days of operation for each bus. There will be some downtime of buses, e.g. due to maintenance activities. Variations in frequency of bus service, e.g. during weekends and the holiday season, lead to a variation of the bus fleet size being in operation at the same time.

Whereas some studies intend to reach their final fleet size within a few years, i.e. before 2025, others plan significantly longer ramp-up periods of more than 10 years such as by 2030 or even until 2040. For this reason, the average fleet expansion per year differs significantly among the studies between less than five and more than 20 buses per year, with an average at around 10 buses/year.

It is important to note that, instead of a continuous yearly expansion of the hydrogen bus fleet, most studies aim for 2 or 3 growth steps at an average of more than 10 new FC buses for each step. Some studies consider even more than 20 new buses in each step. Each extension step has to be accompanied by a similar infrastructure extension, and hence the fewer the steps, the fewer the frequency of necessary construction measures. Buying larger numbers of FC buses at a time will likely also reduce the unit cost and avoid unutilised overcapacities of the HRS infrastructure. Deliverable 3.5 from the NewBusFuel project addresses the requirements and options to cope with the fleet and HRS expansions [NBF – D3.5].

Parameters determining the amount of required hydrogen by the FC bus fleet

Parameter	Typical range	Min/Max values
Number of operational days per bus	250 – 350 days per year	240 / 365 days per year
Typical size of the initial FC bus fleet	10 – 20	3 / 50
Hydrogen demand for the initial FC bus fleet	200 – 600 kg H_2	170 / 1,500 kg H_2
Typical size of the target FC bus fleet	50 – 250	40 / 275
Hydrogen demand for the target FC bus fleet	1,000 – 6,000 kg H_2	700 / 6,000 kg H_2

Table 4 - Parameters determining the amount of required hydrogen by the FC bus fleet

5.1.2 Refuelling regime and number of dispensers

Bus operators are used to short refuelling times for diesel buses and expect similar performance from FC buses. Although H_2 FC buses can be refuelled within very short time periods, the questions related to the number of dispensers and the refuelling regime is more complex than it is for diesel buses.

The target pressure for refuelling the buses within all NewBusFuel studies is 350 bar and only one study considers an additional pressure level at 700 bar for refuelling passenger vehicles.

There are three different refuelling modes in the commonly used SAE protocol for the refuelling of hydrogen buses, each with different maximum refuelling speeds (see SAE J2601-1). Slow fuelling allows a maximum fuelling rate of up to 30 g/s (1.8 kg H_2/min), normal fuelling reaches up to 60 g/s (3.6 kg/min) and fast fuelling permits a maximum fuelling rate of 120 g/s (7.2 kg/min). It is important to note, however, that the average refuelling rate for a bus and for a group of buses might be well below the maximum fuelling rate of the chosen refuelling pattern based on a number of parameters. These include temperature and pressure of the hydrogen in the bus tank, of the hydrogen from the dispenser, ambient conditions as well as the design of the tank system incl. piping which has an impact on the achievable flow rate and also on the temperature change of the hydrogen during the refuelling process [NOW-A].

Within the NewBusFuel project, the time window for refuelling the entire fleet varies significantly but typically is within the range of 4 - 6 hours for refuelling all H_2 buses. Due to the different fleet sizes this results in the need to refuel typically between 10 and more than 40 buses per hour. Since the desired back-to-back refuelling time at one dispenser is about 10 - 20 minutes per bus, various dispensers need to be installed and used in parallel to meet the required refuelling regime.

Most refuelling activities are scheduled for the evening and at night when the bus service can be reduced and the FC buses are available in the depot (72 % between 20.00 and 02.00 – see Figure 12). Extending the refuelling time decreases the number of necessary dispensers which reduces the required investment costs, but at the same time prolongs the working hours and the related personnel costs. Hence, an appropriate compromise needs to be determined ensuring the refuelling of the entire bus fleet at reasonable cost.

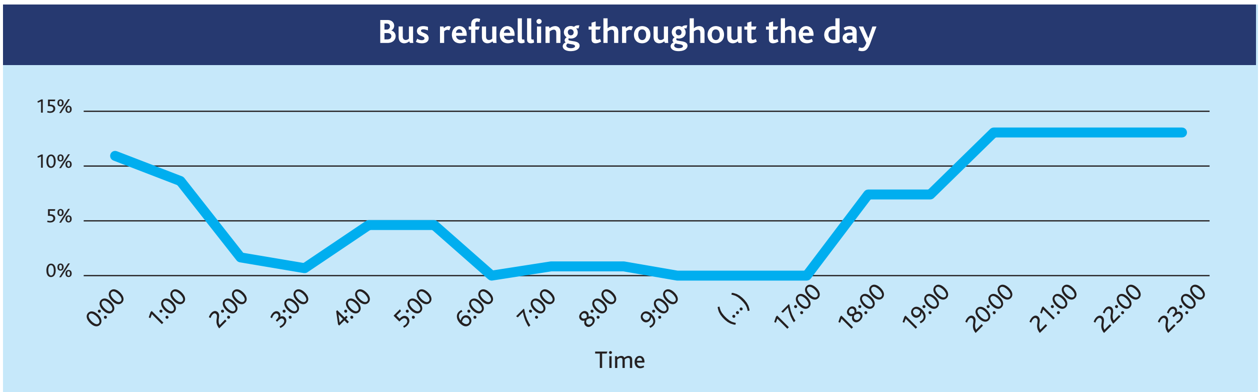


Figure 12 - Temporal distribution of bus refuelling during the day in the NewBusFuel case studies

An interesting approach within the studies of NewBusFuel is the parallel slow-filling of the entire bus fleet overnight. This allows the use of components with lower performance requirements and specifications, and at the same time personnel are only needed before starting and after finishing the refuelling process to connect and disconnect the FC buses from the dispenser units.

5.1.3 Refuelling reliability, redundancy and autonomy

Since bus service is an essential pillar of the public transportation system in urban areas, the ability to refuel the FC buses in the fleet is of highest importance. Within the NewBusFuel project, all bus operators demand high levels of availability in the range of 98 – 100 %, with an average above 99 %. Within the CHIC project the HRS infrastructure reached availability levels of an average of 97 %, a number achieving more than 99 % and none falling below 94 % with availability defined on a 24/7 basis [CHIC – Final brochure], [CHIC – D1.5].

In this context, it is necessary to introduce the terms **reliability** and **availability** as they were defined within the Task 3.5 for the NewBusFuel project, which is summarized within Deliverable 3.6 [NBF – D3.6].

Reliability reflects the ability to refuel a bus as planned by the HRS and bus operators. The HRS reliability is determined based on the number of successful refuelling events. Availability is the ratio of actual operating time and potential operating time. The potential operating time is the agreed refuelling windows. This means the availability of an HRS is not reduced by downtimes, such as for maintenance reasons, if these can be achieved between two scheduled refuelling windows.

Improving the refuelling reliability

The importance of the refuelling reliability requires a detailed assessment of existing risks for failures, strategies to avoid these and actions in case of downtime. Various approaches for analysing and assessing the risks related to the design and operation of an HRS exist. Within NewBusFuel these comprise custom-tailored assessment approaches or established approaches such as Failure Mode and Effect Analysis (FMEA). A supplier of HRS infrastructure often uses a suite of tools, which may also cover risk assessments that analyse the severity of the consequences from certain failures with respect to safety issues, such as Hazard and Operability Study (HAZOP) or Hazard Identification Study (HAZID). More information regarding safety measures with hydrogen can be found in different sources, e.g. [NREL-A].

A number of measures exists for ensuring a high refuelling reliability. A very common one is the **redundancy** of components, often applied as n+1 redundancy. This is the strategy of installing one more component at the HRS, such as an additional compressor over and above the ones that are necessary for normal HRS operation. If one fails the remaining ones can ensure the regular operation of the HRS.

Another advantage of this strategy is that redundant components can be maintained while the HRS can continue normal operation using the remaining components. The experience from previous projects shows that compressors in particular, are critical components to consider for possible redundant installation. They caused more than 50 % of all HRS downtime within the CHIC project [CHIC – Final brochure], [CHIC – D1.5], [CHIC – D3.7].

On the other hand, it is important to keep in mind that redundant components lead to intentionally unused overcapacities and hence increase the capital expenditure (CAPEX) for the HRS. This is especially relevant for smaller HRS systems, for which the relative cost increase caused by one additional component is higher than for a larger HRS system.

Within NewBusFuel, varying redundancy strategies are applied. While some studies only consider an additional dispenser and do not install overcapacities for any other modules, others also integrate additional compressors or additional hydrogen production capacity. An n+1 redundancy strategy of the entire HRS design leads to a high level of refuelling reliability but causes a significant CAPEX which increases the final hydrogen cost.

Another important element for the refuelling reliability is the **hydrogen storage** and its capacity. If the pressure level in the storage is well above that in the bus tanks, overflow refuelling can be used without the need for a compressor which avoids any instantaneous impact of compressor failure. However, high pressure hydrogen storage capacity is quite expensive and installing additional storage capacity might be necessary due to the required overcapacity for cascade refuelling and to reduce the pressure load variation within the storage for extending its lifetime (see Section 2.3.3).

A large high pressure hydrogen storage may require investments of several million € (see Section 5.2.3), increasing the overall hydrogen cost significantly. For this reason, most studies reduced the desired hydrogen storage capacity over the course of the NewBusFuel project from an average of more than 9 t H_2, representing a storage autonomy of 3 days, down to about 5 t H_2 or a storage autonomy of 2 days. They ensured a high refuelling reliability by other more cost effective means. This is considered to be one of the key lessons learnt by the participants of the NewBusFuel project with respect to the storage capacity and the refuelling reliability.

Another popular element for providing a high refuelling reliability is a **back-up supply** option, especially for the hydrogen source. Many studies within NewBusFuel considered a terminal which allows the integration of delivered hydrogen into the HRS in case the on-site hydrogen production unit suffers from any defects. However, the contractual framework for such a supply-on-demand with the necessary high delivery reliability at short response times will cause additional costs.

Independently from choosing H_2 delivery as primary hydrogen source or as back-up supply option, a **risk assessment of the hydrogen supply** is advisable. This includes technological risks, threats with respect to the hydrogen delivery, such as delays due to traffic jams, or weather conditions, but also economic metrics. The contractual framework for the hydrogen supply and delivery should ensure a high security of hydrogen delivery including clear roles and responsibilities, and related penalties.

Numerous other measures exist which improve the refuelling reliability of an HRS. This includes, an on-site or near at hand **supply of spare parts** at the HRS, especially those with long delivery times, and the presence of **trained maintenance staff** close to the HRS site with suitable reaction time, such as reaching the HRS site within 2 – 4 hours. The **contractual enforcement** between the HRS operator and the bus operator needs to set incentives for a high refuelling reliability and might include penalties in case of non-delivery.

If the HRS is based on a **modular design** approach, in which separate hydrogen pathways are operating in parallel, this leads automatically to a certain degree of redundancy for larger HRS. Even more advantageous with respect to the refuelling reliability due to redundancy is the installation of more than one HRS, preferably at a different bus depot [e-mobil BW]. **Maintenance activities** should be conducted between refuelling windows so they do not reduce the refuelling reliability or availability. They can be conducted anytime if the redundancy of the HRS design allows it.

When the required refuelling reliability is specified, not only the hydrogen fuel cell buses but the **overall public transport system** need to be taken into consideration. A downtime of the HRS might be compensated by providing bus services with conventional diesel buses, or, if available by other means of transport, such as rail. The current share of hydrogen fuel cell buses in the overall bus fleet and their importance for the overall public transport system, are the decisive parameters for determining the required level of refuelling reliability and for choosing **the appropriate balance between refuelling reliability and cost**.

All questions related to the risks and the effects on the refuelling reliability of the HRS are essential and need to be addressed together with the technology suppliers, in order to produce appropriate technical designs and reliable operation concepts, including viable maintenance and service strategies.

A common approach to developing a fuel cell bus fleet is to start with a small number of hydrogen fuel cell buses and provide security of the bus service with conventional diesel buses. Later, after testing the hydrogen equipment and confirming the robust operation of the technology, the required refuelling reliability level can be reassessed. Recommendations on appropriate availability enforcement mechanisms are discussed within the deliverable on the Agreed definition of availability for bus depot fuelling stations and recommendations on appropriate availability enforcement mechanisms within the NewBusFuel project [NBF – D3.6].

Compressors

As mentioned previously, the compressors are a crucial component that caused more than 50 % of all HRS downtime within the CHIC project [CHIC – Final brochure]. For this reason, the risk of a compressor failure and the effect on the refuelling availability require comprehensive considerations and the development of a risk mitigation strategy.

Almost all HRS studies that were developed within the NewBusFuel project for handling gaseous hydrogen consider overflow refuelling which does not require the operation of a compressor during the refuelling process (see Figure 13). Instead, the hydrogen is transferred from the storage into the bus tanks by the existing pressure difference. Nevertheless, a compression unit is required for all these proposed HRS designs in order to increase the hydrogen pressure after the production unit to the pressure level required in the hydrogen storage and to restore all target pressure levels in the high pressure banks of the cascade storage after the refuelling of the H_2 buses. Except for direct refuelling, both using a booster compressor for gaseous hydrogen and for LH2, HRS designs usually intend a continuous operation of these compressors with minimum start/stop operation to minimise wear and tear on sealings and other components.

Besides the studies using overflow refuelling, a few studies integrate a booster compressor in the HRS design which operates in order to increase the pressure of the hydrogen in the storage to the higher pressure level that is required for the bus tank. All studies assuming the handling of LH2, integrate the use of a cryo-pump or a cryogenic hydrogen compressor (see Figure 13).

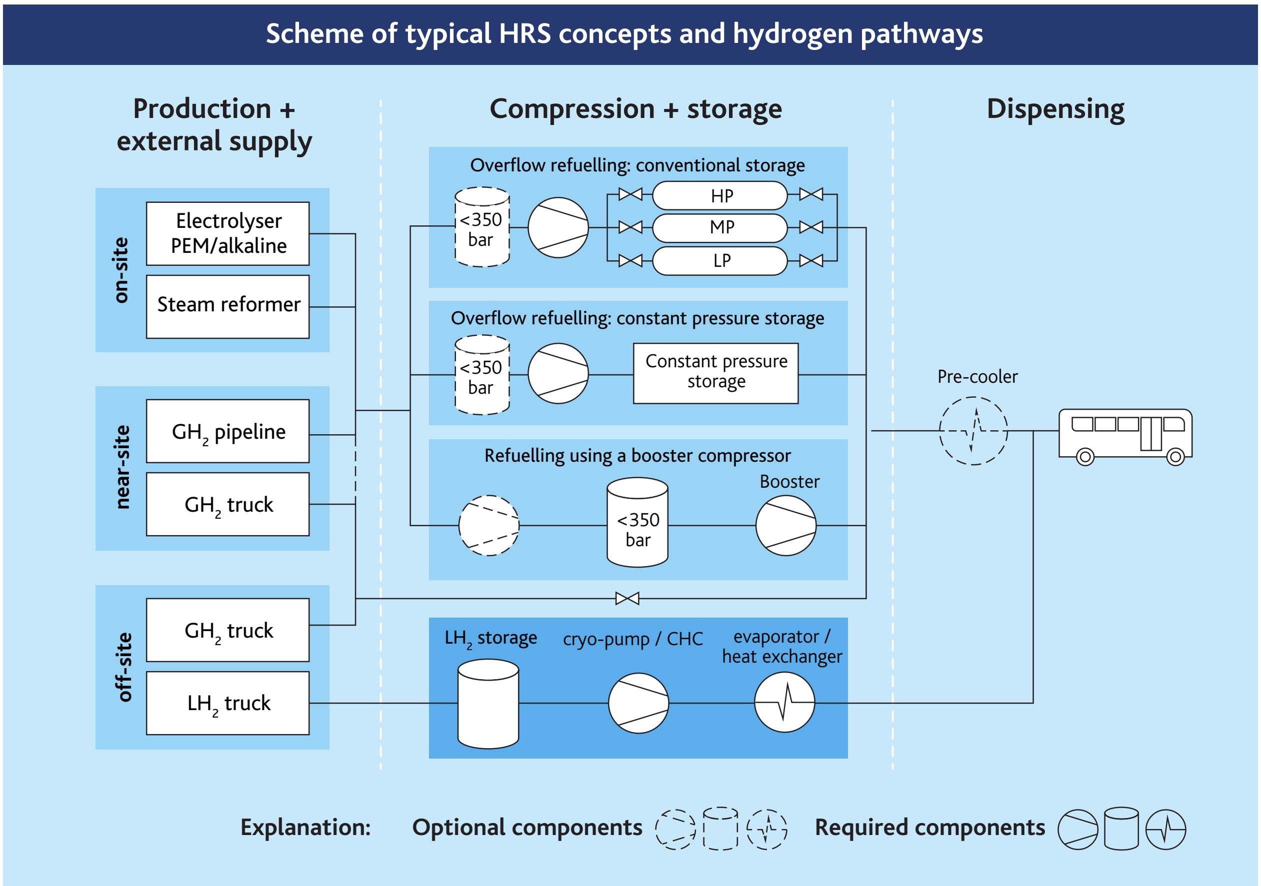


Figure 13 - Scheme of typical HRS concepts and hydrogen pathways

There are many different approaches for choosing an optimal number of suitable compressors for delivering a sufficient pressure increase at an HRS. A general recommendation is the use of compressors with a smaller capacity being operated over longer time periods, instead of using compressors with large capacity at short intervals in intermittent operation mode. This latter operating mode may reduce the compressor's lifetime.

Hydrogen storage

Some case studies consider multiple storages with different pressure levels, e.g. a dedicated low or medium pressure storage (e.g. < 100 bar) and a dedicated high pressure storage (> 350 bar). Most studies, however, consider the hydrogen to be stored in one storage system at a specific target pressure. If overflow filling is used, the pressure in this storage, as well as the pressure of the HP storage in a multi-storage system, needs to be above 350 bar and may contain separate benches if cascade refuelling is applied (see Figure 13 and Section 2.3.3). Alternatively, constant pressure storages (see Section 2.2) can also be used for overflow refuelling.

If the HRS design uses a booster compressor (see Figure 13), the storage pressure can be below the target pressure in the bus tanks, since the booster compressor transfers the hydrogen from the storage into the bus tanks (see Figure 13).

As mentioned earlier (see Section 2.3.3), the installation of overcapacities for the storage is required depending on the chosen technology, e.g. for overflow filling when cascade refuelling, or to reduce the pressure load variation within the storage in order to increase the storage lifetime.

All studies using liquid hydrogen integrate a LH2 storage tank in the HRS design and do not require any further medium or high pressure storages.

5.1.4 Electrical power demand and other utilities

All HRS, independently from their type of operation, require electricity to power and control their components. For HRS with on-site H_2 production, however, the electricity supply but also other required utilities are significantly more important.

Both electrolysis and steam reforming require the supply of fresh water, which usually is not a major concern during the HRS design process. The required water quality is achieved using proven and reliable pre-treatment systems, such as reverse osmosis. Steam reforming additionally needs methane, which is usually supplied from a natural gas grid. The availability of natural gas therefore may have an influence on the site selection process.

The electricity supply for HRS is even more important with on-site electrolysis. Depending on the intended daily hydrogen production, the HRS could require an electricity supply of more than 10 MW. The necessary power for the HRS may exceed the capacity of the common electricity distribution grid and require access to the transmission grid at a higher voltage level (e.g. at 110 kV). This is likely to be an essential parameter that needs to be considered when conducting the site selection for the future HRS.

5.1.5 HRS footprint, height and housing of components

Since bus depots are commonly located within urban areas or within the city outskirts, they are often surrounded by commercial and residential areas. For this reason, space restrictions are usually a very important constraint for an HRS project that may represent a decisive boundary constraint with regard to the technology selection. This section discusses the space that is required by an HRS and its components in more detail and aims at providing a better understanding for the space demand of an HRS. In this regard, the term “footprint” refers to the area that is occupied by a component or the overall HRS, and includes the considered safety distances between components.

An HRS often needs to be integrated into an existing bus depot, which has already been used for buses, usually diesel buses. Sometimes, however, the HRS can be set up at a greenfield site that can be designed and built from scratch, and which can be dedicated to the use of H_2 buses exclusively. This makes the HRS design process a lot easier, since the related space constraints are usually less strict. Such sites for new bus depots may however be located further away from the city centre, which makes the route planning for the buses more difficult, or where the connection to the utilities may not be readily available.

For assessing the footprint required by certain HRS technologies or HRS concepts, this section provides approximations that were determined from the HRS designs developed within the NewBusFuel project and also the CHIC project. Obviously, such approximations can only give a rough estimate of the real footprint, since there are many different design options that influence the overall footprint. Further, the safety distances between the HRS components may vary between different locations with corresponding effects on the HRS footprints [NBF – D3.3].

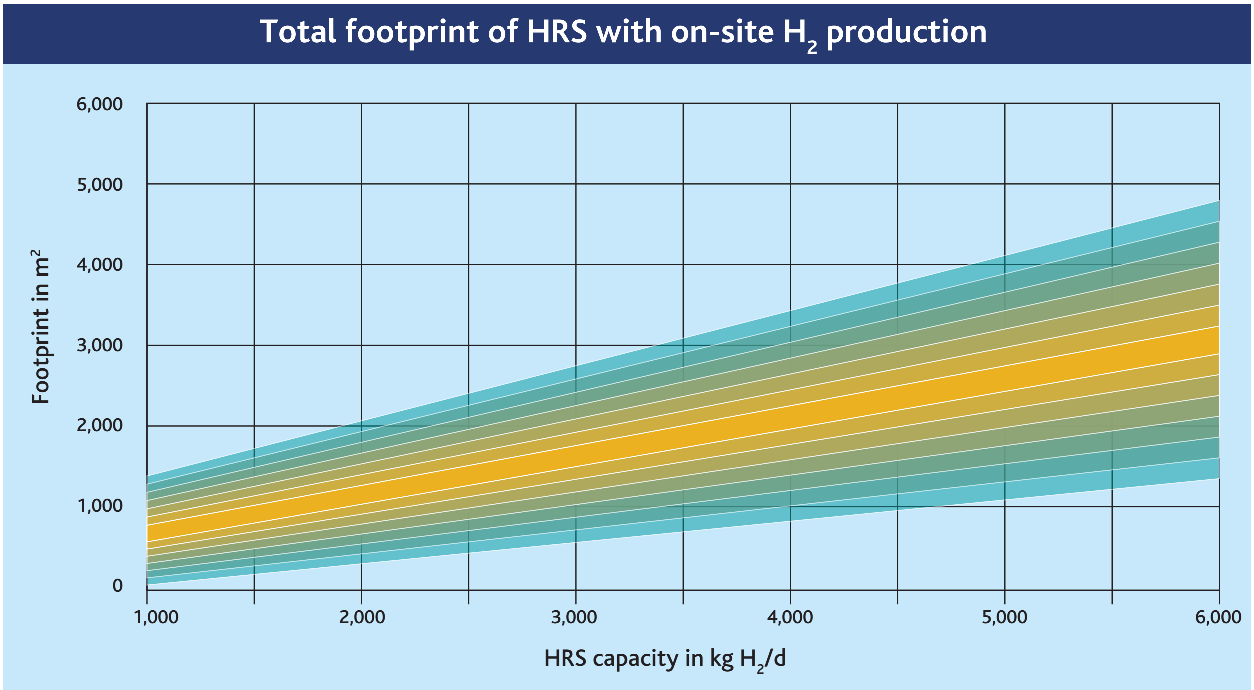
The studies with very significant space constraints have put more effort on the reduction of the HRS footprint than sites with a lot of space available at the desired site. The range of values within the approximations reflects the spectrum of variations encountered among the different studies particularly within the NewBusFuel project but also CHIC.

Overall HRS footprint

The illustration shown in Figure 14 reflect the total footprint of the complete HRS including all necessary components. These can be used to give a first footprint estimation. The plots indicate a mostly linear correlation with the footprint of an HRS (in m²) increasing gradually with higher refuelling capacities (in kg H_2/day), for an HRS with on-site electrolysis and steam reforming production (see Figure 14 - top) and for an HRS with H_2 delivery (see Figure 14 - bottom). From the available data of the NewBusFuel project, no significant difference between the footprint of HRS with on-site electrolysis and on-site steam reforming could be identified. Exemplary layouts for HRS with either on-site H_2 production or LH2 delivery including information on the required footprint are shown in Figure 15 to Figure 17.

Since HRS using delivered hydrogen do not require a H_2 production unit, their footprint is generally below that of HRS with on-site production, especially for larger refuelling capacities. An HRS using LH2 delivery usually requires a smaller footprint than an HRS with GH2 delivery, since the storage and the compression equipment is more compact. Figure 17 (bottom) shows the top view of the HRS with LH2 delivery that is illustrated within Figure 6.

It is important to keep in mind that the approximations provided only reflect the HRS designs considered within the CHIC and the NewBusFuel projects. The typical deviation of the values within these projects is expressed by the blurring shown in the figure. Other HRS designs, however, may require significantly larger or smaller footprints than indicated in the plot, for example by stacking H_2 production and/or storage modules or by installing storage tanks vertically instead of horizontally etc.



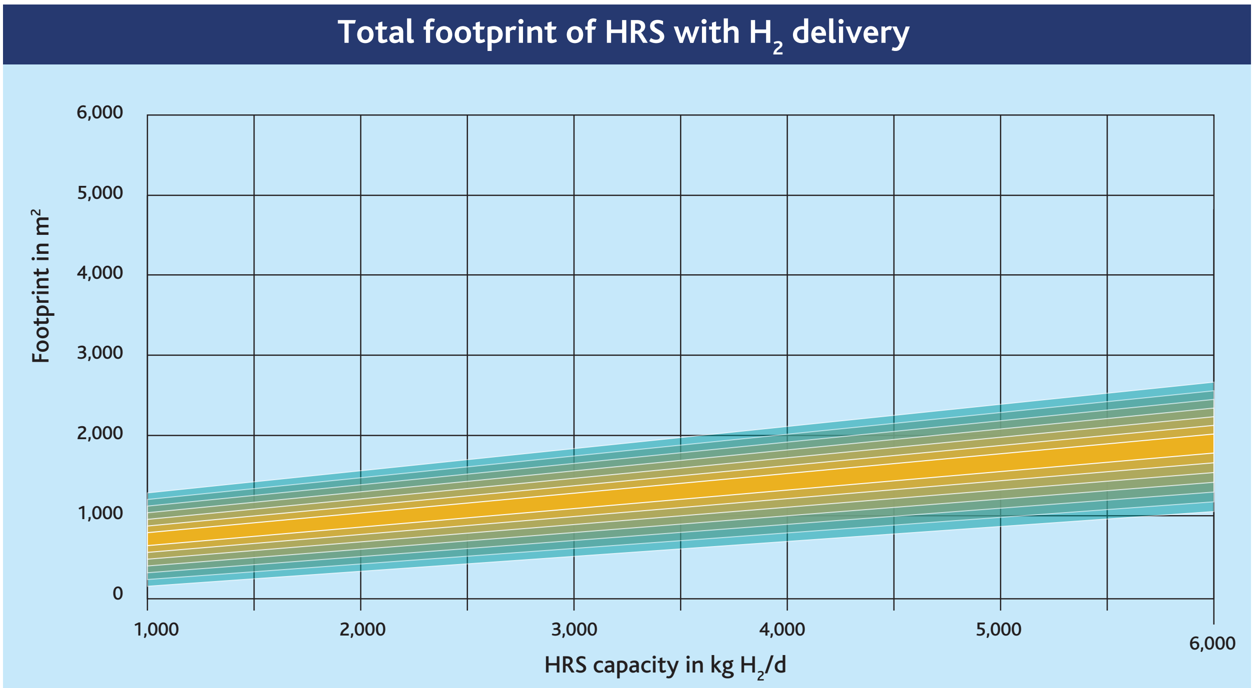


Figure 14 - Approximate footprints of complete HRS with on-site H_2 production (left) and with H_2 delivery (right)

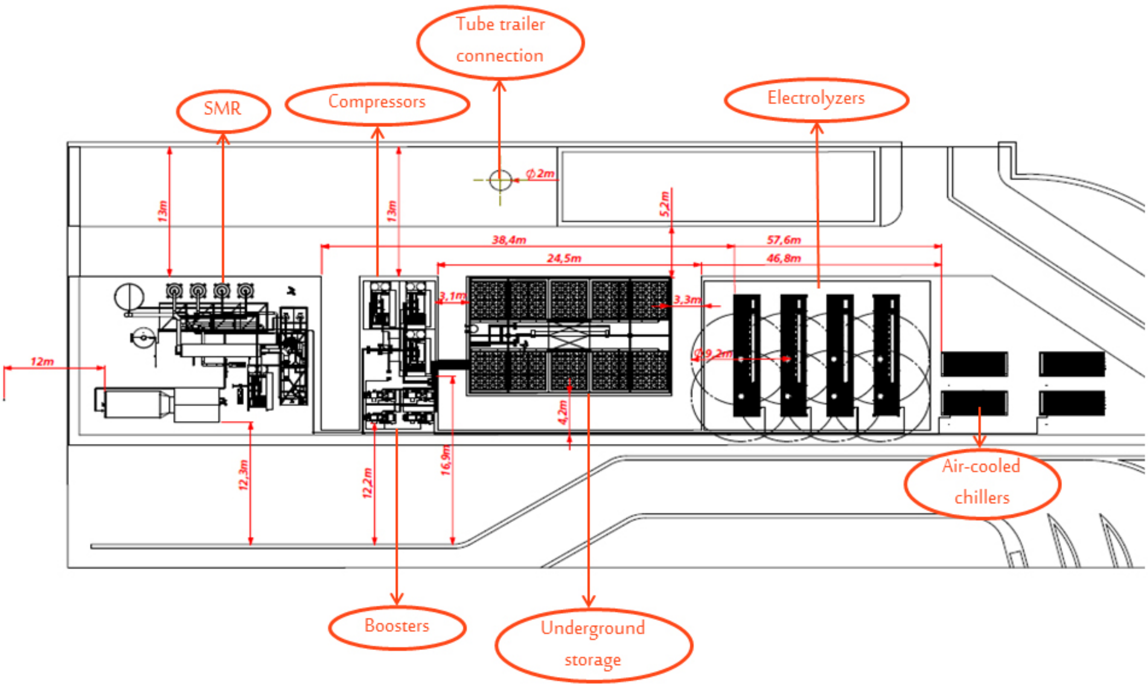


Figure 15 - Layout plan of an HRS with a total refuelling capacity of 3,000kg H_2/d, Source: Abengoa Innovación

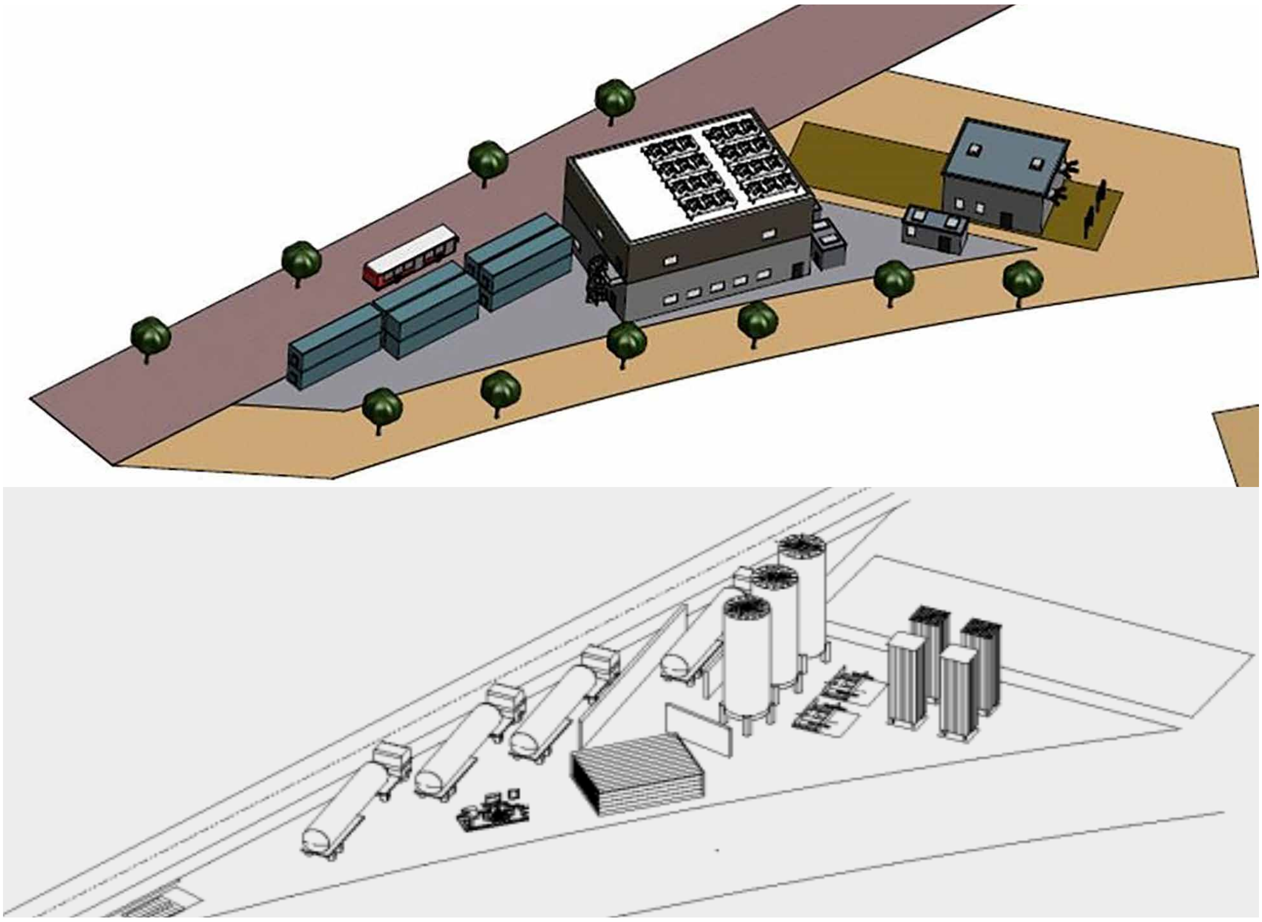
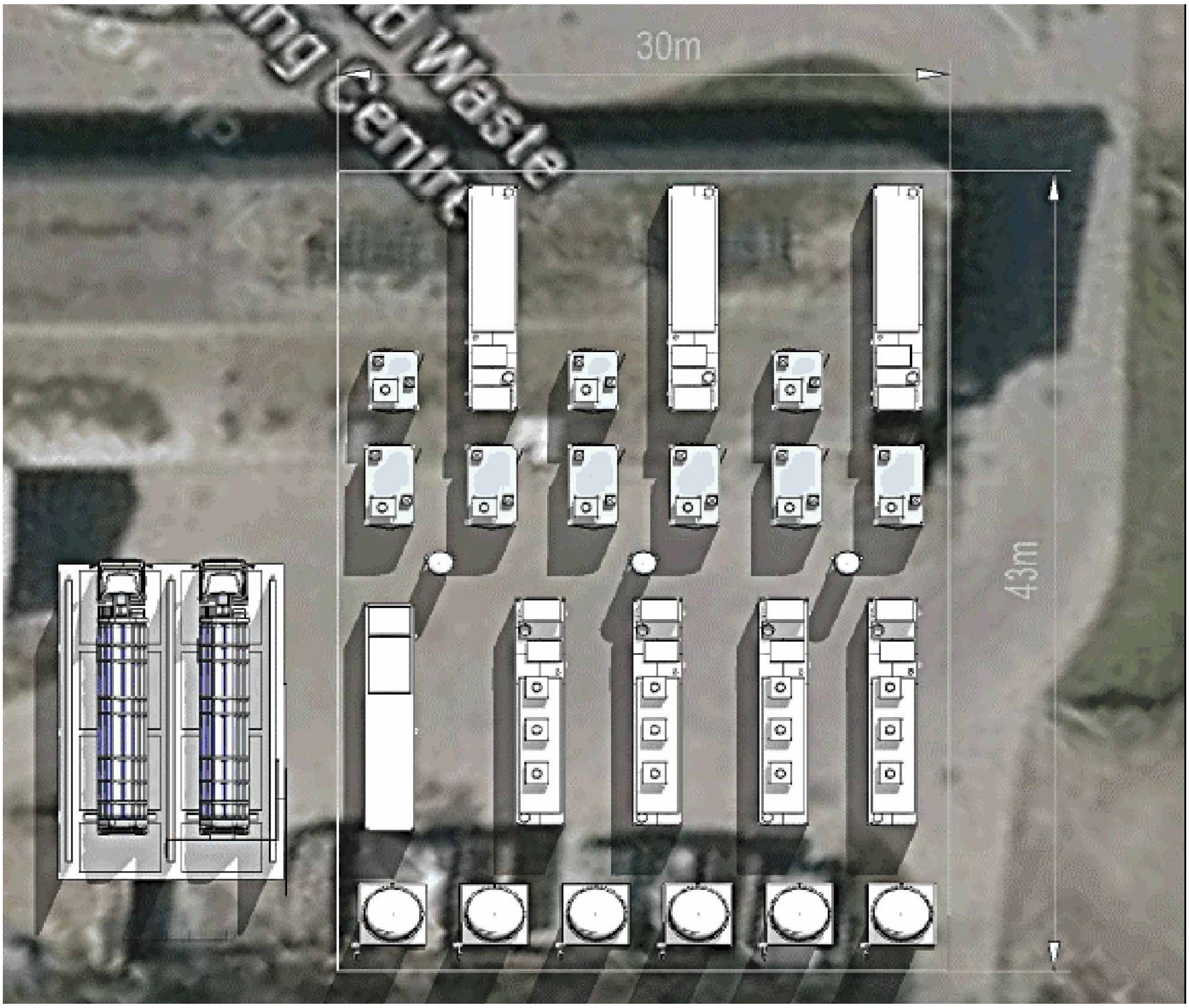


Figure 16 - Two HRS concepts for the same site using on-site electrolysis (top), Source: HySolutions/Hochbahn, and using hydrogen delivery (bottom), Source: Air Products



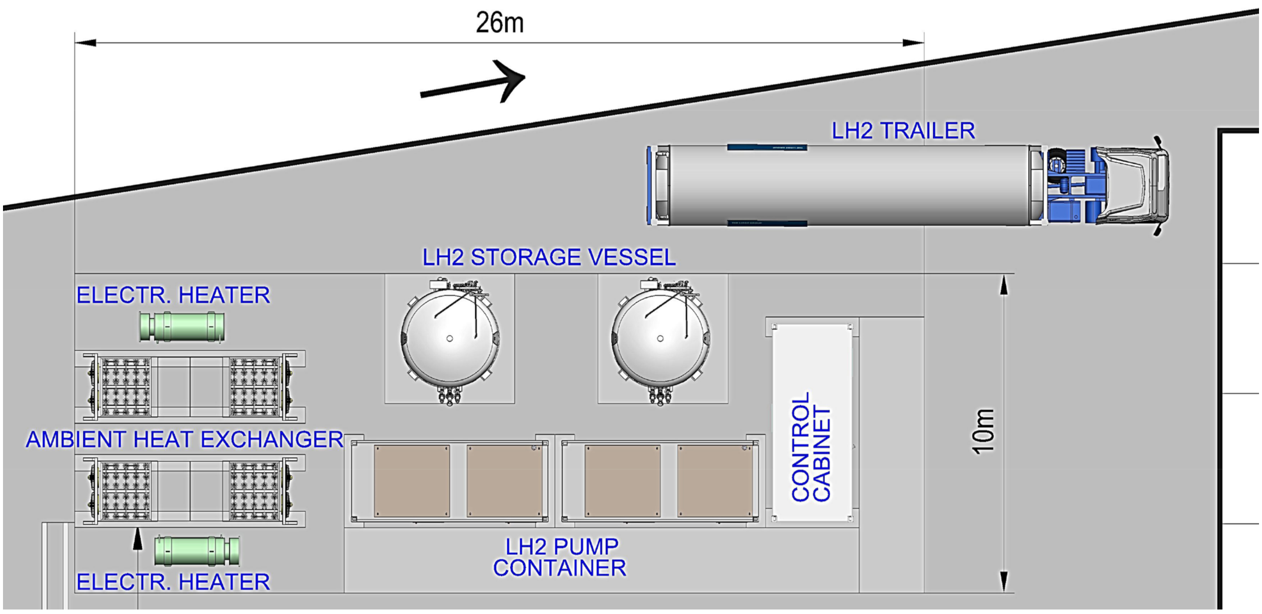


Figure 17 - Exemplary layout of an HRS with on-site steam reforming (output approx. 2.1 t H_2/day) (top), HRS with LH_2 delivery (intended output 2.25 t H_2/d) (bottom), Source: Linde

Footprint of individual HRS modules

Figure 18 shows a trend line for the footprint of an on-site H_2 production unit as a function of the H_2 production capacity. Since similar footprints are considered for on-site electrolysers and on-site steam reformers within the NewBusFuel studies, both H_2 production technologies are merged together in the illustration. For on-site H_2 production units using water electrolysis, it should be noted that PEM electrolysers are considered to generally be more compact and hence to occupy a smaller footprint than alkaline electrolysers.

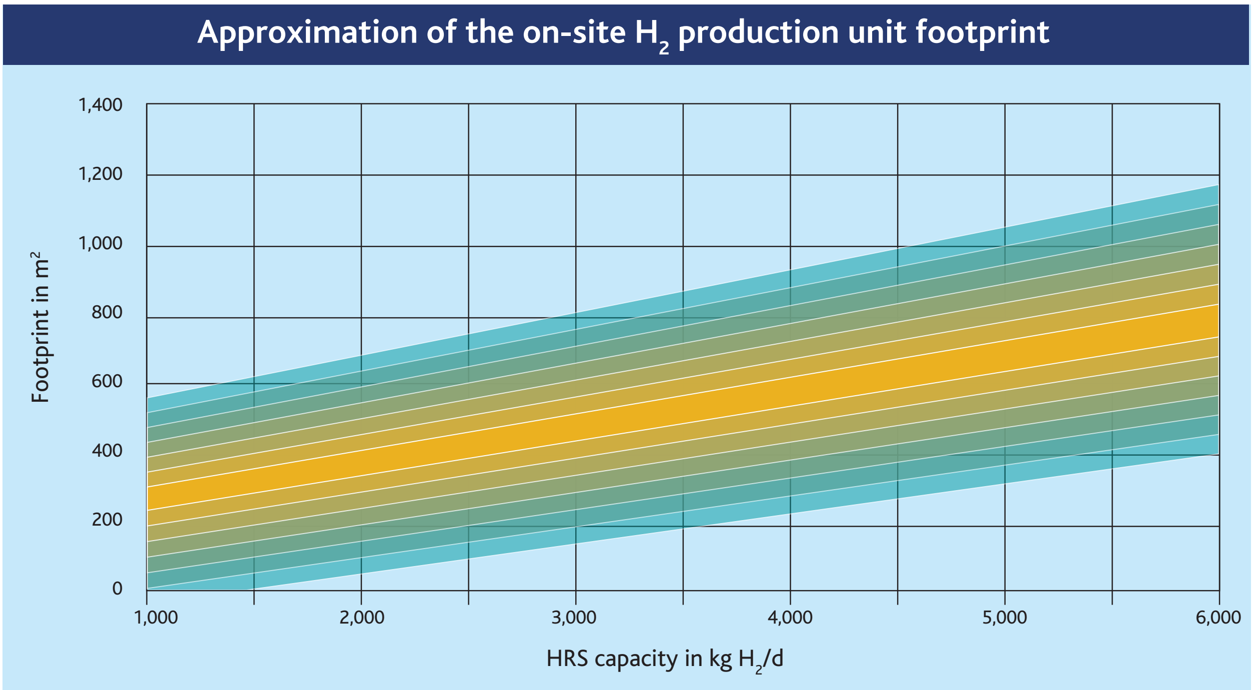


Figure 18 - Approximation of the on-site H_2 production unit footprint8

The footprint occupied by the compression unit strongly depends on the overall HRS concept, especially the potential use of booster compressors in addition to the conventional compressors or the degree of compressor redundancy planned. The compression unit and the hydrogen storage are very much inter-related, and their footprints influence each other strongly. Due to the different concepts that are considered within the NewBusFuel project, the footprint of the compressor unit varies significantly among the reported figures and does not show a clear dependency on the HRS refuelling capacity. An approximation for the average **footprint of a compression unit for gaseous hydrogen is 150 m² with a maximum about 250 m². Cryo-pumps and cryogenic hydrogen compressors (CHC)** achieve higher throughputs of hydrogen than GH2 compressors. Consequently, a smaller number of components are required for the handling of **liquid hydrogen** and the footprint of a LH2 compression unit is usually quite small with footprints of below **100 m²** for typical HRS capacities (see [NOW-A]).

Depending on the desired autonomy of the HRS and the storage concept, the hydrogen storage may have a significant footprint. LH2 storage tanks are usually vertical tanks and hence large amounts of hydrogen can be stored using a very small footprint due to the high density of liquid hydrogen as well as the shape of the storage (see Figure 6). For the typical HRS capacities addressed within the NewBusFuel project, an **LH2 storage requires about 100 m²** or even less (see Figure 17 bottom and also [NOW-A]). Despite the smaller footprint of LH2 components, the use of LH2 may require larger safety distances compared to GH2, depending on the local RCS.

In contrast, gaseous hydrogen storages require a significantly larger footprint than LH2 storages, especially per amount of hydrogen. As described in Section 2.3.3, mainly the pressure level but also the actual storage design determine the required volume and footprint. For example storage containers can be stacked onto each other. For the high pressure storages, which were usually considered in the NewBusFuel studies for overflow refuelling, the footprint required to store a certain amount of hydrogen varies significantly. **An indicative estimate is about 10 - 20 kg H_2/m²**, which means about **50 – 100 m² for storing 1,000 kg** of hydrogen at pressure levels of > 300 bar.

If GH2 tube trailers are integrated into the HRS concept as hydrogen storage, they increase the storage footprint more than the approximation indicated above, since they usually occupy more space per mass of stored hydrogen than dedicated stationary hydrogen storages. Since all hydrogen in a constant pressure storage is useable, whereas unusable overcapacities need to be installed in a conventional stationary GH2 storage used for overflow refuelling (see Section 2.3.3), such a storage requires a smaller footprint despite the additional necessary hydraulic unit (see Figure 17 top).

A hydrogen dispenser does not require a large footprint, even including the surrounding safety area it usually adds up to only a few m². Hence, the size of the dispensing area is rather determined by the footprint of the buses to be refuelled. This is about 31 m² for a 12 m bus and about 46 m² for an articulated bus of 18 m length. Due to additional space requirements for manoeuvring and other activities, the dispensing areas designed within the NewBusFuel project range from about **70 m² to 170 m² per dispenser**, depending on the particular bus depot, with an **average at about 120 m²**.

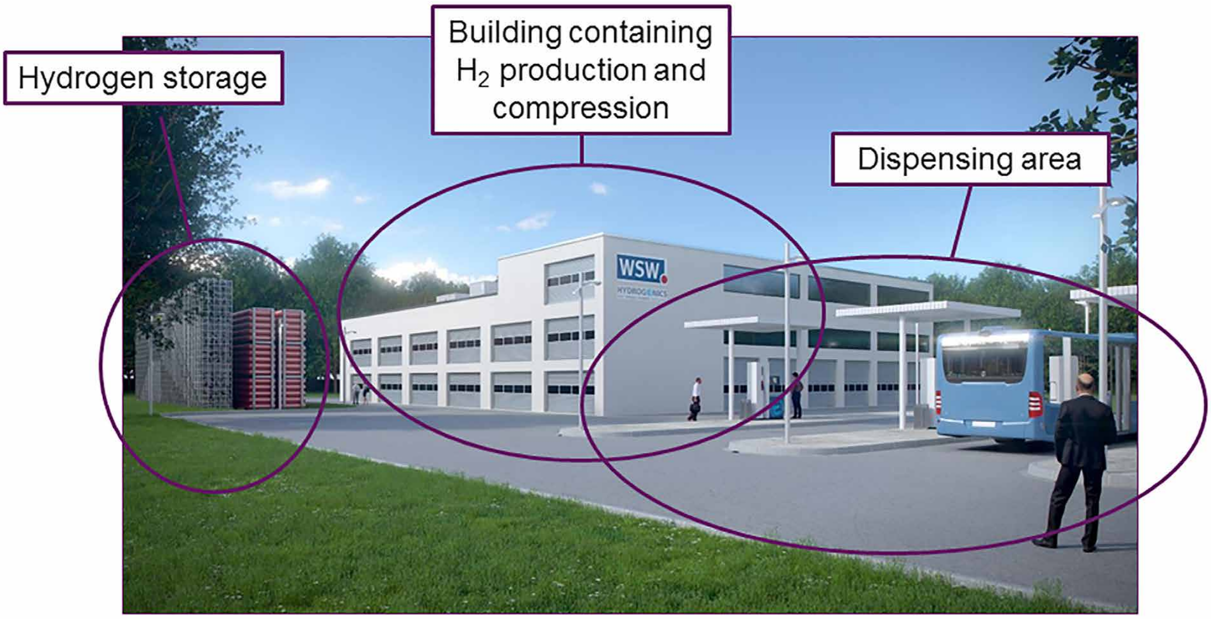
Depending on the HRS technology, additional components may have to be included. Liquid hydrogen needs to be converted into gaseous hydrogen and conditioned in a combined evaporator/heat exchanger before it can be refuelled to the bus tanks. For gaseous hydrogen stored in a stationary tank, pre-cooling is usually not required for 350 bar refuelling. However in specific cases, such as using fast fuelling with max. 120 g/s, it may be necessary. Such additional components increase the required footprint but the data from the NewBusFuel studies are insufficient to provide meaningful approximations.

Ways to reduce the HRS footprint

As already mentioned, the footprint of components can be reduced by increasing the height of the components and by stacking components. However, the maximum height of the HRS may be restricted by general height limitations for the development zone the HRS is built in, or due to passing high voltage lines, regulations related to air traffic, or even the visibility of components and related difficulties for obtaining the building permit from the authorities. Access to components as well as the ability and the required time for exchanging them also needs to be considered, as this also has an important impact on the refuelling reliability of the HRS.

Installing firewalls between components may be a prerequisite to meeting local RCS. It may also help to reduce the necessary safety distances between components and hence the overall HRS footprint. Placing components at different levels, such as lower in an open pit or at an elevated level above the ground, may allow reduction of safety distances. The local RCS need to be assessed individually considering in detail the particular circumstances of each HRS project, since significant RCS variations exist in different countries or even within different regions of the same country country (see [NBF – D3.3]).

The housing of the HRS also influences the overall footprint. Often, the components are delivered within standardized shipping containers (20 or 40 feet, equivalent to 6.1 or 12.2 m). Other HRS designs aim for integrating all components in a reinforced-concrete building such as a refuelling hall (see Figure 19). Some designs locate the components in the open air to ensure proper ventilation. The chosen strategy will influence the footprint, but also the safety and cost.



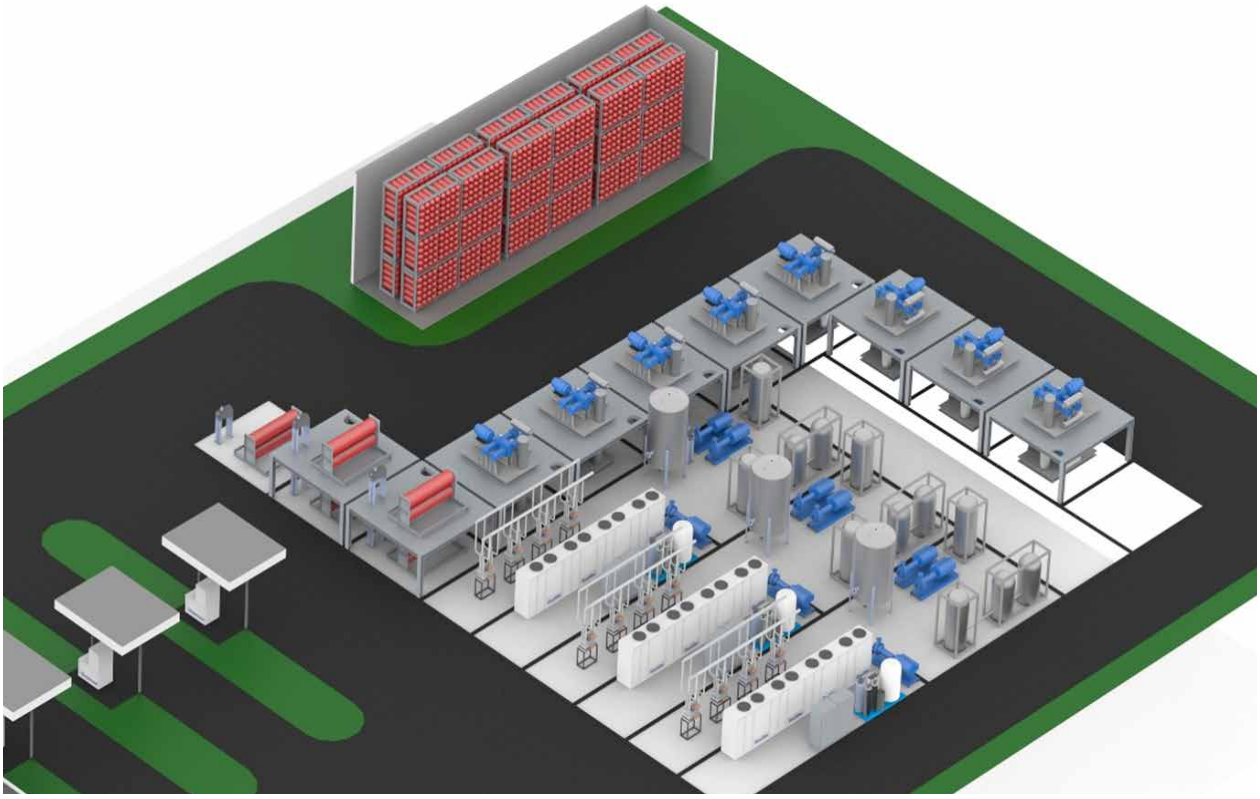


Figure 19 - Illustrations of a HRS with on-site electrolysis and a maximum daily capacity of about 6 t H_2/d, Source: WSW/Hydrogenics

5.2 Basic economic parameters

This section focuses on the economic characteristics of the design and the operation of an HRS. Although precise and reliable cost figures can only be determined based on a detailed engineering design and specific offers from suppliers, this section can be used to guide making the first qualified estimations on the costs for the HRS and the dispensed H_2. These first cost indications can be used in the early stakeholder discussions.

To address the economics of an HRS, both the capital expenditure (CAPEX) and the operational expenditure (OPEX) related to the HRS are essential. The former arises from the investment cost for the HRS, and the latter includes the costs related to the HRS operation. The combination of both cost contributions determines the total cost of hydrogen at the refuelling nozzle. The following sections provide anonymised cost indications as averages or ranges, as far as the data from the NewBusFuel project allows. Where appropriate they are complemented with estimates found in the literature.

5.2.1 Cost related to on-site H_2 production

If the hydrogen is produced on-site within an electrolyser, its electricity requirement is usually the dominant parameter determining the **OPEX** of the HRS. It depends on a number of aspects, such as the type of electrolyser, the operation mode (full or partial load), the age of the electrolyser (ageing of an electrolyser leads to higher electricity consumption in the range of additional 10%) and the electricity consumption of auxiliary systems that are necessary for the electrolysis.

The consumption figures reported within the NewBusFuel project range from about 55 - 70 kWh of electricity consumed per kg H_2, which is a range also confirmed by other sources (see also [CEP], [US DoE H2A - A], [NOW-A]). Future electricity consumption of an electrolyser is assumed to decrease to 50 kWh/kg H_2 [FCH JU – MAWP], [NOW-A]. The cost for the electricity consumed by the H_2 production in the electrolyser may vary significantly depending on local conditions.

Figure 20 shows electricity prices for industrial consumers in Europe with an annual electricity consumption in the range of 500 - 2,000 MWh (or 2 GWh), which is the expected electricity demand of an HRS with on-site electrolysis and a production capacity of only 90 kg H_2/d. The lower of the two stacked columns indicate prices for the electricity and the supply, i.e. network costs such as grid fees, whereas the top columns indicate taxes and levies excluding the recoverable VAT.

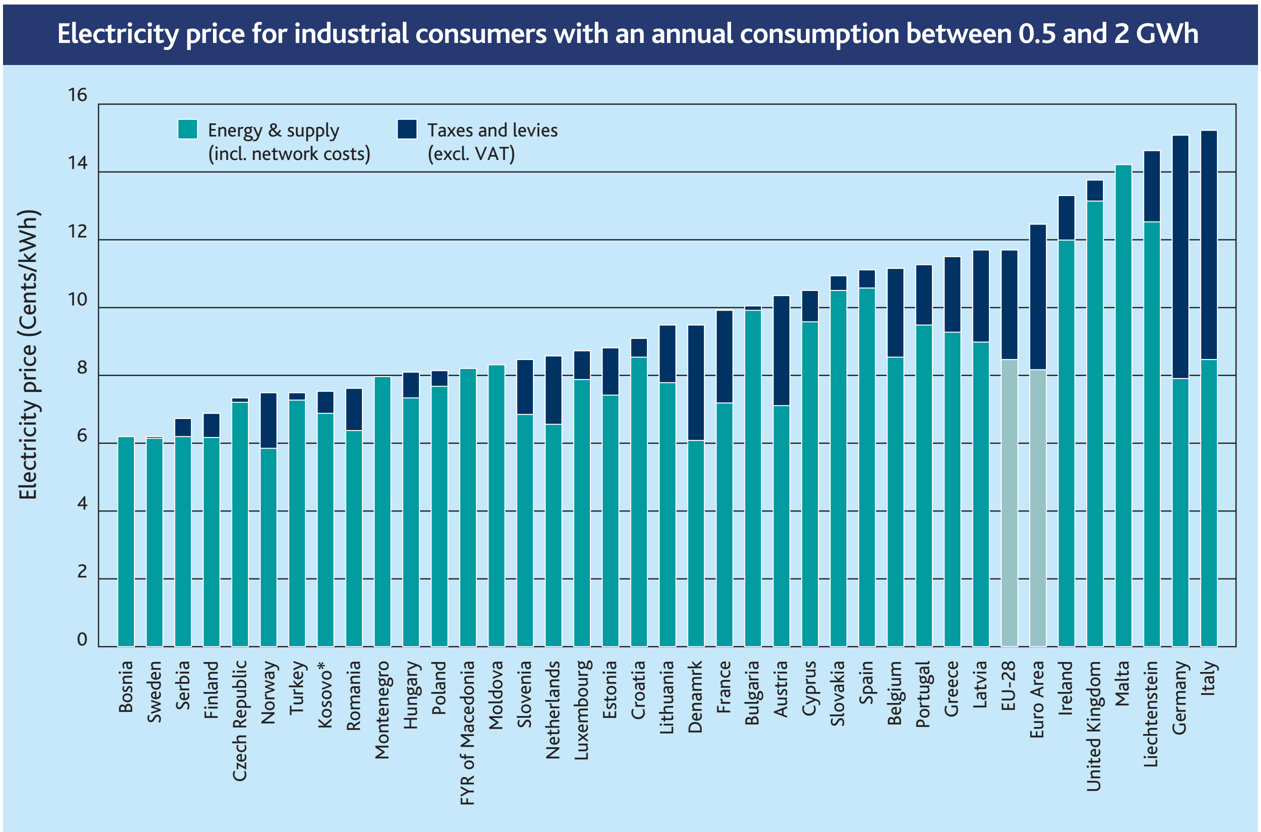


Figure 20 - Electricity price for industrial consumers with a consumption of 0.5 - 2 GWh in Europe [Eurostat 2016, electricity prices]

Accordingly, an HRS with on-site electrolysis requires more than 20 GWh for a capacity of 1,000 kg H_2/d and more than 130 GWh for a capacity of 6,000 kg H_2/d. Figure 21 shows the electricity price for industrial consumers with an annual electricity consumption of 100 GWh in some European countries. The existing variations are related to country specific regulations resulting in different taxes and levies. In many markets, the electricity price for large industrial consumers is in the range of 4 – 6 Cents/kWh.

It is important to mention that these prices reflect the current electricity mix in the mentioned countries.

In order to improve the environmental performance of FC buses compared to conventional, usually diesel driven, buses with regard to e.g. greenhouse gases (GHG) green or low carbon hydrogen needs to be obtained. This means that if hydrogen is produced using an electrolyser, electricity from renewable sources needs to be obtained. Depending on the related local electricity mixes and prices, this may increase the costs discussed in this section considerably. More information on the environmental parameters of hydrogen production is provided in Section 5.3.

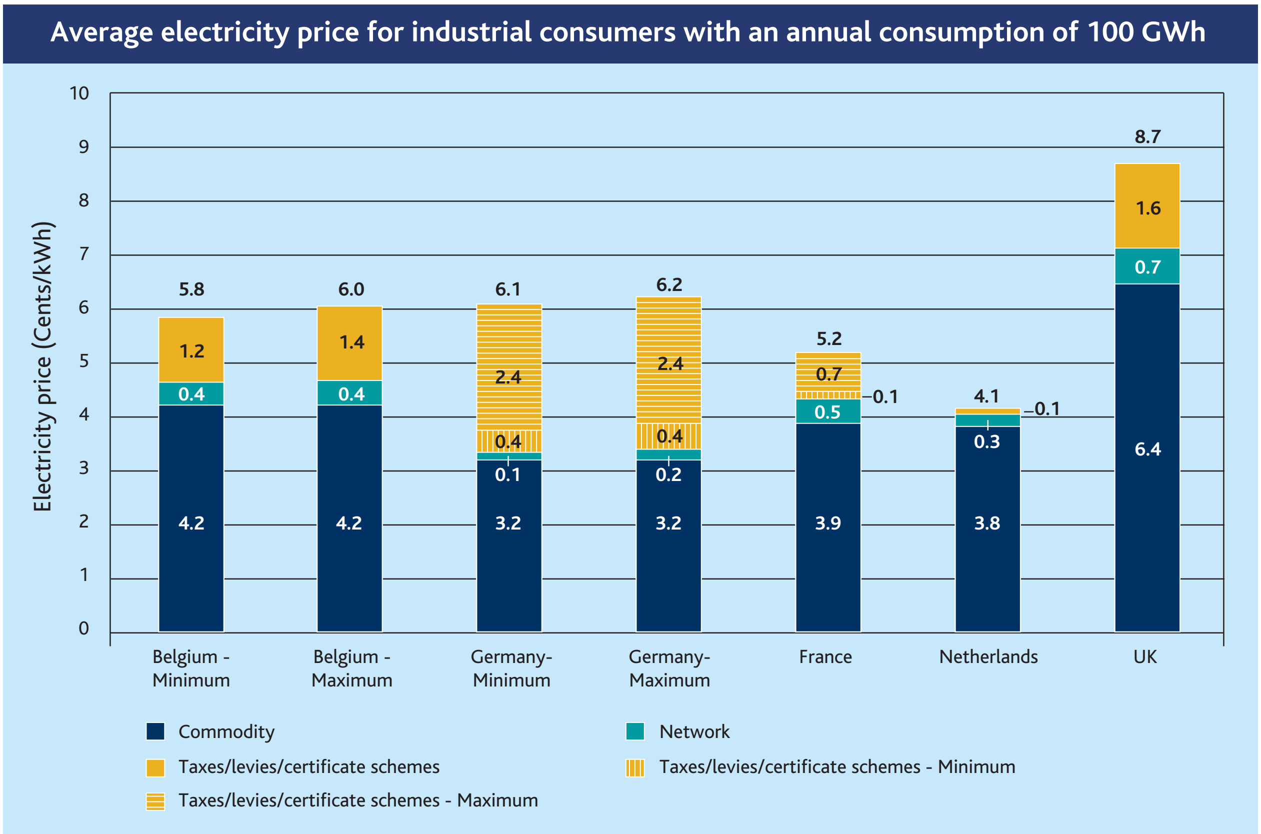


Figure 21 - Electricity price for industrial consumers with an annual consumption of 100 GWh [CREG 2016]

Assuming an electricity consumption of 58 kWh/kg H_2, an electricity price of 6 Cents/kWh leads to a contribution of 3.48 €/kg H_2 to the final H_2 cost. An electricity price of 12 Cents/kWh results in 6.96 €/kg H_2. This covers the electricity cost related to the hydrogen production only, but not the electricity necessary for the compression of the produced gaseous hydrogen nor the investment for the H_2 production unit (see Section 5.2.3 and Section 5.2.6). As can be seen, the electricity price has a major impact on the overall hydrogen cost.

Due to the flexibility of electrolysers (see Section 2.3.1) an HRS may provide grid services which may generate revenues and reduce the overall hydrogen cost (see [E4tech & EE]). Nevertheless, this may lead to additional investments, e.g. through increased storage capacity, which need to be assessed in detail for the individual market together with potential incomes.

In contrast, the cost related to the water consumption is negligible. Most studies with on-site electrolyser in the NewBusFuel project and other sources [CEP] assume a water consumption of 10 - 20 litres per kg H, which usually contributes to the overall hydrogen cost by less than 10 Cents/kg H_2.

If a **steam reformer** is used for the on-site production of hydrogen, the feed gas, usually methane, is the predominant parameter determining the OPEX. Due to the variable share of methane within natural gas or within biogas-methane, and depending on different efficiencies of steam reformers, the consumption of natural gas varies for the production per unit of hydrogen. As a rule of thumb, the consumption of natural gas for the production of 1 kg of H_2 is commonly within the range of 4.5 – 5.5 Nm³/kg H_2.

JJust like the prices for electricity, also the natural gas prices may vary depending on the annually consumed amount. Figure 22 shows the natural gas prices in Europe for industrial consumers with a consumption of 2.8 – 27.8 GWh of natural gas per year. Figure 23 shows the prices for industrial consumers with an annual consumption of 100 GWh.

Assuming a consumption of 5 Nm³/kg H_2 at a lower heating value of 10 kWh/Nm³ for the natural gas results in a total consumption at around 20 GWh of natural gas for an on-site steam reformer with a capacity of 1,000 kg H_2/d and at around 110 GWh for a capacity of 6,000 kg H_2. Assuming a natural gas price of 2.5 Cents/kWh for industrial natural gas consumers in Europe (see Figure 22 and Figure 23), results in a natural gas cost of 1.25 €/kg H_2. This is well below the electricity cost for hydrogen produced in an electrolyser. Also for the hydrogen production in a steam reformer, the cost related to the water consumption is negligible. Note again that the indicated figure does not include the electricity necessary for compressing the gaseous hydrogen (see Section 5.2.3) nor the investment for the H_2 production unit. Same as for hydrogen from electrolysis, the potential requirement for green or low carbon hydrogen will likely increase the production costs of hydrogen from steam reforming due to higher cost for e.g. bio-methane.

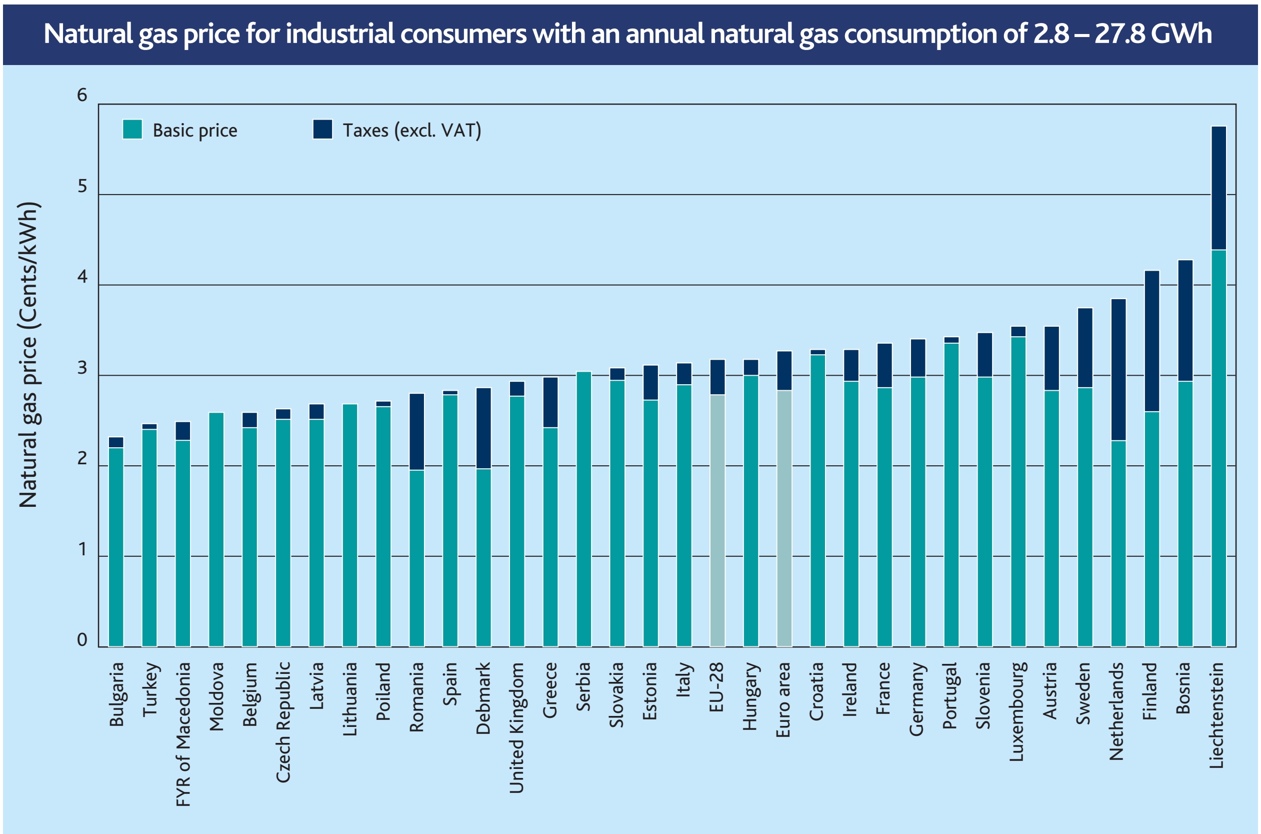


Figure 22 - Natural gas price for industrial consumers with an annual natural gas consumption of 2.8 – 27.8 GWh [Eurostat 2016, natural gas prices]

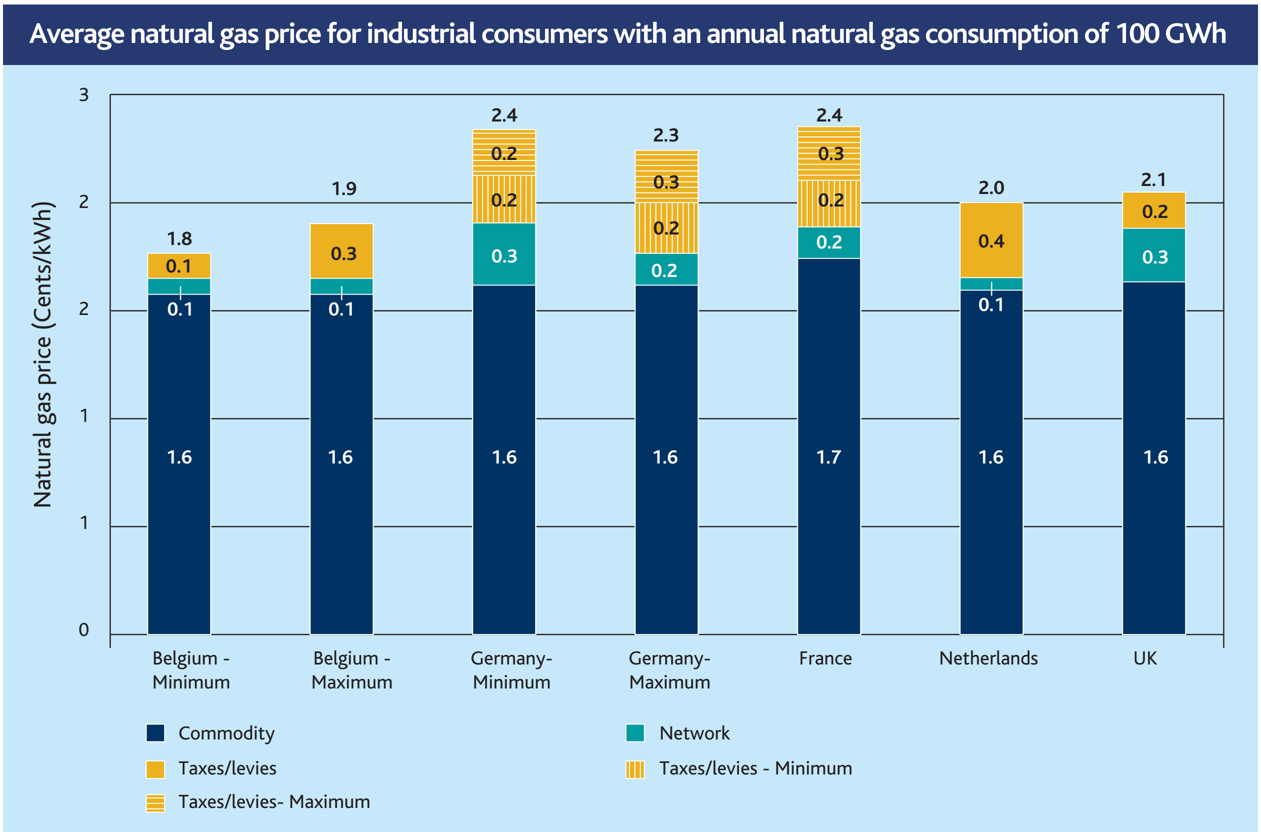


Figure 23 - Natural gas price for industrial consumers with an annual natural gas consumption of 100 GWh [CREG 2016]

In general, the hydrogen production unit is the most expensive module of an HRS and can contribute to more than half of the overall **CAPEX**, depending on a number of aspects, such as the level of redundancy or dedicated civil works for its utility supply, foundation and housing. The investment necessary for an alkaline **electrolyser** is considered to be below that for a PEM electrolyser, but the future cost difference is assumed to close progressively (see [NOW-A], [NOW-B], [E4tech & EE]). Recent publications consider current cost parity or even advantages of the PEM electrolyser, taking all auxiliaries and the building into the cost estimation [FVV]. Here, the reduced footprint of the more compact PEM electrolyser has a positive impact.

The data gathered in the NewBusFuel project is insufficient to show a noticeable cost difference between the two electrolyser technologies at this time. Instead, Figure 24 illustrates a linear approximation derived from the reported investment cost for the total hydrogen production unit, comprising **PEM and alkaline electrolysers**, with all necessary ancillary equipment and other necessary expenses. For an HRS with a reasonable capacity (around 2.5 t H_2/d, which is sufficient to supply 100 12 m buses with a notional daily demand of 25 kg H_2/d) this linear approximation coincides well with the cost target of the FCH JU of 3,700 €/(kg H_2/d) stated in the Multi-Annual Work Plan for electrolysers including ancillary equipment and commissioning in the year 2017 for an HRS with a capacity of 500 kg H_2/d [FCH JU – MAWP].

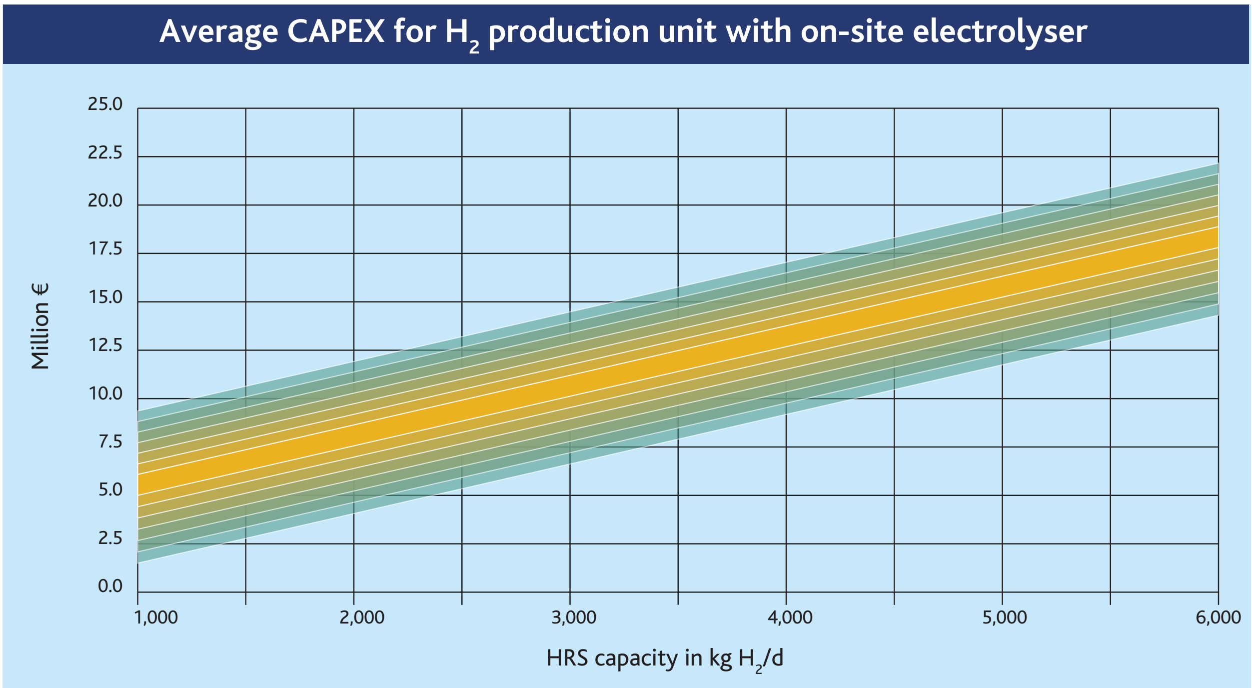


Figure 24 - Average CAPEX for the H_2 production unit with on-site electrolyser

Very few data points are available from the NewBusFuel project for on-site steam reformers and no specific cost indications can be stated. However, values in the literature consider that the necessary investments for steam reformers are below those of electrolysers [NOW-A], [NREL-B]. This cost advantage of a H_2 production unit using steam reforming is supported by the few NewBusFuel cost values obtained.

Although the hydrogen production unit requires a significant investment, the investment cost per mass of hydrogen produced is rather small. The technical lifetimes of the components included in the hydrogen production unit are considered to be between 10 (the PEM electrolyser stack) and 20 years. Assuming an HRS with a capacity of 3,000 kg H_2/d and a CAPEX for the H_2 production unit of 10.5 million € (see Figure 24) at a depreciation period of only 10 years, this results in costs of 1,050,000 € per year and 0.96 €/kg H_2 produced. Compared with the OPEX related to the electricity consumption, this contribution is rather small.

Another aspect with potentially **significant impact on the CAPEX** of the hydrogen production unit arises from the concept of **overcapacity or redundancy**. Figure 25 shows the cost contribution of OPEX and CAPEX for a H_2 production unit using an electrolyser with a maximum capacity of 500 kg H_2/d. For a low utilisation, the contribution of the CAPEX to the overall H_2 cost increases and can, in an extreme case such as a utilisation < 20 %, be even larger than the OPEX. Nevertheless, for a high utilisation level, the OPEX of an on-site electrolyser dominates the total cost.

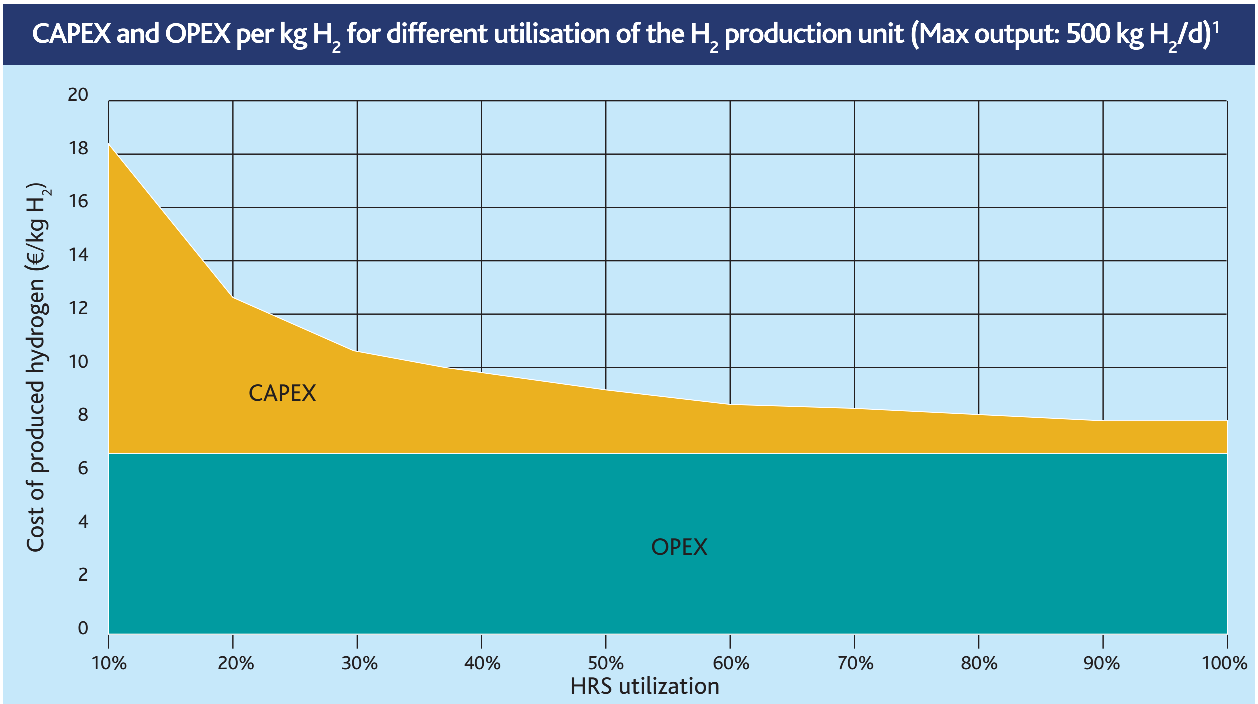


Figure 25 - CAPEX and OPEX per kg H_2 for different utilisation of the H_2 production unit (max. output: 500 kg H_2/d)[1]

Figure 26 illustrates the variation of the OPEX based on different electricity prices (see Figure 18) for two HRS, the first with 1,000 kg H_2/d and the second with 6,000 kg H_2/d capacity. Except for extremely low electricity prices, the OPEX usually dominates the overall hydrogen production cost and it increases significantly for higher electricity prices. This emphasises the importance of access to electricity at relatively low cost for a cost efficient H_2 production using an on-site electrolyser.

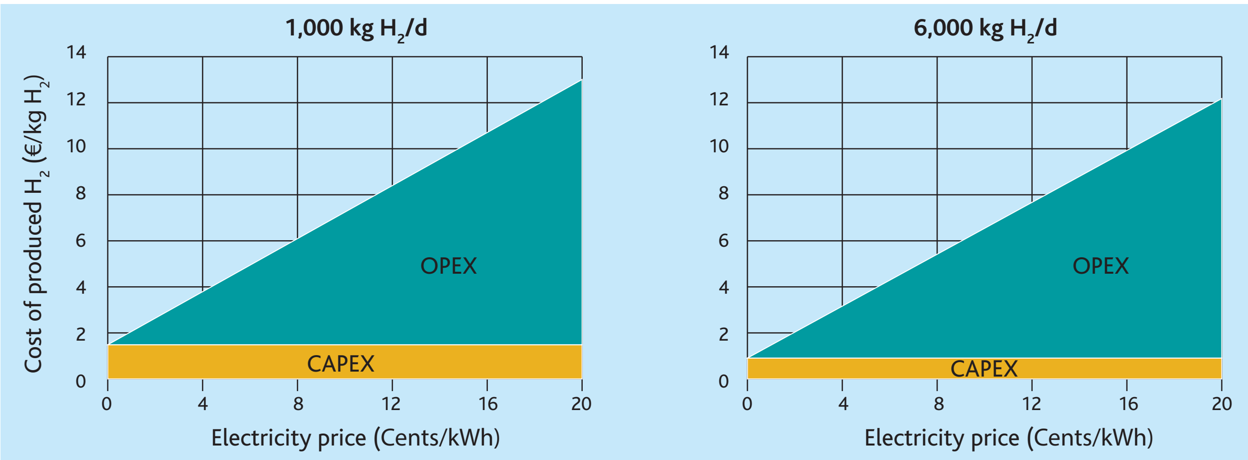


Figure 26 - Hydrogen production cost from on-site electrolysis (left: 1,000 kg H_2/d; right: 6,000 kg H_2/d) for different electricity prices[2]

[1] Assumptions: CAPEX of the H_2 production unit according to Figure 8, electricity consumption: 58 kWh/kg, electricity price: 0.12 €/kWh, HRS for a max. of 500kg H_2/d, 10 years of depreciation

5.2.2 Cost related to off-site H_2 production and transport

An alternative to producing the H_2 on-site is the delivery of hydrogen from an external supplier. In this case, the H_2 is usually produced in large centralized facilities, which may reach a higher efficiency and thus lower production cost than on-site production systems. Alternatively the H_2 may originate as a by-product from industrial processes which may produce potential low H_2 costs. It is therefore highly advisable to get in touch with potential suppliers about the possibilities of using delivered hydrogen, and to discuss the options of H_2 production and delivery. The project specific boundary conditions with regard to technology, cost and environmental performance need to be taken into account in these considerations.

Similar to hydrogen, which is produced on-site, the cost of delivered hydrogen depends on a number of aspects. These include the source of hydrogen and the associated environmental profile, the state of the delivered hydrogen, liquid or gaseous, and in the latter case the pressure level of the delivered hydrogen, the distance profile and the route of the hydrogen delivery, the regular hydrogen demand, the duration of the delivery contract, termination rights, penalties for non-fulfilment of the contract as well as numerous other contractual conditions.

Generally, the production cost for liquid hydrogen at the production facility without delivery, is above the production cost of gaseous hydrogen due to the energy intensive liquefaction process (see Section 2.3.1). However, since a larger amount of hydrogen can be transported when delivered in liquid state compared with gaseous hydrogen, the delivery costs per kg of hydrogen are usually lower for LH2 than for GH2 delivered in tube trailers. As a result, depending on the delivery distance, the final price per kg LH2 can be similar or even below the price of GH2.

As for hydrogen that is produced on-site certain environmental requirements, such as hydrogen from low-carbon sources, may increase the price of delivered hydrogen as the H_2 production is likely to be more expensive. The certification possibilities for a guaranteed origin of delivered hydrogen have been elaborated within the CertifHy project [CertifHy]. Since an HRS using delivered hydrogen does not require an on-site hydrogen production unit, the necessary CAPEX is generally significantly lower than for an HRS with on-site production (see also [NOW-A], [NREL-B]).

The economic advantages of the reduced necessary investment may compensate for a potentially higher hydrogen cost at the storage intake of the HRS. Hence, depending on the individual circumstances, the delivery of hydrogen might be a cost-effective solution that may be competitive or even have cost advantages compared to on-site hydrogen production.

Besides the hydrogen being delivered in trailers, transport is also possible via pipeline depending on the distance and the surrounding area. Due to the different circumstances, the investment indications provided in literature sources (see [Linde – H_2], [US DoE H2A-B]) vary from several hundreds of thousand Euros per kilometre to more than 1 million Euros per kilometre. Accessing an existing pipeline network is advantageous but also building a new pipeline can be a cost-effective solution for short distances (ideally only a few kilometres) and high hydrogen throughput.

More information with respect to the different forms of hydrogen transport and the related costs can be found in the literature (see [Höhnlein, Grube], [McK – Urban buses]).

[2] Assumptions: CAPEX of the H_2 production unit according to Figure 24, depreciation period: 10 years, electricity consumption: 58 kWh/kg H_2

5.2.3 Cost related to storage and compression unit

Since the concepts for the compression unit and the hydrogen storage are strongly interrelated (see Section 2), it is difficult to clearly associate costs only to the compression unit without discussing the financial consequences on the hydrogen storage. For this reason, the sum of the investment costs for the compression unit and the hydrogen storage will be related to the HRS capacity. Prior to this, the investment for the storage in relation to the installed storage capacity will be addressed.

The reported investments that are necessary for the hydrogen storage vary significantly among the studies that were conducted within the NewBusFuel project. This is mainly due to the different technical solutions that were applied. The typical investment for a GH2 storage at a pressure level of 500 bar for overflow refuelling is within the range of 800 – 1,500 €/kg H_2.

This is also in line with the estimates provided in the H2A model of the U.S. Department of Energy, which assumes an investment of about 1,350 €/kg H_2[3] for a 350 bar cascade storage, and about 2,000 €/kg H_2 for a 700 bar system [US DoE H2A-B]. LH2 storages are estimated to have considerably lower costs, at below 100 €/kg LH2 [US DoE H2A-B]. In this regard, it is important to differentiate properly between the possible refuelling approaches and the related technologies.

Since most storages are passive components, they do not consume electricity during operation. Constant pressure storages, however, have active hydraulic units and do consume electricity causing a certain OPEX.

Hydrogen losses from the storage, such as boil-off losses from LH2 storage tanks, could be considered as OPEX but as mentioned previously, they are especially low at HRS with large hydrogen throughput and can be avoided by intelligent system designs, e.g. any boil-off H_2 is refuelled into the bus tanks by using a CHC.

Although the hydrogen storage usually requires a significant investment, typically in the range of several million Euros, its contribution to the final cost of the refuelled hydrogen is rather small, typically below 0.50 €/kg H_2 at an assumed lifetime of 20 years.

The compression unit is an expensive piece of equipment that can require investments of several million Euros.

3 Assuming an exchange rate of 1.12 US$ = 1€ and an using the inflation until 2016 indicated at http://www.usinflationcalculator.com/

The total investment for the compressor unit and for the hydrogen storage is linked to the HRS capacity. The typical investment for these two modules together is within the range of 2,500 – 5,000 €/(kg H_2/d), with the higher cost value applying to smaller HRS, and larger HRS able to achieve costs at the lower end of the range. The resulting contribution to the hydrogen cost per kg H_2, for both storage and compression unit, can still be well below 0.50 €/kg H_2.

Depending on the type and size of a gaseous hydrogen compressor, the H2A model assumes investments of 4,000 – 8,000 €/kW [US DoE H2A-B]. The cost of a LH_2 cryo-pump or a cryogenic hydrogen compressor (CHC) is usually below that of compressors for GH2 [e-mobil BW] and due to the more efficient compression consumes less electricity per kg of H_2.

The electricity consumed by the compression unit contributes to the related OPEX. Again, the different concepts and designs within the NewBusFuel project lead to a wide range of electricity required for the compression. The average is within the range of 3 - 5 kWh/kg H_2, which results in an OPEX potentially below 0.50 €/kg H_2 depending on the electricity price. Due to the higher energy efficiency for the compression of LH_2, cryo-pumps and CHC consume significantly less electricity and hence cause lower related OPEX cost [e-mobil BW].

5.2.4 Cost related to dispensing unit

In line with the many different designs considered for the dispensing area in the NewBusFuel studies, the reported investments differ significantly from each other, ranging from a few hundred thousands of Euros to several million Euros for the entire dispensing unit. The differences depend on issues such as different civil works or special equipment that is required, e.g. precooling for fast-refuelling or combined evaporator/heat exchangers for using LH_2 and also what system boundaries were applied in the different case studies, i.e. which components are actually included in the dispensing unit. The typical investment can be determined to be in the range of 100,000 – 300,000 €/dispenser. Hence, the dispensing unit has little impact on the overall CAPEX per kg H_2. For the commonly used overflow refuelling, the electricity consumption, e.g. for controls, is very small and insignificant for the final hydrogen cost. However, the electricity consumed for active auxiliary systems, such as the precooling of the hydrogen may be of relevance.

The refuelling period needs to be chosen so that costs can be optimised. This could involve extending the time available for refuelling the bus fleet, and reducing the number of dispenser so that the CAPEX can be reduced. On the other hand, a longer refuelling period adds potentially more personnel cost contributing to the OPEX. A carefully considered refuelling strategy may reduce the necessary refuelling infrastructure and shorten the cost and time to refuel the bus fleet.

5.2.5 Other cost elements

Besides the cost elements discussed in the previous sections, there are other types of cost that are relevant for HRS projects, such as financing costs for the necessary loans. These are included in the overall HRS project costs that are addressed within the next section.

Another important cost element that needs to be considered are expenses related to maintenance. Depending on the volume produced and dispensed, and the conditions of a maintenance contract, the related annual costs account for a few percent of the overall investment for the H_2 equipment, which may have a considerable contribution to the overall H_2 cost (see also examples in the next section).

5.2.6 Summary of HRS cost

This section addresses the overall picture of CAPEX and OPEX for the HRS.

Figure 27 shows the approximated investment that was determined from the NewBusFuel studies for a complete HRS with on-site hydrogen production with both electrolyser and steam reformer, including all modules discussed previously plus additional costs such as further general civil works, project management cost, financing etc. As the plot indicates, the total investment rises less steeply for HRS with larger capacities than for smaller HRS.

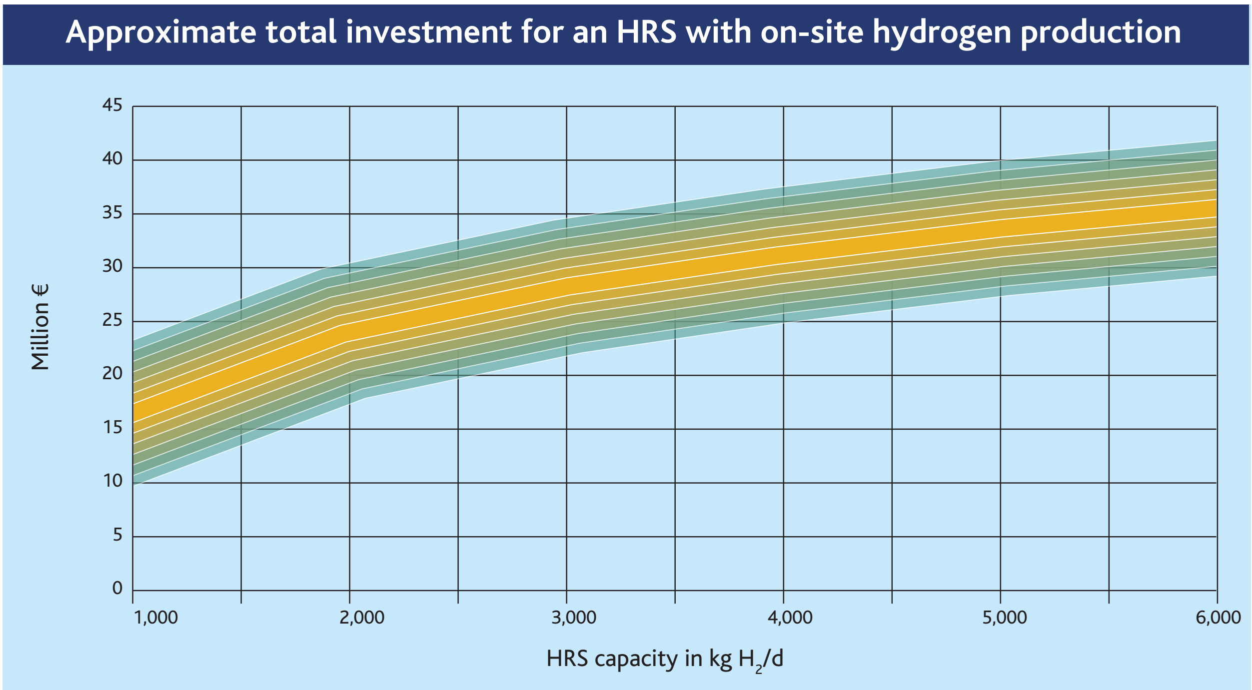


Figure 27 - Approximate total invest for an HRS with on-site hydrogen production

An HRS with a capacity of 1,000 kg H_2/d requires a total investment of approximately 16.5 million Euros, representing a specific invest per daily refuelling capacity of 16,500 €/(kg H_2/d). For a larger HRS with 6,000 kg H_2/d capacity, the HRS costs approximately 35.5 million Euros, which corresponds to less than 6,000 €/(kg H_2/d). The latter investment value in particular is significantly below the range of 13,000-18,900 €/(kg H_2/d) that was indicated for the same type of HRS in the CHIC Project [CHIC – D3.11]. This reduction is likely to be caused by the larger HRS capacities within the NewBusFuel project and the related economies of scale.

Figure 28 and Figure 29 show four current HRS examples two with on-site electrolysis and two with on-site steam reforming, each technology for two different refuelling capacities, i.e. 1,000 and 6,000 kg H_2/d. Due to the shorter assumed lifetime of the HRS with electrolyser (caused by the shorter lifetime of the electrolyser stack), the CAPEX of the HRS with on-site electrolysis is higher than that of the HRS with on-site steam reformer. Both CAPEX and the related maintenance cost are significantly lower for the two HRS with larger refuelling capacity compared to the smaller systems. For the HRS with on-site electrolysis, the hydrogen price is mainly determined by the electricity cost. For the HRS with steam reformer, the hydrogen cost depends very much on the natural gas cost.

However, the overall hydrogen cost level is below that of the HRS with electrolyser in these examples.

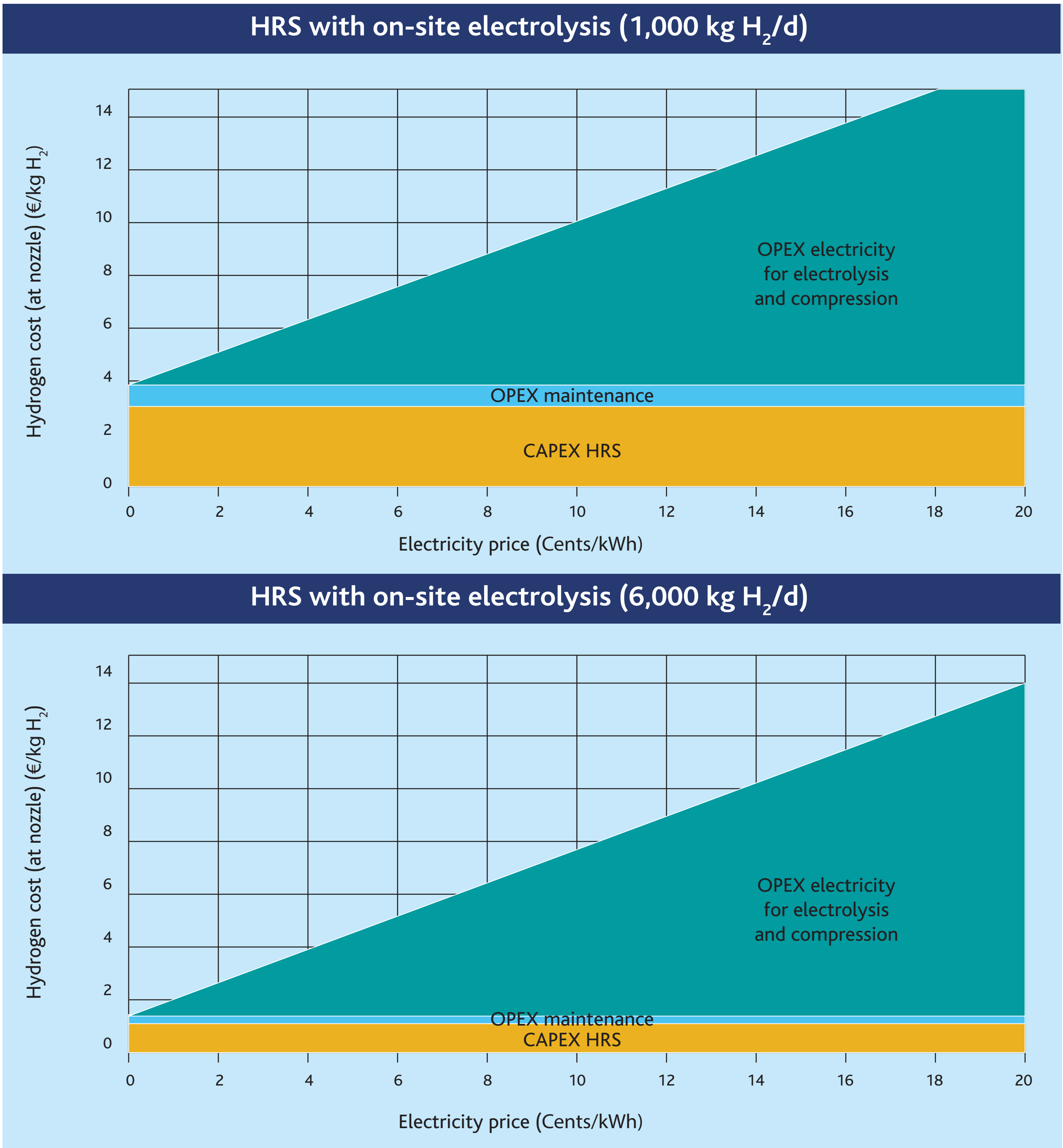


Figure 28 - Example for hydrogen costs (at refuelling nozzle) as function of the electricity price for two HRS with different capacities (1,000 kg H_2/d and 6,000 kg H_2/d) using on-site electrolysis[4]

[4] Assuming: 58 kWh/kg H_2 at electrolyser, 4 kWh/kg H_2 for compression, CAPEX as indicated in the previous sections with an overall lifetime of 15 years, 3% of H_2 equipment investment as annual maintenance cost

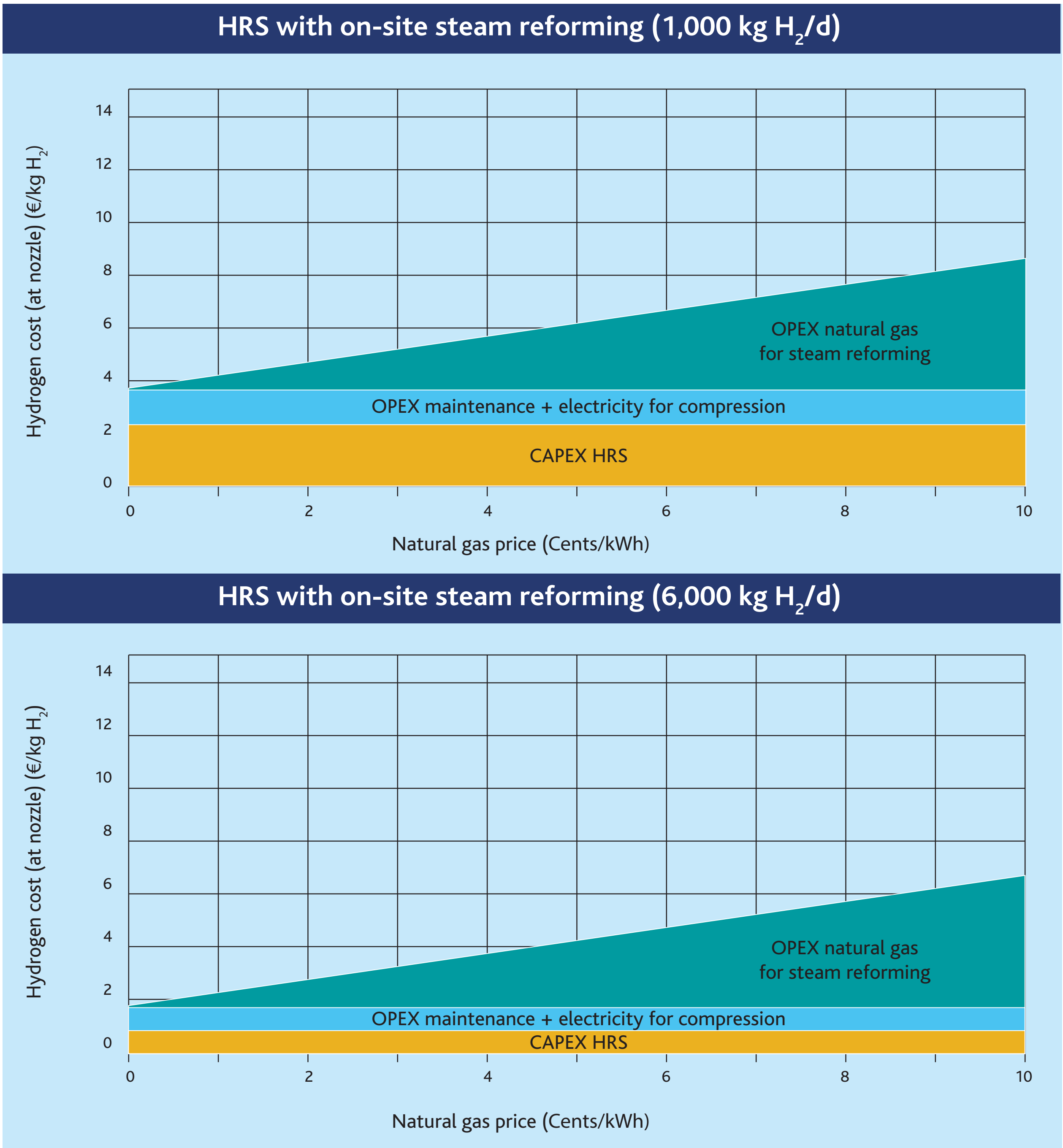


Figure 29 - Example for hydrogen costs (at refuelling nozzle) as function of the natural gas price for two HRS with different capacities (1,000 kg H_2/d and 6,000 kg H_2/d) using on-site steam reforming[5]

[5] Assuming: 50 kWh/kg H_2 natural gas consumption for steam reforming, 4 kWh/kg H_2 electricity consumption for compression, CAPEX as indicated in the previous sections with an overall lifetime of 20 years, same maintenance cost as in electrolyser examples, electricity price of 0.12 €/kWh.

It is important to note, that the provided figures are based on estimates that reflect the current cost situation. In the future, further significant reductions of the CAPEX and the OPEX can be expected. The ***Multi-Annual Work Plan*** of the FCH JU estimates a cost of 1,500 €/(kg H_2/d) for 2023, which is a reduction of 60 % compared with the price in 2017 [FCH JU – MAWP]. Also the OPEX is expected to decrease based on an efficiency gain of 10 % in the electrolyser between 2017 and 2023, representing an electricity consumption that is reduced by 5 kWh/kg H_2. For the HRS example with on-site electrolysis and a refuelling capacity of 1,000 kg H_2/d mentioned above, this represents a cost reduction of 0.49 €/kg H_2 due to the lower CAPEX, and assuming an electricity price of 8 Cents/kWh, an additional OPEX reduction of 0.40 €/kg H_2. Taking into account the effect of the reduced maintenance costs (3 % of the investment for the H_2 equipment), the total achievable cost reduction by the year 2023 according to the mentioned assumptions sums up to 1.07 €/kg H_2. Further information on the future price development of fuel cell technologies can be found, e.g. in [RB – FC electric buses].

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For HRS with off-site H_2 production, the price of delivered hydrogen is critical to the overall hydrogen cost. The contribution of the HRS infrastructure is rather small, generally below 1.00 €/kg H_2 [NOW-A].

5.3 Basic environmental parameters

Since the reduction of the environmental impact caused by public transport is often one of the main drivers for the deployment of hydrogen buses, the environmental performance of different HRS concepts is addressed in this section. The origin of the hydrogen, i.e. what resources are used for the H_2 production, is the key to minimising environmental impact. The various hydrogen supply routes require different amounts and types of energy, and hence they cause different environmental impacts of the refuelled hydrogen.

The locally emission-free operation of hydrogen fuel cell buses, i.e. the avoidance of local NOx and PM emissions from bus operation, is a fundamental advantage compared with diesel buses. However, these emissions may also occur during the hydrogen production, e.g. for producing the electricity needed in the H_2 production process or for the manufacturing of the materials used in an electrolyser stack, compressor or other equipment. Since these so-called “upstream emissions” usually happen in less populated areas, a quantitative assessment of these pollutants with a local impact is beyond the scope of the document at this point. Detailed analyses of a broad spectrum of environmental impacts, considering the complete lifecycle of H_2 production, have been carried out in previous FC bus demo projects such as CHIC, ECTOS, FC HyGuide, HyFLEET:CUTE[6] (see [CHIC – D3.9], [ECTOS – D 16], [FC-HyGuide-A], [FC-HyGuide-B], [HyFLEET:CUTE – D 3.4]).

This section focusses on the globally important emission of greenhouse gases (GHG) and the primary energy demand from non-renewable resources during the on-site and off-site hydrogen production. The former impact comprises a number of emissions and aggregates them into the global warming potential (GWP), which is expressed in kg CO_2-equivalents. The latter impact sums up the demand of primary energy from non-renewable resources, using the net calorific value, and is expressed in MJ (non-renewable PED).

To assess these environmental impacts of the H_2 dispensed to buses, it is important to consider the entire processes. It should comprise all processes that cause emissions, such as the use of energy, during production, transport and dispensing of the hydrogen, as well as for the manufacturing and end of life of all HRS components.

Due to the large amounts of hydrogen produced, the manufacture and end of life of the components used in an HRS generally contributes insignificantly to the overall environmental impact per kg H_2 dispensed. This is confirmed by the findings of previous projects (see also [CHIC – D3.9], [CHIC – D3.15], [ECTOS – D 16]). Similarly, the transport of hydrogen being delivered has a rather small contribution to the overall environmental footprint. For this reason, this section focusses on the different types of H_2 production and the related environmental impacts.

More information on the GHG emissions related to the manufacturing of a hydrogen fuel cell bus was compiled e.g. within the HyFLEET:CUTE and the CHIC Project (see [HyFLEET:CUTE], [CHIC – D3.9], [CHIC – D3.15]).

[6] The life cycle assessments carried out in these projects used the established methodology according to ISO 14040/44 and considered the manufacturing of the equipment, e.g. electrolyser, steam reformer, the needed utilities (e.g. electricity, natural gas) as well as maintenance and end of life of the H_2 production equipment.

Environmental performance of hydrogen from on-site electrolysis

The source of the electricity used for on-site hydrogen electrolysis is the key parameter determining the environmental impact of the produced hydrogen. Each country uses the various power plant technologies available in their network for electricity generation in different proportions. This results in different individual emissions and primary energy consumption per kWh grid electricity. Table 5 illustrates the GHG emissions and the primary energy demand of country-specific electricity generation and for some renewable technologies (from a grid connection > 1 kV) as well as the resulting emissions and the energy demand per kg H_2 refuelled (considering an electricity demand of 58 kWh/kg H_2 for the on-site electrolysis and 4 kWh/kg H_2 for the compression to 500 bar).

GWP and non-renewable PED for electricity generation and for H_2 at HRS with on-site electrolysis incl. compression

	Electricity generation	Electricity generation	H_2 production incl. compression	H_2 production incl. compression
Country / Technology (reference year 2013)	GWP (g CO_2-eq./kWh)	Non ren. PED (MJ/MJ)	GWP (kg CO_2-eq./kg H2)	Non ren. PED (MJ/kg H_2)
EU-28	423	2.06	26.2	459
BE	214	2.17	13.3	484
DE	595	2.09	36.9	467
ES	317	1.62	19.7	361
UK	496	2.28	30.8	508
IT	429	1.67	26.6	373
LV	631	2.16	39.1	481
NO	36	0.13	2.2	30
EU-28: hydropower	6	0.01	0.4	2
EU-28: photovoltaic	31	0.13	1.9	30
EU-28: wind power	9	0.03	0.5	7

Table 5 - GWP and non-renewable PED for electricity generation and for H_2 at HRS with on-site electrolysis (simplified: 58 kWh electricity/kg H_2 for production and 4 kWh electricity/kg H_2 for compression), calculated using thinkstep's GaBi software and LCA databases 2017 [GaBi]

As the figures indicate, hydrogen produced with electricity from renewable sources and in countries with a high share of low-carbon electricity generation, such as Norway and Belgium, have a considerably lower GWP than in countries with a high share of conventional thermal electricity production from fossil fuels, such as Germany or the UK.

Environmental performance of hydrogen from on-site steam reforming

The hydrogen production from natural gas in an on-site steam reformer is influenced by the HRS location and the respective natural gas supply chain. While some countries can use domestic natural gas resources, others have to import natural gas from distant sources with significant effort, which increases the related environmental impact. Table 6 shows the GWP and the primary energy demand of the natural gas supply for several countries. The values for the GWP vary significantly from each other.

However, the influence of the natural gas supply chain on the overall environmental impact of hydrogen produced in an on-site steam reformer is relatively small, since a significantly larger amount of GHG emissions originates from the reforming process itself.

If biomethane from renewable sources is used for the steam reforming process instead of natural gas, the related GHG emissions as well as the non-renewable PED related to the hydrogen production are reduced significantly.

GWP and non-renewable PED for natural gas supply and H_2 at an HRS with on-site SMR incl. compression

	Natural gas / bio-methane supply	Natural gas /bio-methane supply	H_2 production incl. compression	H_2 production incl. compression
Country / Technology (reference year 2013)	GWP (g CO_2-eq./kg gas)	Non ren. PED (MJ/kg gas)	GWP (kg CO_2-eq./kg H2)	Non ren. PED (MJ/kg H_2)
EU-28	518	50.6	13.2	211
BE	220	44.7	11.3	197
DE	458	48.7	13.6	204
ES	656	51.9	13.1	199
UK	232	48.2	12.4	201
IT	722	52.3	13.9	212
LV	758	56.0	14.7	216
NO	85	47.9	10.1	167
EU-28: biomethane mix + conv. electricity mix for compression	1,129	6.0	5.4 (without compres-sion: 3.7)	49.4 (without compres-sion: 19.8)
EU-28: biomethane mix + electricity from EU hydropower for compression	1,129	6.0	3.7 (without compres-sion: 3.7)	19.9 (without compres-sion: 19.8)

Table 6 - GWP and non-ren. PED for natural gas supply and H_2 at an HRS with on-site SMR incl. compression (simplified: 4 kWh/kg H_2 for compression), calculated using thinkstep's GaBi software and LCA databases 2016 [GaBi]

Comparing the environmental impact of on-site steam reforming and on-site electrolysis reveals that the hydrogen production from natural gas causes lower GHG emissions than using the average electricity grid mix in many European countries. Only for countries such as Norway, in which the share of electricity from renewable energies is very high, the GHG emissions related to hydrogen produced in an on-site electrolyser are below that from on-site steam reforming. It becomes clear that in order to achieve low GHG emissions from on-site electrolysis in other countries, electricity from renewable sources needs to be used for the electrolysis process and the compression to 500 bar, which is likely to be related to higher electricity costs. Hydrogen from the steam reforming of biogas/-methane leads to low GHG emissions, which can be further reduced if electricity from renewable sources is used for the hydrogen compression.

Environmental performance of hydrogen from off-site production

The environmental impact of hydrogen that is produced off-site also depends on the chosen H_2 production route and the source used. Common production routes of off-site production are centralized steam reforming, using natural gas or heavy fuel oil, the catalytic reforming of hydrocarbons in a refinery, hydrogen produced as by-product in a chlor-alkali electrolysis or from coke production. The CertifHy project has chosen the steam methane reforming of natural gas as a benchmark for the GWP of hydrogen production with an emission factor of 91.0 g CO_2/MJ, which is equivalent to 10.9 kg CO_2-eq./kg H_2 [CertifHy – D2.4]. Low-GHG-emission hydrogen is based on a 60 % reduction with respect to the baseline, resulting in emissions of 36.4 g CO_2-eq./MJ or 4.4 kg CO_2-eq./kg H_2. These figures, together with the GWP and the non-renewable PED for the most important sources of off-site hydrogen production previously mentioned are summarized in Table 7.

Since the liquefaction of hydrogen is a highly energy intensive process (see Section 2.3.1), which requires about 30% of the hydrogen's energy content, the liquefaction of hydrogen increases the environmental impact (see Table 7). For completeness, the compression to 500 bar with an electricity requirement of 4 kWh/kg H_2 is also included in Table 7. Due to the higher energy efficiency, the compression of LH2 in a cryo-pump or in a cryogenic hydrogen compressor causes significantly lower emissions than the compression of GH2.

GWP and non-renewable PED for various off-site hydrogen production processes (excl. compression), for liquefaction and compression

Technology (reference year 2013)	GWP ($kg\ CO_2$-eq./$kg\ H_2$)	Non-ren. PED ($MJ/kg\ H_2$)
Steam reforming of natural gas	11.0	195.8
Steam reforming of heavy fuel oil	14.1	182.7
Hydrogen at refinery (2011)	1.8	170.9
Hydrogen from chlorine-alkali-electrolysis (membrane)[7]	0.9	15.9
CertifHy benchmark value: natural gas steam methane reforming [CertifHy – D2.4]	10.9	n/a
CertifHy Low-GHG-emissions hydrogen [CertifHy –D2.4]	4.4	n/a
Liquefaction (EU - 28)	5.0	87.4
Electricity for compression of GH2 (EU-28)	1.7	29.6

Table 7 - GWP and non-ren. PED for various off-site hydrogen production processes (excl. compression), for liquefaction and compression, Calculated using thinkstep's GaBi software and LCA databases 2017 [GaBi], as well as CertifHy GHG emissions [CertifHy – D2.4]

[7] The environmental burden of the process is distributed between chlorine, sodium hydroxide, and hydrogen according to the individual mass (allocation by mass) according to the common practice in this industry. If a different approach was chosen, the environmental impact related to hydrogen might vary accordingly.

5.4 Key issues to be considered in the HRS design

Based on the findings of the previous sections, the following key issues for designing an HRS have been identified.

Careful exclusion of available options

The various technical, economic and environmental parameters important for the HRS design and operation as well as the refuelled hydrogen have been outlined. A number of rules of thumb and approximations have been suggested to assist in determining the specific requirements and allow first estimations for the HRS specifications and cost. The purpose is to consider options and develop a limited number of appropriate concepts to focus on and discuss with potential suppliers in more detail.

However, the targets, priorities, and constraints may change during the progress of the project, for example when new stakeholders are integrated into the project definition or when new aspects appear to be relevant. For this reason, considering a particular HRS concept as unsuitable and excluding it from future considerations needs to be done with caution. All technologies can be optimized with respect to certain targets, so it is recommended to revisit discarded options as the HRS project develops and check if they remain an unsuitable solution or if they may become a viable option again due to changed boundary conditions.

Interrelations between FC bus fleet and infrastructure

Fuel cell buses and HRS infrastructure require significantly higher investments than diesel buses and diesel refuelling infrastructure. Further, the hydrogen needs to be provided for refuelling at the right pressure level, temperature and quality as well as quantity before it is refuelled to the buses. For these reasons, the interrelations between the bus fleet and the infrastructure are significantly stronger for hydrogen technology. This requires a certain change in thinking.

The suitability of an HRS concept strongly depends on the fleet size that needs to be refuelled. Since an HRS, especially with on-site hydrogen production, requires large investments, which for small throughputs contribute significantly to the final hydrogen cost, it is advisable to refuel smaller bus fleets e.g. < 10 buses at an existing HRS if available, or using hydrogen delivery instead of on-site production. For larger bus fleets it is important to coordinate the bus fleet size and the infrastructure capacity to avoid unused overcapacities that unnecessarily increase the hydrogen fuel cost. This includes carefully considering and, if necessary revising, the planned ramp-up of the fuel cell bus fleet, since a different fleet size might be advantageous for a certain HRS achieving lower overall costs.

The example provided in Figure 30 illustrates this aspect. With an annual procurement of 3 additional fuel cell buses per year, there remain significant unused overcapacities of the HRS infrastructure that unnecessarily increase the hydrogen cost (see Figure 30 - top). By changing to a procurement of 9 buses every three years, these overcapacities can be reduced, although not avoided completely, and the resulting hydrogen cost can be decreased (see Figure 30 - bottom).

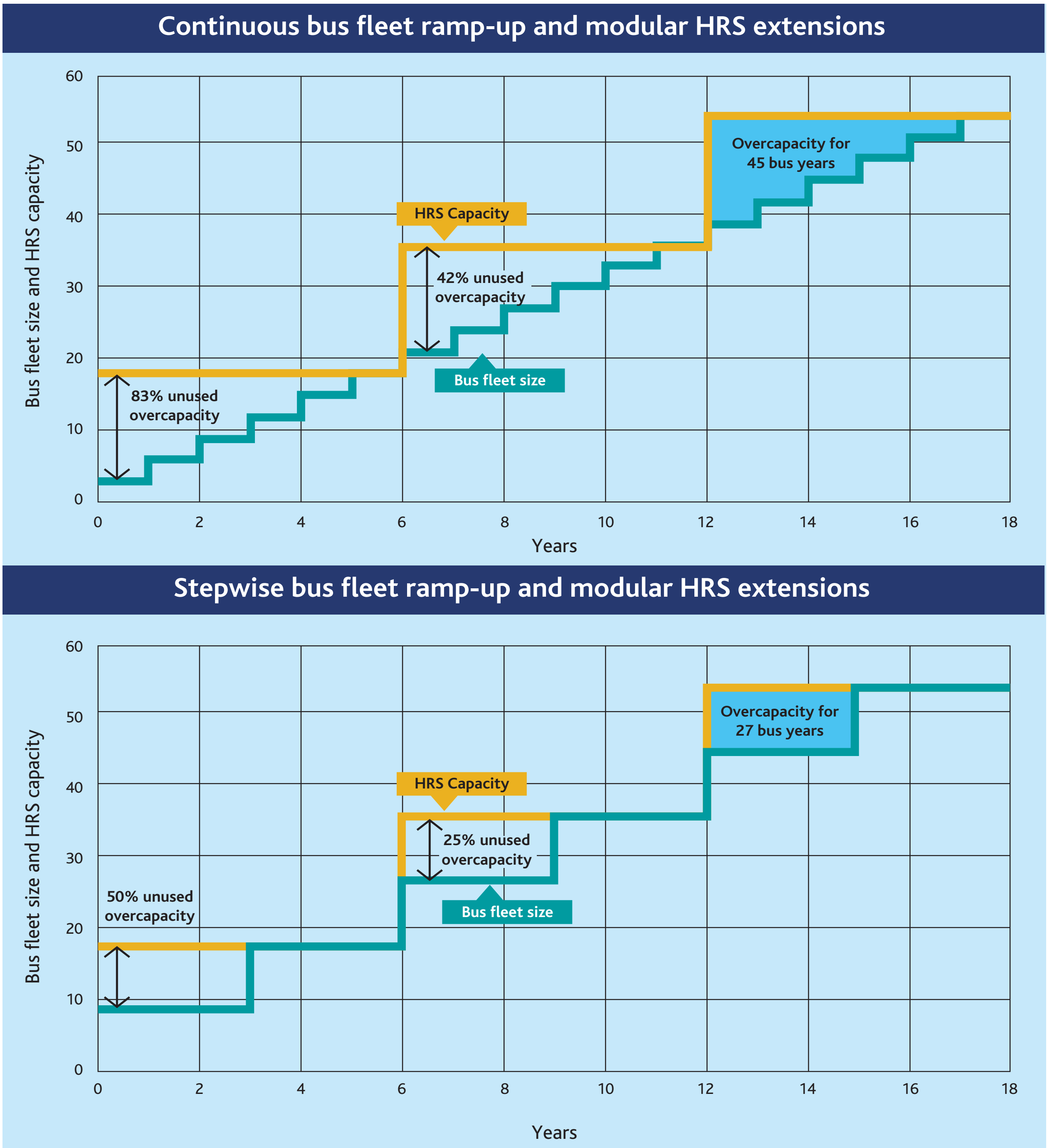

Figure 30 - Overcapacities depending on the bus procurement strategy. Top: continuously 3 buses per year. Bottom: stepwise 9 buses every 3 years

Modularity, redundancy and refuelling reliability of the HRS

The three aspects of modularity, redundancy and refuelling reliability of an HRS are strongly related to each other. As discussed previously, there are a number of reasons for choosing a modular HRS design. The integration of a redundant component, causes a smaller cost increase for an HRS with smaller module size than for an HRS with larger module size. Other means to provide bus service, e.g. through conventional diesel buses should be considered when specifying the refuelling reliability. Further, there are several more cost-effective means to ensure a high refuelling availability (see Section 5.1).

Importance of the electricity price for on-site electrolysis

As discussed previously (see Section 5.2.1), the price of electricity that is used for on-site electrolysis is of fundamental importance. It varies significantly across European countries and high additional taxes and levies apply in some countries. Access to electricity at reasonable cost is essential for a cost-effective H_2 production using on-site electrolysis [NBF – D4.3].

Also for the environmental footprint resulting from on-site hydrogen electrolysis to be minimised, the source of electricity is essential (see Section 5.3).

6. Engagement with stakeholders – Projects are about people too!

Box III in the proposed project framework, see Figure 11 on page 43

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6. Engagement with stakeholders – Projects are about people too!

In managing the successful introduction of any cutting edge technology, it is crucial to identify early who are the **people** important to the success of the venture. This is a truism that has been well understood by the "tech successes" of our era such as Apple and Microsoft. Project managers for the construction of an HRS ignore this component at their peril as many lessons from demonstration projects testify [HyFLEET:CUTE – D6.10].

Fortunately, previous hydrogen projects have developed a wealth of experience and information on this aspect of HRS development and implementation.

This section briefly addresses how this activity should be approached, touching on the who, what and when of engagement with stakeholders in line with the framework (see Section 3) and provide 'go to' resources/references for guidance in this essential aspect of an HRS project.

6.1 Preparation stage of the HRS project – Mapping stakeholders

Box I in the proposed project framework, see Figure 11

As a project manager in charge of installing an HRS, it is likely that there will already be a well-known group of stakeholders. However, there will be some less evident stakeholders that also need to be identified. For this reason, a stakeholder mapping exercise for the entire project should be undertaken early. For assistance with this activity go to People, Transport and Hydrogen Fuel, Guidelines for Local Community Engagement when Implementing Hydrogen Powered Transport [HyFLEET:CUTE – D6.10]. These Guidelines were developed under the guidance of a hydrogen infrastructure supplier, and provide some very useful tips.

As a starting point, project managers should have clear answers to the questions below. These are the people whose goals and priorities need to form the background to all work in the project, and to whom **appropriate** levels of information about progress/issues/challenges must be continually fed throughout the project life.

- Who is driving the project?
- Who is funding the project?
- Who is the responsible in the organisation running the project?
- Who else in the regional context might be invited into the project?
    - Municipal utilities (bus operator might be part of the same entity) or external utility companies: electricity suppliers, natural gas, water, etc. or even of H_2; grid balancing services / synergies; different useful intelligent systems e.g. frequency control, demand management, turn-off
    - Industries: chemical sector, energy sector → for production or additional consumption of hydrogen
    - SMEs: as additional H_2 consumer by means of hydrogen fuelled vehicles (cars, forklifts, …)
    - Hydrogen demand of other fleet operators: Airport/Port/Public vehicle fleets
    - Other bus operators: Bus and infrastructure procurement together with other bus operators can be a cost effective procurement methodology; standardize buses; coordination of HRS design among the cities involved (among other things providing a pool of spare parts users)

The word **appropriate** is very important in relation to the mentioned information level – because while, for instance, a politician may require limited detail of the engineering aspects of the project, they will need significantly more detail of any challenges that it is facing, especially in terms of meeting deadlines and budgets. Other stakeholders may want indicative budgets and others still, more detailed engineering information.

This may be self-evident, but there is clear evidence from previous and current demonstration projects that information flows to and from these people get interrupted, leading to expectations not been met and a loss of support. More information on the factors influencing acceptance and attitudes among this group can be found in Influencing factors to the acceptance process of FCH technologies in public transport (CHIC Project), Chapter 5 (specifically 5.3.1. – Regional Context) [CHIC – D3.5].

6.2 Goals, priorities & constraints – Collaboration and co-operation with stakeholders

Boxes II & IV in the proposed project framework, see Figure 11

While determining the basic parameters of the future HRS is a technical exercise (calculating i.e. capacity; operating imperatives; resource needs, footprint, environmental impact and costs), establishing an HRS is also very much a people exercise. It must involve the bus operators and appropriate other experts to arrive at some sort of 'blue sky' scenario at the desktop.

Having some grasp of the technical information is an essential basis for the next stage of developing a more defined view of what a specific HRS will look like. At this stage there are many stakeholders.

Setting goals and priorities must involve initiators and funders as well as the bus operators. But now is also the time to speak to regulators and the local community. There are many myths that still abound in the local community (even among the authorities) in relation to hydrogen. These are best dealt with by engagement early in the process of planning an HRS – well before talking to suppliers and the RFT process. The conversations also must be on-going. Many different people and groups can and do impose constraints for a wider variety of reasons on what can be built, where it can be built and even what the building may look like. In a celebrated example, one HRS in the UK had to be moved from a preferred position because it was considered to have a too industrial "look" for the particular area in which it was to be sited. In another, a disaffected neighbour spreads the rumour that a hydrogen "bomb" was being installed in the neighbourhood.

Fortunately, there is much written to assist in determining who to engage with and on what and how to engage in relation to the HRS. The previously mentioned resource [HyFLEET:CUTE – D6.10] also gives a wealth of information about engaging with those people who live near to the proposed site and the local authorities who will also need to be involved. Also in relation to certifying authorities there are numerous useful resources [CHIC – D4.3b], [DeliverHy], [NOW-C]. [CHIC – D3.5].

6.3 Key issues to be considered when engaging with stakeholders

For answering the question, of what the key issues for engaging with stakeholders are, the following two have been identified based on the learning from NewBusFuel and other FC bus projects.

Stakeholder prioritisation mapping

Of course, engagement is resource intensive if done properly, and sometimes trade-offs need to be made about whom, how and how often. To assist in assessing this aspect, the four quadrant graph below (see Figure 31) was developed by Rouvroy et al. [HyFLEET:CUTE – D6.10].

Addressing conflicts

Finally, in the case of conflicting goals between the HRS project goal and/or plans and any of the stakeholders identified, a decision has to be made whether to modify the project. This of course will depend on the individual circumstances, but with new technology, it has been the experience of demonstration projects that it is always advisable to err on the side of co-operation; another reason why engagement early in any HRS project is vital.

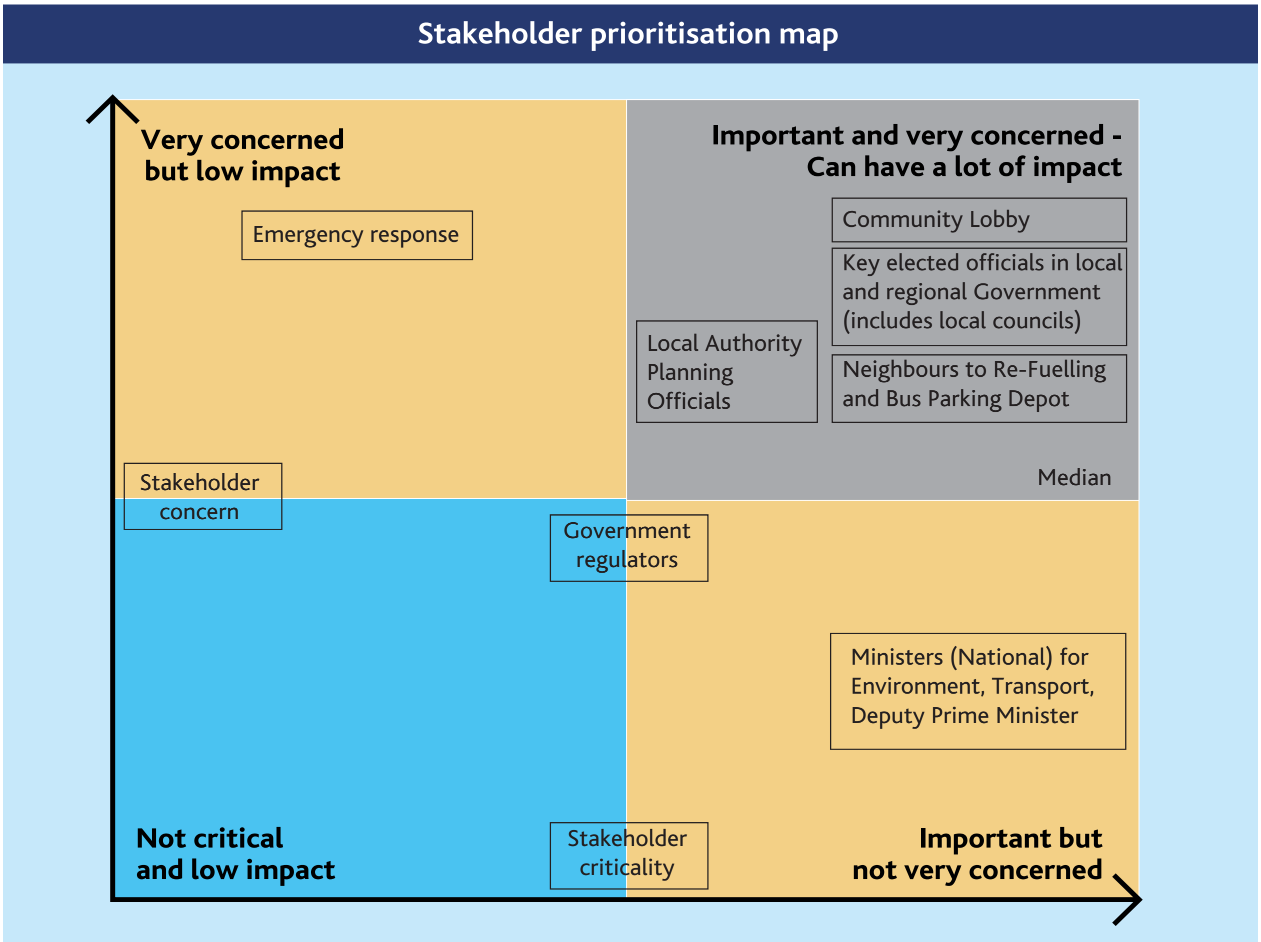

Fig 31 - Stakeholder prioritisation map [HyFLEET:CUTE – D6.10]

7. Defining the HRS project

Box IV in the proposed project framework, see Figure 11 on page 43

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7. Defining the HRS project

Box IV in the proposed project framework, see Figure 11

After the relevant stakeholders have been identified, the characteristics of the HRS project need to be defined. These specifications need to be based on a common understanding of all parties involved. Since conflicts of interest frequently occur when a large number of different stakeholders is included in a project, it is essential to define the HRS project in an accessible and transparent way. This section addresses several relevant aspects and provides approaches and tools that might help for the definition of an HRS project.

As mentioned already in Section 4, checking and revising such a definition regularly is essential for successfully conducting an HRS project. Such revisions need to be done for example when new stakeholders are integrated into the project and the priorities of the project may change, or when new aspects receive attention.

7.1 Project goals – definition and revision by setting priorities

The use of hydrogen buses may be an attractive solution for a variety of reasons, such as the avoidance of local emissions or reducing the carbon footprint of public transport by using renewable energies for hydrogen production. Obviously, other goals that are central, especially for public transport, is providing cost-effective means of transport and a high service availability.

Although it might seem trivial, the definition of goals for an HRS project among all stakeholders is very helpful, since it supports a common understanding of the project and its intentions. It also allows conflicting goals to be identified, and for priorities between goals to be established. All stakeholders that are involved in the project should be able to agree on the chosen priorities.

Common examples of conflicting goals are a high refuelling reliability on one side and the reduction of costs on the other side. The security of hydrogen supply can be improved by various technological measures (see Section 5.1.3), such as installing redundant components or increasing the capacity of the hydrogen storage, but both measures increase the overall cost of the HRS and the supplied hydrogen. Similarly, the use of hydrogen with a low carbon footprint may lead to higher costs. Identifying such conflicts of goals and finding the appropriate priorities based on the individual project circumstances is crucial for finding the ideal HRS solution that takes into account the needs and intentions of all parties involved. Some tools that can help in this process were presented previously in Section 4 and Section 6.

7.2 Identifying requirements and constraints of the project

After defining the project's overall goals, the specific requirements and constraints of the HRS need to be determined. This includes a range of aspects from a variety of topics that are related to different stakeholders, including:

- The requirements set by the bus operator regarding hydrogen demand, number of buses to be refuelled during certain refuelling periods, period available for hydrogen delivery, the planned ramp-up process of hydrogen buses in the fleet etc.
- The space available at the bus depot limiting the possible footprint of the HRS components
- Legal issues, from regulations, codes and standards (RCS) may require certain organisational, technological or civil engineering measures causing higher cost
- Other RCS or individual safety precautions may arise from the local conditions such as overhead power lines, pedestrian walkways, proximity to residential areas etc.
- Local policies may have an important impact on the decision process for the selected HRS technologies, for example wish for locally sourced green hydrogen
- Local private sector or government partners and potential synergies with respect to both hydrogen supply and demand might influence the volume and the choice of technical options
- The possible revenues of providing additional services e.g. grid balancing services may influence the HRS design
- Community and stakeholder acceptance can also play a role favouring one option or another

The list of relevant aspects can be expanded. During an early stage of the project, however, it is essential to identify which of these aspects are mandatory, and which are optional. It is also important to determine conflicting objectives and to define ranges in which the performance may vary without compromising the key expectations.

This is essential, as providing more flexibility can improve the final HRS concept both with respect to the technical solution and cost. Flexibility may also attract a larger number of suppliers able to offer solutions, and allow them to use their product portfolio more effectively leading to reduced HRS costs. For example, flexibility in hydrogen demand may allow a better utilisation of on-site production units. A common unit size for PEM electrolysers today produces about 500 kg H_2/d. If the daily H_2 requirement is specified e.g. to 650 kg H_2/d, two electrolyser units are required which are poorly utilised. The second electrolyser unit may be integrated in the overall redundancy concept, but in order to comply with a strict n+1 redundancy approach a third unit would actually be required.

Requirements are often defined according to expectations that are influenced by previous experience. Hence, HRS requirements may be influenced from previous habits and solutions related to the known diesel technologies that might be more difficult to achieve with hydrogen and lead to higher costs. Since the same outcome might be achievable with other technical solutions in the hydrogen world, it is important to focus on the outcomes rather than on inflexible technical specifications. For example, publishing a requirement to refuel a fleet of 80 +/- 5 buses instead of specifying an HRS with a refuelling capacity of 2.0 t H_2/d.

An advanced approach for addressing soft constraints related to rather optional aspects is defining thresholds of acceptance. This may be a range defining the maximum and minimum number of buses that need to be refuelled. Another concept is determining the willingness to pay for certain services, such as the acceptable extra-cost for using hydrogen from renewable sources, or for increasing the reliability of the HRS by 1%. Note however, that such quantitative monetary values might be difficult to obtain, especially if a large number of stakeholders is involved.

7.3 Choice of HRS concepts and site selection

The definition of the HRS project will require the selection of a certain HRS concept, such as on-site electrolysis, on-site steam reforming, or hydrogen delivery. Following the selection, the available resources can be concentrated on the chosen technology and focus on the specific implications in more detail. It also makes the identification of relevant suppliers easier and simplifies the communication to them. Comparisons between similar HRS solutions are easier than assessing very different HRS concepts.

On the other hand, deciding for one technology based only on rough estimations may exclude a very suitable and cost-effective solution too early from the considerations (see Section 5). For this reason, a certain HRS technology should be selected with caution and only in clear agreement with the common project priorities of all stakeholders.

In accordance with the HRS concept(s) being considered, the sites available for the installation of the HRS need to be evaluated and one selected for the subsequent project progress. This is an important and necessary step that needs to take place before more detailed development can occur together with the authorities or together with technology suppliers. Detailed engineering can be conducted for two or even more sites but the required effort increases accordingly. It may even influence the choice of an HRS concept in case certain concepts cannot be implemented on the available site. Hence, an early decision for the preferred HRS site supports efficient project development.

Another important aspect is the organisational framework envisaged for the future operation of the HRS. The related issues were addressed within the NewBusFuel project [NBF – D3.4] since they are a highly relevant input for the definition of the HRS project. Key questions are:

- Who will be the operator of the HRS - the bus operator, the technology supplier, or a third party?
- What is the appropriate business model for the desired organisational framework? What are the roles and responsibilities of the involved partners, the interfaces between them, and what contractual enforcement is necessary?

7.4 Permitting

Based on the defined HRS requirements, specifications and the site selection, it is recommended to initiate communication with the responsible authorities early, either formally or informally. This could involve requesting the necessary permission(s) that can be obtained at such an early stage of the project, or just meeting to exchange general information and options. It will help to identify potential obstacles that may have been underestimated previously or not yet considered at all and finding ways to solve them early on.

Positive feedback on a permitting request increases the degree of certainty that the HRS can be constructed as planned. It is important to address not only the immediate HRS design in such discussions but all extension stages of the HRS that might be of interest in the future. This is a very important signal to the funding bodies and to the suppliers that may enhance their commitment in the project which likely will help to improve the further HRS planning.

7.5 Key issues to be considered for the definition of the HRS project

Each HRS is different due to the individual needs and circumstances

Although the process of defining goals, identifying conflicts of interests, analysing the various requirements and constraints might seem to be trivial, it is an essential step that needs to be conducted with the participation of all stakeholders. The design of an HRS, its operation as well as the overall project plan need to match the individual requirements. Therefore, it is important that the project definition receives sufficient attention and resources for generating a robust basis for the subsequent project development.

Taking decisions for project definition

The information gained and the decisions taken during this stage are fundamentally important since they define and specify the HRS design, its operation and the contractual interaction of the parties involved for the long term. It is important to keep in mind that the potential lifetime of an HRS will be more than 10 years. Besides the selection of a particular site for the HRS and the feedback from the authorities to the permitting request, all decisions contribute to the specification of the HRS project which paves the way for the next steps in setting up the HRS.

8. Compiling a functional specification sheet

Box V in the proposed project framework, see Figure 11 on page 43

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8. Compiling a functional specification sheet

This section addresses the translation of the definition of the HRS project into a functional specification sheet that synthesises all relevant information about the project. The specifications included in such a sheet are intended to address functional aspects rather than technical aspects in order to provide sufficient technological flexibility to suppliers (see Section 7.2). Important aspects and steps of compiling a functional specification sheet are addressed in the following.

8.1 Feedback on permitting request

As mentioned previously (see Section 7.4), requesting the necessary permissions early from the authorities helps to identify obstacles that will need to be considered later in the project and solutions developed. These obstacles may result in changing the technical or organisational HRS concept or the location where the HRS was planned to be constructed. In contrast, positive feedback confirms the decisions taken and emphasises its practicability. The results of the permitting request need to be part of the functional specification sheet.

8.2 Compiling the functional specification sheet

A functional specification sheet needs to describe all relevant information and circumstances of an HRS project. This includes the different stakeholders involved and their roles, the current financing concept, previous works and experiences, as well as the time schedule of the project, including the construction of the HRS and the subsequent HRS operation period. The purpose of the project and the related goals also need to be addressed (see Section 7).

The functional specification sheet translates the requirements defined previously into functional specifications. The functional character is important since too rigid technical specifications could lead to suboptimal solutions (see Section 7.3). In contrast, specifying the functional outcomes provides the flexibility for finding innovative solutions that are tailored to the existing hydrogen technologies, as well as allowing optimisation of costs.

The functional specification sheet should include as many aspects as possible from different areas such as refuelling reliability, costs, and constraints at the chosen site. It also needs to include issues that are related to the business model and whether the bus operator intends to operate the HRS or if a separate party is responsible. It should differentiate between hard constraints based on mandatory requirements and soft constraints related to optional aspects, and provide ranges and thresholds of acceptance as far as possible. A specification sheet summarizes all relevant information from the earlier stages of the HRS project and helps new parties, especially suppliers but also potential funders, to have access to up to date accurate information on the project. A functional specification sheet might include, but is not limited to, the aspects that are summarized in Annex 13. The standardised questionnaires that were used for the collection of data from the NewBusFuel case studies may also be valuable for the compilation of a functional specification sheet. These questionnaires can be found as excerpts in Annex 13.2 and in full length in [NBF – D3.2].

8.3 Key issues to be considered for compiling the functional specification sheet

Purpose of a functional specification sheet

The functional specification sheet serves as a summary of all relevant information that is related to the HRS project, e.g. goals, priorities, requirements, constraints, etc., and addresses technical and environmental but also organisational issues. It helps to inform new parties, e.g. funding bodies or suppliers for participating in the project development. This makes it a crucial working document which will help to facilitate a successful project implementation. Involving all stakeholders in its development should therefore be given high attention.

How to define the specifications

It is important that the specifications focus on outcomes instead of technical parameters, since this gives more flexibility for developing suitable HRS solutions. This approach also allows for a larger variety of solutions from more suppliers, which may improve the technical HRS concept and reduce the cost.

9. Dialogue with suppliers

Box VI in the proposed project framework, see Figure 11 on page 43

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9. Dialogue with suppliers

During the dialogue with suppliers, the technological possibilities that are available from the suppliers are documented to assess the extent to which they meet the requirements defined in the functional specification sheet. The project requirements may need to be redefined if there is a gap. This phase confirms the defined specification sheet and serves as preparation for the later request for tender (RFT).

Individual business models may also be developed and discussed during this phase. They will need to take into account particular needs of the parties involved in the HRS project.

The dialogue with suppliers is therefore of high importance and sufficient time and resources need be given for the related tasks.

Many participants of the NewBusFuel project consider that the most important benefit of the project was the dialogue between bus operators and suppliers, and the related exchange of knowledge about potential HRS designs.

It is important that this phase does not include any element of an official, binding RFT, such as the selection of a particular supplier or the selection of a proposed HRS design. It is important that no actual or perceived preferences to certain suppliers develop during the communication with suppliers, since all potential tenderers need to be treated equally during and prior to an RFT.

It is essential that the dialogue with suppliers is transparent and equal to all suppliers, especially if communication and negotiations take place to multiple parties at the same time. For compliance with all national and international procurement regulations it may be advisable to consult additional legal advice. For a better understanding of the technical solutions, technical advice from a neutral external party that has knowledge and experience in this field may also be helpful.

9.1 Purpose and goals of this stage

The result of the dialogue with suppliers is not a detailed engineering design containing all the nuts and bolts, nor does it produce at this stage a reliable detailed cost estimation down to the last Euro. For this reason, the members of a project management team might wonder, why this phase is actually necessary, and be tempted to proceed straight to issuing a RFT. However, there are some central reasons, why communication with the suppliers is highly recommended to take place prior to publishing a RFT.

The first is the fact that designing an HRS is a complex task based on the number of different technical solutions that can be employed in an HRS, and the variety of products that can be used. Only a supplier or an experienced planner of HRS, such as an engineering office, may have the in-depth knowledge about the available technologies and their techno-economic performance. This knowledge is necessary to confirm that an HRS can actually be designed according to the requirements defined in the functional specifications sheet, and for assessing certain technological proposals.

If no supplier is able to provide a technical solution that meets the requirements of the project, the defined specifications need to be revised. However, even if the HRS systems proposed fulfil all mandatory requirements, there might still be **potential for technical or economic optimisation**. This can ideally be assessed in-depth during the dialogue with suppliers benefitting from their experience in the field, and may lead to changes in the defined requirements. Hence, the communication with the suppliers helps to define the HRS requirements adequately and **prevents the definition of unfavourable specifications** in a binding RFT, which is especially important for bus operators that are inexperienced with hydrogen technology.

Another important reason for the communication with the suppliers before publishing an official RFT, is discussing the **business or commercialisation model** for installing and operating the HRS [NBF – D3.4]. This includes all questions related to the ownership and the operational responsibility in total or in part. There may be aspects, such as the H_2 production or the refuelling infrastructure that can be owned or operated separately. Hence, the roles and responsibilities as well as the interfaces between all parties involved and an appropriate contractual framework need to be defined. This may include elements of flexibility that take into account cost input variations such as changes in taxes and levies, and to regularly adjust the contract conditions. At the same time, if a larger investment is necessary for the HRS project, an investing supplier needs sufficient security of investment. Questions on how such aspects can be integrated into an overall contractual framework should be addressed, and the suppliers' willingness and ability to participate in the intended business models can be assessed before issuing the desired business conditions later in the RFT.

9.2 Initiating and conducting the dialogue with suppliers

The contact with suppliers can be established in different ways, each with advantages and disadvantages. As this is a common step within the usual business practices of bus operators, only a few examples are briefly described in the following paragraphs.

A request for information (RFI) is seeking general information from potential suppliers about how they might provide HRS solutions. The process may be used to initiate dialogue with multiple suppliers at the same time. The functional specification sheet is published with the RFI to provide all background information related to the HRS project to the interested suppliers. **A dialogue meeting** can serve as a platform for the suppliers to present their product portfolio, as well as their proposed HRS solutions. The bus operator can also answer remaining questions related to the defined requirements. A visit of the bus depot or the greenfield site under discussion for installing the HRS can support the exchange of concepts and ideas.

Technical and economic information of components and technologies can be collected by a **market survey**, e.g. through distributing questionnaires that facilitate the collection of particular techno-economic data.

The functional specification sheet is an ideal starting point for the dialogue with suppliers since it contains all relevant information and summarises the requirements and constraints of the project. The suppliers can propose technical solutions that meet the defined specifications and give a rough estimation of the related costs. However, it is **strongly recommended** to allow suppliers to **propose solutions that may be outside the defined specifications**. This allows the project management team to see and assess viable solutions if the requirements were to be formulated differently.

Achieving technical improvements that can be implemented along with changes in the specifications can take place in an iterative procedure. This applies to finding the ideal technical design, but also with respect to business and commercialisation models. As mentioned previously, it may be advisable to consult technical and legal external advice during this step if necessary.

9.3 Other important aspects

Since the suppliers need to provide a lot of technical and economic information about their available technologies during this communication phase, it may be necessary to sign mutually agreed non-disclosure-agreements (NDA) with the suppliers.

It is essential that the impartiality and fairness of the later RFT is ensured and that the entire procedure complies with national and European procurement regulations. It may be advisable to consult legal advice or using a neutral engineering office as the link between the bus operator and the suppliers that allows the anonymization of the communication with the suppliers and of their proposals, if desired.

9.4 Key issues to be considered for the dialogue with suppliers

Don't rush into the RFT – talk with potential suppliers first

Especially for bus operators who are inexperienced with HRS technologies an intensive dialogue with the suppliers prior to issuing a binding RFT is essential. It prevents the publication of suboptimal requirements and holds a great potential for optimising the techno-economic performance of the future HRS solution. The project management team gets to know the market and can confirm the availability of technical solutions that match the defined the requirements and the willingness of potential project partners to participate in the desired business models.

At the same time, the transparency and fairness of the procedure are essential as it needs to respect and comply with all national and European procurement regulations.

10. Request for tenders

Box VII in the proposed project framework,
see Figure 11 on page 43

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10. Request for tenders

The development and publication of the request for tenders (RFT) is the final step before the HRS project is implemented. It is the result to which all previous steps and developments contribute. Most bus operators have experience in the procurement of buses and infrastructure. Nevertheless, technical or legal advisors can help for issuing an RFT on hydrogen infrastructure. Additional information and tips can be found here [CHIC – D3.7], [CHIC – D3.13].

The European regulations for the procurement of public entities [EU Procurement] provides a number of options for procurement procedures:

- the open procedure
- the restricted procedure
- the negotiated procedure
- the competitive dialogue
- electronic auctions

The negotiated procedure and the competitive dialogue are instruments that provide a significant degree of flexibility for the final definition of the HRS solution and the negotiation of the contractual conditions. However the relevant regulations need to be consulted closely as there are a number of special considerations. These include variables depending on the role of the contracting entity and special rules for the energy and transport sectors (see [EU Procurement], [EC – 2014/25/EU]).

The basis of the procurement process is the specification sheet. However the RFT should focus on the outcomes and not rigid technical specifications, and provide as much flexibility as possible so a large number of suppliers can submit a tender. Nevertheless, the procurement of standardised HRS or submodules may decrease the overall cost due to the economies of scale related to their production.

The criteria according to which the tenders submitted by the suppliers will be ranked depends strongly on the preferences and priorities of the contracting entity. The experience from the procurement of buses and diesel infrastructure is very valuable, but the particularities of the hydrogen technology require special consideration.

11. Summary

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11. Summary

The use of fuel cell hydrogen buses in urban public transport has many advantages, such as zero pollutant emissions during operation and sufficient daily operating range, but the roll-out of hydrogen fuel cell buses together with the required refuelling infrastructure is a complex task. A broad number of HRS concepts and technical solutions exist as well as different operational configurations and associated business models.

At an early project stage, all relevant stakeholders need to be identified and their goals, requirements and constraints need to be collected and aligned to allow the most suitable HRS solution to be identified. This should be done in an iterative process. As a basis for discussion, the basic parameters reflecting the characteristics of different HRS concepts need to be determined. While there is experience with the technology available from operating various existing HRS across Europe, the maximum refuelling capacity to date is for about 10 FC buses. There is currently a lack of experience implementing this technology on a large scale. In this regard, this guidance document aims to support the considerations and actions that are required, e.g. with its numerous analyses, approximations and examples, especially during the early stages of setting up a HRS. These are based on the results from the 13 design studies conducted within the NewBusFuel project and reflect technical parameters and aspects that need to be considered early on, such as the individual footprint of different HRS technologies. Furthermore, the cost related to different HRS concepts and the relevant components is addressed as well as the environmental impact of different available pathways for sourcing hydrogen.

Starting from the provided set of basic parameters, the technical and organisational options can be assessed in more depth and the requirements of the various stakeholders and the available technological solutions can be aligned more effectively. This definition of the HRS project results in the functional specification sheet which summarises all available information of the HRS project both for internal use but also for external communication. For example, it serves as an ideal starting point for the dialogue with suppliers during which the HRS concepts and organisational solutions need to be jointly assessed in more detail in order to ensure the publication of a tailored and need-oriented request for tenders.

The proposed project framework supports an efficient implementation of an HRS. It helps to ask the right questions and find the right answers for determining a suitable and cost-effective HRS solution that is necessary for deploying hydrogen fuel cell buses at a large scale. With the focus on the refuelling infrastructure, which is one of the missing pieces in the puzzle of the H_2 technology roll out, the support provided by this guidance document is a significant step towards the use of zero-emission hydrogen technologies.

The NewBusFuel project has also proven that technological solutions for HRS to refuel fuel cell bus fleets are available and that a cost-effective supply of hydrogen is possible already today. However the hydrogen target cost was not achieved for all studies, and the obstacles and necessary actions by different stakeholder groups to achieve this target were identified. More information on these aspects of the NewBusFuel project that were not in the scope of this guidance document can be found in the High-Level Techno-Economic Project Summary Report [NBF - D4.3].

For more information on the developed HRS solutions, Annex 13.3 contains a list of the study leaders within NewBusFuel as well as a list of the bus operators participating in the FC bus demonstration project CHIC. They can provide valuable information and are available to help to pave the way to a more sustainable future of public transport by using hydrogen fuel cell buses and the related infrastructure.

12. References

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12. References

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13. Annex

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13. Annex

13.1 Potential requirements to be defined in a functional specification sheet

The following list of aspects should be addressed within a functional specification sheet. Obviously, this list is just an example since every project is different and the related specification sheet may require other individual information.

It is especially helpful, if the specification sheet indicates whether the specified requirements are mandatory or optional, providing hard constraints or ranges of acceptance. As mentioned in Section 7 and Section 8, flexibility is important for obtaining appropriate solutions and achieve low costs.

Related to the hydrogen demand and the bus service operation:

- Bus type to be refuelled and the required H_2 pressure level
- Total number of buses, number of buses on the road, distances of routes
- Refuelling regime: number and duration of refuelling windows, back-to-back refuelling time for one vehicle, number of buses that need to be refuelled during a refuelling window
- The intended ramp-up of the H_2 fuel cell bus fleet
- Additional demand for hydrogen, e.g. for refuelling passenger cars or other vehicles, or for the use by other industrial consumers
- The required availability and reliability of
    - The H_2 production / H_2 supply
    - The H_2 refuelling
    - The supply of bus service, e.g. including diesel buses as back-up during the initial phase
- Environmental requirements, e.g. using green or low carbon hydrogen
- Maximum hydrogen cost at nozzle (including HRS infrastructure)
- Limitations of the operation time of on-site H_2 production (e.g. due to noise limits in residential areas)
- Is hydrogen delivery an option?

Related to the site:

- Space available at the bus depot limiting the possible footprint of the HRS
- Existing roads and access to the site
- Utility connections, e.g. limitations of electricity, gas, or water supply
- Visual appearance of the HRS, e.g. necessary for building permit
- Surrounding neighbourhood, e.g. limitation of noise emissions
- Height restrictions, e.g. according to the local land development plan or proximity high voltage power lines or an airport
- Preferences with respect to the housing of components, e.g. open, containerized or within a building

Legal issues:

- Required and preferred RCS, e.g. ISO, SAE standards, national standards
- Already identified safety related RCS and required compliance, e.g. safety measures and other limitations due to surrounding neighbourhood
- Additional regulations imposed from authorities

Stakeholder preferences:

- Preferences of (local) policy makers, e.g. source of hydrogen
- Preferences of other stakeholders, e.g. companies willing to participate in the project
- Preferences of the community, e.g. neighbours, with respect to appearance, design, dimensions

Preferred business models:

- Roles and responsibilities of all parties involved, e.g. ownership and operation of the HRS by the bus operator or buying the required hydrogen from H_2 supplier (H_2 delivery) or from an HRS operator (on-site production)
- Are there other partners (e.g. utilities, local companies, etc.) that are willing to participate in the construction or operation of the HRS and resulting synergies?
- Intentions for providing additional services, e.g. grid balancing service
- Additional hydrogen consumers and the related consumption patterns

Further aspects that are important for suppliers:

- Time schedule of the project, including construction and operation
- Financing of the project: funding sources and current status
- Status of the permitting request and feedback from the authorities
- Detailed information on bus service, e.g. occupancy, frequency of service, routing strategy etc. for precise determination of future average and maximum demand
- Information on planned refuelling process, e.g. time window, refuelling personnel etc.

13.2 Excerpts taken from the questionnaires used for data collection

The data was collected within two standardised questionnaires that were distributed among the leaders of the 13 studies (see excerpts below or [NBF - D3.2] for complete questionnaires)). The first one collected data at the beginning of the project aiming for the initial option assessments within the project, whereas the second addressed the final engineering design of each study. Both questionnaires can be found in the following. Remaining data gaps and data inconsistencies were addressed by following face-to-face or telephone interviews, which were carried out with all study teams.

The technical designs and especially the financial performance of infrastructure solutions which were developed in cooperation with the suppliers, contain sensitive and confidential data, with regard to e.g. intellectual property and costs. In order to protect this information, the figures in this report are anonymised, e.g. by averaging individual data points or by indicating value ranges. If insufficient data was generated within the studies carried out in the NewBusFuel project, figures from literature sources were used to complement the data from NewBusFuel.

Excerpt from the initial Options - Assessment - Step 1: Requirements of bus operator

Technical specification	Unit	Performance requirement (examples)	Performance requirement (actual date supplied by operator)	Reference year for which the performance requirement is valid	Comment *[Please provide additional information on performance req.]*
Number of buses to be refueled (target fleet)	#	> 80 in 2024			
Number of buses to be refueled (initial fleet)	#	Fleet size at start (eg: 10 12m buses)			
Planned fleet ramp up (incramental steps)	#	eg: 5 12m and 10 18m buses p.a.			
Consumption per bus (incl. seasonal fluctuations if applicable or assumed changes over time, e.g. to reflect envisaged improvements in bus energy efficiency)	kg H_2 /100km	12m: 8 (9,5 during summer/winter) 18m: 11,5 (13 during summer/winter)			
Operating range of the bus	km/d	eg: 220km			
Operating days per bus year	#	eg: 270			
Total demand (target)	kg/d	eg: > 1500			
Total demand (initial)	kg/d	eg: 250			
Total storage demand (target)	kg	eg: daily target demand + 2 days demand			
Total storage demand (initial)	kg	eg: daily initial demand + 2 days demand			
Operating pressure value	bar	350 bar			
Required refuelling protocol (if known)		eg: SAE J2601-2 HD, ISO 17268			
Required refuelling comm. (if known)		eg: SAE J2799			
Required H_2 purity (if known)		eg: SAE J2719			
Operating regime refuelling	Hours	eg: 24/7 or 2 time windows (4-6am, 12-2pm)			
	# of buses in x hours	eg: for target fleet size 12 buses per hour, initial size 15 buses in 2 hours			
	Hours	Time slots for any fuel deliveries that may be required eg: 24/7 or 2 time windows (4-6am, 12-2pm)			

Excerpts from the Initial Options Assessment - Step 1: Requirements of bus operator

Excerpt from the Final Engineering Design - Step 4: Data Section

Technical specification (for final design unless otherwise stated)				**Unit**	**Performance requirement** [examples; actual values taken from initial options assessment sheet, input/ changes only required if requirement was adapted]	**Specification of final design** [provided by study team, any available information from the initial assessment of target is used to pre-fill out this column]	**Reference year** [for which the data is valid]	**Comment** [please provide additional information]
Hydrogen demand & supply	Demand	Number of HRS sites		#	default will be 1, potentially more than 1 HRS sites if smaller bus depots, in case of on-ste production # of sites may still be 1			
		Number of buses (target/initial)		#	> 85 / 10		eg: 2024 / 2019	
		Modularity (planned ramp up supply capacity to match bus fleet development over time, quantitive data only, description is provided separately in narrative section			+ 15 buses each year	eg: 3 steps adding x00 kg prod. cap. each		
		Consumption per bus (incl. seasonal fluctuations as applicable)		kg H_2 / 100km	Solo: 9 Articulated: 12,5			
		Operating range of bus		km/d	eg: 220km			
		Operating days per bus per year		#	eg: 270			
		Required refuelly protocol (if known)			eg: SAE J2601-2 HD, ISO 17268			
		Required refuelly communication (if known)			eg: SAE J2799			
		Required H_2 purity (if known)			eg: SAE J2719			
		Operating regime refuelling		Hours	eg: 24/7 or 2 time windows (4-6am, 12 - 2pm)			
				# of buses in x hours	eg: 24/7 or 2 time windows (4-6am, 12 - 2pm)			
				hours	Time slots for any fuel deliveries that may be required eg: 24/7 or 2 time windows			
		Total demand (target, average & peak)		kg/d	> 1500, on wkends 1000, in summer 1800 on wkdays and 1200 on wkends			
		Total demand (initial, average & peak)		kg/d	> 250, on wkends 200, in summer 300 on wkdays and 240 on wkends			
	Availability	Availability / reliability		%	availability: >99.9% (on a 24/7 basis) reliability: >99.9% based on planned number of refuelling events (see WP 3.5 for details)			
		Description of forseen redundancies						
		Maintenance and service strategy		h or d p.a. + explanation		eg: 3 days planned maintenance p.a.		
				h or d p.a. + explanation				
				h or d p.a. + explanation		eg: 3 maintenance 1 d every x months		
				h or d p.a. + explanation		eg: 3 pressure testing every x months/years		
				h or d p.a. + explanation		eg: 3 maintenance 1 d every x months		

Excerpts from the Final Engineering Design - Step 4: Data Section

13.3 List of contacts

Study leaders within the NewBusFuel project
(2015 – 2017)

- Aberdeen
  Contact person: Thomas Bielmeier
  Linde, Seitnerstrasse 70, 82049 Pullach, Germany
  http://www.linde.de

- Birmingham
  Contact person: Charles Purkess
  ITM Power, 22 Atlas Way, Sheffield, S4 7QQ
  http://www.itm-power.com

- Bolzano
  Contact person: Hannes Kröss
  Institut für Innovative Technologien, Enrico Mattei-Straße 1, 39100 Bolzano, Italy
  http://www.h2-suedtirol.com

- Flanders
  Contact person: Thomas Bielmeier
  Linde, Seitnerstrasse 70, 82049 Pullach, Germany
  http://www.linde.de

- Hamburg (on-site and off-site case study)
  Contact person: Dr. Jörg Burkhardt
  hySOLUTIONS, Steinstraße 25, 20095 Hamburg, Germany
  http://www.hysolutions-hamburg.de/

- London
  Contact person: Frank Schnitzeler
  Air Products PLC, Hersham Place Technology Park, Molesey Road, Walton-on-Thames, Surrey KT12 4RZ, United Kingdom
  http://www.airproducts.co.uk

- Madrid
  Contact person: Juan Fernandez García
  Abengoa Innovación, C/ Energía Solar 1, Palmas Altas, 41014 Seville, Spain
  http://www.abengoa.com

- Oslo
  Contact person: Ulf Hafseld
  HYOP, Gunnar Randers vei 24, P.o box 102, 2027 Kjeller, Norway
  http://www.hyop.no

- Potsdam
  Contact person: Sven Schimanski
  McPhy Energy Deutschland, Schmiedestraße 2, 15745 Wildau, Germany
  http://www.mcphy.com/

- Riga
  Contact person: Aivars Starikovs
  H2LV, Akadēmijas laukums 1, kab. 1312, 1050 Riga, Latvia
  http://www.h2lv.eu

- Stuttgart
  Contact person: Dr. Markus Böhm
  Siemens, Process Industries and Drives Division, Large Drives, Hydrogen Solutions (PD LD HY S), Guenther-Scharowsky-Str. 1, 91058 Erlangen, Germany
  http://www.siemens.com

- Wuppertal
  Contact person: Dr. Bernd Pitschak
  Hydrogenics GmbH, Am Wiesenbusch 2, 45966 Gladbeck, Germany
  http://www.hydrogenics.com/

Bus operators within the CHIC, HyTransit, High V.LO-City project:

• Aargau	PostAuto, The Swiss Post
• Aberdeen	First Group, Stagecouch
• Berlin	BVG (Berliner Verkehrsbetriebe)
• Bolzano	STA (Strutture Trasporto Alto Adige), SASA (Società Autobus Servizi d'Area)
• Cologne	RVK (Regionalverkehr Köln)
• Groningen	QBuzz
• Hamburg	Hamburger Hochbahn
• Liguria	Riviera Transport
• London	Transport for London, Tower Transit
• Flanders	Vlaamse Vervoermaatschappij - DeLijn
• Milan	ATM (Azienda Trasporti Milanesi)
• Oslo / Akershus	Ruter
• Whistler	BC Transit

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