



Demonstrating lower polluting solutions for sustainable airports across Europe

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Abstract

The TULIPS project's fourth work package (WP4) focuses on developing zero-emission airside operations through the use of fuel cell-battery hybrid electric ground support equipment (GSE). This project aims to reduce greenhouse gas emissions in airside operations by showcasing the feasibility of hydrogen-powered ground power units (GPU) and tow tractors. The hydrogen-powered GPU prototype has been designed with a high energy capacity (350kWh) and fast refuelling capability, making it a promising solution for decarbonizing airside operations. This comprehensive report provides detailed information on the design, testing, and implementation of the hydrogen-powered GPU, emphasizing its superior energy capacity and fast refuelling capability as key factors in accelerating the decarbonization of airside operations.



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VI. LIST OF ACRONYMS

Acronym	Meaning
APU	Auxiliary Power Unit
eGPU	Electric Ground Power Unit
EU	European Union
FCS	Fuel Cell System
GHG	Greenhouse Gas
GPU	Ground Power Unit
GSE	Ground Support Equipment
H ₂	Hydrogen
hGPU	Hydrogen –Powered Ground Power Unit
HSE	Health, Safety and Environment
HVIL	High Voltage Interlock
KES	KLM Equipment Services
NABO	Narrow Body
PE	Protective Earth
PEM	Proton-exchange Membrane
SAF	Sustainable Aviation Fuel
SAGAT	Società Azionaria Gestione Aeroporto Torino
WP4	Work Package 4



1 Executive Summary

The TULIPS project's fourth work package (WP4) focuses on 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 achieving these objectives, the project will contribute to reaching net-zero goals and showcase the potential of hydrogen as a clean energy solution in the aviation industry. The hydrogen-powered GPU prototype has been designed with superior energy capacity (350kWh) and the ability to be refuelled quickly, making it a promising solution for decarbonizing airside operations.

The development and implementation of the hydrogen-powered GPU involved a comprehensive set of activities. The report provides a detailed account of the design, exploitation, and testing procedures for the GPU. It covers the principles and advantages of hydrogen fuel cells, design concepts, power consumption analysis, and the ideal capacity of the fuel cell, hydrogen tanks, and battery. The report also describes the testing and commissioning procedures for the hydrogen-powered GPU and outlines a demonstration plan. Overall, the report highlights the superior energy capacity and fast refuelling capability of the GPU, positioning it as a promising solution for accelerating the decarbonization of airside operations.



2 Introduction

In order to mitigate the adverse impacts of global warming, the reduction of greenhouse gas (GHG) emissions from fossil fuel usage in airside operations has become a crucial focus. Airside operations encompass the activities carried out during aircraft landing and take-off cycles. Among the various ground support equipment (GSE) utilized in the aircraft turnaround process, ground power units (GPU) and tow tractors are recognized as significant contributors to pollution. To address these emissions, the TULIPS project has established Work Package 4 (WP4), named "Zero Emission Airside Operations."

Work Package 4 (WP4) is specifically dedicated to tackling the emissions arising from airside operations, with a particular emphasis on ground support equipment characterized by high fossil fuel consumption, such as tow tractors and ground power units (GPU). The evaluation revolves around the utilization of hydrogen (H₂) fuel cell (FC)-battery hybrid systems for this equipment. The integration of hydrogen as an energy carrier in airside operations introduces various challenges, including the requirement for safe operation and the need to develop new operating logistics specific to hydrogen-powered ground support equipment at airports. Furthermore, the supply of hydrogen to the airport presents an additional challenge that needs to be addressed.

The primary objectives of WP4 encompass the development and demonstration of a hydrogenpowered GPU (hGPU) at the lighthouse airport, Amsterdam Schiphol, as well as its implementation at selected fellow airports, namely Torino and Larnaca. Additionally, the project aims to demonstrate the feasibility of utilizing H₂ as a power source for tow tractors at the lighthouse airport. By pursuing these objectives, the TULIPS project aims to contribute to achieving zero-emission airside operations. The development and demonstration of hydrogen-powered ground support equipment at European airports will not only contribute to reducing greenhouse gas emissions but will also serve as a practical showcase for the potential of hydrogen as a clean energy solution in the aviation industry.

2.1 Airport decarbonization

Europe aims to become the first climate-neutral continent by 2050, guided by the European Green Deal and the European Climate Law. The Green Deal, while viewed as a growth strategy, seeks to preserve well-being and prosperity while eliminating climate change contributions. To achieve this, privileges gained from past development must be reengineered to maintain societal benefits with reduced external costs, particularly climate change impacts. Aviation, responsible for 14% of European Union's (EU) transport sector emissions, plays a crucial role in significant emissions reduction.



Airport operations, previously overlooked, are vital in achieving a climate-neutral aviation sector. Sustainable energy production, greener transport modes, and efficient resource use at airports can reduce carbon footprints and improve local air quality. The TULIPS project contributes to the European Green Deal by providing decarbonization and resource efficiency roadmaps for

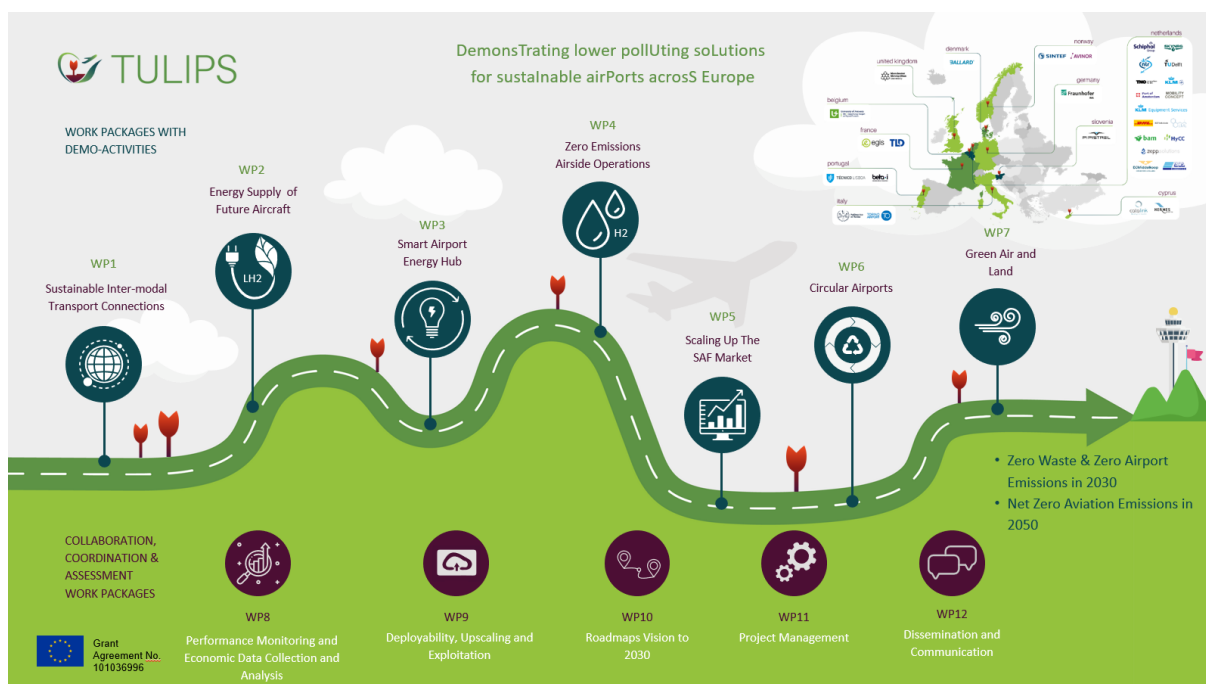


Figure 1: TULIPS Project

European airports, based on innovative technologies and concepts. These roadmaps will be implemented and demonstrated at a lighthouse airport and validated at three other airports. To achieve this, the project will demonstrate technologies and concepts that can support this development, measure their total impact and prescribe actions in form of sustainability “Road Maps” for any type of airports in the EU. In this regard TULIPS has Identified 7 focus areas and 17 demonstrations which resemble the concept of green airports.

2.2 TULIPS Consortium

The TULIPS consortium is composed of key actors in the aviation sector that cover the whole sector’s value chain in order to ensure the achievement of its ambitious objectives and maximum impact. Among the consortium are European airports (SNBV, SAGAT, HERMES, AVINOR), light green aircraft suppliers (PIPISTREL), ground services providers (KES), sustainable aviation fuel (SAF) providers (SKYNRG), green hydrogen providers (HYCC formerly NOBIAN), hydrogen fuel cells providers (BALLARD, ZEPP), hydrogen logistics providers (POA), experts for building infrastructure (BAM), cargo logistics partners (BOS LOGISTICS, DHL, DJ MIDDELKOOP), airlines (KLM), industrial technology providers (CATALINK, BETA-I, EGIS, EME, MOBCON) and research



and academia technology solution providers (SINTEF, SIN-EN, POLITO, FHG, MMU, NLR, TNO, TUD, IST-ID, UANTW).

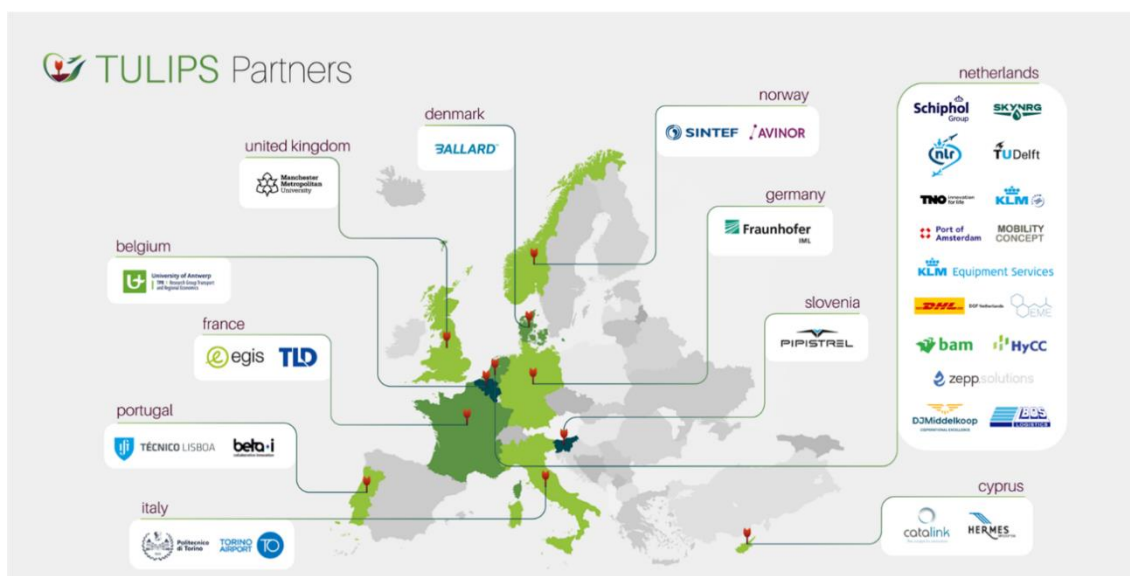


Figure 2: TULIPS Partner Map

2.3 Zero emission airside operation

Ground support equipment (GSE) is to a large extent still powered by fossil fuel. Dependent on airport conditions, ground power units (GPUs) and tow tractors can represent a large share of diesel usage. At Schiphol airport, GPU and tow tractor diesel usage account for 36% and 11%, respectively. However, ZE (Zero Emission) GSE are starting to emerge at airports, for example in Munich (Germany), Amsterdam (The Netherlands), Oslo (Norway) and a number of airports in the United States funded by the VALE program. ZE GSE is currently mainly powered from batteries.

Our hydrogen-powered ground handling equipment offers a strategic component towards achieving zero-emission airside operations at European airports. It plays a leading role in the mix of technologies applied to replace conventional diesel equipment, reducing greenhouse gas emissions, improving local air quality, and reducing noise pollution on the apron.

Airports in 2050 should have a sustainable GSE fleet with GSE using electric and hydrogen propulsion and even sustainable fuels. In 2050, all internal combustion engine GSE relying on fossil fuels should be replaced by a sustainable alternative.

2.4 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 GPU. It is linked to tasks 4.2 and 4.3 of the work package, contributing to the overall objectives of the TULIPS project in achieving zero emission airside operations.



The purpose of this document is to provide a detailed account of the activities carried out in the development of a hydrogen fuel cell powered GPU based on a battery or diesel GPU base. It serves as a comprehensive report that outlines key design and exploitation aspects related to the development and implementation of the hydrogen-powered GPU.



3 Background

The focus of work package 4 is on using alternate technologies for powering ground support equipment that will help the larger goal of decarbonizing airside operations. In this chapter, a brief background about various ground support equipment and handling is provided, followed by a more focused section on one of the key tasks of WP4 i.e., developing a ground power unit. Section 3.2 describes a ground power unit, including its importance, application, available technologies, leading to the need/ advantage of using H₂ to power it. Next in Section 3.3, a brief background about hydrogen fuel cells, including its basic operating principle is provided. Lastly, Section 3.4 elucidates the advantages and challenges of using hydrogen as a fuel.

3.1 Ground support equipment

Ground support equipment (GSE) plays a crucial role in the aviation industry, ensuring the seamless operation of aircraft on the ground. These specialized 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's challenging to provide an exhaustive list of all GSE due to the vast range of equipment available, here is a comprehensive list along with brief descriptions of various types of GSE commonly used in the aviation industry:

1. Aircraft Movement and Positioning:
 - Aircraft Tugs: Powerful vehicles designed to tow aircraft to and from runways, gates, or maintenance areas.
 - Pushback Tractors: Specifically used for pushing aircraft backward, away from a boarding gate or a maintenance area.
2. Loading and Unloading:
 - Baggage Loaders: Conveyor belt systems or vehicles designed for loading and unloading baggage and cargo into and from the aircraft.
 - Cargo Loaders: Specialized equipment for efficiently loading and unloading larger cargo items.
 - Container Dollies: Vehicles designed for transporting cargo containers and pallets.
 - Pallet Loaders/Unloaders: Equipment for efficiently loading and unloading cargo pallets.
3. Passenger Handling:
 - Passenger Boarding Stairs: Movable staircases used for boarding and deplaning passengers.
 - Jet Bridges: Enclosed, movable connectors extending from the airport terminal to the aircraft, allowing passengers to board and disembark 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: Specialized vehicles equipped with de-icing fluid to remove ice or snow from an aircraft's surfaces.
- Lavatory Service Trucks: Vehicles equipped to service and clean aircraft lavatories.
- Catering Trucks: Specialized vehicles equipped with food storage and preparation facilities, providing in-flight catering services by delivering meals, snacks, and beverages directly to parked aircraft.
- Aircraft Wash Trucks: Vehicles equipped with specialized systems for washing and cleaning aircraft exteriors.
- Tire Inflation Carts: Ensure that aircraft tires are properly inflated for safe ground operations.
- Tool Kits and Sets: Specialized tools for routine maintenance and repairs on various aircraft components.
- Aircraft Maintenance Stands: Platforms and stands for technicians to access different parts of an aircraft during maintenance.

5. Power Supply and Air Conditioning:

- Ground Power Units (GPUs): Provide electrical power to aircraft systems while on the ground.
- Air Conditioning Units: Provide temperature control for aircraft interiors during ground operations.
- Heating Units: Ensure that aircraft systems remain operational in cold weather.

6. Communications and Support:

- Airport Communication Systems: Infrastructure and devices facilitating communication between ground control, air traffic control, and aircraft.
- Emergency Response Vehicles: Fire trucks, ambulances, and other vehicles equipped to respond quickly to emergencies on the ground.
- Follow-Me Cars: Vehicles with airport personnel guiding aircraft to and from runways and gates.
- Ground Support Vehicles: Multi-functional vehicles equipped for various ground handling tasks.

Over time, technological innovations have transformed GSE into sophisticated and highly efficient systems, enhancing the overall ground handling experience. Recent technological advancements have greatly enhanced the capabilities and efficiency of GSE. Integrated systems with smart sensors, automation, and data analytics contribute to streamlined ground operations. Telematics and IoT (Internet of Things) solutions enable real-time monitoring of equipment, optimizing maintenance schedules and overall fleet management. The incorporation of electric and hybrid



technologies in GSE is also gaining traction, promoting sustainability and reducing the environmental impact of ground operations.

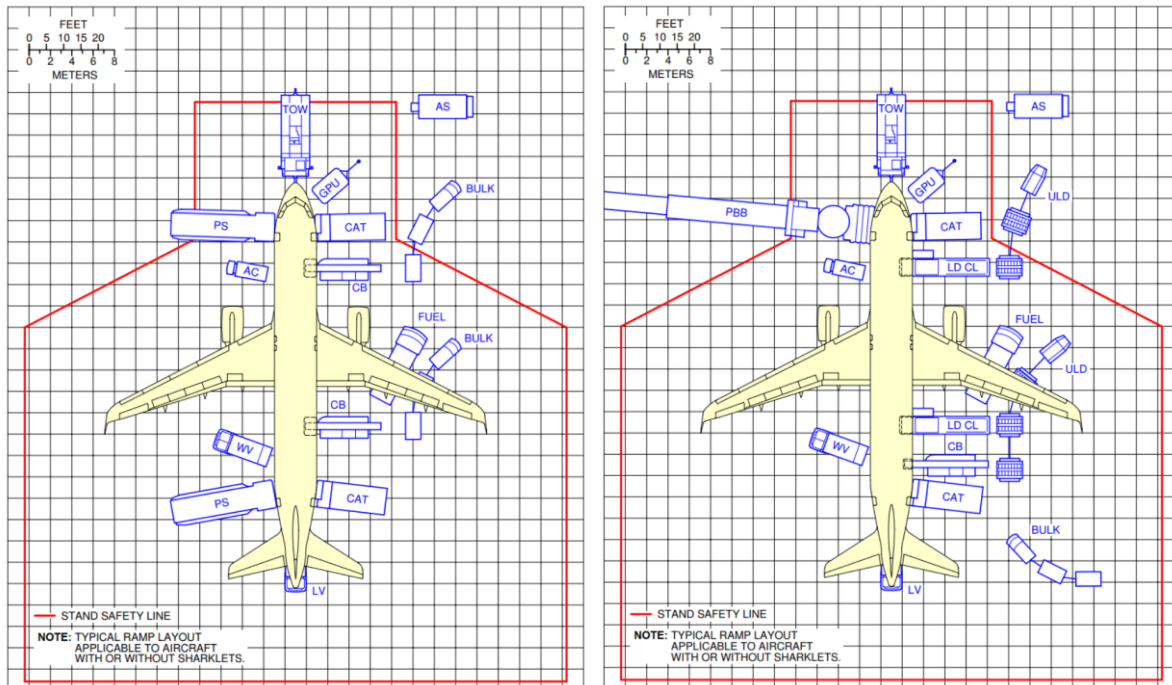


Figure 3 Typical ramp layout for an Airbus A320neo (Airbus, 2020) (a) Servicing arrangement with two passenger stairs. (b) Servicing arrangement with a passenger boarding bridge

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.

Aircrafts consume quite some power to run all the auxiliary components, such as lighting, heating, control system, etc. Between 10 minutes after landing and 10 minutes before taking-off the aircraft is not allowed to use the internal APU (auxiliary power unit) in many countries. Therefore, an external power supply is needed to power the aircraft in the intermediate time. The GPUs satisfies the need for such an external power supply.



3.2 Ground power unit

A ground power unit is a vehicle capable of supplying electric power to an aircraft, while the aircraft is parked, loading and unloading goods and transferring persons. GPUs come in various forms, including mobile, towable, and fixed units. They are equipped with advanced technologies such as variable frequency drives and advanced control systems, allowing for compatibility with different aircraft types. The shift towards cleaner and more sustainable technologies in the aviation industry has also influenced the development of environmentally friendly GPUs.



Figure 4: Mobile ground power unit at airside (Dynell, 2023).

The example shown in Figure 4 is a mobile GPU. Currently most of the mobile GPUs are powered by a diesel engine. A generator converts the motion of the diesel engine in AC electric power. Battery powered GPUs with a DC-AC converter are just introduced to the market.

Personnel has to work in the immediate surroundings of a GPU, the emissions of a diesel GPU have a large effect on their health. Also, diesel units emit quite some noise, which is detrimental for both, personnel health and environment. Regulations regarding the emissions of CO₂ are more and more strict for airports. Especially, a GPU for the major part operates at low partial loads, which makes a diesel GPU less ideal from the emissions standpoint because it reduces fuel efficiency and increases particulate matter. This makes mobile diesel GPUs unsuitable for use in the future.

A battery can remove these limitations due to health problems, regulations and noise. However, the battery solution has limitations in terms of capacity, which means it cannot operate for a full day and will have to be recharged. Recharging the battery is a relatively time-consuming process, which limits the productivity of a single GPU. Additionally, it requires an electric charging infrastructure



that is often not directly at the gate or aircraft parking area, so the GPU has to be moved. This results in additional traffic on already crowded traffic lanes and additional fleet management, resulting in less convenient operations. Thus, a battery GPU has a different workflow as compared to a diesel GPU, which is refuelled during the night.

These limitations make a battery GPU less suitable for applications requiring large amounts of energy or long autonomous operation and the necessary charging intervals are prohibitive. Airports seek a zero-emission alternative to the diesel GPU, but with the same convenience in operations as with the diesel GPU. This means the capability of refuelling on location in a limited time and/or a long operating time. A hydrogen fuel cell system offers the ideal solution, providing zero-emission power generation, extended continuous operation, and quick refuelling times.

In recent years, there has been a growing recognition of the environmental impact of traditional power sources used in GSE. As a result, hydrogen-powered GPUs are emerging as a viable and eco-friendly alternative. The adoption of hydrogen as a power source for GPUs brings several advantages. Hydrogen fuel cells offer a clean and efficient source of constant power supply, producing only water and heat as by-products. They reduce emissions to zero, promoting sustainability in ground operations. Additionally, hydrogen fuel is abundant and can be produced using various methods, further diversifying the energy sources for the aviation industry.

The shift towards hydrogen-powered GPUs represents a forward-looking approach, aligning with global efforts to reduce carbon emissions and promote environmentally friendly practices in aviation ground operations. As technology continues to advance, hydrogen-powered GPUs are poised to play a pivotal role in shaping the future of GSE, ensuring a greener and more sustainable aviation industry.

3.3 Hydrogen fuel cell systems

Hydrogen fuel cells represent a cutting-edge technology in the realm of clean energy, offering a promising solution to the growing challenges associated with conventional energy sources. These cells convert hydrogen and oxygen into electricity, producing water as the only by-product. This makes hydrogen fuel cells a highly attractive and environmentally friendly alternative to traditional combustion-based power generation methods.

Hydrogen fuel cells operate on a simple yet powerful principle known as electrochemical conversion. The process involves the combination of hydrogen and oxygen to generate electricity, releasing energy in the form of electrons. The basic components of a hydrogen fuel cell include an anode, cathode, and an electrolyte. When hydrogen is supplied to the anode and oxygen to the cathode, a chemical reaction takes place, producing electricity, heat, and water vapor.

One of the key advantages of hydrogen fuel cells lies in their minimal environmental impact. Unlike fossil fuels, hydrogen produces no greenhouse gases or harmful pollutants. The only emission from



a hydrogen fuel cell vehicle or power system is water, making it a crucial player in the global effort to reduce carbon emissions and combat climate change.

The electrochemical conversion process in hydrogen fuel cells is highly efficient compared to traditional combustion-based power generation. The absence of intermediate steps, such as the conversion of thermal energy, allows fuel cells to achieve higher energy conversion efficiencies. Additionally, the lack of greenhouse gas emissions during electricity generation contributes to the environmental advantages of hydrogen fuel cells.

Understanding this intricate electrochemical process is fundamental to appreciating the clean energy potential of hydrogen fuel cells. As advancements in materials science and engineering continue, the efficiency and affordability of fuel cells are expected to improve, further solidifying their role in the global pursuit of sustainable energy solutions.

Hydrogen fuel cells find applications across various sectors, showcasing their versatility and potential. Transportation is a significant focus, with hydrogen fuel cell vehicles gaining traction as an alternative to traditional gasoline-powered cars. Additionally, fuel cells are utilized in stationary power generation for residential, commercial, and industrial purposes, providing a reliable and clean source of electricity.

While hydrogen fuel cells offer immense promise, challenges remain in terms of cost, infrastructure, and hydrogen production methods. Addressing these challenges is crucial for widespread adoption. Research and development efforts are ongoing to enhance the efficiency and affordability of fuel cell technology, with a focus on scaling up production and establishing a robust hydrogen infrastructure.

Proton Exchange Membrane (PEM) fuel cells, also known as Polymer Electrolyte Membrane fuel cells, stand out among various types of fuel cells for their high efficiency, low-temperature operation, and versatility. These fuel cells are particularly suitable for applications such as transportation and portable power generation, where their unique characteristics offer significant advantages.

Advantages of PEM Fuel Cells

1. High Power Density

PEM fuel cells offer high power density, making them suitable for applications where space and weight considerations are critical.

2. Fast Start-up and Response

PEM fuel cells can start up quickly and respond rapidly to changes in electrical demand, making them ideal for applications requiring dynamic operation.

3. Clean and Quiet Operation



The only by-products of a PEM fuel cell are water vapor and heat, contributing to a clean and environmentally friendly operation. Additionally, they operate quietly compared to traditional combustion engines.

4. Low Operating Temperature

PEM fuel cells operate at relatively low temperatures (typically around 80°C), enabling faster start-up times and making them more compatible with various applications.

The working principle of Proton Exchange Membrane (PEM) fuel cells can be outlined in a sequential process. Initially, hydrogen gas is supplied to the anode side of the fuel cell, where a platinum catalyst assists in the dissociation of hydrogen molecules into protons and electrons. The protons generated at the anode then traverse the Proton Exchange Membrane (PEM) and move toward the cathode. Meanwhile, the electrons, unable to pass through the membrane, are directed through an external circuit, creating an electric current. Simultaneously, oxygen is introduced at the cathode, where another platinum catalyst facilitates the reduction of oxygen. This process involves the combination of protons, electrons, and oxygen to form water.

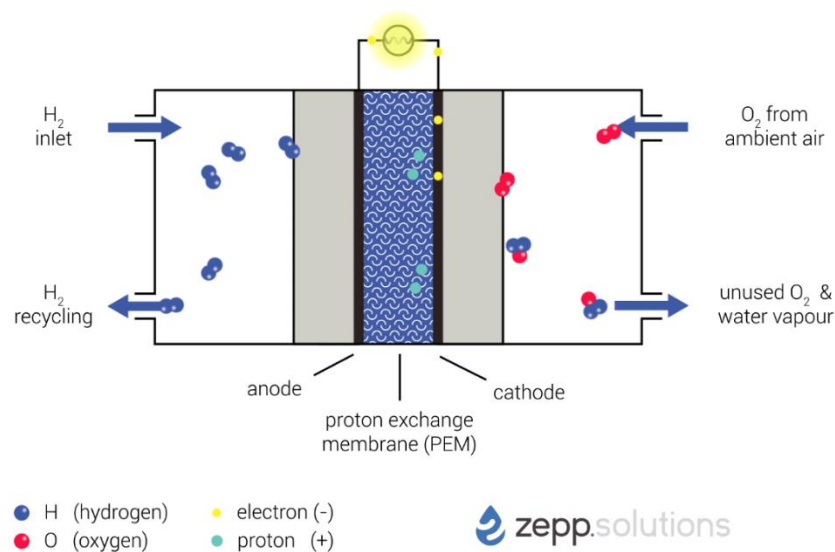


Figure 5 Working principle of PEM fuel cells.

In conclusion, hydrogen fuel cells represent a beacon of hope for a sustainable energy future. Their ability to produce clean electricity without harmful emissions positions them as a key player in the transition to a low-carbon economy. As technology advances and challenges are overcome, hydrogen fuel cells are poised to play an increasingly vital role in powering our world while preserving the health of our planet for future generations.

3.4 Hydrogen as a fuel

Hydrogen, a versatile and abundant element, is emerging as a key player in the quest for clean and sustainable energy solutions. As a fuel, hydrogen offers unique advantages that make it a



promising candidate for a wide range of applications. It has one of the highest gravimetric energy densities (120 MJ/kg = 33.3 kWh/kg), but is also the lightest element, which results in generally low volumetric energy densities.

Hydrogen stands out as a clean fuel option because its combustion or use in fuel cells produces only water vapor as a by-product. Unlike conventional fossil fuels, hydrogen does not release harmful pollutants or contribute to greenhouse gas emissions, making it a useful component in efforts to combat climate change and improve air quality. One of the notable strengths of hydrogen lies in its versatility. It can be utilized in various sectors, including transportation, industry, and power generation.

Hydrogen is, just like electricity, an energy carrier and not an energy source. It must therefore be produced from hydrogen containing compounds. Generally, hydrogen can be produced from a large variety of feedstock, domestic resources including fossil fuels, such as natural gas and coal, as well as biomass, nuclear energy and renewable energy sources such as wind or solar power. The possible production process technologies include chemical, biological, electrolytic, photolytic and thermo-chemical. They can, depending on the chosen technology, be facilitated in large central plants as well as in smaller distributed units near the point of use. However, not all process technologies are at an equal stage of development and only a few are already available in the marketplace for industrial production of hydrogen.

While the first commercial technology for the production of hydrogen was electrolysis of water in 1920, the industrial production has shifted towards a fossil-based feedstock since the 1960s. Natural gas and coal processes are most commonly used for current hydrogen bulk production although producing carbon dioxide as a by-product.

After production, the hydrogen has to be transported to a fuelling station. There are three modes of transportation, gaseous compressed (20 MPa, 35 MPa or 50 MPa), liquid ($-253\text{ }^{\circ}\text{C}$) and by pipeline.

After the transportation the hydrogen arrives at the refuelling station, but still has to be dispensed to the vehicle. The dispensing techniques used at the fuel station, are depending on the state of the hydrogen supplied and the means of mobile hydrogen storage aboard the vehicle. All processes require different safety procedures and are fully automated with the only manual operations being the connecting and disconnecting of the filling nozzle to the vehicle mounted receptacle. The techniques are considered safe and are all commercially available and in use.

There are two types of onboard storage options for hydrogen, which are already in use or have been demonstrated in the mobility sector. Due to the inherently different storage natures of both techniques, they each have their own benefits and downsides.



1. Compressed gas hydrogen (CGH₂) storage

CGH₂ storages use the by pressure increased mass density to store hydrogen at 35 MPa, 50 MPa or 70 MPa at ambient temperature. These high-pressure gas cylinders are equipped with a high-pressure valve for a controlled release of the hydrogen. CGH₂ is the most common storage choice in the automotive sector.

2. Liquid hydrogen (LH₂) storage

LH₂ storages use the increased mass density of hydrogen in its liquid state at 20 K(-253C). The storages are designed to insulate the cryogenic hydrogen as good as possible to maintain its state. The storages are usually equipped with special evaporation systems to transform hydrogen back into its gaseous state for further usage. The insulation requirements of the storage demand use of special materials and techniques. In the past, only a limited number of manufacturers have shown prototype storages for the automotive market although the technology is aerospace proven. The liquid form of hydrogen is generally used in industry for bulk transport or storage of hydrogen.

Hydrogen plays a pivotal role in energy storage, addressing the intermittent nature of renewable energy sources like wind and solar. Excess energy generated during peak periods can be used to produce hydrogen through electrolysis, and later, this hydrogen can be converted back into electricity when demand is high. This capacity for energy storage makes hydrogen a valuable asset in supporting a more resilient and stable electrical grid. Also, this approach is a key method for green hydrogen production, contributing to a more environmentally friendly hydrogen supply chain. While hydrogen has long been used industrially, recent advancements in production technologies, especially green hydrogen produced through renewable energy sources, are enhancing its sustainability.

Despite its potential, challenges remain in the widespread adoption of hydrogen. Issues such as cost, infrastructure development, and efficient production methods need to be addressed. Continued research and innovation are crucial for overcoming these challenges and establishing hydrogen as a mainstream and economically viable fuel source.

The international community is recognizing the importance of hydrogen in the transition to a low-carbon economy. Collaborative initiatives and investments in hydrogen technologies are underway, fostering partnerships between governments, industries, and research institutions to accelerate the development and deployment of hydrogen-based solutions.

To conclude, hydrogen, as a fuel, holds great promise of a cleaner, more sustainable energy future. Its environmental benefits and potential for large-scale applications position it as a key component in the global effort to create a resilient and low-carbon energy landscape. As advancements in



technology continue and collaborative efforts expand, hydrogen is poised to play a major role in reshaping the way we generate and use energy.



4 GPU Design

This chapter throws some light on the design elements of the hGPU. Starting with a description of the various requirements identified through the course of this project, summarised in Section 4.1. Followed by the performance expectations from the hGPU discussed in Section 4.2. Leading to a description of the hGPU preliminary concept design to meet all the requirements and sizing of the various key components in the hGPU in Section 4.3.

4.1 Requirements

At the start of the design phase, all stakeholders of WP4 gathered to put together a comprehensive list of requirements, that formed a framework for the development of the prototype. The MoSCoW method was used to categorize these requirements. This approach helps ensure that the most critical features are addressed first, providing flexibility for handling lesser essential elements based on resource constraints or project timelines. The acronym "MoSCoW" stands for:

1. Must-haves (M): These are critical requirements that must be delivered in the current phase or iteration for the project to be considered successful. Failure to meet these requirements would likely result in project failure.
2. Should-haves (S): These requirements are important but not absolutely critical for the project's success. They are considered high-priority and should be included if resources permit.
3. Could-haves (C): These are desirable requirements, but they are not necessary for the project's success. They are considered nice-to-haves and may be implemented if time and resources allow.
4. Won't-haves (W): These are explicitly agreed upon as requirements that will not be addressed in the current phase or iteration. They might be considered for future releases or projects.

The hGPU is designed to meet a set of operational, technical and safety requirements, to ensure its efficient and safe operation for aircraft ground handling. The unit must demonstrate an extended period of operational capability (of at least 8 handling hours), catering to diverse ground handling scenarios. Accessibility to the remaining power capacity, expressed in percentage or hours before refuelling, is required for effective resource management and planning by ground operators. To facilitate seamless transition from existing GPUs, the handling procedures for the hGPU, including connection/disconnection and engine start/off sequences, must be as user-friendly as current practices. This also implies, minimal additional training is required for ground personnel to adapt to the new system.



Readiness signalling must be incorporated to inform both operators and pilots of the hGPU's preparedness to deliver power, using easily accessible indicators. Approximately 90% of ground operations must align with standard narrow-body procedures and equipment, to streamline integration into existing airport workflows. Additionally, compliance with all relevant airport rules and regulations is a fundamental requirement, to ensure the hGPU operates safely and in accordance with established standards. The hGPU must provide basic on-board health monitoring facilities, enabling the prompt identification and resolution of operational issues. This includes a robust data logging capability to track performance metrics, facilitating analysis for optimization and maintenance purposes.

Performance parity with Diesel derivatives is also a key consideration, it is important that the hGPU matches the performance of its conventional counterpart without compromising aircraft handling or performance on the ground, allowing for the pilot to shut down the Auxiliary Power Unit (APU) during ground time. The design of the hGPU cables must focus on being lightweight, flexible, and optimal length to facilitate efficient ground handling. A real-time fire detection system is critical to promptly alert operators in case of a fire, enhancing overall safety. Moreover, the design must prevent flames, in the event of a fire, from pointing towards aircraft to minimize the risk of damage. The hGPU must allow for quick detachment from the aircraft, for easy and rapid towing in emergency situations. Environmental considerations are just as important for the design, with a particular focus on reducing local emissions and contributing to overall emission and noise reduction during operations. Finally, design and operation of the hGPU maintains high standards of Health, Safety, and Environment (HSE), ensuring that no compromises are made in these critical aspects.

Some of the "Should Have" requirements focus on the operational aspects such as mobility, size and weight of the hGPU. It should be possible to tow the hGPU between parking positions and to easily move it around the aircraft to ensure optimal distance from the aircraft. For this it is also important that the weight of the GPU is optimised. Additionally, the dimensions and footprint should not impair ground service operations and handling should not increase airside traffic notably. The hGPU should be able to be refuelled in an efficient (timewise and action wise) way to ensure a smooth workflow, also allowing for refueling during operation. Noise benefits should be similar to eGPUs.

The hGPU should have remote diagnostics capabilities available to the GSE Maintenance Provider, such as a Health monitoring system in order to react in due time. The remaining power capacity (% or hours of service before refuelling) should be available remotely for the ground handling service provider. 90% of the hGPU repairs should be conducted at the local workshop (on-site), such that the time of operation is maximized, and the hGPU can be swiftly put back in operation.



Requirements with respect to training of personnel for operating and maintenance of the hGPU were identified. Easily accessible instruction material to prepare the employees (Ground handlers, KES mechanics and refuelers) for safe and efficient operation of the hGPU should be provided. They should receive sufficient training and education from the manufacturer to perform efficient and safe maintenance on the hGPU.

4.2 Load profile eGPU

In order to establish the system requirements and determine the load capacity of the hGPU, it is imperative to comprehend the load demand imposed by various aircrafts during each handling process. The interval between an aircraft's landing and take-off, commonly referred to as turnaround time, encompasses all ground handling activities detailed in Section 3.1. In the development of the hGPU, datasets provided by Amsterdam Airport Schiphol (AAS) were reviewed, the summaries of which is discussed below. It is essential to note that the hGPU is primarily designed for narrow-body aircraft (NABO) within this project; therefore, the data analysed is specific to this category. The comprehension of power consumption by different aircrafts, both in terms of peak power requirements and overall energy demand, serves as a crucial input for sizing the fuel cell system and the associated battery pack in the hGPU design. This detailed understanding ensures that the hGPU is appropriately tailored to meet the specific operational needs of narrow-body aircrafts.

This dataset originates from Amsterdam Airport Schiphol (AAS), which conducted a pilot program focused on evaluating the feasibility of battery powered Electric Ground Power Units (eGPUs) in place of diesel GPUs. Throughout the program's duration from September 2021 to October 2022, AAS systematically tested the performance of 12 eGPUs across various aviation scenarios. The recorded data, as presented in Table 1, elucidates the average power consumption per hour associated with different aircraft types. Complementing this tabular information, Figure 6 provides a visual representation of the power consumption per handling, offering insights into consumption patterns.

These datasets play a pivotal role in understanding the peak power requirements essential for sustaining aircraft operations on an hourly basis and the overall energy demand per handling. Notably, the findings underscore a crucial relationship between handling times and power requirements. Shorter handling times are associated with higher average power demands, while longer handling times exhibit lower average power requirements albeit with a greater total energy demand. This nuanced understanding, derived from AAS's eGPU pilot program, holds significant implications for the design of hGPU in this project.

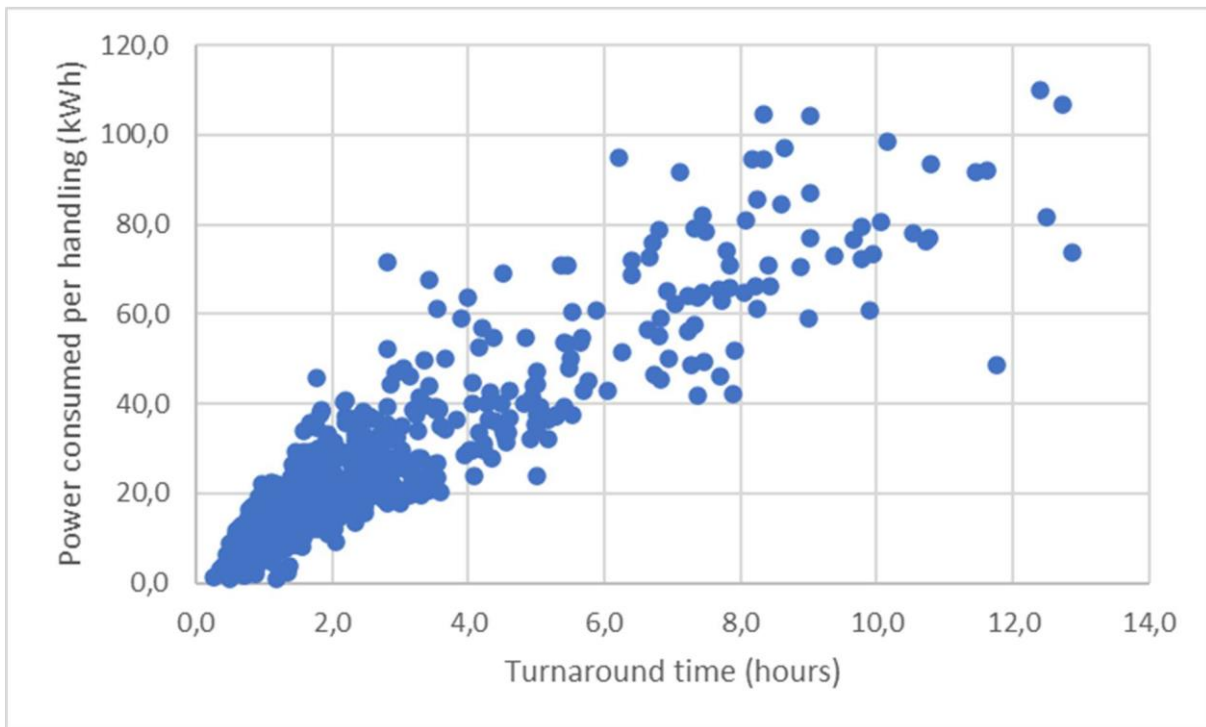


Figure 6 Power consumed per handling vs turnaround time

Aircraft type	ICAO type code	Usage per hour (kWh)
Embraer ERJ-175	E75	9,03
Embraer 190	E90	9,96
Embraer 195-E2	295	10,86
Airbus A318	318	13,10
Airbus A319	319	16,40
Airbus A320	320	15,97
Airbus A321	321	15,02
Airbus A320neo	32N	13,00
Airbus A321neo	A21N	22,29
Boeing 737-800	73H	12,41
Boeing 737-700	73W	10,13
Boeing 737-900ER	73J	11,56
Boeing 737 MAX 8	7M8	12,55

Table 1 Average hourly power consumption per aircraft type. (Poortvliet, 2022)



4.3 Concept and sizing

The preliminary design of the hydrogen fuel cell GPU is based on the chassis and electric powertrain of the battery GPU (eGPU). This includes all components except batteries and charging infrastructure delivered with the eGPU. Using the eGPU as a base offers the opportunity to use an already tested and evaluated powertrain.

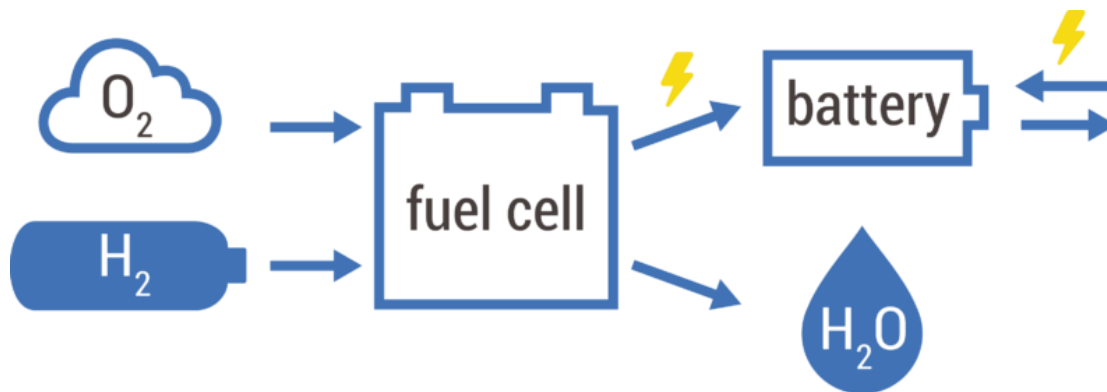


Figure 7 Hydrogen ground power unit prototype concept

In contrast to the eGPU, where the onboard energy is stored in the battery packs (Figure 8), the required energy of the HGPU is stored in form of hydrogen in the hydrogen tanks (blue tank in Figure 7). Via the fuel cell system, the chemical energy is converted into electrical energy and fed to the accumulator. The accumulator is a battery pack of smaller energy capacity compared to an eGPU, but has a high-power density. By means of a DC/DC converter the traditionally low voltage of the fuel cell is boosted to match the DC bus of the accumulator. While the fuel cell system supplies the constant electrical energy demand, the accumulator supplies the peak powers to the inverter. Furthermore, this topology enables a continuous fuel cell operation at its optimal power setpoint.

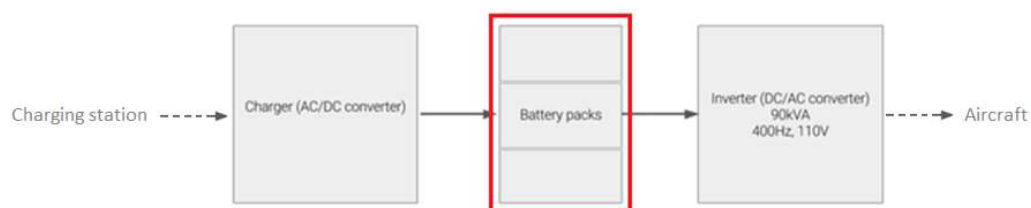


Figure 8 Battery powertrain architecture

The differences in the powertrain architecture between the eGPU and the hGPU are visualised in Figure 8 and Figure 9, respectively. The red frame in Figure 8 surrounds the battery packs that are reduced in size/ number from the standard eGPU to generate the general platform. The BMS (battery management system) takes care of the battery cell monitoring (voltage, state of charge, state of health, temperature) and balancing of the battery cells. Surrounded by a blue frame in Figure 9 is the fuel cell module and the grey box surrounds the tanks added to the GPU platform to keep the battery charged during operation. The red box in Figure 9 surrounds the on-board



charger, that allows the battery to be charged independent of the FCS in case of any technical issues or short-term unavailability of hydrogen for refuelling the tanks. This hGPU design capitalizes on the strengths of both powertrains, marking a significant step toward sustainable and efficient ground power units

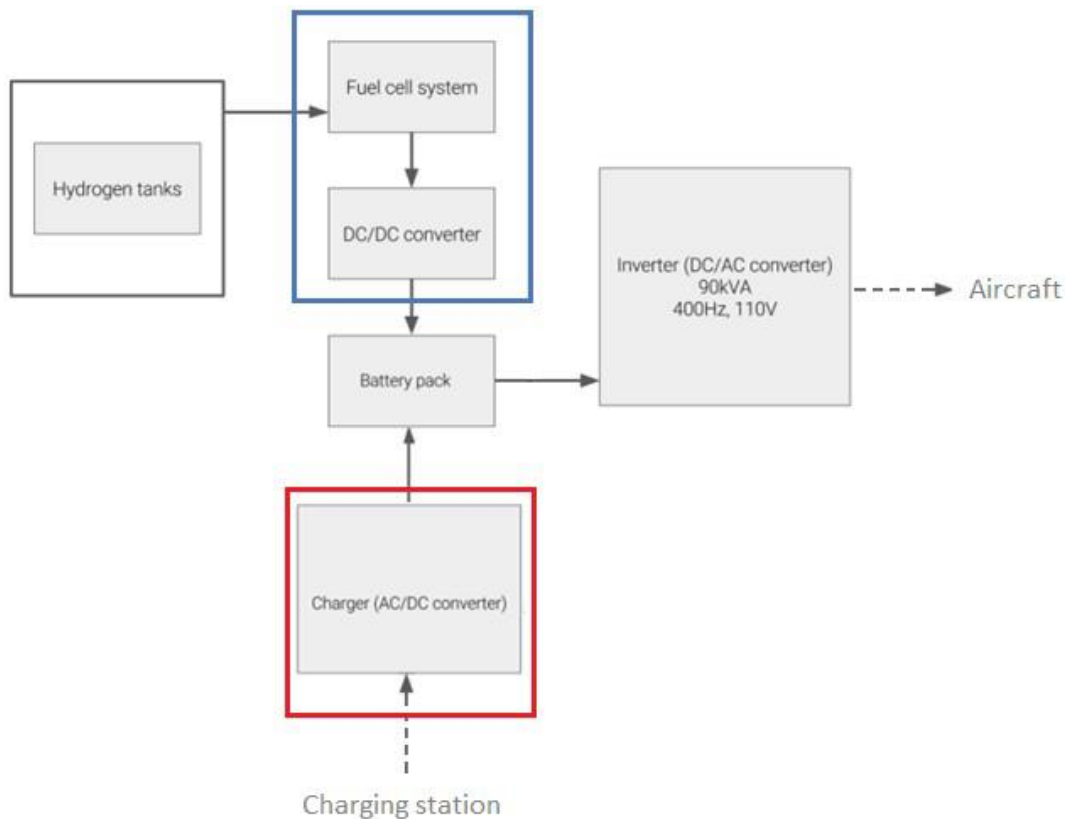


Figure 9: Hydrogen fuel cell powertrain architecture

Figure 10 shows a more detailed top-level illustration of the fuel cell module composition, consisting of the fuel cell system, hydrogen storage, air intake, exhaust, fuel cell cooling, auxiliary cooling, high voltage and low voltage interfaces.

Hydrogen storage

The fuel cell system is integrated together with a controller for the hydrogen storage system. In this case, the hydrogen storage controller fully handles all matters related to the hydrogen storage tanks, including opening/closing, fuel level calculation, keeping track of refuelling cycles (tank lifespan), leakage monitoring and optionally communication with the refuelling station. The hydrogen storage controller is automatically controlled by the fuel cell system over CAN bus.

High voltage interface

The fuel cell system has an integrated DCDC converter and can thus be directly connected to the DC high voltage bus and battery. It is required to apply high voltage to this bus by external means



(e.g. by connecting the battery) and then the fuel cell can be requested to deliver electrical power to this bus, with the bus voltage dictated by the battery.

Low voltage interface

A low voltage supply is required to start the control electronics and power sensors and small actuators. The fuel cell system can operate with both a 12 V and a 24 V supply. The fuel cell system can be put into sleep mode with an enable/ KL15 input, allowing the LV supply to remain always connected.

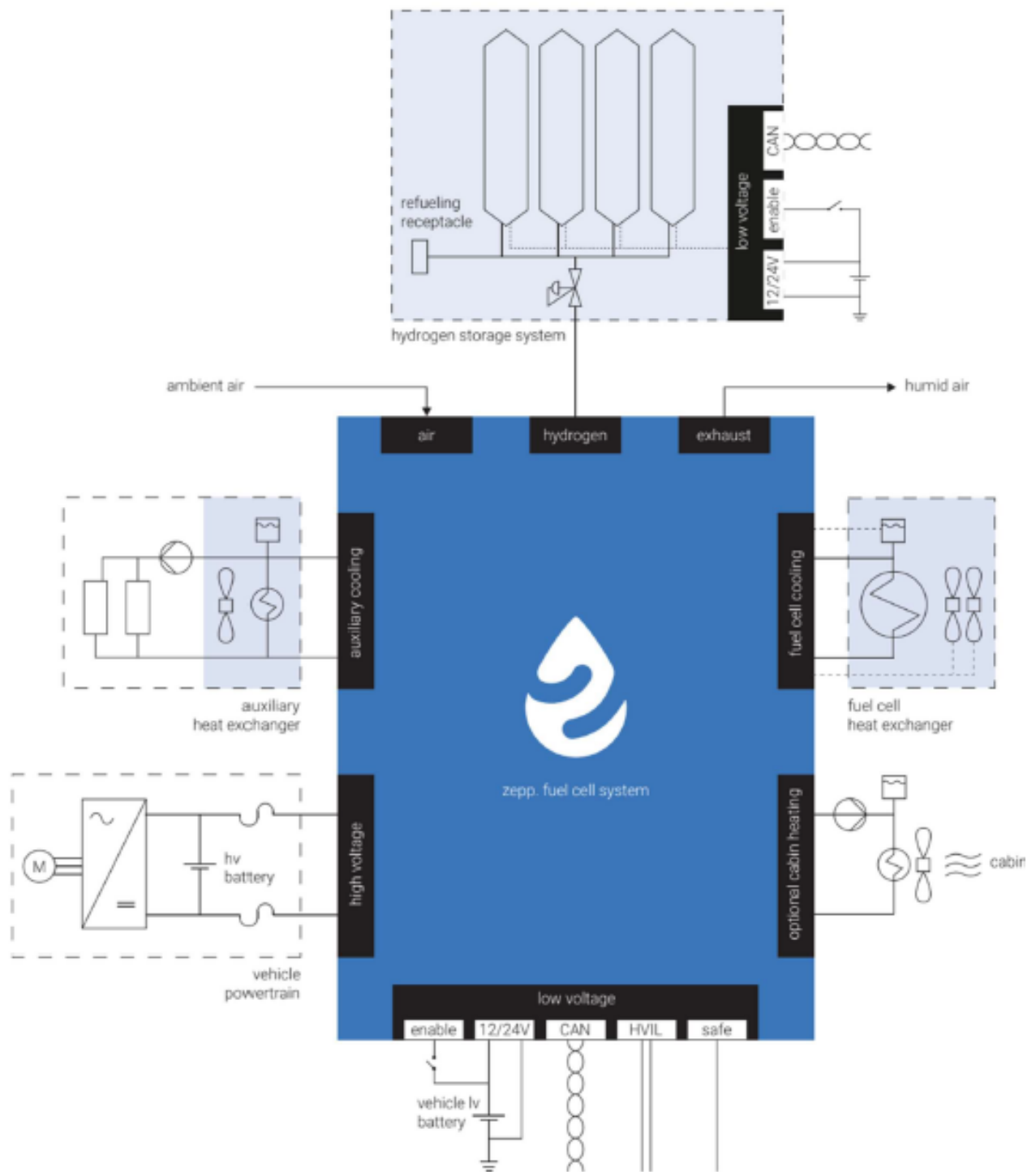


Figure 10 zepp.solutions fuel cell module

Fuel cell cooling

The fuel cell is liquid-cooled, and the fuel cell system is designed with the coolant cycle fully integrated, only requiring a connection to the cooling unit. The fuel cell cooling unit consists of a heat exchanger, fans and a coolant expansion pot with a level sensor, that is directly connected to



the fuel cell system. The fan speed and flow of coolant through the system is controlled by the fuel cell system.

Auxiliary cooling

Apart from the fuel cell itself, the fuel cell system contains several other components which are liquid-cooled. These auxiliary components are cooled by a separate cooling cycle. This cooling cycle can be integrated into any cooling cycle already existing in the vehicle. The fuel cell system contains an integrated coolant pump, such that the external auxiliary cycle consists of a similar setup as the fuel cell cooling cycle i.e., heat exchanger, fans and expansion pot with a level sensor.

Energy management

The fuel cell system is flexible in its integration with the energy management strategy of the battery system. It can receive an energy demand from which the fuel cell system itself can determine the optimal setpoint and moments of turn on/off cycling, taking into account limitations such as allowed battery charge power, efficiency and degradation, or it can exactly follow a desired power output and turn on/off whenever requested.

Safety

The fuel cell system incorporates an advanced diagnostic concept which integrates all necessary safety functions for safe operation. This includes hydrogen leak detection, external safety inputs and a high-voltage interlock.

Compressed hydrogen has a low volumetric energy density compared to liquid hydrogen. However, the extreme low temperatures along with insulation requirements and the necessary auxiliary systems, increase system complexity and material costs. The low temperature also implies an additional safety hazard. Additionally, LH2 automotive tanks are not commonly available. Modern LH2 tanks do not need additional cooling, but do evaporate hydrogen slowly over time. When the pressure inside the tank has increased too much this evaporated hydrogen is blown off. These hydrogen mass losses are called boil-off losses (0.5–3 %/d).

In case of CGH2, the hydrogen diffusion rate through the tank in modern tanks is negligible. However, higher pressure specifications increase costs, mass, as well as the need for additional certification. The high pressure implies a possible additional hazard, although this is not considered significant by the industry due to the good safety record of common high pressure CNG storages. Increased compression required for higher pressure systems takes up more energy, reducing the round-trip efficiency.

Figure 11 shows a schematic of the type of hydrogen tanks used in the hGPU. These high-pressure gas cylinders are equipped with a high-pressure valve for a controlled release of the hydrogen. CGH2 is the most common storage choice in the automotive sector and 35 MPa tanks are



considered the most suited option in this application. The system layout for these tanks is relatively simple and reliable.

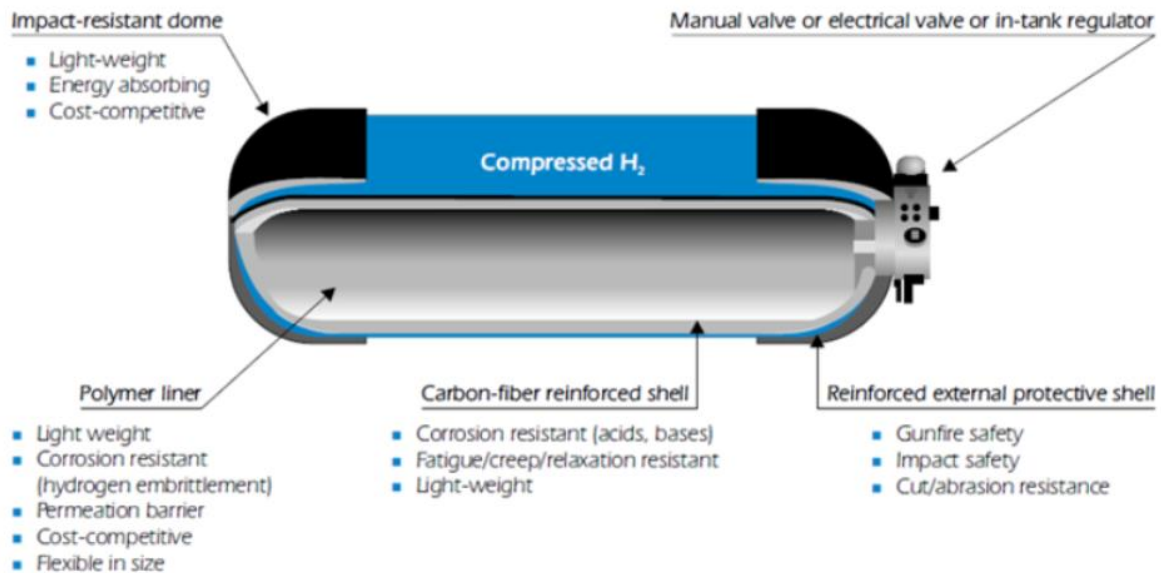


Figure 11 Schematic CGH2 tank. Source: Quantum Technologies.

The sizing of the hGPU is determined based on the data analysis outlined in Section 4.2. The heart of the hGPU lies in its robust power generation system, featuring a 50kW fuel cell system developed by zepp.solutions. Complementing this, an 84kWh battery pack supplied by Dynell is integrated into the design, ensuring a reliable interplay between hydrogen fuel cell technology and advanced battery storage. The hGPU's fuelling capability is facilitated by two 35 MPa compressed hydrogen gas tanks, each holding 8.4 kg of hydrogen, providing a balanced and efficient energy supply. This entire system is incorporated into the chassis of Dynell's largest diesel GPU, ensuring the weight and footprint requirements of airports are met. To regulate the thermal dynamics of the hGPU, a cooling system has been implemented, consisting of a heat exchanger, fans, and coolant reservoirs, ensuring optimal operating temperatures for enhanced efficiency and longevity. This integration of thoroughly tested components and proven technology is designed to meet various requirements identified by the stakeholders of WP4, keeping in mind both power and environmental sustainability requirements.



5 Technical specifications

This chapter delves into the comprehensive technical specifications of the Hydrogen-Powered Ground Power Unit (hGPU), encompassing both the fuel cell and battery components. Drawing from the requirements outlined in Section 4.2 and the load profile analysis detailed in Section 4.3, meticulous sizing and selection of components were executed to optimize performance and efficiency.

The rendered image in Figure 13 provides a visual representation of the hGPU, emphasizing its weight of approximately 2550kg, well within the permissible limits at Amsterdam Airport Schiphol (AAS). Furthermore, Figure 14 delineates the maximum outer dimensions of the hGPU, meticulously designed to meet AAS dimension requirements and align with standard Ground Power Unit dimensions prevalent in the market.



Figure 12 hGPU prototype developed by Dynell & zepp.solutions.

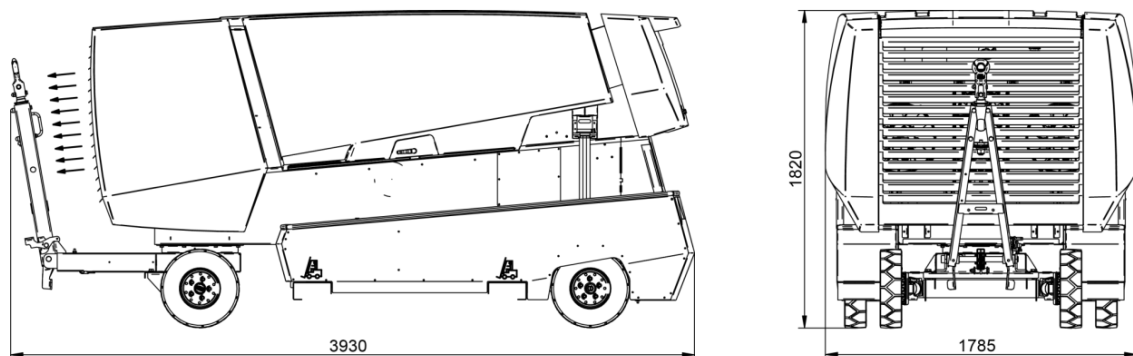


Figure 13 Maximum outer dimensions of hGPU.



The zepp.solutions' Y50 fuel cell module is a key element of this hGPU design. With high efficiency and a durable system design, this fuel cell module ensures robust operation even in the most demanding applications, all while reducing operational costs. Table 2 offers a detailed breakdown of the fuel cell system specifications, covering aspects such as power output, efficiency, and operating conditions. This integration of cutting-edge fuel cell technology not only aligns with environmental sustainability goals but also positions the hGPU as a reliable and efficient ground power solution.

Fuel	
Fuel type	Gaseous Hydrogen
Fuel quality requirement	ISO 14687:2019, SAE J2719
Fuel storage capacity (gross)	16.8kg
Rated tank pressure	350bar
Fuel cell system	
Model	zepp.Y50
Net rated power output¹	50 kW _e
Efficiency at max. power	47% LHV
Efficiency at 50% power	54% LHV
Dimension	585 x 445 x 903 mm (L x W x H)
Mass	180 kg
Output voltage range	450-750 VDC (integrated converter output)
LV supply	12/24 VDC (max 600 W)
Communication	CANbus
Diagnostics	SAE J1939
Oxidant	Ambient air
Coolant	Glysantin® FC G20 RM
Ambient operating temperature	-30-50 °C
IP protection	IP67
Max. operating altitude	2000 m

Table 2 zepp.solutions Y50 fuel cell system – technical specifications

¹ Design life is 15,000h.



Figure 11 zepp.solutions Y50 fuel cell system

Integral to the hGPU is the Dynell Inverter Module (DIM), which plays a crucial role of transforming the DC voltage from the battery into the required 400Hz output. Table 4 outlines the specifications of the DIM, encapsulating details such as power ratings, efficiency, and voltage ranges.

Inverter - output	
Power	90 kVA
Voltage	3 x 200/115 V
Frequency	400 Hz
Efficiency	> 97%
Load power factor	0.6 lagging/ inductive to 0.95 leading/ capacitive

Table 3 Dynell Inverter Module – technical specifications

Battery	
Installed energy	84.5 kWh
Technology	Li-ion NMC

Table 4 Battery specifications

Complementing the power conversion system, the batteries (Table 3) employed in the hGPU are a testament to cutting-edge technology. Leveraging state-of-the-art Li-ion technology with high energy density, these batteries are tailored to meet the demands of rigorous industrial applications.



This advanced battery technology not only enhances the efficiency of the hGPU but also contributes to its overall reliability and longevity.



Figure 12 Dynell inverter module and battery cells

The combined energy storage capacity of the Fuel Cell System (FCS) and battery is a pivotal factor in the hGPU's operational autonomy. With a total usable energy of 350kWh, the hGPU can facilitate multiple ground handling operations over an entire 8-hour shift without the need for refuelling or recharging. This extended operational endurance enhances the practicality and efficiency of the hGPU in real-world airport scenarios.

Usable energy	
In total (FCS + Battery)	350 kWh

Table 5 hGPU usable energy

The inclusion of an onboard charger, as detailed in Table 6, adds a layer of redundancy to the hGPU's power supply. This feature provides a backup option for charging the battery, ensuring continuous operation even in the event of disruptions. The charger's specifications are outlined to demonstrate its capability to maintain the hGPU's operational resilience.

Onboard charger	
Frequency	50/60 Hz +/- 5%
Voltage	3/N/PE AC 230/400 V (other voltage levels on request)
Power	40 kW
Efficiency	> 95.5%
Current	32/63/125 A

Table 6 Onboard charger – technical specifications

Facilitating ground operations, the hGPU is equipped with a towbar for convenient handling by ground operators. Table 7 further details standard features, including full rubber tires and torsion



trailer axles. These features contribute to the hGPU's ease of mobility, ensuring swift and efficient deployment on the airport tarmac. The Human-Machine Interface (HMI) of the hGPU is designed with user-friendliness in mind. Featuring a 7" touchscreen and 5 pushbuttons, the interface mirrors the simplicity and ease of use found in Dynell's eGPU. This design choice minimizes the need for extensive operator training, allowing for seamless adoption and operation of the hGPU in airport ground handling operations.

Standard features	
	Full rubber tyres and torsion trailer axles
	7" touchscreen and up to five pushbuttons
	Large cable trays and forklift pockets
	Remote assistance

Table 7 Standard features of hGPU

Adhering to safety regulations, the hGPU incorporates hydrogen leak sensors, overpressure and temperature gauges, all linked to an acoustic signal for personnel notification in case of any deviations from expected conditions, and in extreme cases, a fire. Furthermore, Table 8 itemizes various protections for electronic components, safeguarding both the GPU and the aircraft from potential damage.

Protection	
Protection class	IP 55 – electronic components
Input/output	Short circuit protection
	Over and under voltage
	Overload protection
General	No break power transfer
	Over-temperature protection

Table 8 Protection features

Prioritizing the safety of personnel and equipment, the hGPU incorporates lighter cables compared to fixed GPUs, addressing health and safety concerns. The software is designed to meet the stringent health monitoring and tracking system requirements of Amsterdam Airport Schiphol (AAS). This integration ensures that ground operations of the hGPU align seamlessly with standard GPU operations, streamlining logistics and maintenance processes.

In terms of safety regulations, the hGPU employs a multi-faceted approach. Hydrogen leak sensors, overpressure gauges, and temperature gauges are integrated, all linked to an acoustic



signal system. This comprehensive safety mechanism notifies personnel of any deviations from expected conditions promptly. In the worst-case scenario of a fire, the system is equipped to respond effectively, mitigating potential risks.

Table 8 provides an overview of the various protections for electronic components. These protections serve as a safeguard, preventing damage to both the GPU and the aircraft during ground handling operations. This meticulous attention to safety features underscores the commitment to ensuring not only the efficiency but also the safety and reliability of the hGPU in airport environments.

Lastly, Table 9 lists the ambient conditions suited for the nominal operation of the hGPU.

Ambient conditions	
Operating conditions	-20°C - +50°C (with discharge and charge power limitations)
Relative humidity	ISO 14687:2019, SAE J2719
Noise level	< 65 dB (A) at 1m

Table 9 hGPU operating conditions

In conclusion, the technical specifications of the hGPU, presented in this chapter, have been achieved by using a holistic approach to design and functionality. By integrating cutting-edge technology, safety features, and user-friendly interfaces, the hGPU emerges as a reliable and efficient solution for ground power requirements at Amsterdam Airport Schiphol and beyond.



6 Factory acceptance testing and commissioning

Factory Acceptance Testing (FAT) is a critical phase in the development and validation of the Hydrogen-Powered Ground Power Unit (hGPU). This rigorous testing process ensures that the hGPU meets all specified requirements and performs reliably before it is deployed for operational use. The FAT encompasses various key elements that validate the functionality, safety, and compliance of the hGPU. In this development process, the commissioning of the hGPU is planned in various stages. First, the eGPU, hydrogen fuel cell system and hydrogen storage system are independently commissioned. Second, after all assemblies are built into to the GPU base frame, the hGPU is commissioned and tested prior to deploying it for operations at the airport. The procedures followed in these various commissioning efforts have been briefly described in this chapter.

6.1 eGPU

The Factory Acceptance Test (FAT) process ensures the quality, safety, and functionality of the eGPU units. The testing approach involves meticulous scrutiny of individual components – namely, the battery, the charger, and the DIM (Dynell Inverter Module) – followed by the comprehensive FAT process.

The battery, a fundamental component of our eGPU, undergoes rigorous testing before integration into the system. The battery, already CE-marked by the manufacturer, is subjected to thorough testing procedures to ensure its compliance with safety and performance standards. Prior to assembly into the eGPU, it undergoes meticulous checks for possible damages, including those that may have occurred during transportation.

Similar to the battery, the charger is also CE-marked and undergoes careful testing before delivery. Comprehensive checks conducted to verify its functionality and adherence to safety standards. Prior to integration into the eGPU, the charger undergoes additional visual inspection to ensure it meets the required specifications.

The DIM, a critical component assembled at the Dynell facility in Austria, undergoes thorough testing and validation before being authorized for production. Each DIM module is meticulously tested and checked to ensure it meets the specified standards for performance and reliability.

The Factory Acceptance Test (FAT) process ensures the quality and functionality of our battery-powered GPUs before they are deployed for use. The following key aspects are rigorously examined during the FAT process:

1. Mechanical Inspection:

The FAT process commences with a detailed examination of mechanical components,



including screws, assembly, and related elements, ensuring secure fastening and proper assembly.

2. Electrical Inspection:

Electrical components undergo scrutiny, encompassing cables, connections, and plug interfaces, to guarantee correct wiring, secure connections, and the absence of any loose or damaged elements.

3. Isolation and High Voltage Testing:

Thorough isolation and high-voltage tests are conducted to verify the eGPU's safety and reliability, ensuring it can handle specified voltages and maintain insulation integrity under very high voltages.

4. Voltage and Current Symmetry at the Output:

Assessment of voltage and current symmetries at the output ensures a consistent and balanced power output, contributing to the overall reliability and performance of the eGPU.

5. Functional Testing:

A comprehensive functional test validates all unit features, including charging and discharging performance, control mechanisms, and specific functionalities tailored to the eGPU.

6. Fault Simulation and Safety Device Verification:

Simulation of potential faults and verification of safety mechanisms are performed to assess the eGPU's robustness under adverse conditions, ensuring user safety.

7. Input and Output Characteristics at Various Load Levels:

The FAT process concludes with a thorough examination of input and output characteristics under different load levels, ensuring reliable performance across various operational scenarios.

6.2 Hydrogen fuel cell system integration

The FCS is almost a stand-alone operating system, meaning besides the described interfaces it controls all its subsystems like the air intake, cooling and the hydrogen storage system by itself. Prior to operational deployment in an application, the FCS undergoes a meticulous testing and commissioning process to ensure its safe and seamless integration before it is being integrated in the GPU. A brief description of the main steps carried out during commissioning/ factory acceptance testing of the fuel cell system in the GPU is listed below.

1. Mechanical Installation.

Verify that the FCS is correctly installed mechanically, ensuring all components are securely in place.

2. Auxiliary Cooling



Confirm the proper installation and supply of auxiliary cooling to maintain optimal operating temperatures.

3. Main FC Cooling

Ensure that the main FC cooling system is correctly filled to support efficient heat dissipation.

4. Low Voltage (LV) Supply

Verify the availability of sufficient LV supply to power the FCS and associated subsystems.

5. Communication System

Confirm the functionality of communication interfaces to facilitate seamless coordination between subsystems.

6. Software interface

Validate that the FCS does not report any errors during the commissioning process due to software interface issues.

7. Emergency Scenario Response

Check the correct response of the FCS and GPU to emergency scenarios, including High Voltage Interlock (HVIL) and Emergency Communication (kill signals).

8. HV Interface and Earth Resistance Checks

- Confirm the proper installation and activation of the HV interface.
- Check the resistance of the FCS protective earth to the application protective earth.
- Verify the resistance between the HV connections and PE (Protective Earth).

9. Leakage test

Test the whole installation for hydrogen leaks.

10. Performance testing

After the previous steps have been completed, the FCS can be started to charge the GPU. The performance of the FCS will be verified.

11. Documentation

The final step of the procedure is to ensure that all procedures and output data are well documented.

6.3 Hydrogen Storage System

After assembling the certified pressure vessels and other components, it is again visually inspected and this process must be repeated on a regular basis after its entry into service, at the time of any



re-installation, or any accident (frame damaged or fire). It is important to note that any such commissioning or inspection test must be carried out by trained and authorised personnel only, and in a well-ventilated area while wearing safety glasses and working gloves. Some of the key steps taken are described as follows:

1. Visual inspection
Inspection of hydrogen gas cylinders and all other gas containing components of the hydrogen storage system, such as on-tank valves, temperature pressure relieve devices, tubing, refuelling receptacles, filters and manual valves.
2. Electrical ground testing of all metal parts
The electrical resistance of all metal parts inside the hydrogen system to the central ground point should be measured. These values should be less than 1 ohm to pass the test.
3. Leak testing
The entire hydrogen storage system is to be checked for hydrogen leaks.
4. Calibration of and response to hydrogen gas detection system and EMCY signal
In this test, the hydrogen detection sensor is triggered and the response of the system to such an event is checked i.e., on detecting hydrogen gas above the acceptable limit, the hydrogen detection alarm is triggered and the system shuts down to a safe state.
5. General working
The nominal working procedure of the system is tested, by turning on the system and checking the functionality of its software communication.
6. Documentation
After all tests have been successfully conducted, the documentation should be reviewed to make sure all steps were carried out and corresponding data has been documented sufficiently. Additionally, the nameplate, warning and safety stickers should be checked prior to wrapping up the factory acceptance testing.

After completion of the above listed checks and test, the hydrogen system is considered to be successfully acceptance tested and ready for operation.

6.4 hGPU

The successful installation of the Fuel Cell System (FCS) and hydrogen storage system is a pivotal milestone in the hGPU development. After all components and assemblies are installed in the GPU base frame, the entire hGPU must be commissioned prior to starting tests and regular operations at the aircraft stand. Listed below are some of the main goals of such a factory acceptance testing/ commissioning.

1. Functional Validation:



During the FAT, the functional aspects of the hGPU are thoroughly tested to ensure seamless operation. This includes validating the performance of the Dynell Inverter Module (DIM) in converting DC voltage to 400Hz, checking the efficiency and reliability of the zepp.solutions' Y50 fuel cell module, and verifying the charging capabilities of the onboard charger. Each component is evaluated against its specifications.

2. Power Generation and Storage:

The FAT specifically focuses on the power generation and storage capacities of the hGPU. The total usable energy derived from both the Fuel Cell System (FCS) and the Li-ion battery, is verified through extended operational testing. The hGPU is subjected to simulated ground handling scenarios to ensure it can sustain multiple operations with varying load scenarios

3. Safety and Compliance Checks:

Safety features are meticulously tested to comply with stringent regulations and ensure the well-being of both personnel and equipment. This includes activating hydrogen leak sensors, overpressure and temperature gauges, and assessing their integration with the acoustic signal system. The response mechanism to potential deviations, is thoroughly examined to confirm the hGPU's adherence to safety protocols.

4. Software and Integration Testing:

Various software communication tests are conducted to ensure that all systems are interacting as intended. Additionally, the software designed for health monitoring and tracking systems is rigorously tested to meet the specific requirements of Amsterdam Airport Schiphol (AAS).

5. Documentation Review:

Finally, a comprehensive review of all documentation related to the hGPU, including specifications, manuals, and maintenance guidelines, is conducted. This ensures that the end-users will have access to accurate and detailed information for the proper operation and maintenance of the hGPU.

In conclusion, the Factory Acceptance Testing serves as a pivotal step in the validation and verification process, assuring stakeholders that the hydrogen-powered GPU is not only technically sound but also compliant with safety standards, user-friendly, and ready for deployment in live airport operations. The results of the FAT contribute significantly to the confidence in the hGPU's performance and reliability in real-world scenarios.



7 TULIPS demonstration plan

This chapter gives an overview of the demonstration plan for the hydrogen-powered ground power unit developed by work package 4 of the TULIPS consortium. Section 7.1 describes the objective of this demonstration. A short write up about the three participating airports is included in Section 7.2. Lastly, Section 7.3 provides more insights into the demonstration plan at the lighthouse airport i.e., Amsterdam Airport Schiphol.

7.1 Objective/ Goal

A demonstration involving the use of a hydrogen-powered ground power unit (hGPU) is scheduled to take place at Schiphol (AMS), Larnaca (LCA), and Torino (TRN) airports as part of this work package. The primary objective of this demonstration is to establish that GPUs can be powered by sources other than fossil fuels and batteries, enabling Zero Emissions Airside Operations with maximum flexibility and a significant improvement in the working environment. Flexibility is a key focus of this demonstration, aiming to showcase that airport operations, including the refuelling of equipment, can be accomplished in similar ways to traditional diesel GPUs. This includes the use of a mobile hydrogen refuelling truck.

7.2 Participating airports

Schiphol is the lighthouse airport for demonstrating the hGPU. In order to extensively prove the design and operation of the hGPU, coop with operational challenges at different logistical environments, the hGPU will also be demonstrated at Larnaca and Torino airports.

7.2.1 Amsterdam Airport Schiphol

Amsterdam Airport Schiphol (IATA: AMS) is the main international airport serving the city of Amsterdam and the entire Netherland. It holds the distinction of being one of the busiest airports in Europe and is a crucial hub for global air travel. Named after the surrounding area of Schiphol, this airport plays a pivotal role in connecting passengers and cargo to destinations worldwide. As a major hub for international travel, Schiphol serves as a primary base for several prominent airlines. It offers a diverse range of flights to destinations across the globe, making it a vital link in the global air transportation network.

Schiphol Airport has a rich history dating back to its establishment in 1916 as a military airbase. Over the years, it evolved into a civilian airport and underwent extensive expansions and renovations to meet the growing demands of air travel. Today, it stands as a modern and efficient facility that caters to millions of passengers each year. The airport comprises a large terminal



complex with a main terminal and multiple piers. Each terminal is equipped to handle both domestic and international flights.

Schiphol is renowned for its innovative approach to airport management and passenger services. It consistently invests in cutting-edge technology to streamline processes, enhance security, and improve overall efficiency. The airport's commitment to sustainability is evident through its eco-friendly initiatives, including energy-efficient infrastructure and waste reduction programs.



Figure 13 Amsterdam Airport Schiphol

7.2.2 Larnaca Airport

Larnaca Airport, also known as Larnaca International Airport (IATA: LCA), is the primary international gateway to Cyprus, serving the city of Larnaca and the surrounding regions. This airport is a key transportation hub for both passengers and cargo, connecting Cyprus to various destinations worldwide. Established in 1975, the airport has undergone several expansions and upgrades to meet the increasing demands of air travel. It has played a pivotal role in the development of Cyprus as a tourist destination and a regional business hub.

Larnaca Airport consists of a single terminal building, efficiently organized to handle both domestic and international flights. While not a hub for any specific airline, the airport serves as a base for numerous international carriers. It offers a broad range of flights, connecting Cyprus to destinations in Europe, the Middle East, and beyond. Larnaca Airport is managed and operated by Hermes Airports, a consortium formed through a joint venture between Cyprus and French companies. Hermes Airports took over the airport's management with an aim of modernizing and enhancing the facilities to meet international standards. Under its management, the airport has undergone significant upgrades in infrastructure, technology, and services, transforming it into a modern and efficient aviation facility.



The airport and its management have demonstrated a commitment to sustainability, implementing various initiatives to reduce the environmental impact of airport operations. This includes energy-efficient practices, waste reduction programs, and the incorporation of eco-friendly technologies.



Figure 14 Larnaka International Airport

7.2.3 Turin Airport

Turin Airport, also known as Turin-Caselle Airport (IATA: TRN), is an international airport serving the city of Turin, located in the northwest of Italy. It is managed and operated by Società Azionaria Gestione Aeroporto Torino (SAGAT). SAGAT is responsible for overseeing the airport's operations, development, and overall management.

Positioned as a key transportation hub in the region of Piedmont, Turin Airport plays a crucial role in connecting this historical and cultural city to various destinations across Europe and beyond. Established in 1953, Turin Airport has undergone expansions and improvements to meet the increasing demands of air travel. The airport has a single terminal building that efficiently manages both domestic and international flights. While not a major hub, Turin Airport serves as a base for several airlines, offering a diverse range of flights to destinations in Europe and beyond. It contributes significantly to the regional air transportation network.

SAGAT collaborates closely with airlines operating at the airport to ensure effective coordination and efficient airside operations. Turin Airport and SAGAT continually invest in modernization efforts to stay abreast of industry standards. Upgrades to infrastructure, technology, sustainability practices and security measures are implemented to ensure a safe and efficient travel experience for passengers.



Figure 15 Turin-Caselle Airport

7.3 Plan

The hydrogen-powered ground power unit (hGPU) prototype will be demonstrated at all the above discussed airports starting with the lighthouse airport i.e., Amsterdam Airport Schiphol. The demonstration plan requirements and procedure were identified by the stakeholders of work package 4 and documented in deliverable submitted at the end of 2022, titled “Demonstration Plan and Operational Concept for the Hydrogen GPU” (SINTEF, 2022). In addition to the demonstration plan, this report also describes a plan to validate that the hGPU can successfully fulfil the high-level requirements, test protocols and validation checklists. These tests serve to (i) check communication between the hGPU and the local data centre, (ii) evaluate the safe operation of the hGPU, and (iii) evaluate the performance of the hGPU during the different phases of testing. The validation checklists are to be verified by relevant stakeholders before, during and after the testing phases

The demonstration plan is divided in two phases. The first phase will focus on the pre-operational checks which will be carried out in the test facility at KLM Equipment Services (KES). The second phase will be the actual demonstration of the hGPU at the apron and the operation of the hydrogen mobile refuelling truck.

In the first phase several checks would be done in the KES test facility to ensure the hGPU is in its optimal state, ready for operation. During this check, the following are checked, among other things: output voltage of each phase, overload protection and maximum power.

The second phase of the demonstration which would take place at the A-Platform of Schiphol, will mainly be focused on a narrow-body aircraft and is planned to be carried out for 3 weeks. In



particular, the Embraer E175/E190/E195 of KLM Royal Dutch Airlines. In this phase data will be collected focussing on the performance of the hGPU and the operations.

After successful demonstration of the hGPU at AAS during the summer of 2024, the hGPU will be demonstrated at Torino and Larnaca airport in the latter half of 2024. The demonstration plan for both these airports would follow the same as AAS, with the intent to include the findings of this demonstration, to ensure a smooth test campaign.



8 Conclusion

Diesel powered Ground Power Units (GPU's) contribute significantly to CO₂ emissions of airports. To reduce the emissions to zero, two alternative powertrain options currently exist. Battery powered GPU's have limits in terms of capacity and operational flexibility. A hydrogen electric GPU can overcome these limitations with a greater energy capacity and the ability to refuel during the operation.

The power consumption of existing equipment has been analysed to determine the ideal capacity of the fuel cell, the hydrogen tanks and the battery capacity. The differences and similarities between a H-GPU and a battery powered GPU have been described. A trade-off between hydrogen storage methods has been made, resulting in a compressed hydrogen storage system with a working pressure of 35MPa

The relevant testing and commissioning procedures for the H-GPU have been described and the demonstration plan has been substantiated.

The current design demonstrates a superior energy capacity (350kWh) and can be refuelled in minutes by a mobile refuelling truck. Therefore, it's a promising solution to accelerate the decarbonisation of airside operations.



Appendix A: LIST OF REFERENCES

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