Milestones H2NODES

Milestone 21

Analysis of cost-effective routes for cities moving towards sustainable transport

H2NODES
Connecting Transport Infrastructures

Co-financed by the Connecting Europe
Facility of the European Union

Milestone 21 Report

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Element Energy have been contracted by Rigas Satiksme to write the M22 report for the H2Nodes project, having been involved in the project providing project management support. Element Energy, an ERM Group company, is a strategic energy consultancy working in sustainability projects in a variety of low-carbon sectors including hydrogen transport technologies and bring a wealth of expertise relating to modelling and advising on hydrogen vehicle use cases and financial considerations, as well as in kick-starting deployment projects for the sector. Element Energy were recently acquired by Environmental Resource Management, ERM, who have been working as strategic advisors to the sustainability sector since 1971.

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1. Summary

This report analyses the successes and lessons learnt from the entire H2Nodes project, including preparation, pre-deployment, commissioning and operational phases within the project, until project completion in June 2021. In particular, project findings are used to inform the business case for hydrogen transport in the vehicle segments explored in this project (buses, trolleybuses and taxis), and this is compared to diesel, diesel hybrid and battery electric vehicle (BEV) alternatives under the current and future alternative drivetrain costs. It is found that, whilst hydrogen fuel cell electric vehicles (FCEVs) perform worse on an economic basis over the short and medium term compared to BEVs, there are some duty cycles and infrastructure conditions that do favour hydrogen. In particular, the business case compares particularly favourably if additional vehicles are needed to accommodate a switch to a BEV alternative, or if an expensive depot and infrastructure conversion needs to be invested in. As such, this report recommends that fleet operators analyse the feasibility of both FCEVs and BEVs on a depot by depot basis, and, using the criteria identified in this report as a guide, conclude which drivetrain will be most feasible for each duty cycle. This analysis will enable cities to choose the most cost-effective route to move forward to a sustainable future.

Beyond purely economic considerations, the H2Nodes project has been able to attain several valuable learnings regarding project planning and vehicle and hydrogen refuelling station (HRS) operation. These are summarised in this report to aid future hydrogen project developers and transport operators when scoping a new technology project. One of the key learnings is to plan for contingency in the potential vehicle offtake demand for a new infrastructure deployment. Alongside the two successfully deployed stations in Riga and Arnhem, a third HRS was initially scoped in Pärnu, however, the transport operator who would have provided hydrogen demand via fuel cell bus operation withdrew from the project and there was a lack of feasible demand elsewhere in the city (despite demand shown for hydrogen vehicles shown from other Estonian cities). For such a first of its kind deployment, it is important that the correct site be located to ensure the investment is well utilised as a technology show case. Note that further detail on the barriers and lessons learnt is available in public H2Nodes Milestones reports[1], and that this report contains excerpts to highlight the key learnings.

The deployments in Riga and Arnhem have provided numerous operational learnings and have, combined, supported a fleet of over 60 vehicles which regularly refuel at the stations. Following the close of the project, the stations plan to remain operational and have scoped plans for potential upscaling of the production and dispensing units, and associated vehicle demand, under the Action H2Nodes (although note that any future deployments will not be supported by project funding). The key next steps for hydrogen deployments along the transport corridor targeted by H2Nodes (the North Sea-Baltic corridor) are to expand the nascent HRS skeleton network, particularly along the Eastern section of the corridor, via existing HRS upscaling and construction of new HRS on or near the corridor (e.g. plans for

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[1] https://www.h2nodes.eu/en/home/publications.html

hydrogen development in a number of cities near the corridor; Tallin, Kaunas and Jelgava, Dobele, following close of the Action H2Nodes).

2. Introduction

2.1 Project Background

The H2Nodes project was developed as part of a global project to facilitate the development of an interconnected network of Hydrogen Refuelling Stations (HRS) along Europe’s core transport network corridors connecting the major urban areas to enable long distance travel with Fuel Cell Electric Vehicles (FCEV). H2Nodes supports the global project with bottom-up demand driven regional development for clean transport in and between the partner cities.

The Trans-European Transport Network (TEN-T) is a European policy that addresses the implementation and development of a Europe-wide network of railway lines, roads, inland waterways, maritime shipping routes, ports, airports and railroad terminals. Besides the construction of new physical infrastructure, the TEN-T policy supports the application of innovation, new technologies and digital solutions to all modes of transport. The objective is improved use of infrastructure, reduced environmental impact of transport, enhanced energy efficiency and increased safety.

H2Nodes aimed to support the growth of new hydrogen infrastructure in Arnhem, Riga and Pärnu, centred on the development of strong local activity by engaging key stakeholders, fostering a positive market-led route to clean urban transport and increasing numbers of FCEVs along the TEN-T corridors.

H2Nodes developed hydrogen as an innovative technical solution with a focus on public transport, optimising existing bus and trolleybus route networks, promoting public transport and reducing pollution and greenhouse gas emissions. When using hydrogen as a fuel, vehicles produce zero harmful tail pipe emissions, with water vapour being their only by-product. Hydrogen also has the benefit of significantly reduced noise emissions, as well as range and refuelling times comparable to diesel equivalents. This enables sufficient operational flexibility for hydrogen to be used as a direct replacement to diesel for public transport such as buses. The H2Nodes project aimed to use a demand led focus to develop clean transport on the North Sea - Baltic core network corridor.

The Connecting Europe Facility (CEF) is an EU funding instrument for strategic investment in transport, energy and digital infrastructure, and CEF funding enables H2Nodes to support the development of hydrogen infrastructure on the North Sea-Baltic Core Corridor. As of October 2021, there are 153 hydrogen refuelling stations across Europe. Germany, France, the UK, the Benelux region and Scandinavia have been early adopters with growing networks of hydrogen infrastructure. Eastern Europe, including parts of the North Sea-Baltic Core Corridor, remain relatively undeveloped in the sphere of hydrogen and H2Nodes aimed to realise the first two HRS in the Baltic states. H2Nodes is the first step to the deployment of hydrogen infrastructure at strategic nodes on the corridor, and aimed to act as a blueprint for further development.

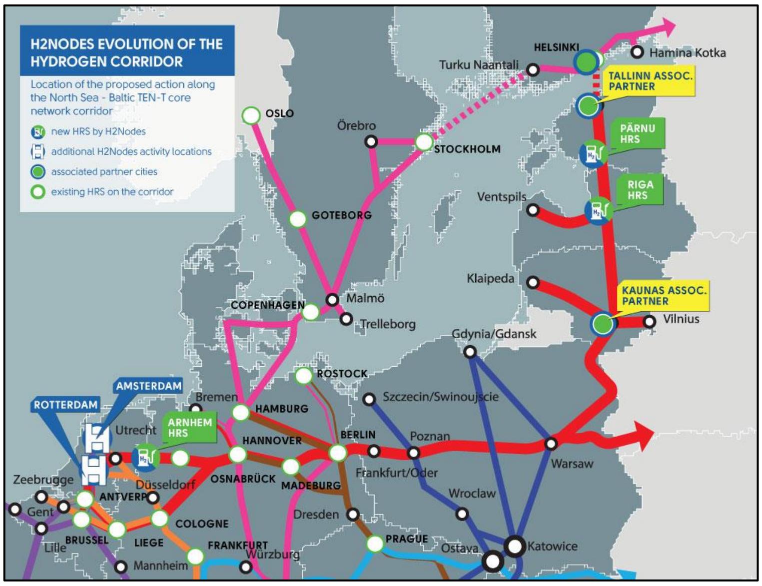

Figure 1: TEN-T Corridors. North Sea - Baltic corridor shown in red.

2.2 Report Structure

The primary function of this report is to provide objective analysis of the feasibility of developing further hydrogen deployments along the NS-B corridor based on the findings of the projects in Riga, Arnhem and Pärnu. The report will analyse the feasibility of hydrogen in the region from an economic, technical and business operational viewpoint, and compare the performance on these metrics to incumbents in the sector including diesel, diesel hybrid and battery electric vehicle (BEV) solutions. The report also considers the temporal aspect of these metrics and how they are expected to change as the alternative fuel technologies begin to reach mass-market manufacturing scales. Data in this report is sourced from H2Nodes project Milestones reports and real-world experiences of procurement and operation of vehicles and HRS in the H2Nodes project.

The report consists of the following sections:

- *Overview of deployment progress to date*, which details the technologies that have, to date, been successfully deployed under the H2Nodes project.
- *Cost-effective approaches for hydrogen deployments in cities*, which outlines the business case for hydrogen infrastructure and vehicle deployments and compares the total cost of ownership (TCO) to those of incumbents and BEV options.
- *Technology Readiness Evaluation*, which contains a summary of the performance of vehicles and infrastructure relative to the expected operational targets.
- *Pathways for Scaling Up*, which analyses the potential and appetite for scaling up the production facilities and vehicle deployments across the 3 cities.
- *H2Nodes Case Study Lessons Learnt*, which summarises all the key learning points gained from the Action H2Nodes.

3. Overview of deployment progress to date under H2Nodes

3.1 Riga deployment

The hydrogen refuelling station and production unit, located in Riga on Vienības Gatve 6, is owned and operated by RM LLC Rigas Satiksme ('Rigas Satiksme'). Hydrogen is produced using a steam-methane reformer with a total capacity of 300kgH_2/day, which feeds hydrogen storage tanks with a total capacity of 600kg/H2, which is split between low pressure hydrogen supply storage tanks and medium and high pressure storage tanks which are used to directly fuel the 350 bar and 700 bar dispensers respectively (see Figure 2). The station was accepted for operation in December 2019, but production performance tests were delayed due to an incident at a Nel HRS in Norway with similar equipment which necessitated inspections at the Riga site. The production, storage and refuelling capability eventually became fully operational in February 2020.

The primary users of the refuelling station are Rigas Satiksme owned Trolleybuses with fuel cell genset ('HyTrolleybuses'), which were fully commissioned and began fuelling at the Riga HRS in March 2020. These Trolleybuses have the capacity to be powered both by electricity from the catenary network, or by hydrogen fuel cells when no such connection is available. There is also a Toyota Mirai deployed in the region outside of project funding, which utilizes the 700 bar dispenser.

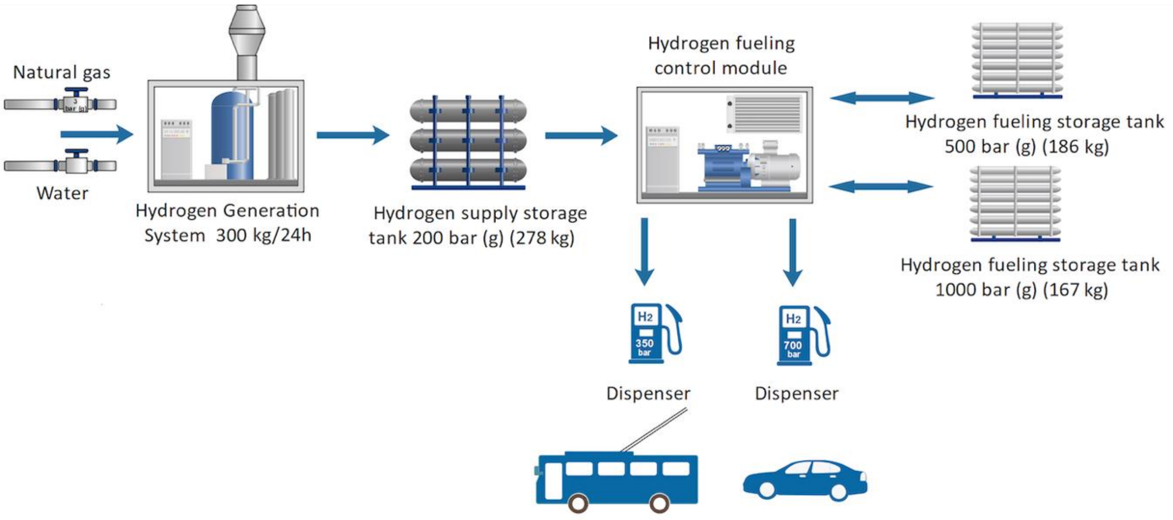

Figure 2: Riga HRS equipment overview

The Riga HRS is designed with the principle of modularity: there are a total of 3 hydrogen generation systems deployed, each with a nominal capacity of 90kg/day. This design was chosen in order to achieve hydrogen availability in case of maintenance or malfunction to an individual unit. This has allowed the Riga HRS to produce hydrogen with reduced capacity if one or more hydrogen generation system is not operating, and has resulted in the extremely high station availability achieved (see the section *Technology Readiness Evaluation*). Several modular compressor systems are also required; there are two natural gas compressors with a total capacity of 60Nm^3/h and two hydrogen compressors that increase the hydrogen to supply storage pressure (200 bar). The hydrogen fuelling control module is connected between the hydrogen supply storage, hydrogen fuelling storage units and both dispensers, as shown in Figure 3. The station maximum capacity is designed to allow the refuelling of up to 10 trolleybuses, 15 FCE-buses and 5 passenger vehicles.

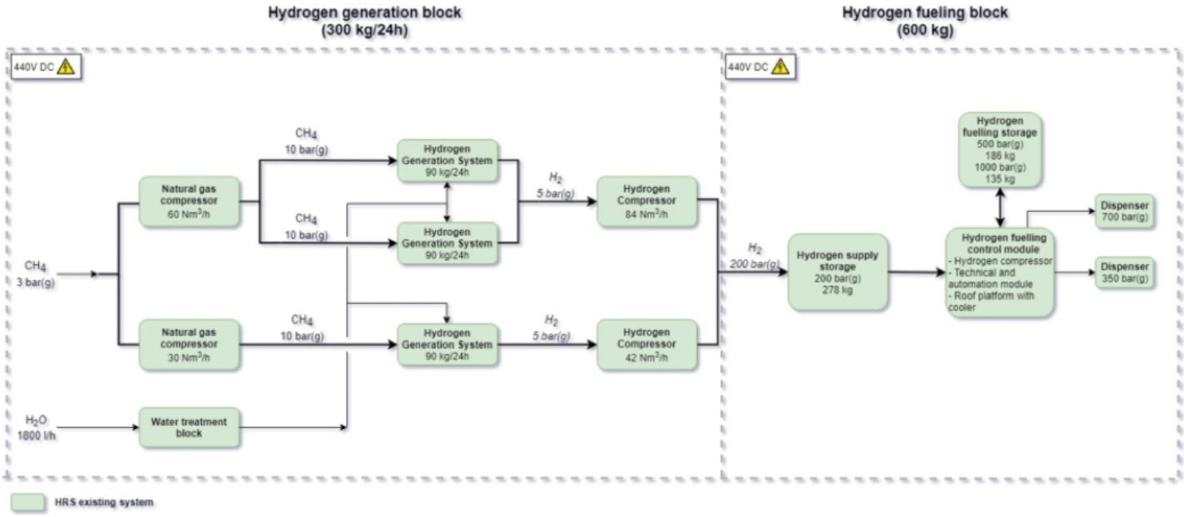

Figure 3: Riga HRS functional units and material flows

3.2 Arnhem deployment

In Arnhem, hydrogen vehicles refuel via a HRS owned and operated by TotalEnergies located at Kleefse Waard. The station is capable of refuelling both passenger cars, buses and trucks via the 700 and 350 bar dispensers respectively. Hydrogen used for the project is supplied by steam reforming of natural gas (SMR), which was deployed in 2019 with an initial capacity of 85kg/day. Since this date, the hydrogen production unit has been scaled up to a technical capacity of 260 kg/day, of which approximately 32 kg/day is expected to be used for the operation of a reference demand of 80 FCEVs in the region. Note that not all these vehicles have been deployed to date as part of the project, however, it is expected that over time market pull will bring the demand closer to the 80 vehicle target from the current group of approximately 50. The expected hydrogen demand in the near term therefore does not match the available capacity at the station, and hence there is significant scope for the upscaling of hydrogen vehicle deployment vehicles in the region without the need for additional production units, further discussed in the section *Pathways for scaling up*.

There were an additional two FCEV buses, operated by the Gelderland public transport company Syntus in the Veluwe public transport concession area, which used the station and provided additional base demand above the expected reference demand. These vehicles, however, have now halted operation due to the operator procurement strategy changing. In 2019 the Veluwe public transport concession was re-tendered by the provinces of Gelderland, Overijssel and Flevoland as part of a larger new public transport concession that covers significant parts of all three provinces. This concession was granted to Keolis, a merger of various regional Syntus public transport companies, including Syntus Gelderland. This public transport concession contract was tendered as a zero-emission contract, leaving the decisions about the composition of the bus fleet to the bidders. Keolis included a 100% BEV bus fleet in its bid and hence the two FCEV buses will be taken out of service in the Netherlands as the specific connections will be operated by BEV buses, and the FCEV buses are to be redeployed in Germany.

3.3 Pärnu deployment

The H2Nodes project proposed the deployment of hydrogen demand to refuel 15 FCE-buses, with the necessary production and dispensing capacity set at 180 kg/day. The H2Nodes project has been unable to meet this target due to a lack of demand from potential FCE-bus operators in Pärnu today, and as it is unlikely that FCE-vehicles and HRS will be deployed in Pärnu in the near term. The intended Pärnu HRS scheme is shown in Figure 4, and a theoretical evaluation of the required equipment for the potential HRS is given below.

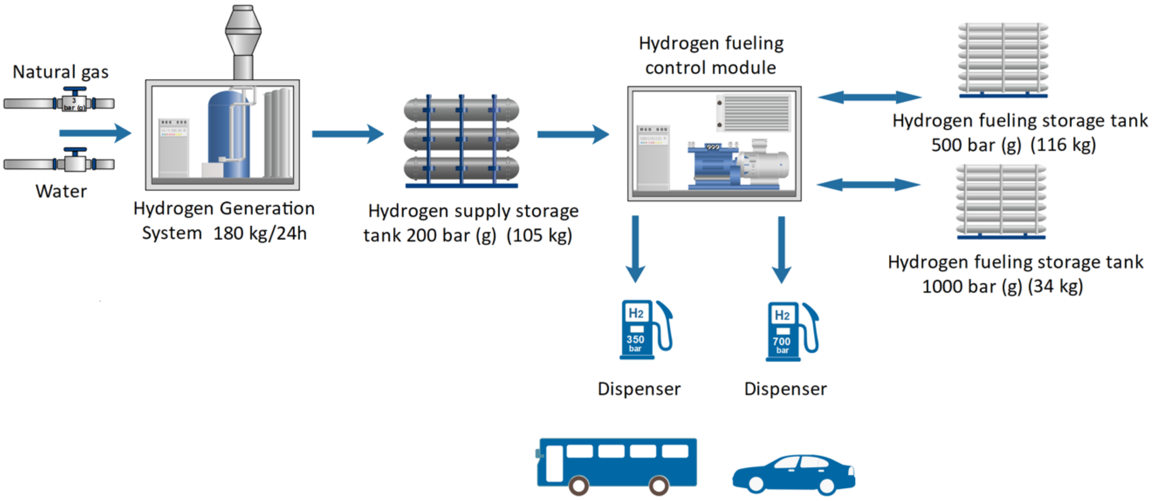

Figure 4: Planned Pärnu HRS equipment overview

It was proposed that the hydrogen is produced by steam methane reforming. In order to achieve the necessary hydrogen availability with a modular system, two separate hydrogen production lines should be installed, each with a capacity of 90kg/day. Both natural gas and hydrogen compressors are required in each line to increase the pressure to the required 200 bar for storage (see Figure 5).

For the storage it would be necessary to deploy one hydrogen supply storage unit with a capacity of 105 kg of hydrogen. One hydrogen fuelling control module, complete with compressors and storage, would be required in order to operate both the 350bar and 700bar dispensers.

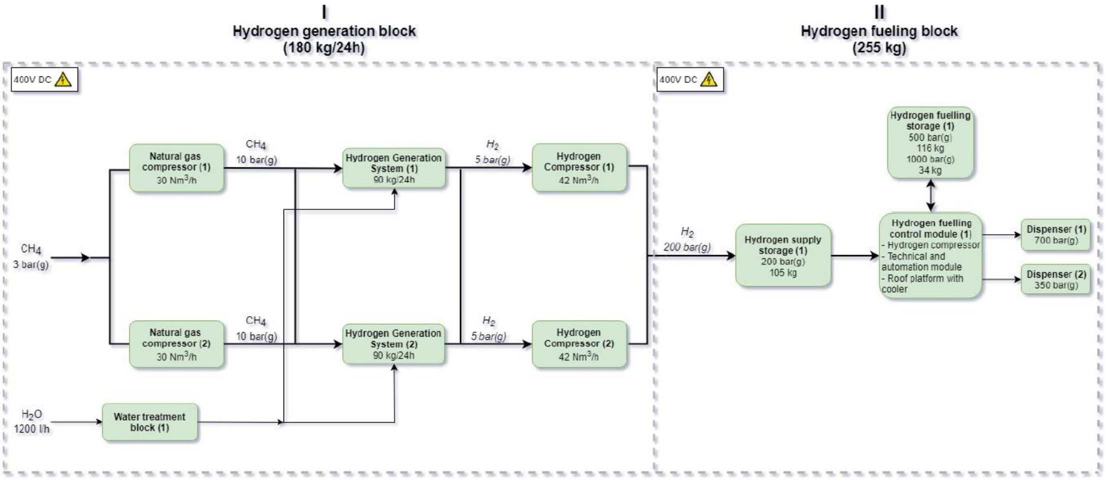

Figure 5: Pärnu HRS functional units and material flows

4. Cost-effective approaches for hydrogen deployments in cities

4.1 Business Case Evaluation

This section analyses the business case for hydrogen vehicle deployments as studied for vehicles along the NS-B corridor. The bulk of this section analyses hydrogen vehicle technologies, and alternative drivetrains, on a total cost of ownership (TCO) basis. This consideration of the cost over a total vehicle lifetime takes into account the substantial maintenance and driver costs of operating fleet vehicles, as well as any additional hidden costs such as depot refurbishment and infrastructure maintenance costs. This TCO approach is typically the key indicator considered by fleet operators during the procurement process. Further non-financial considerations to the hydrogen business case are also considered in the section *Summary and non-financial considerations*.

Project data for the cost contributions to hydrogen production is used to generate 'high', 'medium' and 'low' scenarios for retail hydrogen price. These prices are input into TCO models developed by Element Energy for buses, taxis and trolley buses, alongside a combination of project data supplied by partners and internal Element Energy costing assumptions for vehicle specific data. A summary of this data is provided in *Appendix A: TCO Assumption Data*.

The performance of hydrogen fuel electric cell vehicles (FCEVs) is compared to diesel, diesel-hybrid and battery electric vehicle (BEV) counterfactuals for single deck buses, taxis and trolley buses. Whilst this does not capture all business models for hydrogen vehicle ownership (for instance, only approximately 50% of the passenger car vehicles deployed in Arnhem are taxis), it does cover the vehicles that have been funded by the project (10 Hytrolleybuses), as well as vehicle types explored in the project where hydrogen has been found to present a good business case (buses and taxis in Arnhem). For BEV and FCEV models the current equipment and fuel prices, as well as potential future prices (approximately 5 years into medium scale market deployment), are quantified and analysed. Note that it is important to consider the future expected prices when comparing alternative fuel drivetrains, given that equipment prices for these technologies have fallen considerably over the previous 5 years and are expected to be reduced further in the future.

4.2 Hydrogen Price Scenarios

Both Arnhem and Riga were successful in deploying hydrogen production units (HPUs) using on-site hydrogen production via steam methane reforming of natural gas. The average price of hydrogen dispensed in the project varied slightly between H2Nodes sites, but was approximately €11/kg before tax, taken as the 'high' scenario in the vehicle TCO evaluation. This is significantly above the price point required to achieve diesel fuel cost parity (prices below, estimated at approx. €7/kg), and this was primarily due to two main factors:

- Low station utilization

- Low hydrogen production volumes

These factors are explored further in the following hydrogen price scenario sections which demonstrate that, with significant scale up of production facilities, a price comparable or better than the diesel fuel equivalent is achievable. Note that the main limiting factor to reducing hydrogen price is currently the costs of energy sources and water, which in the H2Nodes project contributed approx. €6 to the pre-tax retail price (52% electricity, 35% natural gas, 13% water). These are the values for the operation of the entire production and dispensing station, including lighting and heating in the station and water usage by the station on daily tasks, as well as electricity and natural gas used in steam methane reforming and water used in osmosis units. Hence, the costs of energy and water usage could be greatly reduced by increasing the station size and utilisation as this would reduce the contribution (on a cost/kg basis) from station operation processes.

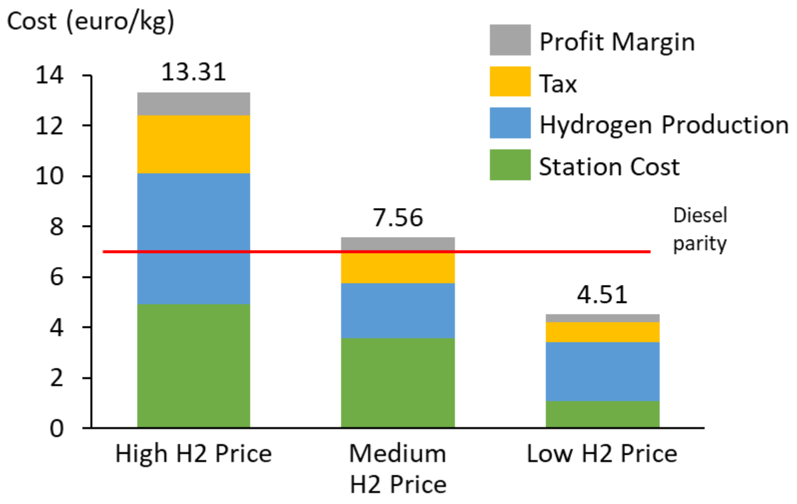

Figure 6: Cost comparison of hydrogen pricing scenarios relative to diesel

4.2.1 Medium price scenario: increasing station utilisation and mild scale up

In Riga, the station operated at only 25% capacity and usage was concentrated to peak times (01:00 – 03:00 AM), whilst in Arnhem the reference vehicle demand (this includes passenger vehicles only as the bus deployment will be discontinued at the end of the H2Nodes project) meets only 12% of the production capacity. The current station sizes therefore leave room for growth and the deployment of additional vehicles, however, the low utilisation currently results in high station amortization and service costs (see Figure 7).

The potential for equipment scale up of the on-site SMR production and delivery in Riga is explored in Table 4-1. This analysis assumes greatly increased station utilisation due to the deployment of an additional 15 FCE-buses (18m). This would lead to an overall hydrogen demand of 453 kg/day and would result in a production utilisation factor of 84% from the proposed 540 kg/day facility. Under these conditions a retail hydrogen price of €6.24 (before tax) is achievable, and this is taken as the 'medium' hydrogen price scenario in the vehicle TCO analysis.

The total capex required for upscaling the existing Riga station to service this demand is significant at €8.5M, and this is reflected in the high station depreciation cost component (38%). However, this is greatly offset by the reduction in hydrogen production cost compared to the current stations in operation, resulting in an overall price reduction of 43%.

Table 4-1: Medium hydrogen sale price scenario (540 kg/day grey hydrogen)

Cost Component	Cost (24 months after launch) (€/kg)
Hydrogen production	1.76
Employees	0.31
Service & dispensing	1.25
Station depreciation	2.34
Financing costs	0.07
Applied premium	9%
Retail price before tax	**6.24**

4.2.2 Low price scenario: large scale electrolyser deployment

Increasing the scale of hydrogen production by a further order of magnitude to 5 tonnes/day has the potential to further reduce the hydrogen price by 40% compared to the medium sale price scenario and allows for a feasible business case for green hydrogen production via electrolysis. Note that this scenario requires significant capital investment (€30M), primarily associated with the deployment of the required electrolysers (11.5 MW) and the associated auxiliaries, as well as costs for the large-scale HRS. Despite this, the overall station depreciation and servicing costs are greatly reduced on a per kg basis compared to previous scenarios due to the increased production volume (sufficient to fuel over 200 FCE buses), resulting in the lowest hydrogen production cost of all scenarios of €3.74/kg pre-tax. This is the lowest feasible hydrogen price that could be available to an end user without significant reductions in today's electricity price, which dominates the hydrogen production costs. €3.74/kg is the price chosen in the 'low' hydrogen price scenario in the vehicle TCO analysis.

The level of demand required to achieve this price, however, is not likely to be feasible from a single bus station as it would require the conversion of the entirety of a very large depot to hydrogen. This is unlikely given that hydrogen will be a complementary technology to battery electric vehicles, at least in the short term, to be used primarily on high mileage routes or in areas where infrastructure capacity for electric charge points is limited. There is some scope, however, for future multimodal vehicle hubs to provide this level of hydrogen demand. Aggregating demand across a variety of vehicle types such as passenger cars, vans, buses and trucks increases the potential local use for hydrogen and this concept is being developed across Europe, for in instance in the Tees Valley Hydrogen Hub (UK) (MacDonald, 2021).

Another method of achieving this critical hydrogen price is to use off-site hydrogen production, potentially close to cheap offshore renewable electricity sources, and transport the hydrogen to end use applications not only in the transport sector but also industry, heat and power sectors where hydrogen has a strong use case. This is the approach taken by the HEAVENN project (Netherlands) (New Energy Coalition, 2021) and effectively tackles the issue of reaching the hydrogen production volume (tonnes per day) to achieve green hydrogen prices competitive to diesel, as well as potentially reducing the hydrogen production costs estimated in Table 4-2 with access to electricity at source. However, note that hydrogen delivery comes with an associated cost of approximately €0.65/kg due to the additional cost of tube trailer depreciation, diesel and driver salaries.

Table 4-2: Low hydrogen sale price scenario (5 tonnes per day green hydrogen)

Cost Component	Cost (24 months after launch) (€/kg)
Hydrogen production	2.31
Employees	0.03
Service & dispensing	0.27
Station depreciation	0.79
Financing costs	0.02
Applied premium	9%
Retail price before tax	**3.74**
Distribution costs (trailer)	0.65
Total retail price before tax	**4.93**

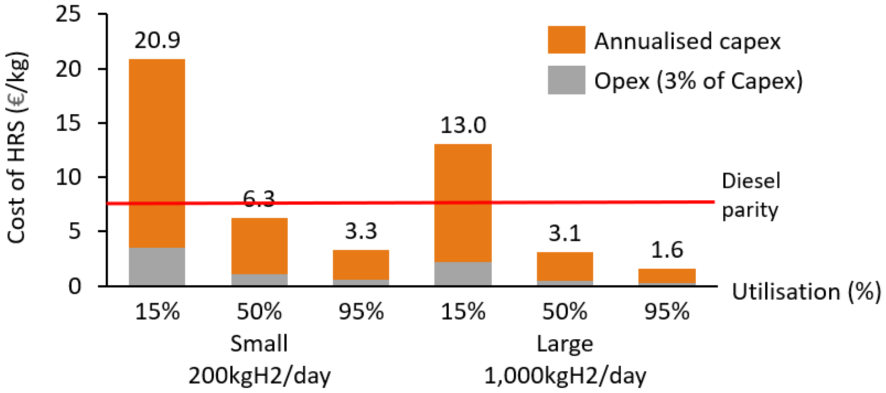

Figure 7: Illustrative effect of station size and utilisation factor on station costs. Note that calculations include station costs only and exclude the variable costs of hydrogen production and energy and water usage.

4.3 Bus total cost of ownership (TCO) Evaluation

The following section compares the economic case for fuel cell electric bus uptake to that of battery electric alternatives and diesel incumbents. Figure 8 shows a high level overview of the findings summarised by the mean yearly total cost of ownership metric; this metric considers all costs incurred as a direct result of vehicle ownership and operation, however, does not consider secondary costs common to all vehicle types such as driver labour due both to the variable values of these figures depending on regional labour rates as well as the lack of benefit gained for the analysis when its primary purpose is to compare different drivetrains. Note that whilst the only buses operated in the H2Nodes project were deployed in Arnhem, the data used to populate the model in this section has been corroborated by Element Energy's own data, ensuring that the analysis is applicable and representative of the business case across the TEN-T corridor studied, and indeed the majority of Europe.

The validity of a business case for a hydrogen bus at current prices is heavily influenced by the presence (or lack of) the monetisation of the effects of health impacts and a CO_2 tax. Many cities around the world have begun implementing Clean Air Zones (CAZ) in order to combat the worsening air quality crisis and its now better understood links to millions of premature deaths each year and impact on lung and cognitive development in children (WHO, 2021). To illustrate the effect of these CAZ charges on the business case for diesel vehicles, Figure 8 includes a €71/day charge for buses operating within the city, in line with the Clean Air Zone being implemented in Manchester, UK from 2022 onwards (Clean Air Greater Manchester, 2021). This charge has a significant impact on the overall total cost of ownership for the vehicles at close to an additional €26,000 per year extra expenditure which, when combined with a carbon tax of €250/tonne CO_2 (in line with projections for carbon pricing by 2030 i.e. half way through a bus bought in the next 2 years' fifteen year lifespan) (Clean Energy and Prosperity, 2020), results in a TCO which is *more* expensive than that of the equivalent FCEV at current prices. Note that clean air taxes in most instances still apply to diesel hybrid vehicles, hence these are also negatively impacted by the levies studied. Prices for both hydrogen vehicles and hydrogen fuel are in particular projected to decrease substantially over the next decade, and hence either one of these diesel taxation methods are likely to be enough by 2030 to result in a FCEV TCO which is cheaper than that of a comparable diesel vehicle or hybrid.

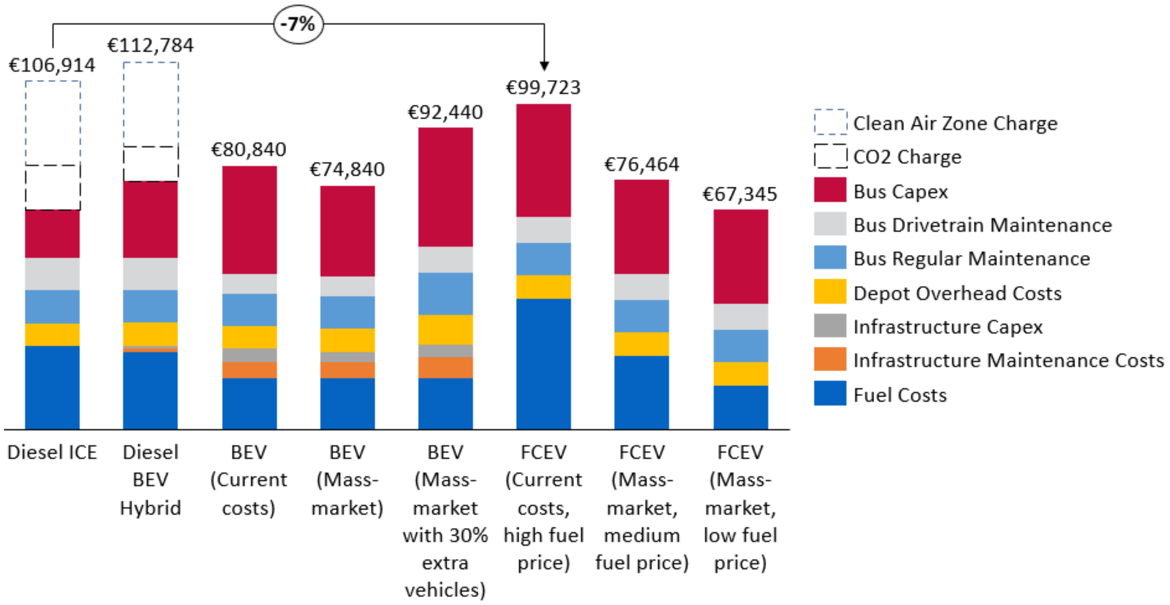

Figure 8: Bus Total Cost of Ownership (€/bus/year)

Due to the high mileage and long operational lifetime of buses, the fuel price and fuel efficiency are the two key factors that greatly influence the total cost of ownership evaluation, since factors such as vehicle capex are depreciated over a very high total vehicle mileage (825,000 km). As such, diesel consumption makes up 38% of the annual expenditure for a diesel bus, and hydrogen consumption is currently even higher for fuel cell buses (40%). This highlights the importance of two factors; sourcing low cost hydrogen (e.g. via upscaling and high utilisation factors as discussed in the section *Hydrogen Price Scenarios*) and using this hydrogen effectively, for instance by use in high-efficiency, well maintained, proton exchange membrane (PEM) fuel cells rather than burning in hydrogen internal combustion engine (ICE) vehicles (which would at least double the fuel cost projections shown in Figure 8). Note that there is scope for increasing the fuel cell efficiency above even the 49% figure achieved in the H2Nodes project (and hence decreasing the projected fuel costs in Figure 8 beyond even the low fuel price scenario) by use of alternative fuel cell types (see Table 3), however, the price and operational requirements[2] of these fuel cells are currently prohibitive to commercial operations and the PEM fuel cell is the only system being widely investigated in hydrogen vehicles at a commercial scale.

Table 3: Fuel Cell Electrical Efficiency

Fuel Cell Type	Efficiency
Alkaline	70%
Molten carbonate	60-80% with cogeneration
Phosphoric acid	40-80% with cogeneration
Solid oxide	60%
Proton exchange membrane	40-50%

The other major contributor to FCEV operating costs is vehicle depreciation, which is substantially higher than the diesel equivalent (over double the price), and is still a significant yearly cost even over a long depreciation window. The fuel cell vehicle capital cost, whilst expected to decrease by up to €100,000 when comparing mass market prices to today's prices, will not be able to rival diesel vehicle costs at any point in the future. Hydrogen vehicle capex costs are projected in this study to trend towards BEV costs over the long term, aided in particular by the higher costs of battery electric powertrain overhaul[3], however are unlikely to be lower than the cost of an equivalent battery electric vehicle at any point owing to the considerable cost of the fuel cell stack and hydrogen tank system.

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[2] Solid Oxide Fuel Cell (SOFC) Prices at 1,000 units per year and 50,000 units per year: \$370/kWe and \$180/kWe respectively (Scataglini *et al.*, 2015)(cf. PEM fuel cell costs: approximately \$30/kWe). SOFC operating temperature: 800-1000°C.

[3] The cost of a vehicle powertrain overhaul is included in the vehicle capex cost calculation. It is assumed that a powertrain overhaul is required after half the vehicle total lifetime (7.5 years)

Therefore, at a surface level, the hydrogen vehicle does not compare favourably with alternatives for low emission vehicles (hybrid and battery electric options) in the immediate future. However, directly comparing the costs of hydrogen to battery electric vehicles is not a fair comparison as battery electric buses have a reduced range and longer refuelling times compared to diesel and hydrogen vehicles, and hence there must be a trade-off between the additional vehicle cost of FCEVs and the reduced business operational capabilities using BEVs. This compromise will be dependent on the specific duty cycle of the vehicles being studied, including the refuelling window, required mileage, average inclination, stop regularity etc., and the following paragraphs outline some of the cases where hydrogen FCEVs offer a competitive or preferable business cases for the decarbonisation of buses.

One problem often cited by vehicle operators when considering the infrastructure cost of transitioning to BEV for on-depot vehicles is the considerable issue of accessing additional electricity supply for the site to power the electrical chargers. The cost of upgrading a commercial or residential electricity supply by up to 70 kVa (sufficient to fast charge most small cars) varies between ~€3-6k, however, the conversion of an entire depot of large vehicles to simultaneously charge is a significant concern for most station operators and the price of such a conversion can vary greatly depending on the station area, existing electricity network and the extent to which the network needs to be upgraded, and whether new electrical substations need to be built (or existing substations upgraded). A mid-range estimate for these potential costs (see *Appendix A: TCO Assumption Data*) is used, and this cost is depreciated over the initial converted vehicle fleet lifetime in Figure 8, along with the additional cost of supplying new fast charger infrastructure to the site. There is significant uncertainty in these additional costs due to the uncertainty in electrical grid upgrading costs, and as such this report recommends that vehicle operators considering low carbon options should size their charging requirement and enquire with the system operator about the additional cost of connecting the required charging devices. If the quote greatly exceeds the assumptions in this report, hydrogen may be the best option for decarbonisation in the near term.

The duty cycle should also be considered carefully when assessing which zero carbon drivetrain is most appropriate. Included in Figure 8 is an illustration of the cost of purchasing and operating an additional 30% more vehicles in the fleet using BEV technology, which could be required to ensure continuation of service using electric vehicles with shorter ranges and longer charge times than diesel and hydrogen refuelling. Note that this 30% figure is an indicative value only and is not based on findings or analysis conducted by H2Nodes partners, however, based on Element Energy work there is anecdotal evidence that this figure provides a useful illustration of the potential impact of measures that may be required to decarbonise bus fleets using BEV technology alone. The additional costs due to vehicle capex, as well as infrastructure and depot overhead costs, quickly worsen the economic case for BEVs as a cost-effective option compared to FCEVs, and this is before considering additional driver wages for time spent in vehicle fuelling or vehicle changeover if required by the operational schedule. The mass market TCO evaluation for BEVs under this scenario is 21% more expensive than the projected mass market costs for the equivalent FCEV, and within 8% of today's FCEV figure based on H2Nodes data, and thus any estimates for additional vehicle requirements close to or above this 30% figure should be considered with some scrutiny when evaluating a bus depot conversion to zero emission technology. The exact additional fleet requirement will vary considerably between vehicle use cases, for instance, intra-city transport operators with low daily mileage and long refuelling windows may not require any additional vehicles, however, the hydrogen business case will compare favourably to the BEV alternative under one or several of the following conditions; high mileage fleets, long operational windows, power-take-off for interior heating or cooling, demanding duty cycles (e.g. stop-start, high gradient hills), limited available depot space.

4.4 Taxi total cost of ownership (TCO) Evaluation

The taxi fleet model is a simplified model compared to the bus fleet business case, as the model assumes that taxis are stored at the personal residence of the taxi driver, compared to the on-depot storage of buses. This factor does notably favour the economics of BEV ownership, as costs to access additional grid connection are not considered and the charger costs for passenger car vehicles such as taxis are lower. The model outputs show that the TCO of a BEV is already competitive with the diesel equivalent, before considering clean air zone and carbon levies (see Figure 9). Note that the diesel hybrid TCO value is slightly above the diesel equivalent, however, the TCO for this drivetrain is largely dependent on the extent to which electricity is used as the primary fuel (a light-hybrid approach is assumed in the model due to a high taxi mileage requiring significant diesel usage).

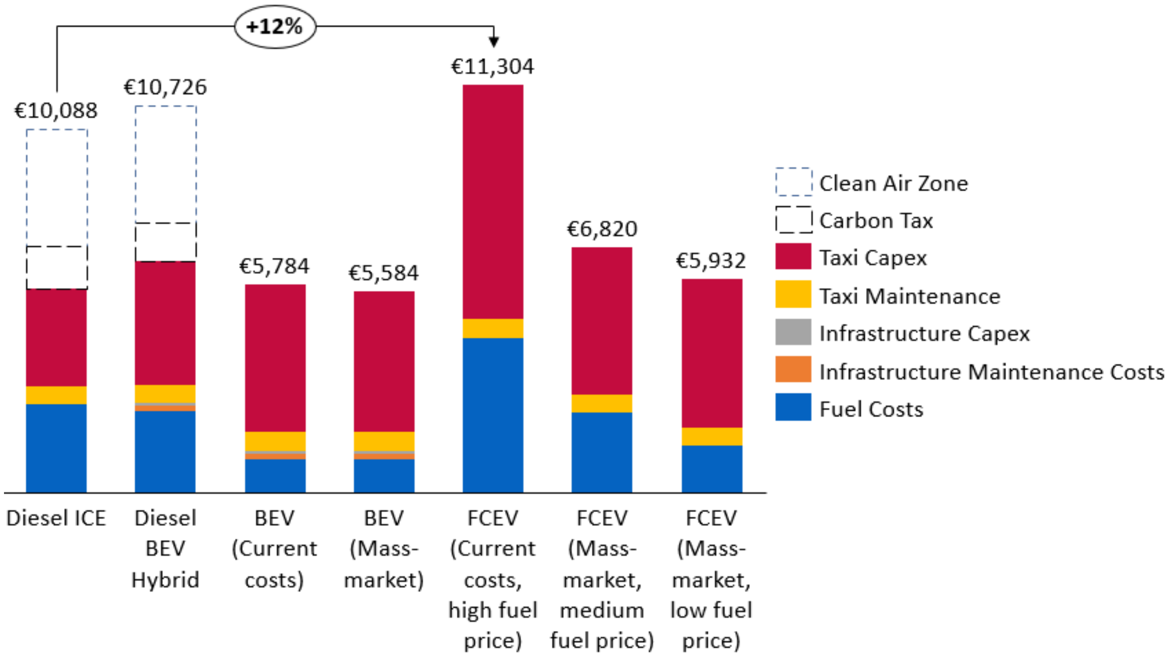

Figure 9: Taxi Total Cost of Ownership (€/taxi/year). Note that *Current Costs* for FCEVs do not include project funding used to reduce fuel costs (the H2-Drive scheme used funding to half the hydrogen cost for taxi users) in order to provide a fair comparison with the present day scenario of other unsubsidised drivetrain types.

The largest difference between the taxi model and bus model studied is the relative effects of capex and fuel costs on the overall cost calculation. Taxi vehicles have shorter operational lifespans and lower mean annual mileages, hence the importance of initial taxi capex is increased as this contributes to the majority (48-58% depending on drivetrain) of the total ownership cost.

Battery electric passenger cars are already commercialised at a significant scale, with an over 10% market share in Europe (IEA, 2021), and hence current models have capex values close to the expected 'mass-market' costs. Meanwhile, FCEVs are still in early stages of commercialisation, with high capex costs and the market dominated by only two global OEMs in Hyundai and Toyota, and hence the taxi business case looks especially poor under the present-day scenario at a 199% increase relative to diesel ICE vehicles (before levies). However, there are expected to be significant reductions in vehicle capex as the market scales up and this has a large impact on the viability of the taxi business case, with mass-market costs expected to bring the hydrogen FCEV TCO to within 20% of that of a diesel ICE vehicle before carbon tax is added. This aligns with the ZEFER conclusion "by 2025 it is widely expected that FCEVs can reach parity with petrol/diesel hybrids", and under the scenario that pollution levies are introduced, the FCEV business case is substantially improved.

The question remains whether hydrogen FCEVs will be able to directly compete with pure battery electric vehicles on a cost basis; the low fuel price of €3.74 is required for hydrogen to approach mass-market BEV prices due to the expected lower vehicle capital cost. Thus, it is likely that in the majority of Europe the viability of the FCEV business case compared to BEVs will depend on whether one of the following criteria is met:

1) If there is a lack of readily accessible parking spaces and public loading points for taxi drivers to park and charge their vehicles overnight, resulting in the need to invest in a depot for vehicle charging. This brings the business case closer to that analysed for buses, which was shown to have several use cases which provide a cost competitive vehicle TCO.
2) If there is a nascent hydrogen ecosystem being developed which allows access to the hydrogen economies of scale through multiple end user demands and can be shown to provide a fuel price below diesel parity and close to the low fuel price scenario shown in this report.
3) If the fuel cell taxis deployed are intended to be operated over a longer time period than the BEV counterpart (greater than 10 years). This could be feasible with a powertrain overhaul (which is expected to be cheaper than for BEVs due to the lower battery size) and increased expenditure on vehicle maintenance, however, it would depreciate the vehicle cost over a longer time period. As this is not standard practice for taxi operation there is limited data available as to the expected costs for such a business model, but using indicative estimates for costings in the TCO model developed for this project it is expected that the mass-market, medium fuel price scenario could cost between c.€5,900-7,100 depending on factors such as vehicle lifetime extension and additional maintenance costs.

4.5 Trolleybus total cost of ownership (TCO) Evaluation

Trolleybuses use a similar operational model to that of buses, and the total cost of ownership results show a similar trend (although scaled up due to the increased size and power requirements of trolleybus operation; the trolleybuses studied in the H2Nodes project were articulated 18m long trolleybuses). Figure 10 again demonstrates the significant reductions expected in FCEV and hydrogen prices as the industry continues to scale up, and the significant impact that a carbon tax and clean air zones can play in stimulating the shift to zero emission vehicles.

The primary difference between trolleybus and bus operation is the use of catenary cables to provide electrical power to the bus throughout a portion of its journey. This results in less variation in the fuel costs for all vehicles as a portion is derived from the same source, as well as less variation in vehicle capex costs since a smaller battery and hydrogen tank is required in BEVs and FCEVs respectively (although note that a powerful fuel cell is still required to ensure sufficient peak power is available).

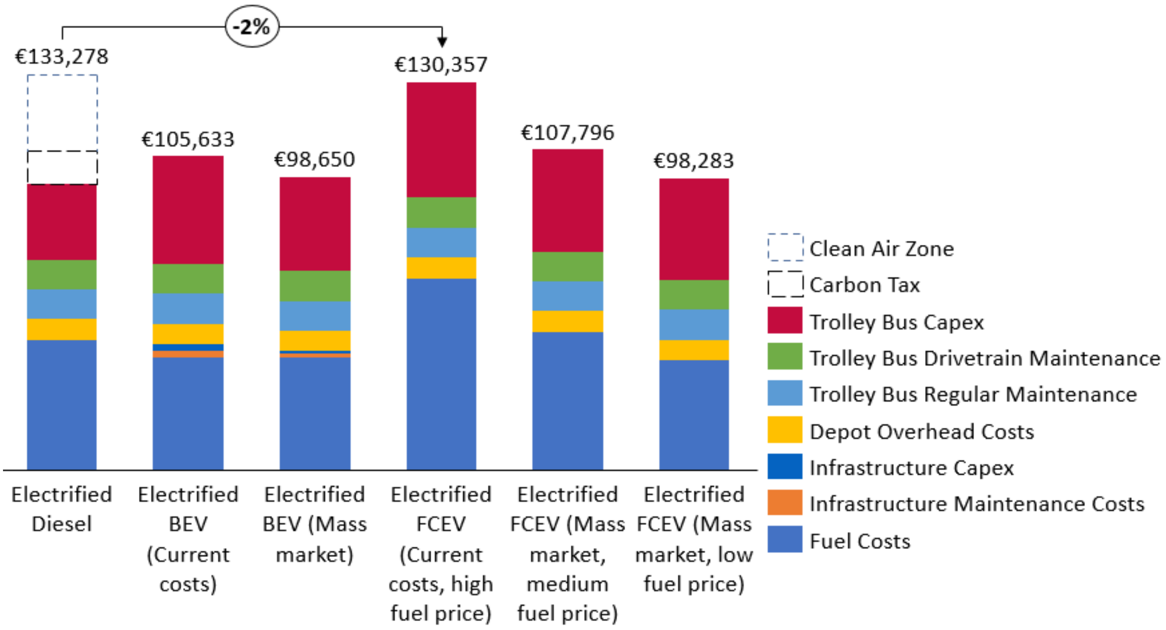

Figure 10: Trolleybus Total Cost of Ownership (€/trolleybus/year). *Current costs* for FCEVs do not include H2Nodes specific funding used to subsidise the trolleybuses.

The business case for hydrogen trolleybuses depends primarily on two key factors: hydrogen cost and any requirements for additional vehicles. Note that the vehicle capex difference has less of an impact on the total cost of ownership than for other vehicle types, as the trolleybus mileage is typically very high, hence the differences are depreciated over a high number of miles.

- The hydrogen cost factor still stands out as the key variable (see fuel cost variation in Figure 10) due to the large size and power demand of the trolleybuses. The cost assumed in the high price scenario, €13.31, is approximately double the diesel parity price and hence, even though less hydrogen is used than for buses, it still makes a significant impact on the TCO model. Further investment in the scale up hydrogen facilities, along with hydrogen demand, is therefore required in the short term to make hydrogen FCEVs cost competitive with BEVs.
- Any requirement for purchasing additional trolleybus vehicles to operate a full BEV fleet has a significant impact on the trolleybus business case, and this impact is even

more stark given the relative lack of variation in TCO model values and considerable time spent operating on catenary cables for all vehicle types (this reduces the ability of the additional BEV capex to be offset by the low running costs of cheap electricity). Whilst the potential for requiring additional vehicles to meet the service demand is lower due to the lower daily mileage under self-propulsion, there is still some scope for this requirement given the long operating hours of trolleybuses (04:00 – 00:00 in Riga) resulting in a short, once a day refuelling window which is not well suited to BEVs.

4.6 Summary and non-financial considerations

Overall, the H2Nodes project has been able to demonstrate hydrogen fuel cell vehicles at close to or below diesel parity, provided that an appropriate monetary cost is applied to carbon and other pollutant emissions in the form of a carbon tax and clean air zone. Whilst these levies are not applied universally across all European cities at present, there will be an increasing number of cities over the next generation of vehicles' lifetimes which chose to adopt such measures, and hence this poses a risk to any new diesel or diesel hybrid vehicles purchased today intended for operation within or between cities.

The business case for FCEVs is also expected to improve substantially over the next decade as the cost of hydrogen and the capital cost of vehicles decreases in line with the scale to which the technology is being deployed. One point to consider here is that this scale-cost reduction benefit also applies at a depot level, and there is a notable synergy in terms of reducing infrastructure costs and ensuring optimal utilization if an entire depot is converted to hydrogen. Using hydrogen as a fuel for only the hardest to decarbonize sectors is more likely to result in a prohibitively expensive hydrogen price for these vehicle segments. Hence, if even a portion of the vehicle fleet operates under a duty cycle which is not suitable for decarbonization via battery technology alone, it may be cheapest in the long term to invest in hydrogen technologies for the entire fleet, instead of investing in the decarbonization of the 'easy wins' in the light duty and low mileage segment of the fleet using today's battery technology. As such, this report has identified several operating conditions under which the adjustment to a battery electric solution would prove prohibitively expensive, and hence a hydrogen solution should be investigated for the depot:

- The vehicle operational cycle would require additional BEVs to be purchased above the fleet replacement rate in order to meet the service demand.
- The grid connection requires significant upgrading costs to allow for the capacity to charge the entire BEV fleet.
- The hydrogen vehicles can be operated for a longer operational lifetime, or at a higher mileage, than the alternative fuel counterfactual.
- The hydrogen vehicle can be deployed as a portion of a 'hydrogen vehicle ecosystem' with additional demand for hydrogen from industry or other vehicle types bringing down the hydrogen cost on a €/kg basis.

4.6.1 Subsidy considerations

This section has analysed the business case of hydrogen transport without assuming subsidies are available to incentivise the uptake of vehicles, such as the H2-Drive scheme in Arnhem. As demonstrated in the analysis above, in most instances transport operators will require subsidies in the short term to achieve cost parity with diesel (assuming a clean air zone tax is not being applied in the chosen city), and whilst there are some regulatory measures available at a national or European level which act to reduce this funding ask, it is expected that project funding or a dedicated support scheme will be required in the near term to ensure continued development towards the mass-market economic case. At the point of mass-market deployment, these subsidies are no longer required as the business case for hydrogen has been shown to be cost competitive with BEV technology (and in some instances even below the diesel parity price).

Included in the section *Pathways for scaling up* below is an overview of the regulatory landscape for national ambitions for the countries involved in the H2Nodes project, however, there is a notable lack of dedicated financial measures available in Latvia and Estonia (although note that Estonia recently announced a government grant to secure the development of HRS in Estonia (Valitsus, 2021)), whilst support schemes in the Netherlands are primarily focused on the hydrogen production business case. Note that there is a capital purchase subsidy available on new FCEV and BEV vehicles in the Netherlands for vehicles under the list price of €45,000, however, fuel cell vehicles do not current qualify for this due to their starting price of ~€60,000+. At a European level, there are several schemes coming into effect to disincentivise the continued sale of diesel vehicles, for instance the CO2 emissions performance standard will add ~€2,375 to the cost of a standard diesel passenger car (120gCO_2/km), which will increase further in 2025 and 2030 (note that these targets apply to manufacturer fleet averages, and with an appropriate level of electric vehicle sales included in the company portfolio it is unlikely the total charge will be paid by any manufacturer). These schemes, however, do not discriminate between BEV and FCEV sales, and the arguments used in this section regarding the choice between BEV and FCEV uptake are still valid under these proposed charge increases. The best opportunity for accessing FCEV specific EU funding is via innovative project funding schemes such as H2Nodes; accessing funding via, for instance, the Important Projects of Common European Interest (IPCEI) scheme could dramatically improve the business case for FCEVs in the short term and help projects access the ‘mass-market, medium fuel price’ scenario analysed in this report at an earlier date.

4.6.2 Non-financial incentives

It is worth highlighting the non-financial incentives for electric vehicle adoption, summarised in Table 4. Clearly the major benefit of the uptake of both FCEVs and BEVs are the reduced GHG and air pollutant emissions, which can help vehicles access clean air zones and reduce the cost of potential future carbon taxes. There are, however, several other system considerations for hydrogen which, whilst not immediately obvious to the end user, will provide benefits to the wider energy system when the technology is applied at scale and hence can help reduce the cost of hydrogen closer to the low fuel price scenario analysed in the examples above. These benefits include, but are not limited to, the examples listed below.

Table 4: Other considerations & incentives for electric vehicle adoption

Fuel Cell Electric Vehicles	Battery Electric Vehicles
Zero GHG Emissions at tailpipe	Zero GHG Emissions at tailpipe
Zero Air Pollutant Emissions	Zero Air Pollutant Emissions
Reduced noise pollution	Reduced noise pollution
H2 production supports electrical grid balancing and storage capability	High efficiency
Improving the business case for production of hydrogen for use in industry & power	
Securing offtake for offshore wind and remote renewable assets without grid connection	

5. Technology Readiness Evaluation

5.1 Performance Data Overview

This section analyses the performance of the hydrogen vehicles and stations deployed under the Action H2Nodes, including the 10 trolleybuses deployed by Rigas Satiksme, and the two hydrogen stations deployed in Riga and Arnhem. Telematics data, as well as station records on dispenser usage and downtime, is used to evaluate the performance of the hydrogen technology and is compared to comparable key performance indicators (KPIs) in conventional fuel technology, as well as hydrogen specific targets developed under the JIVE and MERHLIN projects, and outlined in the JIVE Performance Assessment Handbook (JIVE and MEHRLIN, 2018).

Overall, the H2Nodes deployments performed to a high standard, and vehicles were able to be used in the daily operations of public transport operators to effectively service the operational need, being handled by drivers and maintenance staff without previous experience of hydrogen fuel cell vehicles. As of July 2021, 10 Solaris trolley buses have been operated in Riga over a 15-month period clocking a total of 125,787 km, as well as 2 buses and approximately 50 passenger cars operating in Arnhem. Across both city sites, a total of 37,600 kg of hydrogen has been dispensed, saving approximately 150 tonnes of diesel and 475 tonnes of CO_2 emissions at tailpipe.

5.2 Vehicle Performance Data

This section of the report contains data on the vehicle performance of the 10 Solaris Trolleybuses deployed in the project. All trolley buses were operated by Rīgas Satiksme from a vehicle depot in Riga (Jelgavas iela 37, Riga) and use a Ballard HD85 fuel cell system, with a drivetrain power of 110 kW and a maximum hydrogen storage capacity of 24.5kg. In addition to the hydrogen propulsion system, the trolleybuses have a catenary connection which provides electrical power to the drivetrain when a connection is possible. The catenary wires do not cover the entire operational route of the trolley buses, hence either a diesel or alternative fuel drivetrain is required for these stretches.

Whilst full vehicle performance data is not available for vehicles used in Arnhem, which were not project funded, several other reports have provided useful insights into the level of vehicle performance. Both the Keolis report on fuel cell buses (Keolis, 2020) and the Han University report including an Arnhem passenger car (HAN University of Applied Sciences, 2018) provide overviews to the vehicle performance in the early years of refuelling operations in Arnhem. Both reports confirm the state of the hydrogen industry in that bus and passenger car products are at the most advanced state of technology readiness, in particular, the low hydrogen fuel consumption is highlighted in both reports (6.1kg/100km (Solbus), 1.2kg/100km (Arnhem Hyundai ix35)). The fuel efficiency is particularly important as this impacts the diesel and electricity parity prices for hydrogen, and these studies highlight the system optimisation benefits that have taken place in the hydrogen industry over the past decade, with early hydrogen bus deployments under HyFLEET:CUTE averaging consumption between 18.4 and 29.1 kg/100km (Element Energy, 2016).

Overall, operational comfort was recorded as high (>8/10) by 80% of fuel cell vehicle drivers under the HAN University report survey, with the most negatively judged aspect of hydrogen vehicles deemed to be the availability of fuelling stations. This is in line with expectations, given that, at the time of operation of the Hyundai ix35, there were only three fuelling stations in the Netherlands, however, this finding is promising in that it highlights the high technology readiness level of the vehicles themselves. (HAN University of Applied Sciences, 2018)

5.2.1 Trolleybus Vehicle Usage & Efficiency

The Riga trolleybuses saw good levels of utilisation across the H2Nodes project duration. All vehicles achieved at least 7,000 km travelled (whilst in fuel cell operation mode) over the project period, and a total of 125,787 vehicle km was achieved. This corresponds to a mean vehicle distance covered of 28.3 km/day under fuel cell operation over the entire project duration; when accounting for days out due to vehicle downtime the mean vehicle distance covered increases to 32.9 km/day. Note that this level of utilisation is below the JIVE target for bus utilisation of 44,000 km/year/bus, and that higher levels of fuel cell utilisation would have allowed for the feasibility of greater volumes of hydrogen production (and hence a lower hydrogen price. However, this JIVE target was set for self-powered buses, and due to the nature of trolley bus operation (which present the best business case when maximising the use of cheap electricity from the catenary cables), this lower level of fuel cell utilisation was expected. The addition of the fuel cell powertrain still provided a useful service to the public transport operator (PTO), which would otherwise have had to rely on the use of diesel vehicles in built-up, residential areas.

The average fuel consumption whilst the fuel cell powered the vehicle was 12.6 kgH_2/100km. This is slightly above the Roland Berger estimate for fuel cell bus consumption of 8-9 kgH_2/100km(Roland Berger, 2015) for a number of reasons:

- The stop – start nature of trolleybus operation places high demand on the fuel cell.
- The HyTrolleybuses are considerably larger than the typical 12m buses operated in Europe, see specifications in
- Table 5.

Table 5: HyTrolleybus specifications

Specification	Value
Length	18.75m
Width	2.55m
Height	3.60m
Carrying capacity	135 passengers

The Tank to Wheel (TtW) fuel cell efficiency achieved by the fuel cells in operation was in fact very high (average: 49.1%), indicating the fuel cells performed efficiently and that fuel consumption was close to the minimum feasible value for this vehicle and duty cycle. Fuel cells perform optimally at power outputs below the maximum rated power since increased current flow induces voltage losses due to internal circuit resistances and mass transport limitations and the efficiencies achieved by the vehicles in this project are towards the upper end of what is feasible with PEM fuel cells. This indicates one or both of the following best practice points were enacted in the planning and operation of this project:

- Fuel cells should be sized appropriately for the vehicle type and duty cycle, with added power availability above the expected power demand included for contingency and performance.
- FC vehicle drivers should be trained to operate the vehicle sensibly, and be limited in their ability to draw 100% power from the vehicle fuel cell.

Note that hydrogen consumption can be expected to increase in Winter months depending on the deployment location's ambient temperature. As Figure 11 shows, this is not due to an altered fuel cell efficiency, which remains approximately constant, but primarily due to the use of the onboard electrical heater. Using the heater can lead to a fuel consumption increase of up to 40%, and these results were replicated across both the Riga and Arnhem sites (see Keolis report (Keolis, ZETT, HyMove, 2020)). The heater is expected to be the primary cause of the increased fuel consumption, however, note that the worse road conditions in Riga in Winter may also contribute to the decreased performance. One of the two buses in Arnhem was able to implement the novel approach of heating the bus using excess heat produced by the fuel cell to maintain onboard temperature, and hence decrease the fuel consumption in Winter. This report suggests that using an onboard electrical heater is considered with caution when procuring vehicles, and manufacturers should be asked to quantify the impact of heating so that this can be factored into considerations such as station sizing and business model evaluation.

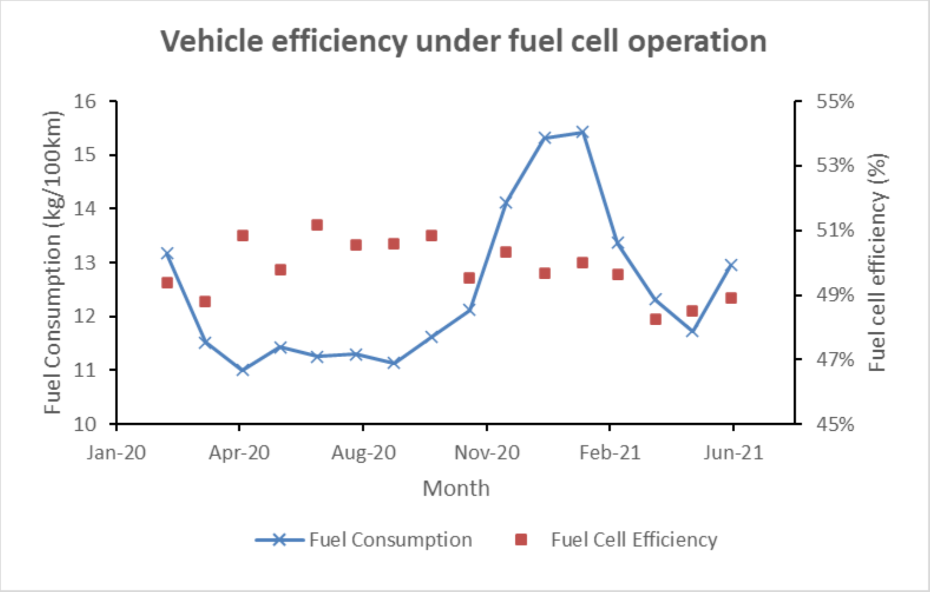

Figure 11: Vehicle fuel consumption whilst under fuel cell operation mode

5.2.2 Vehicle Availability & Faults

The project achieved a mean vehicle availability of 86.1%, indicating that the average vehicle in the licensed fleet was available for operation 86.1% of the time. Note that, with effective preventative maintenance, a bus availability figure above 90% should be feasible for most operators, whilst figures above 85% are considered acceptable (Urban Bus Toolkit, 2006). As such, the performance of the overall fleet in the project was impressive, given that the H2Nodes deployment is the first real world trial for hydrogen trolley buses.

There were a total of 52 failures across all vehicles in the fleet over the project, with a mean distance between failure of 2,419 km. Comparing these figures to targets in the hydrogen bus sector, the JIVE Assessment Handbook (JIVE and MEHRLIN, 2018) targets bus availability and mean distance between failure (MDBF) figures of 90% and 2,500km respectively after an initial 6 month teething in period. The trolleybuses in this project met and exceeded these reference targets; excluding the first 6 months from the H2Nodes data set gives a total of 27 failure events, with an average availability of 89.7% and a MDBF of 3,081 km.

The findings from the H2Nodes project therefore confirm findings, from the JIVE and previous bus deployment projects, that a new technology teething in period of approximately 6-months should be expected for hydrogen vehicle deployments. There were a high number of vehicle faults in this initial period. However, after 6 months the vehicle performance metrics returned to acceptably high levels. Figure 12 demonstrates the gradual improvements seen in vehicle availability seen in the project, which peaked at 100% availability in March 2021 and June 2021. Expectation management regarding the initial availability and teeth-in period for new hydrogen vehicle deployments is therefore important, and there should be clear communication between project coordinators and Public Transport Operators (PTO) as to the expected initial availability and teeth-in period length. If possible, contingency planning (such as making sure additional conventional fuel vehicles are still functional and able to fill gaps left by vehicle breakdown) should be factored in when procuring vehicles to ensure suitable business operation during this period.

Table 5-6: Vehicle Availability and Failure Data by Vehicle ID

Vehicle ID	Vehicle Availability (%)	Number of Failures	Mean Distance Between Failures (km)
22006	62%	8	1,027
22017	87%	7	2,058
22028	80%	6	1,951
22039	98%	2	8,135
22041	78%	3	2,338
22050	84%	5	1,875
22061	92%	7	2,311
22072	89%	4	3,793
22083	93%	5	2,321
22094	96%	5	3,169
All	**86%**	**52**	**2,419**

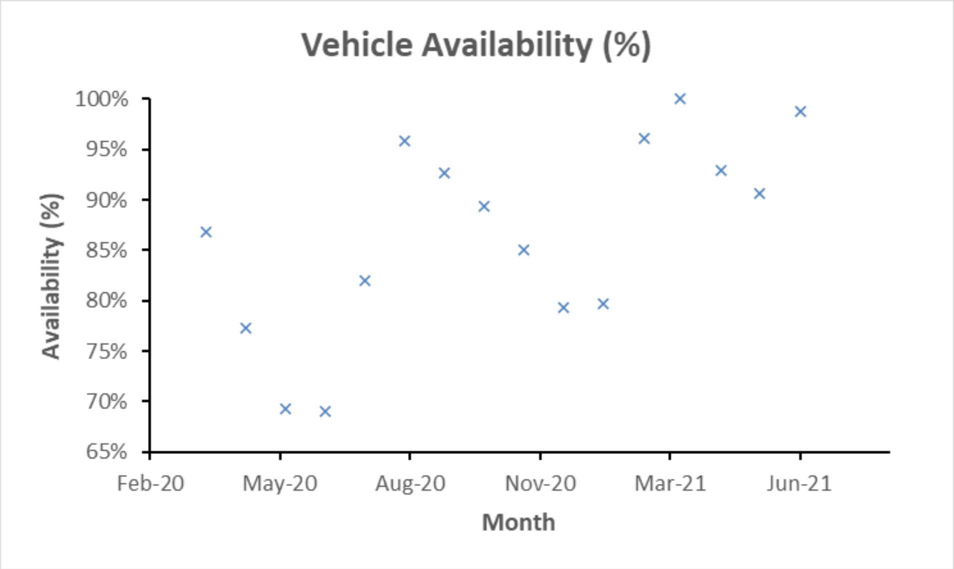

Figure 12: Riga vehicle availability data by month

Faults in the H2Nodes project were categorised according to Table 5-7. As shown in Figure 13, Category E failures were particularly severe and caused close to half of all vehicle downtime in the project, despite a relatively low number of failure events (21% of total failures). This indicates that if a high voltage battery failure does occur it can be particularly time consuming to resolve the fault and highlights the need for provide additional electrical spare parts and dedicated maintenance training schemes as fleets transition to electric drivetrain vehicles.

Table 5-7: Vehicle Fault Category Descriptions

Fault Category	Category Description
A	Stack or ICE Failure
B	Periphery Failure (mechanical components, e.g. compressor, valves)
C	Electrical Components Failure (e.g. electric motor, inverter)
D	Hydrogen Storage Failure
E	High Voltage Battery Failure

Interestingly, the most numerous vehicle fault, a category B fault (periphery mechanical component failure e.g. compressor, valves), contributed very little to the overall downtime during the project (4%) and almost all faults were resolved within one day. Since many mechanical faults are common to all vehicle types, workshops were able to remedy the issues swiftly due to their familiarity with technical issues and availability of non-specialised parts for vehicle repair. As such, it is expected that in the coming years it will be feasible for alternatively fuelled vehicles to improve their performance and availability even further as familiarity with repair techniques and greater numbers of standardised spare parts become available. Promisingly, there were zero Category A faults, indicating that the hydrogen fuel cell system operated perfectly throughout the project across all vehicles. In terms of hydrogen specific maintenance improvements, the hydrogen tanks offer the largest potential area of improvement to increase vehicle reliability.

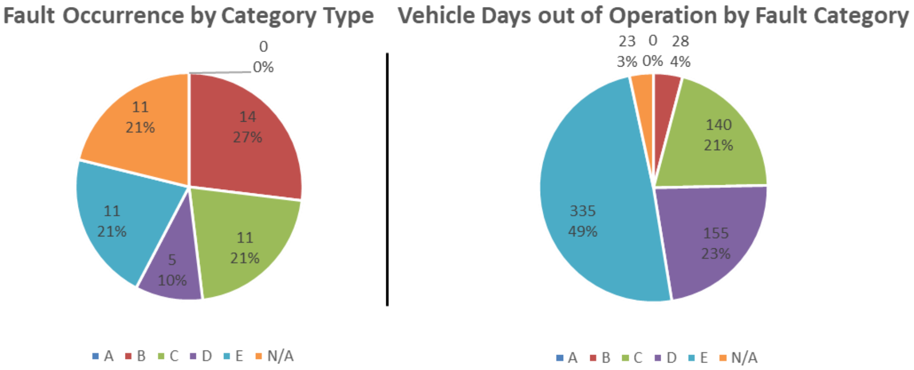

Figure 13: Riga Vehicle Fault data by category type

5.3 HRS Performance Data

5.3.1 HRS Dispensing Performance

The two HRS studied in this project conducted a total of 10,624 refills, of which 89% were successful. Note that the significant number of failed refills is due primarily to the 12% failure rate at the Arnhem site, which was caused by an undetected chiller leak over a 7-month period reducing cooling capacity. After this period the chiller leak was eventually resolved.

The total volume of hydrogen dispensed in the project is approaching 40 tonnes, and the production and dispensing volumes have been gradually increasing throughout the project at a rate of approximately 100 kg/month across both HRS due to an increasing utilization of FCEVs in both city regions.

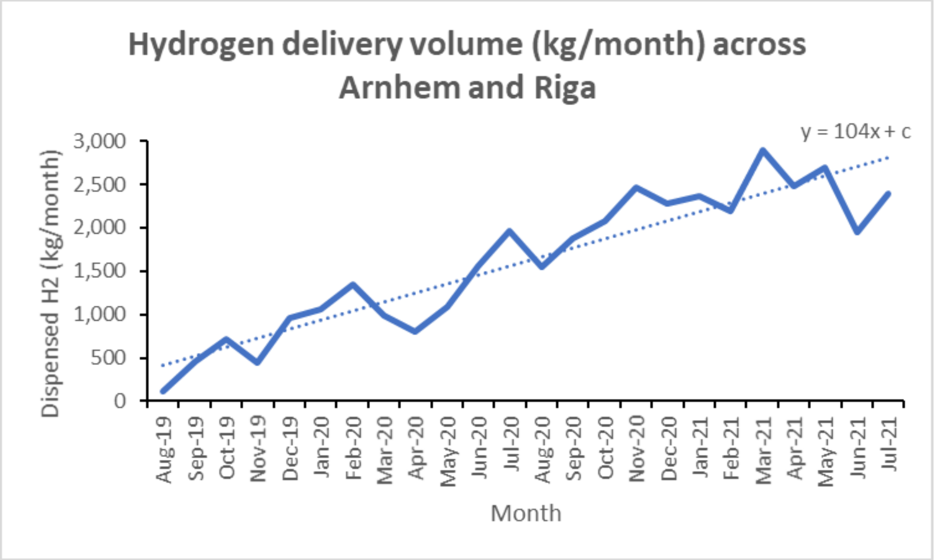

Figure 14: Hydrogen demand increases over time

Refuelling speed varied between 0.71-0.85 kg/minute depending on HRS site, due to the different end users and refuelling pressure required in each city. End users were satisfied with the refuelling speed, with most refills completed in under 10 minutes, however, there is significant scope for increasing the refill speed further if required by the vehicle operational cycle (the CHIC bus project was able to achieve higher speeds (2.1-2.8 kg/minute)) but this requires further station investment to use higher pressure storage banks, dispensing compressors or special cooling equipment for heavy duty truck filling. This equipment was deemed superfluous to the transport operator needs in Riga and Arnhem, and the simplicity of the station design is expected to have contributed to consistently reliable refuelling throughout the project, with high station availability figures. The refuelling rate achieved, whilst slightly slower than typical diesel refuelling, is significantly faster than the time required to fast charge an equivalent electric vehicle (0.5-1.5 hours depending on vehicle type and charger connection).

5.3.2 Hydrogen Station Availability

In Riga, the only reported fault was a several day outage from 31/03/2021 till 04/04/2021, which was caused due to a delay in shipments of spare parts from Denmark and Norway over the Easter holiday, and all other regular maintenance work was conducted without disrupt to regular fuelling procedures. In Arnhem, there were several downtime events, however, a high overall station availability of 97.2% was achieved. There were no major incidents and not injuries of personnel throughout the course of the project.

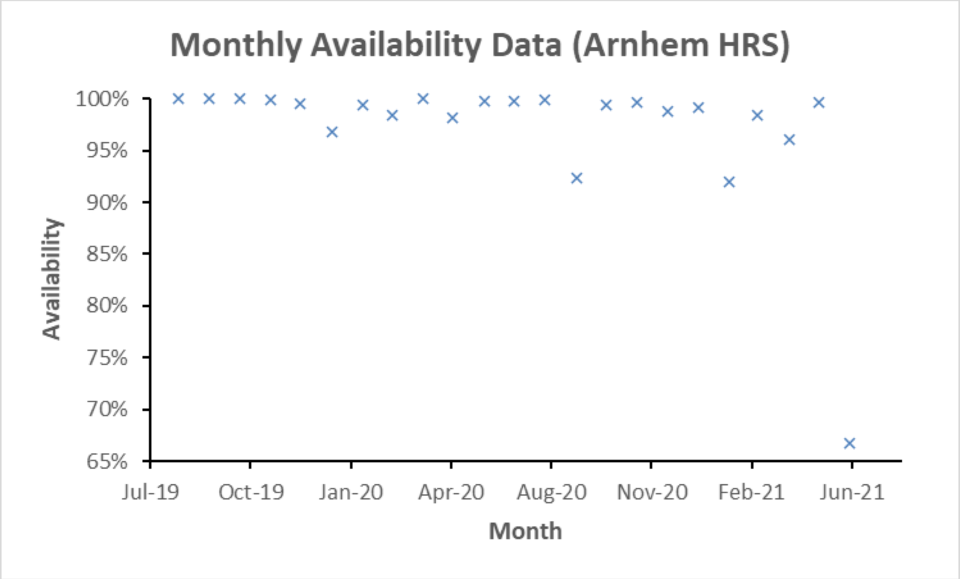

Figure 15: HRS Availability Data (monthly)

The primary cause of the lower availability in Arnhem was an issue in June 2021 with a hydraulic system leak. This leak led to prolonged downtime as due to the COVID pandemic restrictions and supply chain shortages it took longer for the UK supplier to resolve the issue. Excluding this period, a very high availability for a station of this size was reached (98.6%), above the JIVE target of 98%.

The most common HRS faults were category A and category B faults, signifying a fuelling dispenser failure or compressor or pump failure. This is in line with other reports, e.g. the *CHIC report on hydrogen infrastructure operation and performance* (CHIC, 2016), which have found that compressor failures make up a large portion (52.6%) of HRS downtime.

Table 5-8: HRS Fault Category Description

Fault Category	Category Description
A	Fuelling Dispenser Failure
B	Compressor/Pump Failure
C	Hydrogen Storage Failure
D	Onsite Core Production Unit Failure (Electrolyser or Reformer)
E	Electrical Component Failure
F	Other Onsite Fuel Processing Equipment Failure

Whilst compressor failures were a significant cause of downtime (39%), the largest contributor was in fact due to failure of other onsite fuel processing equipment (51%). This is primarily due to the extended downtime in June 2021 caused by the hydraulic system leak following on from routine maintenance. All other fault types were resolved quickly and resulted in minimal downtime. As such, compressors still represent the most significant cause of consistent downtime throughout the project, since the hydraulic leak could have been resolved much quicker given a lack of external factors such as COVID-19, and hence should be the area that is prioritised in terms of regular maintenance procedures and spare part procurement.

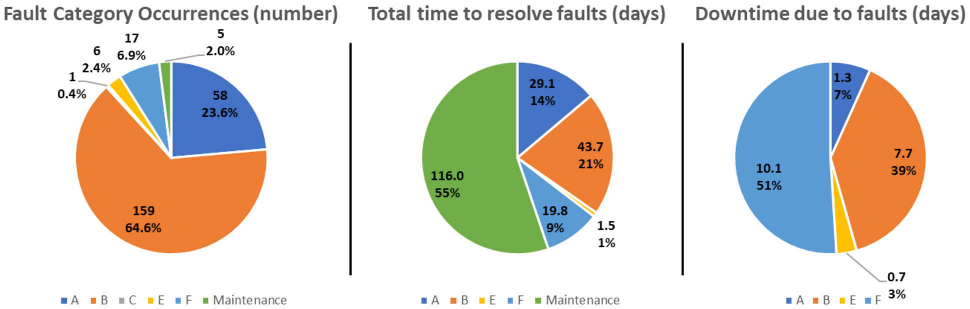

Figure 16: Arnhem HRS Fault Data

5.3.3 Hydrogen Production Performance Data

Hydrogen production at both sites was able to successfully meet offtake demand at all times, and sufficient on-site storage was implemented to ensure security of supply throughout the project.

Despite both Arnhem and Riga using the SMR production method, the production efficiency for hydrogen varied between sites depending on production equipment used and factors such as external temperature and station site electricity and water usage.

The mean production efficiency in Arnhem was 0.057kg/kWh when including energy costs for hydrogen production, compression, delivery and any auxiliaries (see Figure 17). Interestingly, the energy requirement was found to increase in Winter months due to higher delivery requirements (likely due to variation in the refilling speed). The energy required for production was approximately constant over time, and significantly lower than the electricity value required for a green hydrogen electrolysis unit (which would operate at an efficiency of approximately 0.17 kg/kWhe), however, note that an electrolysis unit would reduce natural gas consumption from 6.2 Nm^3/kg to ~0 Nm^3/kg.

The electricity consumption in Riga is higher (c. 0.036 kg/kWh), however, note that these figures are for the entire station usage, and include e.g. electricity for lighting in the station, not just in the production and delivery process. Despite this, it is clear that water and energy consumption remain high at the station, which has inflated the hydrogen price in Riga (accounting for over €6/kg of the final retail price). There are several ways that this can be mitigated in the future, with HRS scaleup and increased utilisation one of the main methods as this will reduce auxiliary consumption on a €/kg basis with a positive impact on the final price.

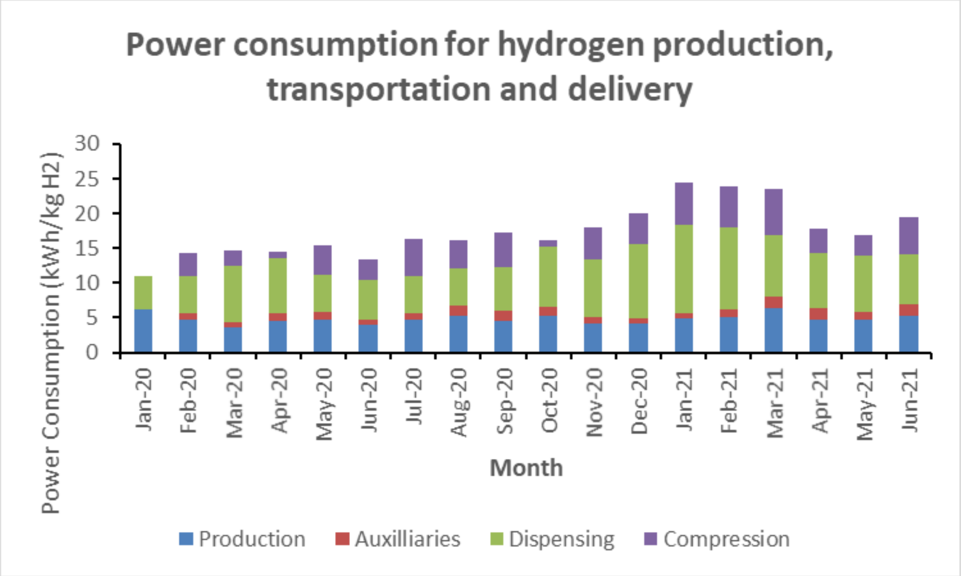

Figure 17: Arnhem hydrogen production electricity consumption breakdown

5.4 Technology Readiness Evaluation

The deployment and real-world operation of hydrogen fuel cell vehicles and infrastructure in the H2Nodes project has provided insight into the state of technology readiness for hydrogen vehicles and infrastructure. Both the vehicles and HRS deployed were used on a daily basis over multiple months at a high availability (once teething issued had been resolved) and were not only demonstrations of novel technology but also effectively used within the commercial operations of transport operators. The performance data highlights several areas of exceptional performance, above even similar industry wide targets, which are as follows:

- The station availability for both Arnhem and Riga was high (98%+), and is showing signs of improvement still since teething period issues have been resolved.

- The fuel cell efficiency of equipment used on the Riga trolleybuses was high whilst in operation, and no vehicle downtime was caused from a fuel cell related issue.
- Fuel consumption of Arnhem buses and taxis was low on a kg/100km basis.
- Maintenance issues were resolved quickly and could be dealt with by personnel who had not previously handled hydrogen technology.

In order to continue to optimize the performance and accelerate the rollout of hydrogen technologies, however, it is important to highlight all issues faced and proposed resolutions to these issues. Hence, the H2Nodes project milestone 22 report: *Final report joint monitoring and evaluation of real-life tests of hydrogen production, HRS and FCEV vehicles approved* contains more in depth analysis and solutions for the critical areas to target for improvement in the next generation of hydrogen deployments in Europe. The main aspects highlighted in this overview, to be scrutinised and mitigated for in future deployment projects, are as follows:

- Issue with the 700 bar compressor in Arnhem led to a significant number of half tank refills, resulting in reduced vehicle range, and significant downtime was attributed to compressor failures. This is not entirely unexpected, with teething issues in compressors highlighted as an area for improvement in the several hydrogen project final reports, and as an emerging conclusion from Hydrogen Mobility Europe (Hydrogen Mobility Europe, 2020).
- The major downtime events experienced by the project were linked to supply chain issues; supply chains for hydrogen equipment need to be bolstered and spare parts procured and made available on site.
- High voltage battery issues were the most significant cause of vehicle downtime and maintenance procedures need to be improved to accommodate for the transition to both battery electric and fuel cell electric drivetrains.

As maintenance workshops and vehicle users become more familiar with the technology, combined with strategic targeting of the key points for improvement listed above, it is expected that hydrogen fuel cell technologies will compete with or even improve upon the performance expected from present day diesel incumbents. One aspect to highlight with respect to this is the expected longer lifetime of a hydrogen vehicle compared to a diesel; with appropriate maintenance and a powertrain overhaul halfway through the operational lifetime it is expected that FCEVs will be able to operate for up to 50% more kilometres than diesel equivalents, drastically changing the commercial picture for many operators and potential resale value. There is still a considerable amount of uncertainty regarding this figure, but if proven in real world applications at the end of lifetime of the vehicle currently deployed this would prove to be a large upside highlighting the technical competitiveness between hydrogen and existing fossil fuel incumbents.

6. Pathways for scaling up

6.1 Riga Deployment Plans

6.1.1 Wider Policy Landscape in Latvia

Following the success of the H2Nodes project, the refuelling station site at Riga has conducted a feasibility study for the expansion of the HRS, as outlined in the *Regional Plans* section below. This proposed expansion is in line with the international targets for hydrogen refuelling infrastructure rollout, with countries such as Germany and Italy leading the way in terms of targeted number of HRS by 2025 (Figure 18), however, today Latvia lacks sufficiently ambitious policy levers or deployment targets to continue to stimulate growth at a national level.

Latvia outlined its plan for the decarbonization of transport in the *Alternative Fuel Infrastructure Implementation Plan of Latvia (NPF)* in 2017. The plan concludes that the absence of a national policy plan prior to this point hindered the rollout of hydrogen and natural gas technology for transport, and the HRS deployed under H2Nodes project is as of October 2021 the first and only public HRS in Latvia. Despite this, the NPF fails to set targets for future hydrogen infrastructure or vehicle deployments, and states that the government of Latvia considers it has “few instruments available to influence this [the purchasing of ‘green’ vehicles]”. Despite recommendations made in the plan for a capital support scheme, no options have been approved and there is no support for zero emission vehicle owners other than tax reduction (FCE vehicles are excluded from circulation tax). Currently the only FCE vehicles registered in Latvia are the vehicles serviced by the Riga station, and the lack of an overall hydrogen road-map or policy support schemes in Latvia are expected to continue to hamper the deployment progress for hydrogen in Latvia.

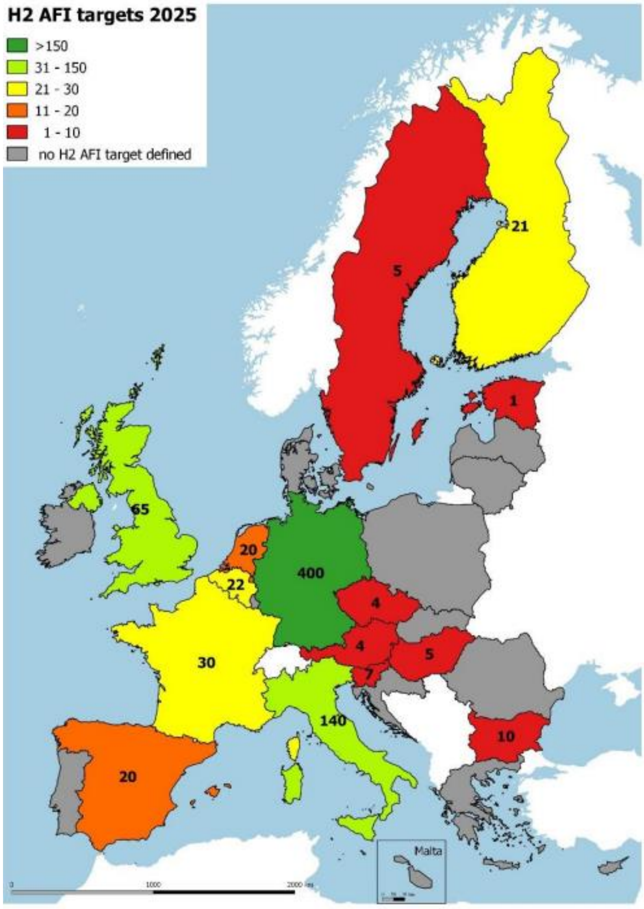

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Figure 18: NPF targets for hydrogen refuelling points for 2025(Report on the Assessment of the Member States National Policy Frameworks, 2019)

6.1.2 Regional Plans

The deployment of the Riga HRS in the H2Nodes project was primarily driven by regional ambition to promote zero emission transport and reduce air pollution in the city. Riga City Council established a Hydrogen technologies advisory board in 2013 and launched an initiative to create a low emission zone in the city centre in 2016 (although this has not been implemented as of October 2021). The development of local policy documents related to hydrogen via EU funded schemes (Europe NewBusFuel, HiT2-Corridors and H2Nodes) led to the final decision to invest in a hydrogen refuelling station at the site in Riga.

Riga has a strong ambition to enact further hydrogen vehicle deployments based on the success of the H2Nodes Trolleybuses in operation. A multi-phase scale up plan for the Riga HRS site has been produced under H2Nodes, which will enable the deployment of future hydrogen vehicles. In this plan there is a continued focus on actively scaling up the deployment of public sector, with heavy and high mileage vehicles to anchor demand for the station, whilst maintaining the option for light duty vehicles to refuel as demand requires via the continued service of the 700-bar dispenser (see Table 6-1).

Table 6-1: Riga HRS Upscaling Projected Vehicle Demand

	Phase 1		**Phase 2**		**Large Scale**	
Vehicle Type	**Units**	**H_2 (kg/day)**	**Units**	**H_2 (kg/day)**	**Units**	**H_2 (kg/day)**
HyTrolleybus	10	110	10	110	-	-
18m FCE-bus	15	337.5	15	337.5	105	2238
15m FCE-bus	-	-	-	-	58	1029
12m FCE-bus	-	-	-	-	68	1040
FCE-passenger	5	5	5	5	5	5
FCE-heavy duty	-	-	8	480	8	480
Shunting locomotive	-	-	1	150	1	150

The initial 'Phase 1' scale up of the station involves the deployment of a further 15 hydrogen buses by the public transport agency by 2026, and this demand volume would allow access to the hydrogen price outlined in the '*medium price'* scenario of *Cost-effective approaches for hydrogen deployments in cities*. It is expected that over the next 4 years, the hydrogen bus market will remain the most commercially mature market for fuel cell vehicles, and the public sector aspect of bus operation simplifies the process of matching the trial vehicles' TCO to that of diesel via funding mechanisms.

'Phase 2' station scale up plans for the expected demand from hydrogen heavy duty trucks. Early movers in the truck market such as Hyzon Motors and Hyundai have already deployed low commercial volumes in this sector in various global markets, with other industry players such as Volvo and Daimler planning to release hydrogen heavy goods vehicle models over the next decade. As such, it is feasible that demand for hydrogen from trucks could start to see volumes as early as 2023, however, significant scale up and expansion of truck model options is expected over the period 2025-2028 and this is the period that could be targeted by this Phase 2 station scale up. Included in these plans is the construction of an industrial fuelling panel and the deployment of MEGC (multiple element gas container) technology which can be used to transport hydrogen to locations where it is not economically viable to deploy hydrogen production equipment. This could supply significant offtake demand from the hydrogen production unit, as shown in the shunting locomotive demand in Table 6-1. At this level of demand, the hydrogen price is projected to fall significantly to a value of €5.20/kg pre-tax.

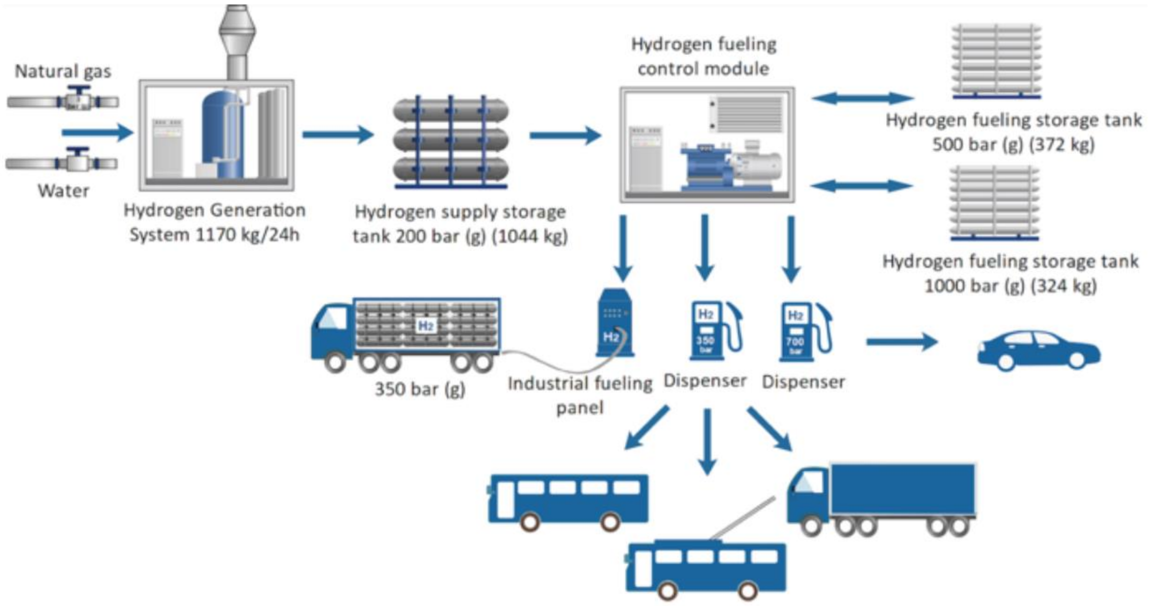

Figure 19: Riga HRS Second Upscaling Schematic

Whilst the near-term strategy in Riga focuses on upgrading the existing SMR facility to facilitate further decarbonisation of large vehicles in the region, there is a realisation that SMR facilities are necessarily an interim solution until the viability of hydrogen production from entirely renewable resources. Analysis conducted in the H2Nodes project indicates that large scale green hydrogen production facilities have the potential to not only be financially viable, but indeed provide a very low-cost option for end users at pump (see section *Hydrogen Price Scenarios*). The main barrier to accessing this low carbon hydrogen is the deployment scale required; Riga estimate that ~5 tonnes per day demand is required to achieve the hydrogen price outlined in the section *Low price scenario: large scale electrolyser deployment* (€3.74/kg pre-tax). This demand could be met by the replacement of a large portion of the Riga bus fleet to hydrogen, including 12m, 15m and 18m buses (see Table 6-1). This level of bus fleet replacement will take place over a period of several years, hence the need for initial smaller scale hydrogen production units and the initial scale up plans as outlined above. The primary reason for this large demand requirement for viable green hydrogen is the high capital cost of the production unit (total HRS price ~€30M), resulting in large depreciation costs at lower deployment volumes.

Table 6-2: Summary of main pieces of equipment in Riga upscaling plans

Equipment	Phase 1	Phase 2	Large Scale Electrolysis
Hydrogen Supply Storage Tank (200 bar)	522 kg	1044 kg	4176 kg
Hydrogen fuelling storage tank (500 bar)	186 kg	372 kg	1860 kg
Hydrogen fuelling storage tank (1000 bar)	162 kg	324 kg	162 kg

Hydrogen SMR Facility	540 kg/day	1170 kg/day	-
Electrolyser	-	-	5000 kg/day
Water connection	3900 l/h	7800 l/h	7000 l/h
Natural Gas connection (10 barg)	180 Nm^3/h	420 Nm^3/h	-
Electricity (400V)	600 kW	1200 kW	27.5 MW
Industrial Fuelling Panel	No	Yes	Yes
350 bar dispenser	Yes	Yes	Yes
700 bar dispenser	Yes	Yes	Yes

6.2 Arnhem deployment plans

6.2.1 Hydrogen ambitions and regulatory factors in the Netherlands

The National Climate Agreement, published 2019, is the overall policy framework for CO2 reduction and the implementation of alternative fuels. The agreement contains targets for hydrogen for mobility, such as deployment volumes, cost reduction and innovation. In addition to this, the Dutch government set out its national hydrogen strategy and corresponding policy agenda in March 2020. The policy outlined the main opportunities for hydrogen production, predominantly via large scale electrolysis, and the potential use cases in the chemical industry, mobility, heating and electricity sectors.

The National Policy Framework (NPF) in the Netherlands set out ambitions for alternative fuel refuelling stations. The progress against these aims are shown in Figure 20, with only 20% of the 20 public hydrogen refuelling station target (2015-2020) being achieved to date. Similarly, there are currently approximately 277 FCEVs deployed in the Netherlands, far below the ambition by 2020 of 2120 vehicles (combined passenger cars, trucks and buses).

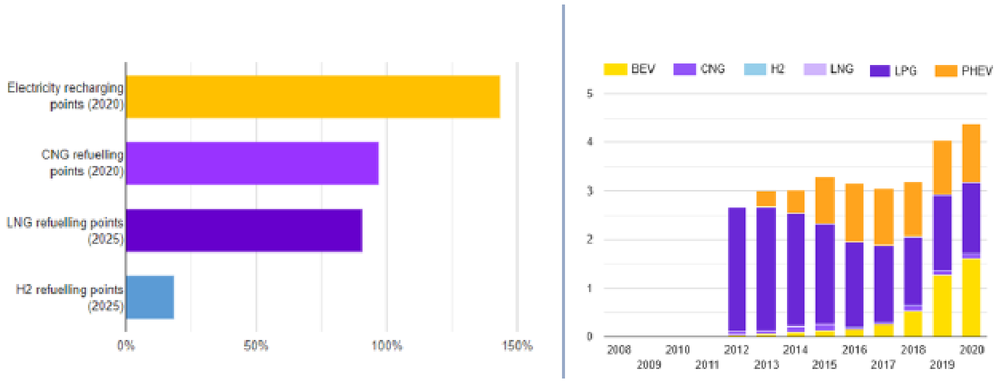

Figure 20: Left: Infrastructure as a % of NPF target, Right: Share of low emission vehicles in total fleet.

The primary reason for the failure of hydrogen to achieve its NPF targets is the lack of a competitive business case compared to the easy wins of electric and gas fuelled vehicles, which can currently decarbonise low mileage, light duty fleets at a low cost. This is highlighted in the NPF, which states that “It is not yet possible to build and operate a hydrogen refuelling station on a commercial, profit-making basis. Government and other external funding is required." In recognition of this, the following policy incentives are available (Dutch Government, 2021):

Policy Incentives for the uptake of Hydrogen (Netherlands)
Zero emission cars are exempt from paying registration tax. For other cars the system is progressive, with different levels of CO2 emissions paying different amounts of registration tax.
There is no road tax on BEVs and FCEVs.
A lower taxation rate (12% in 2021 vs 22% standard) is applied to the BEVs up to a maximum purchasing price of €45,000 and FCEVs (no maximum purchase price). This rate is subject to increase on a gradual scale, to be in line with the 22% standard rate by 2025.
Tax deductible investments: The Netherlands has a system of facilitating investments in clean technology, by making these investments partially deductible from corporate and income taxes. Zero emission and plug-in hybrid cars are on the list of deductible investments, as are accompanying charging points.
Since July 2020, the Netherlands has opened a purchase subsidy for private persons. For 2020 and 2021, the subsidy amounts for electric passenger cars that meet the conditions are: • Used electric passenger car purchase or private lease: €2,000 • New electric passenger car for sale or private lease: €4,000 This subsidy only applies to vehicles with a list price lower than €45,000. This means that FCEVs currently don't quality for this facility, as their list prices are above the threshold (although expected to fall below this level in the next few years, see Toyota Mirai 2022 starting price (US) of $49,500).
Hydrogen mobility specific provisions
The absence of a maximum purchasing price as basis for a reduced vehicle tax rate.
A special subsidy available for the development of HRS, with co-funding up to 50% of the initial investments (DKTI), which has funded many of the existing HRS

With these policy mechanisms, it is expected that electric vehicle uptake will increase in hard to electrify sectors of transport, particularly if FCEVs can achieve a list price the requirement to access private purchase capex funding subsidies.

From the NS-B Corridor point of view the Netherlands has a basic network of publicly accessible HRS in place, co-funded by national and EU grant money and the HRS in Arnhem is also a gateway to the well-developed HRS network in Germany. The following aspects are seen as important from a strategic point of view in order to continue the expansion of this emerging network and ensure national targets are met, and should be areas of future policy prioritisation:

- The need for HRS redundancy to control the risk of range anxiety in case a specific HRS is temporarily not available.
- A possible shift from focus on passenger vehicles to heavy-duty vehicles, given the fact that some major OEMs such as Volkswagen and Daimler concentrate on the production of BEVs in the passenger car segment. Given the specific vehicle characteristics and use in the heavy-duty segments, hydrogen vehicles are expected to be more cost-efficient than BEVs.

6.2.2 Regional hydrogen vehicle deployment progress in Arnhem

The Arnhem HRS is a strategically important link in the Dutch HRS network, connecting Western Netherlands deployments to the HRS network in Germany. There has been significant political will to enact the station deployment, and demand stimulation schemes such as H2Drive, and there are regional ambitions to continue to develop demand for the station. This section provides an overview of involvement in regional initiatives and plans for upscaling of the local vehicle deployments.

In order to stimulate demand in the region, Gelderland and Arnhem supported the launch of H2-Drive in December 2019. This was an initiative to involve potential local users and to contract additional FCEV users. This coalition came up with a distinctive approach that included a preference for spending a relatively large part of the available funds on stakeholder management compared to funding deals for FCE buyers / users. This meant it was able to reach a larger group of potential users compared to other proposals. Financial incentives included in the deal for motorists include a 50% discount on the hydrogen fuel price, and extra services such as free assistance at the roadside if required.

The H2Drive initiative was impacted heavily by the COVID-19 pandemic and technical problems at the refuelling station 700 bar dispenser (hydrogen tanks were able to fill to only 350 bar), resulting in the prospect of investing in the new technology economically or operationally unviable for many vehicle users. Despite this, a group of approximately 50 drivers have been refuelling regularly at the station and have formed the bulk of the hydrogen demand in 2021. It is expected that now the 700 bar hydrogen dispenser is at a 100% operational level there will be some market pull effects, with additional vehicles expected to use the station in the future.

The two FCEV buses operated by the Gelderland public transport company Syntus in the Veluwe public transport concession area will not continue to operate in the period following the project close. In 2019 the Veluwe public transport concession was re-tendered by the provinces of Gelderland, Overijssel and Flevoland as part of a larger new public transport concession. The concession was granted to Keolis, a merger of various regional Syntus public transport companies. Keolis included a 100% BEV bus fleet in its tender, and has begun enacting this transition with the new concession period starting December 2020. As such, the two FCEV buses will be taken out of service.

Table 6-3: Technical Capacity and Free Capacity of Arnhem HRS

Technical HRS Capacity	260 kg/day
Reference Demand:	-
35.6 km/day/vehicle	-
0.01 kg/km consumption	-
80 FCEVs (reference demand)	32 kg/day
Free Capacity	228kg/day

As Table 6-3 demonstrates, there is significant free demand available in Arnhem, particularly after the retirement of the fuel cell buses operating from the station and as such there is not seen to be the need for significant upscaling of the HRS facility at this stage. Instead, upscaling plans to date have focused on initiating vehicle deployments in order to meet the production and dispensing capacity. Since it became clear that there was additional spare HRS capacity, there has been some success in the recruitment of additional hydrogen demand in the region, and the availability of the hydrogen refuelling station attracted interest from the hydrogen refuse collection vehicle (RCV) project HECTOR (Hydrogen Waste Collection Vehicles in North West Europe), which selected Arnhem as one of seven pilot sites for the trial of seven RCVs. Hydrogen RCVs, and trucks generally, are an emerging sector for hydrogen vehicles as BEVs struggle to service the required duty cycles due to the the heavy load and power take off requirements from the vehicles. It is expected that the trial RCV will begin operation in Arnhem in 2022.

The remainder of this section focuses on how Arnhem can continue to ensure sufficient demand recruitment to secure not only high station utilisation in Arnhem, but a continued growth of the network in the Gelderland province. It is proposed that the two main areas of work to focus on for upscaling demand in the immediate future are to: progress regional FCEV demonstration projects, and to unlock opportunities in the tendering of public transport concessions.

Opportunities for future FCEV demonstration projects

Demonstration projects are key for enabling adoption of new road transport technologies pre-serial production. Projects provide an awareness to end users of the issue of decarbonization of transport, the available options to enact decarbonisation and establish a basic HRS network coverage. Currently the Province of Gelderland is closely involved in two hydrogen demonstration projects: the JIVE2 bus project and the H2 truck initiative. Both these projects will help to stimulate heavier vehicle demand for hydrogen in consort with the established FCEV passenger car scheme in the area, H2-Drive.

JIVE 2 project overview

The JIVE (Joint Initiative for hydrogen Vehicles across Europe) project is a European funded initiative aiming at the deployment of a total of nearly 300 FCEV buses and associated refuelling facilities across Europe. The main objectives of JIVE are:

- to demonstrate that fuel cell buses are commercially viable for bus operators to include in their fleets;
- to empower local and national governments to regulate for zero emission propulsion for their public transport systems.

This European demonstration project comes with funding from the FCH-JU (Fuel Cells and Hydrogen Joint Undertaking) for the deployment of the FCEV buses and funding from CEF (Connecting Europe Facility) for the associated hydrogen refuelling infrastructure. The JIVE project ends in late 2023. As of December 2021, 190 FCEV buses are already operational under the first tranche of deployments, with a further 120 vehicles allocated for funding. Since some regional participants cancelled their participation, the province of Gelderland was able to bid for the deployment of 10 FCEV buses, to be deployed in 2022.

These FCEV buses will be deployed into the existing public transport concession Achterhoek-Rivierenland. This public transport concession is currently operated by Arriva and will last for at least 4 years. From the regional point of view this offers the opportunity to continue having FCEV buses in service for a longer period, even now Keolis/Syntus has decided to operate the Veluwe concession area with a fleet of BEV buses only.

Furthermore, the deployment of 10 FCEV buses in the Achterhoek-Rivierenland concession area creates the opportunity to develop a second HRS in the region, as the refuelling demand of 10 FCEV buses creates a significant and constant revenue stream for the HRS operator. The province of Gelderland will demand that such an HRS is publicly accessible for other FCEVs as well, so that it can also support the upscaling withing other vehicle segments. The location of this HRS will most likely be Zutphen, where the current operator of this concession has its main bus garage.

H2 Truck Initiative Overview

The H2 truck initiative refers to the ambition of the Province of Gelderland and the transport sector to initiate a demonstration project more specifically (but not exclusively) targeted at transport and logistics activities. The characteristics of FCEV trucks and road tractors make them particularly suitable as zero-emission alternatives to diesel trucks.

The additional regional HRS capacity created as a part of this demonstration project can be used to facilitate the future growth of refuelling demand originating from policy and incentives set at the national level, and the project will contribute to the wider goal of positioning hydrogen-related activities in terms of regional branding as the region has early refuelling facilities available for all vehicle segments (cars, vans, medium trucks, buses, heavy duty trucks and road tractors).

This demonstration project is now in the preparation phase. A definite scope and location have not yet been determined but a recent study (Project H2 trucks Gelderland, Arnhem (draft version), 2020) includes all feasibility aspects, such as specific private sector appetite to participate, specific transport vehicles and operations qualifying for FCEV-deployment, availability and characteristics of fuel cell trucks replacing ICE trucks and available funding. It is expected that the project will include 10 FCEV trucks, possibly in combination with the deployment of fuel cell forklifts.

The tendering of public transport concessions

In addition to the individual deployment initiatives described above, it is important that transport operators are made aware of the benefits of hydrogen technologies, and appropriate bids for concessions are submitted which include the involvement of hydrogen buses.

In the province of Gelderland, public transport is arranged through three public transport concessions as shown in Figure 21. The current H2Nodes FCEV buses are operated in the Ijssel-Vecht concession region. The majority of the Gelderland region was tendered and awarded to Keolis which will operate a fleet of BEV-buses until December 2030, thus the region is not expecting additional FCEV bus demand until at least this date. This highlights a key learning point from this project, that outreach and engagement with both current and prospective future bus operators should be prioritized during project conceptualization and operation. This outreach should include, but is not limited to:

- Discussions and Q&A sessions with operator groups to address concerns around hydrogen and highlight its relative advantages (e.g. highlighting the additional cost of increasing the vehicle fleet size to tackle BEV bus issues with range and recharging times, see the section *Cost-effective approaches for hydrogen deployments in cities*).
- Production of information brochures for distribution at outreach events.
- Involvement of the local operator in the funding bid and planning process to ensure local buy in and tailor the project specifics to make the proposal attractive from an operational point of view. It should be emphasized to any operators that ambition in their decarbonisation aims, such as the Keolis 100% BEV bid, are likely to be looked upon favourably in tendering and that their bid should be tailored to include a feasible yet challenging ambition.

Given the long operating timescales (10 years) of these tenders, it is especially important that this outreach is tackled successfully. During the tendering phase, project coordinators should also engage with infrastructure solution providers and outline the potential solutions to vehicle operators in order to tackle concerns around the availability of infrastructure. In addition, given the planning and deployment timescales of large reliable hydrogen stations (~2-3 years until station operation), early engagement with station providers is key to avoid planning cost cutting and a low-quality hydrogen station product.

Note that the other concession in the region, Rjin-Waal, is currently being prepared with the winning bid announced by the end of next year, with the potential for both BEV and FCEV buses to be included in the proposal.

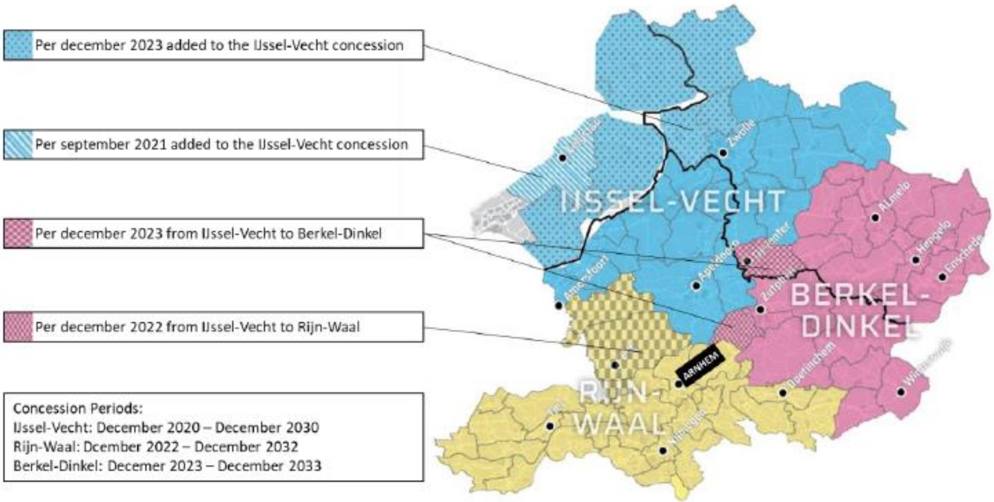

Figure 21: Public transport concessions issued by the provinces of Gelderland, Overijssel and Flevoland

6.3 Pärnu deployment plans

6.3.1 Wider Policy Landscape in Estonia

Estonia has made significant progress against the National Alternative fuel implementation plan targets, exceeding targets for electric vehicle charging points, CNG refuelling points and LNG refuelling points. However, as in Latvia, hydrogen is not seen as a mandatory alternative fuel and the country has been unsuccessful in deploying refuelling infrastructure for hydrogen. The role of hydrogen in the Estonian transport system is still yet to be determined, with the planned release of the Estonian hydrogen road map (2021) expected to further outline its expected role. Note that the HRS planned to be deployed within the Action H2Nodes is still included in the National Alternative Fuel Implementation Plan, setting an at latest completion target of 2025. In this interim period, the country has been successful in switching to alternative low-carbon fuels such as CNG; the public transport operator (PTO) of Tallinn “Tallinna Linnatranspordi” is currently operating 100 CNG buses for public transport, and it is foreseen that this number will increase to 350 units by 2025. Note however that these vehicles cannot offer a zero-emission solution from a CO_2 or air pollution perspective, and that further switching to hydrogen or other zero-carbon fuels will be required over the next few decades.

6.3.2 Regional Plans

Due to a lack of hydrogen bus demand in Pärnu, no vehicles were deployed during the project at the Pärnu site. Parox Energy have considered moving the deployment site to Tallinn, the capital of Estonia and located next to the TEN-T corridor along E67, along with potential project partners in Solaris Bus & Coach Baltic, Bioforce Infra OU, Greenor Energy and University of Tartu. Tallinn’s significantly larger population than Pärnu offered more options for demand development, with Tallinn’s municipal transport operator Tallinna Linnatranspordi AS (TLT) indicating interest in participating in a hydrogen project. The site was scoped for the deployment of an electrolyser with production capacity of 100kg/day, and capability to refuel an expected 5 FCEV buses per day. However, progress on the proposal was significantly hampered by the COVID-19 pandemic and the site alteration request was not possible under the scope of H2Nodes. This project failure raised the following key learning points:

- There is a need for detailed engagement with all stakeholders at an early stage of project conceptualisation. Frank appraisals of vehicle and hydrogen costs, logistical challenges to deployment and other barriers should be shown to all parties to ensure that operators do not commit to project operation under unattainable expectations.
- The HRS should be sited in a region with potential ‘back-up plans’ for vehicle demand, so that should a partner withdraw from the project it is still possible to find appetite for vehicle deployments at the site under project funding.

Despite the failure to deploy vehicles, the feasibility of deploying hydrogen infrastructure and potential upscaling at the site was assessed. This data shows that, given sufficient vehicle demand in the region, it is feasible to achieve competitive hydrogen prices via electrolysis. The suggested next steps for the Pärnu site are therefore to attempt to source external funding for a hydrogen vehicle demonstration trial in a more suitable location (e.g. Tallinn) and to scale up demand at this new site up to the projected 196 FCE-buses that could be used by Tallinna Linnatranspordi.

Parameter	Initial deployment	Large scale electrolysis unit

Hydrogen Price (pre-tax)	€8.80/kg	€4.00/kg
Electrolyser Size	180 kg/day	3000 kg/day
Hydrogen Supply Storage Capacity (200 bar)	105 kg	2088 kg
Hydrogen Fuelling Storage Tank (500 bar)	116 kg	372 kg
Hydrogen Fuelling Storage Tank (1000 bar)	34 kg	162 kg
350 bar dispenser	Yes	Yes
700 bar dispenser	Yes	Yes

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6.3.3 Overview of the current deployment ambitions for FCEVs in Estonia

Having assessed that the use of hydrogen in transport as an element of strategic importance which would have a “positive impact on the economy and people’s wellbeing”, the Estonian government issued a grant for hydrogen transportation proposals, which closed in September 2021 (Valitsus, 2021). This grant support, combined with lessons learnt from the H2Nodes project, should ensure that a successful hydrogen station can be feasibly deployed in Estonia in the near term. The cities of Tartu and Tallinn have both announced ambitious plans for hydrogen vehicle deployments in recent months and there are a number of ways that these ambitions could be financed, including the government grant support program and Innovation funding for hydrogen buses. (ERR News, 2021; Estonian World, 2021)

7. H2Nodes Case Study Lessons Learnt

7.1 Overview of project outcomes, barriers & lessons learnt

It is important that a project of this kind keeps a record of barriers and identifies useful and widely applicable lessons learnt, that can be applied to similar deployment projects in the sector and eventually lead to the scale up and commercialisation of the technology. This is particularly crucial given the first-of-its-kind nature of the Action H2Nodes, which aimed to provide the first hydrogen refuelling station in both Estonia and Latvia.

The primary success of the project has been in the deployment of 2 medium-scale (~300kg/day) hydrogen refuelling stations in Arnhem and Riga which supply fuel to a total of approximately 63 fuel cell electric vehicles, including passenger cars, buses and trolley buses. These real-world actions have led to numerous learnings from vehicle operators and public authorities on hydrogen and fuel cell vehicles and have allowed for the gathering of the below 'hands-on' lessons in vehicle operation and project planning in the region.

The project set out with an ambitious scope both in terms of refuelling infrastructure deployment and hydrogen vehicle market stimulation. The scope of these aims has not been entirely achieved due to a number of factors addressed in the barriers below, which led to a failure to deploy infrastructure in Pärnu due to challenges in identifying hydrogen usage by FCEVs. Moving forward, the primary focus of hydrogen development in the three regional clusters should be to continue to grow vehicle end user demand and expand to the growing number of potential vehicle types, including vans, trucks and buses, that could ensure high station utilization and the resulting HRS upscaling.

7.1.1 Strategy, Planning & Business Cases

From the NS-B Corridor point of view the challenge is to increase the number of HRS on the eastern part of the corridor, in order to establish a basic network for international fuel cell vehicle traffic. Considering that the commercial and financial feasibility is considered to be a bottleneck, the focus should be on the elimination of such barriers, and the H2Nodes project provides some lessons that could contribute to this for future sites.

Lesson 1: Focus on the development of 350 bar HRSs in addition to 700 bar

Currently, a 350 bar refuelling facility is required for heavy vehicles such as trucks or buses. With 350 bar stations in place, the HRS is positioned to provide an income from the refuelling of vehicle segments where hydrogen is seen as a promising zero-emission alternative to fossil fuels.

Lesson 2: Invest in vehicle-deployment rather than solely on HRS-development

The demand aggregation initiative in Arnhem, H2-Drive, shows that availing funds to stimulate the sale and use of FCEVs is necessary to help establish the demand for an acceptable HRS business case for station operators. Deployment of FCEVs provides station operators a basis of recurring revenues, which is a far better basis for upscaling than one-off investment grants. It prevents a situation where an HRS remains underutilised, which is important for the business case as well as for the role of early HRSs as a demonstration of feasibility to interested parties; stations that are used make a better impression than stations that remain empty for most of the time.

It is therefore important to develop the first HRS in areas where such demand-creation initiatives have high chances of success and if these such chances are better at other locations than the originally targeted site, a location switch should be considered. The Estonian HRS is an example of such a situation; the Pärnu hydrogen refuelling and production station were not built within H2Nodes due to issues with securing demand at the site choice. The uncertainty about the location of the station was raised late, and the Pärnu PTO decided to deploy CNG buses for public transport operations as it was a cheaper option with a CNG refuelling station already deployed in Pärnu. Potential alternative sites for the development of hydrogen include the Estonian capital city of Tallinn, with Tallinna linnatranspordi (TLT) expressing commitment to deploy FCE-buses in the near future, and Tartu. The planning conducted and lessons learnt in Estonia under H2Nodes could still therefore have a positive impact on the region with new infrastructure deployed.

Lesson 3: Position the first HRS as a showcase of technology innovation and various hydrogen production methods as well as providing commercial opportunities

The Latvian HRS was positioned as a showcase for HRS development in the Eastern part of the North-Sea Baltic Corridor. In the preparation stage for H2Nodes a number of feasibility studies were carried out, providing an insight of new technologies such as fuel cell vehicles and hydrogen refuelling stations. One of the main achievements of the Riga project has been the stimulation of public awareness of the first hydrogen refuelling and production station in Eastern Europe. Several stakeholders from Latvia, Sweden, Estonia, Lithuania and Poland have visited the site in addition to further engagement at a webinar in December 2020, where information on the Rigas Satiksme HyTrolleybuses and HRS was presented. Furthermore, the hydrogen availability in Riga allowed for Toyota Baltic to start the preparation of Toyota Mirai introduction in Latvia and it is foreseen that by the end of 2021 the vehicle will be available for customers. This is first Toyota Mirai to be registered in Estonia for Toyota Baltic, and it is participating in HRS refuelling tests at the Riga 700bar dispenser.

Lesson 4: Need for revision of Alternative fuel implementation plans

Only a small portion of the countries along the NS-B corridor included hydrogen as a mandatory fuel in National alternative fuel implementation plans. The main reason why (a) some countries did not include HRS development targets in their National Policy Framework and (b) none of the countries that did include HRS targets in their plans were able to achieve them is lack of financial/commercial feasibility. European OEMs that were expected to introduce FCEVs on the European market changed their priorities due to an acceleration of the BEV market. It is also often stated that an expansion of the refuelling infrastructure is needed before FCEVs can be deployed more widely.

- The primary solution to resolve this issue is to revise the Alternative fuel implementation Directive to fill the gaps in the build-up of infrastructure and to replace the system of national plans with more efficient instruments, such as binding and enforceable targets. The scope of the Directive needs to be broadened to cover the TEN-T comprehensive network and urban and regional nodes and make hydrogen infrastructure deployment mandatory to ensure long term decarbonisation aims are prioritised alongside ‘easy wins’ in the battery and CNG markets. The inclusion of hydrogen as mandatory fuel and introduction of binding and enforceable targets would enable for all countries to revise the HRS deployment plans and to develop more realistic scenarios. Note that the AFIR proposal of the European Commission has started to address this, although the final version is still being negotiated and it is unclear to what extent there will be appropriate inclusions for hydrogen.

Lesson 5: Aligning financing and deployment timeline for vehicles & HRS infrastructure in tandem

In a broad economic-commercial perspective the development of hydrogen for mobility is often referred to in terms of the chicken-and-egg dilemma: FCEVs will only be sold if sufficient refuelling infrastructure has been put in place; refuelling infrastructure can only be developed if there are enough FCEVs to provide a commercial basis. So, ideally both vehicles and the first HRS come at the same time. This was also the intention of the H2Nodes project. However, the development of HRS and FCEV at the same time requires the involvement of a large group of parties working together to align timing for confirming financing and starting deployment. The absence of demand can lead to delays to HRS site commissioning or failure of the project. Conversely, delays in the commissioning of a HRS can negate efforts made to expand the FCEV user base as the FCEVs that are supposed to serve as real life proof of the advantages of FCEVs are not operational, either because they are not delivered, or they lack facilities to refuel.

The H2Nodes Arnhem project faced such a timing risk. The Arnhem-based hydrogen fuel cell systems manufacturer HyMove – the supplier of the two Syntus fuel cell buses – was able to deliver the first FCE bus on time, while the development of the H2Nodes HRS faced a delay of about 1 year. Given the importance of a successful demonstration project as a basis for future growth by the involvement of potential users, waiting for the H2Nodes HRS to become operational was not considered to be a viable option, and hence the municipality of Arnhem arranged with HyGear to commit to the development and operation of a temporary 350 bar refuelling facility at its new location at Westervoortsedijk. The municipality also committed to the co-funding of this temporary refuelling facility, and this is a prime example of the steps that may need to be taken to ensure first of their kind deployments are successful in the short term.

Lesson 6: Scaling up deployment volumes & HRS infrastructure in tandem

The section *Hydrogen Price Scenarios* has outlined the importance of scaling up hydrogen production to access a hydrogen price which is competitive with other alternative fuel drivetrains. In order to guarantee high utilisation of these increased capacity hydrogen stations, it is important to guarantee offtake demand via hydrogen transport vehicles. This can be done in a variety of ways, including but not limited to; take-or-pay arrangements, ‘vehicle as a service’ models, fuel tickets, joint procurement activities and projects. Whilst these financing arrangements do not always guarantee against partner withdrawal from a project, it does give some confidence to the infrastructure providers that an acceptable demand level is available in an area. It is important to scope the potential for demand contingency within an area in case of withdrawal, as well as sizing potential additional demand outside of the project in case it is desirable to build a larger station than initially planned.

The most important lesson learned is that the actual establishment of a solid market for the first HRS in a region requires more than just informing potential users. It should be an offer that is substantial enough to compensate for possible drawbacks for early users, such as limited overall HRS availability and HRS performance issues during start-up. This requires a financial commitment from stakeholders to avail funds for incentive packages. For instance, refuelling at HRS Arnhem can't be enforced and it is also not desirable to limit FCEV drivers with respect to the refuelling location. However, a 50% discount on purchased fuel and the fact that the targeted group has a working or living location in the region sufficiently secures the use of the targeted HRS.

Lesson 7: Ensuring engagement of local transport operators or other usages

The vehicle deployment in Pärnu failed due to the lack of engagement with, and identification of, end users in the region prior to project commencement. Meanwhile, the project will not continue to operate fuel cell buses in the Arnhem region due to the transport operator deciding to submit a 100% BEV bus bid.

The fact that public bus transport in the Netherlands is usually operated by private operators in 10-year contracts implies that opportunities to set-up a hydrogen-for-transport demonstration project, that includes the deployment of public transport buses, requires the co-operation of the private transport companies that operate bus services in, from or to the area where the demonstration project is located. In order to secure this co-operation, it is recommended to:

- secure the private operators' participation in future initiatives where new vehicle technologies are demonstrated by including provisions for such participation;
- include penalty clauses in case of an exit for convenience.

However, it is not recommendable to enforce a private operator's involvement on the basis of these provisions only. A demonstration project such as H2Nodes includes a level of uncertainty (which is the reason it is a demonstration project) that can only be managed by partners with intrinsic motivation rather than an enforced one. Penalty clauses may stimulate a participant to wait with its exit until a moment where it is almost impossible to come up with alternatives. To this end, communication with the vehicle operators at all stages of the project is key to ensuring buy-in and continued support for the project. Involving the operators at an early stage of project planning ensures that there is sufficient time for the partners to consider fully the implications of being involved of a first of a kind project such as H2Nodes, and whether the learnings or operational benefits are worth the considerable time and monetary investment required, and also allows for the project to be built around the operators' individual requirements to guarantee maximum benefit for them. Furthermore, involving partners in positive communication around the project, or hydrogen technology generally, helps to promote a culture of optimism and continued support for the project.

In addition, having at least one other operator involved in the process reduces dependency on one single actor and thus secures project continuation in case the targeted operator withdraws. If there are any up-front doubts about obtaining cooperation from a public transport operator, it may be worthwhile to consider an HRS location close enough to bus depot of or bus routes operated by at least one other operator. This provides back-up options in case the intended cooperation of the target operator fails.

The scenario that is considered to be the safest is the one where the public transport authority is the lead partner in partnerships including the deployment of new technology in public transport vehicles. The financial and operational arrangements with the public transport operator are then made on a bilateral basis.

Lesson 8: Consideration of other factors affecting total cost of operation should be included when evaluating alternative drivetrain options

The general total cost of ownership models outlined in the section *Cost-effective approaches for hydrogen deployments in cities* are a good indicator of the potential of a product to gain a substantial market share. At a surface level, these models typically indicate that purely electric vehicles are the most cost-effective vehicle mode for passenger cars, buses and trolley bus decarbonisation, with either a small or zero delta to current diesel incumbents. Despite this, the BEV market, particularly in the heavy-duty sectors, is still failing to monopolise deployment volumes from conventional vehicles, which would be expected given the low cost. This is in part due to the costs and complexity of deploying a suitable charging infrastructure but also because BEVs are not a suitable direct comparison to diesel ICE vehicles in terms of operational capabilities, and it is often not appropriate to directly compare the economic models of electric vehicles and other alternative drivetrains as it is not a like-for-like comparison. FCEVs offer a much closer direct comparison to diesel ICE vehicles in terms of operational performance, however, suffer from a side-by-side economic comparison with BEVs.

This report has attempted to correct for this factor by demonstrating the economic downside of purchasing and operating 30% additional vehicles in the BEV case, which would be required to ensure comparable performance to the existing diesel counterfactual. In addition to this, the feasibility of such a replacement requires consideration of variable factors such as whether there is sufficient space at the depot to permit redundancy vehicles, or on depot charge points. In addition, the costs required to upgrade connection to the grid for a depot should not be underestimated. It is therefore important when developing economic models and communicating the benefits of hydrogen with prospective end users to reference these factors when comparing to BEV alternatives, and where possible quantify the affects for direct comparison (e.g. 30% additional vehicles required for operational redundancy, grid connection costs etc.).

As an example, for bus operators, it is likely that in the following cases public transport operators may now prefer FCE-buses to battery electric buses:

- On certain long-distance routes with no recharging infrastructure where the public transport options for decarbonisation are either the deployment of multiple BEV buses or only one FCE bus.
- On certain long-distances routes where a battery-electric bus can only recharge at a slow charging facility, taking a substantial amount of time and a paid waiting driver

– where a fuel cell bus either does not need refuelling or can refuel in about 10 minutes.

Lesson 9: Reducing distance from public sector operators to public refuelling infrastructure is critical in order to capitalise on the short refuelling time of FCEVs

As the TotalEnergies HRS commissioning in Arnhem was delayed until July 2019, the buses were refuelled at a temporary HRS in an initial period, operated by HyGear. Both the temporary and the TotalEnergies-HRS are not centrally located in the Veluwe public bus transport concession area. Normally a refill takes under 30 minutes, however, given the peripheral location of the HRS, 80 minutes had to be added for the trip to and from the HRS. This is a considerable addition of time to typical diesel refuelling which is conducted on-site, and results in hydrogen losing its advantage over BEV buses in terms of refuelling time and increased duty cycle feasibility. Where possible, refuelling station locations should be carefully planned to allow access to as many vehicles as possible at the shortest detour time possible, whether this results in an on-depot HRS deployment, or a public deployment that is on-route for buses or sufficiently close to the depot to allow for under 5 minutes detour time.

Note also that refuelling of both FCEV passenger cars and buses can cause interference in the sense that the refuelling time is longer if, due to a recent previous refuelling, the compression is limited. This should be considered when evaluating refuelling speed and business cases for detour and refuelling time to a public refuelling station.

7.1.2 Vehicle & HRS operation and technology readiness

The hydrogen vehicles and infrastructure in Arnhem and Riga performed well and demonstrated that hydrogen vehicles have the potential to be used in public transport daily operation. Buses could operate using existing bus schedules and the large operating range and short refuelling times were highlighted by users as reasons for purchase and continued use of the vehicles, with feedback from passenger car users in Arnhem stating that refuelling was "quick and up to 99% state of charge".

Lesson 10: Building in station redundancy and spare part availability increases vehicle uptake and usage

The station availability in Arnhem was high for a demonstration station, at 97.2%, however, for a location with only one HRS it is desirable to achieve an availability above 99%. When redundancy by adding other HRS to the local network is not possible, built-in redundancy may be appropriate. It is expected that availability would increase with station size, as a large commercial station would have multiple dispenser units and hence would have inbuilt redundancy, however, there are some technical issues, particularly with compressor operation and spare part availability, that if resolved could significantly reduce station pump downtime. In particular, in both Arnhem and Riga, supply chain issues impacted the availability of spare parts for regular maintenance and resulted in station downtime events.

Ensuring a fully operational HRS is available to end users at all times is crucial to increasing vehicle uptake. The H2Drive scheme in Arnhem is a prime example of this, as it was significantly delayed by issues with the 700 bar compressor at the station, which lasted for several months and have only recently been resolved. The vehicle uptake has slowed over the period even despite some refuelling capability being available to a lower pressure, and only 50 of the available 80 funded vehicles deployed (although note that 70 of the 80 packages have been allocated and the remaining deployments will be effectuated rapidly).

Lesson 11: It is important to engage with drivers to secure enthusiasm and buy-in to the technology

Prior to the commencement of vehicle operation, drivers in Arnhem received instructions on safety, the technology behind the buses, the requirements for driving with the buses and refuelling in Arnhem, the protocols in the event of breakdown and general information about hydrogen and the project. Providing this level of clarity to vehicle users helps to provide assurance that the technology shift is well reasoned, that operational requirements have been considered in planning and that the vehicles will be easy to use and even provide operational benefits. This level of buy-in is essential to ensure continued support for further vehicle deployments by a public sector operator based on the expected positive feedback regarding driving experiences. The feedback received by the Arnhem drivers can be summarised as: *"You do not have to pay special attention to any aspects of 'new driving', or do anything special, it's more or less automatic and you are used to it within just a few hours"* (Keolis, 2020). Of particular note was the enthusiasm around the way in which drivers are able to make use of recovery of braking energy, and the rapid acceleration of the vehicles meaning it is easier to merge with traffic.

Lesson 12: Fuel consumption is highly dependent on use case and fuel cell quality

The vehicle efficiencies seen in the project were impressive. Fuel consumption for the buses in Arnhem averaged 6.1kg/100km, significantly more efficient than the average, about 40% more efficient than the average fuel consumption reported by the High V.LO-City project (Fuel Cell Electric Buses, no date), and about 50% more fuel efficient than the comparable Citaro FuelCELL Hybrid. In Riga, the HyTrolleybuses used Ballard HD85 fuel cell systems, which were able to achieve an impressive average of 49% efficiency in converting hydrogen chemical energy into electricity despite demanding power requirements on the fuel cell during operation. Vehicle efficiency has a large effect on the total cost of ownership calculation particularly in the early years of vehicle trials and initial deployments due to the high hydrogen price expected over this time period, and measures should be taken where possible to secure the highest efficiency and reliability fuel cell. It must be noted that fuel cell consumption rate varies considerably with the rate of power take off, for instance additional electricity required on buses for onboard heating. For one of the two buses deployed in Arnhem, an electric heater was required during winter months, resulting in a 40% higher fuel consumption. The other bus used the excess heat generated from the fuel cell system and did not require any additional heating.

8. Conclusions

The H2Nodes project has successfully deployed two HRS along the North Sea Baltic TEN-T corridor, which supported over 60 FCEVs for a period of approximately 18 months at the time of writing this report. This included a first of its kind deployment in Riga with the first HRS in the Baltic and the first hydrogen trolley buses trial in the world. The deployments have been seen as a success, with plans to expand the deployment volumes through the expansion of the H2Drive scheme, the targeting of the heavy-duty transport market, and the upscaling of hydrogen production and dispensing capacity at the stations. The project partners in Estonia, despite failing to deploy a station in Pärnu as initially proposed, have been able to investigate the possibility for regional hydrogen deployment, including future HRS in Tallinn and Tartu, which are set to be deployed according to the national plan by 2025.

The successful deployments have been able to provide some useful insights and recommendations for future stations, in order to expand the HRS network along the NS-B corridor and throughout wider Europe. These are summarised in Table 4 below with further details available in the other H2Nodes Milestone Reports prepared throughout the project (H2Nodes, 2021).

Table 4: Lessons learnt and recommendations from the H2Nodes project

#	Recommendations
1	Focus on the development of 350 bar HRSs in addition to 700 bar
2	Invest in vehicle-deployment rather than solely on HRS-development
3	For ‘first of its kind’ deployments in regions, use the HRS deployment as a technological show case as well as a commercial operation
4	Revise the alternative fuel implementation plans to include hydrogen as a mandatory fuel
5	*Aligning financing and deployment timeline for vehicles & HRS infrastructure in tandem*
6	Effectively time the scale-up of deployment volumes & HRS infrastructure in tandem
7	Engage with local transport operators from early in the project
8	Consider all factors affecting vehicle operation and performance when evaluating drivetrain options on a total cost of ownership basis, not just direct incurred costs
9	Where possible, limit the detour distance for anchor demand to reach the HRS
10	Build in station redundancy and secure spare part availability for quick repairs
11	Engage with drivers to ensure project buy-in and continued vehicle operation
12	Operate the vehicles in a way that gives low hydrogen fuel consumption

An important factor to consider during procurement for most transport operators is the vehicle total cost of ownership, and several of the recommendations from this project tackle this aspect for hydrogen (for instance, reducing fuel consumption and reducing hydrogen price from better utilised stations). However, the business case evaluation conducted in this report demonstrates that hydrogen is not likely to be the preferred low carbon solution in the short or medium term for the standard duty cycle of some transport operators using the vehicle types explored within H2Nodes without support from other local stakeholders and a longer-term development strategy. For instance, the projected TCO for hydrogen taxis are 22% higher than that for BEVs at mass-market prices, and there is an even greater differential using existing prices and technology. However, there are expectations that with a hydrogen price at €7.50/kg or below as a result of scaled demand FCEVs could reach parity with petrol/diesel hybrids in 2025 [13]. In the meantime, subsidies are vital to reduce the TCO premium of FCEVs and make a commercial case for fleet operators. As such, it is important when planning projects that end users are made aware of the benefits and downsides of hydrogen vehicles, and expectations regarding price are managed.

Where possible, end users who have done thorough analysis to evidence that hydrogen is the best alternative fuel drivetrain for them should be preferred, either due to one of the conditions outlined in this report for buses, trolleybuses and taxis (e.g. difficulties attaining grid connection for on depot vehicles) or due to the larger weight class of the vehicles, with HGVs, rail and maritime transport sectors notably areas that hydrogen has seen increased interest as a zero carbon solution over the past few years. Additionally, if the vehicle duty cycle is not suited to a battery electric transition and additional vehicles need to be procured to reach the same level of service, this has been found to shift the economic feasibility of decarbonisation solutions dramatically in hydrogen's favour.

Overall, the H2Nodes project has been able to demonstrate that hydrogen is a viable zero carbon energy source for the decarbonisation of sections of the transport fleets that utilise the NS-B corridor, and with upscaling and expansion of the hydrogen stations and vehicle demand a sufficient hydrogen price can be reached to approach cost competitiveness with diesel. The next steps for the deployments achieved under the project funding are to continue to grow the hydrogen end user base and to construct additional stations along the Eastern segment of the corridor in order to start developing a skeleton network of HRS along the entire region.

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10. Appendix A: TCO Assumption Data

Table 10-1: Fuel Cost Assumptions

Input	Value
Diesel price (€/L)	1.40
Electricity price (€/kWh)	0.20
Hydrogen price (high) (€/kg) (after tax)	13.31
Hydrogen price (medium) (€/kg) (after tax)	7.55
Hydrogen price (low) (€/kg) (after tax)	4.53

Table 10-2: Bus TCO Assumptions: Diesel ICE

Input	Value
Bus Mileage (km/year)	55,000
Bus Type	Single Deck
Bus Availability (%)	90
Bus Capex (€)	220,000
Bus Lifetime (years)	15
Bus drivetrain maintenance (€/bus/year)	10,000
Powertrain overhaul capex (€)	5,000
Powertrain lifetime (years)	7.5
Diesel consumption (l/100km)	37
Bus regular maintenance (€/bus/year)	10,000
Driver salary (€/bus/year)	40,000
Depot overheads (€/bus/year)	7,000

Table 10-3: Bus TCO Assumptions: Diesel BEV hybrid

Input	Value
Bus Mileage (km/year)	55,000
Bus Type	Single Deck
Bus Availability (%)	90
Bus Capex (€)	330,000
Bus Lifetime (years)	15
Bus drivetrain maintenance (€/bus/year)	10,000
Powertrain overhaul capex (€)	20,000
Powertrain lifetime (years)	7.5
Diesel consumption (l/100km)	29.6

Electricity consumption (kWh/100km)	32
Bus regular maintenance (€/bus/year)	10,000
Driver salary (€/bus/year)	40,000
Depot overheads (€/bus/year)	7,000
Additional station capex (overall) (€)	30,000
Initial bus deployment volume (no. buses)	20
Additional on-station chargers (€/bus)	12,500
Additional infrastructure maintenance (€/bus/year)	1,250

Table 10-4: Bus TCO Assumptions: BEV (current)

Input	Value
Bus Mileage (km/year)	55,000
Bus Type	Single Deck
Bus Availability (%)	90
Bus Capex (€)	415,000
Bus Lifetime (years)	15
Bus drivetrain maintenance (€/bus/year)	6,000
Powertrain overhaul capex (€)	80,000
Powertrain lifetime (years)	7.5
Electricity consumption (kWh/100km)	160
Bus regular maintenance (€/bus/year)	10,000
Driver salary (€/bus/year)	40,000
Depot overheads (€/bus/year)	7,000
Additional station capex (overall) (€)	200,000
Initial bus deployment volume (no. buses)	20
Additional on-station chargers (€/bus)	50,000
Additional infrastructure maintenance (€/bus/year)	5,000

Table 10-5: Bus TCO Assumptions: BEV (Mass market)

Input	Value
Bus Mileage (km/year)	55,000
Bus Type	Single Deck
Bus Availability (%)	90
Bus Capex (€)	350,000
Bus Lifetime (years)	15
Bus drivetrain maintenance (€/bus/year)	6,000
Powertrain overhaul capex (€)	70,000
Powertrain lifetime (years)	7.5

Electricity consumption (kWh/100km)	160
Bus regular maintenance (€/bus/year)	10,000
Driver salary (€/bus/year)	40,000
Depot overheads (€/bus/year)	7,000
Additional station capex (overall) (€)	100,000
Initial bus deployment volume (no. buses)	20
Additional on-station chargers (€/bus)	40,000
Additional infrastructure maintenance (€/bus/year)	5,000

Table 10-6: Bus TCO Assumptions: FCEV (current)

Input	Value
Bus Mileage (km/year)	55,000
Bus Type	Single Deck
Bus Availability (%)	90
Bus Capex (€)	475,000
Bus Lifetime (years)	15
Bus drivetrain maintenance (€/bus/year)	8,000
Powertrain overhaul capex (€)	43,000
Powertrain lifetime (years)	7.5
Hydrogen Consumption (kg/100km)	6.1
Bus regular maintenance (€/bus/year)	10,000
Driver salary (€/bus/year)	40,000
Depot overheads (€/bus/year)	7,000

Table 10-7: Bus TCO Assumptions: FCEV (Mass market)

Input	Value
Bus Mileage (km/year)	55,000
Bus Type	Single Deck
Bus Availability (%)	90
Bus Capex (€)	400,000
Bus Lifetime (years)	15
Bus drivetrain maintenance (€/bus/year)	8,000
Powertrain overhaul capex (€)	30,000
Powertrain lifetime (years)	7.5
Hydrogen Consumption (kg/100km)	6.1
Bus regular maintenance (€/bus/year)	10,000

Driver salary (€/bus/year)	40,000
Depot overheads (€/bus/year)	7,000

Table 10-8: Taxi TCO Assumptions: Diesel ICE

Input	Value
Taxi Mileage (km/year)	30,000
Taxi Type	Passenger Car
Taxi Availability (%)	90
Taxi Capex (€)	27,000
Taxi Lifetime (years)	8
Diesel Consumption (L/100km)	7
Taxi maintenance (€/taxi/year)	500
Driver salary (€/taxi/year)	40,000

Table 10-9: Taxi TCO Assumptions: Diesel BEV hybrid

Input	Value
Taxi Mileage (km/year)	30,000
Taxi Type	Passenger Car
Taxi Availability (%)	90
Taxi Capex (€)	36,000
Taxi Lifetime (years)	8
Diesel Consumption (L/100km)	4
Electricity Consumption (kWh/100km)	6.9
Taxi maintenance (€/taxi/year)	500
Driver salary (€/taxi/year)	40,000

Table 10-10: Taxi TCO Assumptions: BEV (current)

Input	Value
Taxi Mileage (km/year)	30,000
Taxi Type	Passenger Car
Taxi Availability (%)	90
Taxi Capex (€)	41,000
Taxi Lifetime (years)	8
Electricity Consumption (kWh/100km)	16
Taxi maintenance (€/taxi/year)	500
Driver salary (€/taxi/year)	40,000
Additional station capex (overall) (€)	0

Additional on-station chargers (€/taxi)	1,400
Additional infrastructure maintenance (€/taxi/year)	150

Table 10-11: Taxi TCO Assumptions: BEV (Mass market)

Input	Value
Taxi Mileage (km/year)	30,000
Taxi Type	Passenger Car
Taxi Availability (%)	90
Taxi Capex (€)	37,000
Taxi Lifetime (years)	8
Electricity Consumption (kWh/100km)	16
Taxi maintenance (€/taxi/year)	500
Driver salary (€/taxi/year)	40,000
Additional station capex (overall) (€)	0
Additional on-station chargers (€/taxi)	1,400
Additional infrastructure maintenance (€/taxi/year)	150

Table 10-12: Taxi TCO Assumptions: FCEV (current)

Input	Value
Taxi Mileage (km/year)	30,000
Taxi Type	Passenger Car
Taxi Availability (%)	90
Taxi Capex (€)	65,000
Taxi Lifetime (years)	8
Hydrogen Consumption (kg/100km)	0.8
Taxi maintenance (€/taxi/year)	500
Driver salary (€/taxi/year)	40,000

Table 10-13: Taxi TCO Assumptions: FCEV (Mass market)

Input	Value
Taxi Mileage (km/year)	30,000
Taxi Type	Passenger Car
Taxi Availability (%)	90
Taxi Capex (€)	41,000
Taxi Lifetime (years)	8

Hydrogen Consumption (kg/100km)	0.8
Taxi maintenance (€/taxi/year)	500
Driver salary (€/taxi/year)	40,000

Table 10-14: Trolley Bus TCO Assumptions: Diesel / electrified

Input	Value
Trolley Bus Mileage (km/year)	70,000
Trolley Bus Type	Single Deck
Trolley Bus Availability (%)	90
Trolley Bus Capex (€)	300,000
Trolley Bus Lifetime (years)	12
Trolley Bus drivetrain maintenance (€/bus/year)	10,000
Powertrain overhaul capex (€)	10,000
Powertrain lifetime (years)	7.5
Diesel consumption (l/100km)	24
Electricity consumption (kWh/100km)	180
Trolley Bus regular maintenance (€/bus/year)	10,000
Driver salary (€/bus/year)	40,000
Depot overheads (€/bus/year)	7,000

Table 10-15: Trolley Bus TCO Assumptions: BEV / electrified (current)

Input	Value
Trolley Bus Mileage (km/year)	70,000
Trolley Bus Type	Single Deck
Trolley Bus Availability (%)	90
Trolley Bus Capex (€)	400,000
Trolley Bus Lifetime (years)	12
Trolley Bus drivetrain maintenance (€/bus/year)	10,000
Powertrain overhaul capex (€)	60,000
Powertrain lifetime (years)	7.5
Electricity consumption (kWh/100km)	300
Trolley Bus regular maintenance (€/bus/year)	10,000
Driver salary (€/bus/year)	40,000
Depot overheads (€/bus/year)	7,000
Additional station capex (overall) (€)	100,000

Initial trolley bus deployment volume (no. buses)	20
Additional on-station chargers (€/bus)	25,000
Additional infrastructure maintenance (€/bus/year)	2,500

Table 10-16: Trolley Bus TCO Assumptions: BEV / electrified (Mass market)

Input	Value
Trolley Bus Mileage (km/year)	70,000
Trolley Bus Type	Single Deck
Trolley Bus Availability (%)	90
Trolley Bus Capex (€)	350,000
Trolley Bus Lifetime (years)	12
Trolley Bus drivetrain maintenance (€/bus/year)	10,000
Powertrain overhaul capex (€)	50,000
Powertrain lifetime (years)	7.5
Electricity consumption (kWh/100km)	300
Trolley Bus regular maintenance (€/bus/year)	10,000
Driver salary (€/bus/year)	40,000
Depot overheads (€/bus/year)	7,000
Additional station capex (overall) (€)	50,000
Initial trolley bus deployment volume (no. buses)	20
Additional on-station chargers (€/bus)	25,000
Additional infrastructure maintenance (€/bus/year)	2,500

Table 10-17: Trolley Bus TCO Assumptions: FCEV / electrified (current)

Input	Value
Trolley Bus Mileage (km/year)	70,000
Trolley Bus Type	Single Deck
Trolley Bus Availability (%)	90
Trolley Bus Capex (€)	450,000
Trolley Bus Lifetime (years)	12
Trolley Bus drivetrain maintenance (€/bus/year)	10,000
Powertrain overhaul capex (€)	25,000
Powertrain lifetime (years)	7.5

Hydrogen consumption (kg/100km)	5
Electricity consumption (kWh/100km)	180
Trolley Bus regular maintenance (€/bus/year)	10,000
Driver salary (€/bus/year)	40,000
Depot overheads (€/bus/year)	7,000

Table 10-18: Trolley Bus TCO Assumptions: FCEV / electrified (Mass market)

Input	Value
Trolley Bus Mileage (km/year)	70,000
Trolley Bus Type	Single Deck
Trolley Bus Availability (%)	90
Trolley Bus Capex (€)	400,000
Trolley Bus Lifetime (years)	12
Trolley Bus drivetrain maintenance (€/bus/year)	10,000
Powertrain overhaul capex (€)	20,000
Powertrain lifetime (years)	7.5
Hydrogen consumption (kg/100km)	5
Electricity consumption (kWh/100km)	180
Trolley Bus regular maintenance (€/bus/year)	10,000
Driver salary (€/bus/year)	40,000
Depot overheads (€/bus/year)	7,000