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New Bus ReFuelling for

European Hydrogen Bus Depots

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Review of strategies to ensure adequate availability/ redundancy of hydrogen refuelling stations

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Contents

1 Introduction

For a large hydrogen bus refuelling system, the issue of reliability is of central importance. If a significant portion of a city's public transport fleet is dependent on the supply of hydrogen from a single source, then it is essential that the hydrogen supply is not disrupted, otherwise the daily transport of the city will be severely interrupted. The incumbent fuel (diesel) does not suffer from issues of fuel reliability and hence for hydrogen to compete, an equivalent level of reliability will need to be offered. This issue is made more acute for hydrogen than for other fuels, as it is likely that in the early years hydrogen will only be present at a limited number of bus depots, so a solution involving refuelling buses at an alternative depot is unlikely to be available. Hence, refuelling stations need to be made reliable by design.

NewBusFuel task 3.5 involved a working group dedicated to understanding station reliability and availability requirements for bus operators in the project along with possible approaches to ensure the required reliability and availability. One result of this working group is the recommendation of common definitions of HRS reliability and availability [see D3.6 Agreed definition of reliability and availability for bus depot fuelling stations], the other result is this review. [D3.7 Review of strategies to ensure adequate availability/ redundancy of hydrogen refuelling stations].

Given the pre-set requirement for a fully dependable public transport service by its users, bus operators require ultra high reliable and available refuelling stations to ensure that dependability. Accordingly, the refuelling availability required by operators and transit agencies in the 13 case studies of the NewBusFuel projects is 98 % or greater (based on the time period of the defined refuelling window). Figure 1 gives an overview of the required refuelling availability as requested by the different operators.

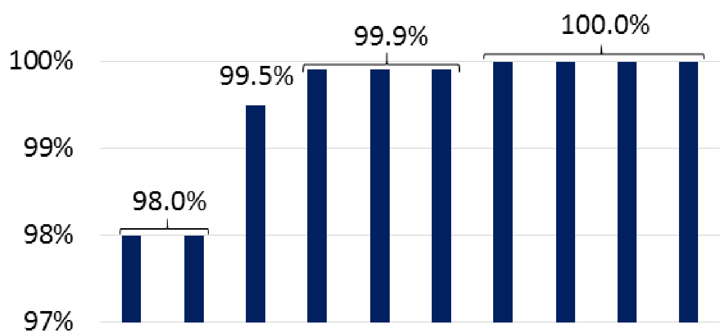

Figure 1 – Required refuelling availability

The goal of this document is to provide an overview on the approaches that were chosen throughout the case studies of NewBusFuel.

Originally another goal of the document was to give an indication on the economic implication of different design options with varying availability levels by design (e.g. „reduction of redundancy on compressor is expected to lead to a reduced availability by ~x-y% and a reduction of CAPEX/ H_2 cost by a-b%"). Given the approach by the case studies to develop one suitable design for each operator that considers its individual boundary conditions, the information on the cost effect of different redundancy measures was not consistently available throughout the studies, often due to commercial sensitivities, and hence it was not possible to systematically analyse and present this information here.

Nevertheless there is some information available which provides first insights into this topic, e.g. in D 4.2.1 Guidance document on large Scale bus refuelling. In D4.2.1 CAPEX and OPEX costs are presented for the individual HRS modules which allow to get some understanding on the economic implications of different design approaches for redundancy.

One example is the H2 storage: Whereas the average storage autonomy was about three days at the beginning of the project, this figure decreased to about two days in average at the end of the project due to the associated costs. Assuming a storage cost of 1,200 €/kg H2 [NBF – D4.2.1], for an HRS with a daily refuelling capacity of 3,000 kg H2/d such a correction of the storage autonomy results in a cost reduction of 3.6 million €.

Another example is the dispenser: with a CAPEX ranging from 100,000 – 300,000 €/ dispenser the implications of an n+1 redundancy for the dispensing unit can be estimated accordingly [NBF – D4.2.1].

2 Chosen redundancy strategies

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).

A limited number of measures exists for ensuring a high refuelling availability and 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 approach is e.g. to have on-site storage which can back up operations in the event of failures. The amount of H2 stored is thereby purely dependent on the period of time for which the operator wants to ensure sufficient H2 supply. But all these strategy come at a cost especially with regard to CAPEX and an increase of the necessary footprint.

The following subsections give an overview of the chosen redundancy strategies. A differentiation is made between HRS with dedicated on- or near site H2 production (section 2.1) and HRS with delivered H2 (section 2.2), i.e. the hydrogen is produced off-site and transported to the HRS. Figure 2 gives a (simplified) overview on the available main design options for HRS that were considered in NewBusFuel.

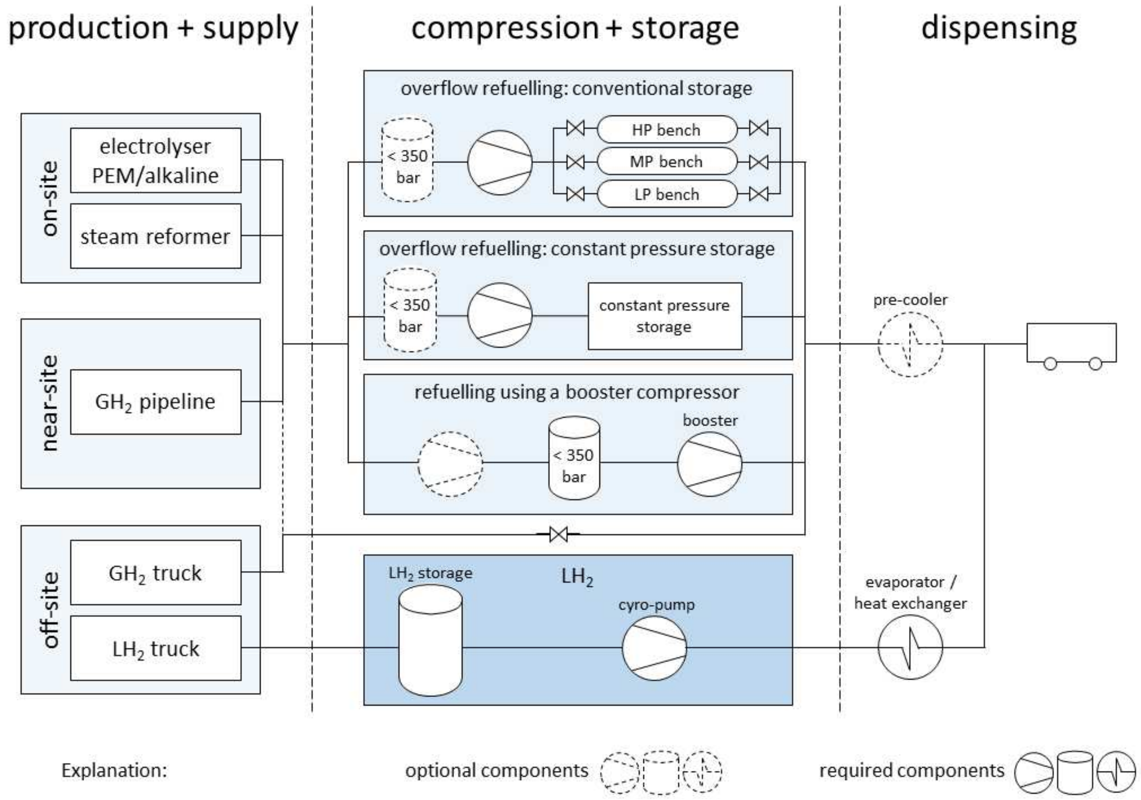

Figure 2 Scheme of the available main design options for an HRS

Data collection

The data was collected using a questionnaire (see Annex A) where the coordinators of each case study were asked to provide information on the failure type and component affected, the envisaged failure probability (described either quantitatively or qualitatively) and the countermeasures considered to remediate the failure.

2.1 HRS with on-/near site H2 production

The HRS designs developed in NewBusFuel which feature an on- or near site H2 production either use electrolyser or steam reformer technology for producing hydrogen. The remaining components such as compressors, storage and dispensers are similar for all HRS design options.

2.1.1 Electrolyser

Two basic concepts for redundancy were deployed:

a) full n+1 modularity

b) > 1 electrolyser modules (failure of one electrolyser is tolerable, a sufficient supply is ensured via the multi-day on-site H2 storage)

These two main approaches were applied not only for the electrolyser, but also for the other main modules of a HRS (see next subsections).

Further measures to ensure a high reliability are:

- Storage of key spare parts on-site or close by (e.g. rectifier, control unit, valve, sensor, stack segment/ complete stack)
- immediate availability of delivered H2 as backup supply (the contractually foreseen reaction time is to be max. 1 day)

The basic assumption for the chosen redundancy approaches was that the repair time is shorter than the multi-day on site storage, which is usually 2-3 days.

Some of the studies investigated the failure probabilities. The list below gives some quantification for selected assumed failure reasons:

- electricity outage: < 1 h/a (< 0.001%)
- electrolyser module: 24 h/a (0.3%)
- Deoxodryer: 5-24 h/a (0.06% - 0.3%)

2.1.2 Steam Reformer

In case the steam reforming process of e.g. natural gas or biomethane is chosen as on-site H2 production route, a modular design is implemented, i.e. more than one reformer module is installed and the failure of one reformer is tolerable, since the required H2 supply is ensured again from the remaining production units in combination with the multi-day on-site storage or via delivered hydrogen. For the delivered hydrogen fast reponse times similar to the electrolyser route are to be foreseen. For the case studies using a steam reformer no "n+1" redundancy was proposed.

The additional measures for ensuring high reliability and availability also include:

- Main spare parts are kept on site (e.g. control unit, valve, sensor, desulphurisation filter)
- A maintenance contract with a fast response time (e.g. < 4 hours) is to be put in place
- Delivered H2 serves as backup supply with a contractually foreseen reaction time of max. 1 day

Pre-Cooling

One case study foresaw the need for pre-cooling the hydrogen to ensure fast refuelling times. A modular design, without a strict n+1 design was chosen. In case of failure of the pre-cooling unit the refuelling speed would be reduced to ensure safe operation, i.e. stay below the max. allowed temperature limit (+85°C) during the refuelling process.

2.1.3 Compressor

With regard to the H2 compressors it is to be noted that in previous demonstration projects the compressors have proven to be a crucial component that caused e.g. in the CHIC project more than 50 % of all HRS downtime [CHIC – Final brochure]. For the compressor modules three different concepts were selected:

a) full n+1 redundancy

b) modularity with installing more than one compressor, i.e. failure of one compressor is tolerable and refuelling is ensured via sufficient (high pressure) H2 storage until its repair

c) The capacity of the installed compressors (> 1) is slightly over-dimensioned so the potential failure of one compressor can be compensated, at least partially

Additional measures to ensure high reliability include:

- Remote surveillance for instantaneous failure alarm
- Main spare parts kept on-/near site

The failure probability ranges from "low" (18 h/a or 0.2%) to "medium". For the medium classification no further quantification was provided.

A more general recommendation is to use compressors with a smaller capacity which are being operated as continuously as possible, instead of using compressors with larger capacity at short intervals in intermittent operation mode. Experience shows that the latter operating mode may reduce the compressor's lifetime.

2.1.4 Storage and piping

For the H2 storage the following two concepts were applied:

a) modular design with multiple storage tanks/ spare capacity

b) trailer supply as back up

A strict n+1 redundancy was not proposed by any of the case studies which used hydrogen in gaseous form. For the case of liquid hydrogen (LH2) storage, two LH2 tanks are foreseen.

The failure probability for H2 storage and also for the pipping was assumed to be “low” (18 h/a or 0.2%). For the piping, and the H2 pipeline, which is foreseen in one case study, a 100% x-ray check of all welding during manufacturing is foreseen.

2.1.5 Dispenser

The redundancy concepts used for the H2 dispensers are :

a) n+1 redundancy

b) modular design with multiple dispenser, i.e. the failure of one dispenser still allows filling of all busses at an increased overall refuelling time

Analogue to the other main modules of the HRS the main spare parts for the dispenser are stored on-site for fast servicing (e.g. pressure regulator, control unit seals, valve, breakaway coupling for hose)

The assumed failure probability is estimated to be low (24 h/a or 0.3%).

2.2 HRS with delivered hydrogen

For HRS that receive the hydrogen via truck trailer, either in gaseous or in liquid form, different reasons for a limited or even disrupted H2 supply were envisaged:

a) H2 Trailer is unavailable or too late
   Mitigation approaches include:
   - Additional trailer in supply chain
   - Surplus LH2 on site to compensate
   - 500 bar gaseous storage on site, equivalent to 1 trailer

b) LH2 tank failure

To minimise this risk, 2 tanks are foreseen in the design (see 0) and the required spare parts are stored on-site.

c) Cryopump failure (LH2)

- A n+1 approach has been chosen and
- the parallel filling from a high pressure trailer is foreseen as an additional option.
- Spare parts are kept on site and
- the extension of the fuelling window is another remediation measure.

3 Conclusion

The public transport bus is the backbone of any public transport system. To offer a dependable service to its passengers, bus operators require fully reliable and available refuelling stations. Such an "ultra high" reliability can be provided e.g. by incorporating redundant components and/ or increased storage, which can back up operations in the event of failures. But such strategies come at a cost especially in CAPEX and increases the necessary footprint. For example, in NewBusFuel most studies reduced the desired storage capacity over the course of the project from 3 days autonomy in average to two days due to the reduction of investment cost[1].

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

The NewBusFuel case studies also provided insights into a variety of other, potentially more cost-effective, means to ensure high refuelling reliability. E.g., attention to logistic arrangements can be very effective. These include stocking critical spare parts with long delivery times at the HRS site and requiring quick response times of trained maintenance staff in case of a failure at the HRS. Enforcement of the availability and reliability via a suitable contractual framework between bus operator and HRS operator is recommended.

It is therefore necessary to evaluate on a case-by-case basis what redundancy concept is most suitable for the individual HRS with its specific boundary conditions. Also, due to the evolving nature of a hydrogen infrastructure industry for buses and passenger cars, which just started to emerge, it is recommended to regularly review the implemented redundancy concepts and adjust them as appropriate.

[1] For an exemplary HRS with a daily refuelling capacity of 3,000 kg H_2/d a reduction of the storage autonomy by one day results in a cost reduction of ~3.6 million €.

4 ANNEX – Questionnaire used for data collection

The table below presents the questionnaire used to collect information on the conducted failure mode and effect analysis (FMEA) along with proposed redundancy measures for 2 exemplary HRS using on-site H2 production via electrolyser.

City 1						City 2			
Failure Type/ Component	*Failure probability : h/year in %*	*Failure probability : qualiative Description*	*Redundancy*	*Fall-back level*	*Redundancy*	*Failure Type/ Component*	*Failure probability : qualiative Description*	*countermeasures taken into account*	*Redundancy*
Elektrolyzer: e.g. Outage Rectifier Fan Control unit Pump Valve / Actor Sensor Stack-Segment	24h/a = 0,27%		Main spare parts stored on site. Repair within 3 days possible. Backup-supply by H2-storage. H2-Production can be continued by other electrolyzer units.	(x)	(x) No full n+1 redundancy. Failure will cause reduced production capacity. However, because of storage volume and response time (local spare parts) 100 % availability can be assured	Electrolyser	Failure probability - medium	One electrolyser unit can function as backup when the other is down for service. It must then operate at 100 % (1125 kg/day). Combined with a two-day hydrogen consumption storage size (2 x 1500 = 3000 kg), one production unit can be out for service for a week without interruption of normal bus operations. If one electrolyser is out for service for a longer period of time, additional hydrogen can be trucked in. Trucked-in sources for this amount of hydrogen (375 kg per day) will have to be developed.	Two electrolysers with 75 % capacity each, 2 day storage, trucked-in hydrogen
Gas-purification & Drying	24h/a = 0,27%		Main spare parts stored on site (e.g. chiller, heater, valves, control units,...). Repair within 3 days possible. Backup-supply by H2-storage. H2-Production can be continued by other deoxo-dryer units.	(x)	(x) No full n+1 redundancy. Failure will cause reduced production capacity. However, because of storage volume and response time (local spare parts) 100 % availability can be assured	Power supply	Low probability for failure	Very stable power supply in - no back-up measures taken	
Pipeline		piping with highly resistent material and welding; no significant issues without external influence expected	100% x-ray check of weld seams during construction; protective sheathing; some safety valves; some clearance in piping						
Compressor		compressors highly used but at moderate pressure levels, which is positive for operation mode; wear minimal due to technology	main spare part set on-site; n+1 redundant compressor; remote control; trained personnel on-site		x	Compressors	Failure probability - medium	Two compressors capable of achieving the scenario above. Service parts for critical items must be made available. In-house competence on service.	
Storage Tanks		standard industry tanks, with highes service	continuous S&M + enough spare capacity		x	Storage	Low probability for failure	Not likely to give serious problems, trucked-in hydrogen is back-up	
Dispenser		dispenser system & hose + breakaway coupling dependent on user; hose with defined lifetime; leakages possible	main spare part set on-site; n+1 redundant dispenser; remote control center; trained personnel on-site		x	Dispensing	Low probability for failure	System based on slow-fill of buses gives low probability for failure. Two dispensers available as back-up and for buses in need for filling outside normal filling window.	
Hydraulic Pump		standard industry hydraulic, with very high service life	continuous S&M, some spare parts on-site						