

## **NewBusFuel – Large scale hydrogen refuelling infrastructure for fuel cell bus fleets**

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### **Summary**

The NewBusFuel project developed 13 individual solutions for hydrogen refuelling stations (HRS) able to be used for the refuelling of fuel cell bus fleets. The technical and economic characteristics of these HRS designs as well as the major influencing factors were analysed. Based on this assessment guidelines and advice were derived for the deployment of large-scale HRS, and recommendations were developed for different stakeholder groups in order to reduce the cost of hydrogen production and refuelling, and hence of the operation of a fuel cell bus fleet.

*Keywords: hydrogen, infrastructure, fuel cell, public transport, fleet*

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### **1 Relevance and obstacles of hydrogen bus technology**

Electric powertrains using hydrogen fuel cells are considered to be a highly promising propulsion system for the future due to a number of reasons. They do not emit any airborne pollutants, such as nitric oxide and nitrogen dioxide (NO<sub>x</sub>), nor particulate matter (PM). Further, they provide flexibility with respect to the source of energy that is used for the hydrogen production, unlike conventional diesel powertrains. This is an important advantage in an energy system with high integration of different fluctuating renewable energy sources, since the hydrogen production can compensate in case of undesired oversupply of electricity. Depending on the energy source chosen for the hydrogen production, fuel cell electric powertrains also offer the potential to significantly decrease the greenhouse gas emissions caused by the public transport sector.

These aspects apply to all types and sizes of fuel cell vehicles, but there are some advantages that are particularly relevant for integrating hydrogen fuel cells in bus transportation. Buses are frequently used within urban areas that may suffer particularly from high pollutant concentrations. Unlike passenger vehicles, buses require a high power propulsion system combined with a long daily range capability. This leads to a large amount of energy that needs to be stored on board a bus operated within public transport. The common situation of parking a large number of buses at a bus depot at night allows the use of one dedicated refuelling facility for a large number of buses and for a large amount of hydrogen to be consumed. The large hydrogen throughput reduces the cost impact of the rather expensive infrastructure components with respect to one kg of hydrogen refuelled and per km driven. This is a clear advantage compared to public hydrogen refuelling stations (HRS) for fuel cell passenger vehicles with a lower hydrogen demand. Last but not least, the reliable predictability of the regular bus operation helps to schedule the hydrogen production and refuelling, and to reduce the related costs.

Based on the benefits of using hydrogen fuel cell buses in public transport a number of projects has been conducted at different locations all over the world within the last years, e.g. JIVE (launched in 2017), CHIC

(2010 - 2016), HyFLEET:CUTE (2006 - 2009), CUTE (2001 - 2006), STEP (2001 - 2005), ECTOS (2001 - 2005) (see [1, 2]).

However, along with all these advantages of fuel cell hydrogen buses, their use is still associated with higher costs compared with the operation of conventional diesel buses [3, 4]. This financial disadvantage is related to the higher capital cost of fuel cell buses compared with diesel buses, since fuel cells still are expensive components that increase the overall bus cost. Another reason for higher cost is the hydrogen consumption of current fuel cells and the cost of hydrogen. It is important to keep in mind that for a high mileage application, such as buses used in public transport, the fuel cost is significantly more important than the purchase price of the vehicle. Hence, the cost of the hydrogen refuelled into a fuel cell bus needs to be as low as possible for economic operation. For this reason, the project *New Bus Refuelling for European Hydrogen Bus Depots* (short: *NewBusFuel*) by the *Fuel Cell and Hydrogen Joint Undertaking (FCH JU)* has focused on the hydrogen production and refuelling infrastructure, and aimed for the optimization of the technological performance and the related infrastructure costs, and hence effectively for a low cost of the hydrogen fuel.

## 2 The NewBusFuel project

Within the NewBusFuel project, site-specific solutions for hydrogen refuelling stations were developed for the individual fuel cell bus fleets of 13 case studies (12 cities in 7 different European countries, see Figure 1). For each of these case studies a number of partners, including a bus operator and hydrogen infrastructure suppliers, joined the individual cooperation cluster. Jointly they developed an individual HRS solution that took into account all project specific requirements and constraints, such as the city's topography, the local climate, the space available at the bus depot, the operation regime of the local bus fleet, e.g. daily mileages, routing, etc., the resulting daily hydrogen demand, local regulations, codes, and standards (RCS), and other aspects that might be important for the set-up and operation of the HRS.

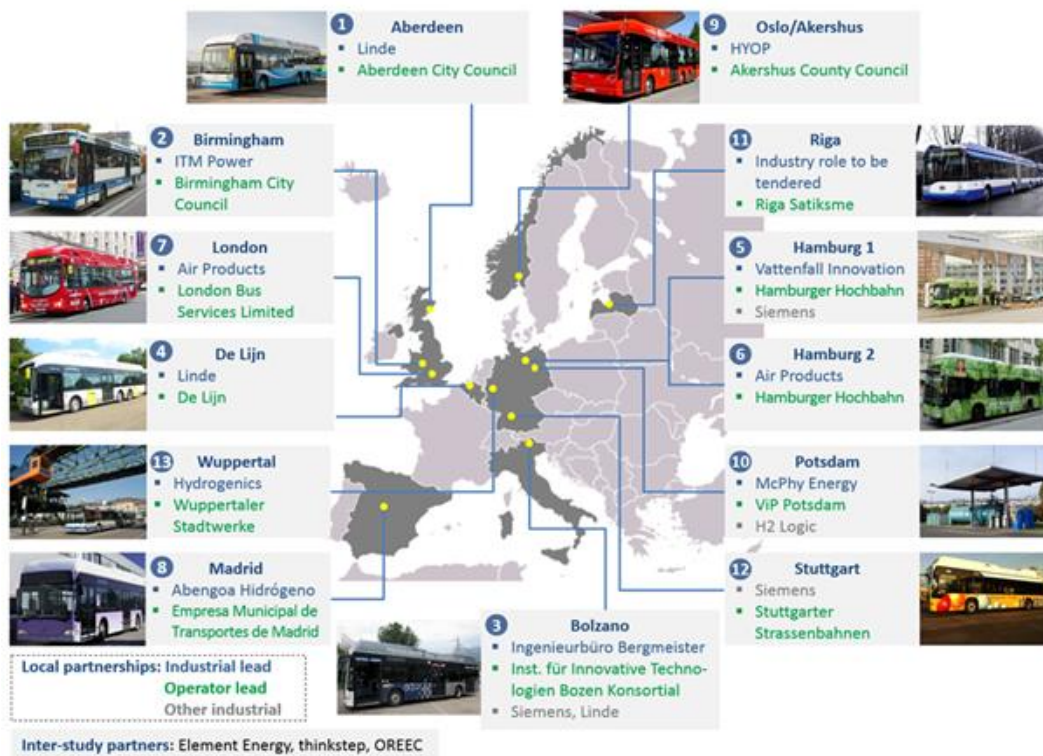


Figure 1: Locations and cooperation partners for the 13 case studies of the NewBusFuel project

The range of the HRS designs developed could then be analysed with respect to their technical and economic performance. This assessment reflects the current state of the art and gives reliable figures on the cost competitiveness of using hydrogen production and refuelling infrastructure for operating hydrogen fuel cell buses. Further, the HRS concepts developed serve as the basis for identifying promising HRS designs and to derive potential for technological but also regulatory improvements in order to increase the competitiveness of fuel cell buses in the future.

The different case studies conducted within the NewBusFuel project consider a variety of different HRS concepts (see Figure 2). The ones with on-site hydrogen production use electrolyzers or steam reformers for the production of hydrogen. Concepts with near-site hydrogen production receive the hydrogen via pipeline or as gaseous hydrogen (GH<sub>2</sub>) in compressed hydrogen truck trailers. If the hydrogen originates from more distant sources, e.g. large-scale steam reforming facilities or hydrogen as by-product from industrial processes, both gaseous hydrogen as well as liquid hydrogen delivery (LH<sub>2</sub>) are considered in the case studies.

Different approaches were also chosen for the compression unit and the hydrogen storage. If gaseous hydrogen is stored at the HRS, two main concepts need to be distinguished for refuelling. The first is overflow refuelling, which means that the hydrogen is released from a storage tank with a high pressure level that is above the pressure level in the vehicle tank, so that the flow of hydrogen is caused by the existing pressure difference. The other concept uses a booster compressor, which takes the hydrogen from a storage at a lower pressure level, which is below the pressure level in the vehicle tanks. The booster compressor increases the hydrogen pressure level and thus transfers the hydrogen into the vehicle tank. In this case, the hydrogen is stored at lower pressures and hydrogen tanks with lower technical requirements can be used for the hydrogen storage. In contrast, for overflow refuelling, the hydrogen storage needs to withstand higher pressures and hence the technical requirements are more challenging. Further, there are two different storage concepts which are both used for overflow refuelling. The first is a so-called cascade storage, which comprises three different pressure benches (low pressure, medium pressure, high pressure) that can be used sequentially during the bus refuelling process as a function of the rising pressure in the vehicle tank. The other is a constant pressure storage, which keeps the storage pressure at a constant level that is suitable for the overflow refuelling of the buses. If liquid hydrogen is stored at the HRS, LH<sub>2</sub> pumps or cryogenic hydrogen compressors (CHC) are used for transferring the hydrogen through an evaporator / heat exchanger unit. There the liquid hydrogen evaporates and is conditioned for being fed into the vehicle tanks.

While delivered liquid hydrogen is usually transferred from the LH<sub>2</sub> trailer into the stationary LH<sub>2</sub> tank, a trailer with compressed GH<sub>2</sub> may be integrated into the overall HRS concept in order to avoid unnecessary transfers and related compression efforts (see Figure 2).

The individual constraints and requirements of each case study had to be considered for the developed HRS solutions. The fact that suitable solutions were developed for all 13 case studies using components and technologies that are available today represents a remarkable achievement of the NewBusFuel project.

The most important influencing factors that determined the technical design of the HRS were the reliability of the bus refuelling, the compliance with given space requirements, and obviously the costs of the HRS and hence of the refuelled hydrogen. The compliance with existing regulations, codes, and standards, as well as considering requests from political decision makers were similarly important.

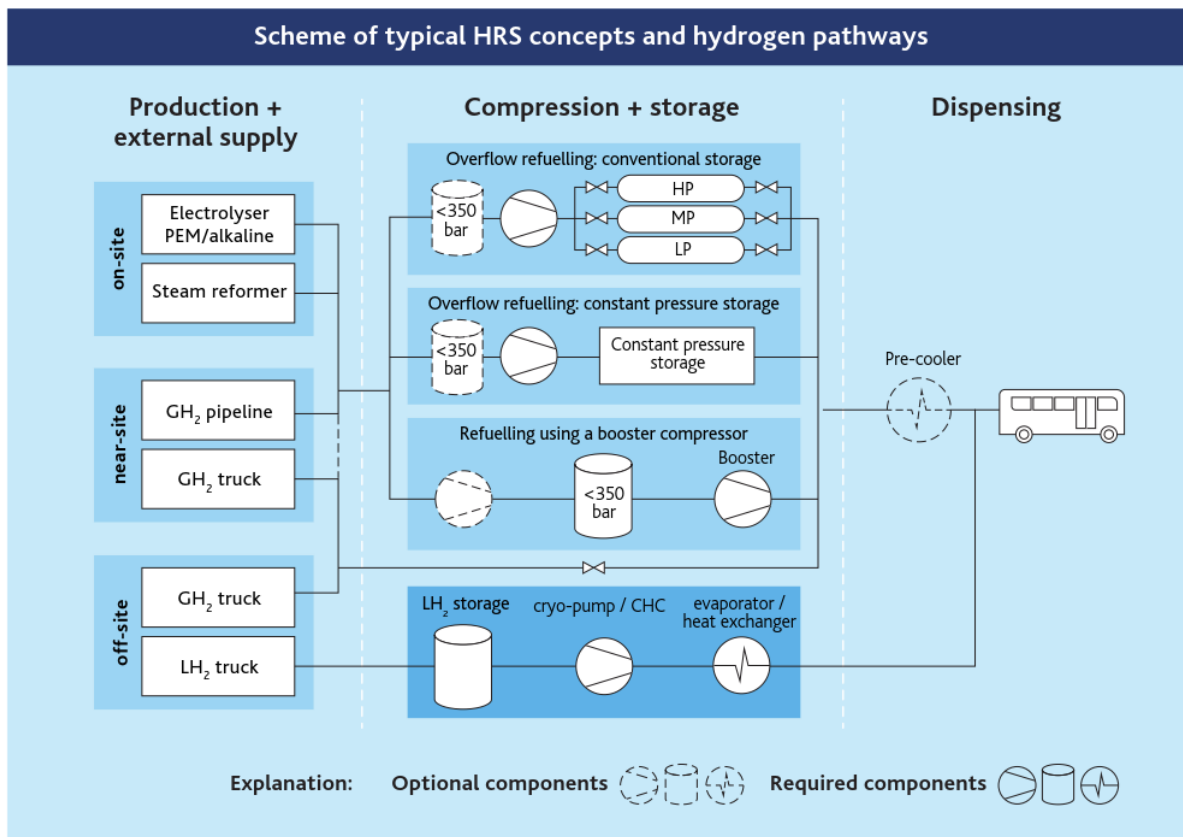


Figure 2: Different HRS concepts assessed within the NewBusFuel project [5]

### 3 Lessons learnt with respect to the HRS concept

The analysis of the technical HRS concepts developed and their economic performance against the background of the specific case study's individual requirements and constraints allowed for deriving several lessons with respect to the HRS concepts.

One of the most fundamental insights for bus operators was the necessary change of perspective towards the unknown handling of hydrogen. Preconceived ideas derived from the experience with diesel may be misleading during the development of a transport concept with hydrogen buses and with the related refuelling technologies. For this reason, such influences should be set aside and replaced with a new 'mind set' [6].

An example of this issues is the required size of the hydrogen storage that was assumed to be appropriately scaled by the project partners. Since the storage capacity is usually not a limiting factor for diesel, an average storage autonomy of three days was planned at the beginning of the project in order to cover down-times of the hydrogen supply. A hydrogen storage of this size, however, leads to significant investment costs and requires a considerable amount of space, which may not be available at an inner city bus depot. For this reason, most case studies reduced the intended storage capacity to an average of two days and found other, more cost-effective means for ensuring a high refuelling reliability. These included stocking critical spare parts on-site or close to the HRS, a quick response times of trained staff, suitable contractual frameworks, or using a modular HRS design, which automatically creates redundancies for larger HRS. [5]

Another interesting aspect, which is not relevant for diesel but which is important for the refuelling of hydrogen is the necessity to match the hydrogen demand of a certain number of fuel cell buses and the available refuelling equipment. In order to decrease the cost contribution from the expensive refueling equipment, a high utilization of the HRS is essential. For this reason, the ramp-up of the fuel cell bus fleet and the HRS extension steps need to be coordinated. In doing so, unused overcapacities can be minimized,

leading to significant cost improvements, especially for small fuel cell bus fleets. Figure 3 illustrates two different procurement strategies for the fuel cell bus fleet, a steady ‘linear’ procurement of 3 buses per year (top) and a more step-wise procurement of 9 buses every three years (bottom). As the illustration indicates, the linear procurement strategy leads to higher overcapacities, especially for smaller HRS sizes, which are not used for the bus refueling. In the linear procurement example the potential to refuel 45 buses during one year is lost during each stage of the HRS ramp-up. In contrast this overcapacity is reduced to the potential of refueling “only” 27 buses during one year for the step-wise procurement approach. These unused overcapacities increase the contribution of the HRS CAPEX and lead to higher hydrogen cost and higher cost per driven km.

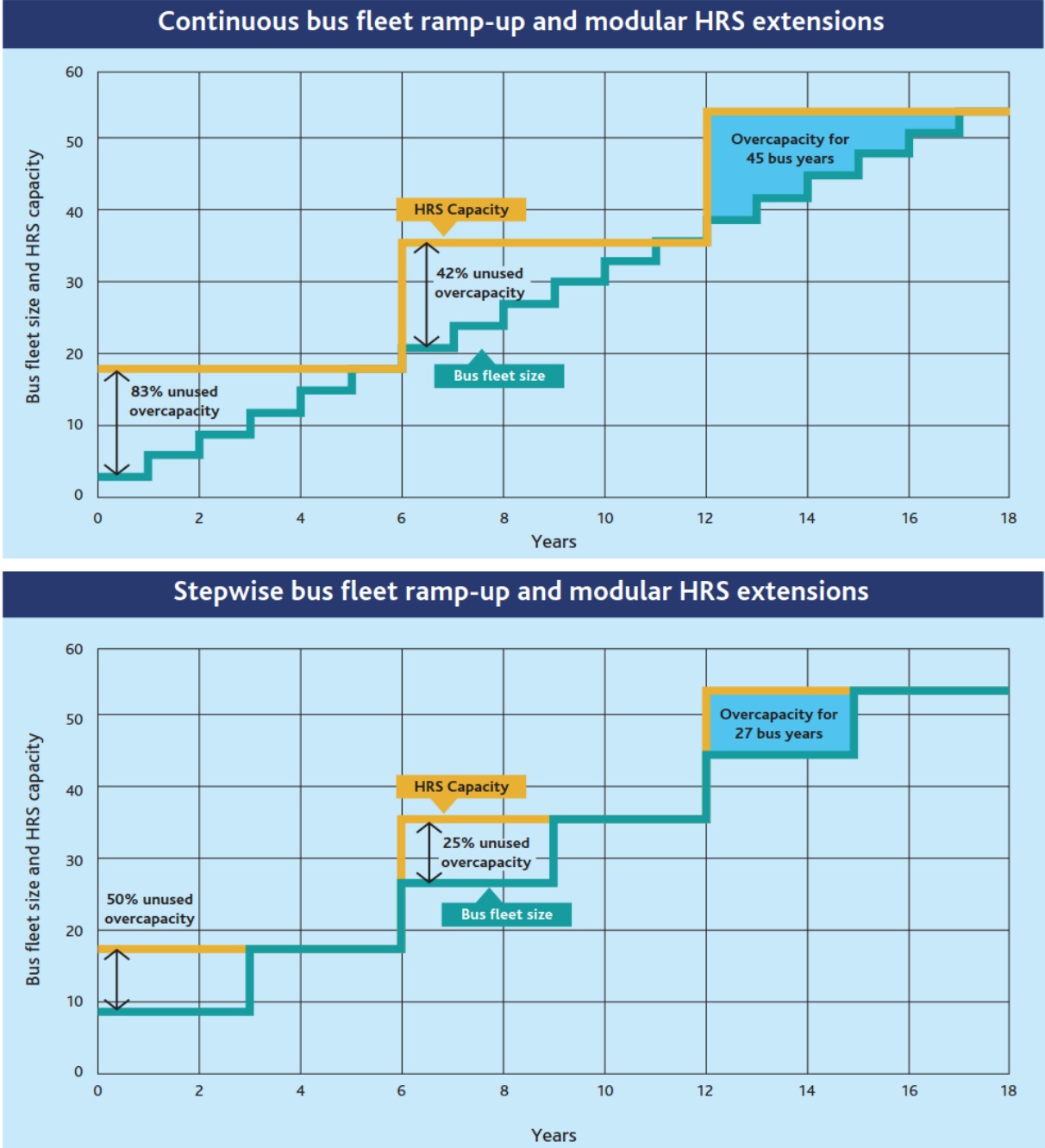


Figure 3: Overcapacities depending on the bus procurement strategy. Top: continuous procurement of 3 buses per year. Bottom: stepwise procurement of 9 buses every 3 years [5]

As mentioned previously, the space constraints existing at a particular HRS site may be decisive for the selection of the HRS concept. Within the NewBusFuel project, the footprints of all HRS concepts were assessed, and linear approximations were derived for both on-site and off-site production HRS as a function of the amount of hydrogen refuelled per day (see Figure 4).

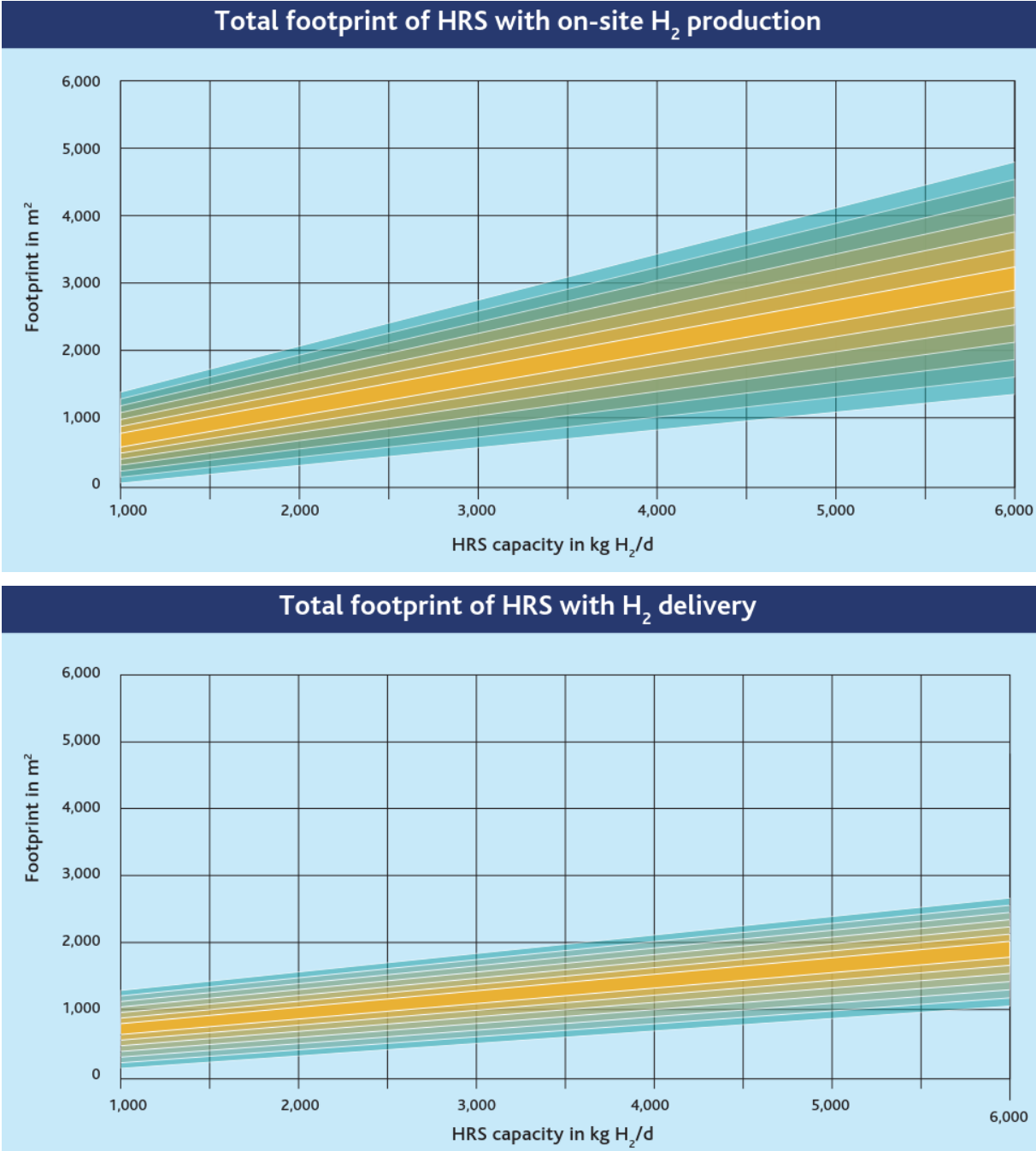


Figure 4: Approximate footprints of complete HRS with on-site H<sub>2</sub> production (top) and with H<sub>2</sub> delivery (bottom) [5]

HRS using delivered hydrogen generally have a smaller footprint than HRS with on-site hydrogen production. This is especially true for the delivery of LH<sub>2</sub>, since the storage tanks for LH<sub>2</sub> require a significantly smaller footprint than GH<sub>2</sub> storages (see Figure 5 and Figure 6).

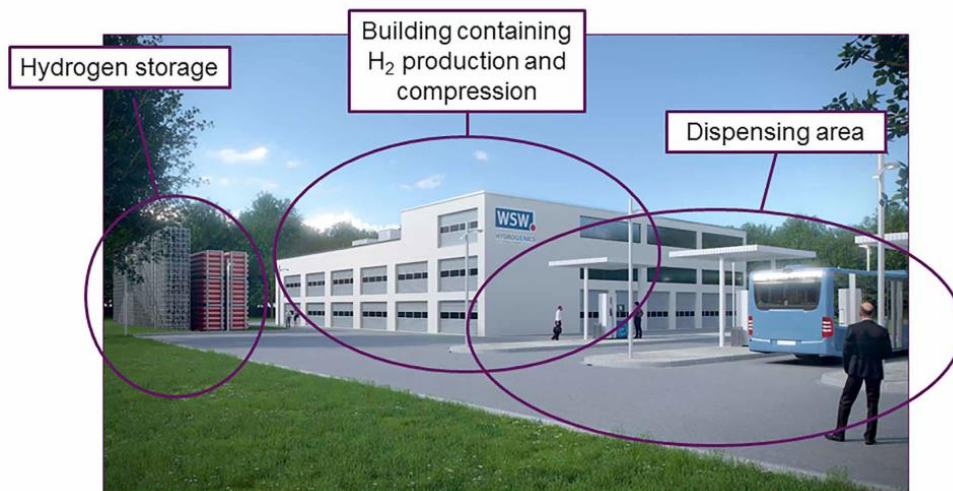


Figure 5: Illustration of an HRS with on-site electrolysis and a maximum daily capacity of about 6 000 kg H<sub>2</sub>/d, Source: WSW/Hydrogenics, [5]

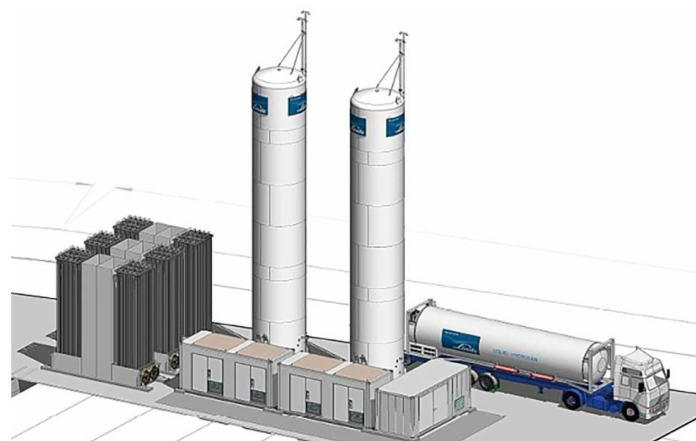


Figure 6: Illustration of an HRS with LH<sub>2</sub> delivery without dispensing area (daily capacity of 2 250 kg H<sub>2</sub>/d), Source: Linde [5]

## 4 Other recommendations

In addition to the lessons learned described above, which aim to support bus operators during the definition of the HRS requirements and the technical specifications, the NewBusFuel project also defined recommendations to improve the cost performance of the hydrogen production and refuelling.

Unlike the largely varying technical requirements of HRS, the hydrogen target cost was defined for all case studies within a narrow range of 4 – 6 €/kg H<sub>2</sub>. This target cost range was reached by the HRS solutions of three case studies considering different HRS concepts, while three other studies achieved final hydrogen costs in the range of 6 - 8 €/kg H<sub>2</sub>. The H<sub>2</sub> cost of the remaining seven studies exceeds 8 €/kg H<sub>2</sub>. The fact that several studies reached the target cost range is a significant achievement. Nevertheless, those HRS solutions missing the hydrogen target cost range can be analysed and valuable recommendations can be derived for improving the future technical and financial performance. These recommendations are numerous and usually address one of the three main stakeholder groups, i.e. bus operators, policy makers, and hydrogen infrastructure suppliers.

The OPEX usually has a dominant role in achieving cost-effective hydrogen refuelling. Depending on the technology chosen for on-site hydrogen production, the electricity cost is crucial in electrolysis, and the cost of natural gas or biogas is of great influence for steam reforming. The cost of delivered hydrogen depends on a number of contractual aspects, such as the amount of purchased hydrogen, the delivery distance, the frequency of the delivery, the duration of the contract, take-or-pay or other contract conditions, which influence the investment risk of the contract parties. Currently, there seems to be a special interest in electrolyzers, since they can be used to match fluctuations of electricity produced from renewable energies, and support the overall energy system, as well as to produce green hydrogen. For this reason, the cost of the electricity used for electrolysis is a decisive parameter in this technology. The hydrogen infrastructure suppliers need to improve the efficiency of their components in order to decrease the related energy cost, but regulatory bodies can also assist in reducing costs. The regulatory framework of the electricity price varies significantly across European countries. There are several countries with a significant share of taxes and levies, not only for domestic but also for industrial consumers. Since the electricity costs dominate the overall hydrogen price from electrolysis, policy makers should revise the current regulatory framework with respect to taxes and levies for electricity if it is used for hydrogen production. This would help to allow a cost-effective production of hydrogen used for transportation or as energy storage.

Another important recommendation for policy makers is imposing and enforcing strict air quality regulations, especially with respect to inner-city NO<sub>x</sub> and PM emissions. The exclusion of polluting vehicles from certain areas or imposing penalty payments creates a demand for emission-free vehicles, for which different zero emission vehicle technologies can compete. A consistent regulatory framework combined with providing resources to bus operators supporting them during the transition phase will help to accomplish cleaner urban areas in the future.

## 5 Conclusions

After the spotlight of recent fuel cell bus activities which have focussed on the vehicle side of the hydrogen well-to-wheel chain, the NewBusFuel project concentrated on the infrastructure that is necessary for producing and refuelling hydrogen at large scale in order to operate large fuel cell bus fleets in an efficient and cost-effective manner. The infrastructure is receiving increasing attention, since obtaining low cost hydrogen fuel is crucial for the economic operation of high mileage vehicles, such as fuel cell buses in public transport.

The NewBusFuel project demonstrated that practical and economic solutions for HRS already exist today. At the same time, it was possible to assess the potential for technical and financial improvements and important recommendations to different stakeholder groups were derived. The major insights are collected and published within two documents. The first [5] addresses bus operators, who are interested in deploying hydrogen fuel cell buses and the required refuelling infrastructure, and supports them during the definition of the HRS requirements and specifications. The document proposes a framework for initiating an HRS project effectively, collects many insights from the NewBusFuel case studies, and contains numerous approximations for the characteristics of different HRS technologies.

The second document summarises the derived recommendations for the three main stakeholder groups, i.e. bus operators or transport agencies, policy makers, and the hydrogen infrastructure suppliers, aiming for improvements of the costs related to hydrogen production and refuelling. [6]

The next steps of action are defined by the numerous recommendations and they will support the economic deployment of fuel cell bus fleets and the related hydrogen infrastructure in the future, which improves the overall environmental impact of future public transport.

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Dr. Michael Faltenbacher joined thinkstep AG in 2006 and is currently responsible for the transport and mobility sector. With more than 15 years of experience in the field of life cycle based environmental and economic evaluation of transport and energy system he has extensive know-how on bus systems for urban public transport as well as conventional and alternative fuels. The main focus of his work is on the holistic assessment of fuels and drivetrain technologies for road vehicles.