TULIPS

Demonstrating lower polluting solutions for sustainable airports across Europe

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Hydrogen Tow Tractor for Demonstrations

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Abstract

Deliverable D4.3 presents the activities performed to retrofit a diesel-electric aircraft tractor in line with user requirements. Included are key design and exploitation aspects such as: operational profile for aircraft tractor service for a typical day and development of hybrid power design, form factor/space limitations, integration strategy, hybrid hydrogen and battery power solution design choices, general arrangement of components in the available spaces, hydrogen system sizing, integration design, and factory and commissioning testing activities performed. Linked to Tasks 4.2 and 4.3.

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II. DOCUMENT HISTORY

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V. LIST OF ABBREVIATIONS

Acronym	Meaning
TGA	TULIPS General Assembly
KOM	Kick Off Meeting
GHG	Greenhouse Gas Emissions
GPU	Ground Power Unit
GSE	Ground Support Equipment
hGPU	Hydrogen-powered Ground Power Unit
hTT	Hydrogen Tow Tractor
H2	Hydrogen
PEM	Proton Exchange Membrane
WP	Work Package

1 Executive Summary

The TULIPS project's fourth work package (WP4) focuses on achieving zero-emission airside operations by developing fuel cell–battery hybrid electric Ground Support Equipment (GSE). The project aims to reduce greenhouse gas emissions from fossil fuel usage in airside operations and demonstrate the feasibility of hydrogen-powered Ground Power Units (GPU) and Tow tractors. By meeting these objectives, the project contributes to European net-zero goals and highlights the potential of hydrogen as a clean energy solution for the aviation industry.

Within this framework, Deliverable D4.3 presents the development and demonstration of a hydrogen-powered Tow tractor prototype. Designed with superior energy capacity (300 kWh) and the ability to be refuelled quickly, the tractor offers a promising solution for decarbonising heavy-duty airside operations. The deliverable provides a comprehensive overview of the retrofit process, beginning with background on airport decarbonisation, the role of GSE, and the operational profile of Tow tractors.

The main body of the report details the key design choices and integration of subsystems, including the fuel cell stack, hydrogen storage, high-voltage battery system, DC-DC converter, and cooling system. Safety considerations are addressed through a dedicated safety assessment. The document further outlines the testing and validation procedures conducted, followed by insights into the deployment of the Tow tractor in the airport environment.

Through this development process, the hydrogen-powered Tow tractor demonstrates the feasibility of applying hybrid hydrogen–battery solutions to mission-critical GSE. Deliverable D4.3 captures the essential technical work carried out, providing the foundation for further evaluation of hydrogen solutions in the TULIPS project's broader effort to enable sustainable, zero-emission airside operations.

2 Introduction

In order to mitigate the adverse impacts of global warming, reducing greenhouse gas (GHG) emissions from fossil fuel use in airside operations has become a crucial priority. Airside operations encompass the activities carried out during an aircraft's landing and take-off cycle, where Ground Support Equipment (GSE) plays a vital role in the turnaround process. Among the different types of GSE, ground power units (GPUs) and Tow tractors are recognised as significant contributors to emissions due to their high energy demand and reliance on fossil fuels.

To address this challenge, the TULIPS project established Work Package 4 (WP4), entitled Zero Emission Airside Operations. WP4 focuses on developing and demonstrating fuel cell–battery hybrid solutions for heavy-duty GSE, particularly Tow tractors and GPUs. The use of hydrogen as an energy carrier in airside operations offers promising decarbonisation potential but also presents challenges, including the need to ensure safe operation, adapt ground handling logistics, and secure reliable hydrogen supply chains to airports.

The primary objectives of WP4 include the development and demonstration of a hydrogen-powered GPU (hGPU) at the lighthouse airport, Amsterdam Schiphol, as well as replication at Rotterdam The Hague airport. In parallel, the project also targets the demonstration of hydrogen as a power source for Tow tractors at Schiphol. By achieving these objectives, TULIPS aims to contribute to zero-emission airside operations and to showcase hydrogen as a viable clean energy solution for aviation ground handling.

Deliverable D4.3 specifically addresses the hydrogen-powered Tow tractor, providing a detailed account of its development process, design considerations, subsystem integration, safety assessment, and testing activities. As such, it serves as the technical foundation for evaluating the feasibility of hydrogen-powered Tow tractors in real airport operations.

2.1 Airport decarbonization

Europe aims to become the world's first climate-neutral continent by 2050, as enshrined in the European Green Deal and the European Climate Law. The Green Deal, framed as a growth strategy, seeks to safeguard prosperity and well-being while ensuring that economic activity no longer contributes to climate change. Achieving this transformation requires rethinking privileges gained from past development to retain societal benefits while sharply reducing external costs, particularly greenhouse gas emissions.

Aviation, which accounts for approximately 14% of the European Union's transport sector emissions and around 3–4% of the EU's total greenhouse gas emissions, plays a crucial role in this transition. While much of the focus has been on aircraft emissions, airport operations themselves are increasingly recognised as an essential lever for decarbonisation. Airside and landside activities, including energy production and use, mobility, and resource management, directly affect both the carbon footprint and local air quality at airports.

Figure 1: TULIPS Project

The TULIPS project contributes to the European Green Deal and the EU's "Fit for 55" package by providing practical decarbonisation and resource-efficiency roadmaps tailored to airports. These roadmaps are grounded in innovative technologies and concepts that will be implemented and demonstrated at a lighthouse airport and validated at three fellow airports. By doing so, the project not only measures total environmental impact but also prescribes concrete actions in the form of sustainability roadmaps applicable to airports of all sizes across Europe.

In this context, TULIPS has identified seven focus areas and seventeen demonstrations, together forming a comprehensive “green airport” concept. These demonstrations range from hydrogen-powered Ground Support Equipment (GSE) and sustainable aviation fuels to circular resource management and improved passenger mobility solutions. Collectively, they aim to accelerate the transformation of airports into critical enablers of Europe’s net-zero aviation ecosystem.

2.2 Zero Emission airside operation

Ground Support Equipment (GSE) remains largely dependent on fossil fuels. Depending on local conditions, ground power units (GPUs) and Tow tractors represent a significant share of diesel consumption. At Amsterdam Airport Schiphol, for example, GPUs account for 36% and Tow tractors for 11% of diesel use. However, zero-emission (ZE) GSE is gradually emerging at airports worldwide. Examples include deployments in Munich (Germany), Amsterdam (the Netherlands), and Oslo (Norway), as well as several airports in the United States supported by the Federal Aviation Administration’s VALE program. At present, most ZE GSE relies on battery-electric propulsion.

Hydrogen-powered ground handling equipment represents a strategic addition to this transition pathway, complementing battery-electric solutions and enabling the decarbonisation of heavy-duty and high-utilisation equipment. Such technologies reduce greenhouse gas emissions, improve local air quality, and contribute to lowering noise levels on the apron, while providing the operational flexibility required by airports of varying sizes and conditions.

Looking ahead to 2050, airport GSE fleets are expected to be fully sustainable, powered primarily by electricity and hydrogen, with the potential inclusion of sustainable fuels where appropriate. By that point, all internal combustion engine GSE relying on fossil fuels should be replaced with cleaner alternatives, ensuring that ground operations contribute fully to the broader goal of climate-neutral aviation.

2.3 Purpose of this document

This deliverable serves as a technical report providing a comprehensive overview of the development process and key design considerations for the hydrogen fuel cell–powered TLD Tow tractor. It outlines the rationale for retrofitting a diesel-electric platform, the requirements guiding the design, and the integration of major subsystems into a functional hybrid hydrogen–battery solution. In addition to documenting testing and validation activities, the report establishes a reference point within the TULIPS project's wider efforts to demonstrate zero-emission Ground Support Equipment (GSE). By presenting the technical foundation of the H2 Tow tractor, it contributes to the overall ambition of WP4 to advance scalable, sustainable airside operations.

3 Background

The focus of Work Package 4 is the application of alternative technologies to power Ground Support Equipment (GSE), supporting the broader objective of decarbonising airside operations. This chapter begins with an overview of GSE and handling processes, followed by a detailed discussion of one of WP4's core tasks: the development of a Tow Tractor (Demo 11 – Prototype developed in T4.2). Section 3.2 introduces the TLD Tow Tractor, outlining its role, applications, and existing technologies, and highlighting the benefits of hydrogen propulsion. Section 3.3 provides a brief background on hydrogen fuel cells and their basic operating principles. Finally, Section 3.4 discusses the advantages and challenges of using hydrogen as a fuel.

3.1 Ground Support Equipment

Ground Support Equipment (GSE) plays a vital role in the aviation industry, ensuring the smooth operation of aircraft on the ground. These specialised tools and vehicles contribute to the efficiency, safety, and reliability of various ground handling processes, ranging from baggage and cargo handling to aircraft maintenance. While it is difficult to provide an exhaustive list of all available GSE due to the wide variety of equipment in use, the following section presents a comprehensive list of commonly used types of GSE, along with brief descriptions:

1. **Aircraft Movement and Positioning**
    - **Aircraft Tugs**: Powerful vehicles designed to tow aircraft to and from runways, gates, or maintenance areas.
    - **Pushback Tractors**: Specialised vehicles used to push aircraft backward from boarding gates or maintenance stands.
2. **Loading and Unloading**
    - **Baggage Loaders**: Conveyor belt systems or vehicles designed for loading and unloading baggage and cargo.
    - **Cargo Loaders:** Specialised equipment for efficiently handling large cargo items.
    - **Container Dollies:** Vehicles for transporting cargo containers and pallets.
    - **Pallet Loaders/Unloaders:** Equipment for the efficient handling of cargo pallets.
3. **Passenger Handling**
    - **Passenger Boarding Stairs**: Movable staircases used for boarding and deplaning passengers.

- **Jet Bridges**: Enclosed, movable connectors extending from the terminal to the aircraft, enabling boarding and disembarkation without exposure to the elements.

4. **Aircraft Servicing and Maintenance**

- **Fuel Trucks**: Mobile units equipped with fuel dispensing systems to refuel aircraft.
- **De-icing Trucks**: Specialised vehicles equipped with de-icing fluid to remove ice and snow from aircraft surfaces.
- **Lavatory Service Trucks**: Vehicles designed to service and clean aircraft lavatories.
- **Catering Trucks**: Vehicles equipped with food storage and preparation facilities, delivering catering directly to parked aircraft.
- **Aircraft Wash Trucks**: Vehicles with systems for washing and cleaning aircraft exteriors.
- **Tire Inflation Carts**: Equipment to ensure proper inflation of aircraft tyres for safe operations.
- **Tool Kits and Sets**: Specialised tools for routine maintenance and repairs of aircraft components.
- **Aircraft Maintenance Stands**: Platforms that allow technicians to access various parts of an aircraft during maintenance.

5. **Power Supply and Air Conditioning**

- **Ground Power Units (GPUs)**: Provide electrical power to aircraft systems during ground operations.
- **Air Conditioning Units**: Supply temperature control for aircraft interiors while on the ground.
- **Heating Units**: Maintain aircraft system functionality in cold weather conditions.

6. **Communications and Support**

- **Airport Communication Systems**: Infrastructure and devices that enable communication between ground control, air traffic control, and aircraft.
- **Emergency Response Vehicles**: Fire trucks, ambulances, and other vehicles designed to respond rapidly to ground emergencies.
- **Follow-Me Cars**: Vehicles that guide aircraft to and from runways and gates.

- **Ground Support Vehicles**: Multi-purpose vehicles used for a range of ground handling tasks.

Over time, technological innovation has transformed GSE into sophisticated and highly efficient systems, significantly improving ground handling operations. Recent advancements, such as the integration of smart sensors, automation, and data analytics, have streamlined processes and improved performance. Telematics and IoT (Internet of Things) solutions now enable real-time monitoring, optimised maintenance scheduling, and more effective fleet management. Furthermore, the growing adoption of electric and hybrid technologies in GSE supports sustainability and reduces the environmental impact of ground operations.

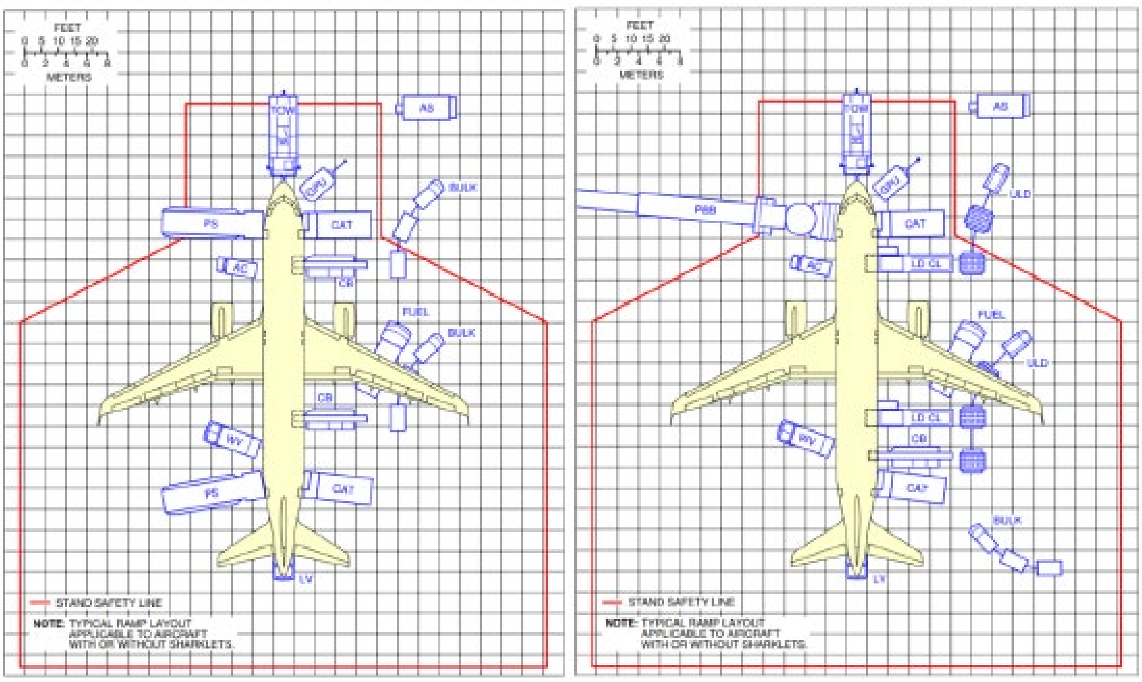

Figure 2:Typical ramp layout for an Airbus A320neo (Airbus, 2020)

While GSEs continue to evolve, challenges such as interoperability between different equipment types, standardization, and adapting to the diverse needs of various aircraft models remain. Future trends in GSE development include increased automation, the integration of artificial intelligence for predictive maintenance, and the ongoing shift toward cleaner, more sustainable power sources. The evolution of GSE has been marked by advancements in technology and a growing emphasis on sustainability. Ground power units, in particular, are essential for supplying electrical power to aircraft while they are on the ground. GPUs are instrumental during pre-flight checks, maintenance procedures, and boarding operations. They ensure a constant and reliable power source, allowing aircraft systems to function without relying on their own engines. This reduces fuel consumption, minimizes emissions, and enhances overall operational efficiency.

3.2 TLD Tow Tractor:

An aircraft Tow tractor, also known as a pushback tractor or tug, is a specialised ground vehicle designed to move aircraft on the ground without using the aircraft's engines. These powerful machines are essential for manoeuvring aircraft in tight spaces, especially at gates and maintenance areas, where precision and safety are crucial. Tow tractors come in various sizes and configurations, some Tow light regional aircraft, while others are capable of pushing wide-body jets such as the Boeing 777 or Airbus A380.

Figure 3: TLD H2 Tow Tractor Overview

Traditionally, aircraft Tow tractors have been powered by diesel or gasoline fuel. The primary advantage of internal combustion engines (ICE) is their high power-to-weight ratio, reliability, and the ability to operate continuously for long durations without needing refuelling pauses. However, ICEs emit significant amounts of CO_2 and particulate matter, contributing to airport pollution and greenhouse gas emissions. Additionally, fuel costs and regulatory pressure on emissions present growing challenges.

Battery-electric Tow tractors are becoming increasingly popular due to their zero on-site emissions, quiet operation, and lower long-term operational costs. They are particularly well-suited for environments aiming to reduce carbon footprints. Nonetheless, battery-powered models face limitations: long charging times, limited operational range, and potential performance degradation in extreme temperatures. High initial costs and infrastructure requirements for charging stations can also be prohibitive for some airports.

Hydrogen fuel cell technology presents a promising alternative, combining the advantages of both ICE and battery systems. Hydrogen-powered Tow tractors can offer fast refuelling, long operational durations, and zero harmful emissions—only water vapor. They are ideal for high-traffic airports seeking a sustainable and scalable solution. However, challenges include the current high cost of hydrogen production, limited fuelling infrastructure, and the need for stringent safety protocols when handling compressed hydrogen.

Switching to hydrogen could significantly reduce the carbon footprint of ground operations while maintaining operational efficiency. As hydrogen production becomes greener and more cost-effective, it may offer the best balance between environmental responsibility and performance for future aircraft towing solutions.

3.3 Fuel Cell

<u>Background on Hydrogen Fuel Cells</u>

Hydrogen fuel cells are electrochemical devices that generate electricity by combining hydrogen gas with oxygen from the air. This process produces electricity, water vapor, and heat as byproducts. Proton Exchange Membrane (PEM) fuel cells are commonly used in heavy duty transportation applications.

For heavy-duty and industrial vehicles such as Tow tractors, hydrogen fuel cells present a compelling solution by offering significant operational benefits. They provide a high energy density, enabling longer run times and fewer interruptions. This makes them well-suited for high-uptime operations like airport ground support equipment, where downtime can significantly disrupt workflows.

<u>Overview of the FCmove™ - HD+ Fuel Cell Module</u>

The Ballard FCmove™-HD+ is a 100-kW fuel cell power module designed specifically for use in heavy-duty vehicle applications. It is a liquid-cooled PEM fuel cell module that integrates several balance of plan sub-systems and control features. At its core, the system includes fuel cell stacks that operate using PEM technology, providing a reliable and durable power source.

Figure 4: Ballard FCmove™-HD+ Fuel Cell Module

The FCmove™-HD+ is a modular design, which simplifies integration into existing vehicle platforms and streamlines servicing. Its robust design, combined with integrated safety and monitoring features, makes it a viable choice for industrial vehicle electrification without compromising performance, operations or reliability.

The module features a comprehensive hydrogen sub-system, which regulates and manages hydrogen flow and pressure. This includes critical components such as a hydrogen shutoff valve, purge valve assembly, water separator, and a recirculation pump. On the air management side, the system is equipped with a built-in compressor, an aftercooler, a humidifier, and various sensors to ensure proper air supply and conditioning for fuel cell operation.

For thermal regulation, the FCmove™-HD+ uses a coolant pump that maintains optimal stack temperature. The module also includes electrical systems, including a 24V low-voltage interface for control signals and diagnostics, and a high-voltage output to power electric drivetrains. The system is designed with integrated safety features such as high voltage disconnects, pressure relief devices, and hydrogen sensors.

4 Tow Tractor Design

4.1 Requirements

The first step of tractor design is establishing operational requirements: towing capacity (based on aircraft weight), duty cycle, expected range or operating time, refuelling speed, and airport environment constraints. Key parameters include tractive force, speed, dimensions, and operating temperatures.

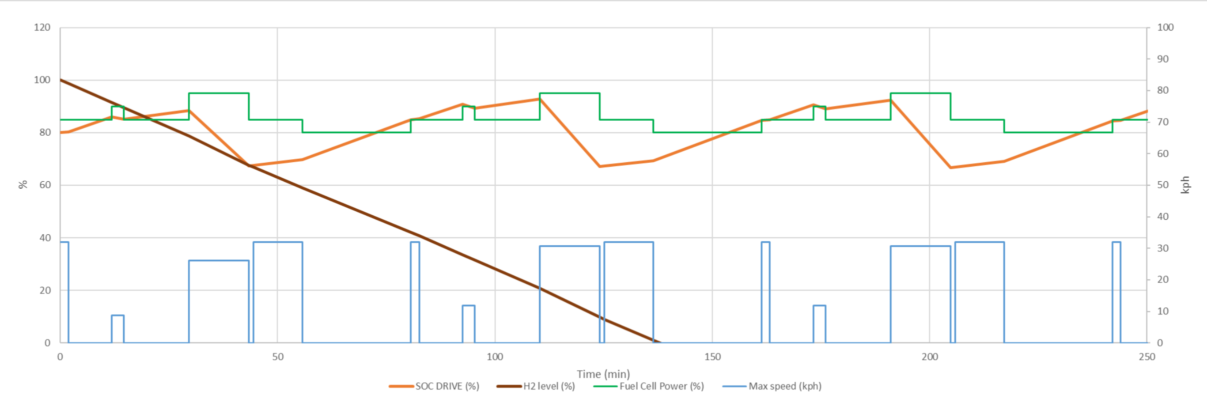

Figure 5: H2 Tow Tractor duty Cycle

The Tow tractor uses a 100kW hydrogen fuel cell system that converts compressed hydrogen into electricity to power the vehicle. The vehicle architecture includes:

- A fuel cell stack
- Hydrogen storage tanks
- High Voltage Battery system for load levelling and regenerative braking
- HV converters to manage energy flow
- Cooling system for the Fuel Cell and Auxiliary components
- Electric motors for propulsion
- Safety systems such as leak detection, crash protection, and high-voltage isolation.

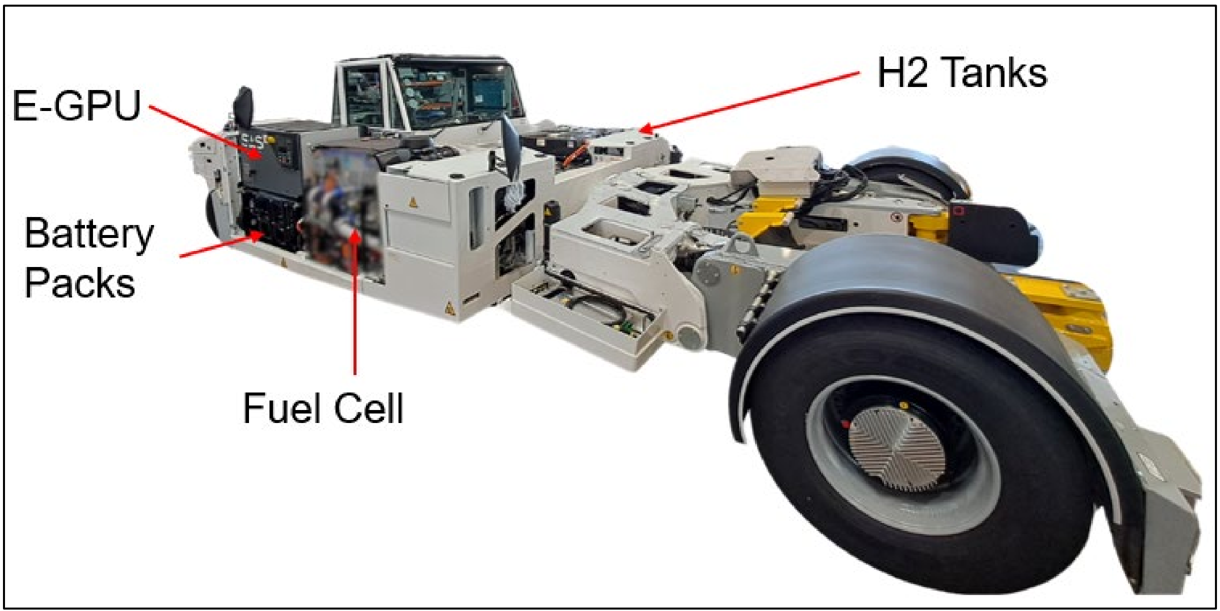

Figure 6: H2 Tow Tractor installation overview

4.2 Safety analysis

When designing a hydrogen-powered aircraft Tow tractor, a comprehensive safety analysis is essential. Hydrogen, while a clean and efficient fuel, presents unique safety challenges due to its flammability, diffusivity, and low ignition energy.

A systematic safety analysis has been carried out to

- identify potential failure modes.
- Evaluate the severity and likelihood of those failures.
- Design mitigation systems to ensure operational safety and regulatory compliance.

This analysis ensures that the Tow tractor can operate safely in complex and variable airport environments.

Two critical failure scenarios have been considered are:

- Hydrogen Leakages:

A leak can occur due to component failure, poor sealing, mechanical damage, or material degradation. Hydrogen's small molecular size allows it to escape through microscopic leaks, posing both flammability and explosion risks, especially in confined or poorly ventilated areas.

- External Fire Sources:

The presence of an external ignition source such as another vehicle fire, fuel spill ignition, or electrical fault can trigger a chain reaction if hydrogen is present. This is especially dangerous if the fire reaches or interacts with hydrogen storage or flow systems.

In the event of such hazards, the design includes a dedicated safety circuit that automatically manages the hydrogen supply. Specifically:

- Detection: Sensors detect hydrogen concentration or external temperature anomalies.
- Isolation: The system isolates the hydrogen source by closing valves and stopping supply.
- Redirect & Extraction: A hydrogen evacuation circuit is activated to draw hydrogen away from the hazardous zone. This circuit vents the hydrogen to the safest possible location, at the rear of the tractor

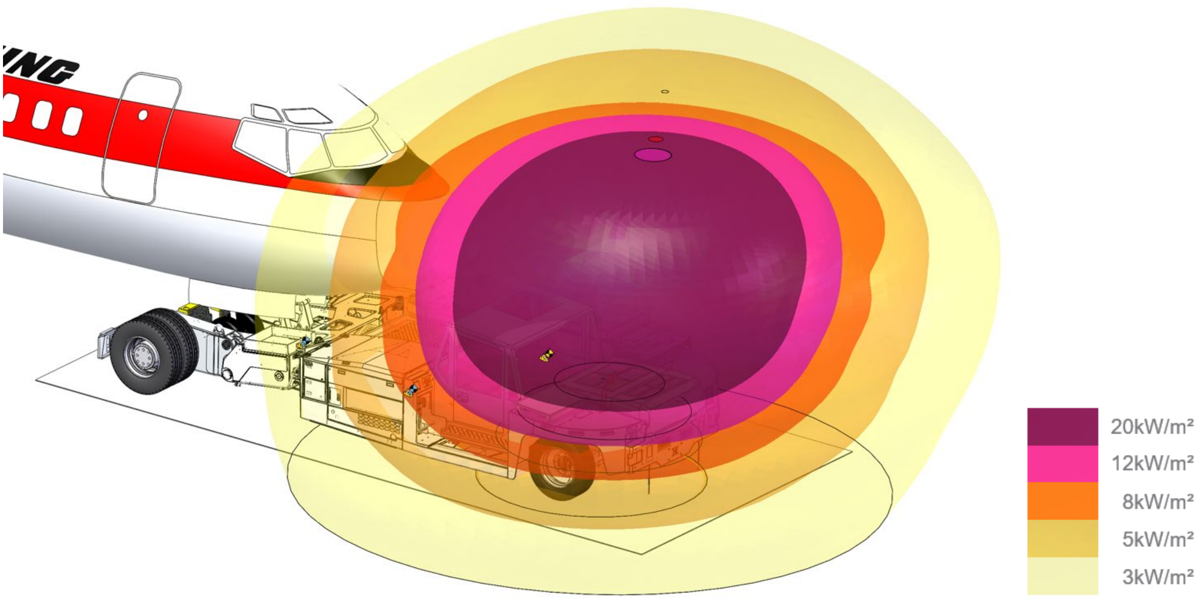

Figure 7: H2 Safety relief circuit in case of fire

This proactive response significantly reduces the risk of ignition or escalation in emergency scenarios.

4.3 Fuel Cell Stack as a primary source of energy

The FCmove™-HD+ module delivers a net power output of approximately 100 kW with an operating voltage range between 280 and 560 volts. It achieves a peak efficiency of over 50% and maintains coolant outlet temperatures between 60 and 70°C. The system supports a maximum hydrogen flow rate of 2.3 grams per second and can operate in ambient temperatures to as low as -30°C. Notably, it can start up in environments as cold as -25°C, making it suitable for a wide range of climates.

For successful integration into the TLD Tow tractor, several considerations were addressed. First, the system requires high-purity gaseous hydrogen conforming to ISO 14687:2019 standards, with an inlet pressure maintained between 7 and 10 bar. The cooling system was designed to handle up to 190 kW of heat rejection, ensuring that the fuel cell stack operates efficiently and reliably even under continuous high-load conditions.

Figure 8: FCMove HD+ Integration

From an electrical standpoint, the system interfaces with both 24V low-voltage and high-voltage power circuits. The low-voltage power supports control functions and communications (e.g., CAN bus and diagnostics), while the high-voltage output is used to drive the electric driveline system.

To ensure safety and maintainability, the FCmove™-HD+ includes a suite of safety features, including hydrogen sensors, pressure relief valves, and electrical isolation mechanisms. Furthermore, the system includes data logging capabilities and Wi-Fi connectivity to facilitate remote diagnostics and system monitoring — key for fleet operations where uptime and maintenance visibility are critical.

4.4 Hydrogen Storage Tanks

The aim of a hydrogen storage system in the TLD Tow tractor is to enable clean, efficient, and sustainable operation by supplying hydrogen fuel to a fuel cell system that powers the vehicle. This transition to hydrogen technology eliminates emissions during ground operations, supports decarbonization goals in airport environments, and reduces reliance on fossil fuels.

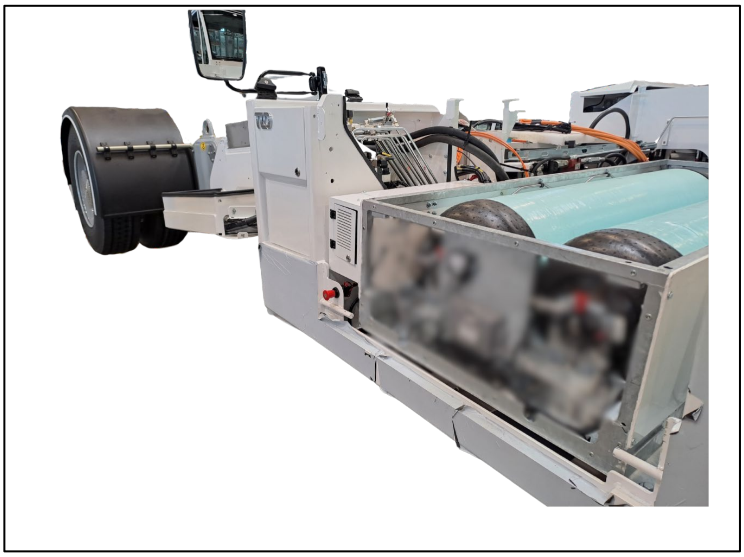

Figure 9: H2 Storage system overview

The storage system is designed to hold hydrogen gas in high-pressure tanks, specifically at 350 bars, to ensure sufficient energy supply for extended operation without frequent refueling. These tanks are made from advanced composite materials to ensure strength, lightweight design, and safety.

Hydrogen from the storage tanks is routed through high-pressure piping to a pressure regulator. This regulator plays a crucial role in the system by reducing the hydrogen pressure from 350 bars down to approximately 10 bars, which is the optimal operating pressure required by the fuel cell system. Maintaining this lower pressure at the fuel cell inlet ensures safe and efficient energy conversion and protects sensitive components from damage due to overpressure.

To safeguard against abnormal operating conditions or catastrophic events (such as tank damage or overheating), the system is equipped with temperature and pressure safety relief devices. These safety mechanisms are designed to vent hydrogen to the atmosphere in a controlled manner when predefined pressure or temperature thresholds are exceeded. This venting prevents uncontrolled pressure build-up that could lead to system failure or even explosion.

By incorporating such pressure relief systems, the hydrogen storage system mitigates the risk of escalation in case of incidents, ensuring that any failure remains manageable and contained.

4.5 High Voltage Battery system as primary power source

In the hydrogen TLD Tow tractor, the battery plays a central role in delivering the necessary power to the vehicle's drivetrain during operation. While the fuel cell system serves as the main source of energy, it does so at a moderate and consistent rate. This complementary relationship allows the battery to act as the primary power provider, while the fuel cell functions as a range extender that sustains the battery over time.

To understand the battery's role, it's important to distinguish between power and energy:

- Power refers to the rate at which work is performed or energy is transferred. In vehicle systems, this translates to how quickly acceleration or torque is delivered.
- Energy refers to the total capacity available to perform work over time.

In a typical Tow tractor operation, high power demand is required during towing operations — particularly during acceleration, starting from a standstill, or supplying the aircraft with an onboard E-GPU. These are moments when the drivetrain demands a quick surge of energy — a function perfectly suited to the battery.

The battery in the hybrid system is sized and configured to handle peak power loads. Its main functions include:

- Instantaneous Power Delivery: The battery responds quickly to power demands, supplying the drivetrain with the necessary torque for towing and manoeuvring.
- Regenerative Braking Capture: During braking or deceleration, kinetic energy is recovered and stored in the battery, improving overall efficiency.
- Buffer for Load Variations: It absorbs fluctuations in power demand, preventing the fuel cell from experiencing rapid load changes, which can reduce fuel cell lifespan.

Because of its ability to deliver and receive energy quickly, the battery is the ideal component for managing the dynamic power needs of the Tow tractor.

The hydrogen fuel cell serves as a continuous, medium-power source. It doesn't respond as rapidly as a battery but provides a stable flow of energy to recharge the battery during operation or when the vehicle is idle.

In this architecture, the fuel cell acts as a range extender prolonging the operational time of the battery without the need for frequent recharging from the grid. This enables:

- Extended Duty Cycles: Tow tractors can operate for longer durations before needing to refuel or recharge.
- Reduced Downtime: Onboard generation of electricity from hydrogen keeps the battery charged, minimizing the reliance on external charging stations.

4.6 High Power DCDC Converter

The primary function of the DC-DC converter into the TLD Hydrogen Tow Tractor is to convert the variable output voltage of the fuel cell to a stable voltage level that matches the rated voltage of the battery and the vehicle’s electrical components. This voltage regulation is essential for the safe and efficient operation of the hybrid powertrain.

Fuel cells do not produce a constant voltage output. Their voltage varies depending on the power demand.

Typically, the voltage output of a fuel cell stack may be lower or more variable than the required voltage for the battery system or traction motor. Batteries, on the other hand, have a relatively fixed operating voltage range. Therefore, a DC-DC converter is necessary to step up or regulate the fuel cell’s voltage to meet the battery's charging requirements and to match the vehicle’s system voltage.

The converter ensures that the fuel cell’s output is adjusted to the correct voltage level required by the battery and electric drivetrain. This avoids undervoltage or overvoltage conditions which could damage system components.

Since fuel cells respond slowly to rapid changes in load, the converter helps buffer and regulate the energy, ensuring smooth and reliable power flow to the battery and traction system.

The converter controls the charging current and voltage, ensuring that the battery is charged safely and efficiently from the fuel cell source.

By managing the energy flow between the fuel cell and the battery, the converter allows the system to operate in its most efficient state, helping to prolong battery life and maximize fuel cell efficiency.

4.7 Cooling system

Fuel cells work by converting the chemical energy of hydrogen and oxygen into electrical energy through an electrochemical reaction. While this process produces zero harmful emissions at the point of use, it is not 100% efficient. In fact, typical PEM fuel cells have an electrical efficiency of around 40–60%, meaning that 40–60% of the energy released from the hydrogen reaction is not converted into useful electricity, but instead becomes waste heat.

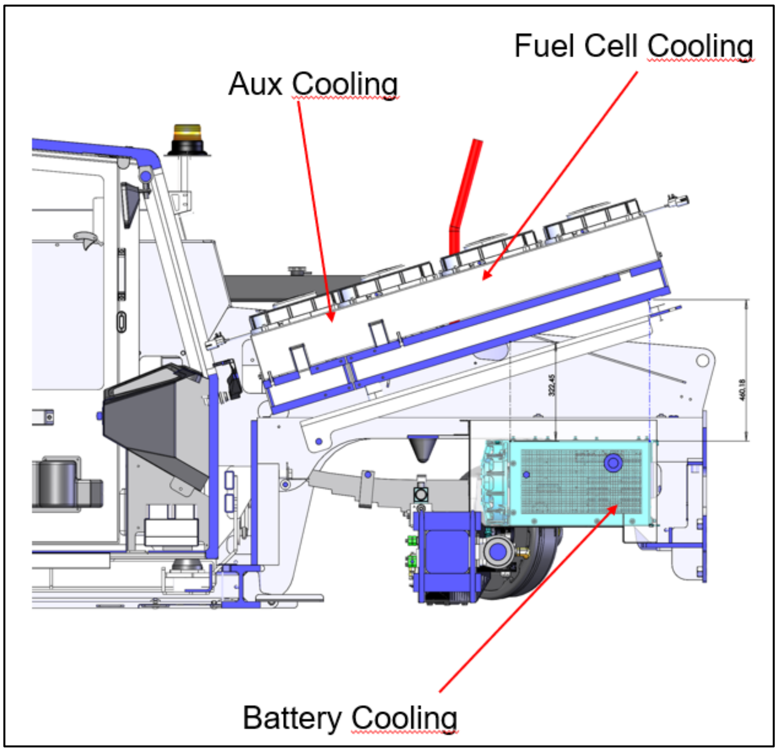

Figure 10: Cooling system overview

This heat accumulation becomes especially pronounced at high power outputs. For instance, in the 100 kW fuel cell system, up to 150 kW may be lost as heat under full load conditions. If not properly dissipated, this heat can:

- Damage cell components,
- Decrease overall efficiency,
- Accelerate material degradation,
- And ultimately cause system failure.

Therefore, managing this thermal load is crucial. The cooling system is capable of continuously removing this heat under varying loads and ambient conditions. In order to maintain the fuel cell stack at its optimal operating temperature of 60°C, the coolant must circulate at high flow rates and absorb heat efficiently.

In mobile applications, such as fuel cell vehicles, the cooling system must be compact, lightweight. A deionized liquid cooling, of water-glycol mixtures, is used including:

- Heat exchangers,
- Pumps and flow control valves,
- Temperature sensors,
- And electronic control units for dynamic heat management.

5 Test And Validation

The validation process of the TLD hydrogen-powered Tow tractor is critical to ensure that all vehicle systems, including the hydrogen storage and fuel cell subsystems, operate safely and reliably under all expected working conditions. The procedure follows a step-by-step approach, starting with electric-only verification and progressing toward full hydrogen operation at maximum power. Each stage focuses on confirming proper integration, system safety, and performance robustness.

5.1 Initial Vehicle Validation in Full Electric Mode

The first step in the validation process consists of operating the Tow tractor exclusively in **battery-electric mode**, without the hydrogen system engaged. This approach ensures that all fundamental vehicle systems are functioning correctly before introducing hydrogen into the system. Key verifications include:

- **Electric drivetrain functionality**: checking traction up to 10t, acceleration, and braking.
- **Auxiliary systems**: validation of sensors, actuators, control units, and communication buses.
- **Baseline operation**: ensuring the vehicle can operate in a predictable and safe manner.

This stage isolates the validation of the vehicle platform itself, avoiding unnecessary complexity while providing a baseline for subsequent hydrogen system testing.

Figure 11: Performance Test without H2 system running

5.2 Hydrogen System Installation Check

Once the TLD Tow Tractor has been validated in electric mode, the next step is to inspect the installation of the hydrogen system. This includes:

- Proper mounting of hydrogen tanks and associated components.
- Verification of mechanical integrity, routing of hydrogen lines, and secure connections.
- Electrical integration of valves, sensors, and control electronics.
- Compliance with relevant safety and regulatory standards.

This step ensures that the hydrogen system is correctly integrated into the vehicle and ready for controlled testing.

5.3 Tank System Purging and Filling

Before operation, the hydrogen storage system must undergo purging and controlled filling to guarantee **gas purity and safety**. Purging removes contaminants or residual gases, while careful filling ensures that the hydrogen entering the system meets purity requirements for fuel cell operation. Any impurity could lead to fuel cell degradation or performance loss.

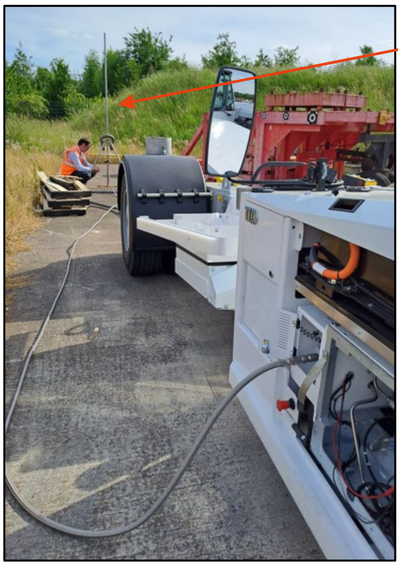

Figure 12: Purging process

Figure 13: Filling process

During this process, monitoring equipment verifies that filing procedures are respected and that the system pressure stabilizes within the expected operating range.

5.4 Tank Safety System Validation

After the tanks are filled, the next step is to validate **safety mechanisms** associated with hydrogen storage. This includes testing sensors and safety responses for:

- **Leak detection**: confirming that any detected leakage triggers immediate closure of the hydrogen valve.
- **Pressure monitoring**: ensuring that overpressure situations activate protective measures.
- **Temperature monitoring**: verifying that abnormal thermal conditions result in automatic system shut-off.

These tests are crucial to confirm that the system reacts instantly and reliably to any hazardous condition.

Figure 14: H2 Leakage check

5.5 Fuel Cell Start-Up and Shut-Down Validation

The fuel cell system is then initiated together with the **DC-DC converter**, starting at **low power operation**. The purpose is to verify:

- Proper coordination of start-up sequences.
- Smooth power transfer from the fuel cell to the high-voltage system.
- Controlled shut-down procedures that prevent residual hydrogen accumulation or stress on components.

These checks guarantee that both normal and emergency start/stop sequences are performed correctly.

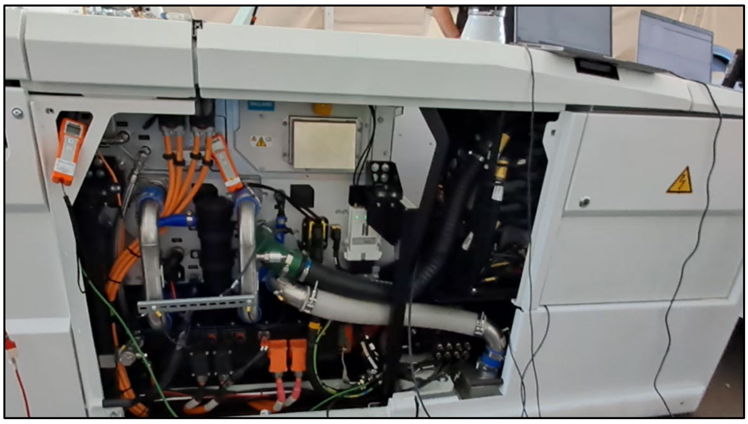

Figure 15: Fuel Cell Start-up Test

5.6 Fuel Cell Safety System Checks

Following initial operation, dedicated tests are performed to validate the **safety logic** of the fuel cell system itself. This includes:

- Monitoring of hydrogen supply and ensuring proper cutoff in case of anomalies.
- Validation of electrical fault detection (overvoltage, overcurrent, or isolation faults).
- Verification of emergency stop functions and communication with the vehicle's central control unit.

These verifications confirm that the fuel cell can safely respond to operational or environmental disturbances.

5.7 Performance Validation at Full Power

The final stage of validation consists of pushing the system toward **maximum operational capacity**, which involves:

- Gradual power increase to confirm stable operation across the entire power range up to 100kW of Fuel Cell Power.
- Monitoring the **cooling system** to ensure adequate heat rejection under peak load.
- Confirming that the **fuel cell can sustain continuous operation** at full power without performance degradation.
- Ensuring that the combined hydrogen and electric systems can supply all vehicle needs in both typical and demanding working conditions.

Successful completion of this stage validates that the hydrogen-powered Tow tractor is fully capable of safe, efficient, and reliable operation in its intended applications.

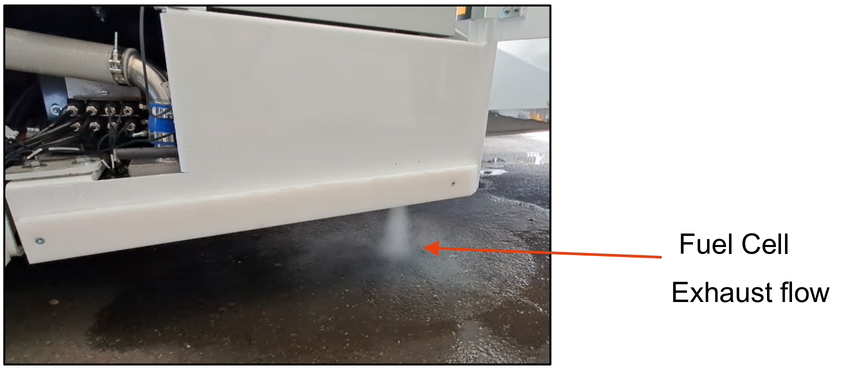

Figure 16: Fuel Cell Exhaust at max power

6 Airport Deployment

The TLD hydrogen-powered Tow tractor (hTT) is currently being deployed at Amsterdam Airport Schiphol during summer and autumn 2025. This large-scale demonstration campaign is testing the feasibility of zero-emission aircraft towing under real operational conditions. The hTT is used for live pushback and towing of commercial aircraft.

The deployment has required an extensive permitting and approval process. Key steps include completion of a Safety Risk Assessment (SIRA) under the Management of Change (MoC) framework, authorisation from the airport authority, safety clearance from the fire brigade, and confirmation of insurance coverage. Supporting documentation, covering technical specifications, operator training records, and emergency response procedures, has been prepared and approved in close coordination with Schiphol Group, KES (TCR Group), KLM Ground Services, the fire brigade, and technology partners.

Stakeholder engagement is an integral part of the demonstration. KLM serves as the main airline partner for towing operations with Boeing 737 aircraft, while technology providers (Ballard, TLD, INSEEGO), hydrogen supplier Linde, and project coordinators to ensure technical and operational readiness. The hTT is refuelled using on-airport hydrogen refuelling infrastructure.

During the demonstration, operational performance, safety, and user experience are being closely monitored. Evaluation criteria include system uptime, energy efficiency, refuelling times, and integration into existing turnaround procedures.

The ongoing deployment of the hTT marks an important milestone in the TULIPS project by proving that hydrogen-powered GSE can be integrated into day-to-day operations at a major European airport. Detailed findings and evaluation results will be consolidated in Deliverables D4.5 and D4.8.

7 Conclusion

The present study has demonstrated that the TLD hydrogen-powered tow tractor represent a mature and technically suitable solution for airport ground operations. The performance evaluations confirm that the tractor is capable of fulfilling operational requirements with reliability, while the autonomy levels achieved are well aligned with the daily demands of aircraft towing activities. These results establish hydrogen technology as a viable alternative to conventional solutions, offering both operational efficiency and environmental benefits.

Looking ahead, the next challenges are no longer primarily technological but rather systemic and regulatory. A key priority will be the harmonization of regulations across airports, which will facilitate the deployment of hydrogen ground support equipment and provide clarity for manufacturers seeking to scale production. In parallel, the availability and distribution of hydrogen at airports must be secured to ensure that the technology can be adopted at scale. Without a robust and reliable supply chain, the potential of hydrogen-powered tractors cannot be fully realized.

Finally, it is essential to recognize that wider adoption and higher production volumes will drive cost reductions, making hydrogen solutions increasingly competitive with conventional alternatives. As more airports and operators invest in hydrogen infrastructure and equipment, economies of scale will accelerate the transition, lowering overall system costs while maximizing sustainability benefits.

In conclusion, this development study has confirmed the readiness of hydrogen tow tractors for operational use. The path forward lies in building the regulatory, infrastructural, and industrial ecosystem that will enable hydrogen technologies to become a standard in airport ground handling operations.

Appendix A: LIST OF REFERENCES

Airbus. (2020). Airbus A320 - Aircraft characteristics, airport and maintenance planning.