

Decarbonizing Aviation Ground Operations: Alternative Bus Technologies

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Executive summary

Total cost of ownership analysis is a pragmatic tool to empower airports to advance strategic decisions on net-zero ground operations.

This paper explores the techno-economic feasibility of replacing fossil-fuelled airport buses with alternative low-emission technologies such as retrofitted diesel-to-electric, battery-electric and hydrogen buses. The aim is to provide actionable insights for airports seeking to decarbonize ground operations and improve local air quality. Using a robust total cost of ownership (TCO) model – validated through industry research and stakeholder interviews – the analysis explores how capital, operating, maintenance and infrastructure costs affect airport bus operations and their costs. Key findings include:

- Technology assessment: Retrofitted diesel vehicles with electric powertrains present a cost-effective transitional solution that enables rapid emissions reduction without the need to procure an entire fleet of battery-electric buses. Battery-electric buses offer zero tailpipe emissions and are increasingly cost-competitive over their life cycle, especially where airport routes are predictable and charging infrastructure can be efficiently deployed and operated alongside flight schedules. Hydrogen buses (using fuel cell batteries or internal combustion engines (ICE)) provide greater range and faster refuelling, making them suitable for larger airports with intensive duty cycles, though they currently face higher upfront and infrastructure costs.
- TCO: The analysis, based on a reference European hub airport, reveals that retrofitted electric buses can offer the lowest TCO per kilometre (km), making them attractive for operators with budget constraints compared to newer diesel fleets. New battery-electric buses require higher upfront investment but can deliver lower operating costs over time, particularly when supported by government incentives. Hydrogen buses, while operationally flexible, are probably the most expensive option at present due to technology and infrastructure costs.

- Operational and strategic considerations: The choice of technology depends on each airport's operational profile, financial capacity and long-term sustainability goals. Sensitivity analysis highlights that driver salaries, utilization rates and the availability of subsidies are the parameters that affect TCO the most.

While further research is recommended to assess more detailed airport load profiling, battery degradation modelling and real-world retrofit performance data, pragmatic recommendations for airports include:

- Adopting common electric vehicle (EV) charging and hydrogen refuelling standards to streamline infrastructure deployment and interoperability, including between ground equipment and future aircraft.
- Integrating renewable energy sources to power electric fleets and reduce life-cycle emissions, and renewable transport fuels where reliance on non-electric powertrains is envisaged.
- Exploring second-life battery applications to maximize asset value, circularity and sustainability.
- Leveraging public-private partnerships and green bonds to finance large-scale fleet transitions.
- Enhancing collaboration among airports, operators and energy providers to share best practices and accelerate innovation.

The paper concludes that decarbonizing bus operations is both technically feasible and economically advantageous, positioning airports as enablers in the broader energy transition of the aviation industry. By adopting a tailored, evidence-based approach, airports can also enhance operational efficiency while contributing meaningfully to the aviation industry's net-zero journey.

Introduction

The aviation industry is committed to achieving net-zero emissions by 2050, with every actor – airlines, airports, ground handling companies and passengers – playing a critical role in this transition. As global air passenger numbers are projected to grow at a compounded annual growth rate (CAGR) of 3.6%, by 2050,¹ airports worldwide will expand rapidly, especially in emerging markets. Major projects such as the Al Maktoum International Airport in Dubai, King Salman International Airport in Saudi Arabia and Istanbul airport in Türkiye are set to accommodate hundreds of millions of new passengers annually, while new terminals and expansions in Asia and Europe further underscore this growth.

This surge in passenger demand is driving significant airport infrastructure investment, including the transformation of ground operations. Promising technologies for flight operations – such as sustainable aviation fuels (SAF) and novel propulsion aircraft (hydrogen and battery-electric) – are advancing quickly, requiring parallel upgrades in airport infrastructure. While these technologies primarily address Scope 3 emissions (which typically account for over 90% of an airport's emissions profile), there is also a growing focus on reducing Scope 1 and Scope 2 emissions from buildings, vehicles and ground operations. Trialling on-the-ground decarbonization initiatives can also pave the way for battery-electric and hydrogen aviation, offering a practical means to test, adapt and build familiarity with the technologies that may eventually power aircraft.

Airports serve as strategic nexuses not only for aviation but also for the industries and communities around them. Infrastructure changes

required for decarbonization may benefit a wider set of stakeholders, making airport master planning increasingly important for both aviation and potential future off-takers who could leverage the airport's energy transition. This broader approach can strengthen the business case for infrastructure upgrades.

This paper provides a practical tool for airports at this transition point, focusing on a key use case: airport bus operations. Converting bus fleets is a tangible and impactful way to reduce Scope 1 emissions, with many airports already piloting or transitioning to new power trains. The airport bus market itself is undergoing rapid transformation; valued at \$15.12 billion in 2024, it is projected to grow at a CAGR of 11.6% to reach \$44.35 billion by 2033. Europe is expected to account for over 37.8% of this market, driven by stringent environmental regulations and strong government support for electric and hybrid buses.

The analysis in this paper covers the main technology options for airport buses that could reduce or eliminate tailpipe emissions: retrofitted diesel buses, battery-electric buses and hydrogen fuel cell buses. It compares the TCO and technical feasibility of each option, while recognizing that different airport archetypes, geographies, operations and ownership models will ultimately affect the feasibility and costs of new technology deployment. Other technologies, such as hydrogen internal combustion engines (ICE), fossil fuel-biofuel blends and natural gas or biomethane buses, are not included in the quantitative analysis but are considered qualitatively in the technology alternatives discussion.

1

Operating buses at airports

Airport bus operations are influenced by several factors including airport size, the number of remote stands that require passengers to be transported between terminals and aircraft, airport business model, the number of travellers transferring between terminals and the number of staff movements.

In very congested international hubs, terminal expansions may have extended outside the original

airport boundaries, requiring airports to operate longer routes.

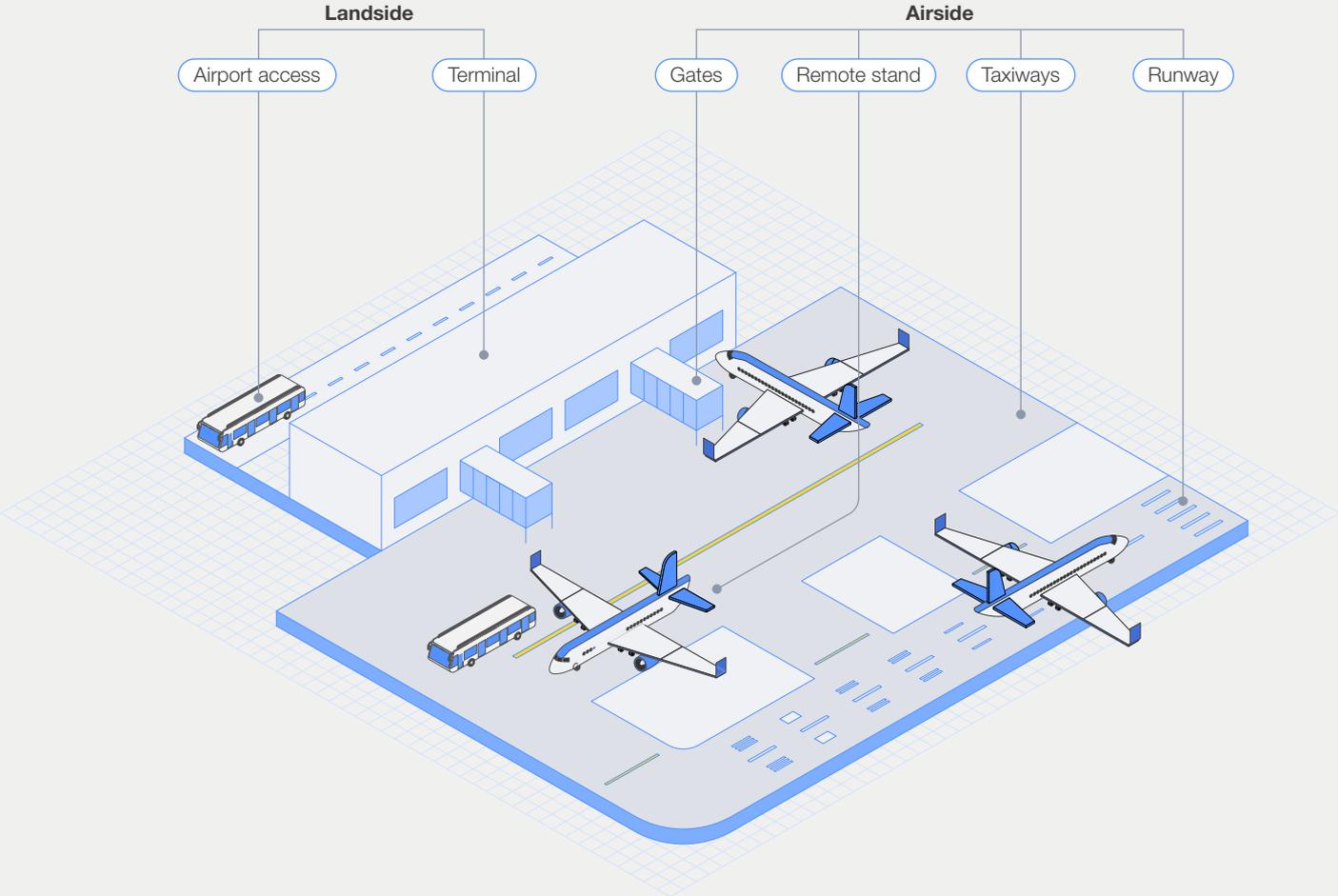
All these factors affect the distance travelled and utilization rate of the buses (typically known as duty cycle), their lifetime, maintenance costs and ultimately their salvage value (the residual value of a bus when retired from service). This study considers these elements to better understand the TCO of alternative propulsion technologies.

1.1 Operating profile

Airport bus operations can be categorized into two main groups: airside and landside, each serving a

distinct function within the airport ecosystem (see Figure 1).

FIGURE 1 Landside and airside buses operations



Landside buses operate outside the security perimeter and are primarily responsible for transporting passengers, staff and occasionally crew between airport terminals, car parks, public transport hubs and other non-restricted areas. These services are integral to ensuring smooth access and connectivity across airport infrastructure for arriving and departing passengers.

Conversely, airside buses function within the secure area of the airport, facilitating the transfer of passengers, crew and ground staff between terminal buildings and aircraft stands. Given the necessity to synchronize precisely with aircraft turnaround times and boarding procedures, airside bus operations are subject to stringent safety and operational requirements.

The configuration and complexity of both airside and landside operations vary significantly with the airport's operational profile. This affects the number of buses operating at airports. For instance, in large hub airports with multiple terminals, high passenger volumes can require extensive landside bus networks to manage inter-terminal traffic and ensure

efficient passenger flow. An example is Dubai International Airport (DXB), which served more than 92 million passengers in 2024;² its 200-strong airside bus fleet transferred over 16,000 passengers per month on average.³

In contrast, intermediate and regional airports may rely on more modest bus fleets, typically ranging between 10 and 20 units. However, these regional airports are usually constrained by gate infrastructure and may host high volumes of low-cost carrier traffic that often prefers bus-to-stand operations, to maximize rapid aircraft turnaround and cost-efficiency over the use of gates, which can be more limited and expensive to operate.

Operating hours at airports, often dictated by legislative restrictions, also impact bus operations. Airports with 24-hour schedules require continuous bus availability and maintenance. On the other hand, airports under night-operating restrictions may plan their activities in a different manner. These restrictions affect maintenance costs, bus lifespans, staffing needs and refuel scheduling.

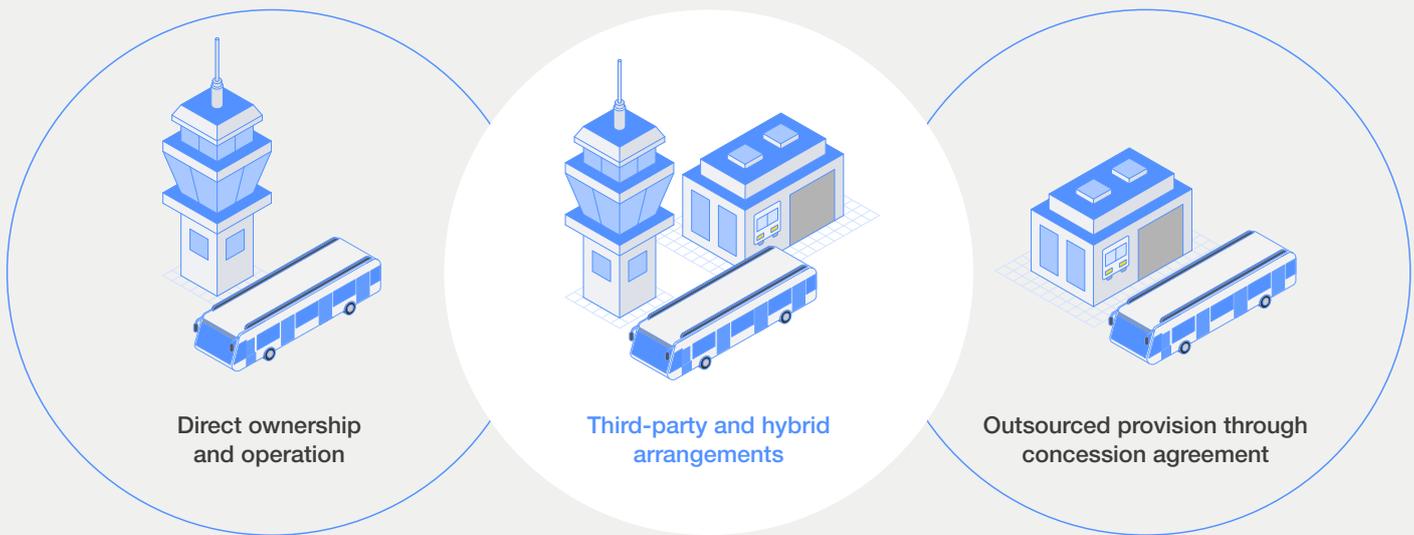


1.2 Bus fleet ownership models

Airport ownership is a factor to consider for preparing a decarbonization strategy and accessing funding sources. Ownership models (private or state) may vary depending on region.⁴ Approaches to decarbonization can differ depending on the ownership model: government-funded airports often operate within the framework of national or regional policies, whereas privately owned airports may have greater flexibility to define strategies according to their operational or market context.

Airports' path to emissions-free bus operations could be significantly influenced by the underlying business strategies that emerge from different airport ownership models, but also from the bus ownership models directly. At a fundamental level, three dominant categories prevail (see Figure 2): direct ownership of bus fleet and operation by the airport authority; outsourced provision through concession agreements; and third-party contracts and hybrid approaches combining both.

FIGURE 2 | Bus operations' ownership models existing at airports



Probably the less common of the models is when the airport authority – often a public entity or vertically integrated airport operator – fully owns the bus fleet and directly manages all related operations. While this approach allows for high levels of operational control and strategic alignment with broader objectives such as decarbonization, it frequently leads to a higher rate of capital expenditure, alongside long-term financial and operational commitments.

Airports more commonly employ a concession-based model for bus services, wherein private contractors may be granted exclusive rights to operate bus fleets for a defined period in exchange for a fee and may be required to comply with certain fleet requirements, sustainability criteria and performance guarantees. Pragmatically, this system allows airports to incorporate bus services into broader ground handling contracts, where operators are responsible for a range of ramp, baggage and passenger transportation services under a unified framework.

In addition, airline business models at the airport directly impact bus services and contracts. In the negotiating mix among service providers, airlines and airports, the latter often maintain decision-making over the infrastructure needed for enabling ground operations, as well as the energy consumption and demand associated with this. This creates potential avenues for the airport to influence investment in greening bus fleets (undertaken by third parties) through investment in green infrastructure, such as electric charging stations, or through local emissions and air quality standards.

Lastly, hybrid models are increasingly common, especially in large or multi-terminal airports where different operational needs coexist. Under this approach, the airport may retain direct control over strategically critical services, while outsourcing landside or non-core services to external providers. This configuration allows airports to maintain control over certain aspects of operations such as safety, security or integration, while benefiting from the efficiency and scalability of outsourced services in less “sensitive” areas. This model ultimately requires well-defined governance structures and performance monitoring mechanisms to ensure coherence across service providers.

The influence of airlines in bus operations

The business models of the airlines served by the airport also have a direct bearing on bus operations and contractual arrangements. Low-cost carriers (LCCs), for example, often prioritize fast turnaround times and minimal ground service fees, influencing the design of bus operations towards high-frequency, low-cost solutions that maximize aircraft utilization. LCCs frequently utilize remote stands to reduce airport charges, thereby increasing reliance on airside buses. Consequently, ground handling contracts that include bus operations must be calibrated to align with the cost sensitivities and operational rhythms of these carriers.

In contrast, legacy airlines may demand tighter integration with lounge and gate infrastructure. All these factors affect bus service coordination between airlines, airport and ground service providers. Therefore, airports serving a diverse airline mix may adopt hybrid ownership and operating models that can accommodate varying service expectations and turnaround profiles.

Regional regulations impacting the ownership model

In some cases, regulatory frameworks largely determine the model adopted. In Europe, for instance, the European Ground Handling Directive⁵ plays a critical role in shaping market access and service provision models. The directive mandates the liberalization of ground handling services, allowing multiple service providers to compete in eligible commercial airports – in this case, those with annual traffic exceeding 2 million passengers or 50,000 tonnes of freight. This has led to increased outsourcing, greater price competition

and a need for airports to establish robust oversight mechanisms to ensure safety, quality and interoperability across competing providers. As a result, procurement processes have become more structured, often requiring competitive tenders, multi-year service-level agreements and detailed performance metrics. Ultimately, all these factors may become barriers if an airport is willing to change the infrastructure needed for changing the bus fleet.

In sum, the business and ownership models of airport bus fleets are neither static nor one-size-fits-all. They reflect a complex interplay of operational configurations, commercial imperatives and regulatory constraints. As airports intensify efforts to reduce their environmental footprint, these models must be carefully assessed and leveraged to pursue the path of least resistance to meaningful progress in sustainability. When fleet decarbonization is elevated to a strategic priority, public-private partnerships and the shift from asset-based ownership to service-oriented mobility contracts increasingly come to the fore – a development further examined in Chapter 4.



Airport bus solutions: Technology overview and developments

Ground transport – particularly bus fleets – has become a key focus for airports seeking to reduce operational emissions and advance sustainability goals. Rapid technology developments are driving a reassessment of fleet strategies and the adoption of innovative solutions.

This chapter provides an overview of the main technological pathways considered for the TCO analysis that are shaping the future of airport bus operations, including battery-electric, hydrogen

fuel cell and retrofitted diesel vehicles with battery-electric powertrain. Renewable biofuel (hydrotreated vegetable oil, or HVO) and biomethane buses, although not considered in the TCO model, have also been assessed. By examining the operational characteristics, infrastructure requirements and decarbonization potential of each option, this chapter aims to equip decision-makers with the insights needed to navigate the complex landscape of technology options and align investments with both immediate needs and long-term climate objectives.

2.1 Technology options

The decarbonization of airport bus fleets is increasingly shaped by three primary technologies: battery-electric, hydrogen fuel cell and retrofitted diesel.

Each option offers distinct operational characteristics and infrastructure requirements, making its suitability dependent on the specific operational context of the airport. While their shared objective is the reduction of greenhouse gas emissions and local pollutants, the underlying technologies differ significantly in energy storage, refuelling or recharging methods, and performance profiles.

Understanding the core features of each technology and weighing it with financial considerations can enable decision-makers to achieve a full techno-economic picture guiding strategic investment.

Electric buses

Battery-electric buses draw propulsion energy from high-capacity lithium-ion or, in emerging cases, solid-state batteries, offering zero tailpipe emissions and high energy efficiency.

Their primary advantage is the relative maturity of the technology thanks to the rise of EVs in the automotive industry, and the rapidly expanding supply chain, which has driven down procurement costs and improved performance. Electric buses

are particularly well-suited to airports with compact layouts, predictable routes and scheduled breaks that align with charging opportunities. Overnight depot charging is often sufficient for landside shuttle services, while high-power opportunity charging can support airside operations with higher duty cycles.

However, battery-electric technology is not without limitations. Range and battery lifetime can be affected by ambient temperature, heavy passenger loads and continuous use of auxiliary systems, with performance degradation more pronounced in extreme cold or heat. Charging infrastructure requires careful integration with airport power systems to avoid grid strain, potentially necessitating upgrades to accommodate the rising energy demands, or the deployment of energy storage solutions at airports. In addition, strategies for end-of-life battery management and disposal remain a critical consideration; some airports are already adopting “second-life” applications,⁶ repurposing retired batteries for stationary storage, which can help mitigate environmental and logistical challenges if properly implemented.

Airports implementing electric buses must consider the operational fit, route length, fleet size and the ability to coordinate charging with operational peaks. Electric buses have seen rapid adoption, especially in European airports such as Aeroporti di Roma, where renewable energy powers 11 fully-electric shuttle buses,⁷ or London Gatwick,⁸ which will entirely replace its 14-bus fleet with fully electric buses.



Hydrogen

Hydrogen fuel cell buses convert gaseous hydrogen into electricity through an electrochemical reaction, emitting only water vapour from the tailpipe, which can be collected for later use. One of their principal advantages lies in operational autonomy: hydrogen vehicles typically achieve ranges of 350 to 500 km on a single refuelling, which is particularly advantageous in large airports with extended apron networks (where buses are specialized vehicles used to transport passengers between terminals and aircraft) or where buses operate on multi-shift cycles with minimal downtime.

Moreover, hydrogen systems can deliver consistent power output regardless of ambient temperature, allowing auxiliary systems such as air conditioning or cabin heating to operate without significantly compromising range – an important consideration in airports located in extreme climates or where passenger comfort requirements are stringent. Refuelling is rapid, often under 15 minutes, enabling high vehicle availability and reducing the need for large spare fleets.

Operationally, hydrogen buses are particularly suited to airside use cases where flexibility, long duty cycles and reduced turnaround times are critical, and where land availability allows for the installation of a dedicated hydrogen refuelling facility. For instance, Greater Toronto Airports Authority's plan for hydrogen bus adoption is strongly linked with the airport's wider ecosystem,⁹ benefiting from the installation of a hydrogen refuelling station outside of airport boundaries for light and heavy-duty vehicles.

Retrofitted buses

Retrofitted diesel buses offer a transitional decarbonization pathway by replacing the internal combustion engine and associated components with alternative powertrain solutions – most commonly full battery-electric, but potentially also hydrogen ICE, or hybrid systems that combine combustion and electric drivetrains (including plug-in variants). For the purposes of this analysis, however, only the conversion from diesel to full battery-electric is examined in detail.

This intermediate solution is particularly interesting for airports with a relatively new bus fleet (fossil-fuel or biofuel based). This allows them to extend the operational life of their fleets while achieving substantial reduction in tailpipe emissions, avoiding the capital cost of procuring entirely new vehicles (a retrofitted bus could cost significantly less than the price of a brand-new electric one). From a technical standpoint, retrofitting can be completed in a fraction of the time required for full fleet replacement, and it enables the reuse of bus bodies and chassis and leaves the interiors in serviceable condition. The main opportunities lie in legacy fleet decarbonization where budget constraints, long procurement cycles or sustainability targets demand rapid emissions reduction.

However, retrofitting presents challenges: the diversity of existing fleet specifications can complicate conversion processes, certification requirements may vary by jurisdiction, and maintenance teams could require retraining to manage the new systems.

Additionally, airports considering this as a solution may double-check if, after the retrofit, the bus fleet would achieve the same efficiency, range and reliability compared to purpose-built zero-emission vehicles, particularly in demanding airside environments.

Geneva Airport¹⁰ illustrates the potential of this approach: in 2024 it invested in two retrofitted buses at an average cost of CHF 350,000 each, with four more to be delivered in 2025. Together with other fleet measures, this brings the airport to 24 electric buses in a total of 27, showing how retrofitting can provide a cost-efficient bridge while infrastructure for next-generation technologies is developed.

Fossil-fuel and biofuel-mix buses

HVO buses represent a growing trend in airport ground transport decarbonization strategies. HVO is a renewable diesel alternative produced from vegetable oils or waste fats, offering a significant reduction in life-cycle carbon emissions – up to 90% compared to conventional diesel. These fuels are in most cases compatible with existing diesel engines and fuelling infrastructure, making them a practical and immediate solution for airports¹¹ seeking to lower their operational emissions without extensive new infrastructure investments.

From an infrastructure perspective, HVO's compatibility with existing diesel fuelling systems means that airports can transition their fleets with minimal operational disruption or capital expenditure. This contrasts with the previously analysed scenarios. As such, HVO serves as a valuable bridge technology, supporting airports' decarbonization goals in the near term and complementing the broader shift towards SAF and zero-emission ground transport.

While this paper has focused on zero-emission technologies such as battery-electric and hydrogen fuel cell, HVO-powered buses have not been included in the core analysis due to their status as a low-carbon, rather than zero-emission, solution. Nevertheless, it is important to acknowledge that HVO buses are being adopted at a growing number of airports as a transitional

technology. These deployments are enabling airports to achieve immediate emissions reduction while longer-term electrification and hydrogen infrastructure are developed.

Biomethane-powered buses

This alternative uses methane produced from biological sources, such as organic waste, sewage sludge or agricultural residues, which is used as a drop-in replacement for compressed or liquefied natural gas in standard gas engines or hybrid systems. It enables airports and transit operators to decarbonize their fleets without completely replacing existing vehicles or refuelling infrastructure. Biomethane buses have quick refuelling times, long operational ranges and significantly lower particulate and nitrogen oxide emissions compared with diesel. When the biomethane is sourced from waste streams, the overall greenhouse gas balance can approach carbon neutrality.

The Munich Airport's biomethane buses¹² have a range of up to 800 km and refuel in about five minutes. They have reduced particulate emissions by roughly 90% and nitrogen oxides by over 60% compared with Euro VI diesel buses.

Hydrogen internal combustion engine

Hydrogen ICE is another retrofit option under development, showing promise particularly as a bridge between existing diesel engines and zero-emission technologies, since many components (such as ignition, cooling and transmission) are shared with conventional buses.

Projects such as the TRIMIS HyFLEET:CUTE¹³ trials in Berlin have already demonstrated the potential of this approach. While hydrogen ICE has not been included in the present TCO analysis, it is an area worth tracking, and its evolution could be captured in future assessments to provide a more complete picture of available decarbonization pathways.

2.2 Key features comparison

As airports advance on their course towards decarbonization, the choice of bus technology is more than a technical decision – it is shaped by evolving priorities, operational realities and the ambition to create a cleaner future.

Across all available technologies – diesel, retrofit diesel, battery electric and hydrogen fuel cell –

the decision to adopt one pathway over another requires a careful analysis of each airport's unique operational constraints, infrastructure readiness, regulatory environment and TCO. Figure 3 represents how these options compare in terms of climate impact, investment, ongoing costs and operational fit.

FIGURE 3 | Cross-technology comparison of buses based on climate impact, operating costs, investments and airport operations

Category	Criterion	Diesel	Retrofit	Electric	Hydrogen
Climate impact					
	CO ₂ emissions during operation	High	Zero	Zero	Zero
	Energy consumption	High	Medium-High	Medium-High	Medium
	Fuel/Energy source	Diesel	Electricity	Electricity	Gaseous hydrogen
Upfront cost and investment					
	Airport bus market availability	Global, >15 OEMs*	Growing, ~10 OEMs and retrofit specialists	>10 OEMs, expanding rapidly	~5 OEMs, limited models, pilot projects
	Infrastructure requirements	Diesel stations	Charging stations	Charging stations	Gaseous hydrogen station
	Technology maturity	High	Medium	Medium	Low
Ongoing operating costs					
	Maintenance requirements	High	Medium	Low	Medium
	Expected service lifetime	15-20 years	10-15 years (battery replacement required)	12-18 years (battery replacement required)	12-18 years
Ongoing operating costs					
	Airport planning implications	Minimum	Grid upgrade	Grid upgrade	Hydrogen ecosystem
	Operational range	Long	Medium	Medium	Long
	Refuelling/Charging time	Short (minutes)	Short/Medium Fast charging <25 min Overnight charging 3-4 hours	Short/Medium Fast charging <25 min Overnight charging 3-4 hours	Short (~10 min)
	Driver/User acceptance	Medium	Medium	High (training needed)	High (training needed)

Note: *OEMs: Original equipment manufacturers

Climate impact

The environmental story of airport buses begins with diesel, a technology that has reliably powered fleets for decades but now stands as the benchmark for emissions and energy consumption. Diesel buses, while robust and familiar, are the primary ground transport contributor to greenhouse gas emissions and local air pollution at airports. Retrofitting these vehicles with electric powertrains offers a meaningful step forward – reducing emissions and energy use.

The real transformation comes with battery electric and hydrogen fuel cell buses. Both technologies promise zero emissions at the point of use, fundamentally changing the airport’s environmental footprint. Battery electric buses can reduce greenhouse gases and local pollutants dramatically, especially when powered by renewable electricity. Hydrogen buses also offer clean operation, emitting only water vapour, but their broader climate benefit depends on how the hydrogen is produced. If sourced from renewables, the impact is profound; if not, some of the environmental gains are offset,

highlighting that the climate impact is not just about the bus fleet itself, but about the energy ecosystem that supports it.

Upfront costs and investment

When looking at their upfront costs, diesel buses remain the most accessible and affordable option for many operators. Their widespread availability and mature supply chains keep purchase prices low. Retrofitting diesel buses offers a pragmatic alternative for airports with newer fleets, enabling emissions reduction at a lower cost than purchasing new vehicles. While often presented as costing around half the price of a new bus, actual expenses can vary significantly depending on the age and condition of the base vehicle. Older units typically require extensive refurbishment – replacing major components and sometimes refitting interiors. Additional logistical expenses, such as transporting buses to specialized refurbishment centres, add further to the investment. Moreover, the retrofit market, though expanding, remains less standardized than that for new electric buses.

Battery electric buses represent a new era of investment. The vehicles themselves are more expensive than diesel ones, and the need for charging stations – and related significant upgrades to airport electrical systems, including grid upgrades and battery storage systems – can make the initial outlay substantial. Yet, as the market matures and more manufacturers enter the space, costs are gradually coming down and the long-term value proposition is improving.

Hydrogen buses, meanwhile, are at the frontier of innovation. Their high purchase price and the need for specialized, often bespoke, fuelling infrastructure make them the most capital-intensive option. For airports considering hydrogen, the decision is as much about future readiness and ecosystem development as it is about immediate cost.

Ongoing operating costs

Diesel buses, while cheap to buy, can be more expensive to run than other options. Fluctuating fuel prices and the maintenance demands of combustion engines add up over time. Retrofitted buses can offer some relief, with newer components reducing maintenance needs, but they still face the dual costs of diesel and electricity, especially when airports choose to have both systems coexist for a while.

Battery electric buses, by contrast, shine in terms of ongoing cost efficiency. Electricity is generally less expensive and more stable in price than diesel, and the simplicity of electric drivetrains can mean fewer breakdowns and lower maintenance bills. Over the lifespan of the vehicle, these savings can be significant, helping to offset the higher upfront investment. Hydrogen fuel cell buses also benefit from reduced mechanical complexity, but the cost and availability of hydrogen fuel remain barriers. As the technology matures and the hydrogen supply chain grows, these costs may fall, but for now, they are a key consideration.

Airport operations

Diesel buses are easy to refuel and maintain, and well-suited to established operational routines. Retrofitted buses fit comfortably into this pattern, requiring only modest adjustments to accommodate charging. Still, the need to remove vehicles from service for conversion and the logistics of refurbishment can create temporary capacity gaps that airports must plan for.

Battery electric buses introduce new dynamics. Charging schedules must be carefully managed to ensure vehicles are ready when needed, and route planning may need to adapt to range limitations, especially in airports with demanding duty cycles.

However, electric buses are quieter and cleaner, enhancing the passenger and staff experience and reducing the airport's environmental footprint.

Hydrogen buses offer the promise of long range and rapid refuelling, combining the operational flexibility of diesel with the environmental benefits of electric. While the lack of widespread hydrogen infrastructure remains a challenge, the introduction of hydrogen also requires tailored training and safety protocols – comparable to the adjustments already made for other fuels such as electricity, diesel, propane or natural gas. Airports investing in hydrogen are already demonstrating that it can be deployed safely and reliably, with affordability expected to improve as adoption scales.

Beyond these day-to-day operational factors, the transition to battery-electric and hydrogen buses introduces a new layer of complexity and uncertainty for airport operators. An industry taskforce led by Airports Council International (ACI) World¹⁴ suggests several steps to tackle these, including:

A comprehensive aerodrome compatibility study before operations can begin, ensuring that infrastructure, safety and operational procedures are fit for purpose – not only for buses, but also in anticipation of future hydrogen or electric aircraft.

Security and fire safety, as both battery and hydrogen vehicles present unique risks. Battery fires can be prolonged and emit toxic fumes, while hydrogen, though clean burning, demands specialized detection and response protocols.

Airports must also **plan for significantly increased electrical power demand**, as stands will need to support simultaneous charging of buses and, eventually, aircraft – potentially necessitating major upgrades to energy infrastructure.

The introduction of new fuel types may require **segregated parking stands**, which could reduce stand capacity and complicate ground support equipment logistics.

Furthermore, **operational procedures** such as verifying electrical connections before energizing cables, and reassessing stand design and risk management, become critical to ensure safety and resilience.

Ultimately, while each technology presents a distinct balance of environmental benefits, operational considerations and investment requirements, the decision for any airport will depend on how these factors translate into long-term value. To provide a clearer basis for comparison and support evidence-based decision-making, the next section delves into the total cost of ownership (TCO) analysis – outlining the methodology, key assumptions and resulting insights that underpin a comprehensive evaluation of each pathway's financial and operational implications over the full life cycle of the fleet.

3

Total cost of ownership (TCO) analysis

The TCO analysis presented in this paper evaluates the high-level economic implications of adopting different sustainable bus technologies in the airport environment, considering both capital expenditure (capex) and operational expenditure (opex) across the expected service life of the vehicles.

Capex includes the upfront costs associated with vehicle procurement, installation of supporting

infrastructure, and any necessary modifications to existing facilities, such as maintenance depots or fuelling stations. Opex covers the recurrent costs incurred during operation, including fuel or electricity supply, scheduled and unscheduled maintenance (including battery replacement), staff training, insurance, licensing and other ongoing operational expenses.

3.1 Reference case study and scenarios considered

To ensure a simple comparison between alternative bus technologies, this study has chosen the archetype of a European international hub airport. It has been assumed that a similar airport may operate a 50-airside bus fleet. Leveraging over 20 interviews with Airports of Tomorrow and aviation stakeholders conducted from March to August

2025 and quantitative research, some operational parameters (e.g. bus distance travelled) have been estimated and validated to ensure the analysis can be as representative as possible of potential real-world applications. The full methodology is set out in the appendix.

TABLE 1 Reference case parameters for the European international hub mid-sized airport

Operational parameter	Value	Comment
Fleet size (number of buses)	50	-
Number of drivers (per bus)	3	-
Bus driver salary (€/driver)	36,580	-
Operating hours (hours/day)	18	-
Operational days	365	-
Utilization rate (%/bus)	25	Share of operating time during which bus is carrying passengers
Bus average speed (km/hour)	20	-
Bus distance travel (km/day/bus)	90	Calculated as utilization rate × operating hours × average speed
Bus annual distance travel (km/year)	32,850	-
Investment date (year)	2030	Applicable for all technology options analysed
Project lifetime (years)	15	Assumed lifespan for buses
Weighted average cost of capital (%)	4.56	Based on average for three regulated airports ¹⁵
Corporate borrowing rate (%)	4.10	Based on European Central Bank (2025) data ¹⁶
Banking department amount considered (%)	0	Full investment assumed to be made upfront

Operational details are harmonized, and all of these have been kept fixed across all technology scenarios. It is assumed that buses travel at an average speed of 20 km per hour within airport grounds, ensuring realistic energy consumption and maintenance estimates. Buses operate 18 hours a day, but carry passengers only for 25% of the operating hours (utilization rate 25%), every day of the year, with an estimated bus range of 90 km/day. Staffing is standardized, with three drivers per bus per day, each earning a fixed annual salary of €36,580. A 15-year project lifetime is assumed, and financial calculations are thus discounted at a weighted average cost of capital (WACC) rate of 4.56%, aligning with industry norms for infrastructure investments.

In this reference case study, airport bus operations continue to rely on a conventional diesel-powered fleet. This approach requires the least infrastructure investment, as it leverages existing fuelling and maintenance facilities. The capex is primarily allocated to the procurement of diesel buses, while the opex is dominated by fuel costs, driver salaries, warranty and insurance, and maintenance. Market average retail price of diesel is assumed at €1.67 per litre and the unit price per bus is €259,000, with no government subsidies considered.

Taking into account the various technology options, the following scenarios have been developed based on the key criteria that influence decision-making in airport master planning.

Scenario 1

Retrofitted electric fleet

In this scenario, the airport opts to retrofit existing diesel buses with electric drivetrains, offering a transitional pathway towards electrification. The retrofit cost is assumed at 50% of a new electric bus, with maintenance costs 10% higher than those of new electric buses (€0.407 per kilometre). The operational and infrastructure requirements mirror those of the new electric fleet, including charging infrastructure and driver training.

Scenario 2

Electric fleet

This scenario explores the transition to a fully electric bus fleet, requiring significant investment in both vehicles and charging infrastructure. The capital expenditure includes the purchase of electric buses (average price €550,000) and the installation of charging stations, with additional costs for civil engineering, grid updates, electrical installation and design. Operational expenditure covers battery replacement, charging costs, driver salaries, warranty and insurance, maintenance and driver training.

Based on market research, each bus is assumed to have a 386 kilowatt-hour (kWh) battery, providing a usable range of 235 km and a daily charging load of 103.45 kWh. Charging is conducted overnight, with a 3.82-hour average charging time and 95% charger efficiency. Maintenance costs are typically lower than diesel when excluding battery replacement. In this analysis, this battery replacement is assumed to happen in year nine. To reflect potential grant schemes and incentives aimed at supporting low-emission bus deployment, 50% of the capital investment is assumed to be subsidized by the government. This scenario significantly reduces emissions and aligns with long-term sustainability goals, though it requires higher upfront investment and operational adjustments.

Scenario 3

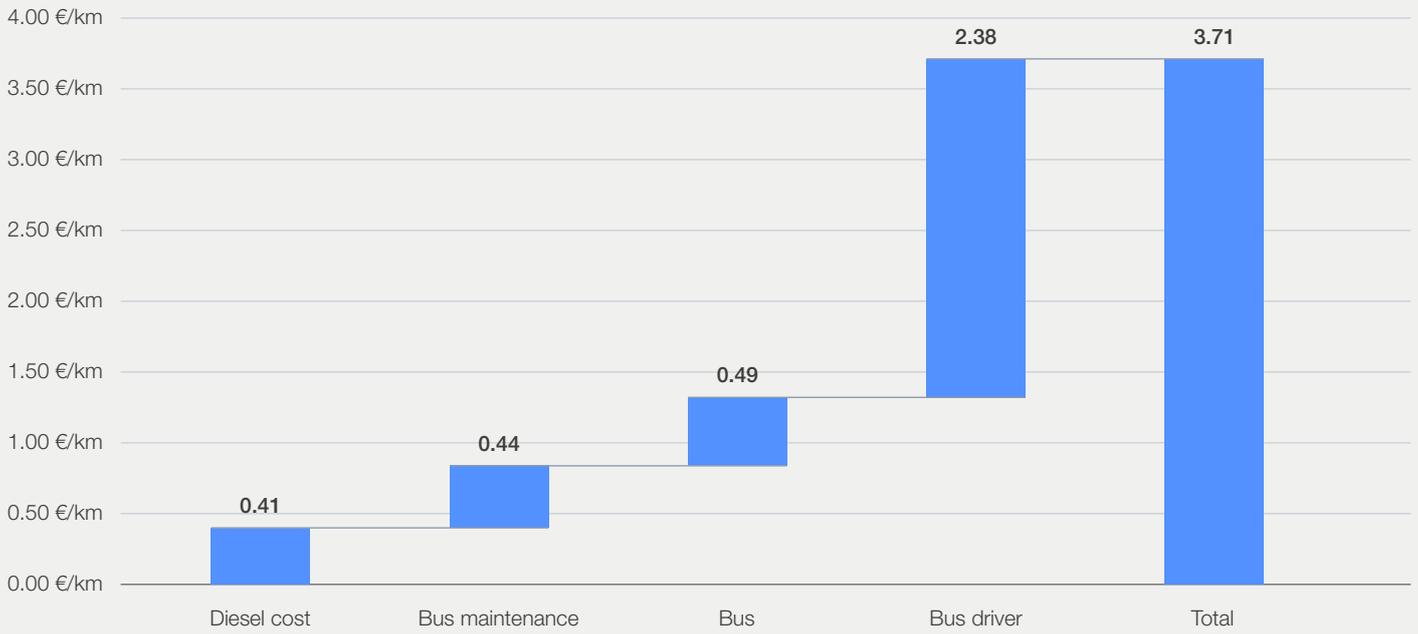
Hydrogen bus fleet – off-site hydrogen production

This scenario considers the deployment of hydrogen-powered buses, with hydrogen supplied from off-site production facilities. The bus fleet operates approximately 4,500 km per day, consuming 428 kilograms (kg) of hydrogen daily, taking average hydrogen bus fuel economy in mind. Each bus is equipped with a 30-80 kg hydrogen tank, offering a range of 200-600 km per refuelling, with refuelling times between 10 and 20 minutes. Based on market research, the average capital cost per bus is €600,000, with a 3.5% annual learning curve and 50% government subsidy on bus capex.

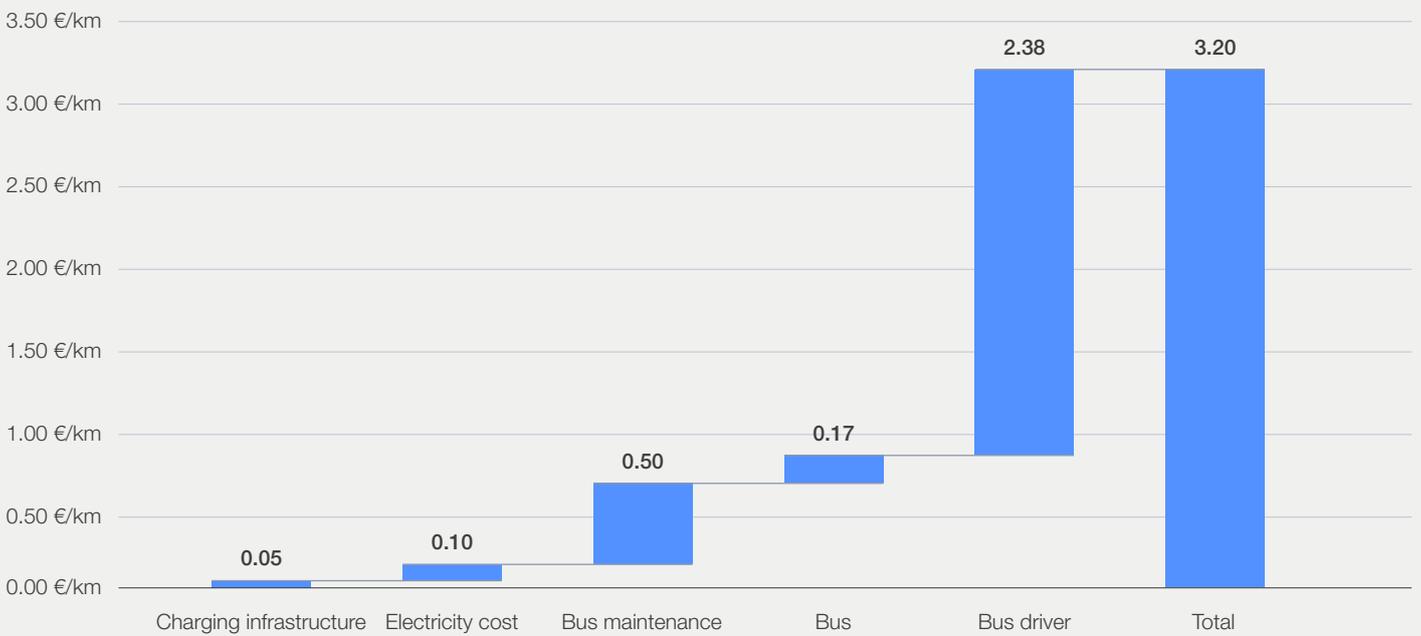
All investments are made upfront, and a dedicated refuelling station is installed at the airport. In line with aviation decarbonization ambitions, the baseline assumption for this scenario is the use of green hydrogen, priced at €2.87/kg. The TCO model can, however, also reflect alternative hydrogen price assumptions (e.g. grey or blue hydrogen), allowing adaptation to different regional contexts and production pathways. This scenario enables rapid refuelling and extended range, supporting operational flexibility.

FIGURE 5 | TCO results for all scenarios, per kilometre

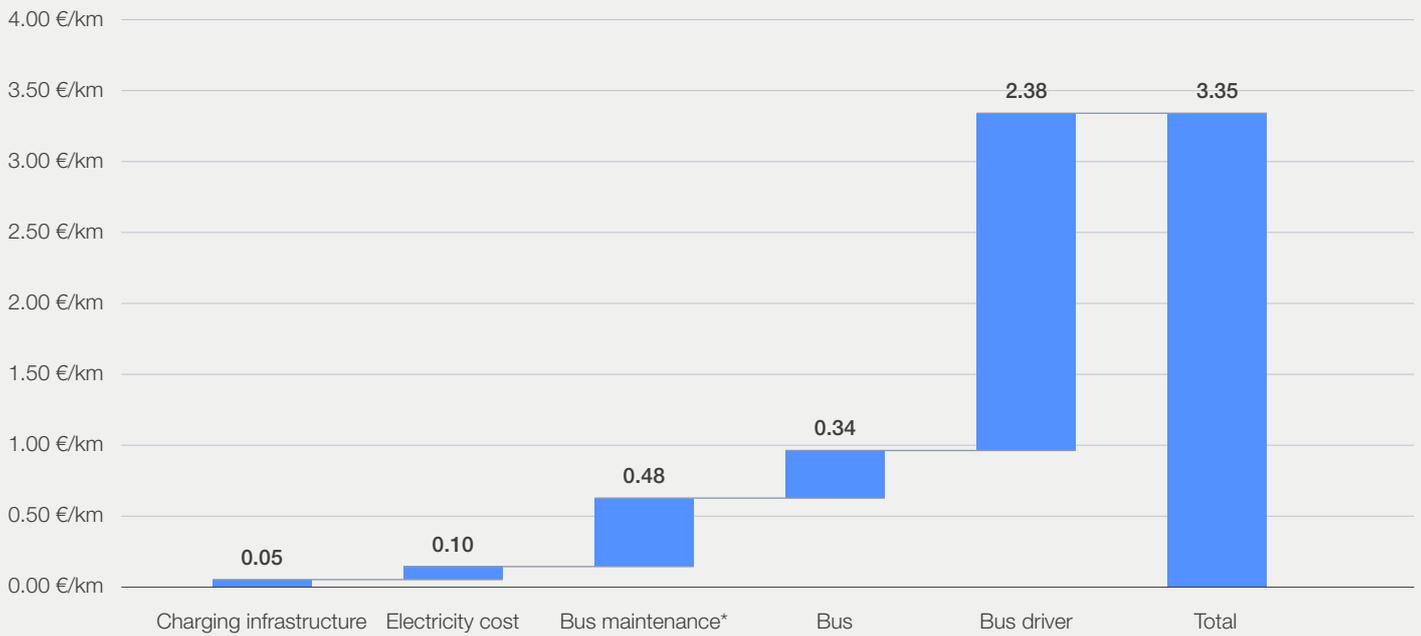
Diesel buses



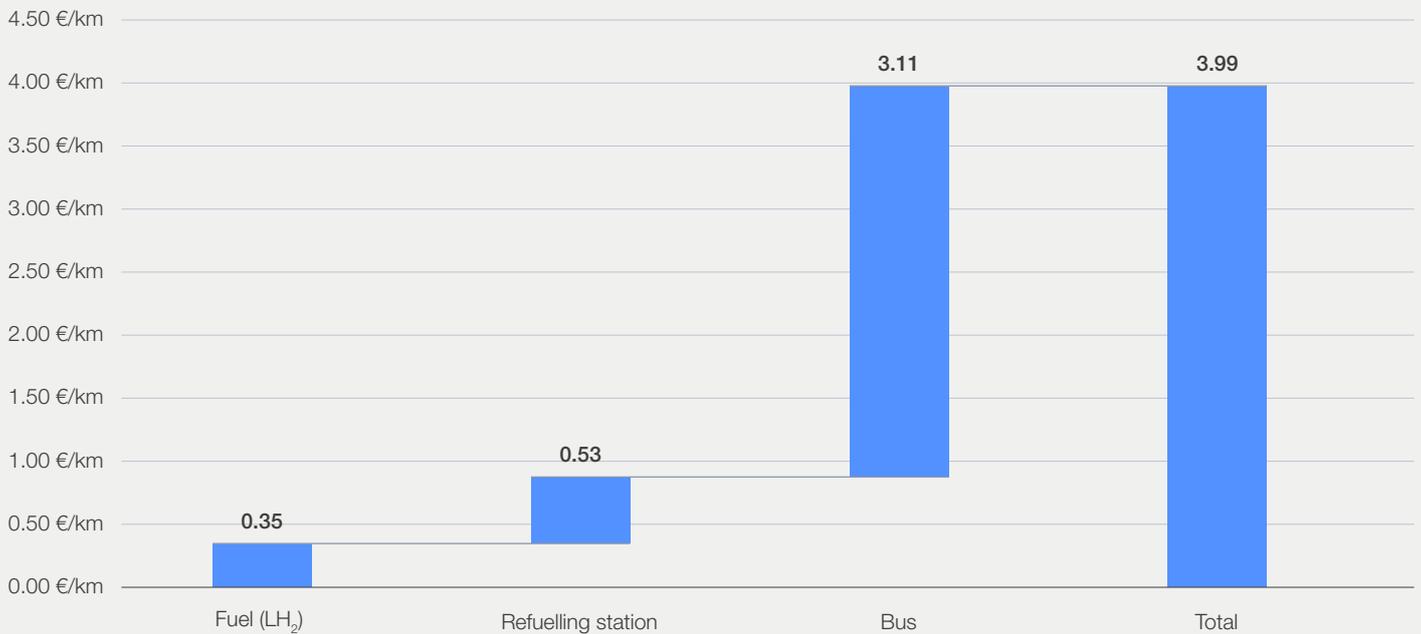
Retrofitted buses



Electric buses



Hydrogen buses



While the initial investment on the conversion of existing diesel buses to electric drivetrains is €5.11 million for retrofitting, the annual operating expenditure is €4.95 million, and a 25% salvage value is assumed.

Retrofitting offers a pragmatic, lower-cost pathway to electrification, with the lowest initial capital outlay among all scenarios (see Figure 6). The retrofit cost is set at 50% of a new electric bus, and 50% of capex is subsidized by government support. The scenario assumes a 2:1 bus-to-charger ratio (each charger supporting two buses) and incorporates a significant battery replacement cost (35% of bus price) around the ninth year. While maintenance costs are slightly higher than for new electric buses, the overall TCO is close to the battery-electric case, and potentially lower when factoring in government incentives, making this scenario particularly attractive for operators seeking to decarbonize with limited budgets and minimal operational disruption. The relatively low electricity and infrastructure costs further enhance the cost-effectiveness of this scenario.

If the boundary conditions and the economic wealth of the airport make it feasible to invest in a new purpose-built electric bus fleet, the initial investment is assumed to be €9.3 million for buses (including approximately €1 million for charging infrastructure, with the remainder allocated to vehicle procurement). Annual operating expenditure is €4.91 million, considering a 25% salvage value at end-of-life (as in the previous case).

While the upfront investment is higher than for retrofitting, the new electric fleet benefits from improved reliability, advanced features and lower maintenance costs.

The electric bus fleet scenario leverages a 3.9% annual learning rate for e-bus costs and a 50% government subsidy on capex, which helps offset the higher initial outlay. Battery replacement is a significant cost in year nine, where the model has assumed that this important maintenance is happening at the same point in time for retrofitted and electric buses, as the maturity of the technology is equivalent. TCO per km (see Figure 5) is slightly higher than in the retrofitted scenario, mainly due to higher capex, but still substantially lower than diesel or hydrogen, when factoring in government grants. The scenario is well-aligned with long-term sustainability and regulatory objectives, offering a balance between operational efficiency and environmental performance.

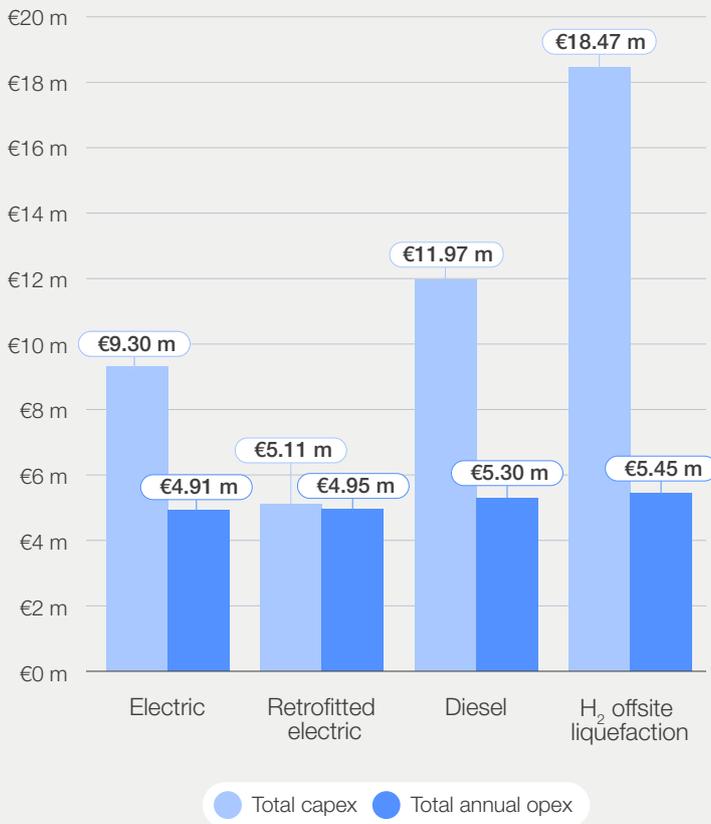
If the technology of choice is hydrogen (supplied from off-site production), this scenario requires the highest initial investment, particularly for vehicles and refuelling infrastructure. The total estimated capex is €18.47 million, split between €12.52 million for bus purchase, and €5.96 million for the refuelling station. Annual opex is €5.45 million, with driver salaries and hydrogen fuel costs as major contributors. While the refuelling station's upfront capex is modest relative to the bus fleet, its opex remains low. The scenario's TCO is driven by high driver costs and the relatively high cost of hydrogen fuel compared to electricity.

However, hydrogen offers operational flexibility and rapid refuelling, which may be advantageous for high-utilization or long-range applications. While the economics remain challenging without cost reduction or policy support, potential revenues from carbon trading mechanisms, such as the European Union's Emissions Trading System (ETS)¹⁷ could strengthen the business case. The availability and treatment of such credits, however, depend on evolving policy frameworks, and may not apply equally to other technologies such as battery-electric buses.

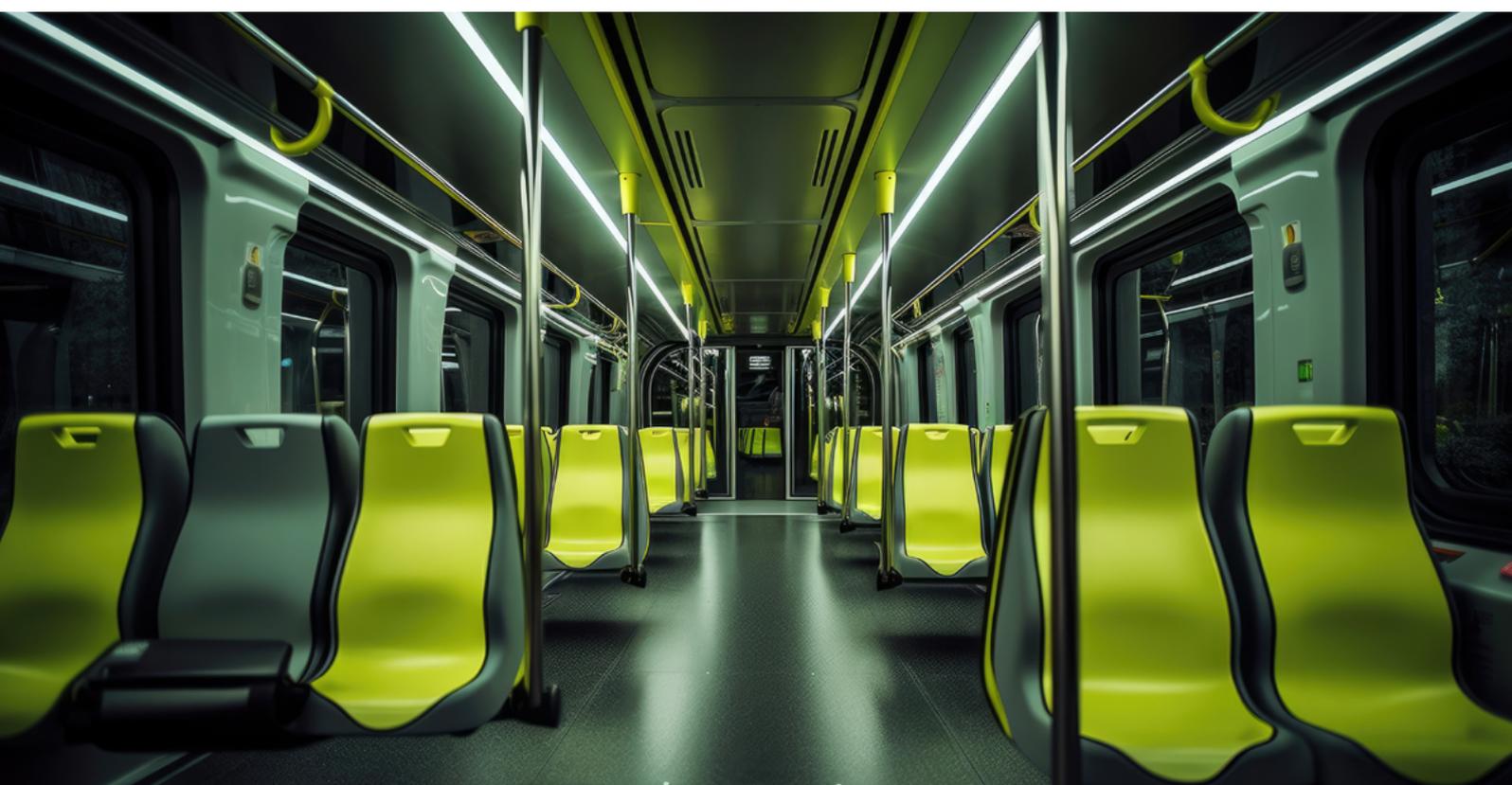
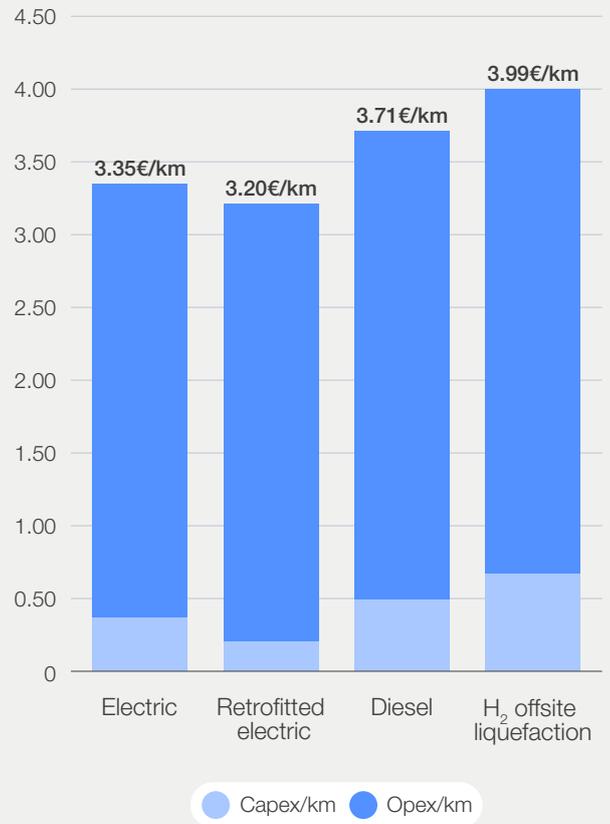


FIGURE 6 | TCO results comparison across technologies divided by capex and opex

TCO results comparison across technologies divided by capex and opex



Total cost of ownership per km



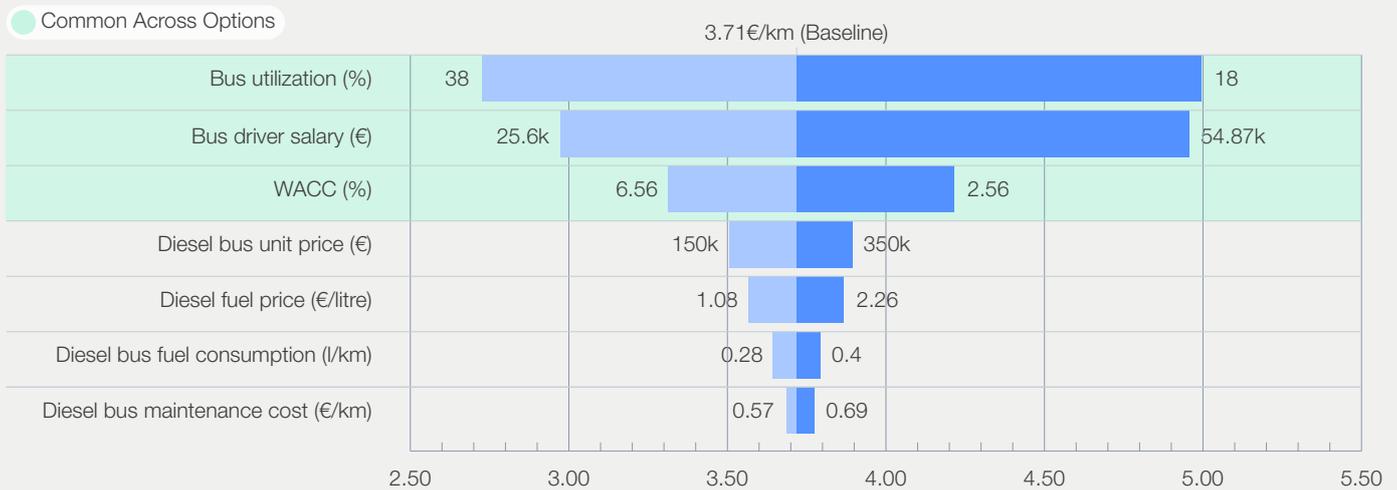
3.3 Sensitivity analysis

To account for uncertainty and variability in existing datapoints, the model assumptions (that could change depending on regional and operational dynamics) and future cost trajectories, a scenario and sensitivity analysis was also undertaken. Geographical factors, market dynamics and operational needs can affect the assumptions used for the analysis, requiring flexibility in the assessment performed. This sensitivity analysis thus aimed to identify the key variables influencing the levelized cost of ownership (LCO, €/km) for each bus technology scenario: diesel, retrofitted, battery electric and hydrogen (see Figure 7).

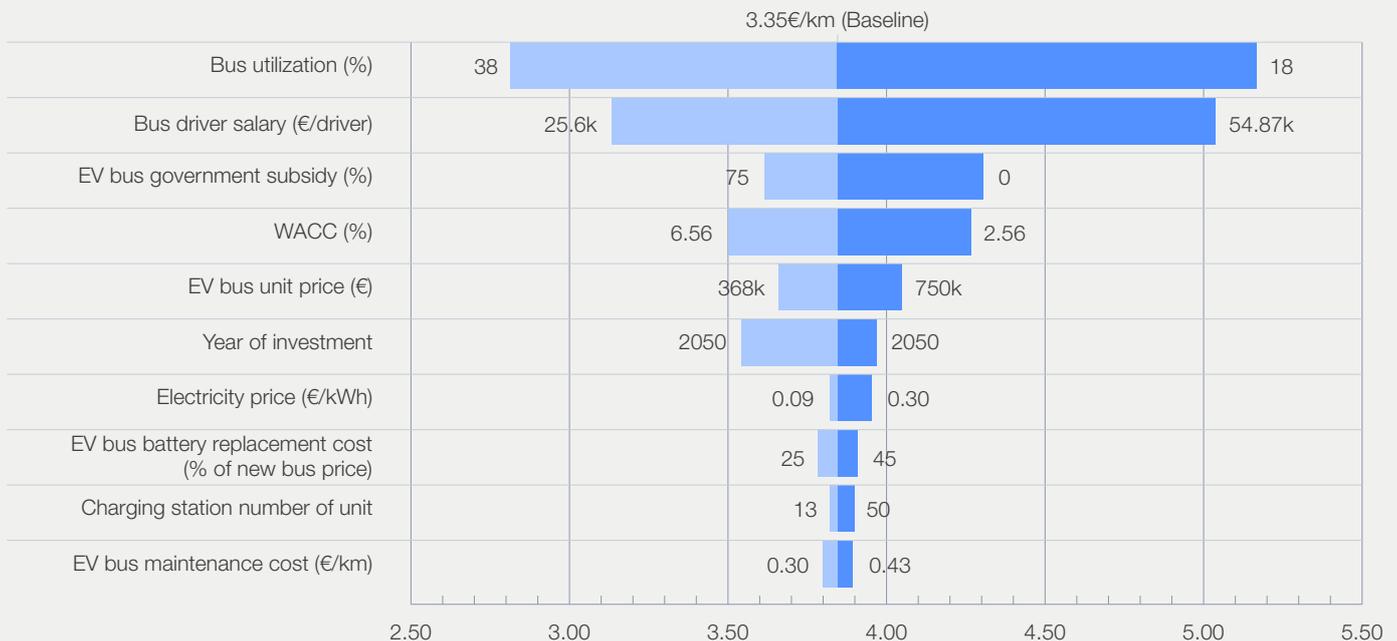
Certain variables, such as bus driver salary, utilization rate and government subsidies, are significant drivers of cost across all technologies. Driver salary, in particular, represents a substantial share of operational expenditure. Utilization rate – defined as the proportion of time a bus is actively in service carrying passengers – directly impacts the amortization of fixed costs and is a key determinant of LCO for all scenarios. The longer a bus is in service carrying passengers, the more its fixed costs are spread out, lowering the overall cost per km. Conversely, if buses are used less, the cost per km can rise dramatically, sometimes by as much as 300% for some of the technology scenarios.

FIGURE 7 Sensitivity analysis for each technology scenario – Main parameters driving levelized €/km price

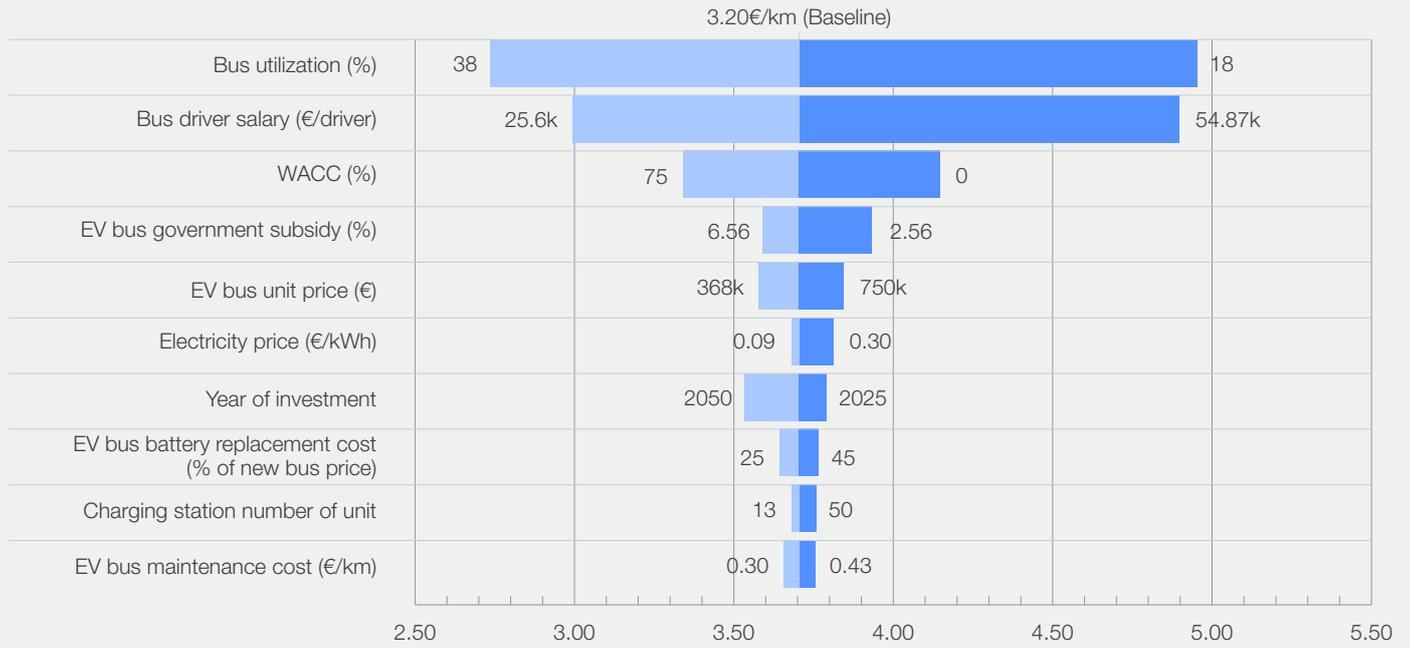
Diesel bus TCO sensitivity



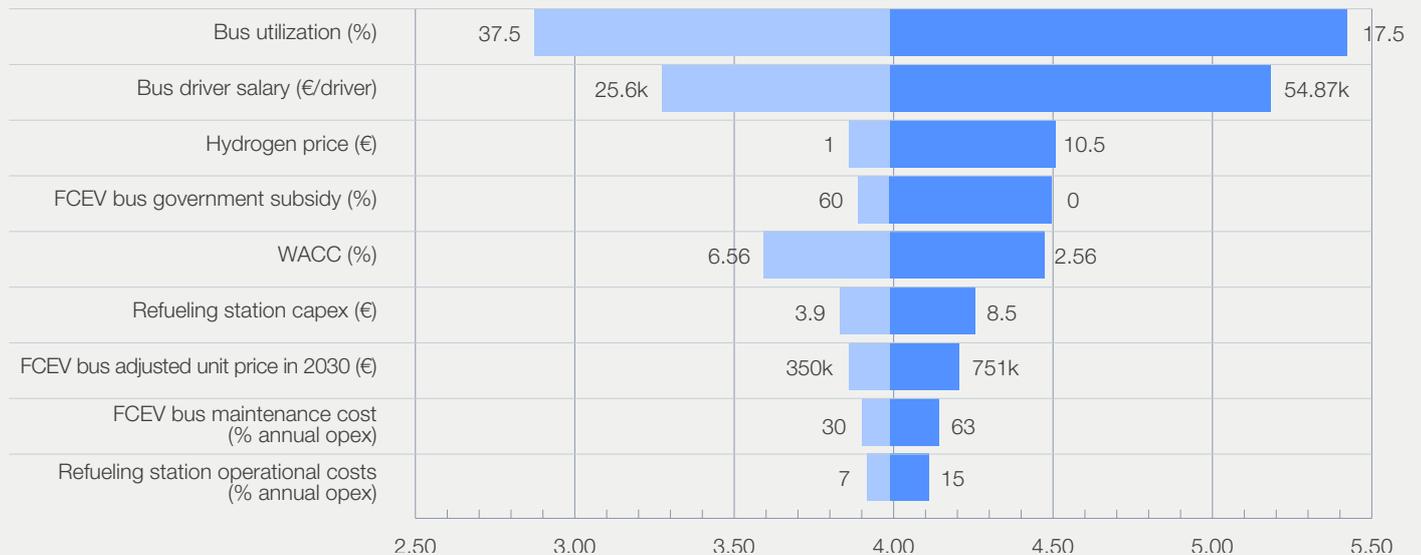
E-bus TCO sensitivity



Retrofitted E-bus TCO sensitivity



Hydrogen bus TCO sensitivity



Government subsidies and incentives are another critical factor shaping TCO. Airports and ground service equipment providers have access to a wide range of support schemes for zero-emission buses and related infrastructure. In North America and Europe, programmes frequently cover 40-100% of the incremental costs for vehicles and charging infrastructure through grants, rebates or tax credits. Notable examples include the Federal Aviation Administration (FAA) Zero Emissions Airport Vehicle Programme (United States), the Zero Emission Transit Fund (Canada) and the EU Alternative Fuels Infrastructure Facility (European Union), all of which provide substantial support tailored to airport projects. Additional opportunities often exist through state, provincial or utility-level programmes.

In the Gulf region, while open-call grants are less common, support is provided through government-led pilot projects, procurement mandates and strategic partnerships aligned with national sustainability strategies. Non-monetary incentives such as tax breaks are also frequently offered, further improving the financial case for adoption. A detailed table of available subsidies and incentives across regions is included in the appendix for reference.

Each bus technology also has its own unique sensitivities. For example, the cost of fuel is especially important for diesel buses, and this price could vary further when factoring in the potential price premium of HVO. The price of electricity and the initial purchase cost matter most for electric buses. Hydrogen buses are particularly sensitive to how long they are used, because their upfront and infrastructure costs are high. If the fleet is not sized correctly or if there are limits on maintenance and refuelling flexibility, it becomes harder to keep costs down.

Other factors, such as the average speed of the buses and the hours that the airport operates, also play a role by affecting how long the buses spend in motion, influencing the maintenance costs and the idle time for refuelling and charging. In Appendix 2, further considerations on the assumptions taken for each of the technologies are analysed.

In summary, while energy prices, purchase costs and how long the buses are used are the most influential factors in all scenarios, it is government subsidies and their influence on capex that would directly affect upfront costs and whether these can be offset over the lifetime of the assets.

The main exception to this analysis concerns the hydrogen bus scenario. Here, both the maturity of hydrogen bus technology and the local availability of hydrogen fuel can significantly influence capex. Additionally, the cost and reliability of

hydrogen supply – linked to hydrogen production infrastructure – can impact opex. For airports considering hydrogen buses, a more detailed assessment of both technology readiness and fuel supply logistics is recommended to ensure efficient fleet operation. These insights highlight the importance of careful planning and local context when choosing and managing alternative bus technologies at airports.

Additional reflections

The transition to hydrogen-powered ground operations is already challenging, but this takes place while air transport is also exploring this technology, with significant opportunities for collaboration but also complex challenges. While some airports are currently studying infrastructure planning for supporting hydrogen bus fleets – primarily through gaseous hydrogen supply – future demand from hydrogen-powered aircraft will require a fundamental shift in both scale and technology, particularly towards liquid hydrogen (LH₂) production, storage and handling.

A key observation is the current disconnect between hydrogen infrastructure for ground vehicles and the anticipated needs of aviation. As hydrogen aviation matures, airports will need to bridge this gap, integrating infrastructure that can flexibly support both gaseous and liquid hydrogen, and ensuring that investments made today are ready for tomorrow's multimodal hydrogen ecosystem. This is because industry and academia suggest that liquid hydrogen may be more suitable for aircraft propulsion in the future, though current ground operations rely predominantly on gaseous hydrogen.

This forward-looking scenario was also part of the research for this paper. The main difference between the off-site hydrogen production scenario (number 3 previously described) and the on-site hydrogen production scenario is the infrastructure needed to adopt a hydrogen bus fleet within the boundaries of an airport that has made a complete transformation of its landscape, including capabilities for liquid hydrogen production, storage and delivery. The capex required for on-site hydrogen production and liquefaction is substantial, with estimates exceeding €450 million and annual opex heavily influenced by electricity prices and liquefaction efficiency. Liquefaction remains the primary cost driver, and the TCO is highly sensitive to both the price of green hydrogen and the cost of electricity. Technological advances are expected to reduce both capex and opex by 2050, but the need for a “green premium” over conventional fuels would persist in the near term.

Importantly, mechanisms such as long-term offtake agreements and targeted subsidies can help manage the high initial costs and financial risks associated with early-stage hydrogen infrastructure. In addition, the availability of renewable energy – especially a balanced mix of wind and solar – can significantly lower hydrogen supply costs and reduce the need for oversized infrastructure. For airports in less favourable locations, combining on-site hydrogen production with imports via vessels or pipelines can further optimize costs and improve resilience.

As hydrogen aircraft are introduced, the interplay between offsite hydrogen production for buses and onsite production for aviation could drive new value chain concepts, particularly as logistical and handling challenges for liquid hydrogen become more pronounced. In summary, airports aiming to become regional hydrogen hubs must adopt a holistic, future-oriented approach – aligning investments in hydrogen and electricity infrastructure, anticipating the needs of both ground and air transport,¹⁹ and building in flexibility to adapt as technology and regulation evolve. This multistakeholder, systems-level perspective will be critical to achieving deep decarbonization and long-term operational resilience.



Conclusion

Airports can lead aviation's net-zero transition by embracing innovative, cost-effective solutions for ground operations decarbonization.

The decarbonization of airport ground operations stands as both an imperative and a strategic opportunity for the aviation sector. As this paper demonstrates, airports are uniquely positioned to drive meaningful emissions reduction by adopting low- and zero-emission technologies across their ground fleets. The comparative analysis of diesel, retrofitted electric, battery-electric and hydrogen fuel cell buses provides actionable insights for decision-makers seeking to balance operational needs, financial realities and sustainability ambitions.

Retrofitted electric buses emerge as a pragmatic, cost-effective solution for the near term, enabling airports to leverage existing assets and achieve rapid emissions reduction with minimal operational disruption. This pathway is particularly attractive for airports with newer diesel fleets or limited capital, serving as a bridge to full electrification while infrastructure and workforce capabilities are developed.

Investing in new battery-electric bus fleets represents a forward-looking strategy, aligning with evolving regulatory requirements and long-term sustainability objectives. While the initial investment is higher, ongoing operating costs are significantly reduced, and the passenger and staff experience is enhanced through quieter, cleaner operations. The economic case for electrification is further strengthened by policy incentives and the maturing technology landscape, making this option increasingly viable for airports with stable financial resources and predictable operational profiles.

Hydrogen fuel cell buses, though currently facing higher costs and infrastructure challenges, offer significant potential for future-proofing airport operations – especially at larger hubs with demanding duty cycles and ambitions to serve as regional energy hubs. As renewable hydrogen becomes more accessible and technology matures, hydrogen buses may become a strategic choice for airports seeking operational flexibility and alignment with broader energy transition goals.

The successful transition to low-carbon ground operations will require coordinated action across the value chain. Airports must engage with airlines, energy suppliers, infrastructure planners and policy-makers to develop robust supply chains, invest in workforce training and advocate for supportive policies and incentives. Early adoption and pilot projects, particularly at regional airports, can create scalable models for larger hubs and for the wider industry.

Ultimately, the choice of bus technology should be guided by each airport's unique operational context, financial capacity, regulatory support and strategic vision. By adopting a tailored, evidence-based approach and leveraging multistakeholder collaboration, airports can position themselves as leaders in sustainable ground operations – delivering cleaner air, quieter environments and long-term value for passengers, staff and surrounding communities. The transition to decarbonized ground operations is not only an environmental imperative but also a strategic opportunity to future-proof airport operations and contribute meaningfully to the aviation industry's net-zero roadmap.

Appendix 1: Methodology

The analysis presented in this paper is based on a comprehensive and multi-faceted approach, incorporating various data collection methods to ensure a realistic perspective from the Airports of Tomorrow community.

The insights presented in this paper are based on the following phases:

An extensive desk research exercise conducted during Q1 2025, led by Judge Business School MBA students at Cambridge University, focused on hydrogen buses as the main alternative technology for benchmarking and comparison. The Airports of Tomorrow community validated the different scenarios considered in this phase and the theoretical assumptions utilized, through workshops and bilateral calls.

A second phase followed during Q2 2025, in which graduate students from Imperial College London explored battery-electric buses and retrofitted diesel buses, with an emphasis on cost structures, infrastructure requirements and operational suitability. As in the first phase, the Airports of

Tomorrow community validated the theoretical assumptions made during the research and provided inputs to ensure both analyses were complementary.

Throughout the exercise, over 20 in-depth interviews were conducted with experts drawn from across the airport ecosystem, ensuring coverage of all industry profiles: airport operators, ground handling service providers, bus manufacturers, bus operators, infrastructure developers and energy suppliers.

The insights gathered from these different sources were carefully analysed to offer a neutral and objective view of the industry's challenges and risks. While most of the assumptions used in the TCO model were validated, some were simplified and may not fully reflect the diversity of perspectives across the industry. As a result, the final figures should be seen as well-supported estimates that depend on certain conditions and are limited by the scope of the interviews. Even so, this analysis provides a useful tool to help airports make strategic decisions about transitioning ground service equipment as part of their decarbonization plans.

Appendix 2: Assumptions for each scenario

Table 1 in the paper presents the general assumptions that apply across all three technologies. These include variables such as average fleet size, range, utilization rate, expected vehicle lifespan and discount rate. Table 2 below summarizes technology-specific cost and performance assumptions, such as refuelling times,

charging infrastructure requirements and battery replacement cycles. The TCO model created for this analysis is available on demand, and all sources are described in detail (including all average assumptions where sensitive data applies). This model can be adapted for different regions and operational contexts.

TABLE 2 **Baseline parameters by bus technology**

Baseline parameters			
	Parameter	Value	Comment
Diesel buses	Average bus price (€/bus)	259,000	Based on an average of six different bus models
	Maintenance cost (€/km)	0.61	Average of three independent sources
	Energy consumption (l/km)	0.34	Based on an average of seven bus models
	Diesel price (€/l)	1.67	Average retail price across 10 European countries
	Lifespan (years)	15	Various sources
	Salvage value (% of purchase price)	15	-
	Driver training cost (€)	0	No additional training required
	Insurance cost (€)	0	Assumed to be self-insured
	Registration cost (€)	0	Assumed that no registration fees apply
	Government subsidy (% of purchase price)	0	No subsidies for diesel buses
Electric and retrofitted buses	Average bus price (€/bus)*	550,000 (electric) retrofitted bus, approximately 50% of new electric bus	Average of five electric buses
	Capex learning rate (%/year)	3.9	Reduction expected as battery technology scales
	Maintenance cost (€/km)*	0.37/0.40	Electric/retrofitted, excluding battery costs
	Energy consumption (kWh/km)	1.15	Average of seven different buses
	Electricity price (€/kWh)	0.12	Validated with stakeholders
	Battery replacement frequency (years)	9	Validated with stakeholders
	Battery replacement cost (% of new e-bus)	35	Based on multiple sources and stakeholder input
	Battery size (kWh)	386	Average of six different buses
	Bus-to-charger ratio	2:1	One charger for two buses; validated with stakeholders
	Bus output power (kW)	150	Two sockets per charger; one socket per bus
Charger efficiency (%)	95	Typical market average; input power reduced to 143 kW	



Electric and retrofitted buses	Charging pattern (min-max%)	20-90	70% usable capacity to limit degradation
	Charger unit cost (€/kWh)	408.48	Based on various chargers in the market
	Charger hidden cost (% of unit cost)	60	Includes design, grid upgrades, site works
	Charging time (hours)	3.77	Based on input power, usable capacity and overnight charging
	Charger maintenance cost (€/unit/year)	2,300	Covers software updates and cooling maintenance
	DC charger warranty cost (€/unit/year)	736	Based on manufacturer warranty rates
	Charger salvage value (% of unit price)	25	Assumed similar to buses due to limited data
	Bus salvage value (% of unit price)	25	Higher resale potential due to battery value
	Lifespan (years)**	15	Based on various sources
	Driver training cost (€)	231	Based on electric bus requirements in Canada and the United Kingdom
	Insurance cost (€)	0	Assumed to be self-insured
	Registration cost (€)	0	Assumed that no registration fees apply
	Government subsidy (% of purchase price)	50	Covers half of the capex for both buses and charging infrastructure
Hydrogen buses	Average bus price (€/bus)	598,240	Average of six hydrogen buses
	Capex learning rate (%/year)	3.5	Reduction expected as hydrogen technology scales
	Bus maintenance cost (€/km)	0.42	Average of six different resources
	Bus fuel consumption (kgLH ₂ /km)	0.10	Average of four different bus models
	Hydrogen price (€/kg; grey, blue, green)	1.84, 1.89, 2.87	Average of sources. Projections of prices by 2030. Validated with stakeholders.
	Refuelling time (minutes)	15	Based on market research
	Bus salvage value (% of unit price)	15%	Resale potential due to asset value. Based on various sources
	Lifespan (years)**	15	Based on various sources
	Insurance cost (€)	0	Assumed to be self-insured
	Registration cost (€)	0	Assumed no registration fees apply
	Government subsidy (% of purchase price)	50	Covers half of the capex for both buses and charging infrastructure

* Differs between new e-bus and retrofitted

** Assumed to have the same life span to compare similar cycles

Appendix 3: Subsidies

To complement the sensitivity analysis, this appendix provides a detailed table of subsidies and incentives available to support the adoption of zero-emission airport buses and associated infrastructure. The information is organized by region and includes both direct financial mechanisms – such as grants, rebates and tax

credits – and non-monetary incentives, including toll exemptions, tax breaks and preferential access. While comprehensive, the table is not exhaustive and reflects the main programmes identified at the time of writing. It is intended to give readers a consolidated view of the support schemes that can significantly influence TCO across different markets.

TABLE 3 **Subsidies in the United States (US)**

Subsidy programme	Jurisdiction (country/state)	Amount/percentage	Coverage
Zero Emissions Airport Vehicle and Infrastructure Pilot Program²⁰	Federal	Up to 50% of project cost	Airport-owned, on-road zero-emission vehicles (ZEVs, such as buses and shuttles) and supporting charging infrastructure for exclusive airport use
Low or No Emission (Low-No) Grant Program²¹	Federal	Up to 85% for buses; up to 90% for facility components	Purchase or lease of low/zero-emission public transit buses, supporting facilities and workforce development. Airport-only services are ineligible.
Commercial Clean Vehicle Tax Credit (45W)²²	Federal	Up to \$40,000 per vehicle	Tax credit for businesses purchasing qualified commercial clean vehicles with gross vehicle weight rating (GVWR) of 14,000 pounds or more
Alternative Fuel Infrastructure Tax Credit (30C)²³	Federal	6% of cost, up to \$100,000 per unit	Tax credit for businesses installing charging infrastructure
EnergIIZE Commercial Vehicles Project²⁴	California	Varies; targeted funding lanes	EV charging and hydrogen refuelling infrastructure for medium- and heavy-duty trucks, buses and equipment
Texas Volkswagen Environmental Mitigation Program (TxVEMP) - All-Electric Grant²⁵	Texas	Up to 100% of incremental cost for government entities; 75% for non-government	Replacement of older diesel vehicles with all-electric models, including shuttle/transit buses and airport ground support equipment, plus supporting infrastructure
ComEd Business and Public Sector EV Rebates²⁶	Illinois (ComEd Service Area)	Up to \$120,000 for a transit bus; up to \$180,000 for select customers	Rebates for the purchase or lease of new or pre-owned fleet EVs, including transit buses
ComEd Make-Ready Program²⁷	Illinois (ComEd Service Area)	Up to \$8,000 per level-2 (L2) charger port; up to \$1,000/kW for direct-current fast chargers (DCFC)	Rebates for electrical infrastructure upgrades required to install EV chargers for non-residential customers
Georgia Power EV Charger Plus Rebate²⁸	Georgia (GA Power Service Area)	\$250/kW for L2 chargers; \$150/kW for DCFC. Maximum \$30,000 per project	Rebates for purchase and installation of commercial EV chargers
Charge Ahead Colorado²⁹	Colorado	Up to 80% of charger cost (maximum \$70,000 for dual-port DCFC)	Grants for Level 2 and direct current (DC) fast-charging stations for public entities, businesses and multifamily housing
Fleet-ZERO Grant Program³⁰	Colorado	Up to \$500,000 per award	Funding for EV charging infrastructure to support light-, medium- and heavy-duty fleet vehicles

TABLE 4 | Subsidies in Canada

Subsidy programme	Jurisdiction (country/province)	Amount/percentage	Coverage
Zero Emission Transit Fund (ZETF) – capital projects³¹	Federal	Up to 50% of eligible costs; max CAD350 million per project	Procurement of zero-emission buses (ZEBs), charging/refuelling infrastructure and facility upgrades
Zero Emission Transit Fund (ZETF) – planning projects³²	Federal	Up to 80% of eligible costs	Feasibility studies, modelling, life-cycle analysis and comprehensive electrification planning
Incentives for medium- and heavy-duty ZEVs (iMHZEV)³³	Federal	Up to CAD200,000 per coach bus; tiered by vehicle class	Point-of-sale rebate on the purchase or lease of eligible new medium- and heavy-duty ZEVs
CleanBC Go Electric Rebates³⁴	British Columbia	Up to CAD50,000 for airport specialty vehicles (manufacturer suggested retail price, MSRP) >\$300,000)	Rebates for various ZEVs, including a dedicated category for airport and port specialty vehicles
BC Hydro EV Fleet Program³⁵	British Columbia	Up to 100% of infrastructure costs for public entities	Funding for fleet electrification planning and electrical infrastructure installation to support EV charging
Écobus Incentive Program	Quebec	CAD240,000 per electric school bus	Subsidy for the purchase of an electric school bus
Electric Vehicle Charging Program (EVCP)³⁶	Alberta	Up to 46% of charger installation costs (max CAD75,000 per DCFC)	Rebates for the purchase and installation of EV chargers for municipalities, businesses and other organizations

TABLE 5 | Subsidies in Europe

Subsidy programme	Jurisdiction	Amount/percentage	Coverage
Zero Emission Bus Regional Areas (ZEBRA) Scheme³⁷	United Kingdom (England)	Up to 75% of cost difference between ZEB and diesel bus; up to 75% of infrastructure cost	Purchase of new ZEBs (single and double deck) and associated charging/refuelling infrastructure
Bus Service Operator Grant (BSOG) ZEB Incentive³⁸	United Kingdom (England)	£0.22 per km operated	Operational subsidy for certified ZEBs running on public routes. This may not cover airside operations but may apply to routes to/from airports
Federal Funding Call for Alternative Drives in Buses³⁹	Germany	Up to 80% of additional vehicle cost; up to 40% of infrastructure cost. Maximum €15 million per project	Purchase of battery-electric and fuel cell buses, retrofits and charging/refuelling/maintenance infrastructure
Bus Funding Programme (Example)⁴⁰	Germany (Bavaria)	Up to €105,000 per articulated (longer than usual) e-bus, plus infrastructure grants	State-level subsidies for the purchase of “climate buses” (electric, hydrogen, biogas) and depot electrification
Advenir Programme⁴¹	France	€960-€2,200 per charging point	Support for installation of charging stations for commercial vehicles
MOVES III Programme⁴²	Spain	Up to 70% of charging infrastructure cost (maximum €2.5 million for companies); up to €7,000 for passenger cars	Grants for purchase of EVs and installation of charging infrastructure, plus tax benefits
Alternative Fuels Infrastructure Facility (AFIF)⁴³	European Union (EU)	Varies by project	EU-level funding for alternative fuels infrastructure, including electrification of ground handling services at major airports

TABLE 6 | Subsidies in the Middle East

Subsidy programme	Country	Key features/type of support	Coverage
DEWA Green Charger Initiative⁴⁴	United Arab Emirates	Historically provided free public charging for non-commercial EV users	Public charging infrastructure network in Dubai
Saudi Vision 2030⁴⁵	Saudi Arabia	Direct government investment in EV manufacturing and deployment of public e-bus services via the Public Transport Authority (PTA)	Public transport fleets in major cities, including airport shuttle services
Qatar National Vision 2030/Electric Vehicle Strategy⁴⁶	Qatar	Tax exemptions, subsidized registration fees, focus on achieving TCO parity for commercial fleets	All vehicles, with a focus on public transport and commercial fleets

Note: Not all these grants and incentives may always apply to airports.

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