TULIPS

Demonstrating lower polluting solutions for sustainable airports across Europe

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Demonstration Plan and Operational Concept for the Hydrogen GPU

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Abstract

There are various challenges and opportunities to decarbonise the aviation sector. In the EU's vision for sustainable airports, the TULIPS project was established. In this project, the fourth Work Package aims to reduce carbon emissions from airside operations with a focus on the operation and propulsion of ground support equipment (GSE). Zero-emission GSE operation will be contributed to by introducing hydrogen-powered GSEs, namely the aircraft tow tractor and ground power unit (GPU). Both will be demonstrated at the Schiphol airport and the hGPU will also be demonstrated at the Larnaca and Torino airports. This report focuses on providing details on the various phases included in a hGPU demonstration at an airport. The report covers the demonstration planning including (i) establishing roles and responsibilities in the planning phase; (ii) defining high level operational requirements and constraints of the hGPU at the airport, (iii) establishing standards for the hGPU, as well as providing certification for green hydrogen supply at the airport in the design and development phases; (iv) performing the demonstration with the established test protocols at Schiphol, Larnaca and Torino airports in the testing phase and (v) evaluating the requirements using the validation checklist in the validation phase.

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21/12/22	V1	Fokko	Final Version

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VI. LIST OF ACRONYMS

Acronym	Meaning
AIB	Association of Issuing Bodies
BAT	Best Available Technology
BMS	Battery Management System
CAPEX	Capital Expenditure.
CEA	Commissariat à l'énergie atomique et aux énergies alternatives
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CHJU	Clean Hydrogen Joint Undertaking
EC	European Commission
EMS	Energy Management Strategy
FC	Fuel Cell
GHG	Greenhouse Gas
GoO	Guarantees of Origin
GPU	Ground Power Unit
GSE	Ground Support Equipment
LBST	Ludwig-Bölkow-System technik
LCA	Life Cycle Assessment
LTO	Landing and Take-off (cycle)
MEA	Membrane Electrode Assembly
OPEX	Operating Expenses
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
SMR	Steam Methane Reformer
WP	Work Package

1 Executive Summary

To help remedy the detrimental effects of global warming, the reduction of greenhouse gas (GHG) emissions from the use of fossil fuels in airside operations has been a topic of interest. Airside operations are the operations carried out during an aircraft landing and take-off (LTO) cycle. Among the many ground support equipment (GSE) used during the aircraft turnaround process, ground power units (GPU) and tow tractors are some of the most polluting. In the *TULIPS* project, the Work Package 4, entitled *Zero emission airside operations,* aims at addressing the emissions from airside operations. This report details the demonstration plan for a hydrogen-powered GPU (hGPU), which will be in tested at the Schiphol (lighthouse) airport, as well as the Larnaca and Torino (fellow) airports. As part of this demonstration plan, logistics of hydrogen production and distribution at the airports will be determined.

In this study, proton-exchange membrane (PEM) fuel cell and lithium-ion battery hybrid systems were selected as the zero-emission technology to employ because hydrogen-powered vehicles are more favourable than battery-electric vehicles for heavy duty applications, and can provide comparable refuelling times to diesel. High level operational requirements for the hGPU were first detailed using the MoSCoW method. The operational requirements obtained from the relevant stakeholders defined operational, technical, safety or other requirements of the hGPU. This includes requirements such as hGPU must handle eight hours of consecutive operation, hGPU must be equipped with necessary safety sensors, etc. Dynell was then selected as the GPU manufacturer. Next, an operational demonstration concept was developed to define what was necessary to successfully demonstrate the hGPU at the various airports. Based on the information gathered throughout this study, the hGPU demonstration is planned to occur during Autumn 2023 at Schiphol, and between Summer 2024 and Autumn 2024 at the Torino and Larnaca airports. The hGPU demonstration is planned to occur in 3 phases, including (*i*) testing in a workshop, (*ii*) testing at an airport from a remote stand with no passengers, (*iii*) testing at an airport gate during an actual aircraft turnaround process involving passengers. The requirements of the hGPU will be verified by the relevant stakeholders during the defined test phases of the demonstration using an established validation concept. Finally, considering the hGPU refuelling, the origin of (part of) the hydrogen used in the demonstrations will be guaranteed green hydrogen, as per the requirements of the CertifHy certification scheme.

2 Introduction

To assist in the reduction of greenhouse gas emissions from the aviation sector, the fourth work package (WP4) of the TULIPS project covers a study of zero emission airside operations. More specifically, ground support equipment with high fossil fuel consumption, such as tow tractors and ground power units (GPU), are evaluated for operation using hydrogen (H_2) fuel cell (FC)-battery hybrid systems. Implementing hydrogen as an energy carrier to airside operations brings forth many challenges, such as the need for safe operation and new operating logistics for a hydrogen-powered GSE at the airport. Additionally, there is a challenge in having to supply H_2 to the airport. As such, WP4 will also cover a detailed investigation into clean, efficient, safe, and cost-effective ways to supply H_2 to the airport, ideally using H_2 produced from renewable energy-powered water electrolysis. This will be done using a techno-economic analysis of the whole value chain, as well as concept development.

The main objectives of WP4 include the development and demonstration of a hydrogen-powered GPU (hGPU) at the lighthouse airport (Amsterdam Schiphol) and selected fellow airports (Torino and Larnaca) as well as the demonstration of a H_2-powered tow tractor at the lighthouse airport. Additionally, an economically and technically feasible plan for the evolution of the hydrogen supply chain to the airports will also be developed, where a focus will be made on the upscale of hydrogen production and transport for future investments. To fulfil these main objectives, work package tasks have been detailed in the TULIPS Grant Agreement. In brief, these tasks cover the concept development, selection, and planning of the hydrogen GPU and tow tractors (Task 4.1), the development of the hydrogen GSE prototypes (Task 4.2), and the demonstration of both GSEs at the designated airports (Task 4.3). Additionally, detailed guidance material will be provided along with perspectives on hydrogen logistics (Task 4.4 and 4.5).

In this report, the demonstration plan of a hydrogen-powered ground power unit is established as part of Task 4.1. First, the minimum operational requirements for the hGPU are defined and hGPU manufacturers for the hGPU are identified. Next, the steps required for the hGPU demonstration are planned with an accompanying timeline. Methods for monitoring and collecting data during the hGPU demonstrations are also provided. To assess the success of the aircraft turnaround process using the hGPU, a validation plan is developed. To ensure the safe operation of the hGPU and evaluate the unit, relevant standards, and certifications to follow during demonstration activities are identified. This also covers green hydrogen supply certification schemes. With the above-mentioned tasks, execution of the plans to demonstrate an hGPU at the Schiphol Lighthouse airport can be performed in a safe and timely manner. Demonstrations for the hGPU will also be performed at the Larnaca and Torino fellow airports. Note that the Demonstration plan for the hydrogen-powered tow tractor will be published later in *Deliverable 4.9 - Demonstration Plan for the Hydrogen-powered Tow Tractor*.

3 Background

3.1 Airside operations and their decarbonisation

For the air transport industry to achieve ambitious climate change goals, such as net-zero carbon emissions by 2050[1], multiple different avenues for reducing emissions must be considered. Once such avenue consists of decarbonizing airside operations. Airside operations include a wide variety of vehicles and equipment (ground support equipment) that are used to carry out the aircraft turnaround process. The role of the equipment during this process is to ensure, among other things, that the passengers move on and off the aircraft safely, the aircraft is refuelled and prepared for pax and freight, the aircraft can move to and from the runway safely[2]. Many of the GSE are motorized and run using conventional fossil fuels, and as such, they emit GHG emissions. Examples of such GSE include the aircraft tractor, baggage tractor, cabin service truck, emergency vehicles, fuel truck and ground power unit[2]. While GSE emissions are small in comparison to other contributors in the aviation sector [3], it is still necessary to reduce or eliminate them to strive towards net-zero emissions by 2050, especially with the growing demand of air travel[1].

3.2 H_2 as an alternative fuel

A promising alternative to fossil fuels for airside operations could be hydrogen. When produced from renewable energy-powered water electrolysis, hydrogen is a clean and sustainable chemical fuel[4]. Not only can H_2 be produced in a clean manner, but it can also be used to produce electrical energy in a H_2 fuel cell, emitting only water as a by-product. In addition to having a low environmental footprint, H_2 is also a favourable alternative energy carrier because it can be used to store energy and can also be transported in a variety of ways[5]. H_2 does have its disadvantages, such as the current cost of its production and its high flammability, however overall, it is an attractive fuel for use, and it does not pose significant additional risks in comparison to other fuels[4, 5]. It should be noted that the cost disadvantage of green hydrogen production can be overcome with an increase in hydrogen production and utilisation.

3.3 PEMFC systems

A proton exchange membrane fuel cell (PEMFC) is an electrochemical device that converts the chemical energy content of a fuel into electrical energy, water, and heat. It is supplied with H_2 as a fuel, air (or oxygen) as an oxidant, then produces water and heat, the latter of which makes up between 40 to 60% of the input energy to the system[6]. A typical PEMFC consists of a membrane electrode assembly (MEA), bipolar plates, gaskets, and end plates. The MEA consists of the anode, cathode, and membrane, all of which make up a single FC unit. Hydrogen is fed at the anode, while air/oxygen is fed at the cathode. The bipolar plates are placed between each MEA. When such FC units are connected in series, a FC stack is made. Coolant flows inside the bipolar plates to maintain cell temperature. The gaskets in the stack are used to seal each single cell, as well as to seal off the coolant channels from the anode and cathode compartments. End plates are used at the beginning and end of the PEMFC stack, where the inlet/outlet ports of the H_2 and air/O_2 compartments are found. Finally, the end plates are connected to the current collectors[7]. A representative PEMFC stack structure can be visualized in Figure 1 below.

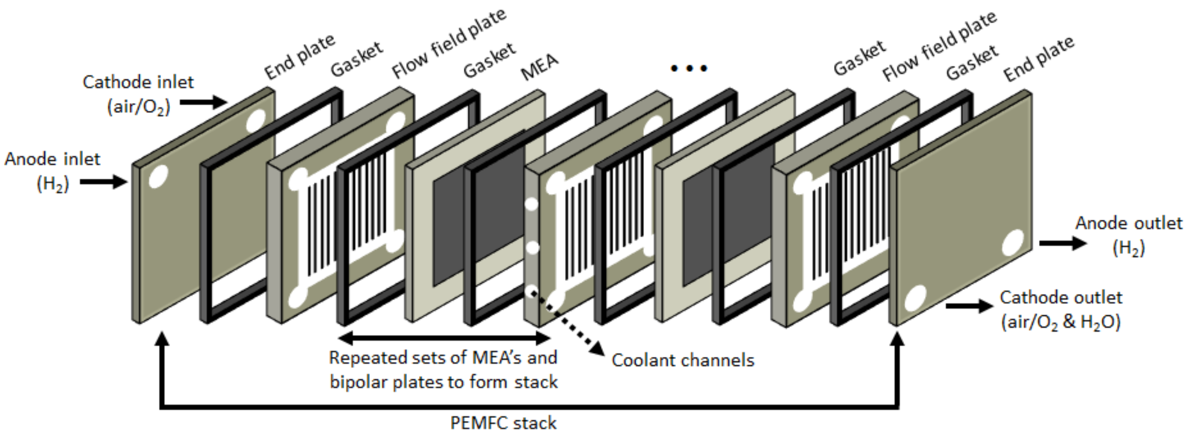

Figure 1: Representative PEMFC stack adapted from[7, 8].

A PEMFC stack system is a complex multi-domain system, which consists of subsystems, as shown by the different coloured arrows in the block flow diagram presented in Figure 2. First, hydrogen is supplied to the anode side (green) of the FC stack and air is supplied to the cathode side (red). These two are then electrochemically converted to electrical power, relatively pure water[9], and heat. The heat generated in the fuel cell must be removed to maintain efficient operation of the PEMFC stack. This is done by flowing a coolant through the FC stack cooling channels (orange). Water (blue) is supplied to the humidifiers on the hydrogen and air feed streams to maintain hydration of membrane and to balance the water usage in the system. At the outlet of the stack, hydrogen is recycled from the anode side and water is recycled from the cathode side once it has been separated from the air stream. Finally, the electrical subsystem (black, dashed) controls the power drawn from the PEMFC stack for the external load.

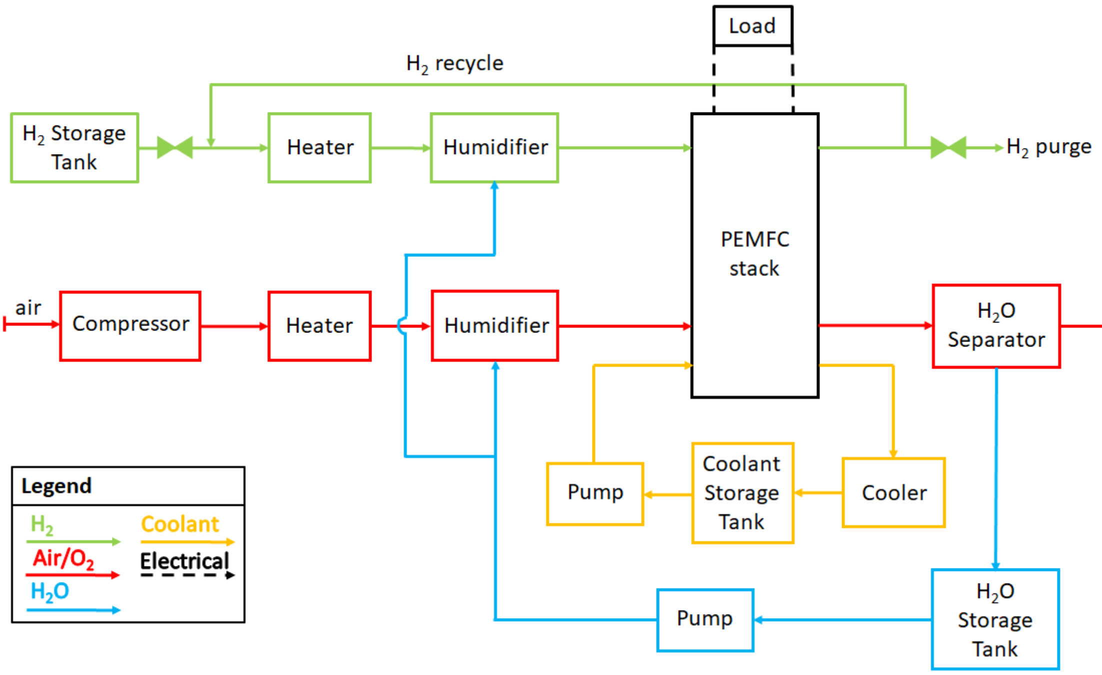

Figure 2: PEMFC stack system block flow diagram adapted from[10].

3.4 FC-battery hybrid systems

During operation, fuel cells have a low dynamic response, therefore they require a complimentary power source to help accommodate the fluctuations in power demand that occur during acceleration and start-up[11–13]. This complementary power source can be a lithium (Li)-ion battery[13]. A Li-ion battery is an electrochemical cell consisting of a cathode, an anode, and a Li-ion-conducting electrolyte to separate the two electrodes[14]. When the battery is being charged using an external power supply, electrons move from the cathode to the anode through an external circuit, while Li^+ ions migrate from the cathode to the anode through the electrolyte. This process stores the supplied electrical energy as chemical energy. During battery discharge, the opposite occurs, and the stored chemical energy is released as electrical energy to an external load[14]. To increase the capacity of a Li-ion battery, multiple cells are combined to form a module, and multiple modules are combined to form a battery pack.

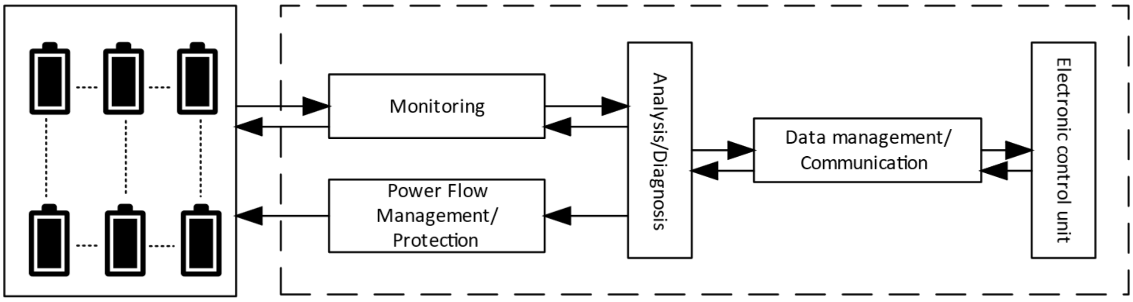

Figure 3: Block diagram of Battery management system adapted from[15]

To ensure the optimal operation of a battery pack, a battery management system (BMS) must be used as shown in Figure 3. The BMS is used to (*i*) ensure the safe and long-term operation of the batteries by helping them operate within the appropriate temperature and voltage ranges, (*ii*) help protect the batteries from being damaged, and (*iii*) ensure the batteries are kept in a state, which can carry out the vehicle requirements[16, 17]. The functionalities of a BMS include monitoring cell parameters, providing protection against system hazards, managing charge and discharge cycles, carrying out diagnosis for efficient performance, communicating for optimal performance, and managing system data[18]. When a FC and battery system are combined in a hybrid electric vehicle, an energy management strategy (EMS) is employed to regulate which energy source will provide what amount of energy to satisfy the required load[19]. Multiple EMSs exist, each with their own advantages and disadvantages[20]. The reader is referred to the following references for more information[21–23].

3.5 Impact assessment

3.5.1 Techno-economic assessment

In fuel cell-battery hybrid systems, it is also important to consider the dimensioning of the system constituents required to satisfy the load. In the context of airside operations, the size of the fuel cell and battery directly affect the cost of the zero-emission GSE, meaning that component sizing is directly related to the GSE's economic feasibility. A techno-economic analysis can be employed to dimensionalise a fuel cell-battery hybrid system for a certain power demand profile, while minimizing certain economic indicators, such as the net present value, which accounts for capital and operational expenditures (CAPEX and OPEX). When techno-economic optimisation is used in conjunction with performance optimisation tools, a hybrid system can be made to deliver the most efficient performance while considering the cost of the system.

3.5.2 Life cycle assessment

To properly assess the environmental impact of zero-emission GSE, it is important to consider the life cycle of the product. This can be done using a life cycle assessment (LCA), which is a tool employed to systematically assess the potential environmental impacts of a defined system, with the goal of quantifying the associated impacts from cradle (raw material extraction) to grave (end of life or second life). LCA can have many uses including to support decision making, inform customers, identify environmental hotspots, and to assess improvement actions. Often LCA is used to compare against alternative systems performing the same function. This can be done if the assumptions and context of each study are equivalent. For example, the environmental impact of a diesel GPU can be compared to that of a hydrogen GPU provided both are delivering the same amount of power under the same conditions. The LCA results of that comparison could then be used for a report to document the different options and compare them with regards to their environmental performance.

While important to carry out a techno-economic assessment and life cycle assessment of the hydrogen-powered GSE, such analyses are considered out of the scope of this hGPU demonstration plan report.

4 Ground Support Equipment

4.1 GSE description and operation

From when an airplane lands at an airport, to the time it takes off again, multiple GSE, each with different specific roles, are working to carry out the aircraft turnaround process. Refuelling, off- and on-loading of goods and baggage, aircraft power supply and air conditioning, aircraft movement, and so on, are all operations that are performed while passengers disembark from the aircraft, and new passengers embark onto the aircraft. Other indirect operations are also performed using GSE, such as the service and maintenance of airside infrastructure. The GSE are summarized and categorized based on area of operation as follows[24]:

- power supply and air conditioning to aircraft
- aircraft movement (pushback from gate, moving internally at airport, to/from maintenance)
- aircraft servicing (refuelling, providing supplies such as catering, de-icing, etc.)
- passenger loading and unloading
- baggage/goods handling
- airside infrastructure service and maintenance (snow removal, underground refuelling maintenance, lawn maintenance, etc.)

The type and function of some motorised GSE are described and categorized in Table 1. It should be noted that there are more GSE than what is discussed in this section. Please see Refs.[2, 24] for more information on other types of GSE.

Category	Category description	GSE	GSE description
Power supply and air conditioning	The equipment is used to aid the start-up process of the plane engines, or for passenger comfort when the plane is stationary and the engines are off.	Air conditioner unit	Also called air cart, is used to supply conditioned air (either heated or cooled) to the aircraft cabin when the main engines and auxiliary power unit are turned off. Some airports have centralized pre-conditioned air units or fixed-gate conditioned air units, but portable devices are also necessary for most airports.
		Air starter unit	Is a start-up aid necessary for some aircrafts, typically larger ones. The units have an engine, which compresses air and delivers it to the aircraft. The compressed air is used to rotate the internal turbine of the engine until the main engine can sustain itself.
		Engine heater unit	Heater designed for heating aircraft engines in cold conditions to avoid the freezing of fluids and lubricants.
		Ground power unit	Engine powered generator used to provide power to the aircraft when the main engine is turned off. Portable GPUs are used when it is inconvenient or impossible to connect the aircraft directly to the internal airport power grid.
Aircraft movement	Most aircrafts have the capability of reversing and turning abruptly on the ground. However, due to safety, limited visibility from the cockpit, and engine straining (when reversing a jet engine), normal mobility operation of an aircraft on the ground requires aid from support equipment for pushback from the gate, relocation at the airport, and, in some cases, taxing.	Tow tractor	Also called aircraft tractors or pushback and/or tow tugs, provide aid for aircraft movement. The equipment is utilized when the aircraft cannot use the main engines, or if enough manoeuvrability is unavailable. Pushback from gate, manoeuvring in confined spaces, or moving aircrafts internally at the airport, for example to and from maintenance hangars, are examples of typical use cases for tow tractors.

Table 1: GSE types and descriptions[2, 24]

Category	Category description	GSE	GSE description
Aircraft servicing	In-between flights, these units are necessary to carry out the refuelling of the aircraft and servicing of multiple on-board applications, such as catering, lavatory, water, etc.	Catering truck	Trucks that are designed to deliver catering supplies to the aircraft while at the gate. These are typically operated by companies specialized in catering to airlines. The trucks are equipped with hydraulic lifting systems capable of lifting the truck bed to the aircraft access door. The trucks are also used for removal of catering-associated waste from previous flights.
		De-icing truck	Trucks that are designed with controllable booms or cherry pickers. The trucks stores, transports, heats, and distributes/sprays de-icing fluid on aircrafts prior to take-off. This is done to remove and prevent snow and ice on aircrafts, which can affect the aerodynamic properties of the airplane. These trucks are often powered by two engines; one for the truck, and one for heating, pumping, and spraying the de-icing fluid.
		Fuel truck	There are two main methods used to refuel aircrafts. The first is a standalone truck with a fuel tank, pumps, filters, and valves capable of refuelling aircrafts directly. The second is an underground airport refuelling system, where a specialized hydrant truck/cart functions as a connector between the underground system and the aircraft.
		Lavatory service truck	A truck specifically designed for recovery and transportation of aircraft lavatory waste. The truck should be equipped with a collection system and a storage tank, as well as equipment for replenishing chemical disinfectants in the aircraft and cleaning of the on-board lavatory tanks.
		Water service truck	Truck designed to service the onboard water needs of the aircraft. The truck is equipped with the necessary storage tanks, pumps, filters, and valves.

Table 1: GSE types and descriptions[2, 24] *(continued)*

Category	Category description	GSE	GSE description
Passenger loading/ offloading	The method of disembarking and boarding passengers between flights is dependent on the airport, plane size, and available parking at the airport. For flights with no access to a jet bridge, stairs for passengers to exit and enter the plane as well as airport shuttle busses are necessary.	Passenger bus	Bus used for transporting passengers from the gate to the aircraft and vice versa, when the aircraft is not parked at a jet bridge or within walking distance from the airport.
		Passenger stairs	Portable stairs, either standalone on a trailer or fixed to a truck, to enable passenger boarding or disembarking at airports.
Baggage/goods handling	Baggage and goods are a large logistical aspect of airside operations. They must be transported internally at the airport and be loaded onto/offloaded from the planes.	Baggage tractor	A recognizable vehicle at any airport used to tug trains of dollies filled with baggage, mail, or goods between the aircraft and the baggage processing facility.
		Belt loader	A vehicle designed with a built-in belt capable of being raised to aircraft height. This is used to transport baggage, mail, and goods from dollies up to the aircraft baggage/cargo compartments, where airport workers stack the items.
		Container loader	Vehicle specifically designed for the loading and offloading of containers, pallets, and storage vessels between the aircraft cargo compartment and container transporter vehicles. It is equipped with pneumatics or hydraulics, and rollers to enable vertical and horizontal movement of cargo.
		Container transporter	Vehicle with similar design to the container loader, used to transport cargo in containers between the aircraft and internal cargo terminals at the airport.
		Ramp equipment tower	Tow vehicle for all equipment unable to move itself such as GPU, stairs, etc.

Table 1: GSE types and descriptions[2, 24] *(continued)*

Category	Category description	GSE	GSE description
Airside infrastructure service and maintenance	Equipment used for maintenance of runways, taxiways, ramp areas, lawns, internal refuelling systems, etc.	Snow removal equipment	Snowploughs, snow sweepers, and snowblowers used for snow removal at runways, taxiways, and ramp areas. Snow sweepers use brushes to clear thin layers of snow, snowploughs use ploughs to remove medium amounts of snow, and snow blowers, use rotating discs to forces snow out of a funnel to move large, hardpacked amounts of snow.
		Emergency vehicles	Vehicles, including cars, smaller trucks, and large trucks, designed to respond to emergencies internally at the airport. This may include police/security vehicles, ambulances and fire trucks.
		Glycol recovery vehicle	Trucks specifically designed to recover the access de-icing chemicals that is used on the aircrafts. These vehicles are designed with on-board integrated storage tank and a vacuum system. These vehicles are expected to operate at the designated de-icing pads, but also at the airport aprons and taxiways.
		Hydrant pit cleaner	A towable trailer designed to recover fuel that can accumulate in the underground fuel distribution system. The cart are equipped with a storage tank, a vacuum system, and an engine to power the vacuum.
		Snow removal equipment	Snowploughs, snow sweepers, and snowblowers used for snow removal at runways, taxiways, and ramp areas. Snow sweepers use brushes to clear thin layers of snow, snowploughs use ploughs to remove medium amounts of snow, and snow blowers, use rotating discs to forces snow out of a funnel to move large, hardpacked amounts of snow.

Table 1: GSE types and descriptions[2, 24] *(continued)*

4.2 GSE contribution to airside operation emissions

As different GSE have different vehicle and power requirements to carry out their specific functions, the energy consumption of the vehicles, and by extension the airside emissions of the vehicles, will vary. Among the many motorised GSE, GPUs and tow tractors are some of the most polluting pieces of equipment used in the aircraft turnaround cycle[25] . As such, the focus of the work in this report will on zero-emission technologies for ground power units, while the focus of Deliverable 4.9 will be on zero-emission technologies for tow tractors.

Some zero-emission alternatives to using diesel powered-engines for GPU operation include the electrification of the unit using batteries, or the use of fuel cell-battery hybrid electric systems, with different degrees of hybridisation. Battery-powered ground support equipment are already being employed in many airports. For example, in 2020, the global ground services provider, Swissport, had 14,6% electric GSE [26]. However, hydrogen fuel cell-battery electric propulsion may be more beneficial for certain GSE applications. For example, utilizing hydrogen to power GSE could be favourable for heavy duty vehicles, due to hydrogen's higher relative energy density. Additionally, utilizing hydrogen as a replacement fuel for diesel will also allow for fast refuelling times [27]. This aspect is important in maintaining quick aircraft turnaround processes. It is for these reasons that it was decided to evaluate the GSE in this project using hydrogen as a primary source of power. Hydrogen-powered GSE have also been the subject of other recent studies, such as the hydrogen fuel cell baggage tow tractors (tugs), evaluated at the Memphis International Airport[28]

5 Demo 1: The Hydrogen Ground Power Unit

In Work Package 4, a demonstration plan was developed, encapsulating the planning of activities, which included the design inputs, as well as the testing and validation of the hGPU and hydrogen-powered tow tractor at Schiphol, Larnaca and Torino airports. In the demonstration plan of this report, the operational concept, and minimum operational requirements of the hGPU were defined. The inputs for the hGPU operational requirements and constraints were collected from different stakeholders in the project using the MoSCoW method, as further discussed below. With the requirements and constraints of the hGPU defined, a detailed technical specifications sheet for the hGPU was developed. Finally, an operational demonstration plan was developed to map out the deadlines, activities, roles, and responsibilities necessary to result in a successful demonstration of the hGPU at different airports. The following chapter is divided in four sections, describing the demonstration requirements (Section 5.1), the operational demonstration concept (Section 5.2), and the validation concept (Section 5.3).

5.1 Demonstration requirements

Requirement prioritisation is a vital step in the requirements analysis in a product development process and an important task for decision makers. Prioritising requirements has benefits, such as (*i*) helping ensure that all the stakeholders build consensus and understand what the main outcomes of a project are, and (*ii*) reducing the risk that valuable project resources are misdirected[29]. The prioritisation process is important due to the following challenges:

- time limitations or availability of right people for the job
- budgetary constraints imposed by the funding party
- team’s skillset limiting the building process
- competing needs of different stakeholders

Many techniques have been proposed for requirement prioritization, each of which help sort requirements efficiently based on their importance in project implementation. There are many challenges when facing these techniques including the need to satisfy the clients’ expectations. For the current project, the MoSCoW method was used because of its ease of getting inputs from all the stakeholders during the planning phase of the project. The MoSCoW method was therefore applied to the demonstration of a newly developed hydrogen-powered GPU, which will operate at Schiphol, Larnaca and Torino airports.

MoSCoW is an acronym for requirements that you “must have”, “should have”, “could have” and “would not (or won’t) have”. “Must have” requirements are the non-negotiable needs for the product, project, or release. “Should have” requirements are important to the product release but not vital. This could, for example, be related to performance improvement, minor bug fixes, new functionalities, etc. “Could have” requirements are not necessary and have a much smaller impact when left out. “Would not have/won’t have” requirements are not included in the scope of the project [30].

A workshop was conducted online in spring 2022 in the early phase of the project with all the stakeholders from the airports, GSE handlers, repair, and maintenance personnel, GSE provider, FC integrator, FC manufacturer, fire department, etc. In this workshop, inputs on high level requirements were collected from all the stakeholders. The inputs from the workshop were compiled/consolidated and categorised into four sections, namely technical, operational, safety and other requirements. The consolidated information has tasks under each requirements category, showing the stakeholders who validate the requirement, and the stakeholders who are responsible for the completion of the requirement. Further actions were also identified to complete each task, with corresponding status and deadlines.

Operational requirements are those that identify the essential capabilities and performance measures of the unit, as well as the process to be taken in effecting the results that are desired to address either mission area deficiencies, evolving applications or threats, emerging technologies, or system cost improvements [31]. In this case, operational requirements include all the requirements associated with the operational phase of the hGPU at the airport, including refuelling, towing, actual operation, maintenance, etc. The hGPU operational requirements include, but are not limited to:

- The hGPU must be able to operate for at least eight consecutive hours and the handling process should not be more complex than current GPUs, requiring only minimal additional training.
- Instructional materials must be provided for safe operation
- The hGPU must be able to handle 90% of the standard operational load for narrow body aircraft.
- It must comply with relevant airport rules and regulations and have basic onboard monitoring and data logging capabilities.
- It must also signal its operational status.

Technical requirements tend to be formal and concrete and are expressed by technical experts [32]. In this case, technical requirements include details on major aspects of the hGPU, its operation including the hydrogen refuelling. The hGPU technical requirements include, but are not limited to:

- The hGPU must have the similar and reliable performance as its diesel counterpart
- The hGPU should not negatively impact aircraft handling or performance on the ground.
- The hGPU's cables must be as light and flexible as possible, with an optimal length for easy handling

Safety requirements specify what the design, context, and usage of the hGPU must comply with to be adequately safe for use [32]. These requirements may be specially annotated to indicate their safety relevance or may just be treated as requirements that the system must satisfy. In this case, the safety requirements should cover any safety risks associated with hydrogen refuelling and hGPU operation. These requirements include, but are not limited to:

- To conduct an adequate safety risk assessment, mitigation measures, and communicate to relevant stakeholders based on guidance from relevant partners.
- The hGPU must be equipped with a safety sensor that provides real-time alerts in case of an emergency.
- Training and manuals should be provided to relevant partners with a focus on risk assessment, adequate knowledge safe operations confidence working with the hGPU.

Any requirements that do not belong to any other category are included in the "Other requirements" category. These requirements are miscellaneous requirements such as

- The hGPU will significantly reduce local carbon emissions, as well as other emissions such as NOx, noise etc.
- Operation with the hGPU will not negatively impact any aspect of health, safety and environment at the airport.

5.2 The operational demonstration concept

In this work package, a demonstration of hydrogen powered ground power unit will be conducted at the Schiphol (AMS), Larnaca (LCA) and Torino (TRN) airports. This section outlines the stages of hGPU product life cycle including the Planning, Research, Development, Demonstration, and Validation phases [31]. There are various stakeholders involved in the hGPU demonstration phase, namely, Schiphol group, Hermes group, Sagat group, KLM equipment services (KES), zepp.solutions (zepp), Dynell, SINTEF AS (SIN-AS), Fraunhofer Gesellschaft (FhG), Hydrogen Chemistry Company (HyCC), KLM and SINTEF Energy (SIN-EN). Table 2 summarizes the roles and responsibilities of the stakeholders involved in the project.

Stakeholder name	Role	Responsibilities
FhG	Lead for WP4 and Task 4.4	Develop guidance material for lighthouse and fellow airports, coordinate tasks and perform risk assessment for hGPU operation at an airport
Hermes	Fellow airport	Demonstrate hGPU at the Larnaca airport. Obtain approvals/clearances/agreement from necessary stakeholders
HyCC	Consultant	Dissemination and certification schemes for green hydrogen supply
KES	Lead for Task 4.2, 4.3	Site preparation and installation of H_2-refuelling station, training of personnel
KLM	Airlines	Provide aircraft for demonstration at Schiphol airport
Sagat	Fellow airport	Demonstrate hGPU at the Turin airport. Obtain approvals/clearances/agreement from necessary stakeholders
SIN-AS	Lead for Task 4.1	Technical support and detailed planning of hGPU demonstration
SIN-EN	Lead for Task 4.5	Perform techno-economic analysis on hydrogen logistics
SNBV	Lighthouse airport	Demonstrate hGPU at the Schiphol airport. Obtain approvals/clearances/agreement from necessary stakeholders
zepp	Fuel cell solutions provider	Develop hydrogen-based power system and its integration with GPU
Dynell	GPU manufacturer	Manufacture GPU and integrate fuel cell in collaboration with ZS

Table 2: Stakeholder roles and responsibilities in the hGPU demonstration phase

The **Planning Phase** includes the planning and conceptualisation of the demonstration. This includes the development of test protocols (for example, testing the telemetry system of hGPU based on the high-level requirement that the GPU shall provide data logging), validation checklists (for example, communication between hGPU, ground operator, cockpit operator, and remote operator is working as expected), as well as getting approvals and clearances from various authorities, such as the airport fire department and the municipality, for on-site testing and hydrogen refuelling. In this phase, the high-level requirements are setup as described in the Section 5.1. During the planning phase, workshops with relevant stakeholders were conducted to establish requirements and to plan activities during the demonstration. The testing protocols were developed for testing in-house, at remote stands and at gates in actual operation. These tests are designed to validate the hGPU safety and performance over 8 hours of operation, without refuelling. This phase started in Fall 2022 and will continue until Autumn 2024.

The **Research Phase** includes (i) the collection of necessary GPU data from the partners, such as an example battery-powered GPU power profile, system constraints and operational requirements, (ii) equipment sizing based on the techno-economic assessment, and (iii) reporting of results. A workshop was conducted to get the abovementioned inputs from the relevant stakeholders and the feedback was incorporated into the analysis. Some of the inputs gathered included a 5-day battery GPU power profile from Schiphol airport. This includes average power delivered by battery GPU, its state of charge, power consumed by battery GPU for charging during the 5 day period. The results from the assessment were used as initial guidelines for the actual sizing of hGPU. The activities in this phase were initiated in March 2022 and are planned to continue until December 2024.

The **Development Phase** includes the identification a GPU original equipment manufacturer (OEM), as well as the design and development of the hGPU based on the high-level requirements of the unit. This phase also includes beta testing and commissioning of hGPU, as well as the development of training materials and the provision of said training materials to relevant stakeholders for the safe operations of the hGPU, including its refuelling. This phase was initiated in January 2022 and is planned to be finished by October 2023.

In the **Demonstration Phase**, the necessary site preparations for the demonstration will be carried out, in addition to the testing of the hGPU. The detailed testing protocols developed in the Planning phase will be performed with the help of necessary equipment and relevant stakeholders, including airport operators and authorities, the fire brigade, the refueler, ground handlers, the hGPU manufacturer, the airline, aircraft technicians, etc. Testing is planned to occur in three phases to ensure the hGPU is safe to use and can deliver the necessary power to the aircraft. The first testing phase is testing from in a workshop. The second is testing at a remote stand at the airport with no passengers in the aircraft. Finally, the third phase will be testing at a gate in the airport under normal operating conditions, or in other words, testing with an aircraft in an LTO cycle involving passengers coming on and off the aircraft. During the hGPU testing, operations will be monitored and the necessary steps to debug any occurring issues will be taken.

In the Demonstration phase at Schiphol airport, the hGPU also needs to be refuelled with hydrogen. This could be done either at the KES workshop or on airside using a hydrogen refuelling truck. The first option would bring some logistics with it as the hGPU needs to be towed to the KES workshop. Besides this, there should be an infrastructure available at KES to provide this refuelling. For the second option, several alternatives are available. The first could be carried out by an external party which will only provide the hydrogen at airside using a hydrogen refuelling truck. Another option is to have a hydrogen storage at the KES workshop and a refuelling truck which refuels the hGPU on airside. It is envisioned that the latter is the future of hydrogen refuelling at Schiphol airport.

There will also be press releases to accompany the demonstrations. Results from these tests can be further used for hydrogen logistics planning and provide guidance material for the future adoption of hydrogen as a clean fuel at fellow airports. The demonstration will happen during Autumn 2023 for Schiphol airport, followed by the Larnaca and Turin airports. Tentative plans for the demonstrations at the fellow airports are Summer 2024 or in Autumn 2024.

5.3 The validation concept

During the validation phase, the validation checklist, formed based on the high-level requirements of the hGPU, will be evaluated and confirmed by relevant stakeholders. The validation checklist includes all the tests designed to evaluate the communication, operation (performance) and safety of the hGPU. The checklist will be filled out during, and after the three demonstration test phases, namely the “in-house”, “remote stand” and “at gate in actual operation” phases. The validation will be done at all the airports. For Schiphol airport, the demonstrations will take place during Autumn 2023 and Winter 2023/2024, and for the fellow airports, the demonstrations will be during Autumn 2024 and Winter 2024/2025.

6 Green Hydrogen Supply

The TULIPS project seeks to identify and assess zero emission airside operations. The initial focus in this report is on GPUs that are currently powered by diesel but could be powered by hydrogen using hydrogen fuel cells as a power source. To reach zero emissions airside operations, the origin of energy source and production method of the hydrogen is relevant to assess in the calculation of the GHG emission. Hydrogen produced by water electrolysis using renewable power (green hydrogen) carries significantly different environmental impact when compared to production via Steam Methane Reforming using naturel gas (grey hydrogen). To transfer the value of renewable power via green hydrogen to the airside operations, certification via Guarantees of Origin (GoO) for hydrogen are needed.

6.1 CertifHy

CertifHy is a consortium led by HINICIO and composed of GREXEL, Ludwig-Bölkow-System technik (LBST), Association of Issuing Bodies (AIB), Commissariat à l'énergie atomique et aux énergies alternatives (CEA) and TÜV SÜD[33]. CertifHy has been initiated at the request of the European Commission (EC) and is financed by the Clean Hydrogen Partnership. CertifHy has developed high-quality hydrogen certification schemes across Europe addressing consumer disclosure (from well to gate) as well as RED II target compliance (from well to wheel). CertifHy certificates support hydrogen's market growth as they are a reliable tool for consumers to track hydrogen's origin and environmental attributes.

6.2 Grades of hydrogen according to CertifHy

6.2.1 Green hydrogen from renewable origin

Hydrogen originating from renewable sources (defined in art 2 of the Renewable Energy Directive II), such as wind/solar/hydro electricity production. Those production processes have zero GHG emissions, hence zero carbon intensity by European convention. Hydrogen from biomass-based production, which could come with GHG emissions as defined by RED II.

6.2.2 Low-carbon hydrogen from non-renewable origin

Nuclear or fossil energy using carbon capture and storage (CCS) & potentially carbon capture and utilization (CCU) which is yet to be defined by the European law. The carbon intensity limit for renewable and non-renewable H_2 is fixed at 60% below the amount of GHG emissions from a Steam Methane Reformer (SMR), being current Best Available Technology (BAT) for merchant H_2 production (benchmark process with a current GHG footprint of 91 gCO_{2eq}/MJ). The GHG intensity of the BAT will be regularly re-assessed, and the emission reduction % targets are to increase over time.

6.3 CertifHy system and certification

CertifHy aims at facilitating the creation of an EU-wide system of GoOs. Therefore, CertifHy certificates are hold into a unique European central database, a Registry, that will manage the CertifHy certificates' life cycle for every account holder. The CertifHy Certificates scheme grants a tradable value to renewable and non-renewable hydrogen. It is therefore essential that the CertifHy Certificates scheme is reliable, accurate and verifiable. Controlling the information and the accuracy of the CertifHy Certificates is of critical importance. As described in the chart here below, controls will be carried out by different actors, such as the Certification and Issuing Bodies.

To have a well established system, Auditors ensure that the producers (production devices) comply with the CertifHy Scheme requirements. The auditors are part of a Certification body, which has a relevant accreditation to perform this activity. The Accreditation body controls the quality assurance system of the Certification body. It increases trust in conformity assessment by ensuring that certification bodies have the technical capacity to perform their duties. Any accreditation body in Europe – member of the International Accreditation Forum – is allowed to accredit certification bodies. The issuance of CertifHy Certificates is under the responsibility of the Issuing body, this entity is under direct control of the Competent authority. Transfer/trade and cancellation of hydrogen CertifHy Certificates are performed by the Account Holder in the CertifHy registry, after review by the issuing body.

6.4 The CertifHy project

CertifHy has known 3 phases. In the first phase, between 2014 and 2016, the CertifHy project brought together multiple stakeholders to develop a common European-wide definition of green hydrogen, develop a hydrogen GO scheme deployable across Europe and a roadmap for its implementation. In the second phase, 2017-2019, GoO's were issued during pilot projects. In the third phase, which started in late 2020, RFNBO certification will be tested, and the scheme will be tested in new pilot projects. Nobian (50% shareholder of HyCC) has been involved in the CertifHy project as of phase one. The large-scale electrolysis installation in Rotterdam (200MW) has been certified according to CertifHy from the first pilot. Following the audit of the hydrogen production plant in Rotterdam, production batches of (green) renewable hydrogen are being certified and CertifHy Certificates issued to Nobian. To manage the issue, transfer and cancellation of CertifHy Certificates, each production unit or supplier holding CertifHy Certificates must have an account in the CertifHy Registry, which Nobian has. CertifHy GoO's can be sold independently from H_2 molecules.

6.5 Demonstration TULIPS

To enable the demonstration of zero-emission airside operations, HyCC via Nobian can deliver renewable Guarantees of Origin for (part of) the hydrogen supplied to the GPU and/or Tow tractor. The volume of hydrogen supplied needs to be known at HyCC 6 months in advance to ensure certificates can be delivered in time. Via the certification the attribute of renewable power is passed on to the hydrogen, which supports TULIPS to demonstrate usage of green hydrogen to enable zero-emission airside operations.

7 Conclusion and Outlook

This report identifies opportunities and challenges in decarbonising airside operations by using hydrogen as a fuel. Hydrogen is a promising fuel to employ as it can be produced in a clean manner through renewable energy-powered water electrolysis, and can also be utilized as a clean fuel in a fuel cell, emitting only water as a by-product. Among the many motorized ground support equipment that contribute to airside emissions, it was identified that fossil fuel-powered tow tractors and ground power units were some of the most polluting GSE. As such, Work Package 4 in the TULIPS project covers the demonstration of hydrogen-powered tow tractors and ground power units, where this report details the demonstration plan of a hGPU, while Deliverable 4.9 will describe the demonstration plan of a hydrogen-powered tow tractor. In these studies, the hydrogen-powered GSE are powered using proton exchange membrane fuel cell and lithium-ion battery hybrid power systems.

To start planning the demonstration, an exhaustive list of high-level hGPU requirements was developed using the MoSCoW method, addressing operational, technical, safety and miscellaneous requirements. The inputs necessary to establish these requirements were gathered from the relevant project partners during an online workshop. The relevant partners included the airports, GSE handlers, repair and maintenance personnel, GSE provider, FC integrator, FC manufacturer, fire department, etc.

Following this activity, a detailed demonstration plan was made, where the roles, responsibilities, and timelines for various activities were defined. The demonstration plan includes having the hGPU designed by Summer 2023, and obtaining the approvals to demonstrate the hGPU at Schiphol airport by Autumn 2023 and Winter 2023/2024. Similar approvals must also be obtained for the hGPU demonstration at the Larnaca and Torino fellow airports, which are anticipated to be in Autumn 2024. To validate that the hGPU can successfully fulfil the high-level requirements, test protocols and validation checklists were established. These tests will serve to (*i*) check communication between the hGPU and the local data centre, (*i*) evaluate the safe operation of the hGPU, and (*iii*) evaluate the performance of the hGPU during the three different phases of testing. The three phases of testing include (*i*) testing at a workshop, (*ii*) testing at a remote stand with the actual aircraft, but without passenger, and (*iii*) testing at the gate in actual operation, with aircraft and passengers. The validation checklists will be verified by relevant stakeholders before, during and after the testing phases. To validate that green hydrogen is used in the GSE demonstrations, HyCC via Nobian will deliver Guarantees of Origin for (part of) the hydrogen. This is done using CertifHy, a European high quality hydrogen certification scheme. Getting this certificate will take 6 months.

Future work in this work package includes the demonstration of a hydrogen-powered tow tractor at Schiphol airport. Activities for the tow tractor will start early in 2023 and the demonstration plan for the tow tractor at Schiphol airport will be summarized in *Deliverable 4.9 - Demonstration Plan for the Hydrogen-powered Tow Tractor in December 2023*.

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