Feasibility study on the general use of gaseous hydrogen in airport machinery

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The BSR HyAirport study examines the feasibility of using hydrogen technologies at airports in the Baltic Sea region. It assesses the technical, economic, and infrastructural conditions for hydrogen-powered ground vehicles and outlines a phased approach to implementing this sustainable technology.

The BSR HyAirport project is investigating the feasibility of using hydrogen technologies at airports in the Baltic Sea region. The aim of this study is to evaluate the technical, operational and economic aspects of using hydrogen-powered ground vehicles and the associated infrastructure. The study shows that H_2 technologies have great potential for airport operations but recommends a gradual introduction.

The aviation industry plays a crucial role in the global economy, facilitating mobility, trade, and tourism. However, the environmental impact of airport operations and air travel, particularly in terms of greenhouse gas emissions, has become a pressing concern. As countries and industries worldwide strive to meet ambitious decarbonization targets, the search for sustainable energy alternatives is intensifying. In this context, hydrogen has emerged as a promising energy carrier, offering the potential for significant reductions in CO_2 emissions across various sectors, including airport operations.

Hydrogen's versatility as a fuel for ground support equipment (GSE), stationary power sources, and potentially even aircraft makes it an attractive solution for airports seeking to reduce their carbon footprint. The Baltic Sea Region (BSR), with its unique geographic and environmental characteristics, is particularly well-suited for early adoption of hydrogen technologies. Given the region's reliance on short-haul flights, the introduction of hydrogen-powered solutions presents an opportunity to not only mitigate environmental impacts but also set a benchmark for sustainable airport operations.

As of today the market for airport equipment does not offer any hydrogen powered vehicles in series production, as the technology is still young, which as well partly explains the dominance of battery-electric vehicles (BEV) on the market. Nevertheless, the market analyses done in this study shows, that several airport equipment manufacturers have hydrogen powered alternatives of their products planned within the next 5 years.

1. Hydrogen as a power source for airport equipment

There are two main types of hydrogen vehicle echnologies that leverage hydrogen's chemical properties in different ways. The first is fuel cell technology, which generates electricity through an electrochemical reaction between hydrogen (H_2) and oxygen (O_2) from the air. This process produces electricity by releasing electrons, with water (H_2O) and heat as the only by-products, making it a highly clean energy source.

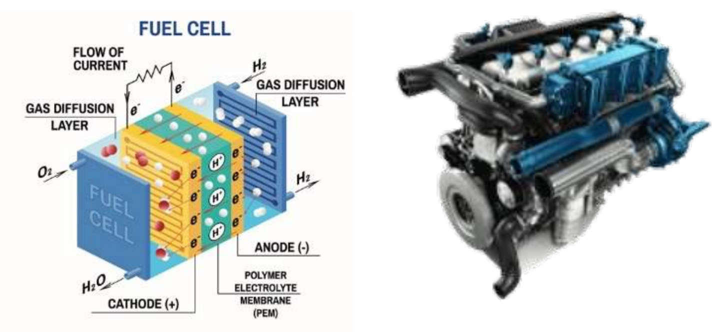

Figure 1: Fuel Cell [7] and ICE [8]

The second are hydrogen combustion engines also called H_2 engines, where hydrogen is burned as fuel, similar to traditional internal combustion engines. While water is also a by-product, this method produces nitrogen oxides (NO_x) due to the high-temperature combustion, making it less environmentally clean compared to fuel cells. However, hydrogen combustion engines can often be integrated more easily into existing internal combustion engine infrastructure.

Fuel cell technologies

The most prevalent type of fuel cell used in mobile applications is the Proton Exchange Membrane (PEM) fuel cell. It offers a multitude of advantages fo mobile applications, including:

- o Low operating temperatures: 60 - 80 °C
- o Fast start-up within a few seconds
- o Compact design
- o Low weight

To achieve the desired power output, several individual fuel cells are connected to form a fuel cell stack. The power can be scaled by the number of cells.

In fuel cell vehicles, the power of the fuel cell stack is usually matched to the average power requirement. Short-term load peaks, such as those during acceleration or starting, are a sorbed by a small buffer battery (battery pack). At the same time, the buffer battery also acts as an energy store for energy generated from renewable sources, e.g. when braking or driving downhill. Since the buffer battery cannot be overcharged, it is important that the capacity of the buffer storage is also designed accordingly for these requirements, e.g. when baggage tractors with trailers are driving down a long ramp.

In addition to fully integrated fuel cell systems, which are tailored by the vehicle manufacturer to meet the vehicle's performance specifications, there are stand-alone fuel cell systems designed for industrial vehicles. These systems can replace conventional lead-acid batteries in existing battery-powered vehicles. The SAE J2601-3 standard, „Fueling Protocol for Gaseous Hydrogen Powered Industrial Trucks," refers to these systems as Battery Replacement Modules (BRM).

One major advantage of these modular fuel cell systems is that they allow existing vehicle models to be quickly modified into production-ready fuel cell vehicles with minimal factory modifications. This means that the same vehicle series can be equipped with either a conventional battery or a fuel cell system. However, it's important to note that manufacturers generally do not offer retrofitting options for vehicles that have already been delivered to customers. Instead, this approach enables new models to be rolled out as fuel cell-ready versions with only minor adjustments required for mass production. In some cases, vehicle-side modifications, such as changes to the air intake or refuelling connection access, may be necessary to optimize the integration of fuel cell systems into the vehicle design.

"Cold start" option forPEM fuel cells

PEM fuel cells offer significant advantages over batteries, especially in low-temperature conditions. Due to the waste heat generated during the electrochemical reaction, the operating temperature of the fuel cell remains stable, ensuring consistent performance even in cold environments. In contrast, battery-powered vehicles experience a more pronounced decrease in performance under these conditions.

However, one challenge arises: when the system is turned off for extended periods in winter temperatures (longer than 30 minutes), the water produced during the reaction can freeze, potentially damaging the fuel cell membrane. This can lead to irreversible performance issues in the fuel cell stack. To address this, manufacturers of Battery Replacement Modules (BRMs) are developing cold-start options that preheat the fuel cell before operation. The first systems featuring this capability are expected to be available from 2024/2025.

In fully integrated fuel cell systems — especially in the automotive sector—this issue is already accounted for. When operating in winter temperatures, the start of the fuel cell vehicle is slightly delayed to allow for preheating of the components, typically taking less than a minute.

H_2 internal combustion engines

Hydrogen, as the smallest chemical element, present distinct differences compared to conventional and other gaseous fuels, particularly in its chemical and thermodynamic properties. These characteristics influence how hydrogen behaves during combustion, necessitating adaptations in storage and fuelling. Due to its very low density and boiling point, hydrogen requires significantly larger storage volumes or the use of energy-intensive method for liquid storage to achieve practical energy densities. [1, p. 12]

Hydrogen internal combustion engines (H_2-ICEs) represent a promising alternative to traditional fossil-fuelled internal combustion engines. They are largely based on conventional Otto or Diesel engines and use hydrogenasafuel,whichisefficientlycombustedbymodified components and processes.

The technology is currently at various stages of development, with companies such as MAN, VOLVO, Keyou, and Deutz having made significant progress. [1]

In evaluating hydrogen engines as a propulsion technology, it is essential to compare them with conventional combustion engines. The basis and reference for the hydrogen engine are petrol engines in the passenger car sector [2] and diesel engines in heavy commercial vehicles [3]. From a mechanical perspective, the core driving components — such as the transmission and drivetrain — remain similar across these technologies when operating at the same power level. The primary differences lie in the fuel system and the combustion engine itself. [1, p. 44] This similarity allows manufacturers to use existing vehicle platforms and to expand them to include hydrogen engines and tanks without extensive redesign. The most relevant components are in particular the piston and the piston rings as well as the valves and valve seat rings. [2] [3]

Today's hydrogen engines are usually gas engines, i.e. the hydrogen in the vehicle tank is stored in gaseous form in 350 or 700 bar tanks.

In addition to the basic engine, the air and fuel supply, the ignition system, the turbocharging and exhaust gas aftertreatment as well as the sensors for recognising the operating status must be adapted to primary operation with hydrogen. In addition, the engine control software must be adapted to the new or modified components and to the new operating conditions, and corresponding operating maps must be created. [4]

The publications analysed mostly assume a spark-ignition combustion process – which is the current state of the art for gas engines – and this is implemented experimentally in the known prototype setups. Furthermore, the rapid combustion of hydrogen (based on the higher flame speed) is emphasised, which leads to an approximation of the real combustion process to the more efficient Otto cycle process. [1, p. 17]

There are many statements in publications about the efficiency and performance of hydrogen propulsion systems. It should be noted that in many areas of application, there is still little experience with series production, and therefore much of the information relates to research work and test engines. This applies in particular to the higher power classes.

For hydrogen combustion engines, efficiency varies depending on the technology and injection method. Average H_2-ICEs achieve an efficiency between 30 and 44 %, while more modern DI engines can achieve efficiencies of up to 45 %. This is comparable to diesel engines operating in similar load ranges.

Fuel cells, on the other hand, have higher efficiencies, typically between 45 and 60 %. In particular, under partial load conditions and in urban driving cycles with frequent starting and braking, fuel cells have an advantage due to their recuperation capability. This efficiency advantage is particularly visible in light-duty commercial vehicles and city buses, where fuel cell systems can recover more energy.

The major difference in efficiency between fuel cells and H_2-ICEs is particularly evident in partial-load operation. While fuel cells reach their maximum efficiency here, H_2-ICEs benefit more from constant loads at higher loads, such as those commonly found in heavy-duty commercial vehicles. [1, p. 28]

Fuel cell efficiency varies considerably depending on the load. Although the theoretical calculation is based on an average efficiency, the actual efficiency may be higher in certain driving conditions, particularly at low to medium loads, where the fuel cell reaches its maximum efficiency. The NOW meta study indicates that fuel cells exhibit higher efficiency at low to medium loads, whereas diesel engines tend to reach their peak values at higher loads. An H_2 combustion engine has the potential to release heat more evenly over the entire duty cycle due to the rapid spread of the flame and the higher combustion temperatures of hydrogen. This can help maintain efficiency at mid-range loads. In contrast, diesel engines can demonstrate a steeper decline in efficiency at part-load (low load) because combustion is not completely homogeneous and waste heat losses become more significant. [1]

Initial findings from other EU-funded projects, such as H_2Haul and HyCET, also show that the efficiency of fuel cells decreases with increasing power, while the efficiency of hydrogen combustion engines improves. These findings are to be verified in operational tests in these projects. [5]

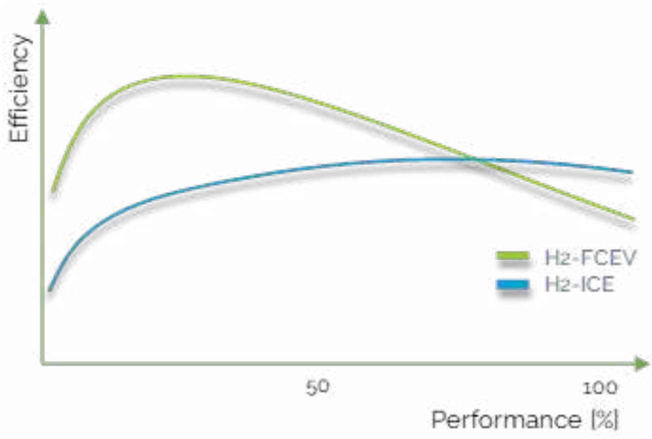

Figure 2: Efficiency Levels of FC and ICE [5]

Air-fuel ratio

H2 combustion engines are able to operate over a wide air-fuel ratio, including lean mixtures. This means that they can operate more efficiently at part load, as less fuel is required to achieve the same power output. With diesel engines, the optimum air-fuel ratio is narrower, which has a greater impact on their efficiency at varying loads.

Idling and start-stop conditions

An electric motor, powered by a fuel cell system, switches to a standby mode when idling and consumes a minimal amount of energy in comparison to a combustion engine, which is also kept at speed when idling. This finding is also seen in the divergent recording of operating hours. While these are also counted when idling in numerous combustion engines, no evaluation takes place in electric motors.

With regard to the possibility of increasing efficiency through start-stop systems, H_2 engines show greater advantages due to the higher ignitability of hydrogen. Fast ignition can lead to a more efficient engine restart. Diesel engines are potentially disadvantaged due to the longer ignition delay and the need to achieve a higher compression temperature.

System integration and energy management

Integration of the fuel cell system into the vehicle can impact the system's overall efficiency. For instance, energy recuperation and hybridization with a battery may enhance the fuel cell system's efficiency beyond what is predicted by basic calculations. Additionally, regenerative braking in some designs may provide supplementary energy not reflected in a straightforward range comparison.

Tank size and usable hydrogen storage

The actual, usable volume of the hydrogen tank and the pressure fluctuations that occur during the storage period can diverge from the theoretical values that were previously assumed in the calculations. Furthermore, due to the modifications that have been made to the technologies, there are also different space requirements. As a result, volumetrically larger tanks may receive greater priority from manufacturers for hydrogen drives, which can influence the effective range.

2. Availability of airport machinery with hydrogen propulsion

Fuel cell systems are more efficient than hydrogen combustion engines and are therefore the more favourable solution in many areas of application. However, an electric drive train is required for the use of fuel cell systems, meaning that the transformation of a conventional combustion engine vehicle into a fuel cell vehicle is associated with a high level of effort for vehicle manufacturers.

In the context of technology transfer, hydrogen combustion engines represent an interesting option for vehicle manufacturers, as only the engines and fuelling technology of already established combustion engine platforms need to be modified in order to be able to ffer hydrogen-powered vehicles more quickly. Furthermore, hydrogen combustion engines may also be a suitable option for specific applications in the future, particularly in environments with high loads and demanding operating conditions. Ultimately, the decision between hydrogen engines and fuel cells will depend largely on the specific application requirements.

The survey of the vehicle fleet and the market analysis of the availability and development of hydrogen-powered vehicles have shown that only a few vehicle types are currently commercially available with hydrogen drives. The early adopters include passenger cars, vans and material handling equipment. The first heavy-duty trucks are now also being offered with a hydrogen drive.

Material handling equipment also offer the potential that the fuel cell systems (BRMs) used there can be integrated into ground support equipment (GSE) with relatively little effort. However, this adaptation for new, application-related areas poses a few design challenges, including

- o Cold start options
- o Continuous draining of the by-product water
- o Adaptation of the tank sizes to meet the more power-intensive requirements at the airport
- o Coordination of the performance profile between the fuel cell system and the vehicle.

These vehicles already open up the possibility of utilising hydrogen at airports on a larger scale.

Two distinct types were identified during the analyses of production approaches, illustrated in Figure 3. As some manufacturers had strategy to perform market orientally, some manufacturers were already developing their hydrogen powered products. Market-based production is following the markets without any significant purchases made by customers. Manufacturers who are willing to produce the product once the customer is making the purchase are clustered to ''production on demand''.

Manufacturers of trucks, transporters and ground handling equipment were mostly producing hydrogen powered machinery based on the markets and following trends. Winter maintenance machinery was mostly manufactured on demand; however, one manufacturer was producing based on market situation. Hydrogen powered rescue service vehicles were produced on demand with limitation of insight assistance requirement. Furthermore, electric and hybrid rescue service vehicles were already launched on the market. Apron buses were manufactured based on both two practices Ambulifts were produced only by customer demand. Aircraft handling equipment were mostly manufactured following the market situation, apart from one manufacturer which produces equipment only by customer orders.

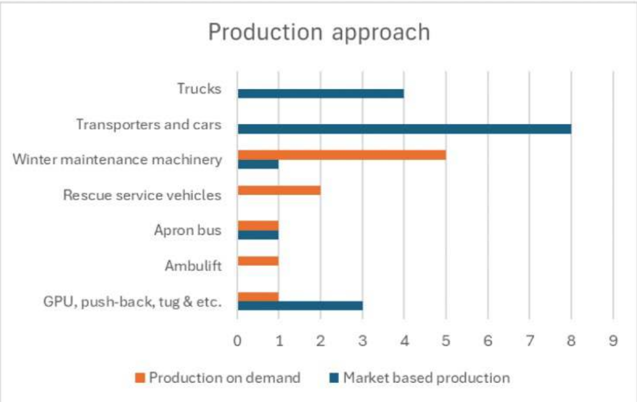

Figure 3: A chart of production approaches of manufacturers

3. Hydrogen storage, infrastructure and refuelling standards

In general, two refuelling technologies are mainly used for hydrogen-powered vehicles: 350-bar and 700-bar technology. The advantage of the 350-bar technology is that it has lower requirements for the refuelling infrastructure and is therefore cheaper to implement. By contrast, the advantage of the 700-bar technology on the vehicle side is that almost twice as much hydrogen can be stored in the same tank volume, which significantly improves the range. The choice between these technologies presents vehicle manufacturers with the challenge of finding an optimal compromise between infrastructure requirements and range.

In addition to the two common pressure classes, there are also others, such as 110 bar, 250 bar and, in the USA, even 500 bar. However, these no longer play a role in vehicle applications. The Mercedes H_2Gen, which uses liquid hydrogen for refuelling, holds a special position. The use of liquid hydrogen makes it possible to store even larger quantities of hydrogen in the vehicle tank and thus further increase the range, but it places higher demands on the infrastructure due to the low storage temperatures.

This chapter explains the various refuelling technologies and how a corresponding H2 refuelling system is set up. It also discusses the differences between gaseous and liquid storage methods and presents the infrastructure requirements for different pressure and temperature levels.

Refuelling couplings

The refuelling couplings for gaseous hydrogen in land vehicles (GHLV – gaseous hydrogen land vehicle) are specified in ISO 17268 „Gaseous hydrogen land vehicle refuelling connection devices." This standard sets the requirements for Europe, defining the design, safety, and operational characteristics of refuelling nozzles and receptacles.

The refuelling connections that meet the requirements of ISO 17268 may only be used for the refuelling of GHLVs with pure hydrogen. Refuelling with hydrogen-natural gas mixtures is explicitly prohibited.

The dispenser nozzle, according to this standard, must prevent vehicles from being refuelled at higher nominal working pressures or flow rates than they are certified for. Additionally, the refuelling coupling must prevent refuelling with any other gases (non-hydrogen gases).

For 350-bar hydrogen tanks, there are two types of refuelling couplings that differ in their flow rate:

- The H35 refuelling coupling is typically used for vehicle tanks with a refuelling capacity of up to 10 kg of hydrogen, as found in forklifts, tuggers, and cars.
- To optimise refuelling speed for larger hydrogen tanks, such as those used in buses and lorries, the H35HF refuelling coupling has been developed offering a higher flow rate and thus faster refuelling.

These two couplings, H35 and H35HF, are not compatible with each other.

Interoperability in hydrogen refuelling protocols

The refuelling interfaces for hydrogen vehicles are designed to support the common standards H35, H35HF and H70, thus offering broad interoperability. This is comparable to the variety of fuel nozzles for diesel, petrol and super at conventional petrol stations, enabling flexible and uniform refuelling of hydrogen vehicles.

Despite this interoperability, there is the challenge that for the fastest possible refuelling, it is important to know the temperature and pressure profile in the vehicle tank precisely. When refuelling hydrogen vehicles, several critical factors related to refuelling temperature, pressure, and sensor requirements must be considered to ensure safety and efficiency. Key parameters such as initial tank temperature, surrounding temperature, and refuelling pressure impact the refuelling process. However, during the refuelling process, live data is often not exchanged between the vehicle storage system (H_2 tank) and the dispenser, and if it is transmitted, a cross-manufacturer exchange of refuelling data is missing in current refuelling protocol until now. [6]

Therefore, in many current applications, the optimal pressure ramps are determined individually for each location through trial refuellings. While this approach can achieve acceptable refuelling speeds, the tanks used are usually of a similar size, such as in intralogistics, where capacities range from 0.25 to 1.8 kg. However, for airport applications, tank sizes vary much more widely, with capacities of around 1 to 50 kg. The pre-set pressure ramps are often based on the requirements of the smallest tanks at high ambient temperatures, which can result in significantly longer refuelling times for larger vehicles such as winter maintenance machines in winter.

It is important to note that although there is a standard for the infrared interface in the form of SAE J2799, practical experience in the field of intralogistics has demonstrated that the infrared components lack robustness. Furthermore, the normatively required replacement of the refuelling nozzle in the event of damage can result in unacceptably high costs. It is only advisable to consider an infrared interface if it can be ensured that the personnel will carry out the refuelling with the level of care and caution that is required.

General layout of an H2 infrastructure

A suitable hydrogen infrastructure for airports should offer three nozzles:

- o H35 (350 bar):
  e.g. ground support equipment, material handling equipment, smaller vehicles such as multifunctional cars or sweepers
- o H35HF (350 bar high flow rate):
  e.g. for apron buses, lorries and larger machines, e.g. also winter machines
- o H70 (700 bar)
  e.g. for cars, lorries and larger winter machines

Figure 3 shows a simplified general layout to illustrate the basic structure of an H_2 infrastructure for airports. On the right, for example, are two dispensers (350 and 700 bar) that could be set up at the airport as combined refuelling stations, so that all three common pressure classes are offered – similar to today's petrol stations with pumps for diesel, petrol and premium petrol.

On the left side, the hydrogen refuelling system ('outside pad') is shown, where the hydrogen is stored and compressed to the required pressure. The 350- and 700-bar dispensers are connected to the H_2 refuelling system via pipelines. The dispensers and the H_2 storage tank can be up to a kilometre apart. This allows the hazardous area

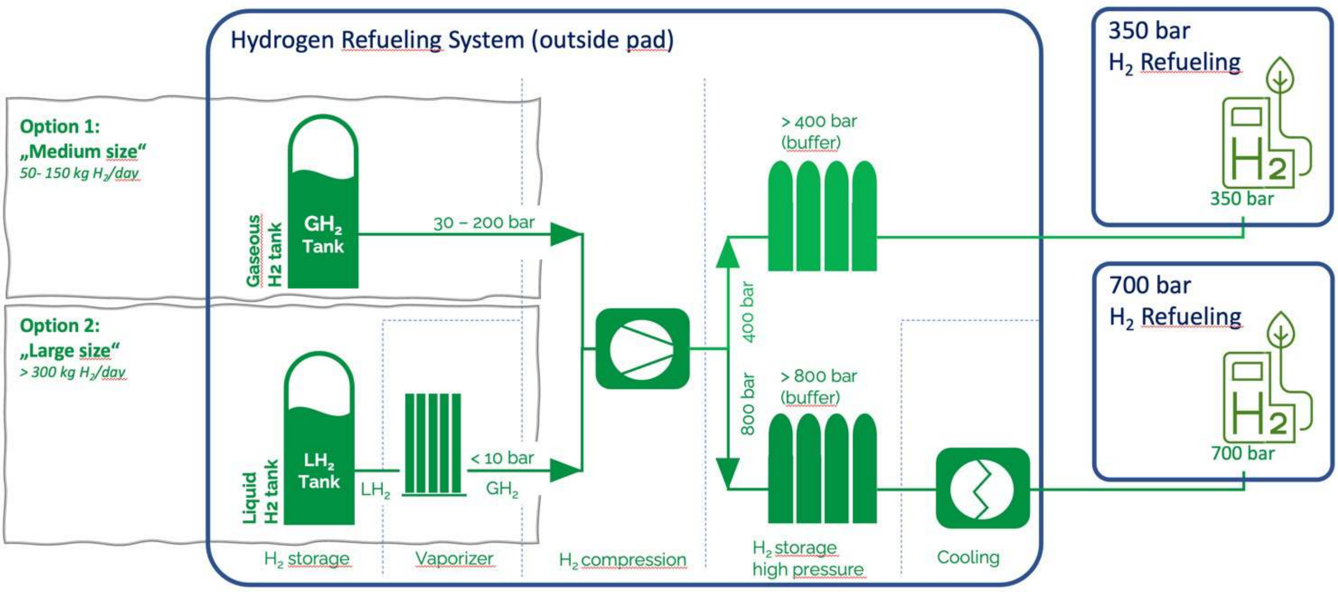

Figure 4: General concept of Hydrogen Refuelling System concept, 350 vs 700 bar

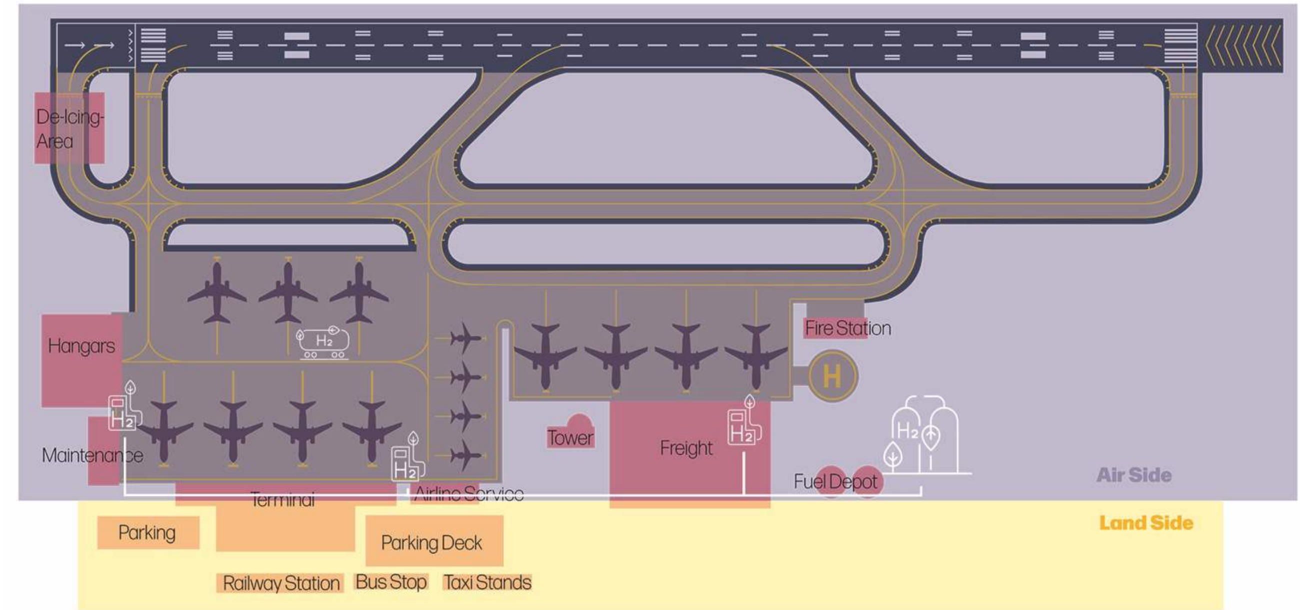

Figure 5: Conceptual layout of H_2 infrastructure positioning at a fictional airport, focused on optimal operational efficiency

around the large hydrogen storage tank to be relocated to safe areas, comparable to the fuel depots at airports today. No significant quantities of hydrogen would be stored in the dispensers themselves, only the small amount in the pipes. This means that the risks can be minimised in the event of an accident involving the dispenser.

The illustration shows the area of the H_2 refuelling system in such a way that it allows for various configuration options depending on the specific requirements of the airport.

Medium-sized applications with a hydrogen demand of up to 150 kg/day at 350 bar

In this configuration, the hydrogen is stored in a medium-pressure storage tank at around 30 to 200 bar. The maximum pressure of the storage tank can vary depending on the provider. What is crucial is that the pressure in the storage tank decreases continuously with increasing dispensing. Direct refuelling of the vehicles from the storage tank is therefore not recommended, as the vehicle's tank would only be partially filled as the pressure decreases. Instead, an H_2 compressor is used to increase the pressure to the maximum operating pressure according to pressure classes of ISO 17268. However, to enable fast refuelling, the hydrogen is not taken directly from the compressor, but from smaller high-pressure intermediate storage tanks that have already precompressed the hydrogen to the desired refuelling pressure.

Medium-scale applications with an H_2 demand of up to 150 kg/day at 350 and 700 bar

If both 350-bar and 700-bar vehicles are to be refuelled, the infrastructure would have to be expanded to include three additional components:

- a compressor with a higher pressure stage of over 800 bar,
- high-pressure storage for pressures over 800 bar,
- pre-cooling of the hydrogen before refuelling.

These additional components increase the complexity and cost of the infrastructure.

Large-scale applications with an H_2 demand of up to 150 kg/day at 350 and 700 bar

If the demand for hydrogen increases sharply, it may make sense to store the hydrogen in liquid form (LH_2). Liquid hydrogen stores significantly more hydrogen in relation to its volume, keeping the infrastructure dimensions manageable. In this case, delivery by liquid hydrogen trailer would also make sense to avoid daily deliveries with H_2 tankers. The hydrogen can then continue to be refuelled in gaseous form; for this, a vaporiser would have to be integrated between the H_2 storage tank and the compressor.

To summarise, it can be said that a medium-scale H_2 infrastructure for 350-bar places the least demands on the required components. 700-bar refuelling requires more powerful compressors, additional high-pressure storage tanks and pre-cooling of the hydrogen. When storing liquid hydrogen, a vaporiser is also needed, which further increases infrastructure costs.

Figure 5 shows the conceptual positioning of a hydrogen infrastructure in an exemplary airport layout, based on an idealised operational perspective. Centralised H_2 refuelling points are provided in the maintenance, cargo and terminal gates areas, each offering the three refuelling couplings H35, H35HF and H70. The central refuelling system with hydrogen storage and compression is ocated on the right side of the picture, near the fuel depot. In this layout, hydrogen is transported to the vehicles via pipelines, without the need for large quantities of hydrogen to be stored in the dispensers themselves. This allows hydrogen to be supplied close to the operational areas, keeping the distances driven by vehicles to refuel short. This ensures that the vehicles have a high level of availability during operation.

The pipelines between the H_2 depot and the refuelling points could be routed over existing roof structures to allow the hydrogen to escape safely upwards in the event of a possible leak, minimising the risk to people. In areas where it is not possible to route the hydrogen pipeline over the roof, it could be laid underground.

This conceptual layout represents an optimised scenario from an operational point of view and does not take into account any specific regulations or permitting requirements, which would still have to be examined. However, it is based on fundamental layouts that have already been implemented, for example, in the H_2 supply for automobile production.

4. Classification of the regulatory framework

A complete regulatory framework for the use of hydrogen-powered vehicles at airports and the corresponding development of a hydrogen infrastructure for refuelling does not yet exist.

On the one hand, there are established guidelines and standards that are applied in practice when developing public and industrial H_2 infrastructure. However, these have not yet been bindingly incorporated into the regulatory framework for airport applications. During the approval process, the extent to which existing standards for H2 infrastructure can also be applied at airports must therefore be evaluated in cooperation with the relevant local authorities, and it must be determined whether further requirements arise from the existing general regulations, standards and guidelines at airports that must be taken into account when setting up the H_2 infrastructure and operating H_2 vehicles.

Two main areas need to be considered:

H_2-powered vehicles

The European Machinery Directive 2006/42/EC is one of the key directives for vehicles. There are also othe directives, such as the Low Voltage Directive 2014/35/EU, the EMC Directive 2014/30/EU, the Pressure Equipment Directive 2014/68/EU and the ATEX Directive 2014/34/EU.

BRM fuel cell systems, which replace conventional traction batteries, play a special role. Due to the regulatory European framework conditions, the vehicle manufacturer must approve the use of these fuel cell systems for the individual vehicle.

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H_2 Infrastructure

For the potential installation of a hydrogen infrastructure, the design and layout can be based on many recognised standards that are known for public H_2 filling stations, among other things, or that also serve as a basis for other larger in-house applications.

These include the ISO 19880 series of standards, which defines comprehensive requirements for the safety of refuelling stations for gaseous hydrogen. This standard specifies guidelines for the design, construction, commissioning, operation and maintenance of H_2 refuelling systems and is particularly relevant for light commercial vehicles, but also for medium and heavy vehicles such as buses and trucks. Manufacturers often refer to the current SAE J2601-1 to 5 for refuelling protocols, although this is not directly legally binding in Europe. The current refuelling protocols of SAE J260-1 are also more relevant for larger vehicles and cooled hydrogen. There is therefore currently some activity in the standardisation committees and both SAE J2799 for the infrared interface and ISO 17268 are being revised. In ISO 17268, an additional 700 bar refuelling coupling with a larger volume flow of 300 g/s for truck refuelling is to be included, which should enable faster refuelling of the larger H_2 tanks. With ISO 19885, a new standard is currently being created that is intended to address the current requirements for H_2 refuelling. In this context, AFIR 2014/35/EU should also be mentioned for the recommendation on the standardisation of the H_2 infrastructure, which is relevant for the interoperability of the infrastructure for the refuelling of motor vehicles. [6]

Additional requirements may arise for the H_2 infrastructure due to

- o larger H_2 storage volumes of approx. 2 – 3 tonnes (depending on the region),
- o potential interaction with other notifiable substances

or

- o if hydrogen is to be produced on site using electrolysis, for example.

These permitting procedures are usually much more extensive and require significantly more time in the permitting process. In this case, it may make sense to operate only part of the fleet with hydrogen in the first phase and to design the H_2 infrastructure in such a way that no extensive authorisation procedure is required. Additional H_2 vehicles and the associated expansion of the infrastructure will then take place in a second project phase. The operational risks for a technology change can therefore also be tackled gradually.

In addition, regional requirements and regulations can lead to further adjustments to the infrastructure. National regulations such as the German Betriebssicherheitsverordnung (BetrSichV) or European directives such as DIN EN 17127 set minimum standards, but can be supplemented by local building regulations or specific requirements from authorities.

The Acorn project technical
report also criticises the lack of a regulatory framework for the use of hydrogen at airports in the UK and the lack of established regulatory precedents on the airside that can be used as a guide. The project highlights the need to develop specific standards and procedures for the safe use and refuelling of hydrogen-powered vehicles in order to drive the decarbonisation of ground support equipment (GSE).

Which is certainly the right way forward in the long term. However, concrete initiatives from H_2 projects at airports are also needed to promote the need for standardisation in this area of application in the standard development organisation (SDO).

5. Operational challenges and advantages of H_2 as fuel for ground handling

It would be misguided to view hydrogen-powered vehicles as the sole solution for decarbonising the entire airport fleet. There are alternative fuel and energy sources that can assist in reducing CO_2 emissions, including but not limited to
- o Green electricity (with different battery technologies)
- o HVO (Hydrotreated Vegetable Oil)
- o Bio diesel
- o other eco-fuels

Consequently, an assessment of the availability of sustainable fuels and energy sources at the airport, along with the requisite infrastructure requirements must be undertaken. To achieve this, it is essential to conduct a realistic estimation of the energy requirements of the vehicle fleet. Not only annual averages, but also possible peak loads must be considered. Fuels and energy sources that will not be available in sufficient quantities in the foreseeable future should either no longer be considered or only used within the limits of their availability. This may, for example, include converting part of the fleet.

A conclusion on the economic viability of hydrogen-powered vehicles cannot be given in the context of a general study such as this one, since a valid assessment would require an in-depth analysis of the regional and specific conditions at the respective airport. Nevertheless, the following explains how fundamental factors can potentially influence the economic viability of hydrogen use in a TCO analysis.

First, a comparison of the purchase costs of vehicles reveals that those equipped with a hydrogen combustion engine are more expensive than those with a conventional combustion engine. A similar conclusion can be drawn when comparing battery-powered vehicles with those powered by fuel cells. The costs associated with the installation and maintenance of hydrogen infrastructure are frequently higher than those incurred for the development of a charging infrastructure. Only in the case of very large sites, which require an expansion of the energy supply, can a hydrogen infrastructure require a lower investment. In the context of airports, however, a very high energy demand is usually to be expected.

In addition to the initial investment costs, the operating costs play a decisive role in a full economic feasibility study and TCO analysis. In many cases, operating vehicles with hydrogen means initial additional investments compared to other alternative energies. Only if these additional investments are offset by operational advantages can the business case for hydrogen become positive.

The operational disadvantages of using hydrogen are usually:
- o Low efficiency
- o Sourcing hydrogen is usually more expensive than electricity from the grid
- o High lease costs for fuel cell systems
- o Maintenance costs are higher compared with batteries

The main operational advantages of using hydrogen are:
- o Higher productivity through fast and flexible refuelling
- o Infrastructure layout optimized for operational needs
- o Reduction of electricity peak loads

6. Illustrative TCO Analysis of Baggage Tractor Operations: A Case Study for Airport 1 and Airport 2

In order to gain a deeper understanding of the factors that determine whether the use of hydrogen-powered vehicles can be considered an economically viable solution, a simplified analysis of the total cost of ownership (TCO) is outlined below, which is to be carried out on the basis of two contrasting application scenarios for baggage tractors.

Both airports operate without scheduled flights between 23:00 and 06:00 and have the same fleet size of operational baggage tow tractors. Peak activity for flight and passenger handling occurs during the morning and evening at both locations.

The primary distinction between the two airports lies in their utilization patterns and the duration of peak periods. At ‚Airport 1,' morning and evening peaks are significantly longer, resulting in a total energy demand for baggage tow tractors that is double that of ‚Airport 2.'

Battery handling processes

The no-flight break is sufficient to fully charge the batteries at both airports overnight.

Airport 1:

The midday off-peak time is only five hours, so it does not provide sufficient time to fully charge lead-acid batteries. Therefore, each trucks owns a 2nd (exchange) battery, that is charged in a centralized battery charging and changing room. This room is fitted with a portal crane and has an optimized food print of appr. 400 sqm. The batteries are charged on demand at a SOC between 20 – 30 % and gets fully charged.

Airport 2:

All tractors below SOC 40% are charged overnight. The midday off-peak time is ten hours and provide sufficient time to fully charge all batteries when needed. The centralized charging room has a footprint of 700 sqm and has charging slots for all baggage tractors.

H_2 refuelling processes

The H_2 infrastructure is like the concept shown in Figure 5 and provides H_2 dispensers close to the operation area, thus time for travelling for refuelling can be eliminated.

Sensitivity Analysis: Impact of Regional Conditions on Economics

In the exemplary total cost of ownership (TCO) analysis, specific cost factors, including labour and energy costs, were modelled within defined sensitivity ranges. The objective of presenting a range of potential variations in these assumptions is to illustrate the potential effects of different regional conditions. The objective is to demonstrate the impact of disparate economic circumstances on the overall costs, thereby facilitating a more profound comprehension of the variability in the economic viability of hydrogen technologies across diverse application contexts. The analysis underscores the pivotal role of location-specific parameters in facilitating well-informed decision-making in the context of sustainable

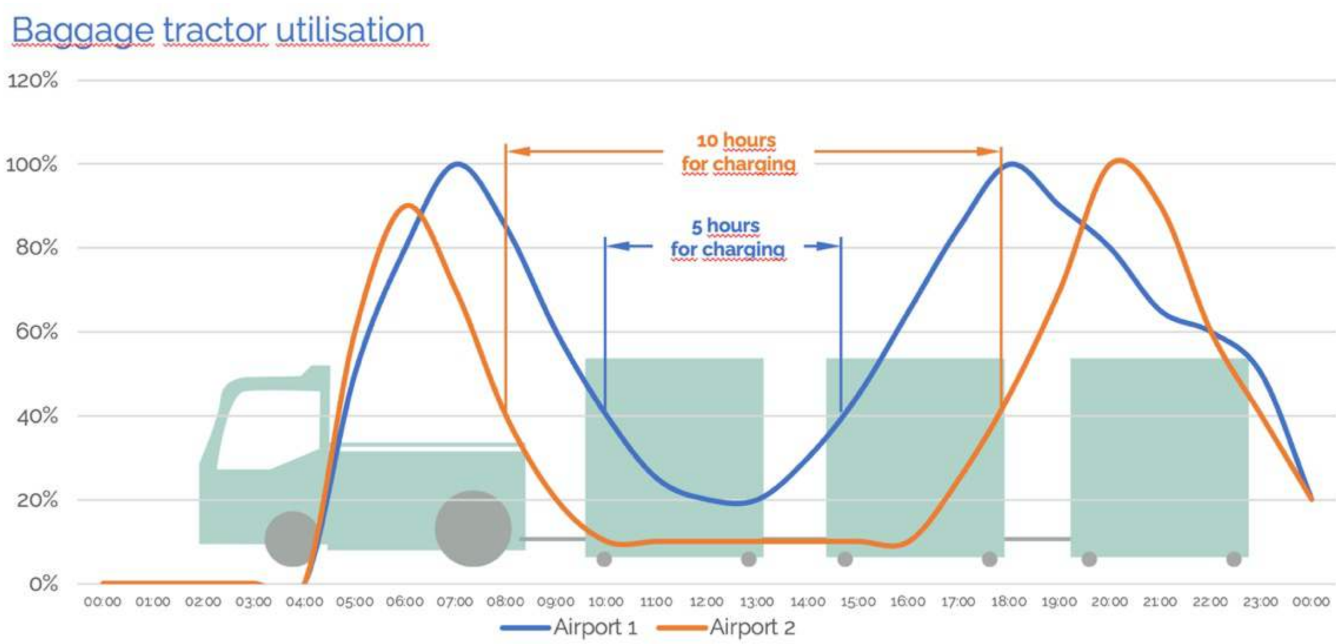

Figure 6: Illustrative example of two different utilisation patterns for baggage trucks

Application profile	Scenario ” Airport 1“	Scenario ” Airport 2“
Annual Working days	365	
Daily operating time, GSEs	05:00 am to 23:30	
Shifts per day	2.5	
Operative fleet size:	30 baggage tractors	
Energy consumption Electricity from grid Hydrogen	4,00 MWh/day 170 kg/day	2,00 MWh/day 85 kg/day
Morning peak	05:00 –10:00	05:00 –08:00
Evening peak	15:00– 21:00	18:00 –21:30
Battery charging cycles per day and truck	2.6	1.3
Process time for battery changing intermediate. charging	30 minutes	15 minutes
Process time for H_2 refuelling	3 minutes	

Table 1: Key Parameters of Application Profiles for scenarios ‚Airport 1‘ and ‚Airport 2‘

logistics planning. The remaining costs have been assigned indicative values, which are not intended to be binding but rather to serve as reference points for the illustrative TCO analysis.

Results of the TCO analysis 'Airport 1'

The operation of a battery-electric vehicle fleet would require approximately 45 battery changes per day. The additional time needed for the battery change process in comparison to hydrogen refuelling is estimated to be approximately 20 hours per day for the entire vehicle fleet. This equates to a potential saving of two baggage tractors and an increase in productivity of 6.6%. Consequently, the number of operational drivers required per shift is reduced by two, resulting in a total saving of six workers over the course of a year, with 2.5 shifts and 365 working days.

The total investment costs (CAPEX) for the implementation of a hydrogen-powered fleet amount to a total of 4.76 million euros, representing a 49% increase in comparison to the investment costs associated with a battery-electric vehicle fleet. These additional investments are primarily attributable to the costs associated

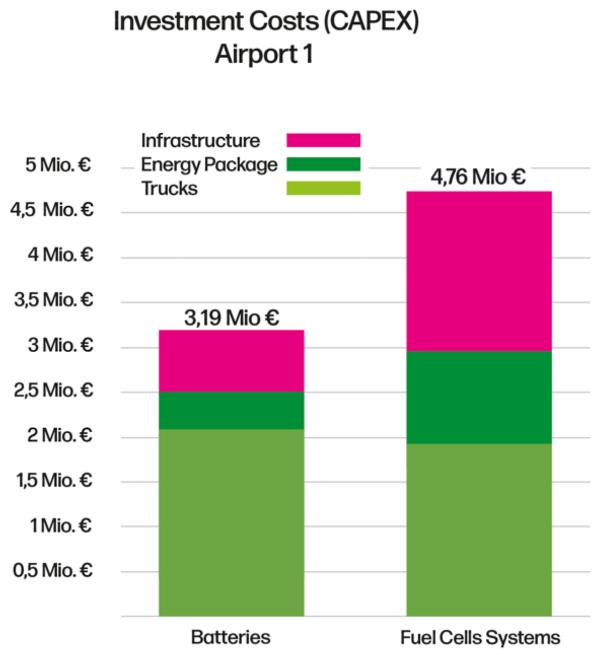

Figure 7: Efficiency Levels of FC and ICE [5]

with the corresponding H_2 infrastructure. The vehicle costs (comprising vehicles and the energy systems batteries or fuel cells) are comparable between the two variants. Despite the acquisition costs per vehicle being

Parameter	Range	Base Scenario
Labour costs 2	0,00 – 50,00 €/hour	40,00 €/hour
Costs for electricity	0,12 – 0,30 €/kWh 0	,23 €/kWh
Costs for H_2 supplied onsite	6,00 – 20,00 €/kg	11,00 €/kg

Table 2:Sensitivities for TCO analysis

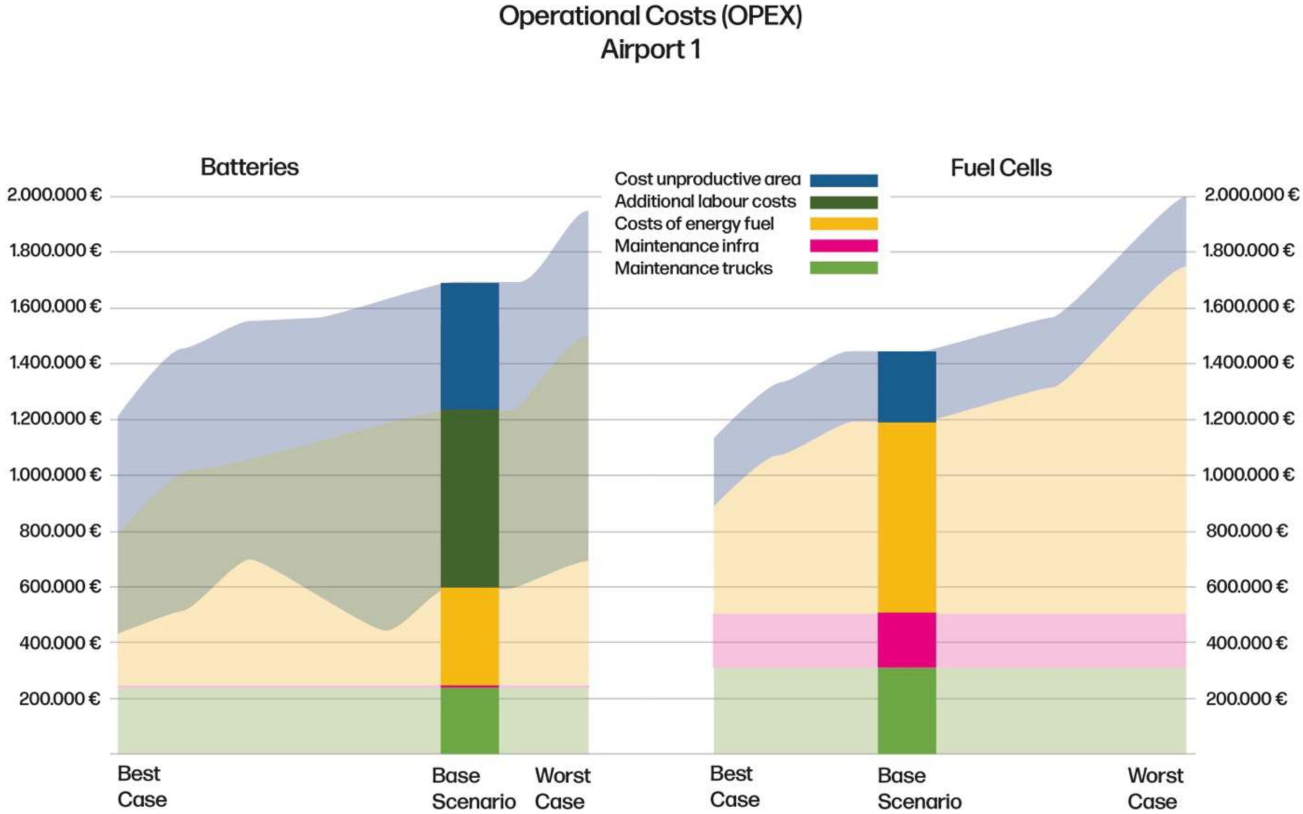

Figure 8: TCO analysis Airport 1 - OPEX

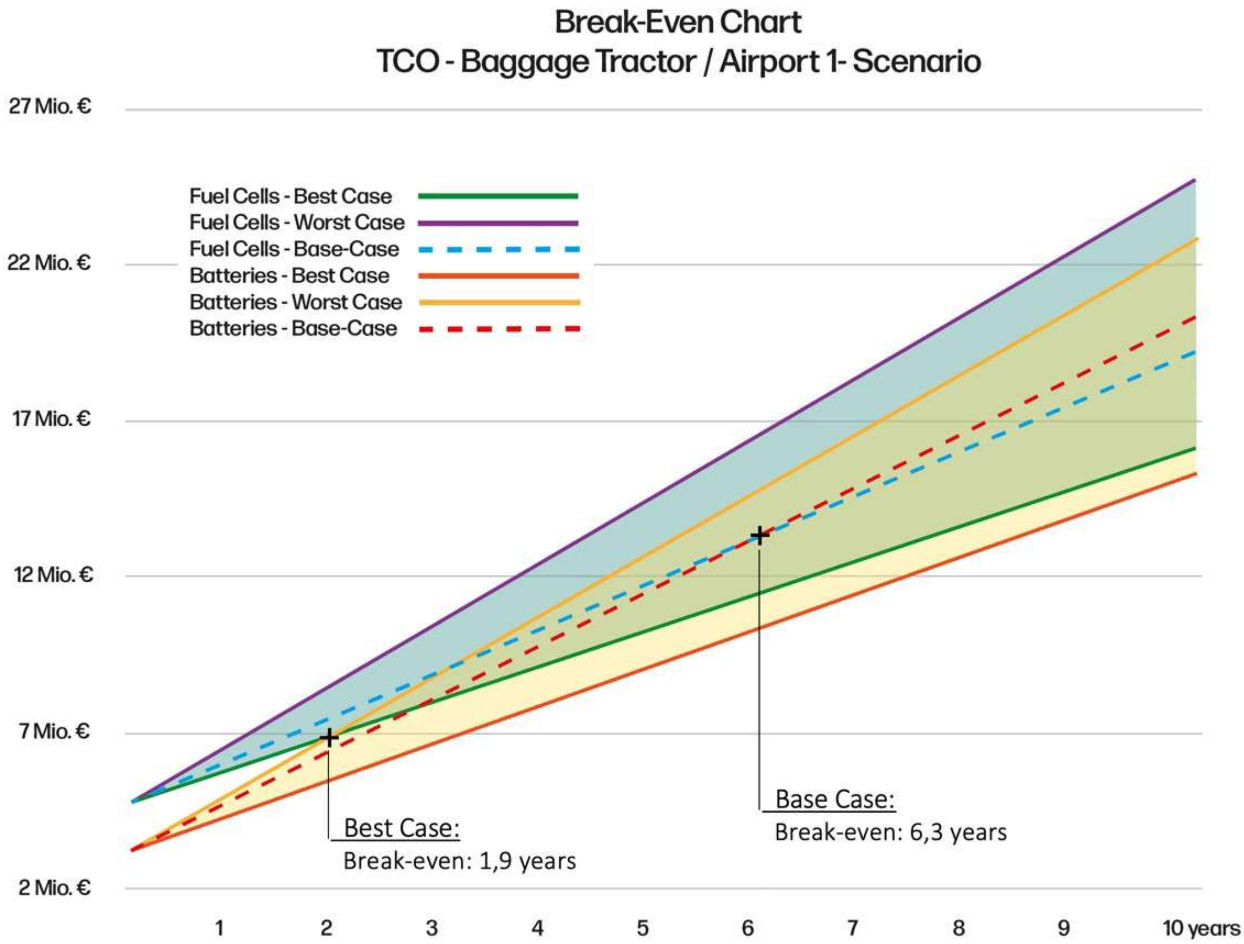

Figure 9: TCO analysis Airport 1 - break-even chart

approximately 35 % higher for the H_2 baggage tractors, the battery-electric fleet necessitates the inclusion of two supplementary vehicles and a replacement battery for each baggage tractor. **The Fehler! Verweisquelle konnte nicht gefunden werden.**

Figure 8 illustrates the operating costs of batteries and fuel cells based on the defined sensitivityranges of the specific costs for energy, hydrogen and personnel. On the left of the graphic, the scenario with the lowest total costs ('best case') is shown, on the right the scenario with the highest costs ('worst case'). The corresponding costs for the base scenario are highlighted.

Base scenario:

On the operating costs (OPEX) side, the maintenance costs for H_2 vehicles and H_2 infrastructure, as well as the energy costs for hydrogen, are initially significantly higher than for battery-powered vehicles.

However, the battery scenario requires more personnel and space. As a result, the total annual operating costs can be effectively reduced by €0.25 million to €1.44 million by using hydrogen.

The final assessment of the cumulative investment and operating costs indicates that Airport 1 can expect a return on investment within a period of approximately six years if it invests in an H_2 vehicle fleet.

Evaluation of sensitivities:

It is probable that a return on investment will be achieved through the implementation of an H_2-powered vehicle fleet in this context. In particular, higher personnel costs can contribute to a positive business case for hydrogen. Conversely, the high cost of hydrogen, which exceeds €14/kg, would appear to favor the use of battery-powered vehicles.

Results of the TCO analysis 'Airport 2

For the operation of a battery-electric vehicle fleet at Airport 2, it is sufficient to utilise a single battery per vehicle. The projected time required for vehicles to reach the battery charging room is estimated at 15 minutes per vehicle on a daily basis. While the installation of a hydrogen infrastructure could entirely eliminate the necessity for vehicle operators to travel to the battery charging room, this would result in a marginal reduction in travel time, amounting to approximately three hours per day. Such a reduction would not be justified on the basis of the savings that could be made.

The total initial investment costs (CAPEX) for the provision of a hydrogen-powered fleet are only marginally lower than those for Airport 1. Although the investment costs for the hydrogen infrastructure are somewhat lower due to the lower hydrogen consumption, there is no potential for savings in the vehicle fleet. In conclusion, the investment costs total 4.70 million euros, representing a 60 % increase compared to the investment costs for a battery-electric vehicle fleet. In contrast to the circum-stancesatAirport1,thebattery-poweredvehiclesat Airport 2 do not necessitate the replacement of a battery per vehicle.

In terms of operating costs (OPEX), maintenance costs for H_2 vehicles and H2 infrastructure, as well as energy costs for hydrogen, remain considerably higher than for battery-powered vehicles. As the personnel requirements remain unchanged for both technologies, the sole advantage of the hydrogen-powered fleet is the smaller space requirement. Nevertheless, the TCO analysis indicates that this does not result in a potential saving in terms of total operating costs.

In the final evaluation of the cumulative investment and operating costs, the additional investment in a hydrogen-powered vehicle fleet for the application at Airport 2 is not subject to amortisation.

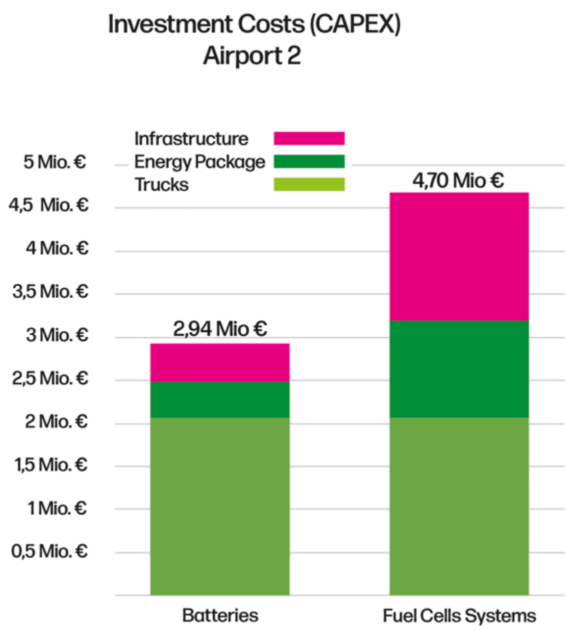

Figure 10: A chart of production approaches of manufacturers

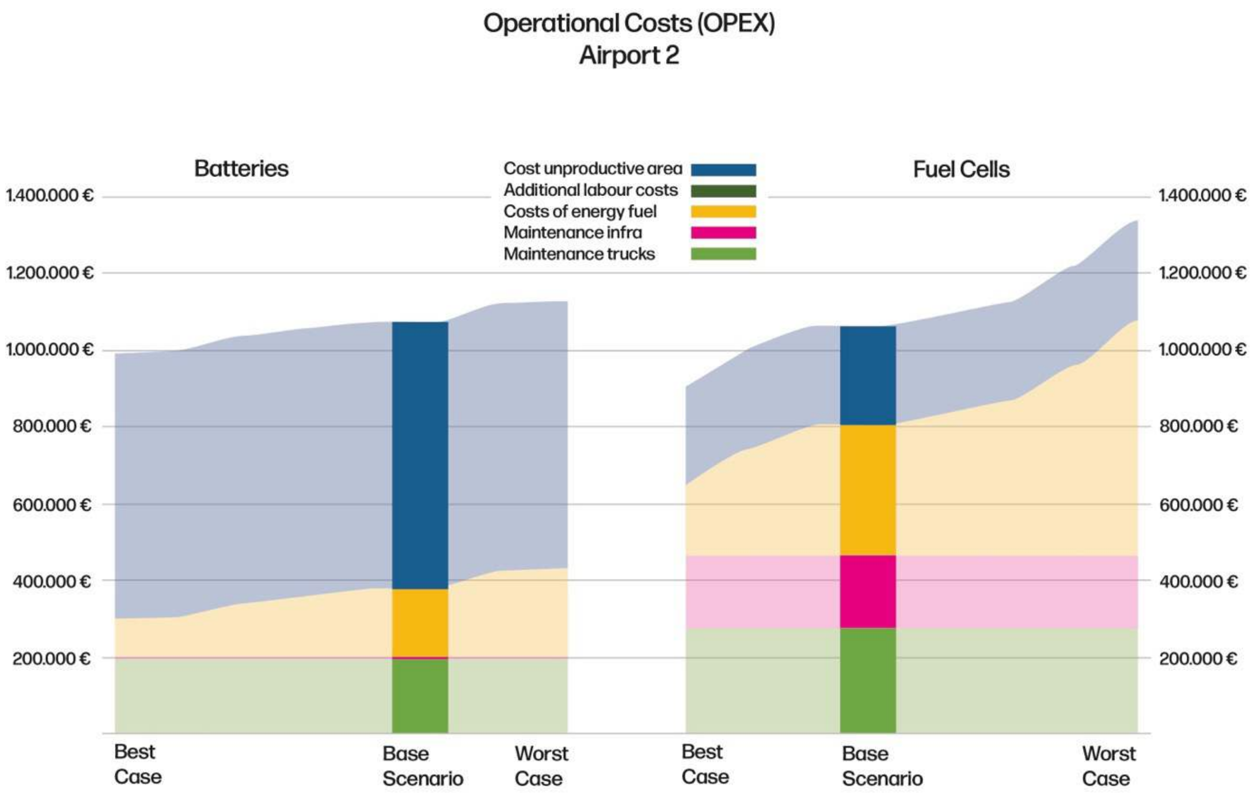

Figure 11: TCO analysis Airport 2 - OPEX

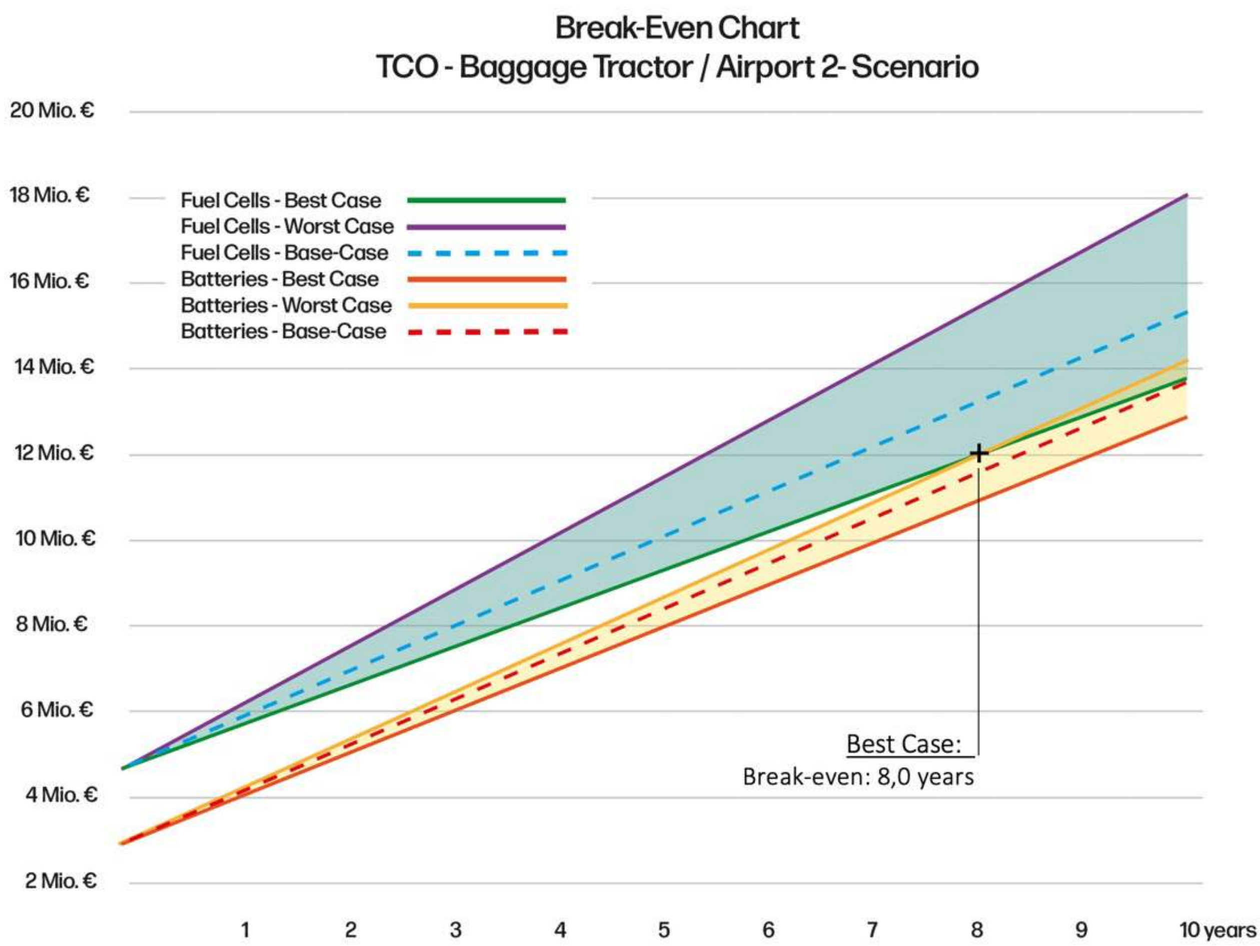

Figure 12: TCO analysis Airport 2 - break-even chart

Evaluation of the sensitivities:
It is unlikely that the investment in a hydrogen-powered vehicle fleet will result in a net positive return under the given operating conditions. It is only at a significantly lower hydrogen price of below €8/kg and simultaneously high electricity costs of over €0.28/kWh that the operating costs for hydrogen-powered vehicles could be lower. Nevertheless, in the unlikely scenario of opposing energy prices for electricity and hydrogen under the set sensitivity range, the amortisation period would still be 8 years in the best case.

Closing remarks on the exemplary TCO analysis
The TCO analysis of the baggage tractor example shows approaches that can be applied to other vehicle types. In most cases, however, the use of hydrogen vehicles will only become economically viable if significant operational advantages can be achieved. These include, in particular, the productivity increase highlighted in the example. In addition, other advantages may also justify the use of hydrogen-powered vehicle fleets, such as:

- Lower vehicle weight and thus potentially higher payloads,
- Constant performance even at low ambient temperatures,
- High interoperability between different vehicle types and applications,
- Reduced space requirements for infrastructure compared to battery-electric solutions,
- Synergy effects through parallel use of hydrogen in adjacent applications,

It is important to acknowledge that this simplified TCO analysis excludes certain economic factors that are essential for a comprehensive and well-founded analysis. These include, but are not limited to, tax advantages, financing conditions, and long-term provisions or replacement investments. Such aspects can also influence the results of a TCO analysis in both positive and negative directions and should be taken into account in a more detailed and comprehensive analysis.

7. Hydrogen Demand Estimation and Scenario Assumptions

Given the different hydrogen strategies of manufacturers and the fluctuating efficiency of fuel cells, the hydrogen demand can vary widely. Nevertheless, this study provides a rough estimate based on a scenario that approximates a large BSR airport.
To ensure a comprehensive estimate, the scenario assumes the following:

- All vehicles are currently diesel-powered and will be converted to hydrogen.
- Annual diesel consumption is modelled after a larger airport in the BSR region.
- The engine power remains the same across drive types, simplifying the conversion process.
- The following efficiency ranges are used in the sensitivity analysis:
- Diesel engines: 40 – 44 %
- Hydrogen combustion engines: 30 – 44 %
- Fuel cells: 45 – 60 %

Additionally, it was considered that diesel engines continue running even in idle mode, while electric motors would switch to standby, reducing energy consumption. This idle-time reduction was factored in with a sensitivity of 10–30%. The availability of commercially viable hydrogen solutions across different vehicle classes was also evaluated, with timelines divided into:

- Short-term availability: 1–3 years
- Medium-term availability: 4–7 years
- Long-term availability: over 8 years or not yet planned

Operational Considerations and Fleet Composition
The analysis reveals that hydrogen demand can vary greatly between airports, influenced by factors such as seasonal fuel consumption, fleet composition, and climate. For instance, winter operations in northern airports place different energy demands on vehicles compared to more temperate locations. Furthermore, the involvement of third-party ground handling companies remains a variable factor in determining total hydrogen needs.

To address these uncertainties, a reference scenario was developed to represent an idealised fleet of 460 vehicles. This fleet is divided into three main operational areas:

1. **Airport Operations (Year-Round):** Includes all year-round tasks such as airport maintenance, security, emergency management, and a portion of passenger handling services.

2. **Airport Operations (Winter):** Focuses on vehicles used seasonally for winter operations, assuming an extended winter season of at least three months. Airports with less intense winter operations can adjust this requirement.

3. **3rd Party Ground Handling:** Includes aircraft handling, cargo services, and remaining passenger handling activities.

Fleet mix				
Operation	Machinery	Qty	Potential H2 propulsion	Reference Diesel consumption (in litres)
Airport operation (all year) incl. security & passenger handling	Aircraft Heater unit	20	H2 engine	94.443
	Apron bus	19	Fuel cell	61.530
	Excavator	2	H2 engine	8.769
	Forklift	2	Fuel cell	4.000
	Grader	2	H2 engine	-
	Ground Power Unit	3	Fuel cell	4.122
	Heavy duty truck	25	H2 engine	68.443
	Passenger car	51	Fuel cell	14.539
	Passenger car, Pick-Up	6	Fuel cell	6.146
	Rescue, command vehicle	3	Fuel cell	2.588
	Rescue, Fire fighting truck	6	H2 engine	23.209
	Rescue, others	2	Fuel cell	3.935
	Suction car	10	H2 engine	49.039
	Others - street sweeper	6	Fuel cell	2.208
	Tractors	11	Fuel cell	17.357
	Van	57	Fuel cell	48.040
	Wheel loader	16	Fuel cell	84.720
	Others - Deicing truck - spreader	26	FCS	19.100
Airport seasonal winter operation	Winter - Snow blower	6	H2 engine	24.797
	Winter - Snow plough	7	H2 engine	71.872
	Winter - Snow plow sweeper blower (PSB)	23	H2 engine	580.770
3rd party ground handling (Aircraft, cargo & passenger)	Baggage tractors	38	Fuel cell	311.460
	GPU	14	Fuel cell	113.335
	Belt loaders	26	Fuel cell	62.292
	Cargo Loaders	13	Fuel cell	93.438
	Lavatory trucks	10	Fuel cell	10.119
	Pushbacks	10	Fuel cell	124.584
	Passenger stairs	46	Fuel cell	15.573
	TOTAL	**460**		**1.920.431**

Table 3: Reference Scenario

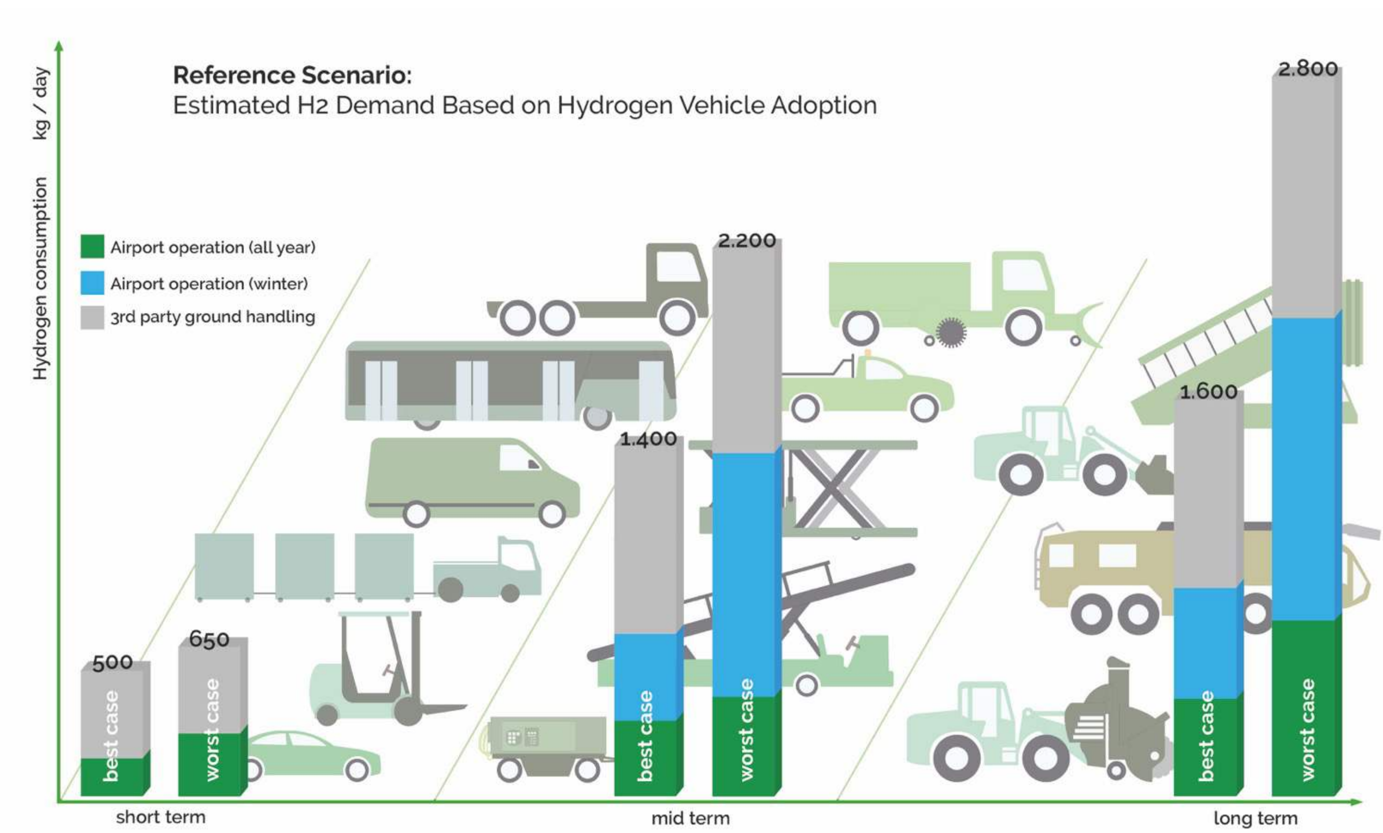

Figure 13: Reference Scenario – a potential road map to a complete fleet conversion to hydrogen

Due to incomplete data, the reference diesel consumption for vehicle classes was aggregated, and missing data — such as for ground power units and lavatory trucks — was supplemented with average values from industry research to create a more complete picture.

Hydrogen Demand and Infrastructure Implications

The scenario assumes an expedited transition of all vehicles to hydrogen propulsion. This provides an estimate of the maximum hydrogen demand, which is crucial for developing demand-oriented H_2 infrastructure and supply concepts. For high-power vehicles (200 kW and above), hydrogen combustion engines are preferred, while fuel cells are considered for lower and medium power classes. Efficiency ranges were used to calculate H_2 consumption, with both best-case (high efficiency) and worst-case (lower efficiency) scenarios factored in to capture the range of potential outcomes.

This reference scenario provides a framework for airports to understand the potential hydrogen demand and begin planning for infrastructure that aligns with their unique operational requirements.

8. Interpretation of the Reference Scenario Results

In the short term, several key airside vehicles could already be converted to hydrogen. These include:

- Passenger cars
- Light commercial vehicles
- The first standardised heavy-duty trucks
- Material handling equipment
- Likely also baggage tractors.

Looking at previous pilots of ground support equipment, baggage and cargo tractors have been the primary focus. A commercial solution for these vehicles, derived from intralogistics BRM systems, is foreseeable. This could generate a significant hydrogen demand of approximately 500 – 650 kg per day in this scenario.

The most substantial fleet conversion and extension of the H_2 infrastructure is expected in the medium term (3–7 years). For GSE vehicles, particularly belt loaders, cargo loaders and GPUs, some solutions could become available even sooner. However, there are still uncertainties regarding market-ready options for these vehicles, as not many comprehensive demonstrations have yet been conducted.

The largest increase in hydrogen demand is anticipated from snow removal vehicles, which could represent a significant portion of fuel consumption in northern regions. Additionally, the first tractors and wheel loaders are expected to be introduced in the medium term.

For this reason, a nearly fully developed hydrogen infrastructure for airport vehicles could already be operational within the medium-term period.

In the long term, further vehicles such as passenger stairs, wheel loaders with attachments, and rescue vehicles could potentially come into play even if these are not in manufactures roadmap today. However, their overall contribution to total airport consumption is smaller, meaning that while hydrogen demand will continue to grow in this third phase, it will not significantly impact the layout requirements of the H_2 infrastructure.

A particular challenge may arise in planning hydrogen storage and compression capacities for airports with heavy winter operations. During winter, high fleet availability and high fuel consumption are expected, making this season the most demanding on H_2 infrastructure capacity. Conversely, the summer months present an ideal opportunity for more extensive maintenance and necessary repairs to the infrastructure.

9. Discussion and Conclusion

One of the key challenges in the technology transfer towards a sustainably operated vehicle fleet at airports is that the development and transition of infrastructure, fuel, and energy supply will take several years. Each airport will need to determine whether there will be sufficient access to sustainable fuels, such as HVO100, to continue running conventional combustion engines, whether the electricity grid can support the full electrification of all vehicles with batteries, and whether hydrogen — whether green or at least blue — can be provided at economically viable prices. These factors will influence the selection of preferred technologies, which may vary over time.

Although baggage tractors are a significant focus, other material handling equipment (MHE) generally plays a less prominent role at airports. However, there may be valuable synergies in the cargo area, particularly with logistics companies based at airports, which could present interesting opportunities for hydrogen supply, hubs and infrastructure development.

Airports bring together a wide variety of vehicle types, including both traditional on-road vehicles and off-road vehicles. The technological maturity of hydrogen propulsion systems for these various types of airport vehicles varies greatly, ranging from commercially available, established models to prototypes and vehicles still under consideration. At the same time, it is often challenging for OEMs to identify suitable applications for scaling up new technologies ('chicken-and-egg problem'), particularly during a period of rapid technological change driven by climate targets and the energy transition. The diversity of airport operations makes it an especially attractive environment for innovation. The standardised refuelling couplings for gaseous hydrogen — particularly at 350 to 700 bar — offer ideal conditions for high interoperability between vehicles and hydrogen infrastructure.

The gradual introduction of hydrogen technologies into airport operations, considering both short- and long-term development perspectives, should be reflected in the planning and design of the H_2 infrastructure and supply systems.

The BSR HyAirport study shows that hydrogen can have significant potential as a sustainable energy source for ground support equipment (GSE) and other vehicles and offers a possible way to reduce pollutant emissions from airport operations. The results show that hydrogen fuel cells and combustion engines are already available on the market or are about to be launched for some relevant vehicle types. These include forklifts, tractors and other GSE equipment used in baggage handling. Hydrogen-powered passenger cars and light commercial vehicles, such as the Toyota Mirai or Renault Master, can also be integrated at an early stage. Heavy vehicles such as trucks and airport tractors are expected to be available from the mid-2020s. The use of these vehicles makes it possible to reduce CO_2 emissions in the short term and gain initial experience with the hydrogen infrastructure.

With the planned pilot of high-performance snow clearing equipment, the demand for hydrogen can increase significantly in the medium to long term, particularly at the northern BSR airports.

Therefore, the development of a robust and flexible hydrogen infrastructure that can meet both short-term and long-term energy needs is essential. A key challenge is managing seasonal fluctuations in fuel consumption, particularly in regions with high winter demand, which places a strain on hydrogen storage and distribution capacities. Careful planning and infrastructure scalability are therefore crucial to meeting these peak operational demands. This applies not only to hydrogen, but also to potentially alternative sustainable forms of energy. The switch to purely battery-powered vehicles is already proving to be an insurmountable challenge at some airports.

A major obstacle to the rapid introduction of hydrogen technologies at airports is the lack of a comprehensive regulatory framework. Although standards for the use of hydrogen already exist, for example in the industrial ector or in public road transport, these have not yet been explicitly applied to airport operations. This leads to uncertainties when planning approval procedures and creating the corresponding infrastructure, especially with regard to safety-related aspects such as the storage and refuelling of hydrogen. Closer cooperation with the relevant authorities is therefore essential to develop and clarify the regulatory framework for the use of hydrogen at airports.

In the BSR (Baltic Sea Region), the availability of green hydrogen is currently limited. However, countries such as Germany and Sweden have already presented comprehensive plans to increase hydrogen production, especially from renewable energies. While Germany has already achieved a production capacity of around 1.9 million tonnes of hydrogen per year, other countries such as Finland and Sweden are also further expanding capacities.

The hydrogen demand of airports places high demands on local production. This should be taken into account during the ramp-up. In the long term, however, the hydrogen demand of ground vehicles will only account for a fraction of the airport's total hydrogen demand due to the expected use of hydrogen in aviation. It is therefore crucial that the ramp-up goes hand in hand with all stakeholders.

10. Outlook on research priorities

Future research and development work should concentrate on the following topics:

- **Testing and adapting the regulatory framework**

Detailed standards for the safe use of hydrogen at airports must be developed. This includes, in particular, the development of guidelines for refuelling, storage and the operation of hydrogen vehicles in safety-critical areas.

- **Individual economic feasibility studies**

Each airport has specific infrastructure and operational requirements. It is therefore important to conduct a separate economic feasibility study for each location, considering both the technical feasibility and the long-term cost advantages of hydrogen applications.

- **Focus on short- to medium-term available vehicles**

For the first phases of hydrogen adoption, airports should focus on vehicles that are already available in the short to medium term and account for a large share of energy consumption, e.g. GSE vehicles such as baggage tractors, snow clearing vehicles and airport tractors. These vehicles make it possible to gradually establish hydrogen demand and use the infrastructure efficiently.

By implementing hydrogen technologies step by step and continuously improving the regulatory and infrastructural framework, hydrogen can play a key role in the decarbonisation of airports. The economic viability of the individual measures remains central to the long-term success of the transformation.

11. Disclaimer

The Feasibility Study on the General Use of Gaseous Hydrogen in Airport Machinery was prepared by Tim Schultz-Harzheim of greecon CONSULTING. The findings and conclusions presented here are based on the author's experience, as well as discussions with partners of the BSR-HyAirport project and Katariina Oukkonen, whose master's thesis, A Market Analysis of Annual Delivery of All Ground Handling and Airfield Machinery in Europe, contributed to this study.

Additional information was obtained from publicly accessible sources and conversations with manufacturers of commercial vehicles, construction machinery, and GSE equipment. Where necessary, clarifications were sought from these third parties without disclosing the background, purpose, or content of this study.

All data and information were carefully researched and handled to the best of our knowledge and efforts to ensure that no proprietary rights were infringed. However, no explicit or implicit warranty can be provided regarding the accuracy, completeness, or usability of any information, products, or processes contained within the study. In particular, no responsibility can be assumed for the accuracy of information that was anonymized and included in the study. Any potential misinformation cannot be attributed to the authors of this study.

The contents of this study are for informational purposes only and do not constitute professional or legal advice. Users should consult relevant experts before making any decisions based on the information provided. The study is governed by applicable laws and regulations, and any disputes shall be resolved under the jurisdiction of the relevant legal system.

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