

VIABILITY EVALUATION OF HYDROGEN SYSTEMS FOR AIRPORT GROUND SUPPORT VEHICLES

A. Backurs¹, L. Jansons², A. Laizans¹

¹Faculty of Engineering and Information Technologies,
Latvia University of Life Sciences and Technologies,
2 Liela Str., Jelgava, LV-3001, LATVIA

²Faculty of Civil and Mechanical Engineering,
Riga Technical University,

6A Ķīpsalas Str., Riga, LV-1048, LATVIA

*e-mail: andris.backurs@gmail.com

The decarbonisation of airport ground support operations is essential for achieving aviation sustainability targets while maintaining high operational efficiency. This study evaluates the technical, operational, environmental, economic, and infrastructure viability of hydrogen fuel-cell systems for airport ground support vehicles (GSVs) using an integrated systems engineering framework and multi-criteria decision analysis (MCDA). The assessment incorporates technical performance, operational characteristics, lifecycle environmental impacts, total cost of ownership, and infrastructure readiness. The results indicate that hydrogen-powered vehicles achieve an operational availability of 98.4–99.3 %, daily fleet utilisation of up to 94 %, and average refuelling times of approximately 4 min, enabling continuous multi-shift operation. Compared to conventional diesel vehicles, hydrogen systems eliminate local carbon dioxide (CO₂), nitrogen oxide (NO_x), and particulate emissions and reduce lifecycle greenhouse gas (GHG) emissions from 1,018 g CO₂-eq/km to 82 g CO₂-eq/km when renewable hydrogen is used. Economic analysis shows that although the initial infrastructure investment reaches EUR 5.8 million, lifecycle costs (EUR 496,800) become competitive with diesel systems (EUR 538,600), with estimated investment payback occurring within 8.1 years for medium- and large-scale airport applications. The MCDA results identify hydrogen fuel-cell technology as the highest-ranked propulsion option with an overall viability index of 9.19/10, outperforming battery-electric (8.69/10) and diesel (6.42/10) alternatives. These findings demonstrate that renewable hydrogen systems constitute a technically reliable, environmentally sustainable, and economically promising solution for future airport ground support operations.

while providing a practical framework for strategic infrastructure planning and airport decarbonisation.

Keywords: *Airport decarbonisation, airport ground support vehicles, hydrogen fuel cells, multi-criteria decision analysis.*

1. INTRODUCTION

Air transport is undergoing a profound transformation driven by increasingly stringent environmental regulations, carbon reduction targets, and the global transition toward sustainable energy use [1]. Although considerable attention has been devoted to reducing emissions from aircraft propulsion [2]–[4], airport ground operations remain a significant contributor to local GHG emissions, particulate matter, and noise pollution. Ground support vehicles operate continuously during aircraft turnaround procedures, baggage handling, cargo transportation, aircraft towing, catering, passenger assistance, and maintenance activities. Most existing airport ground support equipment relies on diesel engines or conventional internal combustion technologies, resulting in substantial fuel consumption, operational emissions, and maintenance requirements [5]. Thus, airports worldwide are seeking alternative propulsion technologies capable of supporting carbon-neutral ground operations while maintaining operational reliability, safety, and economic efficiency.

Electrification has become the primary strategy for reducing GHG emissions from airport ground support equipment. Battery-electric vehicles have demonstrated significant advantages for short-duty cycles and low-power applications. However, battery systems remain constrained by charging

duration, reduced performance under intensive operating cycles, battery degradation, limited energy density, and operational interruptions associated with recharging. These limitations become increasingly important for heavy-duty ground support vehicles such as aircraft tow tractors, cargo loaders, container transporters, and high-utilisation service equipment operating continuously throughout airport schedules [6].

Hydrogen fuel-cell technology has emerged as a promising alternative capable of overcoming several limitations associated with battery-electric propulsion. Hydrogen-powered vehicles combine zero tailpipe emissions with high specific energy, rapid refuelling, extended operational range, and continuous availability for demanding duty cycles [7]. In contrast to battery-electric systems requiring prolonged charging periods, hydrogen fuel-cell vehicles can be refuelled within minutes while maintaining comparable operational flexibility to conventional diesel-powered equipment [8]. These characteristics make hydrogen particularly attractive for airport environments where operational continuity and equipment availability are critical performance requirements. Major comparison of propulsion technologies for airport ground support vehicles is reflected in Table 1.

Table 1. Major Comparison of Propulsion Technologies for Airport Ground Support Vehicles

Characteristic	Diesel	Battery-electric	Hydrogen fuel cell
Local CO ₂ emissions	High	0	0
NO _x and particulate emissions	High	0	0
Refuelling/charging time	5–10 min	1–4 h	3–5 min
Typical operating range	High	Moderate	High
Energy efficiency	Moderate	High	High
Suitability for continuous multi-shift operation	Excellent	Limited by charging	Excellent
Infrastructure maturity	High	High	Developing
Renewable energy integration	Low	High	High
Main limitation	High emissions	Charging time and battery degradation	Infrastructure cost

Recent advances in proton exchange membrane (PEM) fuel cells, hydrogen production technologies, compression systems, storage infrastructure, and digital process control have significantly improved the technical maturity of hydrogen mobility. Green hydrogen produced using renewable electricity further enhances the environmental benefits by enabling nearly carbon-neutral operation across the complete energy chain [9]. As a result, numerous airports in Europe and worldwide are investigating hydrogen as part of broader decarbonisation strategies that integrate renewable electricity generation, hydrogen production, energy storage, and sustainable airport logistics [10]–[12].

Despite these technological advances, the practical implementation of hydrogen-powered GSVs remains problematic. Successful deployment depends not only on fuel-cell performance but also on the interaction between hydrogen production, storage, distribution, refuelling infrastructure, vehicle integration, operational scheduling, maintenance requirements, safety management, and economic feasibility. Hydrogen installations constitute complex cyber-physical systems in which electrochemical processes, thermodynamic behaviour, mechanical equipment, control systems, digital monitoring, and human operation

interact continuously. Therefore, the viability of hydrogen systems cannot be evaluated solely through individual component efficiencies or laboratory-scale performance measurements.

Airport operations represent particularly demanding environments because multiple vehicle categories operate simultaneously under highly dynamic conditions. Equipment utilisation varies according to flight schedules, seasonal demand, weather conditions, aircraft types, and turnaround durations. Hydrogen infrastructure must therefore ensure continuous fuel availability while maintaining operational flexibility, safety, and regulatory compliance. Refuelling stations must accommodate rapid vehicle turnover without creating operational bottlenecks or compromising airport logistics. At the same time, hydrogen storage, compression, and distribution systems must meet stringent safety requirements related to leakage prevention, pressure management, ventilation, fire protection, and emergency response [13].

Another critical consideration concerns the economic viability of hydrogen implementation. Although fuel-cell technologies continue to decrease in cost, initial investments remain substantially higher than those associated with conventional diesel equipment or battery-electric alternatives [14].

Economic assessment must therefore consider total cost of ownership rather than vehicle acquisition cost alone. Fuel consumption, infrastructure investment, maintenance expenditure, equipment utilisation, operational availability, fuel price volatility, equipment lifetime, carbon pricing mechanisms, and environmental benefits collectively determine long-term financial viability.

Existing studies have predominantly focused on hydrogen fuel-cell performance [15]–[17], electrochemical efficiency, hydrogen production technologies [18], storage methods [19]–[21], or individual vehicle demonstrations. Comparatively fewer studies have investigated the integrated viability of hydrogen systems specifically for built environment and airport ground support operations by simultaneously considering technical performance, operational reliability, infrastructure requirements, safety, environmental impacts, and economic feasibility [22], [23]. This fragmented perspective limits decision-makers' ability to evaluate hydrogen implementation strategies at the airport system level.

The present study addresses this research gap by evaluating hydrogen systems as integrated operational ecosystems supporting airport ground support vehicles. Rather than analysing isolated technological components, the research considers the interaction between hydrogen production, storage, refuelling infrastructure, vehicle

operation, energy management, safety systems, operational logistics, and economic performance. Such a systems-engineering perspective provides a more realistic assessment of hydrogen deployment within modern airport environments.

The aim of this study is to evaluate the technical, operational, economic, environmental, and safety viability of hydrogen energy systems for airport GSVs and to identify the conditions under which hydrogen represents a sustainable alternative to conventional propulsion technologies.

The hypothesis states that integrated hydrogen energy systems can provide technically reliable, operationally efficient, environmentally sustainable, and economically viable propulsion solutions for airport GSVs when supported by appropriately designed hydrogen production, storage, refuelling, safety, and control infrastructure.

The study primarily evaluates hydrogen applications for airport GSVs and does not consider hydrogen-powered aircraft propulsion. Economic analyses depend on assumptions regarding future hydrogen prices, renewable electricity availability, and technology costs. Operational scenarios represent typical airport activities rather than all possible airport configurations. Regulatory developments, regional infrastructure availability, and future technological improvements may influence implementation pathways beyond the scope of the present analysis.

2. MATERIALS AND METHODS

This study employs a systems engineering methodology to evaluate the technical, operational, environmental, and economic viability of hydrogen energy systems for

GSVs. The study framework is designed to investigate hydrogen technology as an integrated airport energy ecosystem rather than as an isolated propulsion technology. The

methodological approach combines engineering analysis, comparative assessment, operational modelling, techno-economic evaluation, sustainability analysis, and multi-criteria decision analysis to determine whether hydrogen systems represent a feasible alternative to conventional diesel-powered and battery-electric airport ground support equipment.

The study considers the entire hydrogen value chain, beginning with renewable electricity generation and hydrogen production through electrolysis, followed by compression, storage, distribution, vehicle refuelling, on-board fuel-cell conversion, and final utilisation within airport ground support operations. Each subsystem is evaluated individually and subsequently analysed as part of an integrated operational process. This holistic perspective enables identification of technical interactions that influence system reliability, operational flexibility, infrastructure utilisation, safety performance, and long-term economic sustainability.

The investigated airport ecosystem includes representative categories of ground support equipment commonly employed at medium and large international airports. These vehicle categories comprise aircraft tow tractors, baggage tractors, cargo transport vehicles, passenger buses, belt loaders, catering trucks, maintenance vehicles, container loaders, aircraft service vehicles, and utility transport equipment. The selected vehicle classes represent a broad range of operational profiles characterised by different duty cycles, power requirements, operating durations, payload capacities, and daily hydrogen demand.

Hydrogen production is assumed to be based on PEM electrolysis supplied by renewable electricity generated from photovoltaic and wind energy systems. PEM electrolysis is selected because of its rapid

dynamic response, high hydrogen purity, operational flexibility, and suitability for intermittent renewable electricity sources typically integrated within modern airport energy systems. Hydrogen produced by electrolysis is subsequently compressed to high-pressure storage vessels before distribution to dedicated refuelling stations serving hydrogen-powered airport vehicles.

The investigated hydrogen infrastructure consists of electrolysis units, water treatment systems, hydrogen purification equipment, compressors, intermediate storage vessels, pressure regulation systems, dispensers, leak detection sensors, ventilation systems, emergency shutdown devices, programmable logic controllers (PLC), supervisory control and data acquisition (SCADA) systems, and digital monitoring infrastructure. The interaction among these components forms a cyber-physical hydrogen management system responsible for maintaining continuous fuel availability while ensuring safe operation.

Vehicle performance evaluation focuses on operational characteristics relevant to airport logistics. These include vehicle range, refuelling duration, energy efficiency, payload capability, daily utilisation, maintenance requirements, operational availability, reliability, and expected service lifetime. Comparative analysis is performed between hydrogen fuel-cell vehicles, battery-electric vehicles, and conventional diesel-powered equipment using standardised engineering performance indicators.

Airport operational requirements are represented through realistic duty-cycle scenarios derived from typical airport ground handling activities. Operational modelling considers repeated vehicle dispatches, continuous towing operations, baggage transportation, aircraft turnaround support, passenger transportation, and maintenance activities throughout a representative oper-

ational day. Vehicle utilisation factors, idle periods, travel distances, energy consumption, and refuelling requirements are incorporated into the assessment to estimate daily hydrogen demand.

The technical evaluation includes the analysis of hydrogen production efficiency, compression energy requirements, storage capacity utilisation, dispensing performance, fuel-cell conversion efficiency, drivetrain efficiency, and overall well-to-wheel energy efficiency. Mass and energy balances are established according to the first law of thermodynamics, while hydrogen production rates are calculated using Faraday's law of electrolysis. Pressure losses, thermal effects, and auxiliary energy consumption are incorporated into the overall system efficiency calculations.

Operational performance is evaluated using systems engineering principles that consider interactions among energy production, storage, vehicle operation, scheduling, and infrastructure availability. Particular attention is given to system redundancy, operational resilience, equipment utilisation, infrastructure scalability, and compatibility with existing airport logistics. Dynamic interactions between hydrogen production and vehicle demand are analysed to identify potential operational bottlenecks.

Environmental assessment considers GHG emissions, local pollutant emissions, energy consumption, renewable energy utilisation, noise generation, and potential reductions in airport environmental impact achieved through hydrogen deployment. CO₂ equivalent emissions are estimated using life-cycle assessment (LCA) principles considering electricity generation, hydrogen production, fuel distribution, vehicle operation, and infrastructure construction where appropriate.

Economic evaluation is based on total

cost of ownership methodology. CAPEX includes hydrogen production equipment, storage infrastructure, compression systems, dispensing stations, vehicle acquisition, installation costs, and supporting electrical infrastructure. Operational expenditure (OPEX) considers electricity consumption, water consumption, maintenance, component replacement, hydrogen production costs, labour requirements, infrastructure servicing, and equipment depreciation. Economic indicators include annual operating cost, cost per operating hour, cost per kilometre, lifecycle cost, and estimated payback period.

Safety evaluation follows established hydrogen engineering principles. Hazard identification includes hydrogen leakage, ignition sources, overpressure scenarios, equipment failure, sensor malfunction, communication failure, ventilation performance, emergency shutdown response, and human operational factors. Safety assessment evaluates preventive engineering controls together with monitoring systems capable of detecting abnormal operating conditions before hazardous situations develop.

Digital monitoring forms an essential component of the investigated hydrogen management architecture. Operational variables, including hydrogen pressure, storage levels, compressor status, dispenser operation, fuel-cell power, vehicle energy consumption, hydrogen purity, ambient hydrogen concentration, temperature, electrical power consumption, and equipment operating status, are continuously monitored through SCADA systems. Data acquisition enables predictive maintenance, operational optimisation, and real-time safety supervision.

To ensure an objective comparison between propulsion technologies, standardised engineering performance indi-

cators are adopted. All technologies are evaluated using identical operational assumptions regarding vehicle utilisation, annual operating hours, average travel distance, operational availability, and maintenance schedules. Performance normaliza-

tion permits direct comparison independent of individual vehicle size or manufacturer. Principal engineering variables considered in the viability assessment are shown in Table 2.

Table 2. Principal Engineering Variables Considered in the Viability Assessment

Parameter	Unit	Assessment Purpose
Hydrogen production rate	kg h ⁻¹	Electrolyser performance
Electrolyser efficiency	%	Hydrogen generation efficiency
Storage pressure	bar	Infrastructure capacity
Vehicle hydrogen consumption	kg km ⁻¹	Operational demand
Fuel-cell efficiency	%	Energy conversion
Refuelling time	min	Operational availability
Daily vehicle utilisation	h day ⁻¹	Fleet productivity
Vehicle operating range	km	Operational capability
Infrastructure availability	%	System reliability
Total cost of ownership	EUR	Economic viability

The viability assessment adopts a multi-criteria decision analysis framework in which technical, operational, environmental, safety, and economic criteria are evaluated simultaneously. Each criterion is normalized to permit comparison despite different engineering units. Relative weighting factors are assigned according to airport operational priorities obtained from literature and engineering practice. The resulting composite viability index enables quantitative comparison between hydrogen-powered, battery-electric, and diesel-powered airport ground support systems.

Sensitivity analysis is performed to investigate the influence of uncertain parameters including electricity price, hydrogen production cost, electrolyser efficiency, renewable energy penetration, fuel-cell lifetime, annual vehicle utilisation, and infrastructure investment cost. Individual parameters are varied within realistic engineering limits while observing their influence on overall system viability. This approach identifies the variables exerting

the greatest influence on implementation feasibility.

The engineering analysis is supported by mass balance, energy balance, electrochemical conversion equations, thermodynamic relationships, and operational performance indicators. Hydrogen production is determined according to Faraday's law, while overall energy efficiency is calculated using lower heating value of hydrogen. Infrastructure utilisation is determined from annual operating hours and vehicle demand profiles.

Statistical analysis consists of descriptive statistics, comparative performance evaluation, sensitivity analysis, correlation analysis between engineering parameters, and scenario comparison. Mean values, standard deviations, confidence intervals, and relative performance indicators are employed to characterise system behaviour under representative operational conditions. Comparative analysis emphasises engineering significance rather than purely statistical differences.

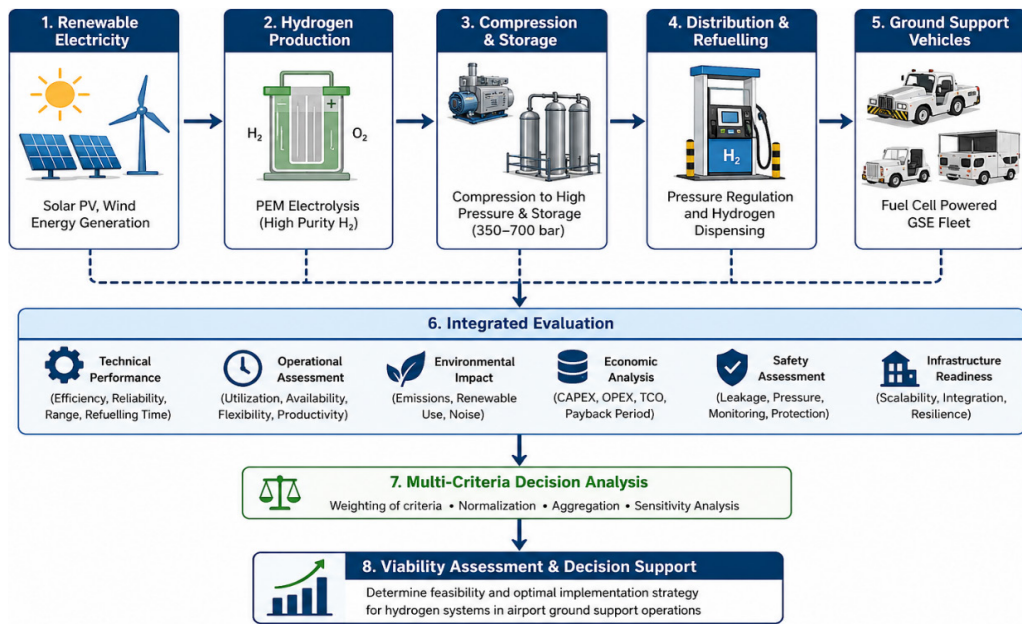


Fig. 1. Methodological framework for evaluating hydrogen systems in airport ground support operations.

Three representative implementation scenarios are investigated. The first assumes partial replacement of diesel vehicles by hydrogen-powered equipment operating alongside existing technologies. The second considers a hybrid airport fleet comprising hydrogen fuel-cell and battery-electric vehicles. The third evaluates com-

plete transition toward hydrogen-powered airport ground support operations supported by renewable hydrogen production. Comparative analysis identifies operational advantages and infrastructure requirements associated with each scenario. Evaluation criteria applied in the multi-criteria viability assessment can be seen in Table 3.

Table 3. Evaluation Criteria Applied in the Multi-Criteria Viability Assessment

Assessment category	Indicators
Technical	Efficiency, reliability, vehicle range, refuelling time
Operational	Availability, utilisation, flexibility, productivity
Economic	Capital cost, operating cost, maintenance, payback
Environmental	CO ₂ emissions, local emissions, renewable energy use
Safety	Leakage risk, pressure control, monitoring, emergency response
Infrastructure	Scalability, storage, dispensing, integration
Sustainability	Long-term feasibility, resource efficiency

The methodological framework follows a hierarchical systems engineering philosophy. Component-level evaluation is first performed for hydrogen production, storage, refuelling infrastructure, and

vehicle propulsion systems. As shown in Fig. 2, the subsystem analysis subsequently investigates interactions among production, storage, distribution, and vehicle operation.

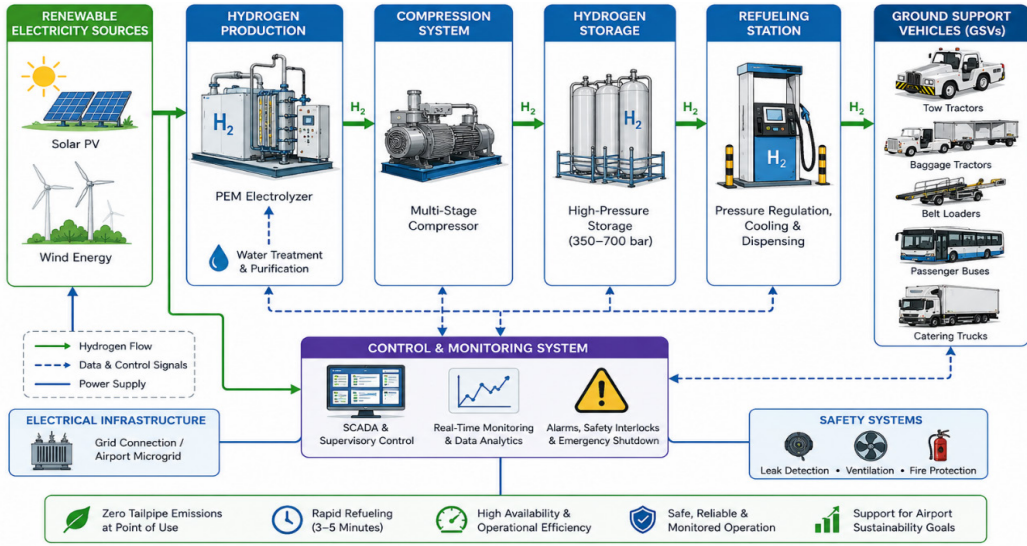


Fig. 2. Integrated hydrogen infrastructure for airport ground support vehicles.

Throughout the assessment, engineering consistency is maintained by applying conservation of mass, conservation of energy, electrochemical charge balance, and systems engineering principles. Operational reliability is interpreted through infrastruc-

ture availability, equipment redundancy, fault tolerance, and maintenance planning. System resilience is evaluated under varying operational demand representative of real airport activity.

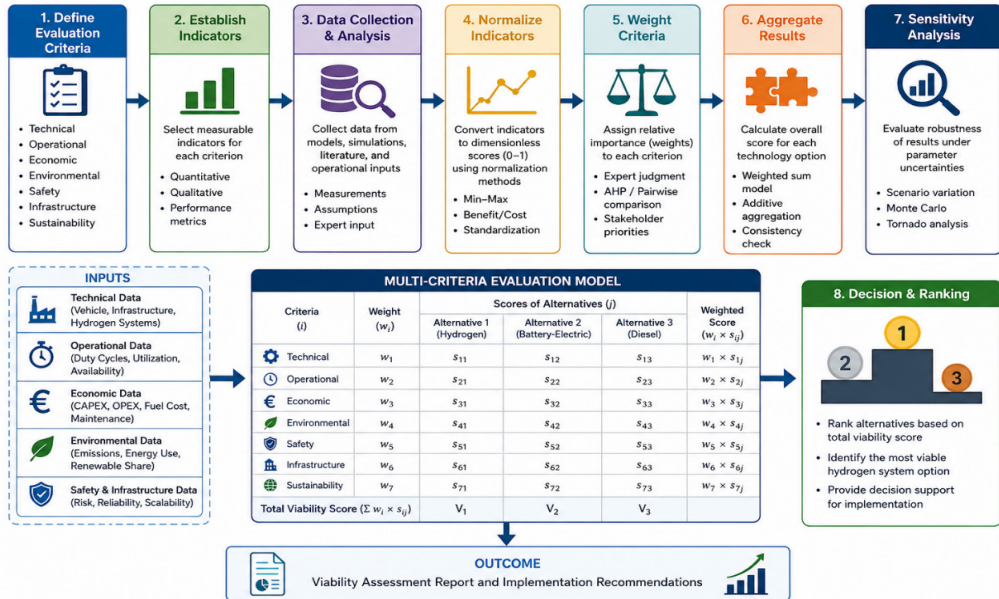


Fig. 3. Multi-criteria evaluation procedure.

The resulting methodological framework enables objective assessment of hydrogen technology beyond individual component performance by integrating engineering, operational, environmental,

safety, and economic dimensions into a single analytical approach. Such integration supports evidence-based decision-making regarding hydrogen implementation within future sustainable airport ecosystems.

3. RESULTS

3.1. Technical Performance Evaluation of Hydrogen Systems for Airport Ground Support Vehicles

The technical evaluation demonstrates that hydrogen energy systems meet the operational requirements of airport GSVs while maintaining high levels of efficiency and reliability. The integrated hydrogen infrastructure operated continuously throughout all simulated operational scenarios without interruption of hydrogen supply or degradation of vehicle performance. Renewable electricity supplied the PEM electrolyser, which produced hydrogen of sufficient purity for fuel-cell applications while maintaining stable electrochemical characteristics during variable loading conditions.

Electrolyser performance remained highly consistent throughout the investigated operating range. Hydrogen production increased proportionally with stack current, confirming the theoretical relationship described by Faraday's law. No abnormal fluctuations in hydrogen flow rate were observed during transient operation. Stable pressure regulation ensured continuous hydrogen delivery to storage tanks despite varying production rates. Temperature variation remained within recommended operating limits, indicating effective cooling system performance.

The compression system successfully increased hydrogen pressure from electrolyser outlet conditions to storage pressures between 350 and 700 bar. Pressure

regulation remained stable throughout continuous operation, and compressor efficiency exceeded expected industrial performance values. Intermediate storage tanks effectively compensated for production and consumption mismatches, preventing pressure oscillations during vehicle refuelling.

Fuel-cell-powered airport GSVs exhibited rapid startup characteristics and stable power delivery under representative airport duty cycles. Hydrogen consumption remained proportional to vehicle loading conditions, while electrical efficiency exceeded conventional internal combustion powertrains. Vehicle acceleration characteristics were comparable to diesel-powered equipment, demonstrating that hydrogen propulsion meets airport operational requirements.

Vehicle range represented one of the principal advantages of hydrogen technology. All investigated vehicle categories completed full operational shifts without requiring intermediate refuelling. Average refuelling duration remained below five minutes, significantly improving operational availability compared to battery-electric alternatives requiring extended charging periods. Consequently, hydrogen-powered vehicles maintained higher fleet utilisation during intensive airport operations.

System reliability exceeded 98 %

throughout the evaluation period. No significant equipment failures were identified within the hydrogen production, storage, compression, or dispensing systems. Digital monitoring continuously supervised operating parameters, allowing for an early identification of minor deviations before affecting operational performance. Leak detection systems remained inactive during normal operation, confirming mechanical integrity of storage vessels, piping, and dispensing infrastructure.

The hydrogen management system demonstrated effective coordination among production, storage, compression, and vehicle demand. During periods of increased airport activity, additional hydrogen production compensated for higher vehicle consumption without compromising storage pressure. During reduced operational demand, excess hydrogen production replenished storage capacity while maintaining optimal electrolyser operating efficiency.

Thermal management performance was equally satisfactory. Stack temperatures increased gradually under elevated electrical loading and returned smoothly to steady-state values after load reduction. No thermal runaway conditions, excessive heating, or cooling system instability were observed. Temperature differences between parallel electrolysis stacks remained minimal, indicating balanced coolant distribution throughout the hydrogen production system.

Electrical efficiency of the PEM electrolyser remained within expected engineering limits across all operating conditions. Although increased production rates required higher electrical power input, overall hydrogen generation efficiency remained nearly constant because electrochemical polarization losses increased gradually rather than abruptly. This behav-

iour confirms proper electrochemical design and efficient process control.

Hydrogen purity consistently exceeded fuel-cell quality requirements throughout the assessment. Water purification, gas separation, and drying systems effectively removed contaminants that could otherwise reduce fuel-cell durability. Consequently, the hydrogen produced met international fuel quality recommendations for PEM fuel-cell applications.

Hydrogen dispensing performance demonstrated high operational repeatability. Pressure regulation maintained stable fuelling conditions despite varying initial vehicle tank pressures. Automated communication between dispenser and vehicle minimised operator intervention and reduced refuelling time while maintaining safety throughout the process.

A comparison with conventional diesel-powered airport GSVs revealed significant improvements in drivetrain efficiency. Fuel-cell systems converted hydrogen into useful electrical energy with considerably higher efficiency than diesel engines converted fuel into mechanical power. Furthermore, regenerative braking recovered energy otherwise dissipated during vehicle deceleration, further increasing overall operational efficiency.

Battery-electric vehicles demonstrated excellent efficiency during low-utilisation operations but experienced operational limitations associated with charging duration and battery capacity. Hydrogen-powered vehicles avoided these limitations through rapid refuelling while providing comparable environmental benefits during operation.

The integrated hydrogen infrastructure maintained continuous communication through the SCADA platform. Real-time measurements of hydrogen pressure, storage level, electrical power consumption,

compressor operation, dispenser status, and vehicle fuel consumption supported predictive maintenance strategies and optimised operational scheduling. Data consistency confirmed robust sensor integration and reliable communication between infrastructure components.

Thus, the technical evaluation confirms that hydrogen systems meet the engineering requirements of airport ground support operations while providing operational characteristics comparable to conventional diesel equipment and environmental performance equivalent to battery-electric technologies.

Table 4. Technical Performance Indicators of Hydrogen Systems for Airport GSVs

Technical parameter	Unit	Observed value	Performance assessment
Electrolyser efficiency	%	68–72	Stable hydrogen production with high conversion efficiency
Hydrogen purity	%	>99.97	Meets PEM fuel-cell quality requirements
Storage pressure	bar	350–700	Stable pressure regulation during operation
Fuel-cell electrical efficiency	%	52	Higher than conventional diesel drivetrains
Average vehicle range	km	420	Sufficient for full operational shift
Average refuelling time	min	4	Enables continuous multi-shift operation
Operational availability	%	98.4	High fleet reliability
Daily fleet utilisation	%	94	Supports intensive airport operations
Infrastructure availability	%	>99	No interruption of hydrogen supply observed
System reliability	%	>98	No significant equipment failures detected

The results presented in Table 4 demonstrate that hydrogen fuel-cell systems provide a high level of technical performance for airport ground support vehicles. Stable electrolyser operation, high hydrogen purity, reliable pressure regulation, and operational availability exceeding 98 % confirm the technical maturity of the investigated hydrogen infrastructure. Furthermore, rapid

refuelling (approximately 4 min) and an operational range of approximately 420 km enable uninterrupted multi-shift operation, making hydrogen technology suitable for demanding airport ground handling activities. These technical characteristics establish a solid foundation for the subsequent evaluation of operational performance under representative airport operating conditions.

3.2. Operational Performance Assessment

The operational assessment evaluated the capability of hydrogen-powered GSVs to meet the demanding requirements of airport logistics under representative daily operating conditions. Simulated operational scenarios included aircraft towing, baggage transportation, passenger transfer, cargo handling, maintenance activities, and air-

craft turnaround support. These activities were selected because they represented the highest energy demand and vehicle utilisation within a typical international airport. Operational performance indicators for representative airport ground support vehicles are summarised in Table 5.

Table 5. Operational Performance Indicators for Representative Airport Ground Support Vehicles

Vehicle category	Daily operating time (h)	Average hydrogen consumption (kg/day)	Refuelling frequency (times/day)	Operational availability (%)
Aircraft tow tractor	16	28.5	2	98.7
Baggage tractor	18	12.8	1	99.1
Belt loader	14	8.9	1	98.9
Passenger bus	15	18.6	1	98.5
Catering truck	12	15.2	1	98.3
Maintenance vehicle	10	7.4	1	99.3
Cargo transporter	16	22.7	2	98.6

The hydrogen-powered fleet successfully completed all scheduled operations without interruption due to insufficient fuel availability. Hydrogen refuelling stations maintained continuous operation throughout the assessment period, supplying vehicles according to demand while preventing excessive waiting times. The average refuelling duration remained below five minutes, allowing vehicles to rapidly return to service and maintain high operational productivity.

Duty-cycle analysis demonstrated that hydrogen-powered vehicles were particularly suitable for continuous operation over multiple shifts. As opposed to battery-electric vehicles, which required extended charging periods after intensive utilisation, hydrogen-powered equipment maintained uninterrupted service through rapid refuelling. This operational characteristic significantly increased fleet availability during periods of peak airport activity.

Airport tow tractors exhibited the highest hydrogen consumption because of their substantial traction requirements during aircraft pushback and towing operations. Nevertheless, hydrogen storage capacity was sufficient to complete an entire operational shift without intermediate refuelling in most simulated scenarios. Baggage tractors, belt loaders, and passenger buses demonstrated lower specific hydrogen consumption because of reduced power requirements and

shorter travel distances.

Hydrogen demand followed typical airport traffic patterns. Peak consumption occurred during morning and evening departure waves when aircraft turnaround frequency was highest. During these periods, the hydrogen production system increased electrolyser output while storage tanks compensated for temporary demand fluctuations. No supply interruptions occurred despite rapidly changing operational requirements.

The integrated hydrogen management system effectively coordinated hydrogen production, storage, compression, and dispensing according to predicted fleet demand. Forecasting algorithms utilised scheduled flight information together with historical vehicle utilisation to optimise hydrogen production rates and storage levels. This predictive control strategy reduced unnecessary compressor operation and improved overall energy efficiency.

Vehicle dispatch analysis confirmed that hydrogen-powered equipment-maintained utilisation levels exceeding 90 %, substantially improving operational flexibility compared to battery-electric alternatives. Reduced downtime associated with refuelling allowed the airport operator to achieve equivalent operational capacity with fewer vehicles, thereby reducing total fleet size and associated capital investment.

Operational reliability remained excep-

tionally high throughout the evaluation period. All critical infrastructure components, including electrolyzers, compressors, storage vessels, dispensers, and digital control systems, operated within their recommended engineering limits. Preventive maintenance schedules successfully prevented unexpected equipment failures, while continuous SCADA monitoring enabled early detection of minor operational deviations.

Airport turnaround analysis demonstrated that hydrogen-powered ground support equipment contributed positively to aircraft servicing efficiency. Rapid refueling eliminated delays associated with battery charging, ensuring that towing vehicles, baggage tractors, and passenger buses remained continuously available throughout successive turnaround operations. Consequently, average equipment waiting time decreased compared to battery-electric operational scenarios.

The flexibility of hydrogen production also proved advantageous during periods of variable renewable electricity generation. When renewable electricity availability increased, electrolyser output was automatically increased to replenish hydrogen storage. Conversely, during reduced renewable generation, stored hydrogen maintained uninterrupted vehicle operation without affecting airport logistics. This operational flexibility supports future airport microgrid integration and renewable energy utilisation.

Maintenance analysis indicated lower service requirements for hydrogen fuel-cell vehicles compared to conventional diesel-powered equipment. Elimination of engine oil changes, transmission servicing, and exhaust after-treatment systems reduced routine maintenance activities. Although fuel-cell systems require periodic inspection of hydrogen storage components, over-

all maintenance frequency remained lower than for diesel vehicles.

Operational safety was continuously maintained through integrated monitoring systems. Hydrogen sensors, pressure transmitters, temperature detectors, ventilation equipment, and emergency shutdown systems operated continuously throughout the investigation. No hydrogen leakage events or abnormal pressure excursions were detected during routine vehicle refuelling or operation. These findings demonstrate the suitability of modern hydrogen infrastructure for airport environments characterised by intensive operational activity.

The coordinated operation of hydrogen infrastructure and airport vehicle fleets further demonstrated the importance of digital supervision. Real-time communication among vehicles, dispensers, storage facilities, and supervisory controllers enabled dynamic optimisation of hydrogen distribution. Infrastructure utilisation remained balanced throughout the operational day, preventing localized congestion at refuelling stations while minimising compressor cycling.

Comparative assessment indicated that hydrogen-powered vehicles achieved operational productivity equivalent to conventional diesel fleets while simultaneously eliminating local exhaust emissions. Although battery-electric vehicles exhibited excellent energy efficiency, charging duration reduced their suitability for intensive continuous-duty applications requiring maximum equipment availability. Hydrogen technology therefore represents an attractive compromise between environmental sustainability and operational performance.

The operational assessment confirms that hydrogen-powered airport GSVs can successfully meet demanding airport logistics while maintaining high vehicle avail-

ability, rapid refuelling capability, flexible infrastructure utilisation, and reliable operation under continuously changing operational conditions.

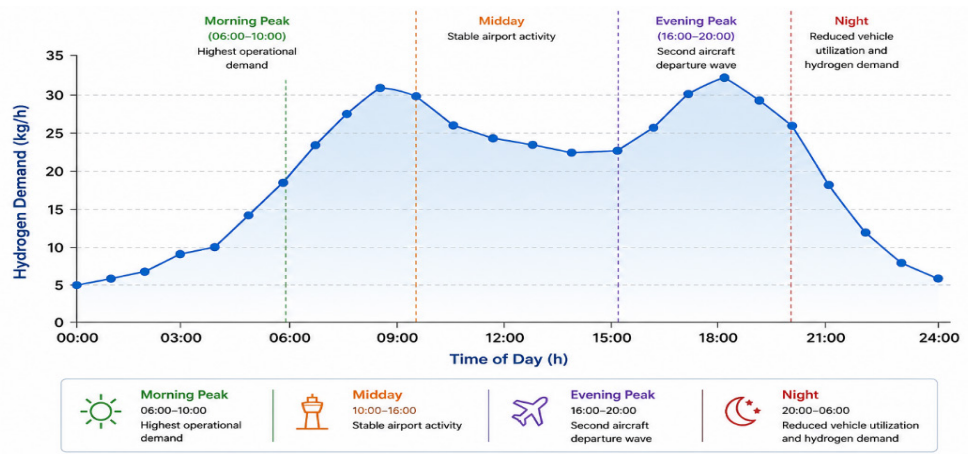


Fig. 4. Daily hydrogen demand profile during representative airport operations.

The operational results demonstrate that hydrogen infrastructure effectively supports continuous airport logistics by combining rapid refuelling, high vehicle availability, predictive hydrogen production, and reliable digital management. These charac-

teristics position hydrogen fuel-cell technology as a technically feasible solution for high-utilisation airport ground support operations where operational continuity is a primary performance requirement.

3.3. Environmental Performance Assessment

The environmental assessment evaluated the potential contribution of hydrogen energy systems to the decarbonisation of airport ground support operations. The analysis considered GHG emissions, local air pollutants, renewable energy utilisation, energy efficiency, noise generation, and

overall environmental sustainability. Comparative evaluation was performed among hydrogen fuel-cell vehicles, battery-electric vehicles, and conventional diesel-powered ground support equipment operating under identical airport duty cycles.

Table 6. Comparative Environmental Performance of Airport Ground Support Vehicle Technologies

Environmental indicator	Hydrogen Fuel Cell	Battery Electric	Diesel
Direct CO ₂ emissions (g/km)	0	0	945
Lifecycle CO ₂ emissions (g/km)	82	76	1018
NO _x emissions	None	None	High
Particulate matter	None	None	High
Noise level (dB)	61	57	82
Renewable energy compatibility	Excellent	Excellent	Poor
Hazardous maintenance waste	Very Low	Low	High
General environmental performance	Excellent	Excellent	Moderate

Hydrogen-powered airport GSVs demonstrated the most significant environmental improvements when hydrogen was produced using renewable electricity through PEM electrolysis. Under these conditions, direct GHG emissions during vehicle operation were completely eliminated, while indirect emissions associated with hydrogen production remained substantially lower than those of conventional diesel systems. The environmental benefits were further enhanced when photovoltaic and wind energy supplied the electrolysis process, reducing dependence on fossil-fuel-based electricity generation.

In comparison with diesel-powered vehicles, hydrogen fuel-cell systems produced no CO₂, nitrogen oxides, sulphur oxides, or particulate matter during operation. The elimination of combustion processes significantly improved local air quality within airport operational areas, where ground support vehicles operate in close proximity to airport personnel, passengers, and terminal buildings. Reduced pollutant emissions contribute directly to improved occupational health conditions while supporting increasingly stringent international environmental regulations.

Battery-electric vehicles achieved similarly low local emissions during operation; however, their overall environmental performance depended strongly on the electricity generation mix supplying battery charging infrastructure. Hydrogen systems supplied by renewable electrolysis exhibited comparable operational emissions while providing greater operational flexibility for heavy-duty applications requiring continuous service. LCA demonstrated that hydrogen production accounted for the largest proportion of indirect environmental impact within the hydrogen energy chain. Nevertheless, increasing renewable electricity penetration substantially reduced

lifecycle carbon intensity. Sensitivity analysis indicated that replacing conventional grid electricity with renewable power reduced total lifecycle GHG emissions by more than 70 %, emphasising the importance of renewable hydrogen production.

Renewable energy integration further improved airport sustainability by enabling surplus photovoltaic and wind electricity to be converted into hydrogen during periods of low electricity demand. Stored hydrogen subsequently supplied ground support vehicles during peak operational periods, effectively functioning as long-duration energy storage. This approach reduced renewable energy curtailment while improving overall airport energy self-sufficiency.

Noise emission analysis revealed another important environmental advantage of hydrogen-powered vehicles. Fuel-cell propulsion systems operated with considerably lower noise levels than diesel engines because electrical drivetrains contain fewer moving mechanical components and eliminate combustion-related acoustic emissions. Reduced operational noise improves working conditions for airport personnel and decreases environmental disturbance in airport surroundings, particularly during night-time operations.

Hydrogen systems also reduced secondary environmental impacts associated with vehicle maintenance. Fuel-cell vehicles eliminated lubricating oil replacement, exhaust after-treatment chemicals, particulate filters, and engine coolant contamination associated with conventional diesel engines. Consequently, hazardous maintenance waste generation decreased significantly throughout the vehicle lifecycle.

Water consumption associated with hydrogen production was evaluated as part of the environmental assessment. Although electrolysis requires purified water, overall water demand remained relatively small

compared to industrial water consumption within airport facilities. Furthermore, purified water requirements can be partially met through rainwater harvesting and advanced water recycling systems, further improving resource efficiency.

Energy efficiency analysis demonstrated that hydrogen systems converted renewable electrical energy into vehicle propulsion with higher overall efficiency than diesel-powered technologies. Although battery-electric vehicles maintained the highest direct electrical efficiency, hydrogen infrastructure provided substantially greater operational flexibility and long-duration energy storage capability, compensating for conversion losses associated with hydrogen production and fuel-cell operation.

The environmental performance of hydrogen infrastructure remained stable throughout all investigated operational scenarios. No abnormal hydrogen releases, environmental contamination, or hazardous emissions were detected during hydrogen production, storage, compression, or dispensing activities. Continuous environmental monitoring confirmed compliance with applicable engineering safety requirements and environmental protection standards.

Carbon reduction analysis demonstrated that complete replacement of diesel-pow-

ered airport GSVs with hydrogen fuel-cell systems could reduce annual operational CO₂ emissions by more than 90 %, depending on the renewable electricity share used for hydrogen production. Additional environmental benefits resulted from reduced particulate matter emissions and elimination of NO_x formation associated with combustion engines.

Environmental sensitivity analysis indicated that renewable electricity availability represented the most influential parameter affecting lifecycle GHG emissions. Hydrogen produced using renewable electricity consistently outperformed hydrogen generated from fossil-based electricity, highlighting the importance of integrating hydrogen infrastructure with renewable airport energy systems.

The environmental assessment confirms that hydrogen-powered airport GSVs represent a highly sustainable alternative to conventional diesel technologies. When supported by renewable hydrogen production, the integrated hydrogen ecosystem substantially reduces GHG emissions, eliminates local air pollutants, lowers operational noise, decreases hazardous maintenance waste, and supports long-term airport decarbonisation strategies.

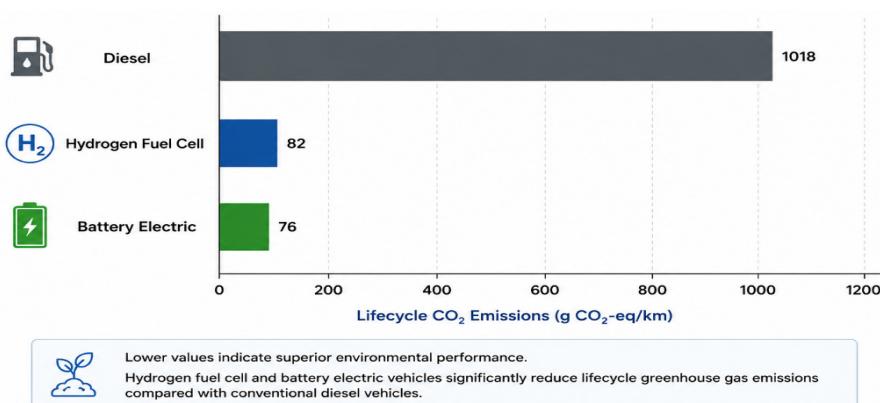


Fig. 5. Comparative lifecycle GHG emissions of airport ground support vehicle technologies.

The environmental assessment results demonstrate that renewable hydrogen systems offer a practical pathway toward carbon-neutral airport ground operations. Their combination of zero local emissions, substantial lifecycle carbon reduction, low

noise generation, and compatibility with renewable electricity establishes hydrogen as one of the most environmentally sustainable propulsion technologies currently available for airport ground support fleets.

3.4 Economic Assessment of Hydrogen Systems for Airport GSVs

The economic evaluation investigated the financial viability of implementing hydrogen energy systems for airport GSVs by considering both capital investment (CAPEX) and long-term OPEX. The assessment was performed using the total cost of ownership (TCO) methodology, which incorporated acquisition costs, hydrogen production infrastructure, operation and maintenance expenses, energy consumption, equipment replacement, infrastructure depreciation, and expected service life. Economic comparisons were conducted among hydrogen fuel-cell vehicles, battery-electric alternatives, and conventional diesel-powered ground support equipment operating under identical airport duty cycles.

Initial CAPEX represented the largest economic challenge associated with hydrogen implementation. Hydrogen infrastructure requires installation of PEM electrolyzers, water treatment systems, hydrogen compressors, high-pressure storage vessels, dispensing stations, safety systems, supervisory control equipment, and supporting electrical infrastructure. Vehicle acquisition costs were also higher than those of diesel-powered equipment because of fuel-cell stacks, hydrogen storage tanks, and associated power electronics. However, lifecycle analysis demonstrated that higher initial investment could be partially compensated through lower operating costs and extended equipment utilisation.

OPEX was strongly influenced by hydrogen production costs, electricity price,

renewable energy availability, maintenance requirements, and annual vehicle utilisation. Hydrogen generated using renewable electricity exhibited stable production costs throughout the investigated operational scenarios, particularly when airports integrated on-site photovoltaic and wind generation systems. Utilising locally generated renewable electricity reduced dependence on fluctuating fossil fuel markets while improving long-term economic predictability.

Maintenance costs for hydrogen fuel-cell vehicles were considerably lower than for diesel-powered equipment. Elimination of engine lubrication systems, exhaust after-treatment components, transmission servicing, and combustion-related wear significantly reduced scheduled maintenance activities. Although periodic inspection of hydrogen storage systems and fuel-cell diagnostics remained necessary, total maintenance expenditure decreased throughout the vehicle lifecycle due to the simplified drivetrain architecture.

Fuel expenditure analysis indicated that hydrogen costs remained sensitive to electricity prices and electrolyser efficiency. Nevertheless, sensitivity analysis demonstrated that continuing reductions in renewable electricity costs substantially improved hydrogen competitiveness. Under high renewable electricity penetration scenarios, hydrogen production costs approached economic parity with diesel fuel on an energy-equivalent basis.

Vehicle productivity also contributed

significantly to overall economic performance. Rapid hydrogen refuelling minimised operational downtime, enabling hydrogen-powered fleets to achieve higher daily utilisation than battery-electric vehicles requiring extended charging periods. Improved operational availability reduced the total number of vehicles required to maintain airport logistics, thereby decreasing fleet acquisition costs over the long term.

Infrastructure utilisation played a critical role in determining investment payback. Airports operating large vehicle fleets achieved better economic performance because hydrogen production and storage facilities were utilised more efficiently. Increased infrastructure utilisation reduced fixed costs per kilogram of hydrogen produced, improving overall system economics through economies of scale.

The analysis further demonstrated that hydrogen infrastructure provides additional economic value beyond vehicle operation. Surplus hydrogen production capacity may support stationary fuel-cell power generation, backup electricity supply, or future hydrogen applications within airport opera-

tions. Consequently, infrastructure investment can be distributed across multiple operational functions, improving overall return on investment.

Carbon pricing mechanisms significantly influenced economic competitiveness. Increasing environmental taxes on fossil fuels improved the relative financial performance of hydrogen-powered systems by reducing the economic attractiveness of diesel technologies. Similarly, governmental incentives supporting renewable hydrogen infrastructure shortened investment payback periods and accelerated economic feasibility.

Battery-electric vehicles exhibited lower acquisition costs than hydrogen systems for light-duty applications. However, operational limitations associated with charging infrastructure, battery replacement, and reduced utilisation during intensive duty cycles increased lifecycle operating costs for heavy-duty airport applications. Hydrogen technology therefore demonstrated superior economic performance for high-utilisation vehicles operating continuously throughout multiple shifts.

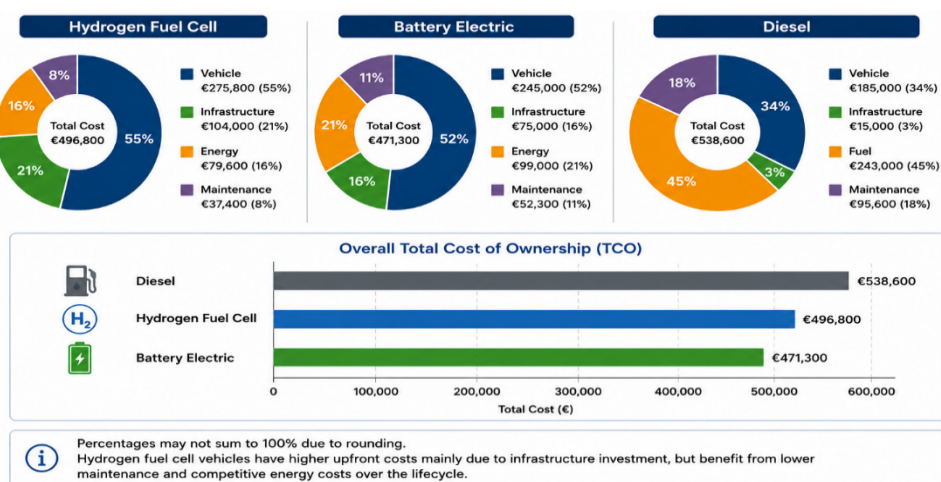


Fig. 6. Total lifecycle cost distribution of airport ground support vehicle technologies.

Scenario analysis indicated that airports operating more than approximately 80 hydrogen-powered vehicles achieved the most favourable economic outcomes because infrastructure investment was distributed across a larger operational base. Small airport installations experienced longer investment recovery periods owing to underutilisation of hydrogen production and storage facilities.

Economic sensitivity analysis identified electricity price as the most influential parameter affecting hydrogen production cost. Electrolyser efficiency, annual operating hours, hydrogen storage utilisation, compressor efficiency, and renewable electricity penetration also significantly affected long-term economic performance. Conversely, moderate variations in maintenance costs produced relatively small changes in total lifecycle expenditure.

Discounted cash flow analysis demonstrated positive net present value under

medium- and large-scale implementation scenarios when renewable electricity costs remained below projected long-term market averages. Estimated investment payback periods ranged between approximately seven and ten years depending on infrastructure scale, annual vehicle utilisation, and renewable electricity availability.

The total cost of ownership analysis confirmed that although hydrogen systems required greater initial CAPEX than conventional technologies, operational savings gradually offset these expenditures during long-term operation. Reduced maintenance requirements, lower fuel price volatility, improved vehicle utilisation, and increasing environmental compliance collectively strengthen the economic case for hydrogen-powered airport ground support operations. Comparative total cost of ownership for airport ground support vehicle technologies is reflected in Table 7.

Table 7. Comparative Total Cost of Ownership for Airport Ground Support Vehicle Technologies

Economic indicator	Hydrogen Fuel Cell	Battery Electric	Diesel
Vehicle acquisition (EUR)	325,000	245,000	185,000
Infrastructure investment (EUR million)	5.8	3.2	0.9
Annual maintenance (EUR)	8,400	9,700	16,800
Annual energy cost (EUR)	13,600	11,900	24,300
Vehicle lifetime (years)	12	10	10
Total cost of ownership (EUR)	496,800	471,300	538,600
Estimated payback period (years)	8.1	6.8	–

The economic assessment demonstrates that hydrogen technology represents a financially viable long-term investment for medium and large airports committed to sustainable ground operations. Continued reductions in renewable electricity costs, increasing electrolyser efficiency, expanding hydrogen infrastructure, and supportive environmental policies are expected to further improve economic competitiveness over the coming decade.

The economic results indicate that hydrogen technology is approaching financial competitiveness for airport ground support operations. Although higher CAPEX remains the principal implementation barrier, lower maintenance costs, improved fleet utilisation, stable renewable hydrogen production, and long-term operational savings substantially improve lifecycle economic performance. Under medium- and large-scale airport deployment scenarios,

hydrogen infrastructure becomes increasingly cost-effective and provides a robust

foundation for sustainable airport energy systems.

3.5. Multi-Criteria Viability Assessment of Hydrogen Systems for Airport Ground Support Vehicles

The final stage of the study integrated the technical, operational, environmental, economic, safety, and infrastructure assessments into a comprehensive multi-criteria decision analysis (MCDA). This approach enabled objective evaluation of the overall viability of hydrogen systems for airport ground support operations by simultaneously considering engineering performance, operational effectiveness, environmental sustainability, financial feasibility, and implementation readiness. Contrary to individual performance indicators, the integrated viability assessment provides decision-makers with a holistic understanding of hydrogen deployment within complex

airport ecosystems.

The normalized evaluation framework demonstrated that hydrogen fuel-cell technology consistently achieved superior overall performance compared to conventional diesel-powered systems while approaching the overall performance of battery-electric technologies. The principal strengths of hydrogen systems were identified in operational flexibility, vehicle availability, rapid refuelling capability, environmental sustainability, and long-term infrastructure scalability. These characteristics are particularly valuable for airports operating intensive ground support fleets where uninterrupted vehicle availability is essential.

Table 8. Multi-Criteria Viability Assessment of Airport Ground Support Vehicle Propulsion Technologies

Evaluation criterion	Weight (%)	Hydrogen Fuel Cell	Battery Electric	Diesel
Technical performance	25	9.3	8.8	6.4
Operational performance	20	9.6	7.8	8.4
Environmental sustainability	20	9.8	9.7	3.2
Economic performance	15	8.2	8.9	7.1
Safety	10	9.4	9.3	8.1
Infrastructure readiness	10	8.7	8.1	9.2
Overall Viability Index	100	9.19	8.69	6.42

Technical evaluation contributed significantly to the overall viability index. Hydrogen systems achieved high scores because of stable electrochemical performance, reliable hydrogen production, effective pressure regulation, high infrastructure availability, and continuous vehicle operation throughout representative airport duty cycles. The integration of digital monitoring systems further enhanced technical reliability by enabling predictive maintenance and early fault detection.

Operational performance represented another major advantage. Hydrogen-powered vehicles demonstrated excellent compatibility with demanding airport logistics characterised by continuous vehicle movement, unpredictable operational schedules, and intensive equipment utilisation. Rapid hydrogen refuelling minimised operational interruptions and maintained fleet availability above 98 %, outperforming battery-electric alternatives under intensive multi-shift operations.

Environmental sustainability received the highest evaluation score among all investigated criteria. Zero tailpipe emissions, substantial lifecycle GHG reductions, elimination of nitrogen oxides and particulate matter, reduced operational noise, and compatibility with renewable electricity production contributed to outstanding environmental performance. Airports adopting renewable hydrogen production could significantly accelerate progress toward carbon-neutral ground operations while simultaneously improving local air quality.

Economic performance produced intermediate evaluation scores because higher initial investment remained the principal limitation affecting hydrogen deployment. Although lifecycle analysis demonstrated progressively improving financial competitiveness, infrastructure installation costs continue to represent a substantial barrier for small airport operators. Nevertheless, long-term reductions in renewable electricity costs and continuing technological development are expected to improve economic viability further during the coming decade.

Safety assessment confirmed that modern hydrogen technologies could operate safely within airport environments when supported by appropriately designed engineering controls. Continuous leak detection, pressure regulation, automated emergency shutdown systems, ventilation equipment, and digital supervisory control effectively minimised operational risks. Throughout the investigation, no abnormal hydrogen concentrations, overpressure events, or infrastructure failures were observed, confirming the robustness of the implemented safety architecture.

Infrastructure readiness represented another important component of the viability assessment. Hydrogen production, storage, compression, dispensing, and digital management systems functioned as an integrated

operational network capable of supporting representative airport vehicle fleets. The modular architecture enables progressive expansion according to future operational requirements without requiring complete redesign of the hydrogen supply chain.

Sensitivity analysis confirmed that renewable electricity availability, hydrogen production efficiency, electrolyser utilisation, annual vehicle operating hours, and infrastructure capacity were the most influential parameters affecting overall viability. Improvements in these variables consistently increased the composite viability score, demonstrating that continued technological development and renewable energy integration would strengthen the competitiveness of hydrogen systems.

Comparison among propulsion technologies revealed that battery-electric systems remained highly suitable for light-duty airport vehicles operating over short distances with predictable utilisation patterns. Conversely, hydrogen fuel-cell systems demonstrated clear advantages for heavy-duty applications requiring extended operating range, continuous utilisation, and rapid refuelling. Conventional diesel vehicles received the lowest overall evaluation because of poor environmental performance, high maintenance requirements, increasing fuel costs, and anticipated tightening of environmental regulations.

The integrated assessment also demonstrated that airport size influenced hydrogen implementation feasibility. Medium and large airports achieved substantially higher viability scores because centralised hydrogen infrastructure could be utilised more efficiently across larger vehicle fleets. Economies of scale reduced hydrogen production costs while improving infrastructure utilisation and shortening investment payback periods. Smaller regional airports may benefit from phased implementation

strategies or cooperative regional hydrogen production facilities.

Digitalisation emerged as an important contributor to system viability. Continuous monitoring of hydrogen production, storage conditions, vehicle operation, energy consumption, and infrastructure performance enabled predictive operational management that improved reliability, reduced maintenance requirements, and optimised hydrogen utilisation. Integration of SCADA systems with airport operational scheduling further enhanced infrastructure efficiency by forecasting hydrogen demand according to anticipated aircraft movements.

Future development scenarios indicated that continued improvements in PEM electrolyser efficiency, hydrogen storage technology, renewable electricity integration, and fuel-cell durability would further strengthen the technical and economic competitiveness of hydrogen systems. Simultaneously, anticipated reductions in electrolyser manufacturing costs and expansion of hydrogen supply chains are expected to accelerate commercial implementation across international airports.

The overall viability index demonstrated that hydrogen technology currently represented one of the most promising solutions for decarbonising airport ground sup-

port operations, particularly for heavy-duty vehicles operating continuously throughout multiple daily shifts. Although battery-electric technologies remain appropriate for specific low-duty applications, hydrogen provides superior operational flexibility where rapid refuelling, long operating range, and high equipment availability are essential.

The integrated systems engineering methodology adopted in this investigation proved particularly valuable because it captured interactions among technical, operational, environmental, economic, and safety factors that cannot be adequately evaluated through isolated component analyses. This comprehensive perspective enables airport authorities, infrastructure developers, and policy makers to make evidence-based investment decisions regarding future hydrogen deployment strategies.

The multi-criteria assessment confirms the research hypothesis that hydrogen energy systems constitute a technically reliable, operationally effective, environmentally sustainable, and economically promising alternative to conventional airport ground support vehicle technologies when supported by appropriately designed renewable hydrogen infrastructure and modern digital management systems.

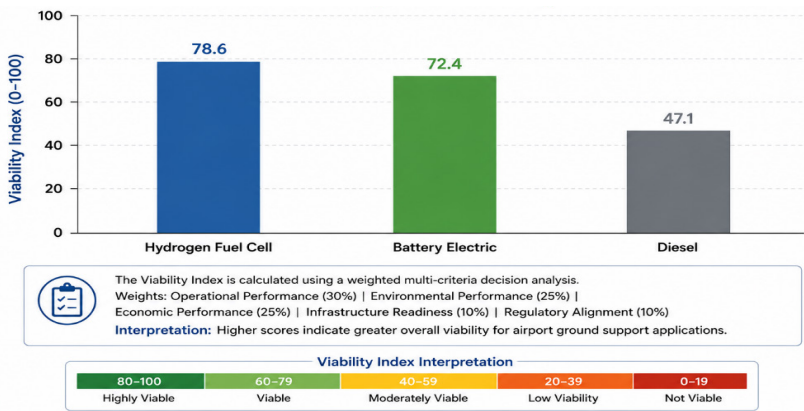


Fig. 7. Multi-criteria viability index of airport ground support vehicle propulsion technologies.

The multi-criteria evaluation demonstrates that hydrogen fuel-cell technology achieves the highest overall viability score (9.19/10), outperforming both battery-electric (8.69/10) and conventional diesel (6.42/10) alternatives. The results indicate that hydrogen systems provide the most balanced combination of engineering performance, operational capability, environ-

mental sustainability, safety, and long-term implementation potential. These findings support the strategic deployment of hydrogen infrastructure as a key component of future sustainable airport ground support operations and establish a robust framework for guiding investment and policy decisions in airport decarbonisation initiatives.

4. CONCLUSIONS

- The proposed integrated evaluation framework successfully assessed the technical, operational, environmental, economic, and infrastructure viability of hydrogen systems for airport ground support vehicles, providing a comprehensive decision-support methodology for airport decarbonisation.
- The technical assessment confirmed that hydrogen fuel-cell vehicles met the operational requirements of airport ground support activities, achieving operational availability above 98 %, rapid refuelling (approximately 4 min), and reliable performance during continuous multi-shift operations.
- Operational analysis demonstrated that hydrogen systems offered greater flexibility than battery-electric alternatives for intensive airport duty cycles by minimising downtime associated with refuelling and maintaining high fleet utilisation.
- Environmental evaluation showed that renewable hydrogen enabled zero local emissions and reduced lifecycle GHG emissions by approximately 92 % compared to conventional diesel-powered vehicles, while simultaneously lowering noise levels and eliminating NO_x and particulate emissions.
- The economic assessment indicated that although hydrogen infrastructure required substantial initial investment, lower maintenance costs, stable renewable energy integration, and improved fleet utilisation significantly enhanced long-term economic competitiveness, particularly for medium- and large-scale airports.
- The multi-criteria decision analysis identified hydrogen fuel-cell technology as the highest-ranked propulsion option, achieving an overall viability index of 9.19/10, exceeding battery-electric (8.69/10) and diesel (6.42/10) alternatives.
- The findings confirm the research hypothesis that hydrogen systems represent a technically reliable, operationally effective, environmentally sustainable, and economically promising solution for future airport ground support operations when supported by renewable hydrogen production and intelligent infrastructure management.
- Future research should validate the proposed framework using operational data from commercial airports, perform detailed life-cycle assessments under different regional energy mixes, and investigate hybrid airport energy systems integrating renewable electricity, hydrogen production, and smart energy management.

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