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SMART GREEN MOBILITY
BSR HyAirport

Airport Equipment



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CONTENT

1 Introduction 4

2 Scope 4
2.1 H_2 ground support equipment testing at Hamburg Airport 5
2.2 H_2 fuel cell baggage tractor testing in Riga Airport 8
2.3 H_2 powered winter maintenance equipment testing at Helsinki, Riga, Kaunas and Tallinn Airports 10
2.4 Bus Road Show 12

3 Operational Data (Qualitative) 14
Overall qualitative information on hydrogen equipment testing 14
3.1 H_2 Ground support equipment testing in Hamburg Airport 15
3.2 H_2 fuel cell baggage tractor testing in Riga Airport 23
3.3 H_2 powered winter maintenance equipment testing at Helsinki, Riga, Kaunas and Tallinn Airports 25
3.3.1 Helsinki Airport 25
3.3.2 Riga Airport 35
3.3.3 Kaunas Airport 38
3.3.4 Tallinn Airport 42
3.4 Bus Road Show 45

4 Technical Data (Quantitative) 49
4.1 H_2 Ground support equipment testing in Hamburg Airport 49
4.2 H_2 powered winter maintenance equipment testing at Helsinki, Riga, Kaunas and Tallinn Airports 54
4.2.1 Helsinki Airport 54
4.2.2 Riga Airport 57
4.2.3 Kaunas Airport 60
4.2.4 Tallinn Airport 61
4.2.5 Bus Road Show 62

5 Economic Data Summary 66
5.1 H_2 vehicle testing in Hamburg Airport 66
5.2 H_2 powered winter maintenance equipment testing at Helsinki, Riga, Kaunas and Tallinn Airports 67
5.2.1 Helsinki Airport 67
5.2.2 Riga Airport 69
5.2.3 Kaunas Airport 69
5.2.4 Tallinn Airport 69
5.3 Bus Road Show 70

6 Conclusions 71
6.1 H_2 vehicle testing at Hamburg Airport 71
6.2 H_2 fuel cell baggage tractor testing in Riga Airport 72
6.3 H_2 powered winter maintenance equipment testing at Helsinki, Riga, Kaunas and Tallinn Airports 74
6.3.1 Helsinki Airport 74
6.3.2 Riga Airport 74
6.3.3 Kaunas Airport 76
6.3.4 Tallin Airport 76
6.4 Bus Road Show 77
6.1 Executive Summary 79

7 Recommendations 80
7.1 H_2 vehicle testing at Hamburg Airport 80
7.2 H_2 powered winter maintenance equipment testing at Helsinki, Riga, Kaunas and Tallinn Airports 82
7.3 Bus Road Show 84

1 INTRODUCTION

This report is one of a series produced by BSR HyAirport WP1.4 Airport Equipment and WP2.3 Airport Equipment summarising the Ground Handling Equipment and Airport Maintenance Equipment demonstrations at the following airports:

- Hamburg (Germany)
- Helsinki (Finland)
- Riga (Latvia)
- Kaunas (Lithuania)
- Tallinn (Estonia)

The hydrogen-powered vehicle demonstrations were implemented as the practical pilot phase following the initial feasibility study work conducted under **BSR HyAirport Airport Equipment Work Package 1.4**. The pilots form part of **BSR HyAirport Airport Equipment Work Package 2.3,** focusing on the real-world validation of hydrogen-powered airport equipment in an operational airport environment.

The demonstrations were carried out within the EU Interreg Baltic Sea Region funded BSR HyAirport project and represented the continuation from conceptual and regulatory analysis into hands-on operational testing in an airport environment.

The outcome of the equipment demonstrations is described in this report under the following topics:

- Scope
- Operational Data (Qualitative)
- Technical Data (Quantitative)
- Economic data summary
- Conclusions
- Recommendations

2 SCOPE

The objective of the equipment demonstrations at each airport are described below. At the airports Helsinki, Riga, Kaunas, Tallinn and Hamburg, the following vehicles were tested:

Airport	**Vehicle tested**
Hamburg Airport (Germany)	– Retrofitted Mulag 4CNG baggage truck with H2 rotary engine
Helsinki Airport (Finland)	– Hyzon HyMax 250 fuel cell truck modified for snow cleaning operations
Riga Airport (Latvia)	– Mulag Fuel Cell baggage truck – Hyzon HyMax 250 fuel cell truck modified for snow cleaning operations

Kaunas Airport (Lithuania)	– Hyzon HyMax 250 fuel cell truck modified for snow cleaning operations
Tallinn Airport (Estonia)	– Hyzon HyMax 250 fuel cell truck modified for snow cleaning operations

2.1 H_2 GROUND SUPPORT EQUIPMENT TESTING AT HAMBURG AIRPORT

Objectives

The objective of the demonstration at Hamburg Airport was to evaluate the technical, operational, and economic feasibility of retrofitting existing conventional ground support equipment with a hydrogen-based internal combustion engine (H_2-ICE) hybrid system. The project focused on converting a conventional compressed natural gas (CNG) powered MULAG baggage tractor into a hydrogen-powered hybrid vehicle and assessing its performance under real operational airport conditions.

Specifically, the demonstration pursued the following objectives:

- Gather knowledge regarding the general feasibility and usability of implementing an H_2-ICE retrofit into an existing MULAG CNG 4 vehicle, particularly under real airport operating conditions.
- Measure the gaseous hydrogen (GH_2) consumption of the retrofitted vehicle and understand consumption patterns during practical use as well as under defined test scenarios.
- Support the manufacturer (HTM Hydro Technology Motors GmbH (HTM)) in collecting real-life operational data, enabling iterative optimisation and further development of the hydrogen powertrain system.
- Perform a Total Cost of Ownership (TCO) analysis in order to evaluate the economic viability of such retrofit solutions for future fleet decisions.
- Analyse the overall cradle to cradle emissions differences between a newly build equipment and the retrofit solution

Beyond these core objectives, the project aimed to generate a comprehensive data basis covering operational performance, technical reliability, emissions behaviour, and user acceptance. The collected data contributes to assessing whether hydrogen-based retrofit solutions can represent a viable transition technology towards low-emission ground handling operations.

The operational testing phase was conducted over a period from May 2025 to April 2026, during which the vehicle was deployed in regular airport operations as well as in dedicated test scenarios. The demonstration vehicle consisted of a retrofitted MULAG 4 CNG baggage tractor, which was converted from its original natural gas configuration to a hydrogen-powered drivetrain. The retrofit included the replacement of the conventional CNG system with a hydrogen-based hybrid propulsion system developed by HTM. The overall vehicle architecture retained core mechanical components such as chassis, transmission, and axles, while introducing a new hydrogen energy system to replace the CNG ICE.

The new hydrogen propulsion system is characterised by:

- A hydrogen-fuelled rotary engine internal combustion engine (H_2-ICE)
- A parallel electric motor forming a hybrid drivetrain with an LTO battery (3,2 kWh nominal energy capacity)
- Integrated hydrogen storage tanks with a nominal pressure level of up to 350 bar
- An energy management system enabling energy recuperation and hybrid operation

This hybrid architecture allows the combustion engine to operate within a more stable and efficient load range, while the electric motor compensates for dynamic load peaks and improves overall efficiency and drivability.

The demonstration combined real operational deployment with structured technical testing in order to enable both qualitative and quantitative evaluation of the system.

The main activities included real-life operations and dedicated testing conditions. The vehicle was integrated into regular airport ground handling processes, replacing a conventional baggage tractor in daily use. This allowed assessment of usability, reliability, and operational suitability under realistic working conditions. Additional tests were conducted using predefined weights and standardised scenarios. These tests enabled direct comparison with conventional CNG vehicles and provided reproducible performance data (e.g. acceleration, torque behaviour, and consumption). This dual approach ensured that both operational experience and scientifically comparable performance data were collected.

To enable the demonstration, a temporary hydrogen refuelling infrastructure was installed on-site. The refuelling concept was delivered by RyzePower (today FPS.Energy GmbH) and consisted of a mobile hydrogen refuelling station fed by a hydrogen trailer with approximately 300 kg capacity at 300 bar pressure level. The refuelling was based on overflow mechanics (pressure equalisation between trailer and vehicle tank). The chosen setup was designed as a flexible and temporary solution suitable for pilot operations. It allowed refuelling without additional compression infrastructure but also introduced limitations in achievable tank filling levels due to decreasing trailer pressure over time.

Demonstration Period

- May – Nov 2025

Demonstration Vehicle

- Retrofitted MULAG 4CNG
- H_2-ICE hybrid (rotary engine with parallel electric motor)

Section	Parameter	Value
Basic chassis data	Manufacturer	Mulag Fahrzeugwerk Heinz Wössner GmbH u. Co. KG
	Model	Comet 4CNG
	Vehicle type	Baggage Towing Tractor
	Cab type	Closed
Dimensions	Wheelbase, mm	1787,5 mm
	Length, mm	3600 mm
	Width, mm	935 mm
	Height, mm	2100 mm

Weights	Actual mass, kg	4500 kg
	Permissible max laden mass, kg	11 500 kg
	Permissible max laden mass of the combination, kg	11 500 kg
	Permissible max laden mass of the semi-trailer, kg	11 500 kg
	Maximum speed, km/h	30 km/h
Powertrain	H_2 Engine Power, kW	
	Parallel electric engine Power, kW	40 kW (at max. turning speed) 38 kW Peak
Hydrogen storage	Tank pressure, bar	350
	Tank type	3
	Hydrogen storage size, kg	9 kg
	Refuelling connection type	H35
Battery	LTO battery voltage, V	80 V
	Capacity – nominal Energy	3,2 kWh
Suspension	Front	leaf springs
	Rear	leaf springs

TABLE 1:
Baggage tractor retrofit technical specifications



FIGURE 1:
Retrofitted baggage tractor

Demonstration Activities

- Real life operations, replacing a conventional vehicle/machine
- Additional fixed testing with dedicated loads to pull

Refuelling Facility

- Temporary small H2-refuelling Station (overflow) by RyzePower
- 300 kg 300-350 bar Hydrogen trailer

2.2 H_2 FUEL CELL BAGGAGE TRACTOR TESTING IN RIGA AIRPORT

Objectives

- Gain practical experience on hydrogen powered vehicles in an airport environment
- Gain practical experience on hydrogen fuel cell vehicles
- Cold start testing for the H2 fuel cell (after cold temperatures)
- Measure GH2 consumption in operations and estimate overall demand in future
- Learn how refuelling and hydrogen storage/logistics work in practice
- Evaluate safety, usability, reliability and user experience of hydrogen usage and GH2 vehicles
- Spread general knowledge on hydrogen among staff
- Gain positive sustainability publicity

Demonstration Period

- 17-31 March 2026

Demonstration Vehicle

- MULAG Comet 4FC H2 powered fuel cell baggage tractor (see table 1 and figure 2)

Demonstration Activities

Section	Parameter	Value
Basic chassis data	Manufacturer	Mulag Fahrzeugwerk Heinz Wössner GmbH u. Co. KG
	Model	Comet 4FC
	Vehicle type	Baggage Towing Tractor
	Cab type	Closed
	Axle configuration	Sturdy brake steering / leaf springs / shock absorbers
Dimensions	Wheelbase, mm	1870 mm
	Length, mm	3740 mm
	Width, mm	1320 mm
	Height, mm	1050 mm
	Distance from front end to coupling device, mm	3907 mm
Weights	Actual mass, kg	4250 kg
	Permissible max laden mass, kg	11 500 kg
	Permissible max laden mass of the combination, kg	11 500 kg
	Permissible max laden mass of the semi-trailer, kg	11 500 kg
	Maximum speed, km/h	30 km/h
Powertrain	Fuel cell power, kW	9 kW Fuel Cell Only
	HV battery voltage, V	80 V (REMA 320 A battery plug)
	Refuelling connection type	H35
	Traction motor net power, kW	70 kW for 5 seconds 35 kW for 300 seconds

Hydrogen storage	Tank pressure, bar	350
	Tank type	4
	Hydrogen storage size, kg	1,8 kg
Suspension	Front	leaf springs
	Rear	leaf springs
Tires	1st axle	195/75 R16 C, pressure 5,5 bar (80 psi)
	2nd axle	195/75 R16 C, pressure 5,5 bar (80 psi)

TABLE 2:
MULAG Comet 4FC technical specifications



FIGURE 2:
Pilot vehicle MULAG Comet 4FC

- Hydrogen powered ground support equipment testing in regular operational settings mainly for transportation of cargo and baggage to and from aircraft.

Refuelling Facilities

- Temporary small H2-refuelling Station (overflow) by HySol SIA (Latvia).
- 4 Hydrogen cylinder bundles of 9 kg with 200 bar pressure, but total hydrogen consumption was 7.507 kg of H2. Average hydrogen consumption rate (kg per motor hour): 0,44 kg/h.

2.3 H_2 POWERED WINTER MAINTENANCE EQUIPMENT TESTING AT HELSINKI, RIGA, KAUNAS AND TALLINN AIRPORTS

Objectives

- Gain practical experience on hydrogen powered fuel cell vehicles in airport environment
- Harsh weather/ winter testing
- Measure GH2 consumption in operations and estimate overall demand in future
- Learn how refuelling and hydrogen storage/logistics work in practice
- Evaluate safety, usability, reliability and user experience of hydrogen usage and GH2 vehicles
- Spread general knowledge on hydrogen among staff
- Gain positive sustainability publicity

Demonstration Period

- Helsinki, 12 January - 30 January 2026
- Riga, 16 February - 6 March 2026
- Kaunas, 9 March - 13 March 2026
- Tallinn, 16 March 2026

Demonstration Vehicle

- Hyzon HyMax 250 fuel cell truck (see table 1 and picture 1) modified for snow clearing operations
    - Modifications / equipment
        - front plough with hydraulics and controls
        - controls for sweeper-blower
        - extra weights for increased traction on rear axle
        - equipped with airport vehicle identification number on the exterior
        - equipped with orange beacon on the roof
- Towable snow sweeper-blower Vammas SB3600H (see table 2)

Section	Parameter	Value
Basic chassis data	Manufacturer	DAF
	Model	CF
	Vehicle type	Tractor unit
	Cab type	Day cab
	Axle configuration	4x2
Dimensions	Wheelbase, mm	4000
	Length, mm	6360
	Width, mm	2550
	Height, mm	3955
	Distance from front end to coupling device, mm	4900

Weights	Actual mass, kg	9510
	Permissible max laden mass, kg	20500
	Permissible max laden mass of the combination, kg	40000 (44000)
	Permissible max laden mass of the semi-trailer, kg	30490
	Maximum speed, km/h	85
Powertrain	Fuel cell power, kW	120
	HV battery voltage, V	700
	HV battery voltage and capacity, kWh	140
	Charging connection type	CCS / Type 2
	Traction motor net power, kW	248
	Traction motor torque, Nm	3410
Hydrogen storage	Tank pressure, bar	350
	Tank type	Type 4
	Hydrogen storage size, kg	39
Suspension	Front	Leaf
	Rear	Air (Wabco)
Tires	1st axle	315/70 R22.5 (single tire)
	2nd axle	315/70 R22.5 (twin tires)

TABLE 3:
Hyzon HyMax 250 technical specifications

Parameter	Value
Maximum working and transportation speed	60 km/h
Working width, broom-axle angle 30°	3,6 m
Sweeping capacity	216 000 m²/h
Broom-axle angles	± 30-40°
Temperature range	-35 ...+40 °C
Length in working position	10,88 m
Width in working position	4,46 m
Width in transportation position	2,55 m
Height in transportation position	2,62 m
Weight	10 000 kg
Wheel base	7,62 m

TABLE 4:
Vammas SB3600H technical specifications



FIGURE 3:
Tested Hyzon truck with towable sweeper-blower.

Demonstration Activities

- Hydrogen powered maintenance vehicle - a hydrogen truck with a snowplough and a towable sweeper-blower – testing in live operational settings as part of the normal airport winter maintenance fleet.

Refuelling Facilities

- Several procedures were used to refuel the hydrogen vehicle at pilot airports. Descriptions are presented in the following chapters individually for each airport.

2.4 BUS ROAD SHOW

INTRODUCTION, MOTIVATION AND GENERAL OBJECTIVES

The BSR HyAirport project participated in the 4th Nordic Bus Roadshow organised under the JIVE 2 project with piloting of fuel cell bus operations at Helsinki Airport and Växjö Smaland Airport. Aligned with the objectives of previous roadshows, this initiative aimed to promote hydrogen mobility, educate residents about the technology, and bring together a wide range of stakeholders including local authorities, transport operators, politicians, academics, and representatives from industry. The JIVE 2 Nordic bus roadshow took place in Sweden and Finland during the spring and summer of 2025.



The aim of the 4th roadshow was to build on the momentum gained from the previous events across other regions where the deployment of fuel cell buses is still limited to give interested cities the opportunity to experience and test fuel cell technology with the perspective of stimulating future sector-related announcements. In addition, a key aim was to identify potential use cases for hydrogen buses, and several cities in this roadshow operated the demonstration bus in airport applications.

The roadshow included a total of 15 events, including national workshops, student events, professional workshops, media events and test trials that were attended by over 1,000 participants. The different events reached out to a wide range of stakeholders, including government representatives, public transport operators and local authorities, students, and members of the academic world and industry, thus ensuring that the roadshow had the largest possible impact. In addition to this, communication strategies involving different media types were developed, allowing the dissemination of knowledge and increased public awareness about hydrogen in transport. Extensive media coverage and social media presence allowed the roadshow to reach an audience of approximately 70,000 people. It has also helped to reduce preconceived ideas around the safety and environmental performance of hydrogen buses.

OBJECTIVES FOR AIRPORT OPERATIONS

The Bus Roadshow was organised to demonstrate hydrogen fuel cell vehicle technology in real operational environments and to increase awareness of hydrogen-powered mobility among public authorities, transport operators, airports and other stakeholders. The activity provided an opportunity to evaluate both the technical performance of hydrogen-powered passenger transport and the practical requirements related to hydrogen logistics, refuelling and operations.

For Helsinki Airport, the primary objective was to assess the suitability of hydrogen-powered passenger transport in an airport environment and to gain practical experience of integrating hydrogen-powered vehicles into airside operations. The demonstration also supported the wider objectives of the BSR HyAirport project by increasing stakeholder awareness and providing practical evidence of hydrogen mobility applications beyond conventional road transport.

DEMONSTRATION ACTIVITIES

The demonstration included operation of a hydrogen fuel cell bus in Finland during May 2025. At Helsinki Airport the vehicle was used in airside passenger transport operations between aircraft stands and terminal facilities.



FIGURE 4:
The pilot vehicle H2.City Gold, co-branded by CaetanoBus and Toyota

The demonstration enabled assessment of hydrogen fuel cell vehicle performance in airport operations, passenger transport suitability in airside conditions and general user acceptance among drivers and airport stakeholders.

STRATEGIC IMPORTANCE

The Helsinki Airport demonstration represented a particularly significant milestone as it marked the first known use of a hydrogen-powered vehicle in Nordic airside passenger transport operations. The demonstration extended hydrogen mobility from conventional public transport applications into a highly regulated airport environment where operational reliability, safety and availability requirements are especially demanding.

3 OPERATIONAL DATA (QUALITATIVE)

OVERALL QUALITATIVE INFORMATION ON HYDROGEN EQUIPMENT TESTING

Chapter 3 summarises the qualitative operational experience gained during the hydrogen equipment demonstrations conducted at Hamburg, Helsinki, Riga, Kaunas and Tallinn Airports. While the individual pilots differed in vehicle type, duration, climatic conditions and operational application, they shared a common objective: to assess how hydrogen-powered airport equipment can be introduced into real airport operations safely, reliably and with acceptable impact on daily procedures.

Across the demonstrations, the first operational learning was that hydrogen pilots at airports require structured internal preparation, even where no separate civil aviation authority permit is necessary for the vehicle test itself. All airports implemented internal assessment and approval processes before operation. These processes typically included safety management reviews, site-specific risk assessments, definition of operating boundaries, training requirements and coordination with rescue or fire safety functions. In Hamburg, the temporary hydrogen refuelling infrastructure required a formal approval process due to its stationary installation and proximity to existing fuel infrastructure, while the other airports primarily managed the pilots through internal safety management processes and temporary operating arrangements.

Hydrogen-specific risk management was a central element in all pilots. The main risk topics were related to hydrogen storage, refuelling, leak prevention, ignition source control, indoor parking restrictions and emergency preparedness. As a common mitigation measure, refuelling was carried out outdoors and in designated areas using mobile or temporary hydrogen supply solutions. Airports also applied restrictions on indoor storage or indoor operation where hydrogen was present in the vehicle tanks, particularly during the early stages of testing or where existing facilities were not equipped with hydrogen detection and ventilation systems. Operators, maintenance personnel and relevant airport staff received targeted instruction on hydrogen safety, refuelling procedures, vehicle-specific functions and emergency behaviour. In several pilots, refuelling and technical maintenance were performed or supported by external specialists, reflecting the prototype character of the equipment and the limited operational experience with hydrogen systems at airports. This external support reduced operational risk and helped build confidence among airport personnel.

From an operational perspective, the hydrogen vehicles were generally able to perform the intended airport tasks in a manner comparable to conventional or battery-electric alternatives. The Hamburg pilot demonstrated the integration of a retrofitted hydrogen combustion hybrid baggage tractor into ground handling processes, while Riga tested a fuel cell baggage tractor in cargo and baggage transport. The winter maintenance demonstrations in Helsinki, Riga, Kaunas and Tallinn assessed hydrogen fuel cell truck operation under cold-weather and airfield maintenance conditions. The Bus Road Show further demonstrated the potential use of hydrogen fuel cell technology for airport passenger transport applications.

Drivers generally highlighted smooth drivability, immediate power availability and sufficient performance for the intended tasks. In several cases, the driving experience was described as similar to electric vehicles, particularly for fuel cell systems. At the same time, the demonstrations also

revealed practical limitations, including refuelling duration, infrastructure availability, vehicle-specific integration issues, spatial constraints, and the need for clear procedures for parking, refuelling and maintenance. These limitations were not considered fundamental barriers, but they underline the importance of infrastructure planning, staff training and technology maturity for future deployment.

No hydrogen-related emergency situations requiring intervention by rescue services were reported in the pilots described in this chapter. This indicates that, under controlled conditions and with appropriate organisational and technical safeguards, hydrogen-powered airport equipment can be tested safely in operational airport environments. However, the pilots also showed that hydrogen applications must be treated as integrated operational systems rather than isolated vehicles: the vehicle, refuelling infrastructure, site layout, personnel competence, maintenance concept and emergency preparedness all need to be considered together.

3.1 H_2 GROUND SUPPORT EQUIPMENT TESTING IN HAMBURG AIRPORT

PERMITS AND APPROVALS FROM AUTHORITIES

The installation and operation of the hydrogen infrastructure required a formal approval process. The temporary hydrogen refuelling station was approved via a building permit procedure in accordance with the Hamburg Building Code, supported by a comprehensive set of technical and safety documentation, which took around 6 months until the final approvals were given. The regulatory framework was primarily based on the German Operational Safety Ordinance (BetrSichV), as the stored hydrogen quantity was below 3 tonnes. As this installation was not permanent but temporary, the permit is valid for 3 years and needs to be renewed if the usage would exceed this timeframe. A fixed and permanent installation most probably would have taken longer time to permit due to the higher complexity and requirements.

The approval process included the preparation and submission of multiple documents, such as:

- Site and layout plans
- Explosion protection and fire safety concepts
- Hazard and risk assessments
- Technical documentation and system descriptions
- Emergency response and safety planning documents

Additionally, due to the proximity to the kerosene storage facility, specific approval from the airport fuel storage operator (AFS) was required, supported by dispersion and explosion analyses (see below).

HYDROGEN-SPECIFIC SAFETY MEASURES AND RISK MANAGEMENT

A comprehensive safety framework was developed for the hydrogen infrastructure and vehicle operation. This included:

- Explosion protection documentation defining hazardous zones and safety distances
- Detailed hazard assessments/risk assessment covering mechanical, electrical, fire and explosion risks
- Dispersion and explosion modelling to evaluate worst-case scenarios
- Fire protection, lightning protection, and emergency response concepts

The safety documentation ensured that all regulatory requirements were met and that risks associated with hydrogen handling were mitigated to an acceptable level. Based on the outcomes from the safety assessment work instructions for the safe use of vehicle and infrastructure have been created. It was for example important, that the flow rate of hydrogen at the fuelling station could not be changed and stayed at the preset value of 10g/s, therefore a Box was built around the Needle valve (compare Figure 10). While refuelling, safety gloves, glasses and non-static clothes were needed to be worn. Prior to each refuelling a leak test on the systems connections had to be done and no electric devices should be used in close proximity of the refuelling station.

TRAINING

Hydrogen-specific training and structured instruction measures were implemented for all relevant personnel involved in the project. Vehicle operators received dedicated training covering the safe handling of hydrogen as well as the operation of high-voltage systems integrated into the hybrid drivetrain. The safety functions of the Vehicle like H2 detection, safety algorithms and behaviour in case of emergency were told and trained. In addition, airport staff participating in operational processes were instructed in the procedures for hydrogen refuelling and the associated safety requirements. Further training measures included the familiarisation of fire brigades and technical personnel with the hydrogen installation, its functional principles, and the applicable emergency procedures in case of incidents. From an organisational perspective, refuelling operations were formally restricted to trained personnel from the infrastructure provider. Nevertheless, airport employees also received practical operational instruction to ensure smooth integration of the refuelling process into daily airport operations and learning effects.

TEMPORARY REFUELLING STATION

For the execution of the test, the provision of a suitable refuelling infrastructure was required. The existing hydrogen infrastructure at the Shell station “Weg beim Jäger” on the landside could not be used, as no permit was available for the use of the baggage tractor on public roads and the station was not designed for the tank size of the vehicle.

After reviewing various options for refuelling solutions and system capacities, an “all-in-one” concept from Ryze Power (today FPS Energy) was selected, which included both the dispenser and the hydrogen supply via a 300 kg trailer. This solution is relatively simple in design and well suited for a temporary test operation. Refuelling is carried out exclusively based on the pressure differential between the trailer and the vehicle tank. One advantage of this approach is that no additional compressor is required, and therefore no electrical connection is needed. However, a disadvantage is that the vehicle tank cannot be completely filled, as the pressure level in the trailer decreases with each refuelling process, thereby reducing the maximum achievable pressure level. The dispenser station was controlled entirely pneumatically, meaning that no electrical connections were required. The control pressure needed to open the valves was provided by nitrogen. For this purpose, a 200 bar nitrogen cylinder with pressure reduction to approximately 10 bar served as the pressure source. By applying pressure to the distribution panel, the valves in the storage container were actuated, causing the safety valves to open and allowing hydrogen to be released. This function also served as an emergency shutdown feature in the event of a malfunction or hazardous situation. The system could be depressurised via emergency stop switches by venting the nitrogen, which caused the safety valves to close automatically.

For the test period, an area next to the existing CNG filling station was initially selected, as hydrogen refuelling stations had already been operated at this location (2010-2015) in previous years and the necessary approvals were available. However, during the detailed assessment it became clear that this site was not suitable due to its proximity to a public road and the additional safety

distance requirements associated with the trailer. This was particularly relevant for the adjacent traffic area and the turning area for internally used articulated buses. In addition, it would have been necessary to arrange for the temporary closure of a lane of the public bypass road. (compare Figure 5)

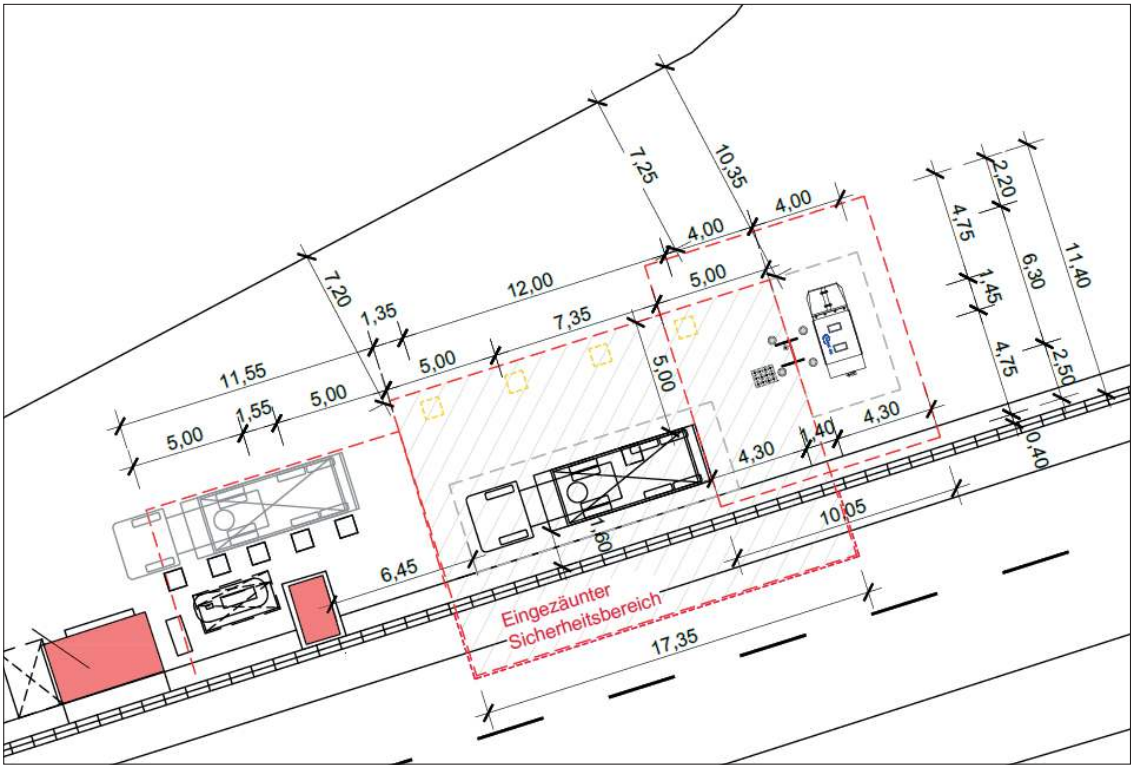

FIGURE 5:
Layout for first location placement idea

The final site selected for the installation was therefore an area at the end of the turning circle near the kerosene storage facility, which had previously been used as a parking area for Cobus vehicles. For the duration of the test, these vehicles had to be relocated to alternative parking locations. Approval for the installation required the submission of a building permit application, including all necessary documentation. As part of the approval process, a lightning protection concept, a fire protection concept, a fire brigade plan, and various risk assessments were developed. In addition, due to the proximity to the kerosene storage facility, approval from the fuelling service provider and owner of the kerosene storage facility AFS (Aviation Fuelling Services) was required, for which supplementary dispersion and explosion analyses were carried out. The images below (Figure 6 and Figure 7) show the placing and spacing of the equipment as filed in the permit. It shows the parking location of the hydrogen trailer, location of the fuelling dispenser and the fuelling spot for the hydrogen retrofit Mulag, as well as the safety zones around the applications.

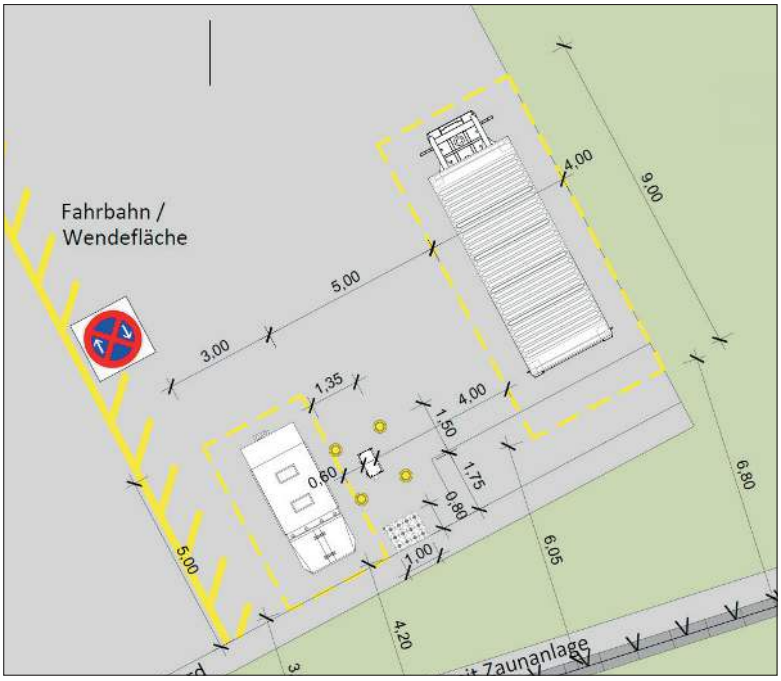

FIGURE 6:
Final placement layout

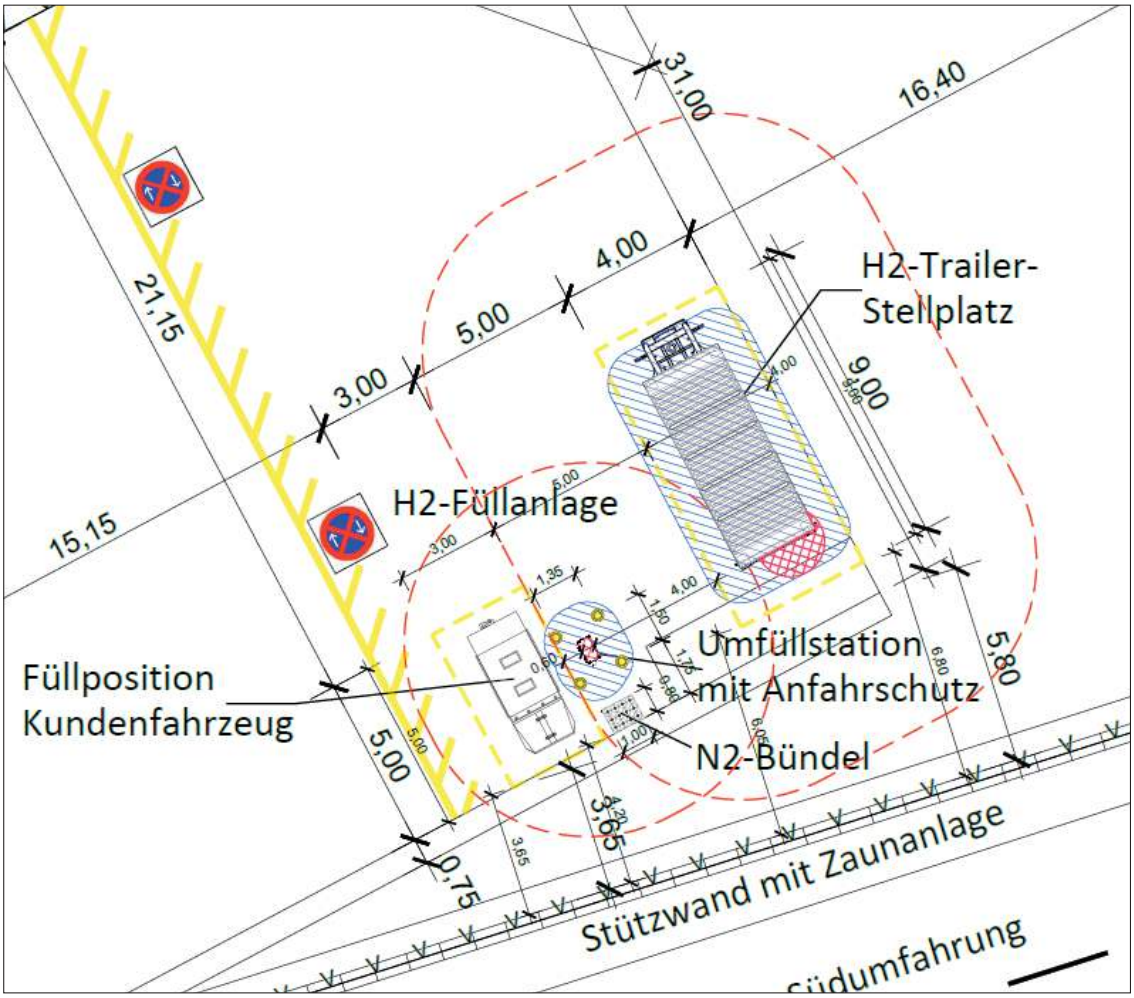

FIGURE 7:
Safety Zone layout for refuelling infrastructure placement

The existing yellow marking of the bus parking area indicated a boundary for turning buses and other cars not to enter the explosion protection zone of the refuelling station, which is in place while refuelling. In Figure 8 below, the physical barrier ensures that any vehicle will not enter the permanent explosion safety area of the trailer. This represented a key boundary condition in the planning of the installation site. The approved safety distances particularly included a clearance radius of five metres around the trailer, within which neither external vehicles could be parked nor any movements were permitted, as well as a radius of four metres around the filling unit. In these areas, the presence of any potential ignition sources was strictly prohibited.



FIGURE 8:
Final hydrogen fuelling installation

Due to the potential risk of a hydrogen jet release or the ignition of an explosive mixture, as well as the resulting interactions with the nearby kerosene storage facility, corresponding dispersion and hazard calculations were carried out. Based on the results obtained (Figure 9) the company AFS, which operates and owns the kerosene storage and facility, approved the construction and operation of the temporary mobile refuelling station. The use of the system required compliance

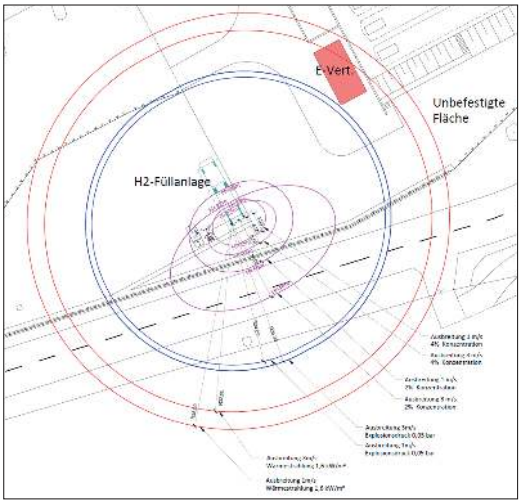

FIGURE 9:
Incident Analysis - Heat radiation radius and pressure radius

with defined safety measures and the wearing of appropriate personal protective equipment. The necessary instructions were displayed on the valve panel and formed part of the approval-relevant safety requirements, including the mandatory use of gloves, safety goggles, and antistatic clothing, as well as the prohibition of open flames and mobile phone use within the explosion risk area. (Figure 10 and Figure 11)



FIGURE 10:
Hydrogen Dispenser station with safety requirements - Front



FIGURE 11:
Hydrogen Dispenser station with safety requirements - Side

In addition, a hazard response plan was mounted on the valve panel. Due to the temporary and mobile nature of the installation, daily leak checks prior to the usage of the equipment were required. These were carried out by internal Hamburg Airport personnel using both a handheld hydrogen detector and leak detection spray to identify potential leaks.

OPERATIONAL RESTRICTIONS AND LIMITATIONS

Due to the use of hydrogen as an energy carrier and the temporary nature of the refuelling infrastructure, a number of operational restrictions were defined and implemented to ensure safe and compliant operation within the airport environment.

A key aspect was the establishment of clearly defined safety and exclusion zones around the hydrogen refuelling station. These zones were based on approved safety distances and included restricted areas around the hydrogen trailer and dispensing unit that can be seen in Figure 7. On

all sides of the trailer, a safety clearance of five meters had to be maintained at all times. Within these areas, no unauthorised access, vehicle movements, or parking were permitted. In addition, the presence of potential ignition sources was strictly prohibited, and appropriate markings and physical barriers ensured compliance with these requirements.

Regarding vehicle operation, initial restrictions were implemented for indoor parking. During the early stages of the demonstration, the hydrogen-powered vehicle was primarily stored and operated in outdoor areas to minimise risks associated with potential hydrogen leaks. Only after a stable and incident-free operation over an extended period were these restrictions gradually relaxed, allowing limited indoor use under controlled conditions, as the infrastructure was not equipped with hydrogen sensors or respective safety features.

Additional procedural constraints included the requirement for trained and certified personnel for the refuelling process and the supervision of hydrogen deliveries. Refuelling activities were carried out exclusively in the designated area and in accordance with defined safety procedures, including the use of personal protective equipment and adherence to operational guidelines.

Overall, these operational restrictions were essential to ensure safe integration of the hydrogen-powered system into the airport environment while maintaining compliance with regulatory requirements and minimising risks to personnel and infrastructure but did not affect the daily business at all.

MAINTENANCE – PLANNED AND UNPLANNED

Maintenance activities during the demonstration reflected the prototype character of the retrofitted hydrogen vehicle and the associated system components. In the initial phase of operation, commissioning and optimisation activities were carried out in close cooperation with the system developer (HTM), including on-site support to ensure stable integration of the hydrogen powertrain into the existing vehicle platform.

Planned maintenance was limited and mainly consisted of routine inspections and system checks required for safe operation. These included regular visual inspections of the hydrogen system, monitoring of key components, and periodic leak checks using handheld hydrogen detectors and appropriate testing equipment. In addition, predefined inspection procedures were implemented for the temporary refuelling infrastructure to ensure continued compliance with safety and operational requirements. These inspections included leak checks, visual inspection of system components, pressure checks for slow leakage detection and functionality as well as controlling if the fuelling station has been transferred into a safe state after usage.

Unplanned maintenance occurred intermittently during the test period, as is typical for prototype systems undergoing real-life operational testing. Several technical adjustments and corrective interventions were necessary, particularly in auxiliary subsystems. These included modifications to the cooling system and the resolution of issues related to the battery system. In some cases, external partners were involved to provide technical expertise and implement solutions in a timely manner.

Furthermore, failures of peripheral components occasionally led to temporary interruptions in operation. For example, a defect in the coupling system required modifications to the drivetrain, resulting in an extended downtime. While testing, no failure or defect from the engine itself occurred, which proves the robustness of the engine itself. Anytime a problem occurred, the safety measures like sensors, thresholds and other safety algorithms worked perfectly and the vehicle was set into a safe condition. Such incidents highlighted the complexity of integrating new hy-

drogen-based propulsion technologies into existing vehicle platforms and the associated need for iterative development and system optimisation. Responsibilities for maintenance were clearly defined. While airport staff were primarily responsible for daily operational checks, visual inspections, and basic safety-related measures, more complex maintenance tasks and system modifications were carried out by the vehicle manufacturer and specialised partners. This collaborative approach ensured that technical issues could be addressed effectively while maintaining safe operation throughout the demonstration.

Overall, the maintenance experience demonstrated that prototype hydrogen systems require increased technical oversight and close coordination between operators and manufacturers. At the same time, the results provided valuable insights into reliability, typical failure modes, and optimisation requirements for future large-scale deployment. Throughout the entire testing period, no leakages occurred either on the vehicle or at the fuelling station.

EMERGENCY RESPONSE AND INCIDENTS

Emergency procedures for hydrogen-related incidents were predefined in the Rescue Plan, including coordination with airport rescue services. No emergency situations requiring intervention by rescue services occurred during the pilot.

OPERATOR EXPERIENCE

During the initial phase of operation, specific training and the assignment of selected, dedicated drivers proved essential. This approach ensured consistent vehicle usage and enabled operators to become familiar with the new drivetrain characteristics and safety requirements. Over time, this contributed to a stable operational routine and reliable system usage.

Overall, the handling and driving characteristics of the retrofitted vehicle were assessed positively through testing and interviewing the drivers. Operators reported that the vehicle exhibited behaviour comparable to conventional MULAG baggage tractors, allowing it to be integrated into existing workflows without fundamental changes to operational procedures. In particular, the hybrid drivetrain demonstrated favourable performance characteristics, including improved torque behaviour. This was especially noticeable under high load conditions, where the vehicle provided strong pulling power and responsive acceleration. At the same time, certain limitations affecting operator acceptance were identified. A key point of feedback concerned the increased noise level of the hydrogen-powered system compared to the CNG reference vehicles. This was perceived as disadvantageous by operators and highlighted the need for further optimisation in terms of acoustic performance.

From an operational perspective, the use of the vehicle across different application areas including baggage handling, cargo operations, and varying load scenarios demonstrated its versatility. The fact that the vehicle could be used in a manner largely equivalent to conventional equipment contributed positively to user acceptance and reduced barriers to integration into daily operations. Furthermore, the experience showed that continuous technical support and close coordination with the manufacturer were important factors for maintaining operator confidence, particularly during early-stage prototype operation. The presence of knowledgeable contacts and the ability to resolve issues quickly contributed significantly to the overall positive perception of the system.

In summary, operator feedback indicates that hydrogen-based retrofit solutions can achieve a high level of acceptance if they provide comparable or improved performance to conventional systems. However, aspects such as noise emissions, system maturity, and reliability remain critical factors influencing long-term user acceptance and should be further addressed in future development stages.

3.2 H_2 FUEL CELL BAGGAGE TRACTOR TESTING IN RIGA AIRPORT

PERMITS AND APPROVALS FROM AUTHORITIES

There was no formal permitting from the Civil Aviation Agency (CAA) or other authorities necessary. No state or municipal permits were needed for handling the goods on site. The transportation of H2 was procured by external experts.

The authorities were informed of the temporary nature of the demonstration and the defined operational boundaries. The pilot complied with existing Latvian state legislation and standards related to hydrogen handling and fire safety.

HYDROGEN-SPECIFIC SAFETY MEASURES AND RISK MANAGEMENT

Risk assessments and safety cases

The pilot was implemented under Riga Airport's formal Safety Management System (SMS) and internal approval process. A comprehensive hydrogen-related risk management framework was implemented prior to the pilot.

TRAINING

Hydrogen-related training for vehicle operators was delivered by:

- **MULAG** Fahrzeugwerk Heinz Wössner GmbH u. Co. KG (hydrogen vehicle supplier).
- **Globe Fuel Cell Systems** GmbH (hydrogen fuel cell supplier).
- **HySol SIA** on hydrogen refuelling.

TEMPORARY REFUELLING STATION

Location

Hydrogen refuelling was carried out using a temporary, mobile hydrogen refuelling station installed at a designated location in the technical zone (landside).

- Manufacturer: HySol SIA (Latvia)
- Model: HyPanel
- Supplier (to the Riga Airport pilot): HySol SIA (Latvia)
- Hydrogen provider: Hysol Ltd (Latvia) with support from Elme Messer Gaas.

Red dot indicates refuelling station location



FIGURE 12:
The location of the temporary gaseous hydrogen refuelling station at Riga Airport for MULAG Comet 4FC refuelling.

The temporary hydrogen refuelling station was on landside in the Technical zone (see Figure 12). The area is being rebuilt in 2026.

OPERATIONAL ENVIRONMENT AND TEST CONDITIONS

Testing was carried out under cold weather conditions. Ambient temperatures during the pilot ranged from approximately 1,8°C to +11,2 °C, but freezing, subzero temperatures during night time. These conditions allowed evaluation of cold start and ground handling (including cargo transportation) operations.

The vehicle was used as standard airport ground support equipment.

OPERATIONAL RESTRICTIONS AND LIMITATIONS

The hydrogen-powered tractor was piloted in normal apron operations, specifically in airside cargo and baggage transportation tasks.

However, defined limitations included:

- The vehicle could not get into the baggage sorting area as the gates were too low for the vehicle height.
- Indoor storage of the vehicle was prohibited whenever hydrogen was present in the onboard tanks, due to fire safety considerations.

Apart from these constraints, the truck was used operationally in a manner comparable to conventional baggage tractors at the apron.

MAINTENANCE – PLANNED AND UNPLANNED

There were no technical issues during the pilot and no maintenance for the vehicle was necessary. However, the refuelling station was maintained regularly within refuelling service contract with external service provider (HySol Ltd.).

EMERGENCY RESPONSE AND INCIDENTS

Emergency procedures were not changed for the testing and the procedure for response was predefined in the Rescue Plan, including coordination with airport rescue/firefighting services. No emergency situations requiring intervention by rescue services occurred during the pilot. In icy conditions performance was good and there were no other hazards/extreme weather conditions during testing.

OPERATOR EXPERIENCE

Operator feedback was collected through an evaluation process involving all trained drivers participating in the pilot. Key findings from operator interviews:

- Driving characteristics were rated positively, with strong acceleration and immediate power availability typical of electric drivetrains.
- Work performance was considered fully sufficient and comparable to conventional vehicles and electric alternatives.
- Vehicle stability and handling were described as good and suitable for apron operations.
- Operating comfort was assessed as good; very low noise levels and smooth operation were highlighted.
- Refuelling was done by external specialists, so the tank pressures significantly above 200 bar required relatively long refuelling times with the pilot's mobile refuelling equipment.

Overall operator acceptance was clearly positive, and all interviewed drivers expressed willingness to use the hydrogen-powered truck in future operations.

3.3 H_2 POWERED WINTER MAINTENANCE EQUIPMENT TESTING AT HELSINKI, RIGA, KAUNAS AND TALLINN AIRPORTS

3.3.1 HELSINKI AIRPORT

PERMITS AND APPROVALS FROM AUTHORITIES

The pilot was implemented under Finavia's (internal) formal Safety Management System (SMS) and temporary change approval process. In Finland the classification between minor-scale and large-scale hydrogen operations is determined by the quantity of hydrogen handled or stored and the resulting regulatory authority. For hydrogen inventories exceeding 100 kg but remaining below 2,000 kg, the permitting authority may be either the local Rescue Department (minor-scale operation) or TUKES (large-scale operation), depending on the overall chemical inventory, site conditions, and surrounding operational environment.

Minor-scale operations are regulated by the Rescue Department and focus primarily on emergency preparedness, personnel safety, and the safe management of operational risks through relatively limited documentation requirements. In contrast, large-scale operations fall under the supervision of TUKES and require significantly more comprehensive documentation, including detailed risk assessments, process and chemical safety analyses, explosion protection documentation, consequence modelling, and extensive emergency preparedness arrangements. TUKES permitting places greater emphasis on the technical integrity of the hydrogen system and the management of risks between adjacent operational functions.

A practical implication is that large-scale permitting requires considerably more engineering evidence, safety demonstrations, and technical studies, resulting in a longer and more resource-intensive approval process compared with minor-scale permitting. Since this pilot falls under the category of minor-scale hydrogen operations the preparatory work was carried out in close cooperation with the local permitting authority (external) Keski-Uusimaa Rescue Department, including detailed correspondence during the autumn preceding the pilot.

The approval process (internal and external) included:

- Notification of small-scale industrial handling and storage of hazardous chemicals
- Formal Safety Justification document for the temporary hydrogen refuelling station and hydrogen-powered vehicle.
- Risk identification, assessment and mitigation
- Hydrogen safety data sheet complies with the requirements of Annex II to Regulation (EC) No 1907/2006
- Site-specific Rescue Plan for the hydrogen refuelling point and vehicle operations.
- Hydrogen-specific Explosion Protection Document (ATEX) addressing storage, refuelling and operational use of hydrogen on the apron.

The authorities were informed of the temporary nature (even though it does not change the requirements) of the demonstration and the defined operational boundaries.

The notification, including its appendices, was submitted to the rescue authority approximately two months (one month is required minimum) before the start of the pilot. The rescue authority inspected the pilot's storage arrangements and facilities before the activity began. Supervision fees for decisions and inspections were charged by the authority.

HYDROGEN-SPECIFIC SAFETY MEASURES AND RISK MANAGEMENT

Risk assessments and safety cases

A hydrogen-related risk management framework was implemented prior to the pilot. This included the documents and evaluations mentioned in the previous chapter. As presented in Table 3, the hydrogen truck and refuelling station risk assessment identified the highest initial risks in leak, refuelling, fire, security and indoor operation scenarios. The assessment demonstrates that the planned mitigation measures, including outdoor-only refuelling, controlled storage arrangements, operator training, hydrogen detection, emergency procedures and physical protection of equipment, reduce all identified risks to an acceptable residual level. Overall, the residual risk ratings remain low across all assessed scenarios, indicating that the demonstration can be operated safely when the defined controls and operating procedures are implemented and maintained.

Risk type	Risk description	Likelihood (0-5)	Severity (1-5)	Total risk	Risk control measures	Likelihood (0-5)	Severity (1-5)	Residual risk total
Truck storage (when the vehicle is not in use)	In the event of a hydrogen leak from the truck, gas may accumulate indoors in the upper parts of structures because hydrogen is lighter than air.	2	4	8	Outdoor storage, so that a leak scenario does not create a significant risk.	2	1	2
Hydrogen leak from the truck inside a building	The truck is temporarily driven indoors into facilities without hydrogen detectors. A potential hydrogen leak from the tank and ignition, for example by a spark.	2	4	8	The truck is driven indoors only for essential repairs, such as tyre replacement. If work is carried out on the vehicle that involves a risk of sparks, hydrogen is emptied from the vehicle's tanks before driving it indoors. After emptying, the vehicle can be driven using the battery's electric energy.	1	3	3
Hydrogen leak from the truck outdoors	The truck leaks hydrogen gas and creates a hazard in the immediate surroundings.	1	3	3	The truck is not driven in areas, such as under buildings, where a potential leak could cause significant danger to third parties.	1	2	2
Truck fire scenario	The truck leaks hydrogen gas and creates a hazard if it catches fire.	1	5	5	Driver training on actions to be taken in the event of a fire. The fire will be handled in accordance with the airport rescue unit's firefighting procedures.	1	3	3
Refuelling station, location	The refuelling station contains flammable pressurised hydrogen.	1	3	3	The refuelling station location is selected so that the tank and truck can be refuelled safely, at a sufficient distance from buildings and protected from other traffic. The refuelling station is placed on an aircraft stand so that there are no aircraft or buildings within a 25-metre radius. The refueller/driver has a hydrogen detector attached to their work clothing.	1	1	1
Refuelling station, truck refuelling	A problem or fault during refuelling causing a leak.	2	4	8	Leaking hydrogen rises directly upwards and does not create a hazard unless it ignites. The manufacturer's operating instructions for the refuelling equipment must be followed, and operations must be carried out carefully. Refuelling is permitted outdoors only. The operation of the emergency shut-off must be verified/checked regularly. The refueller/driver has a hydrogen detector attached to their work clothing.	1	3	3
Refuelling station, leak scenario	Leak at the refuelling station.	2	2	4	Any leaking hydrogen rises directly upwards and does not create a hazard unless it ignites. The manufacturer's operating instructions for the refuelling equipment and tanks must be followed, and operations must be carried out carefully. The refuelling station is protected against vehicle collisions with heavy barriers. The refueller/driver has a hydrogen detector attached to their work clothing.	2	1	2
Refuelling station, fire scenario	Fire at the refuelling station.	1	5	5	The area is isolated and an alarm is raised. The fire will be handled in accordance with the airport rescue service's firefighting procedures.	1	4	4
Refuelling station, tank replacement	A leak occurs during replacement of the refuelling station tank.	2	3	6	Only trained personnel participate in replacing and connecting the tank. The airport rescue unit is notified before the replacement.	1	2	2
Weather conditions	Severe frost or thawing/freezing causes failure of the vehicle or refuelling equipment and a potential leak.	1	3	3	The vehicle is not used or refuelled at temperatures below -20 °C. Equipment manufacturers' instructions are followed. After exceptional conditions, such as the temperature falling below -30 °C, the condition/functioning of the equipment is checked before use.	1	2	2

Cybersecurity	Sabotage of the equipment, such as the refuelling equipment, via a network connection.	2	3	6	The refuelling station is not connected to any data network. No one remains in the vicinity of the refuelling station unnecessarily.	1	2	2
Security	Hostile attack against the equipment or intentional damage.	2	4	8	The refuelling station and the hydrogen truck are continuously kept in a security-controlled area. The area has continuous recorded CCTV surveillance. The user training includes a visual inspection of the condition of the equipment.	1	3	3
Users' lack of experience in operating a hydrogen truck	Collision scenario or unintentional release of hydrogen from the tanks.	2	3	6	Use of the hydrogen truck is permitted only for designated employees, all of whom are trained in the use of the vehicles and equipment and provided with information on hydrogen safety. Apron tasks are selected so that there is no elevated collision risk.	1	2	2
Exposure to gases in a leak scenario	The driver is exposed to gas during a leak scenario, in the cab or near it.	1	2	2	The vehicle manufacturer's/owner's instructions are followed. There is no direct connection from the hydrogen tanks to the cab, and any leaking hydrogen rises rapidly upwards. Hydrogen is not toxic when inhaled, but in high concentrations it may displace oxygen in breathing air. Users are trained to identify symptoms of oxygen deficiency, such as headache, confusion and rapid fatigue. The driver has a hydrogen detector attached to their work clothing.	1	1	1

TABLE 5:
Risk assessment and mitigation.

TRAINING

Hydrogen-related training for vehicle operators was delivered by:

- Zerobus (hydrogen truck supplier),
- MP Logistiikka (hydrogen refuelling station supplier), and
- P2X Solutions (hydrogen supplier).

The training covered normal operation, refuelling procedures, safety awareness, and emergency actions specific to hydrogen systems. Only trained and nominated drivers were authorised to operate the hydrogen-powered vehicle during the pilot.

TEMPORARY REFUELLING STATION

Location

As part of the hydrogen pilot implemented at Helsinki Airport, a temporary hydrogen refuelling unit and associated hydrogen storage container were installed close to stand 802 (see picture 2) based on a combined assessment of operational suitability, electrical safety, and risk management considerations. General information on the refuelling station:

- Manufacturer: Fuel Cell Systems Ltd, United Kingdom
- Model: HyQube 350 (350 bar hydrogen vehicle refuelling assembly)
- Supplier (to the Helsinki Airport pilot): MP Logistiikka Ltd, Finland
- Hydrogen provider: P2X Solutions Ltd

The selected location provided direct access to the required electrical infrastructure, enabling a compliant and technically robust grounding solution via the airport's main equipotential bonding system. In addition, the position allowed compliance with the recommended safety distances (30 m) to aircraft, traffic flows, and other critical infrastructure, while remaining close to the operational area where the hydrogen-powered equipment was used. The indicative separation distances used are presented in JIVE document (D4.13: Mobile HRS and MEGC truck operation safety guidelines) and are not based on a single EU regulation but on a risk-based assessment methodology derived from the Seveso III Directive (2012/18/EU), EIGA hydrogen safety guidance (EIGA Doc 15/21 and Doc 75/21), Dutch PGS guidelines and the Dutch Purple Book quantitative risk assessment methodology. The recommended distances in the document were established through consequence modelling of representative hydrogen leak, fire and explosion scenarios and therefore represent risk-based engineering recommendations rather than fixed regulatory requirements.



FIGURE 13:
The location of the temporary gaseous hydrogen refuelling station at Helsinki Airport.

The location (Figure 13) was reviewed and agreed in coordination with airport electrical engineering, safety specialists, and rescue authorities, ensuring that the installation met airport safety standards, hydrogen safety requirements, and regulatory expectations, while minimizing operational disruption during the pilot implementation. The layout of the refuelling station is presented in picture X.

The Hydrogen container was next to the refueler (Figure 15) and connected with a suitable hose. The technical specifications of the refuelling station are described in Table 6.

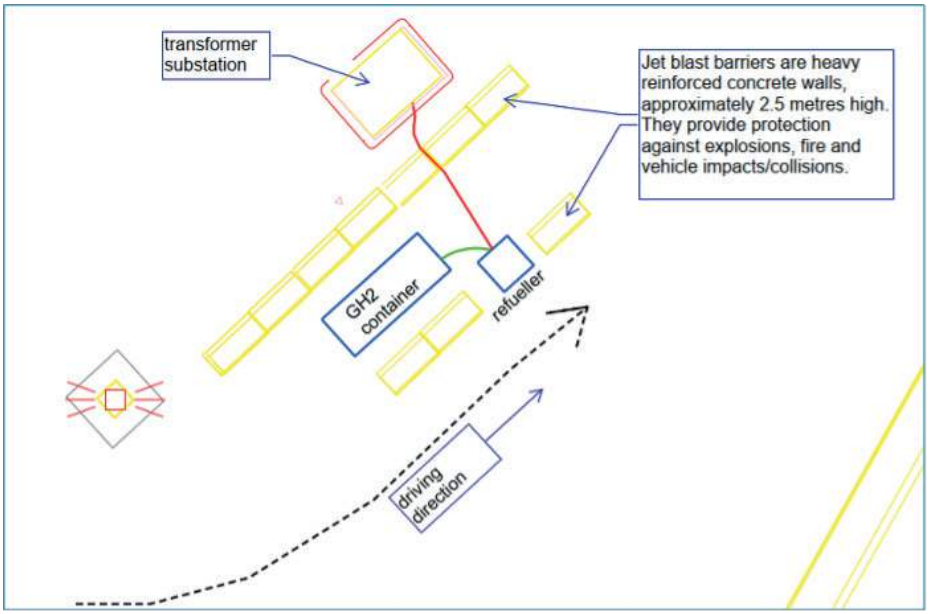

FIGURE 14:
The layout and arrangement of the temporary gaseous hydrogen refuelling station at Helsinki Airport.



FIGURE 15:
Hydrogen container (300 bar) is connected to the refueller.

Parameter	Hydrogen system	Air system	Unit
Operating Temperature (Ambient)	-10 to +50	-10 to +50	°C
Operating Pressure (PN)	350	8	bar
Max. Allowable Pressure (PS)	413	11	bar
Max. Compression Ratio	4:1		
Electrical Connection		415 / 50 / 32	VAC / Hz / A
Ingress Protection	IP 35		
Hydrogen Inputs	3 x 350		bar
Tubing	DN 3/8 / 316 Stainless Steel	DN 1 / Hydraulic hose	inch
Safety Devices	PRV 413	PRV 11 (Tank) / PRV 15 (Comp)	bar
Hydrogen Output	350 / SAE J2600		bar

TABLE 6:
HyQube 350 mobile refuelling station technical specifications

ELECTRICAL GROUNDING AND VERIFICATION OF HYDROGEN REFUELLING UNIT

During the preparation phase, the need for dedicated grounding and electrical verification of the hydrogen refuelling unit was identified by the airport development and technical experts. The installation involved mobile equipment placed in an operational apron environment, which necessitated specific attention to grounding, equipotential bonding, and electromagnetic compatibility (EMC).

Airport electrical engineering specialists reviewed the planned installation and defined the acceptable grounding solution. It was determined that the refuelling unit must be connected directly to the main equipotential grounding bar of the adjacent equipment infrastructure. Grounding via external structures or chained connections was deemed non-compliant. Minimum conductor sizing requirements were specified, with a larger cross-section recommended for robustness and lightning tolerance.

The grounding solution and related electrical works were coordinated internally in advance of the equipment delivery. The physical location of the refuelling unit was reviewed from an electrical supply and grounding perspective, and responsibilities were assigned to ensure availability of electrical support during installation and commissioning if required.

Electrical safety arrangements were supported by manufacturer documentation for the hydrogen refuelling unit, including grounding instructions. In addition, the project produced and distributed safety documentation as part of the permitting process, including a safety justification, risk assessment, explosion protection documentation, and emergency planning materials.

INSPECTION AND APPROVAL

Prior to operational use:

- A certified electrical professional was designated to perform the required electrical conformity and verification inspection of the refuelling unit.
- A separate fire and rescue authority commissioning inspection was completed to verify hydrogen safety and overall readiness.

Required notifications were submitted to the competent authorities, and the installation received the necessary approvals.

The electrical grounding and verification of the temporary hydrogen refuelling unit were addressed through a structured process involving early identification of requirements, expert technical definition, coordinated implementation, documented verification, and formal authority inspections. This ensured that the hydrogen pilot was conducted in compliance with applicable electrical safety standards, regulatory requirements, and airport operational safety expectations.

The refuelling system was inspected by the refuelling equipment provider prior to use. A high-sensitivity hand-held gas leak detector was used to check for leakages. During initial commissioning at approximately –18°C ambient temperature, a minor hydrogen leak was detected at pipe connections within the refuelling station. The issue was mitigated by installing heat tracing cables around the pressure pipes and joints (see Figure 16), ensuring adequate temperature at the connections. Following this corrective action, no further hydrogen leaks were observed, and refuelling operations proceeded safely for the remainder of the pilot.



FIGURE 16:
Heat tracing cable (green cable, 10 W/m) was installed to keep the critical parts warmer during very cold weather

OPERATIONAL EXPERIENCES

The refueller unit (HyQube 350) is not originally designed for operating temperatures below −10°C by the manufacturer. Therefore, in the initial conditions of −15... −25 °C did cause problems in operations. The internal operating system of the refueller had been set to prevent the use of the equipment when the temperature is too low. The user interface panel showed an error code, and the refuelling was not possible. On-site work-around to overcome this problem was to use a mobile aircraft heater to blow warm air on the refueller. This way the temperature of the critical parts of the refueller were raised significantly and normal operations could be started. User experiences during normal refuelling operations are described in the paragraph 'Operator experience".
Operational restrictions and limitations

The hydrogen-powered truck was not subject to reduced operational use within its defined scope. The vehicle was piloted in normal apron maintenance operations, specifically in airside winter maintenance tasks.

However, defined limitations included:

- The vehicle was not operated on runways or taxiways, but only on apron and designated airside maintenance areas to limit the risks of disruption to air traffic in case of pilot vehicle failure or emergency.
- Indoor storage of the vehicle was prohibited whenever hydrogen was present in the onboard tanks, due to fire safety considerations.

Apart from these constraints, the truck was used operationally in a manner comparable to conventional maintenance vehicles at the apron.

MAINTENANCE – PLANNED AND UNPLANNED

During the project period, several technical issues were observed in the operation of the vehicle. All corrective maintenance actions were carried out by the vehicle owner, Zerobus, in accordance with agreed responsibilities. These issues can be categorized as follows:

- Low Voltage System Issues: An occasional low-voltage battery drain was identified throughout the project. This issue persisted even after battery replacements, indicating that the root cause is not limited to battery condition alone.
- High Voltage Battery Failure: The high-voltage (HV) battery experienced a sudden failure mode, caused by underperformance of certain cells. This resulted in a complete system shutdown. The reason why the battery management system did not isolate the weak cells or transition to a controlled degraded mode remains unclear and requires further investigation.
- Fuel Cell Failure: A failure occurred in the fuel cell system due to an internal coolant leak, with leakage exiting through the exhaust outlet. The leakage location has been identified and reported to the manufacturer. A likely root cause of the failure is freezing. This is assumed to have occurred following an abrupt system shutdown, during which moisture was not purged from the system. The shutdown itself appears to have been triggered by the high-voltage battery failure.
- Cabin Heating Performance: Reduced cabin heating performance was observed in connection with the above failures. The heating system was automatically shut down as part of the system's emergency mode, which is considered normal behaviour under such conditions.
- 12V System Energy Consumption: Significant energy consumption was detected within the 12V system. However, the underlying cause and the destination of the energy usage remain unclear. One hypothesis is that the issue may be linked to the high-voltage battery management system, but this requires further validation through simulation and testing.

No maintenance tasks were performed by airport maintenance staff on the hydrogen powertrain nor the vehicle itself and no GH2 leaks were detected.

EMERGENCY RESPONSE AND INCIDENTS

Emergency procedures for hydrogen-related incidents were predefined in the Rescue Plan, including coordination with airport rescue services. No emergency situations requiring intervention by rescue services occurred during the pilot. The only safety related incident was very minor refuelling system hydrogen leak from some pipeline joints during commissioning.

OPERATOR EXPERIENCE

Operator feedback (see Table 7) was collected through an evaluation process involving all three trained drivers participating in the pilot. Key findings from operator interviews:

- Driving characteristics were rated positively, with strong acceleration and immediate power availability typical of electric drivetrains.
- Work performance (towing and ploughing, see Figure 17) was considered fully sufficient and comparable to conventional vehicles.
- Vehicle stability and handling were described as good and suitable for apron operations.
- Cold weather did not affect negatively in vehicle operator experience.
- Operating comfort was assessed as good; low noise levels and smooth operation were highlighted.
- Refuelling was perceived as safe, easy and straightforward, although slower than diesel refuelling when high tank pressure was required. Achieving tank pressures significantly above 300 bar required relatively long refuelling times with the pilot's mobile refuelling equipment.

Overall operator acceptance was clearly positive, and all interviewed drivers expressed willingness to use the hydrogen-powered truck in future operations.



FIGURE 17:
The general work performance of the truck was considered adequate.

Refuelling	**Quotes**
The operators described hydrogen refuelling as relatively easy once they had become familiar with the equipment. However, the pilot period included technical difficulties, and exceptionally cold weather had a clear negative impact on refuelling performance.	"Refuelling was easy and simple once you got to know the equipment." "The technical problems were mainly caused by the severe frost. In summer, there probably would not have been the same issues."
Interviewees noted that refuelling slowed down significantly towards the end of the process. As a result, the vehicle was often not filled completely, because waiting for the final part of the tank to fill was not considered worthwhile.	"The refuelling speed was reasonably good up to about half a tank, but after that it slowed down significantly." "At the end of refuelling it slowed down so much that it was not worth waiting."
Compared with diesel refuelling, hydrogen was also seen to have some practical advantages from the operator's perspective.	"Compared with diesel refuelling, it was more pleasant because there was no fuel smell on the gloves." "You did not have to keep holding the trigger like with diesel."
For larger-scale use, the operators considered that the temporary refuelling arrangement used in the pilot would not be sufficient. A more permanent and higher-capacity refuelling solution would be needed, especially if several vehicles were operated.	"For larger-scale use, with several vehicles, a different type of refuelling system would be needed."
Safety	**Quotes**
The operators did not report major safety concerns during the pilot. Hydrogen safety was clearly considered, but the actual operation, including	"Safety was something you thought about, but it still felt safe, including refuelling."
refuelling, was perceived as manageable and generally safe.	"There was nothing unusual from a safety perspective. It was not much different from a gas-powered vehicle."
However, one interviewee noted that the temporary nature of the setup affected the perception of safety. A permanent installation would probably feel more robust and reassuring.	"Everything was built as a temporary arrangement, but a more permanent system might have felt even safer."
Driving and operational use	**Quotes**
The driving experience was assessed positively. The hydrogen truck was perceived as powerful, quiet and suitable for apron use. The operators especially appreciated the immediate availability of power and the balance of the semi-trailer configuration.	"The vehicle felt powerful compared with a combustion engine truck. The power was available immediately." "The semi-trailer configuration felt good to use." "It was a well-proportioned combination and suitable for apron operations."
Compared with older towed equipment combinations, the vehicle combination was considered pleasant and stable to drive. The operators noted that it behaved broadly like a semi-trailer, including some cutting-in during turns, but not excessively.	"Compared with old, towed units, the combination felt meaningful to drive." "It did not cut corners too much. It was a balanced combination."
The vehicle was also considered quiet, although some noise was generated by the fans when they were running.	"The truck was quiet, although the fans made some noise when they came on."
The operators also saw possible uses for this type of vehicle beyond winter operations, for example in summer maintenance tasks.	"This type of truck could also be used in summer with a gravel trailer." "It would be worth testing hydrogen operation also in summer, for example with a basic truck body, tipper body, hooklift or off-road use."

Technical reliability	Quotes
The main critical feedback concerned technical reliability. The pilot experienced several technical issues, particularly with the vehicle's electrical system and hydrogen/fuel-cell-related functionality. These issues affected operational confidence and availability.	"There were many faults in the vehicle's electrical system." "In the end, the fuel cell had to be changed." "At times, it did not charge the battery." "At one point, the truck worked like a dream."
One interviewee also noted that the vehicle heating system was dependent on the hydrogen side functioning properly, which caused operational inconvenience when problems occurred.	"The heating did not work if the hydrogen (fuel cell) was not working."
Future potential of hydrogen at airports	**Quotes**
Interviewees considered hydrogen a potentially viable power source at airports, especially for heavier vehicles and tasks where battery-electric solutions may be less suitable. However, they emphasised that future deployment would require a more permanent refuelling solution, better technical reliability and continued attention to safety.	"Hydrogen could work at an airport." "Hydrogen itself feels like a workable power source."
At the same time, the operators did not see hydrogen as the best solution for all airport vehicle categories. For some applications, such as apron buses and	"Apron buses would probably still be better as full electric vehicles, as would some other equipment."
certain smaller equipment, battery-electric solutions may still be preferable.	

TABLE 7:
Details of the driver interviews.

When the truck is stationery and idling, the fuel cell system produces steam (see Figure 18 and Figure 19) and condensate water that can accumulate rapidly underneath the vehicle, forming a visible puddle on the ground. In cold weather conditions, this water may freeze quickly, creating a slippery surface and a potential safety hazard for both personnel and vehicles operating nearby. This phenomenon should therefore be considered in operational planning and risk assessments, particularly during sub-zero temperatures, and appropriate mitigation measures should be applied where necessary.



FIGURE 18:
The fuelcell creates a lot of steam in cold weather conditions.



FIGURE 19:
Steam and condensate water quickly create a puddle on the ground.

3.3.2 RIGA AIRPORT

HYDROGEN VEHICLE OPERATIONAL OVERVIEW

The pilot system consisted of a Hyzon 250 hydrogen fuel cell truck manufactured by Hyzon Motors Inc., integrated with a Vammas-Vitera SB3600 sweeper-blower unit adapted for winter operations. The truck was supplied and technically supported by Zerobus OU, with logistical and advisory support from the Latvian Hydrogen Association. The sweeper-blower equipment was provided by Finavia Corporation, and hydrogen refuelling services were carried out under contract by AI Cooperation.

Preparatory activities took place between December 2025 and mid-February 2026 and included equipment delivery, coordination of responsibilities, and operational readiness planning. Operational testing was conducted from 16 February to 6 March 2026 in designated airside and technical areas of the airport. Refuelling was on airside apron Nr. 3 (near RAF-AVIA hangar) (see Figure 20).



FIGURE 20:
Hydrogen refuelling at Riga Airport on airside with mobile refuelling station (red dot on the map).

ELECTRICAL GROUNDING AND VERIFICATION OF HYDROGEN REFUELLING UNIT

Prior to operational use of mobile hydrogen refuelling station, electrical safety and grounding arrangements were carried out to ensure compliance with airport safety standards, applicable electrical regulations, and hydrogen handling requirements. During the preparation phase, the need for dedicated grounding and electric power supply for the hydrogen refuelling unit was provided by the airport Electrical technician team.

During the installation of the mobile refuelling station, the electrical technician team controlled the electrical grounding and the operation.

TRAINING

Hydrogen-related training for vehicle operators was delivered by:

- **Zerobus OU** (hydrogen truck supplier),
- **AI Cooperation SIA** (hydrogen refuelling station supplier and hydrogen supplier).

The training covered normal operation, refuelling procedures, safety awareness, and emergency actions specific to hydrogen systems. Only trained and nominated drivers were authorised to operate the hydrogen-powered vehicle during the pilot.

OPERATIONAL ENVIRONMENT AND TEST CONDITIONS

Testing was carried out under typical Latvian winter conditions. Ambient temperatures during the pilot ranged from approximately -16°C to +7.5°C, with snow accumulation reaching up to 26 cm. These conditions allowed evaluation of system behaviour under both stable freezing conditions and thaw-freeze transitions.

The vehicle was used for standard airport winter maintenance tasks, primarily snow clearing of apron areas and operational surfaces supporting aircraft ground movements (see Figure 21).



FIGURE 21:
Snow cleaning on Riga Airport apron

OPERATIONAL PERFORMANCE AND HYDROGEN CONSUMPTION

During the pilot, the vehicle covered a total distance of 179 kilometres and operated for 40 hours and 40 minutes. Total hydrogen consumption was 31,01 kg, corresponding to an average consumption of approximately 17,32 kg per 100 km.

Hydrogen consumption varied depending on operational load and environmental conditions. Higher consumption was observed during intensive snow clearing operations and at lower temperatures, indicating sensitivity of the system to both workload intensity and cold weather conditions. Due to technical issues, no technical data on precise consumption and performance was received and quantitative analysis is not possible.

SYSTEM PERFORMANCE AND RELIABILITY

The hydrogen-powered truck demonstrated generally stable and reliable performance throughout the pilot period. It provided sufficient traction power for snow removal operations and maintained consistent operational behaviour suitable for airside use. The system also showed typical characteristics of electric drive systems, including low noise levels and smooth power delivery.

No critical failures or safety-related incidents occurred during testing, and all planned operational tasks were completed successfully.

COLD WEATHER PERFORMANCE AND ENERGY MANAGEMENT

A key observation from testing relates to reduced system efficiency at temperatures below -10°C. Under these conditions, the battery discharge rate exceeded the ability of the fuel cell system to replenish energy, resulting in reduced overall efficiency.

This behaviour indicates limitations in the current energy management and thermal control strategy. It suggests that the interaction between the fuel cell system and the battery requires further optimisation, particularly in cold climate and high-load operating scenarios. Improvements in thermal management of both subsystems are required to maintain stable energy balance under extreme conditions.

HYDROGEN REFUELLING PERFORMANCE

Hydrogen refuelling was performed using a HyQube 350 mobile refuelling station located on the apron, about 350 metres north of the terminal and 10 metres from the nearest hangar, in a designated green safety zone.

The planned high-pressure tube trailer supply system was not available due to technical issues, so hydrogen was instead supplied using cylinder bundles. Each bundle contained 12 cylinders (50 L each) with a total of approximately 9 kg of hydrogen at 200 bar. Refuelling performance was mixed. Initial hydrogen transfer was fast when pressure differences were high, with around 4-4.5 kg delivered within 5-7 minutes. However, once pressures equalised both in truck and bundles, the process slowed significantly, where the limiting factor was the HyQube 350 compressor.

Overall, the system functioned for demonstration purposes but showed clear limitations in compressor capacity and supply pressure. Cylinder bundles also required frequent replacement by external experts personnel, creating logistical constraints within the airside access system.

SAFETY MANAGEMENT AND OPERATIONAL CONTROLS

During the preparation and execution of the pilot, involvement of the Civil Aviation Agency (CAA) was not required. The operation was conducted under existing airfield operating procedures and integrated into the airport's internal Safety Management System (SMS) framework.

The safety case for the testing activities was developed in accordance with SMS requirements and defined operational constraints for hydrogen handling and airside use. The hydrogen storage tanks were positioned in a designated airside area located near the service road, with a defined buffer

zone of 10 metres established because the only national legislation having safety distances for gas cylinder bundles (natural gas) requires 10 meter distance/protection zone. Still there are dicussions if the same could be applied to H2 as it has different properties due to its nature (it is lighter than air and cannot accumulate in such quantities as natural gas).

A key operational requirement was the mandatory training of Riga Airport personnel involved in hydrogen truck operations. Refuelling activities were carried out by trained airport staff (training was provided by Finavia), while hydrogen cylinder bundle switching was made by external specialists to reduce operational risk exposure.

RELIABILITY AND CONCLUSIONS

Testing confirms that hydrogen-powered heavy-duty ground support equipment can be successfully integrated into airport winter operations. The system demonstrated acceptable reliability and completed all planned tasks over the full test distance without critical failures.

At the same time, the pilot identified clear technical limitations. Reduced performance at low temperatures and variability in hydrogen refuelling time indicate that for a full operation a careful design of infrastructure performance and size is needed to fuel equipment fast and convincing manner. The setup was sufficient for this kind of demonstration but not for a consistent operation.

Overall, hydrogen-powered ground support vehicles show strong potential for airport use, but reliable large-scale deployment in Northern European winter conditions will require adjusted technical optimisation and system refinement.

3.3.3 KAUNAS AIRPORT

PERMITS AND APPROVALS FROM AUTHORITIES

The pilot was implemented under SE Lithuanian Airports Kaunas aerodrome manual Safety Management System (SMS) and procedure - AOP02 Entry into the Aerodrome Movement Area. The safety assessment prepared as part of the BSR HyAirport project, titled "BSR HYAIRPORT - STUDY ON SAFETY IN THE OPERATION OF A HYDROGEN-POWERED SNOW PLOW-SWEEPER-BLOWER," was also reviewed. After analysing the vehicle's documents (based on the fact that the vehicle had a valid registration certificate and a technical inspection report issued by the European Union), in cooperation with staff from the Aviation Security Permits Office, it was decided to issue a temporary vehicle permit. No additional approvals from the local authority were needed regarding that refuelling was made not in the airside territory.

HYDROGEN-SPECIFIC SAFETY MEASURES AND RISK MANAGEMENT

Risk assessments and safety cases

In identifying potential threats and hazards, the impact of the upcoming temporary change on the operations and maintenance processes at the aerodrome was assessed. The following potential hazards were identified: improperly performed snow removal operations, delays in runway cleaning, improper vehicle operation, and a vehicle becoming stuck on the aerodrome manoeuvring area.

Based on the conclusions of the safety risk assessment process, it was decided to locate the hydrogen refuelling equipment outside the aerodrome boundaries—in the airport's service vehicle maintenance area. Based on the fact that the vehicle had a valid registration certificate and a technical inspection report issued by the European Union, in cooperation with staff from the Aviation Security Permits Office, it was decided to issue a temporary vehicle permit.

It was also concluded that employees operating the snowblower and the specialized fuel (hydrogen) refuelling equipment must be properly trained (risk mitigation measure).

TRAINING

Hydrogen-related training for vehicle operators was delivered by:

- **Zerobus OU** (hydrogen truck supplier),
- **AI COOPERATION SIA** (hydrogen refuelling station supplier), and

The training covered normal operation, refuelling procedures, safety awareness, and emergency actions specific to hydrogen systems. Only trained and nominated drivers were authorised to operate the hydrogen-powered vehicle during the pilot. Refuelling station operations (hydrogen refuelling) training for the Kaunas Airport staff members was performed on site and via remote tools.

TEMPORARY REFUELLING STATION

Location

Hydrogen refuelling was carried out using a temporary, mobile hydrogen refuelling station installed at a designated location outside airside (see Figure 22).

- Manufacturer: Fuel Cell Systems Ltd, United Kingdom
- Model: HyQube 350 (350 bar hydrogen vehicle refuelling assembly)
- Supplier (to the Kaunas Airport): AI Cooperation, Latvia
- Hydrogen provider: AI Cooperation, Latvia

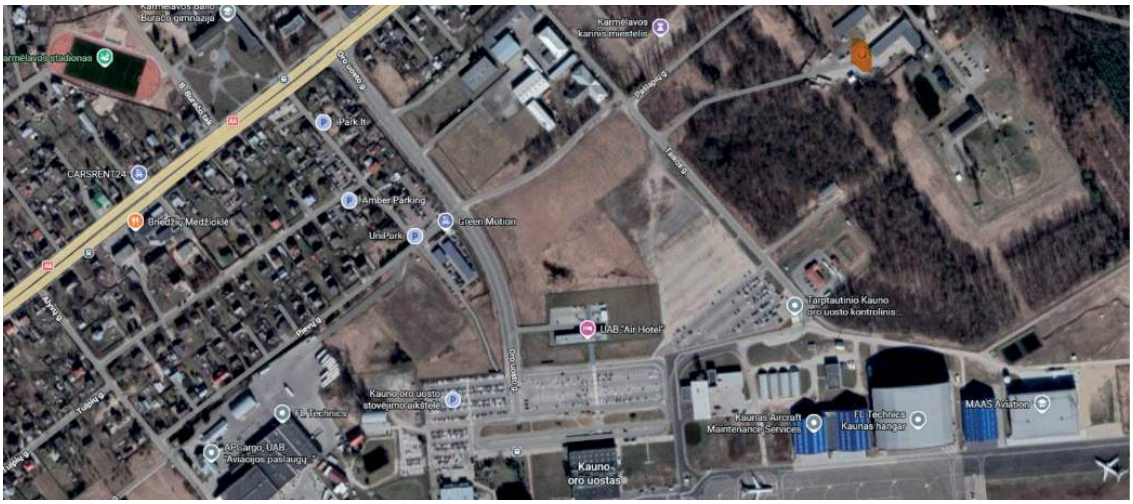

FIGURE 22:

The location of the temporary gaseous hydrogen refuelling station at Kaunas Airport (orange area)

The temporary hydrogen refuelling station was located in garage territory where heavy vehicles (like snow trucks) are usually located, based on a combined assessment of operational suitability, electrical safety, and risk management considerations.

The selected location provided direct access to the required electrical infrastructure, enabling a compliant and technically robust grounding solution via the airport's main equipotential bonding system. The location is outside the aerodrome boundaries and beyond the fence surrounding the main airport grounds. As a result, entering the aerodrome area after each refuelling required passing through a checkpoint, which took additional time. The location was chosen due to a lack of space on the apron and safety recommendations. The location was reviewed and agreed in coordination with airport electrical engineering, safety specialists, and rescue authorities, ensuring

that the installation met airport safety standards, hydrogen safety requirements, and regulatory expectations, while minimizing operational disruption during the pilot implementation.



FIGURE 23:
Hydrogen container (300 bar) is connected to the mobile refueller.

As shown in Figure 23, the hydrogen container was positioned in close proximity to the building. However, according to the airport's assessment, the applicable separation distance requirements were met. The building was unoccupied and did not contain any equipment or operational assets; therefore, no additional safety concerns related to the reduced apparent distance were identified.

Parameter	Hydrogen system	Air system	Unit
Operating Temperature (Ambient)	-10 to +50	-10 to +50	°C
Operating Pressure (PN)	350	8	bar
Max. Allowable Pressure (PS)	413	11	bar
Max. Compression Ratio	4:1		
Electrical Connection		415 / 50 / 32	VAC / Hz / A
Ingress Protection	IP 35		
Hydrogen Inputs	3 x 350		bar
Tubing	DN 3/8 / 316 Stainless Steel	DN 1 / Hydraulic hose	inch
Safety Devices	PRV 413	PRV 11 (Tank) / PRV 15 (Comp)	bar
Hydrogen Output	350 / SAE J2600		bar

TABLE 8:
HyQube 350 mobile refuelling station technical specifications

ELECTRICAL GROUNDING AND VERIFICATION OF HYDROGEN REFUELLING UNIT

As part of the hydrogen pilot implemented at Kaunas Airport, a temporary hydrogen refuelling unit and associated hydrogen storage container were installed in the airport's service vehicle maintenance area. Prior to operational use, electrical safety and grounding arrangements were required to ensure compliance with airport safety standards, applicable electrical regulations, and hydrogen handling requirements. During the preparation phase, the need for dedicated grounding and electrical verification of the hydrogen refuelling unit was identified by the airport development and technical experts. The installation involved mobile equipment placed in non-operational garage territory.

Airport electrical engineering specialists Rytis Čėsna reviewed the planned installation and defined the acceptable grounding solution. It was determined that the refuelling unit must be connected directly to the main equipotential grounding bar of the adjacent equipment infrastructure. The airport cable was not compatible for refuelling station, after the airport service cable was modified to ensure required connectivity connection standard.

Due to conclusions of the safety risk assessment process, it was decided to locate the hydrogen refuelling equipment outside the aerodrome boundaries—in the airport's service vehicle maintenance area. Electrical safety arrangements were supported by manufacturer training for the hydrogen refuelling unit, including grounding instructions. In addition, the project produced and distributed safety documentation as part of the permitting process, including a safety justification, risk assessment, explosion protection documentation, and emergency planning materials.

Prior to operational use:

- A certified electrical professional was designated to perform the required electrical conformity and verification inspection of the refuelling unit.
- A separate fire and rescue authority commissioning inspection was completed to verify hydrogen safety and overall readiness.

The electrical grounding and verification of the temporary hydrogen refuelling unit were addressed through a structured process involving early identification of requirements, expert technical definition, coordinated implementation, documented verification, and formal authority inspections. This ensured that the hydrogen pilot was conducted in compliance with applicable electrical safety standards, regulatory requirements, and airport operational safety expectations.

OPERATIONAL RESTRICTIONS AND LIMITATIONS

During the truck testing at Kaunas Airport, there were no days when it snowed. Therefore it was unable to fully utilize the equipment and test it in snowy conditions, in that case the hydrogen-powered truck was not used in snow conditions. Main part of operation was to clean the apron after a long winter, with snowdrifts and other duties.

However, defined limitations included:

- The vehicle was not operated on runways or taxiways, but only on apron and designated airside maintenance areas.
- Indoor storage of the vehicle was prohibited whenever hydrogen was present in the onboard tanks.
- Apart from these constraints, the truck was used operationally in a manner comparable to conventional maintenance vehicles at the apron.

MAINTENANCE – PLANNED AND UNPLANNED

Several technical issues were encountered during the pilot, including the discharge of the vehicle's 24 V auxiliary battery system. One of the major technical problems was that the vehicle stopped unexpectedly on the apron several times while in operation. The reason was that, once it started running, the vehicle would warm up after 20–30 minutes and all hydrogen cells were charged up to 80%, then the engine stopped working and the truck automatically stopped. When truck stops, it takes more than a minute to start up again, this issue causes some safety issues on the apron and operational disruptions. All corrective maintenance actions were carried out by the vehicle owner, Zerobus, in accordance with agreed responsibilities (as far as we know, one cell in the electric battery was replaced).

No maintenance tasks were performed by airport maintenance staff on the hydrogen powertrain itself.

EMERGENCY RESPONSE AND INCIDENTS

During the pilot, there were no hydrogen leaks and no emergency situations requiring intervention by rescue services occurred.

OPERATOR EXPERIENCE

Operator feedback was collected through an evaluation process involving four trained drivers participating in the pilot. Key findings from operator interviews:

- Driving characteristics were rated positively, with strong acceleration and immediate power availability typical of electric drivetrains.
- Work performance (blowing) was considered fully sufficient and comparable to conventional vehicles. The employees noted that the machine was equipped with two separate control panels—one for the snowplough and the other for the trailer's snow brushes and snow blower. The employees greatly appreciated the snow-shaking feature on the machine.
- Vehicle stability and handling were described as good and suitable for apron operations.
- Operating comfort was assessed as good; low noise levels and smooth operation were highlighted.
- Refuelling was perceived as safe, easy and straightforward, although slower than regular fuels refuelling when high tank pressure was required. Achieving tank pressures significantly above 300 bar required relatively long refuelling times with the pilot's mobile refuelling equipment.

While the vehicle was in operation, technical support was required due to a possible malfunction, which was later resolved.

Overall operator acceptance was clearly positive, and all interviewed drivers expressed willingness to use the hydrogen-powered truck in future operations.

3.3.4 TALLINN AIRPORT

PERMITS AND APPROVALS FROM AUTHORITIES

The Tallinn demonstration did not require a separate permit from the Estonian Civil Aviation Authority, as no permanent or temporary hydrogen refuelling infrastructure was installed at the airport. The pilot was implemented within Tallinn Airport's existing Safety Management System (SMS) and internal operational approval procedures.

The main external administrative process concerned the approval and registration of the Hyzon HyMax 250 vehicle for operation in Estonia. The vehicle was officially registered with the Estonian Transport Administration and received standard registration documents and licence plates, allowing it to operate on public roads without a special road-use exemption. This was particularly important because hydrogen refuelling was carried out at the external Alexela Väo hydrogen refuelling station.

The overall approval, registration and preparation process for the demonstration took approximately three months. In parallel, Tallinn Airport coordinated the planned testing internally with the relevant operational, safety and airside departments. The pilot was carried out in accordance with existing airport requirements for airside vehicle operation, access control, occupational safety and emergency response.

Since hydrogen was not stored or transferred at Tallinn Airport, no separate permitting procedure related to the handling or storage of hydrogen on airport premises was required.

HYDROGEN VEHICLE OPERATIONAL OVERVIEW

- Analyse the overall cradle-to-cradle emissions differences between newly built equipment and the retrofit solution

Preparatory activities included coordination between Tallinn Airport, Zerobus OÜ and project partners regarding vehicle delivery, vehicle registration, operational readiness, safety procedures, airside access and testing arrangements. The demonstration was conducted in March 2026 within designated airport operational areas. The objective of the pilot was to evaluate the operational suitability of hydrogen-powered heavy-duty winter maintenance equipment under airport conditions and to collect practical feedback from experienced maintenance operators.

OPERATIONAL ENVIRONMENT AND TEST CONDITIONS

The demonstration was conducted under relatively mild (1-6°C) weather conditions. During the testing period there was no significant snowfall and no active snow clearing operations were required. Therefore, unlike the earlier demonstrations in Helsinki and Riga, the Tallinn pilot did not provide representative sub-zero or heavy-snow operating conditions.

As a result, the vehicle could not be evaluated under full winter maintenance workload conditions. Testing therefore focused on vehicle operation, manoeuvrability, equipment functionality and operator experience. The vehicle was operated on airport service roads and airside maintenance areas, allowing assessment of driving behaviour, acceleration, visibility and handling characteristics in a typical airport environment.

OPERATIONAL PERFORMANCE AND HYDROGEN CONSUMPTION

During the demonstration, the vehicle covered approximately 35 kilometres. Due to the absence of operational snow-clearing activities, it was not possible to determine representative hydrogen consumption figures under actual working conditions. The pilot therefore focused on functional and operational assessment rather than fuel consumption analysis. The vehicle demonstrated strong acceleration characteristics and responsive handling throughout the testing period. Operators reported that the vehicle behaved similarly to a conventional DAF truck and required only minimal familiarisation.

A notable advantage observed during testing was the low noise level of the hydrogen-powered drivetrain. Operators highlighted the absence of diesel engine noise and vibrations, which significantly improved driving comfort and reduced operator fatigue.

SYSTEM PERFORMANCE AND RELIABILITY

The hydrogen-powered truck demonstrated stable and reliable performance throughout the demonstration period. No critical failures, operational interruptions or hydrogen-related safety incidents were reported. The vehicle successfully completed all planned testing activities.
The electric drivetrain provided smooth power delivery and immediate torque response, resulting in very good acceleration performance. Operators reported that vehicle manoeuvrability was excellent and suitable for airport maintenance operations. The Vammas sweeper-blower system functioned correctly during operational checks. Operators noted that the brush and blower mechanisms responded quickly to control commands and that transitions between operating positions were efficient.

Several minor observations were recorded during testing. When the brush was raised from the ground, brush rotation stopped automatically and resumed when lowered into working position. Operators also noted a slight delay between control inputs and equipment response, although this did not significantly affect usability. Additionally, the demonstrated sweeper-blower was observed to be narrower than similar equipment currently used by Tallinn Airport, which may affect productivity during large-scale snow removal operations.

No hydrogen leaks were detected during the Tallinn demonstration. No hydrogen-related technical failures or safety incidents occurred during vehicle operation or refuelling.

WINTER MAINTENANCE EQUIPMENT EVALUATION

Because no snow-clearing operations could be performed during the testing period, the actual snow removal capability of the vehicle could not be fully assessed.

Consequently, it was not possible to evaluate:

- snow removal capacity;
- hydrogen consumption under operational load;
- performance under deep snow conditions;
- productivity compared with conventional diesel-powered snow removal vehicles.

Further testing during periods of significant snowfall would be required to verify operational performance under realistic winter maintenance conditions.

HYDROGEN REFUELLING PERFORMANCE

Unlike the demonstrations at several other pilot airports, hydrogen refuelling at Tallinn Airport was carried out using an existing public hydrogen refuelling station rather than temporary on-site infrastructure. The vehicle was refuelled at the Alexela Väo hydrogen refuelling station located outside the airport area., approximately 10 km away. During the demonstration, a total of 18.6 kg of hydrogen was supplied.

Although the public refuelling station functioned reliably and provided hydrogen at the required pressure level, the refuelling process introduced additional operational complexity. Before leaving the airport, part of the winter maintenance equipment had to be removed or adjusted to enable safe road transport. The vehicle then had to travel from the airport to the refuelling station and return afterwards. Upon returning, access procedures required passage through airport security control and re-entry to the restricted airside area. As a result, the total time associated with refuelling was significantly longer than the actual hydrogen transfer process itself. This reduced equipment availability and would represent an operational limitation if hydrogen-powered vehicles were deployed regularly without dedicated on-airport refuelling infrastructure.

The Tallinn pilot therefore demonstrated that while public hydrogen refuelling infrastructure can support initial demonstration activities, large-scale operational deployment would benefit from dedicated airport-based hydrogen refuelling facilities.

SAFETY MANAGEMENT AND OPERATIONAL CONTROLS

The demonstration was conducted within Tallinn Airport's existing Safety Management System (SMS) and operational safety framework. Testing arrangements permitted operating areas and airside access were coordinated internally with the relevant airport operational and safety departments.

Vehicle operation was restricted to trained personnel familiar with airport maintenance operations. Standard airport procedures regarding vehicle movement, airside access and operational safety remained applicable throughout the demonstration.

No safety-related incidents, hydrogen leaks or emergency situations occurred during testing.

RELIABILITY AND CONCLUSIONS

The Tallinn Airport pilot demonstrated that hydrogen-powered heavy-duty winter maintenance vehicles can be successfully integrated into airport operational environments. Operator feedback was overwhelmingly positive regarding vehicle handling, acceleration, comfort and noise levels. The vehicle performed reliably throughout the demonstration and completed all planned activities without technical failures. The most significant operational benefit identified was the exceptionally quiet operation of the hydrogen-powered drivetrain compared with conventional diesel-powered equipment.

At the same time, the demonstration highlighted an important infrastructure-related challenge. The absence of an on-airport hydrogen refuelling facility increased refuelling time and reduced equipment availability due to transportation and security procedures associated with off-site refuelling. Overall, the pilot confirmed the technical feasibility of hydrogen-powered airport maintenance vehicles and demonstrated strong operator acceptance. However, future large-scale deployment would benefit from dedicated airport hydrogen refuelling infrastructure and additional testing under actual snow-clearing conditions to fully evaluate operational performance and hydrogen consumption.

3.4 BUS ROAD SHOW

COURSE OF THE JIVE 2 NORDIC ROADSHOW

The roadshow in Sweden commenced in Stockholm (Solna), where the national workshop took place on 23 April 2025, followed by test trials and a members event hosted by Vätgas Sverige. The roadshow then continued to Gothenburg, hosting both a professional workshop on 29 April and a public-facing event on 30 April at the Lindholmen Science Park within the Hydrogen Dome of Sweden, with test trials occurring over both days. Travelling next to Ljungby, the roadshow held a professional event on the morning of 5 May at Strandmöllen's hydrogen production site, with test trials taking place that afternoon at the central bus terminal in Ljungby. The following day focused on education and public engagement, with a dedicated outreach event held at Sunnerbogymnasiet a local high school on 6 May, including a number of test rides with student passengers. The final stop of the roadshow in Sweden was Växjö Småland Airport, where test trials transported passengers from the city centre to the airport and a professional workshop took place on 7 May 2025. On May 14 and 15, test trials took place at Helsinki Airport.

Country	Roadshow event	Type	Number of participants
Sweden	Stockholm, 23 - 24 April 2025 Gothenburg, 29 - 30 April 2025 Ljungby, 5 - 6 May 2025 Växjö, 7 May 2025	Test trials	~500
	Stockholm, 23 April 2025	National Workshop	~52
	Ljungby, 5 May 2025	Professional workshop	~28
	Växjö Airport, 7 May 2025	Professional workshop ("Vätgasdagen")	~24
	Gothenburg, 30 April 2025 Ljungby, 6 May 2025 Vätgas Sverige, 24 April 2025	Student workshops & Member event	~310
	Swedish Roadshow, 23 April – 7 May 2025	**All events**	**~500**
Finland	Helsinki Airport, 14 - 15 May 2025 Tampere, 27 - 28 May 2025 Jyväskylä, 3 June 2025 Pori, 25 - 26 June 2025	Test trials	120 200 30 25
	Helsinki, 15 May 2025	National Workshop	42
	Tampere, 27 May 2025	Professional workshop	34
	Jyväskylä, 3 June 2025	Professional workshop	38
	Pori, 25 - 26 June 2025	Participation in Vetyareena	~ 300
	Finnish Roadshow, 14 May – 26 June 2025	**All events**	**~500**

TABLE 9:
Bus-Roadshow Events

OPERATIONAL ENVIRONMENT

The hydrogen fuel cell bus operated successfully during the demonstration period and was integrated into normal passenger transport activities. The vehicle demonstrated smooth and quiet operation, characteristics typically associated with electric drivetrains.

The demonstration confirmed that hydrogen-powered passenger transport can be implemented within airport operations without fundamental changes to passenger handling processes.

OPERATOR AND PASSENGER EXPERIENCE

Feedback collected during the demonstration was positive. Key observations included:

- Low noise levels.
- Smooth acceleration and driving characteristics.
- High passenger comfort.
- Driving experience comparable to full battery-electric buses.
- No significant operational limitations identified during normal use.

The demonstration also provided airport personnel with practical experience regarding hydrogen-powered mobility and increased confidence in the technology.

HELSINKI AIRPORT AIRSIDE DEMONSTRATION

The Helsinki Airport trial was of particular importance because it demonstrated hydrogen-powered mobility in a safety-critical airport operating environment. This trial was the first time a hydrogen





FIGURE 24:
Vätgasdagen at Växjö Smaland Airport, 7 May, 2025



FIGURE 25:
Bus-Roadshow Pilot at Växjö Airport

powered vehicle or machine was in operational use on the apron in Finland. Unlike conventional public transport demonstrations, airport airside operations require integration with aircraft handling activities, strict safety procedures and high operational reliability. In this short trial the bus was not refuelled at the airport.

The successful operation of the vehicle demonstrated that hydrogen-powered passenger transport can be considered for future airport applications especially where rapid refuelling and high vehicle availability are important operational requirements.



FIGURE 26:

Hydrogen powered low-floor bus was piloted in real passenger operations at Helsinki Airport.

4 TECHNICAL DATA (QUANTITATIVE)

Chapter 4 presents the quantitative technical data collected during the hydrogen-powered airport equipment demonstrations carried out at Hamburg, Helsinki, Riga, Kaunas and Tallinn Airports. While Chapter 3 focused on operational experience, safety procedures, user feedback and qualitative lessons learned, this chapter provides a data-based assessment of the tested equipment and its performance under real airport operating conditions. The technical evaluation includes key measurable parameters such as hydrogen consumption, operating hours, vehicle availability, refuelling behaviour, drivetrain performance, energy demand and other equipment-specific indicators recorded during the demonstrations. The data is structured by use case and airport in order to reflect the different vehicle types, operating profiles, infrastructure setups and environmental conditions encountered during the pilots.

The purpose of this chapter is to establish a comparable quantitative basis for assessing the technical feasibility, maturity and operational suitability of hydrogen-powered ground support equipment, winter maintenance vehicles and passenger transport applications. These findings also provide an important foundation for the subsequent economic evaluation, conclusions and recommendations regarding future hydrogen deployment in airport environments.

4.1 H_2 GROUND SUPPORT EQUIPMENT TESTING IN HAMBURG AIRPORT

The objective of the test was to operate the retrofitted baggage tractor under normal operational conditions at the airport. The aim was to assess whether the vehicle meets the site-specific requirements and can be used without restrictions in operational service. Even before the actual conversion, a reference vehicle was equipped with sensors in order to collect drivetrain-specific operational data and to design the prototype according to the real-world requirement profile. After a three-week data collection phase, a MULAG vehicle was transported to HTM and retrofitted there. Due to the novel technical modifications as well as existing supply chain constraints, the conversion took longer than originally planned.

The vehicle was first publicly presented in Darmstadt in March 2025. The initial development stage still exhibited a significantly high noise level, making further adjustments necessary. Operational testing in Hamburg began in May 2025. Besides the daily operations, defined testing scenarios have been developed and carried out with both, CNG Model and H2-ICE-Model. To ensure technical comparability with the CNG vehicles and to allow a robust evaluation of the system's performance, dedicated performance tests with defined trailer loads were conducted. These tests were scientifically supported as part of a master's thesis at HAW Hamburg. The objective of these tests was, on the one hand, to investigate whether the performance of the new drivetrain system is comparable to that of the CNG vehicles. On the other hand, clearly defined load profiles were to be generated in order to enable HTM to carry out a detailed evaluation of the system. In regular operations, the actual load being towed at any given time is not precisely known, which means that without standardized test profiles, no reliable conclusions can be drawn regarding performance.

For the dedicated performance tests, dollies were used in combination with ballast weights. An unloaded dolly has a mass of approximately 1.3 tonnes, while each individual ballast weight has a mass of 1 tonne. Based on these weight classes, the following test configurations were investigated:

Scenario	No weight	4,6 t	9,2 t
Acceleration flat surface	x	x	x
Driving in big circles	x	x	x
Driving positive slope (2%)	x	x	
Driving negative slope (-2%)	x	x	

The individual test runs were carried out multiple times using both a CNG vehicle and the H_2 hybrid MULAG in order to minimise outliers and to establish a reliable basis for comparison. The test driving slopes could not be performed with 9.2 tons because of the limitation of the available trailers and the allowance to drive on the used path, not because of the limitations of the vehicle. Among the parameters recorded were torque and engine speed profiles, specific fuel consumption, as well as acceleration data. In addition, noise levels inside the vehicles were measured, as the H_2 hybrid had previously been observed to have a higher noise level compared to the CNG variants, which was perceived as disadvantageous by the operators.

The results provided detailed insights into engine behaviour and the respective consumption characteristics of the vehicles. At the same time, the standardised tests contributed significantly to the further development of the vehicle, as they enabled the identification of technical weaknesses and optimisation potential for control strategies. Figure 27 shows several loggings for a set time frame of testing. The upper graph shows the vehicle speed in orange and the acceleration in blue. The second graph shows the engine speed in orange and the pedal position in blue. The third graph shows the engine speed in orange and the Torque in blue and last but not least in the fourth graph shows in orange the throttle valve position and in blue the fuel consumption.

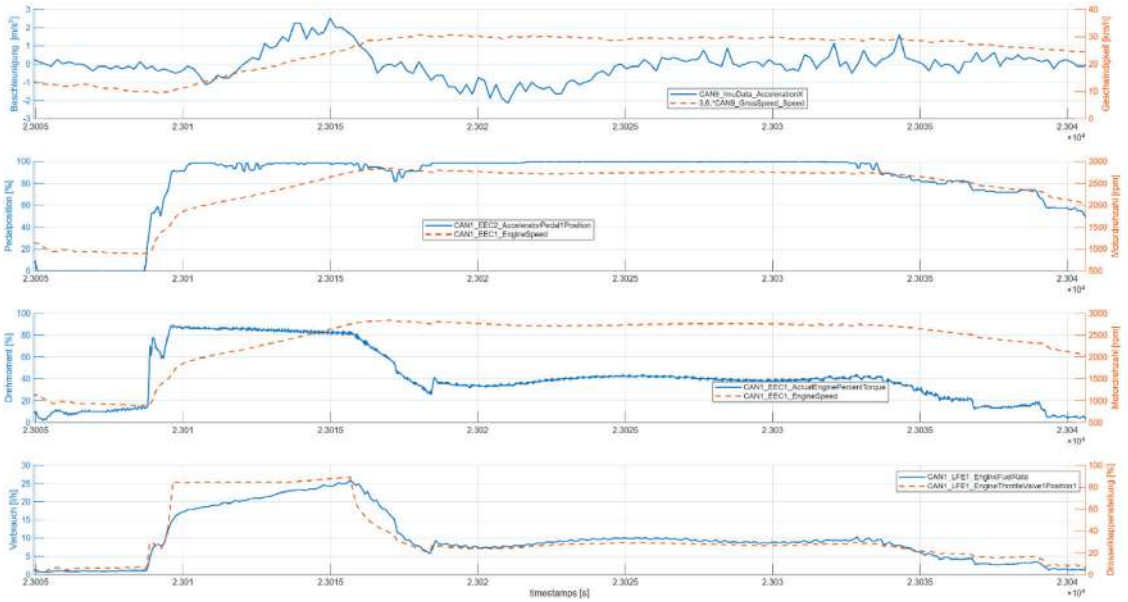

FIGURE 27:
Test logs for H2-ICE-Mulag

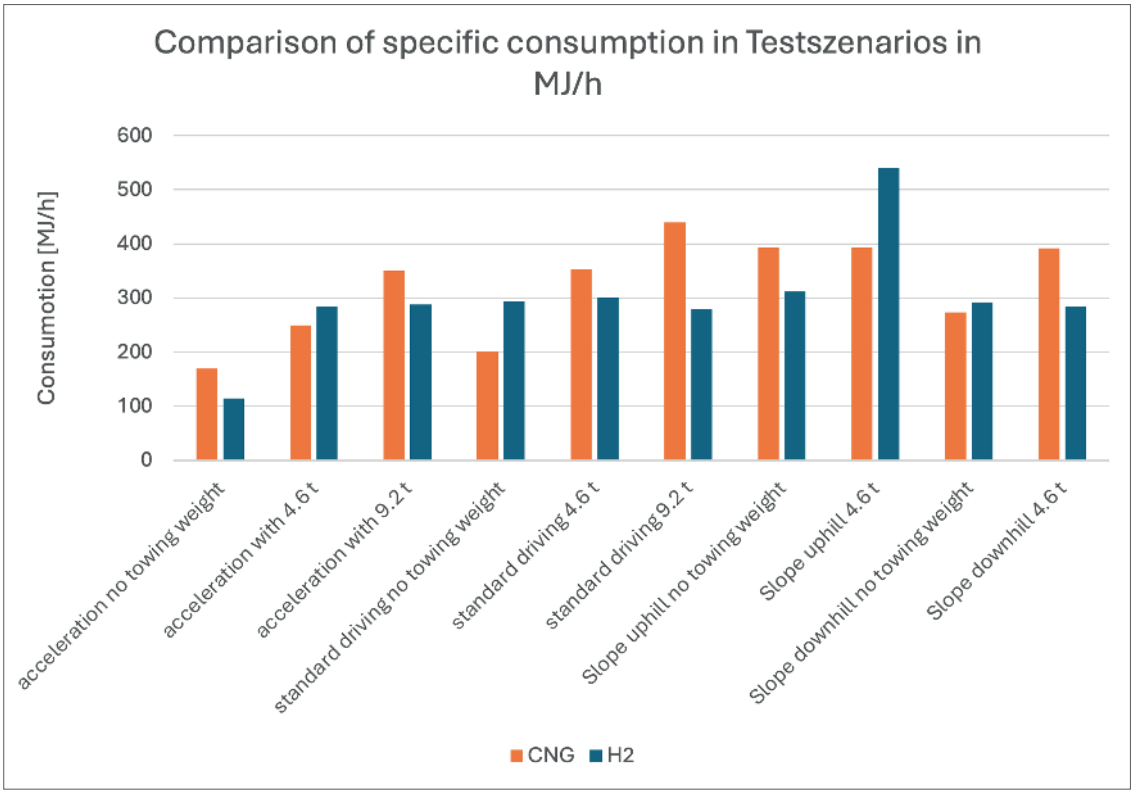

FIGURE 28:
Comparison of specific consumption in Testszenarios

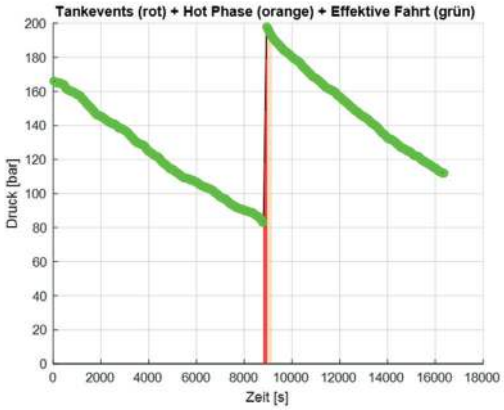

FIGURE 29:
Hydrogen Fuelling event

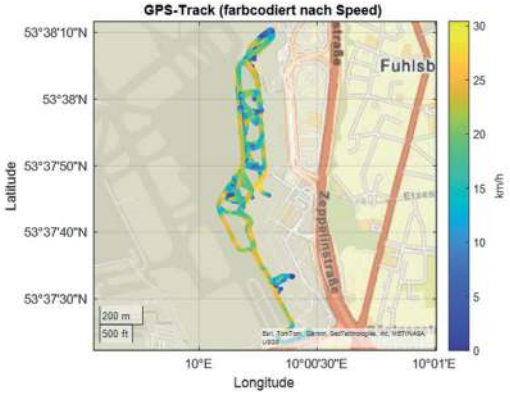

FIGURE 30:
GPS track of Mulag-Movement

EMISSIONS MEASUREMENT

Towards the end of the test period, an emissions measurement was carried out using the latest available prototype version in order to identify and quantify the emissions occurring in the exhaust system. These results are particularly relevant for a potential deployment of the vehicle in areas of the baggage handling system. During the combustion process, hydrogen reacts with ambient air, which can lead in particular to the formation of nitrogen oxide (NOx) emissions. As the engine requires external lubrication, a specially developed lubricating oil is injected in addition to the hydrogen to ensure proper internal lubrication of the engine. The combustion of this oil results in CO_2 emissions, which must be taken into account in the overall evaluation.

The oil used was supplied by the company ROWE with a specific additive formulation tailored to this application. It consists of a base oil and additives. The base oil is of biogenic origin and has a negative CO_2 footprint, while the additives are of fossil origin.

For the test a so called PEMS-measurement system was used to measure Emissions (CO2, NOx and CO). PEMS stands for “Portable Emission Measurement System” and is a mobile device to measure exhaust emissions directly at the exhaust of a vehicle. The device is directly connected to the ending of the exhaust pipe. In Figure 31 the installation of the system on the car as well as the piping can be seen. The system measures the named emissions in real life operations and in real time. The test was carried out with two drivers with different tasks and weights for approximately 1 hour each, as the systems battery only lasts 70 minutes. In the tables below, the results of the measurements can be seen.

The following information is available for classifying the lubricant used:

PCF SUNSPEED oils:

For the base oil, a certified life cycle assessment (LCA) from the manufacturer is available. However, no reliable primary data are available for the additives, meaning that only general secondary data can be used for their evaluation.

The base oils exhibit a Global Warming Potential (GWP) of approximately –0.50 kg CO_2e/kg, with the following shares:

SUNSPEED H2 SAE 5W-30 ca. 73%
SUNSPEED H2 Rotary Engine Oil ca. 83%

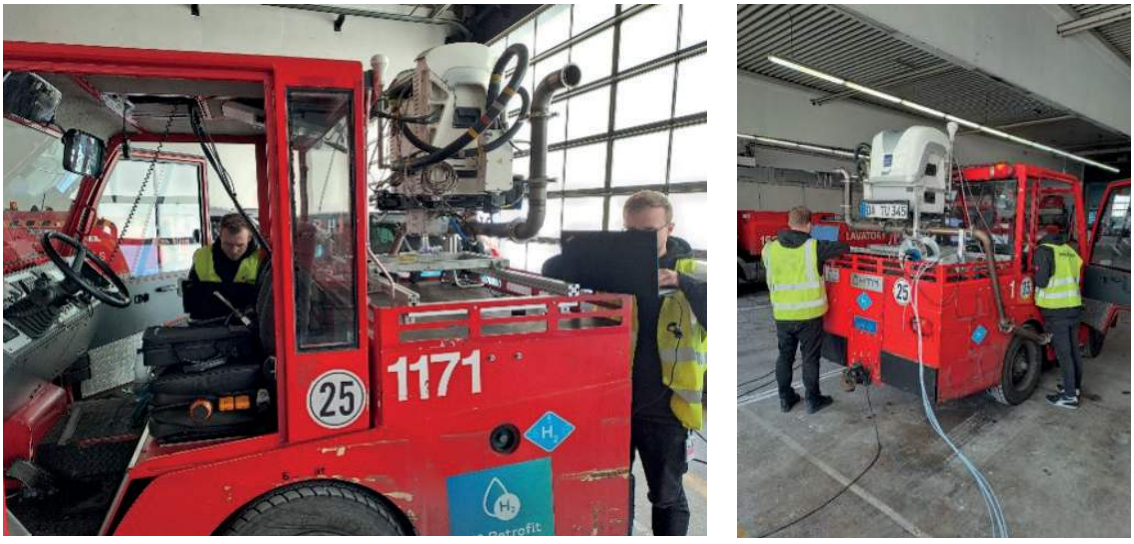

FIGURE 31:
Emissions measurement setup (PEMS)

The following Table 10 presents the emission measurements from the respective test runs.

CO2-Emissions:

		Specific emissions in g/kWh (without ambient-CO_2) of the measured operations	Typical Emissions Diesel Engine g/kWh	Typical Emissions CNG-Engine g/kWh	Relative Value Emissions compared with Diesel-Engine	Relative Value Emissions compared with CNG-Engine
Driver 1	CO_2	7,0	824,2	770	-	-
Driver 2	CO_2	10,5			-	-
Mean	CO_2	8,75			1,06 %	1,14 %

TABLE 10:
CO_2-Emissions measurement

- *Average specific consumption of a diesel engine: 260 g diesel/kWh_mech (≈32.6% average efficiency), emission factor diesel: 3.17 g CO_2 per g diesel*
- *Average specific consumption of a natural gas engine: 280 g natural gas/kWh_mech (≈25.9% average efficiency), emission factor natural gas: 2.75 g CO_2 per g natural gas (assuming pure methane)*

Pollutant emissions:

		Specific Emissions in g/kWh of the measured operations	EU V Limit value for diesel engines of this engine class g/kWh	Relative value Emissions compared to EU V Limit Value
Driver 1	NOx	1,15	2,7	42,6 %
	CO	close to the detection limit	5,0	-
Driver 2	NOx	2,1	2,7	77,8 %
	CO	0,18	5,0	3,6 %

TABLE 11:
Pollutant emissions measurements

Note: *HC and particulate emissions cannot be measured with the PEMS system. For NOx, there is only a combined limit value together with HC, specifically: NOx + HC < 2.7 g/kWh. On the test bench for this particular engine, the average HC emissions upstream of the catalyst are approximately 0.5 g/kWh. Under warm operating conditions, the catalyst oxidises the majority of the HC (around 90%) into CO_2, resulting in values close to the detection limit. Therefore, only NOx was considered for the comparative evaluation in this context.*

4.2 H_2 POWERED WINTER MAINTENANCE EQUIPMENT TESTING AT HELSINKI, RIGA, KAUNAS AND TALLINN AIRPORTS

4.2.1 HELSINKI AIRPORT

The Pilot took place under real Nordic winter conditions, including sub-zero temperatures and snowfall. The average temperature during the Helsinki Airport Pilot was -9 °C and the lowest temperature -24 °C. Furthermore, the truck was tested under typical operational loads relevant to airport winter maintenance, such as towing and ploughing.

Operational data collection focused primarily on qualitative and functional performance rather than detailed quantitative KPIs, due to the pilot nature and limited duration of the demonstration.

For the total duration at Helsinki Airport apron area the vehicle had:

Key-on time	23 hours and 3 minutes
Driving time (of key-on time)	17 hours and 22 minutes
Idle time (of key-on time)	5 hours and 41 minutes
Total distance covered	302 km
Average driving speed (when moving)	17 km/h
Total refuelled / used hydrogen	81,7 kg / 52 kg
Average consumption per distance	19 kg/100 km
Average consumption per hour (moving)	3,0 kg/h

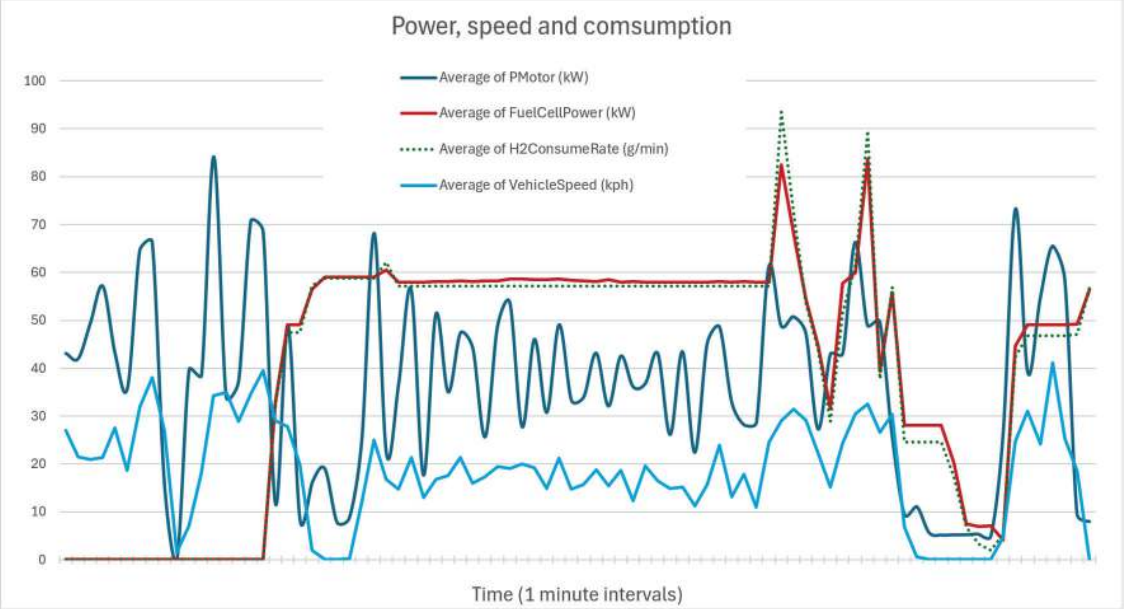

FIGURE 32:
26.1.2026: 90 minute period, average temperature -8 C. "PMotor" is the power produced by drivetrain motor.

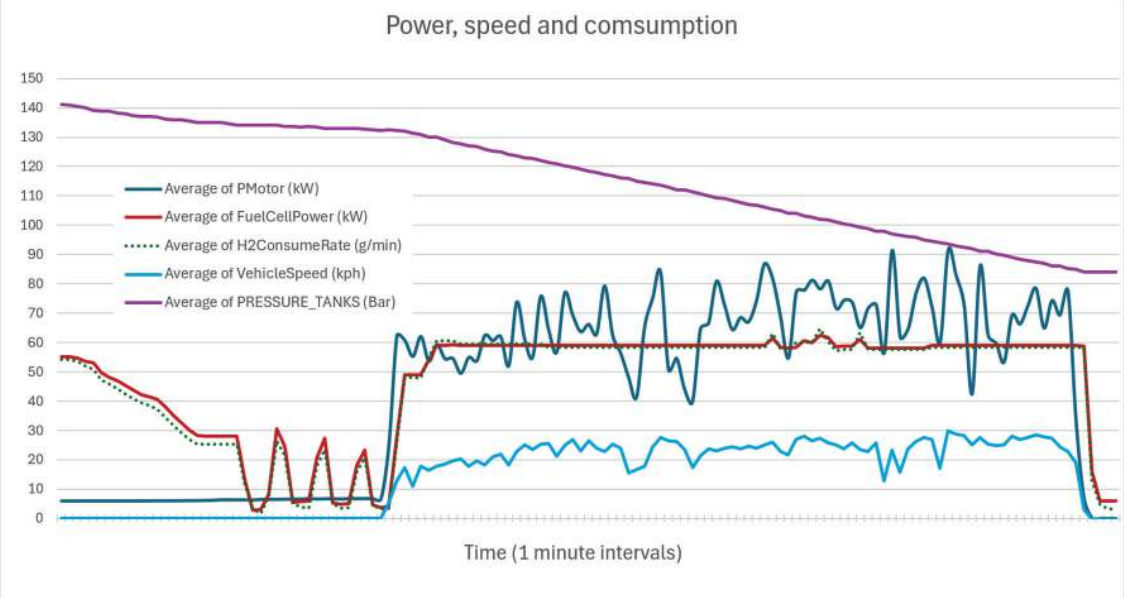

FIGURE 33:
29.1.2026: 130 minute period, average temperature -10 C. "PMotor" is the power produced by drivetrain motor.

As seen in Figure 30 and Figure 31 the drivetrain motor power fluctuates significantly according to vehicle speed (acceleration) and load during ploughing and brushing. The fuel cell power, however, is mostly constant.

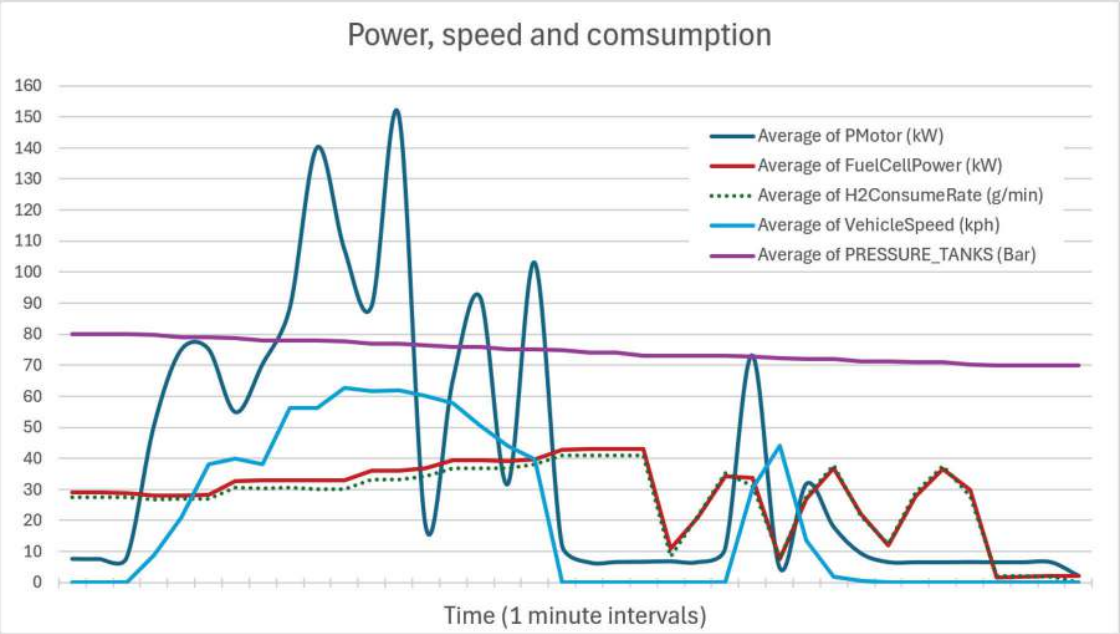

FIGURE 34:
30.1.2026: 38 minute period. Average temperature -14 C. "PMotor" is the power produced by drivetrain motor.

When vehicle combination speed increases up to 63 km/h the power consumption is clearly higher. Figure 32 illustrates that drivetrain motor peak power even exceeds 150 kW momentarily. Since the fuel cell relatively stable power production is significantly lower than used power the difference must be taken from the battery.

On one example day 29 January 2026 measured consumption per distance was **22,9 kg/100 km.** This is calculated by dividing total consumption of 12,96 kg by travelled distance of 56,5 km on that day. The date was selected as an example because on that day there were two relatively long continuous working cycles (see picture 8) which present normal operative winter maintenance use quite well.

It is to be noted, that measuring the consumption per distance is not as straightforward as with traditional combustion engines. This is due to the nature of the fuel cell + battery system which often recharges the battery also when the vehicle is not moving. The graph shows how the consumption stays relatively high during the rest interval of 66 minutes between the driving cycles. Therefore, the calculation of consumption for short periods of time or distance is not feasible. It is rather more recommended to measure the consumption for the duration of the one or even several refills.

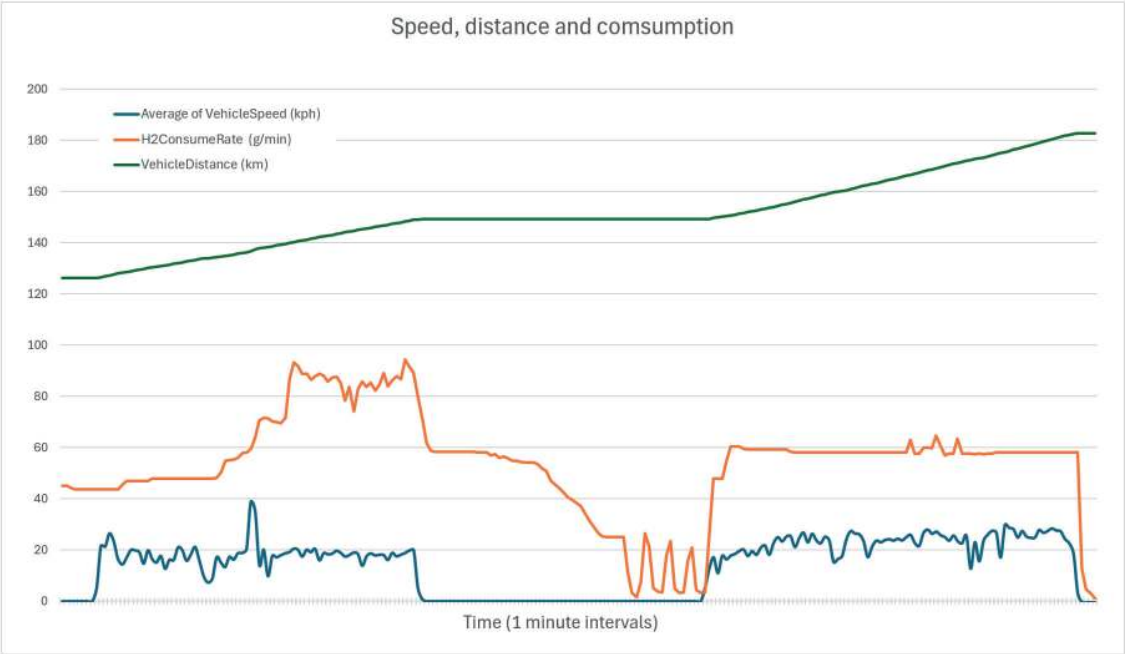

FIGURE 35:
29.1.2026: 4 hour period including two working (ploughing + brushing) cycles of 76 and 87 minutes.

4.2.2 RIGA AIRPORT

The piloting at Riga Airport winter conditions included sub-zero temperatures and snowfall as well above zero. During the Riga Airport Piloting the lowest temperature was –16 °C on 16.02.2026 during training. Furthermore, the truck was tested under typical operational loads relevant to airport winter maintenance, such as towing and ploughing.

The testing focused on evaluating the operational performance of a hydrogen-powered snow removal vehicle during real airport winter maintenance activities. The assessment examined how effectively the vehicle could perform snow-clearing duties, maintain reliable operation over extended working periods, and operate under varying weather conditions.

Performance data collection concentrated on hydrogen consumption, operational efficiency, mileage achieved, total operating hours, reliability during daily airport activities, and behaviour under cold-weather conditions. The tests also assessed the consistency of vehicle performance during snow removal operations and the practical aspects of hydrogen refuelling during airport use.

For the total duration testing at Riga Airport apron area the main parameters are described in Table 12.

Key-on time	40 h 40 minutes
Total distance covered	179 km
Average driving speed (when moving)	15 km/h
Used hydrogen	31,01 kg
Average consumption per distance	17,32 kg/100 km
Average consumption per hour (moving)	0,78 kg/h

TABLE 12:
Main testing parameters at Riga Airport

The weather conditions are described in tables X2 and X3. We can see that most of testing period there was snow cover (gradually decreasing amounts), also the temperature was below 0 degrees C, and the temperature increased over time, testing ended with stable positive temperatures (above freezing).

Test day	Temp. range C
16.02.2026 09:00 – 13:00	(-16.0) - (-13.0)
19.02.2026 10:50 – 11:40	(-7.5) – (-6.7)
20.02.2026 13:00 – 21:45	(-3.5) – (-3.0)
21.02.2026 09:00 – 09:30	(-5.8) – (-5.2)
24.02.2026 09:00 – 11:00	(-0.5) – (-0.8)
25.02.2026 16:00 – 17:40	(-1.8) – (-3.7)
26.02.2026 20:20 – 21:20	(-0.4) – (-0.2)
27.02.2026 14:00 – 15:00	3.7 – 3.6
28.02.2026 10:00 – 11:00	3.6 – 4.1
01.03.2026 14:45 – 15:30	6.4 – 7.5
02.03.2026 11:00 – 12:00	2.2 – 3.0
03.03.2026 10:00 – 21:30	0.1 – 3.4
04.03.2026 19:30 – 21:00	2.9 – 3.4
05.03.2026 12:20 – 21:30	5.0 – 1.9

Data source: Latvijas vides, ģeoloģijas un meteoroloģisjas centrs, VSIA

TABLE 13:
Ambient Temperature at Riga Airport during the test drives

Test day	Snow cover (cm)
16.02.2026 09:00 – 13:00	(25)
19.02.2026 10:50 – 11:40	25
20.02.2026 13:00 – 21:45	24
21.02.2026 09:00 – 09:30	24
24.02.2026 09:00 – 11:00	25
25.02.2026 16:00 – 17:40	26
26.02.2026 20:20 – 21:20	24
27.02.2026 14:00 – 15:00	23-22
28.02.2026 10:00 – 11:00	16
01.03.2026 14:45 – 15:30	9
02.03.2026 11:00 – 12:00	5
03.03.2026 10:00 – 21:30	4-1
04.03.2026 19:30 – 21:00	0
05.03.2026 12:20 – 21:30	0

Data source: Latvijas vides, ģeoloģijas un meteoroloģisjas centrs, VSIA

TABLE 14:
Weather conditions at Riga Airport - Snow cover thickness

During the testing period, the hydrogen powered truck demonstrated stable and generally efficient performance under normal operating conditions. The vehicle showed relatively low (17,32kg/100km) hydrogen consumption considering the nature of operations and environmental factors.

However, several important observations were identified:

- Temperature sensitivity: At low temperatures (below -13°C), e.g. during training, the system performance decreased as indicated by the drivers. It was observed that battery discharged faster than it could be replenished by the hydrogen fuel system, indicating reduced efficiency in cold weather conditions.
- Energy management balance: The imbalance between battery discharge and hydrogen energy generation suggests that the current system may require optimization for extreme climates, particularly in terms of thermal management and energy distribution.
- Operational efficiency: Despite the challenges in low temperatures, the truck maintained overall functional reliability and completed the test mileage of 179 km without critical failures.
- Hydrogen usage (31.01 kg over 179 km) indicates that consumption rates may vary depending on environmental conditions and operational load, highlighting the importance of adaptive energy management strategies.

4.2.3 KAUNAS AIRPORT

The piloting at Kaunas Airport winter conditions included above zero temperatures without snow-fall. During the Kaunas Airport Piloting the lowest average temperature was 4.7 °C on 08.03.2026 during initial staff training. During one week, the truck was tested under typical operational loads relevant to airport winter maintenance, such as towing and sweeping

The testing focused on evaluating the operational performance of a hydrogen-powered snow removal vehicle during real airport winter maintenance activities. The assessment examined how effectively the vehicle could perform snow-clearing duties, maintain reliable operation throughout extended working periods, and function under varying weather conditions.

Performance data collection concentrated on operational efficiency, hydrogen consumption, mile-age achieved, reliability during daily airport activities, and behaviour under no freezing weather conditions. The tests also assessed the consistency of vehicle performance during snow removal operations and the practical aspects of hydrogen refuelling during airport use.

For the total duration testing at Kaunas Airport apron area the main parameters are described in Table 15.

Total distance covered	101 km
Average driving speed (when moving)	15 km/h
Used hydrogen	16 kg
Average consumption per distance	16 kg/100 km

TABLE 15:
Main testing parameters at Kaunas Airport

The weather conditions are described in Table 16. During most of the testing period, snow and ice cover were minimal, the temperature remained above 0 degrees C, and the temperature gradually increased over time (except the last day).

Test day	Temp. average C
08.03.2026	4.7
09.03.2026	5.2
10.03.2026	6.3
11.03.2026	6.6
12.03.2026	8.9
13.03.2026	8.5
14.03.2026	10.6
15.03.2026	9.7
16.03.2026	9.9
17.03.2026	6.1

Data source: Kaunas aerodrome operational data

TABLE 16:
Ambient Temperature at Kaunas Airport during the test drives

4.2.4 TALLINN AIRPORT

The Tallinn Airport demonstration was conducted on 16 March 2026. Due to the short demonstration period and the absence of significant snowfall, quantitative data collection was more limited than during the longer demonstrations at Helsinki and Riga Airports. During the Tallinn demonstration, the vehicle covered approximately 35 km in airport operational areas and during associated vehicle movements. The vehicle was tested together with the Vammas-Vitera SB3600 sweeper-blower, including functional operation of the brush and blower systems. However, no actual snow-clearing operation was required during the demonstration.

Consequently, representative hydrogen consumption under winter maintenance load could not be calculated. A total of 18.6 kg of hydrogen was refuelled during the Tallinn pilot; however, this value represents the refuelling event and should not be interpreted as hydrogen consumption over the 35 km demonstration distance.

No critical technical failures or operational interruptions occurred during the Tallinn test. The hydrogen drivetrain, snowplough controls and sweeper-blower functions operated as expected during the functional tests. No hydrogen leaks were detected. Detailed key-on time, driving time and idle time were not recorded in a form that allows reliable quantitative comparison with the Helsinki and Riga demonstrations. Therefore, no average consumption per operating hour or per kilometre is reported for Tallinn.

From a technical perspective, the demonstration confirmed the basic functionality of the hydrogen-powered truck and associated winter maintenance equipment. However, a longer testing period under representative snowfall, sub-zero temperatures and full auxiliary load would be necessary to establish meaningful quantitative performance and consumption indicators.

4.2.5 BUS ROAD SHOW

RESULTS FROM THE TEST DRIVES OF THE FUEL CELL BUS DURING THE NORDIC BUS ROADSHOW IN FINLAND AND SWEDEN

The bus was driven across Finland and Sweden, traveling over 1,900 km. During Roadshow test trial activities, the fuel cell bus drove a total of 645.30 km and consumed 37.87 kg of hydrogen. The distribution of distance travelled per city is shown in Figure 36, and the fuel efficiency per city is shown in Figure 37.

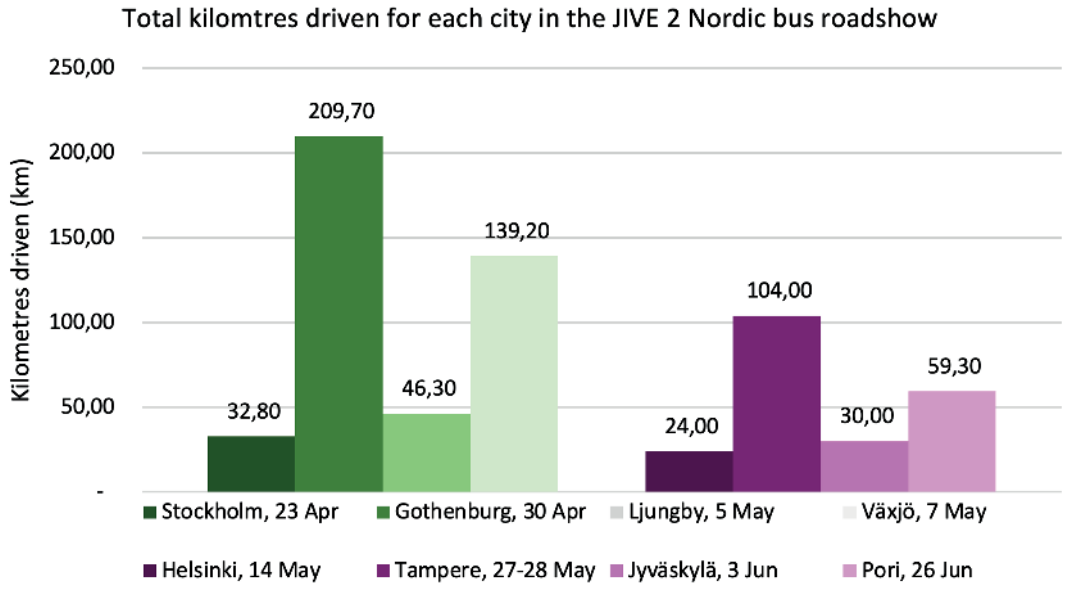

FIGURE 36:

otal kilometres driven for each city in the JIVE 2 Nordic bus roadshow

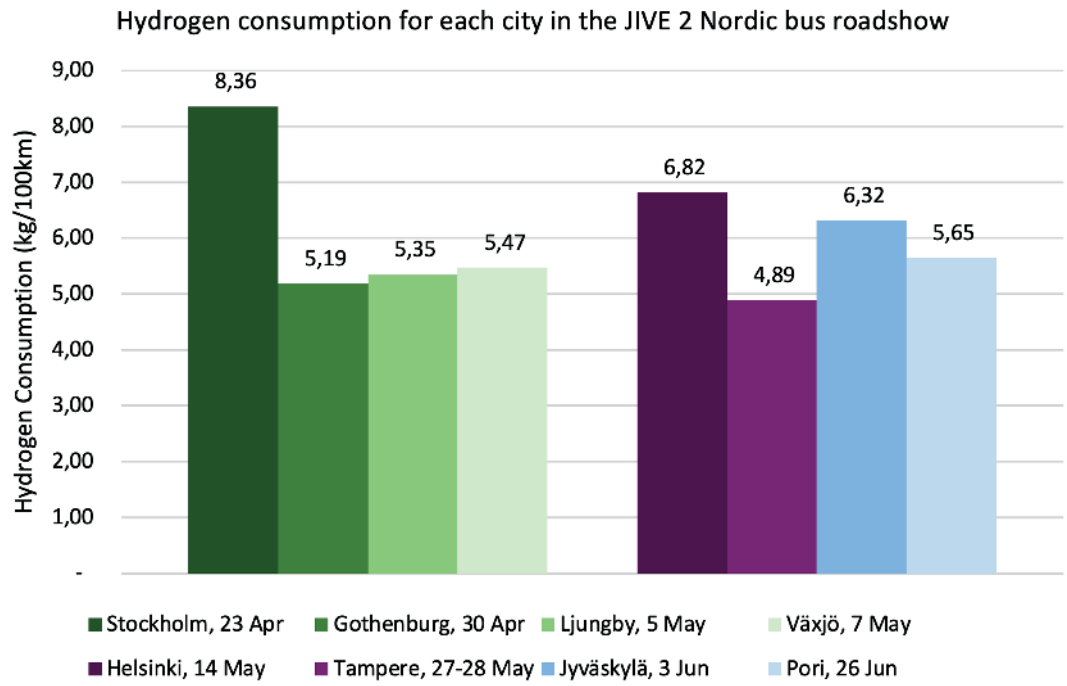

FIGURE 37:

Hydrogen consumption for each city in the JIVE 2 Nordic bus roadshow

The average hydrogen consumption during the Sweden and Finnish leg of the Roadshow was 5.55 kg/100km and 5.54 kg/100km, respectively. This is lower than the average fuel consumption in JIVE 2 which is 7.4kg/100km, and lower than the 3rd CEE Roadshow's consumption of 5.92 kg/100 km. The breakdown of efficiency per city is shown in Figure 37. This low consumption level indicates high energy efficiency and reflects favourable operational conditions during the trials. It should be noted that higher consumption at the trials in Stockholm (23 April) and Helsinki Airport (14 May), compared to other trials, was due to increased idling times (referring to when a bus's engine is running while the vehicle is not in motion) relative to the distance driven.

There were many factors affecting the bus's fuel efficiency, which changed from city to city:

- Terrain: The overall flat topography was likely a contributing factor to the low hydrogen consumption observed during the test period. However, this did vary in some cities (namely Tampere and Jyväskylä) where hilly terrains were encountered, and the steeper inclines contributed to reduced fuel efficiency and a higher level of consumption.
- Passengers: Throughout the duration of the roadshow, the bus was operated with and without passengers depending on whether it was taking part in a test trial or travelling between city stops. If buses are in operation with passengers, the added weight tends to increase the energy requirements of the bus, lowering fuel efficiency.
- Driver's experience. The experience held by the bus drivers in operating electric buses contributed to professional and calm driving experience throughout the test trials. Regenerative braking was used effectively, contributing to the vehicle's overall efficiency. The smooth and consistent driving style helped maintain low hydrogen consumption.

The demonstrations and workshops initiated by the JIVE 2 Nordic Roadshow sought to show participating cities that fuel cell busses and their associated refuelling infrastructures are ready for deployment in their area. Bus operators, drivers, passengers, and politicians were able to experience the technology for themselves during the roadshow. Notably, the JIVE 2 Nordic Roadshow saw the marked the first time in the Nordic region of Europe that a hydrogen-powered vehicle was used airside to transport passengers from the aircraft to the terminal, as part of the test trial in Helsinki on 14 May 2025.

VEHICLE PERFORMANCE AT HELSINKI AIRPORT

During the Finnish demonstration activities included:

Parameter	Value
Distance travelled	217 km
Hydrogen consumption	12.0 kg
Average consumption	5.54 kg/100 km

The demonstration indicated a good level of energy efficiency under practical operating conditions. Hydrogen consumption was influenced by route profile, passenger load, vehicle idle time, driving style and ambient operating conditions. It is estimated that outside temperature has a significant effect on the consumption (per hour or per passenger operation) since cooling and heating consume a lot of energy. During this trial the weather conditions were mild: approximately 15-20°C.

DRIVERS' AND PASSENGERS' EXPERIENCES

In Sweden, the feedback from drivers across the test trial locations was consistently positive. Several drivers highlighted that the Caetano hydrogen bus drove very similarly to a high-quality battery electric bus, with smooth acceleration, responsive handling, and low noise levels. Even though



FIGURE 38:
The hydrogen bus was operated in mild conditions at Helsinki Airport

most drivers had no prior experience with fuel cell technology, they adapted quickly and felt confident behind the wheel. The regenerative braking was intuitive and contributed to a seamless driving experience. Overall, the bus was described as modern, comfortable, and easy to operate – a vehicle that would integrate well into regular operations from a driver's perspective.

Approximately 500 individuals trialled the fuel cell bus during the Swedish leg of the roadshow. This included municipal officials, transport professionals, journalists, students, and members of the public who participated in demonstration events across Stockholm, Gothenburg, Ljungby, and Växjö. The broad level of engagement reflected strong interest in the technology and exposed the technology to a wide audience. Passenger feedback during the Swedish roadshow was highly positive. Many described the ride as quiet, smooth, and modern, noting the low interior noise and absence of vibration compared to diesel buses. Several passengers expressed surprise at how similar the experience was to that of a high-end electric bus. The clean design, fast boarding, and stable ride contributed to a professional and comfortable impression. The bus was perceived as a serious and mature transport solution, not a prototype. Overall, the response from passengers reinforced the perception that fuel cell busses are ready for public service in Sweden.

TECHNICAL OBSERVATIONS AT HELSINKI AIRPORT

The vehicle demonstrated stable fuel cell operation and consistent driving performance. Even though the bus was not refuelled at the airport the range was estimated to be adequate for operational airport use. No significant technical limitations were detected during the demonstration period.

The results confirm that fuel cell bus technology has reached a level of maturity suitable for operational demonstrations and pilot deployment.

REFUELLING STATION PERFORMANCE

During the Swedish test trials, all refuelling was carried out using permanent hydrogen refuelling stations (HRS). The use of Sweden's existing HRS infrastructure proved highly effective, with no reported issues or delays. Refuelling was completed quickly and safely, underscoring that the current network can support fuel cell bus operations. The ability to rely on fixed stations further strengthens the case for broader deployment of hydrogen buses in Sweden without requiring temporary or mobile setups.

Outline of the bus's performance during Roadshow test trial activities

During the fuel cell bus trial	Sweden	Finland	TOTAL/AVERAGE
Bus KPI			
Total distance travelled	428.00 km	217.30 km	**645.30 km**
Hydrogen used	25.84 kg	12.04 kg	**37.87 kg**
Average Hydrogen Consumption data	5.55 kg/100 km	5.54 kg/100 km	**5.545 kg/100 km**
Average outside temperature	5 - 15°C	16 °C (average)	-
Landscape	Overall, the topography was flat with no mountainous or steep terrains.	Mixed landscape with some cities consisting of flat routes, whilst some (Tampere and Jyväskylä) contained steeper landscapes.	-
Average speed	34.675 km/h	31.675 km/h	**33.175 km/h**

5 ECONOMIC DATA SUMMARY

Chapter 5 summarises the economic findings derived from the hydrogen-powered airport equipment demonstrations conducted at Hamburg, Helsinki, Riga, Kaunas and Tallinn Airports, as well as from the Bus Road Show. Building on the operational and technical assessment presented in the previous chapters, this chapter focuses on the economic implications of introducing hydrogen-powered vehicles and associated refuelling solutions into airport environments. The economic evaluation considers key cost drivers such as vehicle acquisition or retrofit costs, temporary refuelling infrastructure, hydrogen supply and logistics, maintenance requirements, operational availability and potential scalability effects. Where available, the analysis also reflects comparative considerations against conventional diesel, CNG or battery-electric alternatives in order to assess the economic maturity and competitiveness of hydrogen-based solutions.

The purpose of this chapter is not to provide a final investment decision for all use cases, but to establish an indicative economic basis for understanding the cost structure, financial challenges and future optimisation potential of hydrogen-powered airport equipment. The findings therefore support the subsequent conclusions and recommendations by identifying where hydrogen applications may already offer strategic value, where cost barriers remain, and which framework conditions would be required for broader deployment in airport operations.

5.1 H_2 VEHICLE TESTING IN HAMBURG AIRPORT

The economic evaluation of the hydrogen retrofit demonstration for the MULAG baggage tractor at Hamburg Airport is based on operational data collected during real-life deployment as well as dedicated testing under defined conditions. As the project was carried out with a prototype vehicle and a temporary infrastructure setup, the results should be interpreted as indicative rather than fully representative of long-term, large-scale operation.

A central parameter for the economic assessment is the observed hydrogen consumption. The vehicle achieved an average consumption of approximately 0.988 kg of hydrogen per operating hour over more than 200 operating hours. This figure reflects mixed operational conditions, including active-duty cycles and idle periods, and therefore provides a realistic basis for estimating operational fuel costs. However, the data is subject to a certain degree of uncertainty due to intermittent failures of the data logging system during the test period. From an efficiency perspective, the hybrid drivetrain demonstrated advantages compared to conventional CNG systems, primarily due to the integration of an electric motor and battery that enables energy recuperation. Despite this efficiency benefit, the overall hydrogen consumption remains higher for the H2 ICE than that of comparable fuel cell systems, which directly affects operating costs in comparison to alternative zero-emission technologies.

A further important cost driver identified during the demonstration is idle operation. The analysis showed that a significant portion of fuel consumption occurs when the vehicle is stationary with the engine running. It was estimated that the introduction of a start-stop system could reduce total fuel consumption by up to 15%, indicating a clear opportunity for future optimisation and cost

reduction. Integrating such a system is a topic for future development.

Maintenance-related costs were also influenced by the prototype nature of the system. During the test period, several technical adjustments and unplanned interventions were required, including modifications to subsystems such as cooling and the battery system. These activities resulted in additional effort and occasional downtime, which would not be expected at the same level in a fully mature system. At the same time, the retrofit approach itself represents a potentially cost-efficient strategy from a capital expenditure perspective. By reusing existing vehicle platforms and replacing only the powertrain and associated systems, the need for complete vehicle replacement can be avoided. This can extend the service life of existing assets and reduce investment costs, particularly in situations where full electrification is not yet feasible due to infrastructure limitations.

Overall, the economic results show that while the current prototype-based operation involves higher costs due to limited scale, temporary infrastructure, and ongoing optimisation, the hydrogen retrofit concept offers clear potential for cost improvements. With further technological development, increased system efficiency, and the implementation of permanent hydrogen infrastructure, the Total Cost of Ownership is expected to decrease significantly. It is well established that hydrogen-based applications generally entail higher operating costs compared to battery-electric solutions. However, within a retrofit approach, significantly reduced capital expenditure may offset these higher operating costs, potentially resulting in a Total Cost of Ownership (TCO) that is comparable to or even lower than that of fully electric alternatives. A comprehensive economic assessment must also take into account the required supporting infrastructure, whether for vehicle charging or hydrogen refuelling. Depending on the specific location and implementation concept, these infrastructure-related costs can vary considerably and effect the comparison of both options. The demonstration therefore provides a valuable foundation for evaluating the economic viability of hydrogen-based retrofit solutions in airport ground support equipment fleets.

As several cost indications related to the retrofit are subject to non-disclosure agreements, this analysis cannot disclose detailed pricing information. Consequently, the results are presented at a more aggregated level.

5.2 H_2 POWERED WINTER MAINTENANCE EQUIPMENT TESTING AT HELSINKI, RIGA, KAUNAS AND TALLINN AIRPORTS

5.2.1 HELSINKI AIRPORT

The Helsinki Airport Pilot provides indicative economic data on hydrogen use, hydrogen logistics and the cost structure of a temporary demonstration setup. During the pilot, the refuelled hydrogen amount was a total of 81,7 kg of gaseous hydrogen. The pilot started with 0 kg hydrogen in the vehicle and ended with approx. 25 kg hydrogen in the vehicle, therefore the used hydrogen amount was approximately 52 kg. Distance covered was 302 km at the airport. The energy consumption includes some high voltage battery recharging from the grid which lowers the average

hydrogen consumption slightly. The recharged energy, however, was not measured. Based on these figures, the average hydrogen consumption was approximately 19 kg/100 km. The hydrogen commodity price was approximately EUR 12/kg, resulting in a direct hydrogen cost of about EUR 690 in total, which corresponds to approximately **EUR 2,3 per kilometre.** During heavy work cycles the consumption of hydrogen was significantly higher than the average

In addition, hydrogen transport cost was approximately EUR 1 500 for a delivery distance of around 200 km (one-way) which would in the case of the Pilot with 302 driven kilometres on the apron translates to approx. 5 EUR per kilometre. An alternative and more realistic way to interpret the transport cost is to allocate the delivery cost across the full hydrogen content of the transported container instead of only the hydrogen consumed during the Helsinki pilot. The container used in the pilot held approximately 300 kg of hydrogen. If the same approximately EUR 1 500 transport cost for a 200 km delivery is divided by the full 300 kg container content, the transport cost per kilometre becomes significantly lower if the full container is utilised in vehicle operations. With the Helsinki pilot consumption level of approximately 19 kg/100 km, full utilisation of a 300 kg hydrogen container would correspond to about 1 600 km of driving. On that basis, the transport cost would still be approximately EUR 1 500 per container delivery but spread over about 1 600 km this would correspond to approximately **EUR 0,9 per kilometre.** This illustrates that transport cost efficiency improves materially when a larger share of the delivered hydrogen is used for operations, and it would improve further if both utilisation increased and delivery distance decreased or especially if the hydrogen would be produced locally at the airport. It may also be possible to combine the transport of two containers which would naturally cut the transport cost roughly by 50 %.

Therefore, the combined variable hydrogen commodity and transport cost was approximately **EUR 3,2 per kilometre.**

In addition to variable hydrogen and transport costs, the Helsinki demonstration required temporary refuelling infrastructure with relatively high fixed monthly costs. The rental cost of the temporary hydrogen refuelling unit was approximately EUR 8,350 per month, and the hydrogen container rental was approximately EUR 5,000 per month. Together, these infrastructure rental costs amounted to approximately EUR 13,350. This amount is in not fully representative of long-term operation but rather reflects the level of fixed costs of a temporary rental-based infrastructure solution. In a steady-state solution with longer utilisation time, higher hydrogen volumes and permanent infrastructure arrangements, the fixed-cost burden (especially calculated per kilometre driven) would be clearly lower.

Helsinki Airport pilot also incurred direct local setup and compliance costs. Inspections and similar authority-related direct costs were initially approximately EUR 1,000, including the electrical conformity inspection required before operational use. In addition, the airport incurred internal work costs for the grounding arrangements of the refuelling unit and related site preparation activities. While these internal labour costs were not quantified separately in this report, they form part of the actual implementation cost of the pilot and should be included in any more detailed airport-level cost review.

Taken together, the Helsinki pilot demonstrates that the economics of hydrogen operation in a short demonstration are driven less by fuel cost alone and more by temporary infrastructure, logistics and setup requirements. Based on the figures available, the direct hydrogen commodity and transport cost for the hydrogen consumed during the pilot was approximately EUR 3,2 per kilometre. For future deployment decisions, the most important economic variables are likely to be local hydrogen supply distance, utilisation rate of the refuelling infrastructure, permanence of

the installation, achieved vehicle availability, and the extent to which one-off permitting and setup activities can be avoided or standardised.

5.2.2 RIGA AIRPORT

Although economic aspects of technologies supporting moving closer to Net Zero 2035 goal for Riga Airport is important, the main objective for testing was to understand the overall technical feasibility, potential issues and hidden costs. Currently in Baltic states the H2 market is very under-developed and lacks demand and competition. So the prices are higher than in Nordic countries or Germany with more stable demand. Also, the H2 powered snow cleaning equipment for airports is not yet commercially available. The concept was proven to work, but the costs for any testing are higher than everyday operations. This is why there is no clarity on potential costs, however, some estimates could be calculated.

During the pilot, the refuelled hydrogen amount was a total of 31 kg of gaseous hydrogen. The total distance travelled was 179 km. H2 consumption for snow cleaning equipment was 17,32 kg/100 km, which is a bit lower than consumption in Helsinki Airport.

The costs in normal market conditions could be calculated as follows. During the testing period H2 supply and storage unit replacement was provided by external service provider “AI Cooperation” SIA, Riga Airport consulted one of gas market leaders Elme Messer Gaas about the pricing of the H2 in larger amounts. The overall price estimate was not less than 16 EUR/kg (including transportation costs). From that it can be estimate that costs for just hydrogen would be 2.77 EUR/km. There were no maintenance issues during testing, but before the testing in Riga Airport the high voltage battery broke down, the costs were covered by equipment provider (Zerobus OU), causing 2 week delay, but during testing only maintenance by Riga Airport was adding distilled water to the fuel cell of testing equipment (Hyzon truck).

The testing at Riga Airport was conducted only using standard load the VAMMAS snow sweeper-blower and the amount of snow varied, in some days it was cleaning the apron the rain or melting water.

5.2.3 KAUNAS AIRPORT

The Kaunas Airport pilot provided limited economic information due to the short demonstration period.

During the pilot, the refuelled hydrogen amount was a total of 16 kg of gaseous hydrogen. The total distance travelled was 101 km. H2 consumption for snow cleaning equipment was 16 kg/100 km, which is a bit lower than consumption in Riga Airport which results due to the lower snowfall and thus lower utilisation of power.

5.2.4 TALLINN AIRPORT

The Tallinn Airport pilot provided limited economic information due to the short demonstration period and the absence of operational snow-clearing activities.

The demonstration required one hydrogen refuelling event and recorded hydrogen purchase of 18.6 kg at a total hydrogen cost of €210.

This corresponds to:

- Hydrogen cost: approximately €11.3/kg H_2
- Hydrogen plus refuelling service cost: approximately €14.0/kg H_2

No direct maintenance or repair costs were reported for the Tallinn demonstration. However, the use of an external public hydrogen refuelling station generated indirect operational costs that were not quantified separately during the pilot.

These indirect costs included staff time, vehicle travel between Tallinn Airport and the external refuelling station, preparation of the winter maintenance vehicle for public-road transport, and the time required for security procedures when the vehicle returned to the restricted airport area. Consequently, the hydrogen purchase price alone does not represent the full operational cost of the Tallinn refuelling concept. For regular fleet operation, these indirect costs and the associated loss of equipment availability would need to be included in the economic assessment.

Due to the absence of active snow-clearing operations and the lack of long-term operational data, it was not possible to determine:

- cost per operating hour;
- cost per kilometre;
- cost per square metre of snow cleared;
- total cost of ownership (TCO).

The Tallinn demonstration showed that the use of existing public hydrogen infrastructure can minimise the initial infrastructure investment required for a short pilot. However, this approach transfers part of the cost from infrastructure investment to operational logistics, particularly vehicle travel, staff time and reduced equipment availability.

A longer demonstration under representative winter maintenance conditions would be required to establish robust operating-cost indicators and to compare the hydrogen-powered vehicle directly with conventional diesel or battery-electric winter maintenance equipment.

5.3 BUS ROAD SHOW

The Bus Road Show was primarily intended as a technology demonstration and awareness-building activity rather than a full economic evaluation. However, some observations can be made. Firstly, fast refuelling can provide operational advantages compared with battery-electric solutions in high-utilisation applications since vehicle availability can be maintained without long charging breaks. Secondly, future economics will depend strongly on hydrogen availability, refuelling infrastructure utilisation and hydrogen production costs.

For airport applications, the economic attractiveness of hydrogen-powered passenger transport is expected to improve as hydrogen supply infrastructure develops, and utilisation rates increase. The demonstration also highlighted the potential value of shared hydrogen infrastructure supporting multiple airport vehicle categories, thereby improving overall infrastructure utilisation and reducing unit costs.

6 CONCLUSIONS

Building on the operational, technical and economic assessments presented in the preceding chapters, this chapter draws overall conclusions regarding the feasibility, maturity and practical suitability of hydrogen-powered vehicles and associated refuelling solutions in airport environments. The conclusions are structured by demonstration case in order to reflect the different use cases, vehicle technologies and operational settings assessed during the project. This includes the hydrogen retrofit baggage tractor tested at Hamburg Airport, the fuel cell baggage tractor demonstrated at Riga Airport, the hydrogen-powered winter maintenance equipment tested across several Baltic Sea Region airports, and the hydrogen bus application demonstrated in airport passenger transport.

Overall, the chapter aims to identify the main lessons learned from the pilots, including strengths, limitations, safety-related considerations, infrastructure requirements, operational integration aspects and remaining barriers to broader deployment. The conclusions provide the basis for the subsequent recommendations by highlighting where hydrogen-powered airport equipment already shows practical potential and where further technological, organisational or economic development is required before large-scale implementation can be considered.

6.1 H_2 VEHICLE TESTING AT HAMBURG AIRPORT

In summary, the test operation demonstrates that the hydrogen-powered retrofit concept for baggage tractors is fundamentally technically functional and operationally viable under the specific boundary conditions of the airport. The vehicle was successfully operated over a relevant period of time and showed particular advantages compared to the investigated CNG reference vehicles in terms of efficiency and torque characteristics. At the same time, the technical adjustments required during the test, the increased organisational effort associated with infrastructure, permitting, and operation, as well as the need for further optimisation regarding noise behaviour, clearly indicate that the system remains a prototype with ongoing development requirements. Overall, the results show that hydrogen-based retrofit solutions can represent a viable approach for the lower-emission continued use of existing vehicle platforms, provided that technical maturity, operational integration, and accompanying safety and infrastructure measures are further developed. Generally, it is important to mention that the hydrogen propulsion is at a mature phase, only the architecture around it needs to be developed as peripheral systems sometimes tended to fail.

In addition, targeted training of operational personnel is required for continuous and stable operation. This particularly applies to ground handling staff as well as workshop and maintenance personnel, in order to ensure safe handling, repair work, and integration into regular operations.

One of the key findings from the test operation is that prototype systems with hydrogen propulsion require close technical monitoring, and that continuous support by (internal) experts is a critical success factor. Furthermore, it has been shown that trained personnel should be permanently available within the organisation to address faults, maintenance requirements, and safety-related issues promptly.

The test operation involved employees from various disciplines, including vehicle operators, technical services, project managers, and external partners responsible for workshop provision, system development, and infrastructure. Interdisciplinary collaboration proved to be essential for both the execution of the test and the iterative development of the system. In addition, it is crucial for such tests that qualified technical contacts are continuously available on-site. The test must be closely supervised at all times, adjustments must be monitored, and all stakeholders must be actively coordinated.

During the test, it was often necessary to carry out hands-on interventions in order to restore operational capability at short notice. In this case, these tasks were taken on directly by the project manager. For future implementations, it will be important to ensure that appropriate certifications and authorisations are in place for such activities. Furthermore, it is advisable to keep spare refuelling couplings in stock, as failures occurred during the test due to malfunctions and suitable replacement parts were not readily available within the required timeframe.

Furthermore, for a continuous operation besides the pilot demonstration phase, drop-and-swap hydrogen trailer delivery should occur landside, as otherwise the delivery takes a lot of effort and time. If it is possible for an airport operator to store the trailer landside with easier access for deliveries and refuel landside, a lot of effort and time can be saved.

Due to the positive results, after the test, Hamburg Airport procured a set of retrofit systems in order to introduce a small series of hydrogen powered baggage tractors in full operations.

6.2 H_2 FUEL CELL BAGGAGE TRACTOR TESTING IN RIGA AIRPORT

The main challenge experienced during the testing was hydrogen refuelling. At Riga Airport, it was not possible to refuel the tractor to 100% capacity because the refuelling system used during the test was not equipped with a compressor. As a result, refuelling had to be carried out more frequently, which increased downtime and required additional staff time.

Another challenge was the location of the hydrogen refuelling station, which was relatively far from the terminal and active aircraft stands. The tractor's hydrogen tank capacity was only 1.8 kg, which also limited its operating range. The manufacturer planned to increase the tank capacity in order to extend the operating range.

The main challenge was not the technical operation of the hydrogen tractor itself, but rather the hydrogen refuelling infrastructure and limited tank capacity. The drivers did not experience significant difficulties when switching from conventional or electric baggage tractors to the hydrogen-powered tractor. After becoming familiar with the equipment, the drivers were able to operate it without significant problems.

It was also observed that, as the drivers gained experience with the equipment, hydrogen consumption decreased. Overall, driver feedback and attitude were positive, and the transition to the hydrogen-powered tractor did not create significant operational difficulties.

Summary of capital costs and operational costs for the tested model and alternative power type equipment:

Model	Procurement cost	Repair costs/year	Refuelling/charging costs/year	Average total costs/year
MULAG Comet 4FC – Hydrogen	€160,000–199,000	€1,800	€3,600	**€16,388**
MULAG Comet 4E – Electric	€70,000–90,000	~€1,800	€322.67	**€6,187**
MULAG Comet 4D – Biodiesel	~€85,000	~€3,000	€2,560.56	**€9,027**

TABLE 17:
Cost comparison for various types of baggage tractors

The calculations are based on an estimated average of 400 motor hours per year. For the hydrogen-powered tractor, the calculation assumes a green hydrogen price of €15/kg. The hydrogen-powered tractor is significantly more expensive in terms of both procurement and operating costs compared with the electric alternative. The electric model has the lowest average annual total cost.

The main infrastructure-related challenge was the hydrogen refuelling system. It was not equipped with a compressor, which prevented the tractor from being refuelled to full tank capacity. The recommendation is future hydrogen refuelling solutions should be equipped with a compressor or higher-pressure storage tanks, for example 450–500 bar tanks.

The MULAG Comet 4FC functioned satisfactorily and was technically capable of performing baggage tractor operations at the airport. The cold-start test was successful with the tractor starting in less than 30 seconds, and no issues were observed, and no significant technical problems were identified during the testing period. No significant technical or operational problems were identified during the testing.

However, practical availability was limited, mainly due to the hydrogen refuelling infrastructure. The average operating time between refuelling events was 4.1 hours, and the need for frequent trips to the refuelling station reduced the tractor's effective availability.

One relevant safety-related event occurred when the hydrogen tank became empty while the integrated electric battery charge was below 50%. The emergency shutdown system activated, followed by activation of emergency mode, which allowed the driver to drive the tractor to the refuelling station.

Compared with the hydrogen- powered tractor, the electric alternative was able to operate for a longer period without refuelling/recharging and was assessed as having better performance under the conditions tested at Riga Airport.

The hydrogen-powered tractor is technically functional and suitable for certain airport operations. However, its use under the current conditions at Riga Airport is limited by the refuelling infrastructure, tank capacity and operating costs. The costs should be reduced for hydrogen powered equipment and the hydrogen fuel production.

6.3 H_2 POWERED WINTER MAINTENANCE EQUIPMENT TESTING AT HELSINKI, RIGA, KAUNAS AND TALLINN AIRPORTS

6.3.1 HELSINKI AIRPORT

The Helsinki Airport pilot demonstrated that hydrogen-powered heavy-duty winter maintenance equipment can be integrated into airport operations and used in real Nordic winter conditions. Even though milder weather conditions (> +10°C) were not included in the test period it can be concluded with high confidence, that the operation of the piloted hydrogen powered vehicle would be as fluent or more fluent during summer season than during cold winter season. The vehicle showed good driving characteristics, sufficient towing and ploughing performance, and strong operator acceptance. At the same time, the pilot highlighted that cold weather, temporary refuelling arrangements and immature vehicle reliability remain critical constraints. The most important lessons learned were the need for robust winterisation of both vehicle and refuelling infrastructure. The pilot also showed that hydrogen-related safety and permitting can be managed successfully within an airport SMS framework when supported by dedicated risk assessments, authority coordination, training and emergency planning. Economically, the demonstration confirmed that short pilot operations are strongly affected by temporary infrastructure, logistics and setup costs rather than fuel cost alone.

Overall, the Helsinki test confirmed technical feasibility and positive user acceptance but also showed that reliable routine deployment requires improved system architecture reliability, higher utilisation of refuelling infrastructure, and more mature vehicle and refuelling solutions for sub-zero conditions. Important to mention is, that the downtimes occurred in the test were results from problems of the battery and energy management system, never due to the hydrogen system itself. This finding significantly indicates that hydrogen can be properly used as a fuel for vehicles, but that the design and architecture and energy management must improve for continuous operations.

6.3.2 RIGA AIRPORT

The conducted testing confirmed that the hydrogen powered truck can perform standard ground support operations with overall stable and reliable performance. The vehicle successfully completed the planned test mileage, demonstrating functional suitability under normal operating conditions and acceptable hydrogen consumption level. However, several limitations were identified during the testing period. The system showed reduced efficiency at low temperatures (below -10°C), where the battery discharged faster than it could be charged by the hydrogen fuel system. This indicates a need for improved energy management and thermal control in cold climate conditions.

In addition, inconsistencies in the hydrogen refuelling process were observed. Specifically refuelling duration increased when the hydrogen level in the stationary storage tank was lower, suggesting potential inefficiencies related to pressure management or refuelling system configuration.

Driver feedback is summarised in the following conclusions. The Hyzon truck was more quiet than conventional equipment, comfortable and easy to use. The refuelling process was relatively simple, but slow when pressure in stationary storage gas cylinders was low as the compressor power was quite low.

Capital costs and operational costs cannot be directly derived from testing experience, but as real fuel provider stated, the minimal cost for H2 delivery (including transportation) woudl be 16 EUR/kg and average cost of hydrogen per km would be 2.77 EUR/km.

During the preparatory phase main tasks were arranging the delivery of equipment, dealing with administrative questions, including safety management system risk assessment, harmonisation and signing of user contract between lessor (Zerobus OU) and the testing organisation (SJSC “Riga International Airport”). The challenge was to get all relevant information on equipment (both the snow plow-blower-sweeper and the mobile refuelling station) and get approvals from airside management. Additionally, there was a 2 week delay for delivery to Riga Airport.

In order to ensure the testing of the above-mentioned equipment at the Riga Airport airfield, a safety risk assessment had to be provided, because the mentioned equipment was different from the equipment currently used at Riga Airport. The safety risk assessment was implemented within the airport SMS and an additional external risk assessment process was not necessary. During the safety risk assessment, no unacceptably high risks were identified, provided that the mentioned equipment is operated in accordance with the requirements specified by the equipment manufacturers and the process procedures specified at the airfield.

There was minimal maintenance required during the testing at Riga Airport. Only distilled water was added to the fuel cell system.

Deployment time can be summarised as preparation phase lasting about 2 months before testing. Testing started on 16.02.2026, and ended on 06.03.2026. The training was provided on 16.02.2026 and 19.02.2026 (for refuelling). Overall testing period was sufficient to draw conclusions. Still longer tests and better data availability could give more accurate results.

During the testing and preparatory phase Riga Airport team has knowledge on hydrogen driven heavy duty equipment and in future could continue testing or start using such equipment. While the hydrogen powered truck demonstrates strong potential for operational use, targeted improvements required to ensure reliability and efficiency in challenging environmental conditions, and to streamline the refuelling process.

The snow cleaning equipment was tested on apron and taxiways, but not runway. For the runway Riga Airport uses wider snow plow, snow sweeper-blower and higher performance vehicles. So additional testing with wider snow plow and snow sweeper-blower of 8 m would be recommended to see full spectrum of operations at Riga Airport snow cleaning operations. Also, comparison between H2 equipment and diesel-powered equipment should be made as next tests.

While the hydrogen powered truck demonstrates strong potential for operational use, targeted improvements required to ensure reliability and efficiency in challenging environmental conditions and to streamline the refuelling process. Same as in Helsinki the fuel cell system was never the reason for downtimes. Most problems occurred due to battery faults or energy distribution problematics.

6.3.3 KAUNAS AIRPORT

The demonstration project at Kaunas Airport demonstrated that hydrogen-powered heavy winter snow removal equipment can indeed be integrated into airport operations and used in winter conditions. Although there were no particularly cold temperatures (< +5 °C) or adverse weather conditions (heavy snow or freezing rain) during the tests at Kaunas Airport, operation and use of the vehicle in colder temperatures would not change significantly. The vehicle demonstrated good driving performance and effective dry snow clearing capabilities. At the same time, the pilot project showed that the temporary refuelling conditions are more difficult than usual, the refuelling process used while the pilot required additional time and training costs. The pilot project also demonstrated that safety and permitting issues related to hydrogen can be successfully managed, however, the legal framework is not adequately defined in the legislation governing airport operations, and a specific risk assessment and coordination with external authorities is required. Due to the short timeframe the demonstration was done, no economic analysis can be presented.

6.3.4 TALLINN AIRPORT

The Tallinn Airport demonstration confirmed that the Hyzon HyMax 250 hydrogen fuel cell truck can be integrated into airport maintenance operations and operated successfully together with winter maintenance equipment. Operators evaluated the vehicle positively, particularly in terms of acceleration, manoeuvrability, driving comfort and significantly lower noise compared with conventional diesel-powered equipment.

The preparation and approval phase for the Tallinn demonstration took approximately three months. The main administrative activities concerned vehicle approval and registration for road use, coordination of equipment delivery, airside operational arrangements, safety procedures and internal airport approval. No separate permitting process for hydrogen infrastructure was required because hydrogen was neither stored nor dispensed at Tallinn Airport.

One of the main practical challenges was the absence of dedicated hydrogen refuelling infrastructure at the airport. Refuelling at the external Alexela Väo hydrogen station was technically feasible and reliable, but required the vehicle to leave the airport, travel on public roads and subsequently pass security procedures when returning to the airside. This significantly increased the total time associated with refuelling and reduced equipment availability.

From a safety perspective, the pilot was completed without hydrogen-related incidents or leaks. Existing Tallinn Airport Safety Management System procedures, combined with trained personnel and established airside operational controls, were sufficient for the defined demonstration setup. No critical technical failures or unplanned maintenance were recorded during the Tallinn demonstration. The hydrogen drivetrain and Vammas-Vitera winter maintenance equipment functioned as expected during the available testing activities.

A major limitation of the pilot was the weather. As no significant snowfall occurred during the demonstration, the equipment could not be evaluated under full winter maintenance load. Therefore, representative hydrogen consumption, snow-clearing productivity and direct comparison with conventional diesel equipment could not be established.

Overall, the Tallinn pilot demonstrated strong technical feasibility and operator acceptance but also showed that dedicated on-airport or near-airport hydrogen refuelling infrastructure would be important for routine operational deployment. Future testing should be conducted over a longer period and under representative sub-zero temperatures and significant snowfall to allow evaluation of fuel consumption, productivity, reliability and economic performance under actual winter maintenance conditions.

6.4 BUS ROAD SHOW

The Bus Road Show successfully demonstrated the operational feasibility of hydrogen-powered passenger transport under real-world conditions.

The most significant outcome was the successful airside passenger transport demonstration at Helsinki Airport. The trial demonstrated that hydrogen-powered vehicles can operate safely and effectively within a demanding airport environment and can be integrated into normal operational processes.

Key conclusions include:

- Hydrogen fuel cell bus technology has reached operational maturity.
- User acceptance was high among both passengers and operators.
- The Helsinki Airport demonstration validated the suitability of hydrogen-powered passenger transport in airport operations.

Hydrogen-powered vehicles can complement battery-electric solutions in applications requiring high utilisation (fast refuelling compared to battery charging) and operational flexibility.

Besides the experiences shared by the BSR HyAirport project partners Finavia and Växjö Smaland Airport, we include in this report lessons learned from the fourth roadshow (JIVE 2 Nordic Roadshow):

Overall, the JIVE 2 Nordic Roadshow was highly successful in raising awareness and building momentum around hydrogen mobility, garnering positive feedback from participants in the event and key stakeholders in the industry.

- **Hands-on demonstrations of hydrogen buses.** These allowed stakeholders—including city officials, transport operators, energy companies, technology developers, and the public—to experience the technology firsthand. This tangibly raised awareness and built trust in the technology. Notably, the JIVE 2 Nordic Roadshow saw the first use of a hydrogen-powered vehicle in an airport setting in the Nordic region. The high-impact expo sure and engagement was evidenced by the participants consistently highlighting the opportunity to test-drive or experience the vehicles first-hand as the most memorable and convincing aspect of their roadshow experience.

- **Stakeholder engagement workshops.** The high-quality workshops provided a valuable platform for dialogue between regional transport companies, energy authorities, public transport operators (PTOs), and industry players. These sessions helped align local needs with national and EU-level hydrogen strategies. The workshops also fostered new connections and strong cross-sector collaboration between the stakeholders who provided a rich mix of perspectives.

- **Visibility.** The roadshow deployed effective and consistent branding which, alongside the use of clear messaging, high-quality materials, and partner visibility, created a cohesive experience that strengthened the identity of the project. The social media coverage was strong, especially in cities like Jyväskylä, where the roadshow supported ongoing pilot projects and infrastructure development.

- **The Nordic context of the roadshow.** The roadshow drew direct connections with the local context and highlighted the critical role of hydrogen in energy independence, cold climate performance, and long-distance transport, and the ways in which this was particularly relevant for Sweden and Finland, making the event regionally significant.

- **Notable presence of local politicians in smaller municipalities.** One of the most impactful outcomes was the strong local interest observed, particularly in smaller municipalities. Local politicians and stakeholders in towns like Ljungby and Växjö were notably engaged—demonstrating a real appetite for hydrogen and other zero-emission transport solutions outside of traditional focus areas. This stands in contrast to Sweden's larger urban centres, where high-level decision-makers were largely absent despite extensive outreach efforts. Despite these challenges, the roadshow succeeded in accelerating conversations and creating momentum on both national and local levels. In Finland, the presence and engagement of local politicians was balanced between smaller and larger cities, with the Ministry of Transport and Communications, the Energy Authority, and H2 Cluster Finland further attending the national workshop in Helsinki.

The roadshow also provided a learning opportunity to consider areas for improved delivery of similar initiatives in potential future projects. The following factors were highlighted as avenues to ensure successful roadshow deliver and strengthen the deployment of fuel cell busses: early coordination with local stakeholders, a stronger follow-up process, improved contingency planning for vehicles and infrastructure, ensuring senior decision-makers are reached, and bridging national and international perspectives.

Overall, the roadshow served as a catalyst for action, collaboration, and long-term commitment to clean public transport solutions. Through a combination of technical demonstrations, stakeholder engagement, student outreach, and public events, the roadshow effectively showcased the maturity, flexibility, and operational readiness of fuel cell bus technology.

The roadshow helped address several barriers to fuel cell bus deployment—particularly by demystifying the technology through hands-on demonstrations and by fostering dialogue around infrastructure readiness and funding opportunities. It brought hydrogen technology to life—not as a distant innovation, but as a practical solution ready for immediate application.

In conclusion, the roadshow has played a catalytic role in addressing both practical and perceptual barriers to hydrogen adoption. It reinforced local demand, showcased operational readiness, and laid a foundation for future investment and procurement. In both Sweden and Finland, this momentum toward fuel cell bus deployment must now be sustained and scaled, with the support of a national hydrogen strategy, and active cross-sector collaboration.

6.5 EXECUTIVE SUMMARY

Overall, hydrogen technology shows strong potential for selected airport applications, especially where high utilisation, heavy-duty tasks or fast refuelling are required. Broader deployment will depend on improved infrastructure availability, further technical maturation, clear safety procedures and economically viable operating models. The key findings are as follows:

- **Hydrogen-powered airport equipment proved technically feasible** across the demonstrated use cases, including baggage tractors, winter maintenance equipment and passenger transport applications.

- **Operator acceptance was generally positive,** especially where vehicles provided familiar handling, smooth drivability, immediate power availability and sufficient performance for daily airport tasks.

- **Vehicle performance was broadly suitable for operational use,** with the tested equipment able to fulfil its intended functions under real airport conditions, including apron operations and winter maintenance scenarios.

- **Refuelling infrastructure is a key limiting factor:** temporary and mobile fuelling stations enabled the demonstrations, but showed constraints regarding filling pressure, refuelling time, logistics effort and scalability. For Full operations more powerful refuelling stations are recommended.

- **Hydrogen systems work**, but the overall battery management as well as energy distribution needs improvement for arctic temperatures. System design is necessary.

- **Safety management was effective:** no hydrogen-related emergency incidents requiring rescue service intervention were reported during any pilot.

- **Structured risk assessments, exclusion zones, training and emergency procedures were essential** for safe implementation and should be treated as mandatory elements for future airport deployments.

- **Hydrogen applications must be planned as complete systems,** combining vehicle, refuelling infrastructure, site layout, operating procedures, maintenance responsibilities and safety management.

- **Hydrogen technology shows strongest potential where battery-electric solutions face limitations,** particularly in high-utilisation, heavy-duty, time-critical or fast-refuelling airport applications.

7 RECOMMENDATIONS

7.1 H_2 VEHICLE TESTING AT HAMBURG AIRPORT

Based on the results of the hydrogen retrofit demonstration at Hamburg Airport, hydrogen-based retrofit solutions should be considered a technically feasible option for reducing emissions from existing ground support equipment fleets. The demonstration showed that the retrofitted MULAG baggage tractor could be integrated into regular airport operations and used in a manner broadly comparable to conventional vehicles. In particular, the vehicle demonstrated favourable torque behaviour and sufficient operational performance under typical baggage and cargo handling conditions. Future deployment should therefore further investigate hydrogen retrofit solutions as a potential transition pathway, especially where existing vehicle platforms still have significant remaining service life. The recommendations presented below are intended to support airports, equipment manufacturers and other relevant stakeholders in the planning of future demonstrations and the preparation of possible wider implementation.

1. **Stakeholder coordination:** For future demonstrations or implementation projects, early and comprehensive coordination with permitting authorities, fire safety experts, airport safety management, infrastructure operators, and affected operational departments is recommended. The Hamburg case demonstrated that even temporary hydrogen infrastructure requires substantial preparation, including building permit procedures, explosion protection documentation, fire protection concepts, risk assessments, and safety distance planning. Sufficient lead time of at least 6 Month should therefore be included in project schedules, particularly where refuelling infrastructure is located close to sensitive airport assets or fuel storage facilities.

2. **Temporary refuelling:** The temporary mobile refuelling concept proved suitable for demonstration purposes, but its operational limitations should be carefully considered in future projects. The pressure-equalisation-based refuelling approach enabled flexible and comparatively simple operation without additional compression infrastructure. However, the achievable vehicle tank filling level decreased as trailer pressure declined, limiting refuelling efficiency and operational predictability. For longer-term or larger-scale deployment, airports should therefore assess more advanced refuelling concepts, including compressor-based systems or fixed hydrogen refuelling infrastructure, to ensure reliable filling performance and higher operational availability.

3. **Hydrogen delivery:** For short term demonstration purposes, a trailer delivery into airside locations is a suitable concept. For long term demonstration or operation purposes it is highly recommended to store the hydrogen landsite, close to the security border and provide the refuelling station “through the fence” in order to reduce effort and expenses for the delivery.

4. **Operations:** From an operational perspective, hydrogen vehicles should initially be introduced through controlled pilot phases with a limited group of trained operators. The Hamburg demonstration confirmed that dedicated driver training, clear operating

instructions, and close support during the early deployment phase were essential for safe and reliable operation. Future projects should therefore include structured onboarding, hydrogen safety training, refuelling instruction, and emergency response familiarisation for all relevant personnel, including operators, maintenance staff, fire brigade teams, and line management.

5. **Maintenance:** The demonstration also highlighted the importance of close cooperation between the airport operator, vehicle manufacturer, infrastructure provider, and maintenance partners. As the tested vehicle represented a prototype-level retrofit solution, technical issues and optimisation needs occurred during the test period, particularly in auxiliary systems and integration-related components. Future projects should therefore include clearly defined maintenance responsibilities, fast escalation paths, spare parts availability, and sufficient manufacturer support to minimise downtime and maintain operator confidence. If available, using an onsite workshop to do maintenance activities is highly recommended.

6. **Acceptance:** In terms of user acceptance, the generally positive operator feedback indicates that hydrogen-based retrofit vehicles can be accepted by operational staff if vehicle performance is comparable to or better than existing equipment. However, noise emissions and prototype reliability remain important factors requiring further optimisation. Future development should therefore focus on improving acoustic performance, system maturity, component durability, and overall vehicle availability before considering broader fleet deployment. The acceptance of the drivers is one of the most important indicators for a new car-development. The feedback of drivers should be taken serously

7. **Change management and awareness:** The integration of hydrogen into airport operations is a company-wide undertaking that extends beyond technical implementation and permitting. It requires coordinated internal decision-making, financial evaluation, defined safety procedures, integration into the airport's safety management system, infrastructure investment, and a comprehensive strategy for hydrogen supply, delivery pathways, and contractual arrangements. In this context, it is essential to raise awareness at C-level and among key decision-makers. Practical demonstrations play an important role in proving the operational feasibility of hydrogen technologies, demonstrating safe handling under real airport conditions, and building confidence among stakeholders who may initially be sceptical. Such demonstrations can help illustrate both the opportunities hydrogen offers for decarbonising airport operations and the fact that safe and reliable operation is achievable when appropriate technical, organisational, and safety measures are in place.

Finally, the Hamburg demonstration should be used as a reference case for future airport hydrogen pilots. The project provided valuable practical insights into permitting, safety management, temporary refuelling infrastructure, operational restrictions, training requirements, maintenance needs, and user acceptance. These lessons should be transferred into future airport hydrogen strategies and used to define minimum requirements for safe, scalable, and economically viable hydrogen ground support equipment deployment.

7.2 H_2 POWERED WINTER MAINTENANCE EQUIPMENT TESTING AT HELSINKI, RIGA, KAUNAS AND TALLINN AIRPORTS

Based on the demonstrations conducted at Helsinki, Riga, Kaunas and Tallinn Airports, hydrogen-powered PSB and heavy-duty winter maintenance equipment has demonstrated clear technical potential for airport applications. At the same time, the demonstrations confirmed that further technical, operational and organisational development is required before such equipment can be considered ready for routine deployment. The recommendations presented below are intended to support airports, equipment manufacturers and other relevant stakeholders in the planning of future demonstrations and the preparation of possible wider implementation.

1. **Stakeholder coordination.** Future hydrogen demonstrations should be prepared in close cooperation with airport operations, rescue and fire services, safety management, infrastructure specialists, maintenance organisations and, where relevant, competent authorities. Early and transparent coordination with the authorities as well as internally at the airport is recommended to reduce approval delays, improve site selection, and clarify operational responsibilities, safety boundaries and emergency preparedness arrangements.

2. **Vehicle technical development.** Equipment manufacturers should prioritise the further development of system architecture, including low-voltage and high-voltage systems, cold-weather start-up capability, and winterisation of critical subsystems, as those systems were the main reason for faults and cascaded in faults in the Fuel cell, which has never been the starting point of such. For winter maintenance applications, validation should be carried out under representative auxiliary loads, including ploughing, sweeping and blower operation, and under sub-zero conditions requiring full cabin heating performance.

3. **Operational introduction.** During the initial deployment phase, the use of hydrogen-powered vehicles should be limited to clearly defined operating areas and duty profiles in which safety arrangements, access procedures and emergency response measures are well established. Wider deployment should be considered only after sufficient evidence has been obtained regarding technical reliability, operational safety and availability and overall suitability in comparison with conventional and battery-electric alternatives.

4. **Refuelling infrastructure.** Dedicated on-airport hydrogen refuelling capability (both stationary and suitable mobile refuelling station) is strongly recommended for any routine operational use. Temporary and off-site refuelling solutions may be considered acceptable for demonstration purposes; however, they introduce operational inefficiencies, additional logistics and greater complexity of use. Future refuelling solutions should provide adequate throughput, sufficient supply pressure, reliable cold-weather performance, and robust arrangements for grounding, leak detection and technical inspection.

5. **Maintenance and technical support.** Future demonstrations should be supported by clearly defined maintenance responsibilities, rapid fault diagnostics and direct access to OEM or supplier technical support. Before the start of testing, a structured maintenance and fault-reporting process should be established, including spare parts availability, escalation procedures and a clear division of responsibilities between airport personnel and external technical specialists.

6. **Procedures and training.** Hydrogen-specific operating procedures should be documented and standardised for vehicle operation, refuelling, storage, fault management and emergency response. Available ISO (or similar) standardised documents shall be utilised where possible. Training should be provided not only to vehicle operators, but also to supervisors, maintenance personnel and rescue services. During the early deployment phase, operation and refuelling of hydrogen-powered equipment should be restricted to trained and specifically authorised personnel.

7. **Safety and risk management.** The deployment of hydrogen-powered equipment at airports should continue to be managed within the airport Safety Management System and supported by site-specific risk assessments. Attention should be given to indoor storage restrictions, permitted operating areas, leak scenarios, emergency shutdown procedures, refuelling safety distances, and the effects of low temperatures and other extreme weather conditions on both vehicle and infrastructure performance.

8. **Future testing and data collection.** Longer and more representative test campaigns are recommended to generate sufficiently robust data on hydrogen consumption, vehicle availability, maintenance requirements, operational productivity and economic performance. Future testing should include more actual winter maintenance tasks, repeated refuelling cycles, a broader range of ambient temperatures and, where possible, direct comparison with conventional diesel and battery-electric reference equipment.

9. **Change management and scaling**. The introduction of hydrogen should be approached not only as a technical transition, but also as an organisational change process. Wider deployment will require attention to user acceptance, revised working methods, infrastructure investment, local hydrogen supply arrangements and integration into standard airport asset management and maintenance processes. Decisions regarding scaling should therefore be based not only on technical feasibility, but also on demonstrated operational reliability, safety maturity and economic viability.

In conclusion, the demonstrations indicate that hydrogen-powered airport maintenance vehicles are promising for heavier duty applications in which battery-electric solutions may face operational limitations. However, successful routine deployment will depend on improved technical maturity, the availability and economic efficiency of airport-compatible and operationally efficient refuelling infrastructure, standardised operating procedures, and a sufficient scale of use to improve the economic case beyond that observed in short-term demonstration conditions.

7.3 BUS ROAD SHOW

Based on the demonstration results, the following recommendations are proposed:

1. **Airport Operations.** Hydrogen-powered passenger transport should continue to be evaluated as part of airport ground transportation and passenger transfer operations. The demonstration confirmed that hydrogen fuel cell vehicles can be integrated into airport processes without significant operational disruption. Hydrogen should be considered a complementary solution alongside battery-electric vehicles, particularly in applications where rapid refuelling and high vehicle availability are operationally important.

2. **Infrastructure.** Future development should focus on shared hydrogen refuelling infrastructure capable of serving multiple airport vehicle categories. Improving infrastructure utilisation across buses, maintenance equipment and other ground vehicles can enhance overall cost-effectiveness. Priority should be given to refuelling solutions that enable efficient operations, minimise downtime and support high fleet availability.

3. **Future Demonstrations.** Future demonstrations should be conducted over longer operational periods and under a wider range of seasonal and operational conditions. Additional testing would provide better understanding of vehicle performance, energy consumption and operational suitability throughout the year. Airports should also investigate opportunities to gradually integrate hydrogen-powered passenger transport into routine operations to validate long-term operational and economic performance.

4. **Strategic Development.** The Helsinki Airport airside demonstration should be regarded as a proof-of-concept for future hydrogen mobility at airports. Future projects should build upon this experience and explore wider applications for hydrogen-powered ground transportation as part of long-term airport decarbonisation strategies.

Airport Equipment



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