Sustainable Airport Logistics and Regional Hydrogen Economies:
A TCO-Based Assessment from Warsaw Chopin Airport

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Abstract

Decarbonizing hard-to-abate sectors, such as airport logistics, is essential to achieving climate neutrality goals but entails complex challenges due to high energy intensity and operational constraints. This study examines the economic and environmental sustainability of hydrogen-powered heavy-duty vehicles (HDVs) in airport operations through a case study at Warsaw Chopin Airport, conducted within the HORIZON-JU CLEANH2 HySPARK initiative.

Framed within the contributions of sustainability transitions theory and regional innovation systems, the research adopts an extended Total Cost of Ownership (TCO) approach that includes the social costs of CO_2 emissions and local air pollutants.

By comparing diesel, battery electric, and hydrogen fuel cell technologies, the results show that fuel cell vehicles powered by hydrogen produced via methane reforming offer the best economic performance, while green hydrogen and battery-based solutions outperform in terms of environmental impact. Once externalities are internalized, low-or zero-emission technologies emerge as the most advantageous options from both economic and environmental perspectives.

The study contributes to the debate on territorial energy transitions by providing empirical evidence on the role of hydrogen valleys as experimental settings for systemic change. The findings offer valuable insights for sustainable transport policies, green industrial strategies, and regional infrastructure planning.

1. Introduction

Climate crises represent one of the most critical challenges of our era, with the transport sector accounting for a significant share of global greenhouse gas emissions. Within this sector, "*hard-to-abate*" segments such as aviation, maritime, and heavy-duty transport pose distinct decarbonization challenges owing to their high energy intensity and complex operational requirements. In response, the European Union has introduced ambitious policy frameworks, including *Fit for 55*, *REPowerEU*, and the *EU Hydrogen Strategy*, aimed at accelerating emission reductions and fostering the uptake of clean energy technologies. These strategies highlight the pivotal role of renewable fuels and technological innovation in driving the transition toward a more sustainable and resilient transportation system.

In recent years, scholars in regional and environmental economics have increasingly emphasized that the energy transition is not only a technological process but also a spatial and institutional one (Coenen et al., 2012; Truffer et al., 2015). As sustainability transitions unfold, their impacts tend to be uneven across regions, depending on local capabilities, infrastructure, and socio-economic structures. This underscores the need for place-based approaches that integrate decarbonization strategies within regional development trajectories. The concept of “hydrogen valleys” aligns with this perspective, positioning clean energy infrastructure as a lever for green industrialization, job creation, and territorial resilience (Diercks et al., 2019).

Grounded in an inductive research approach inspired by sustainability transition theory, this study frames the HySPARK project, developed under the HORIZON-JU CLEANH2 initiative and backed by the Mazovian Hydrogen Valley, as an experimental environment for systemic change and a model for scaling clean hydrogen technologies through regional innovation ecosystems.

The aviation sector is integral to this transition[1], as it is a crucial node in global mobility. Airports are increasingly investing in sustainable technologies to mitigate environmental impacts and align with decarbonization targets. One promising pathway involves the use of hydrogen-powered heavy-duty vehicles, including ground support equipment (GSE) and airport trucks (Blanchard J., 2020).

These alternatives offer enhanced environmental performance and operational reliability. In particular, green hydrogen, with its high energy density and zero local emissions, emerges as a strategic energy carrier for powering airport logistics, improving energy efficiency, air quality, and noise reduction.

This paper offers an original contribution by assessing the economic and environmental implications of hydrogen-based logistics at Warsaw Chopin Airport. The project serves as a valuable testbed for exploring how clean technologies can be integrated into regional development pathways. Building on insights from transition theory and regional innovation systems, the study employs an extended TCO framework that incorporates the social cost of CO_2 and local pollutants. This allows for a multi-dimensional comparison among diesel, battery-electric, and fuel cell propulsion technologies, considering not only their private costs but also their broader social and spatial impacts.

By focusing on a specific regional case and applying a multi-scalar perspective, the study contributes to two critical areas of research: comparative assessments of sustainable transport technologies, with implications for policy design in place-based decarbonization strategies.

The remainder of this paper is structured as follows: Section 2 explores hydrogen’s role in decarbonizing airport operations, focusing on ground support equipment. Section 3 describes the methodological framework, including the TCO model used for assessing economic, environmental, and social impacts. Section 4 details the case study at Warsaw Chopin Airport, including vehicle types and data sources. Section 5 presents and analyses the results, comparing hydrogen-powered vehicles to diesel and battery-electric alternatives. Section 6 concludes with key findings and recommendations for future implementation and research.

2. The Role of Hydrogen in Airport Operations

Hydrogen, as an alternative fuel, offers significant advantages over traditional diesel-powered airport vehicles. It enables zero emissions at the point of use, reduces reliance on fossil fuels, and improves air quality within airport environments. Unlike battery-electric solutions (BEVs), which often require extensive charging infrastructure and longer downtime, hydrogen fuel cell vehicles (FCEVs) can be refuelled quickly, making them particularly well-suited for the high operational demands of airports.

[1] www.infrajournal.com/it/w/hydrogen-a-new-challenge-for-greener-airports-1

This is especially relevant for heavy-duty vehicles such as baggage tractors, aircraft tugs, and cargo loaders, which must operate continuously on tight schedules with high levels of reliability. Furthermore, adopting hydrogen technology helps airports future-proof their operations (Bruce et al., 2020) aligning with long-term sustainability objectives and supporting the increasing need for efficient, round-the-clock logistics. Hydrogen fuel cell vehicles present several advantages for airport operations, including fast refuelling times (5–10 minutes), which enhance operational continuity compared to the long charging times of battery electric vehicles. Their modular and scalable refuelling infrastructure is well-suited to centralized depots, with lower expansion costs and minimal impact on the electrical grid. FCEVs also benefit from reduced maintenance needs, as they avoid battery degradation issues common in BEVs, leading to a lower total cost of ownership. Environmentally, they offer zero tailpipe emissions, emitting only water vapor, and combine long driving ranges (up to 1,000 km) with high payload capacity, making them ideal for demanding and energy-intensive airport logistics.

These characteristics make FCEVs a strategic and forward-looking choice for decarbonizing heavy-duty airport transport, offering a robust and sustainable alternative to conventional and battery-electric solutions.

The underlying idea is to integrate mobility and industrial flexibility with decarbonization strategies to drive the widespread adoption of hydrogen as a clean energy carrier. Within the hydrogen valley framework, stakeholders collaborate to optimize energy systems and industrial processes, ensuring efficiency, reliability, and environmental sustainability (Testa et al,. 2014). Additionally, hydrogen's role as an industrial feedstock, such as in green ammonia production, diversifies energy sources and reduces carbon footprints. This flexibility allows industries to respond effectively to evolving energy demands and regulatory frameworks, enhancing resilience and competitiveness with a strategic opportunity (Testa et al,. 2014).

The establishment of the Mazovian Hydrogen Valley through HySPARK aims to stimulate economic growth and create new business opportunities by investing in hydrogen infrastructure, technology development, and hydrogen-related industries. By positioning Mazovia as a hub of excellence in hydrogen technology and innovation, the project strengthens regional energy security and attracts further public and private investments.

The expansion of hydrogen-related businesses and industries in Mazovia generates employment opportunities in engineering, technical fields, administration, and regulatory sectors, thereby contributing to lower unemployment rates and improved social well-being (European Commission., 2020).

3. Methodological Framework: Total Cost of Ownership Analysis and Energy Scenarios

The TCO framework is widely used in sustainable transport analysis to evaluate long-term economic performance across alternative vehicle technologies (Bubeck et al., 2016). It offers a comprehensive assessment of the economic impact associated with the acquisition and operation of a specific asset over its entire lifecycle.

Rather than focusing solely on the initial purchase price, this approach integrates all relevant cost components, providing a holistic understanding of the overall financial burden an asset imposes throughout its operational life. In the aviation sector, and particularly for heavy-duty vehicles powered by hydrogen fuel cells, the TCO methodology serves as a critical decision-making tool.

Although hydrogen-powered vehicles may present higher upfront capital costs compared to conventional diesel alternatives, a detailed TCO evaluation highlights their long-term advantages. These include lower energy expenditures, reduced maintenance requirements, and notable environmental and social benefits, which are essential in the context of growing sustainability commitments.

This study focuses on a specific category of heavy-duty airport vehicles, luggage tow tractors, and compares three alternative powertrain technologies: Diesel, Battery Electric, and Fuel Cell Electric Vehicle. The Battery Electric configurations include two variants of energy sources: E-HV Grid, which assumes electricity is entirely sourced from the national Poland grid, and E-HV Green; in this latter case energy is purchased from the market (TGE exchange) and therefore actually comes from the general grid, which is a mix of different sources. To make it legally and environmentally "green," green certificates (Renewable Energy Certificates - REC) are purchased separately, certifying that the same amount of energy has been produced from renewable sources somewhere else. Additionally, green energy is exempt from excise tax, whereas conventional energy is subject to a small excise tax plus a substitution fee that significantly increases the total cost of conventional energy. Similarly, the Fuel Cell configurations comprise three options of energy sources: Fuel Cell H_2 Green, which uses hydrogen produced via electrolysis powered by photovoltaic panels and grid electricity (self-produced); Fuel Cell H_2 Reforming (SMR – Industrial), which relies on hydrogen derived from steam methane reforming; and Fuel Cell H_2 Commercial, which assumes hydrogen is procured directly from an external supplier. When considering hydrogen purchased from an external supplier, it is common to assume a fixed price per kilogram (or per unit of energy) regardless of the production method employed by the supplier. This assumption is based on the perspective of the end customer, for whom the purchase price is the relevant factor, rather than the underlying hydrogen production process.

The differentiation in energy sources allows for a detailed assessment of how variations in energy origin impact both overall costs and long-term economic viability. The comparative analysis is conducted over a 10-year operational horizon, aligned with the average service life of such vehicles. A fixed annual discount rate and an inflation rate of 5% are applied throughout the evaluation.

For each vehicle type, the total cost per unit is calculated by aggregating all key cost drivers, including capital expenditures (CAPEX), operational expenditures (OPEX) such as maintenance and insurance, energy or fuel consumption, and associated infrastructure costs. This approach enables a thorough evaluation of the economic competitiveness of alternative powertrains in airport ground operations, providing valuable insights for strategic investment planning.

The initial purchase cost for each vehicle type is based on the market price or literature review case for the selected model. The annual fuel energy cost for each vehicle type is based on its fuel consumption (from the Chopin Airport datasheet) and the specific fuel used. For diesel vehicles, the fuel cost is calculated by multiplying the annual fuel consumption (Liters per hour × total operating hours) by the average diesel price per Liter, estimated at €1,33 /l (it refers to the fuel cost before taxes and distributor profit margins i.e., the price at which fuel in UE is sold to large purchasers such as companies, retailers, or industrial consumers), provided by Warsaw Chopin Airport. This price includes production and distribution costs but excludes fuel taxes, VAT, or other additional charges, making it generally lower than the final consumer price.

For BEVs, energy consumption is measured in kilowatt-hours (kWh). Electricity costs are assumed to be €0.22/kWh for power from the Polish grid[2]. For green electricity, the cost components include the wholesale electricity price on the Polish Power Exchange (TGE), which ranges approximately from €0.09 to €0.10 per kWh, plus the price of green certificates, around €0.012 per kWh. Since green electricity is exempt from excise taxes, no excise cost applies. However, value-added tax (VAT) at 23% is added.

[2] Source from LSAS and ORLEN data

Summing these components, the estimated gross cost of green electricity reaches approximately €0.11 to €0.12 per kWh.

For FCEVs, hydrogen consumption is measured in kilograms per hour (kg H_2/h). Hydrogen costs are estimated based on different supply scenarios: €5.43/kg for green hydrogen generated from renewable energy using a simulation developed by ATENA, €1.75/kg for hydrogen generated via steam methane reforming (SMR Industrial), and €17.00/kg when purchased directly from external suppliers (commercial)[3]. The main objective of the simulation is to determine the levelized cost of hydrogen (LCOH) produced by an integrated system at Chopin Airport, consisting of a PEM electrolyser powered primarily by a photovoltaic (PV) system, supplemented by grid electricity to ensure continuous operation. A battery storage system is modelled but excluded from the final CAPEX calculation to avoid inflating costs. The energy-economic model, developed in Excel, estimates LCOH by considering CAPEX, OPEX, annual hydrogen output, and grid contribution.

The PV system, sized to meet the electrolyser's electricity demand, has an installed capacity of 21,598 kW. Costs decrease with system size, ranging from €1,000/kW for smaller installations to €600/kW for larger ones, while annual OPEX varies between €15/kW and €5/kW. The PEM electrolyser features a nominal capacity of 3,879 kW, an electrical efficiency of 57.4%, a specific energy consumption of 58 kWh/kg H_2, CAPEX of €2,000/kW, and OPEX at 2% of CAPEX. Grid electricity, priced at €0.20/kWh, covers periods of insufficient PV generation, with additional grid maintenance and capacity costs of €100/kW and €5,000/year, respectively. PV system data are sourced from the JRC Europa tool Photovoltaic Geographical Information System [4].

The simulation assumes a 10-year horizon without technology degradation. Energy flows to and from the grid are included in operational costs. The Excel model calculates annual costs and hydrogen production, accounting for daily PV output and grid support to maintain electrolyser operation.

LCOH is calculated by dividing the total annual costs (CAPEX plus OPEX) by the annual hydrogen production. The simulation assumes an annual hydrogen yield of 523,095 kg, corresponding to the 500 tonnes of hydrogen projected in the proposal and total costs of €2,839,893, the resulting LCOH is €5.43/kg H_2. The electrolyser operates at an 89.3% capacity factor, with a favourable energy balance and a grid purchased-to-sold energy ratio of 0.91. The specific energy consumption aligns with typical PEM electrolyser performance.

The results demonstrate the technical and economic viability of a hybrid PV plus grid system for industrial hydrogen production, achieving an LCOH below €5.5/kg. The grid's role is essential for sustaining high electrolyser utilization and lowering green hydrogen cost.

For this analysis, the starting point is the diesel model currently in use at the Polish airport, along with some electric vehicles. Starting from operational data provided directly by the terminal, such as vehicle utilization patterns, the energy demand is estimated and then converted into equivalent values: kilowatt-hours for BEVs and hydrogen consumption for FCVs, using standard conversion factors and fuel cell efficiency assumptions. The overall driveline efficiency of FCEVs reaches approximately 45.9%, resulting from the combined efficiencies of the fuel cell system, the DC/DC converter, and the electric motor. While not as high as the efficiency of BEVs, which can achieve up to 80%, FCEVs still represent a significant improvement over conventional diesel internal combustion engines, which average only 25% efficiency, as shown in *table 1*. What makes FCEVs particularly compelling is their ability to deliver high operational performance with rapid refuelling times and greater energy density than batteries, key

[3] Source from Confidential internal document from the Polish Ministry of Climate and Environment "Ministerstwo Klimatu i Środowiska"
[4] https://re.jrc.ec.europa.eu/pvg_tools/en/

advantages in sectors such as heavy-duty transport and airport ground operations, where uptime and payload capacity are critical.

LUGGAGE TOW TRACTOR			
	ICE DIESEL	H_2 FC	BEV
Consumption [l/h]	4,7		
Consumption [kg/h]	3,9	0,74	
Consumption [kWh]	44,4	24,6	13,8
Eta Driveline	**0,25**	**0,45**	**0,8**
Average Traction Power[kW]	11,1	11,1	11,1

Table 1: Comparison ETA driveline[5]

In this analysis, the estimated annual mileage for the towing tractor 26,280 km, is provided by project partners. Maintenance costs are based on internal data from manufacturers of diesel, BEV, and FCEV commercial vehicles. Diesel vehicles typically have higher maintenance costs due to the complexity of their internal combustion engines and the need for regular servicing of mechanical components. BEVs, in contrast, exhibit lower maintenance costs, mainly associated with battery management and fewer moving parts. FCEVs fall between the two, with maintenance needs related to the fuel cell system and supporting technologies (Kukutschka, R. M., & Heidenreich, S., 2019).

4. Case Study Context and Analytical Scope

As part of a broader initiative to promote the development of a cross-regional Hydrogen Valley, this technical assessment aims to demonstrate the economic and social viability of FCEVs in heavy-duty and airport applications.

The project underlying the study includes the annual production of over 500 tons of Green hydrogen to be used across several sectors, including road freight (54 tons/year), urban public transport (13–28 tons/year), airport ground handling (12–16 tons/year), and green ammonia production (402–421 tons/year), yielding substantial CO_2 savings, up to 630 tons/year from transport applications and an additional 900 tons/year from ammonia synthesis.

The data for this study are based on a combination of primary and secondary sources. Primary data are collected through direct consultations with airport operators and equipment manufacturers, including operational profiles and technical specifications of GSE at Warsaw Chopin Airport. These are complemented by secondary sources such as published literature, commercial reports, and regulatory benchmarks.

The goal is to evaluate the long-term economic and social benefits of FCEVs GSE compared to conventional diesel and BEV alternatives, and to support the selection of sustainable technologies for airport and heavy-duty logistics applications. The resulting insights are critical for guiding future investments in carbon-neutral mobility solutions in complex and high-demand environments like airports.

[5] Source: authors' own elaboration based on internal datasheets of the vehicles

5. Results and Comparative Assessment

The configurations analysed share an operational profile of 2,359 hours annually (approximately 1,179 traction hours), operating daily over 364 days per year, with an estimated lifetime of 10 years[6].

The diesel tow tractor has a purchase cost of €120,000 and an average fuel consumption of 4.68 Liters per hour, resulting in an annual fuel consumption of 11,040 Liters. This leads to an annual energy cost of approximately €14,633, assuming a diesel price of €1.33 per Liter. In addition to fuel, the diesel model incurs the highest maintenance costs, totalling €8,306 per year, primarily due to the complexity of the internal combustion engine. Tire replacement and insurance bring the total annual service cost to €11,306 (including maintenance).

The battery electric tow tractor has a significantly higher initial cost of €225,000 but lower operating costs. Its annual energy consumption is estimated at 16,364 kWh, with energy costs ranging from €3,600/year (at €0.22/kWh from grid electricity) to €1,800/year (green at €0.11/kWh). Maintenance costs are much lower, amounting to €3,902 annually, due to fewer moving parts (including insurance).

The hydrogen fuel cell tow tractor is priced at €270,000 and consumes approximately 0.74 kg of hydrogen per hour, totalling 873 kg annually. When powered by green hydrogen at €5.43/kg, the energy cost is €4,739/year in alternative if it is purchased from a productor the cost is €17/kg with a total energy cost of €14,837/year. If using industrial hydrogen produced via SMR at €1.75/kg, the energy cost drops to €1,527/year. Maintenance costs are consistent with the electric version, totalling €3,902/year.

For each vehicle category, service costs include general maintenance, accounting for labour costs and scheduled annual service hours, along with preventive maintenance such as drivetrain components, filters, lubricants, and related labour. Corrective maintenance covers the replacement of brake parts and other key components. Additionally, tire replacement costs are estimated based on tire lifespan, quantity, and unit price. Insurance expenses are also included as part of the annual service cost.

5.1 Annual Operating Costs and Energy Consumption

The OPEX shows that diesel vehicles have the highest costs, mainly due to elevated fuel and maintenance expenses. BEVs, especially when powered by green electricity, offer the lowest OPEX thanks to lower energy prices and reduced service requirements. FCEVs, as shown in *Figure 1*, exhibit varying energy costs depending on the hydrogen production method. Hydrogen from steam methane reforming (SMR) is the most cost-effective option, whereas purchased hydrogen leads to significantly higher OPEX.

[6] Source: data provided by LSAS and ORLEN regarding activities carried out at the terminals of Chopin Airport

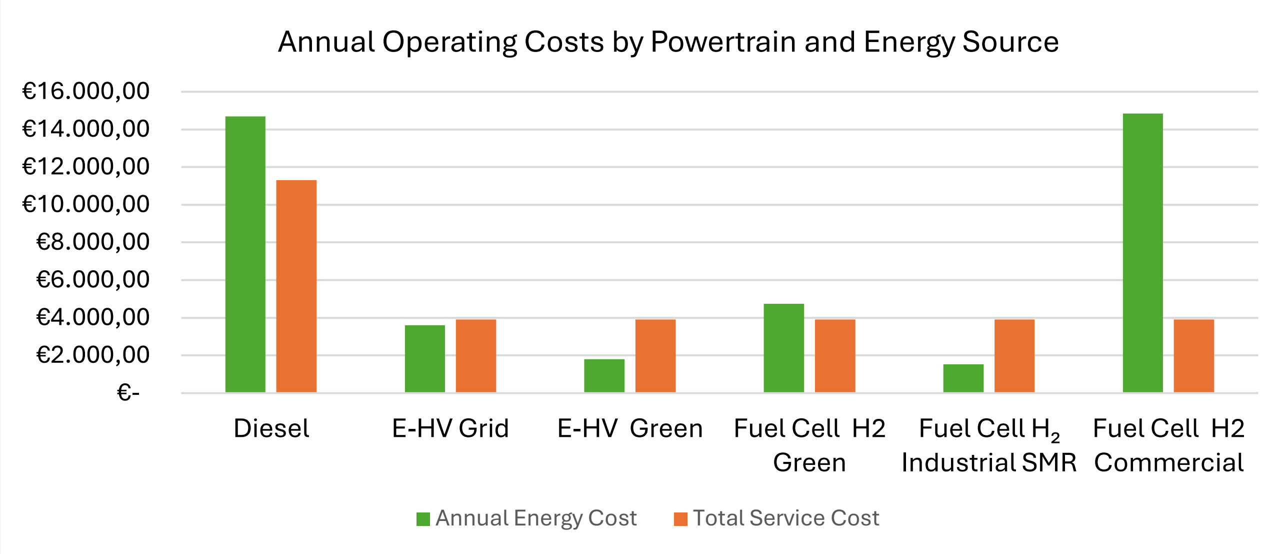

Figure 1: Annual Operating Expenditures (OPEX) for Luggage Tow Tractor

The *table 2* below summarizes the annual total costs, divided into CAPEX and OPEX categories, for each vehicle.
This breakdown provides a comprehensive comparison of the capital expenditures (CAPEX), such as vehicle purchase and the OPEX, including energy and maintenance costs, associated with each technology option.

Description	**Diesel**	**E-HV Grid**	**E-HV Green**	**Fuel Cell H_2 Green**	**Fuel Cell H_2 Industrial SMR**	**Fuel Cell H_2 Commercial**
Purchasing Price	120.000 €	225.000 €	225.000 €	270.000 €	270.000 €	270.000 €
Annual Energy Cost	14.683 €	3.600 €	1.800 €	4.739 €	1.527 €	14.837 €
Total Service Cost	11.306 €	3.902 €	3.902 €	3.902 €	3.902 €	3.902 €
Annual Operating Hours (tOt)	2359					
Annual Traction Hours (trC)	1179,5					
Energy Consumption (l/h - kwh/h - kg/h)	4,68	13,87	13,87	0,74	0,74	0,74
Annual Energy Consumption (l-kwh - kg)	11040	16.364	16.364	873	873	873
Daily Traction Hours	4,8					

Table 2: Annual Total Cost of Ownership (TCO)[7]

5.2 Traction Energy Cost Analysis

In the context of a comparative analysis of energy costs for airport vehicle traction, *Table 3* provides a concise yet meaningful overview of fuel, hydrogen, and electricity prices, as well as the resulting traction

[7] Source: authors' elaboration based on LSAS , ORLEN and ATENA datasheets

energy costs (expressed in €/kWh) for each technology considered: diesel, BEV, powered by either grid or green electricity, and FCEV, using green hydrogen, hydrogen from reforming, or purchased hydrogen.

Description	Diesel	E-HV Grid	E-HV Green	Fuel Cell H_2 Green	Fuel Cell H_2 Industrial SMR	Fuel Cell H_2 Commercial
Fuel Price (€/l)	1,33 €					
H_2 Price (€/kg)				5,43 €	1,75 €	17 €
Price (kWh)		0,22 €	0,11 €			
Traction Energy price (kWh)	0,50 €	0,29 €	0,14 €	0,36 €	0,12 €	0,64 €

Table 3: Unit Energy Prices and Traction Energy Costs for Each Powertrain[8]

The term *traction energy price* refers to the cost of the energy effectively used to propel the vehicle, that is, the energy required to produce mechanical traction power.

Diesel, with a price of €1.33/l, results in a traction energy cost of €0.50/kWh, the highest among the options considered. This reflects both the relatively high fuel price and the low efficiency of internal combustion engines, confirming diesel's economic as well as environmental disadvantages.

For BEVs, the source of electricity significantly impacts the traction cost. When powered by grid electricity (E-HV Grid), at €0.22/kWh, the corresponding traction cost is €0.29/kWh. Conversely, when using green energy (E-HV Green), with a cost of electricity of €0.11/kWh, the traction cost drops to €0.14/kWh, making it one of the most affordable and sustainable solutions.

In the case of FCEVs, traction costs vary considerably depending on the hydrogen source:

- With on-site produced green hydrogen (€5.43/kg), the traction cost is €0.36/kWh;
- With industrial hydrogen from steam methane reforming (SMR) (€1.75/kg), the cost drops substantially to €0.12/kWh, making it the most economically advantageous option;
- With purchased commercial hydrogen (€17/kg), the cost increases to €0.64/kWh, higher than diesel and all electric alternatives.

These results highlight how the origin of energy, whether electricity or hydrogen, strongly influences operational costs. Renewable-based solutions offer an effective balance between environmental sustainability and economic feasibility, while hydrogen from reforming, though less sustainable, presents a compelling cost advantage. On the other hand, commercially purchased hydrogen remains the least cost-effective option.

5.3 Ten-Year TCO and Economic Viability

The 10-year Total Cost of Ownership (TCO) of a standard airport tow tractor is assessed, considering the initial capital costs, annual operating expenses (energy and maintenance), scheduled replacements, residual value at year ten, and the discounted value of future cash flows as detailed in *Table 4*.

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[8] Source: authors' elaboration based on LSAS , ORLEN datasheets and ATENA simulation

Diesel

The conventional diesel-powered option involves an initial investment of €120,000, with steadily increasing fuel and maintenance costs over time. By year ten, the cumulative cost reaches €440,892. Considering a residual value of €6,000, the TCO remains €440,892, with a discounted present value of €297,851 calculated using a discount rate of 4%.

BEV – (Energy source: Grid)

The battery electric variant, powered by National Grid electricity, starts at €225,000. It offers lower annual operating costs compared to diesel but requires a battery pack replacement in year five, costing €67,500. This replacement cost is prudently estimated at 30% of the vehicle's purchase price, a conservative assumption slightly above typical market ranges (15%–25%) to account for variability in battery chemistry, capacity, and supplier pricing.

Although airport tow tractors use lower-capacity batteries than larger electric vehicles, battery replacement remains a significant lifetime expense. This cautious estimate ensures robustness in the TCO analysis by incorporating potential cost fluctuations and technological differences across manufacturers.

The total cumulative cost amounts to €375,612, with a residual value of €11,250 and a present value of €253,750 calculated using the previously applied discount rate.

BEV – (Energy source: Green)

This version shares the same vehicle configuration as the grid-powered BEV, including the battery replacement. However, the use of green energy (purchased with green certificates) significantly reduces energy costs. As a result, the total TCO is lowered to €352,970, with a present value of €238,454, making it economically advantageous option among alternatives evaluated.

Fuel Cell – (Energy source: H_2 Green)

The fuel cell vehicle powered by green hydrogen entails a higher upfront investment (€270,000[9]), but it does not require major component replacements over its operational life. In particular, fuel cell stack replacement is not considered within the 10-year analysis horizon, as Ballard specifies a useful life of up to 25,000 operating hours for its latest-generation fuel cell modules (e.g., FCmove™-HD), depending on the specific application and operating conditions. This durability is generally sufficient to cover the duty cycles of heavy-duty vehicles such as airport tow tractors, buses, and trucks without requiring a stack replacement within the evaluation period.

Assuming moderate energy costs, the total TCO over 10 years amounts to €365,187, with a discounted present value of €246,707.

Fuel Cell – (Energy source: H_2 Reforming)

This configuration proves to be the most cost-effective fuel cell option, due to the relatively low energy costs associated with hydrogen produced via methane reforming. The total TCO is the lowest among all options at €324,790, with a present value of €219,416.

[9] Source: internal ATENA estimate based on the purchase costs of the electric vehicle, fuel cell conversion, and sales price, considering a 30% markup

Fuel Cell – (Energy source: H_2 Purchase)

The variant relying on externally purchased hydrogen incurs the highest energy costs among fuel cell options. This leads to a total TCO of €492,198 and a present value of €332,512, positioning it closer to the diesel alternative in terms of economic performance.

LUGGAGE TOW TRACTOR						
10-Year Lifetime						
Diesel	**Purchasing Cost**	**Energy Cost**	**Service Cost**	**Residual Value**	**Total TCO**	
Y0	120.000 €					
Y1		14.683 €	11.306 €		25.989 €	
Y10		184.686 €	142.206 €	**6.000 €**	**440.892 €**	
Present Value	**297.851 €**					
E-HV Grid	**Purchasing Cost**	**Energy Cost**	**Service Cost**	**Residual Value**	**Total TCO**	**Replacement Battery**
Y0	225.000 €					67.500 €
Y1		3.600 €	3.902 €		7.502 €	
Y10		45.283 €	49.079 €	**11.250 €**	**375.612 €**	
Present Value	**253.750 €**					
E-HV Green	**Purchasing Cost**	**Energy Cost**	**Service Cost**	**Residual Value**	**Total TCO**	**Replacement Battery**
Y0	225.000,00 €					67.500,00 €
Y1		1.800 €	3.902 €		5.702 €	
Y10		22.641 €	49.079 €	**11.250 €**	**352.970 €**	
Present Value	**238.454 €**					
Fuel Cell H_2 Green	**Purchasing Cost**	**Energy Cost**	**Service Cost**	**Residual Value**	**Total TCO**	
Y0	270.000,00 €					
Y1		4.739 €	3.902 €		8.641 €	
Y10		59.608 €	49.079 €	**13.500 €**	**365.187 €**	
Present Value	**246.707 €**					
Fuel Cell H_2 Industrial SMR	**Purchasing Cost**	**Energy Cost**	**Service Cost**	**Residual Value**	**Total TCO**	
Y0	270.000,00 €					
Y1		1.527 €	3.902 €		5.429 €	
Y10		19.211 €	49.079 €	**13.500 €**	**324.790 €**	
Present Value	**219.416 €**					
Fuel Cell H_2 Purchase	**Purchasing Cost**	**Energy Cost**	**Service Cost**	**Residual Value**	**Total TCO**	
Y0	270.000,00 €					
Y1		14.837 €	3.902 €		12.630 €	
Y10		186.619 €	49.079 €	**13.500 €**	**492.198 €**	
Present Value	**332.512 €**					

Table 4: TCO over a 10-Year Lifetime[10]

[10] Source: authors' elaboration based on ATENA simulation

The analysis highlights clear economic distinctions across propulsion options for airport tow tractors. Diesel represents the most expensive option due to escalating fuel and maintenance expenses. Battery electric variants offer lower operating costs but incur significant upfront investment and battery replacement costs, with green-powered BEVs further improving economic viability.

Fuel cell vehicles, particularly those using hydrogen from methane reforming, demonstrate the most competitive TCO, benefiting from lower energy costs and minimal component replacements within the evaluation period. Conversely, fuel cells reliant on purchased hydrogen approach diesel in total cost due to higher energy expenses. Overall, fuel cell technologies powered by cost-effective hydrogen production pathways present a promising, economically advantageous alternative for airport ground support equipment.

5.4 Emissions and Social Cost Integration

The increasing focus on environmental sustainability and greenhouse gas emission reduction has made the integration of CO_2 emission assessments indispensable in the Total Cost of Ownership calculations of vehicles. Accurately accounting for emissions within TCO frameworks is essential to fully capture the environmental and economic impacts of different vehicle technologies (IPCC, 2022). Recent studies emphasize that including CO_2 emissions in ownership cost analyses supports more informed decisions towards low-carbon mobility solutions.

Specifically, for airport vehicles such as tow tractors, considering emissions not only on a "*tank-to-wheel*" (TTW) basis, that is, those generated directly during vehicle operation, but also on a "*well-to-wheel*" (WTW) basis, as shown in *Table 5*, which includes the entire lifecycle of fuel or energy production and distribution, allows for a more comprehensive and realistic estimation of the environmental impact associated with different propulsion technologies. This approach is essential to guide operational and strategic decisions aimed at sector decarbonization and to holistically evaluate the economic and environmental costs associated with each technological option.

Starting with the diesel model, the Tank-to-Wheel emissions are quite high, amounting to approximately 28,704 kg of direct CO_2 over 10 years. This value is based on an emission factor of about 2.64 kg of CO_2 per Liter of diesel consumed, multiplied by the total Liters of diesel used during the period. The Well-to-Wheel emissions are even higher, reaching around 35,328 kg of CO_2, corresponding to an overall emission factor of approximately 3.2 kg of CO_2 per Liter of diesel, as these emissions include the entire supply chain from extraction, refining, to fuel transportation. Overall, the total emissions of the diesel vehicle amount to roughly 64 tonnes of CO_2 over 10 years.

Considering the BEV case with grid electricity, there are no Tank-to-Wheel emissions since the vehicle produces no emissions during operation. The Well-to-Wheel emissions amount to approximately 12,764 kg of CO_2, calculated using an emission factor of 0.73 kg CO_2 per kWh multiplied by the annual energy consumption[11]. These emissions stem from the electricity consumed, which is generated from a mixed energy mix not fully renewable. The total emissions equal about 13 tonnes, significantly lower than those of the diesel vehicle.

In the case of a BEV powered by green energy, there are also zero Tank-to-Wheel emissions since the vehicle produces no emissions during use. The Well-to-Wheel emissions amount to only 327.9 kg of CO_2, based on data from the IPCC Sixth Assessment Report (AR6, 2022), which accounts for greenhouse gas emissions (in g CO_2/kWh) associated with major electricity generation technologies over their full life cycle (including production, construction, operation, and disposal). These emissions

[11] Source: SunEarthTools CO_2 emissions calculator

are minimal because the electricity is sourced from renewable energy. The total emissions amount to just 0.33 tonnes.

For FCEV refuelled by green hydrogen (green H_2), the Well-to-Wheel emissions are approximately 1 kg CO_2 per kg of H_2 consumed. Given a consumption of 872.8 kg over 10 years, this results in about 873 kg of CO_2, or a total of 0.87 tonnes of CO_2 emissions.

For FCEVs refuelled with hydrogen produced via Steam Methane Reforming, the Well-to-Wheel emissions are significantly higher, approximately 10 kg CO_2 per kg of H_2 consumed. With a consumption of 872.8 kg over 10 years, this corresponds to about 8,728 kg of CO_2, or roughly 8.73 tonnes of total emissions.

In the absence of information regarding its origin, purchased hydrogen is generally assumed to be produced via Steam Methane Reforming, currently the most prevalent production method. Since SMR relies on natural gas, it is associated with a relatively high carbon footprint.

CO_2 Emissions	**Diesel**	**E-HV Grid**	**E-HV Green**	**Fuel Cell H_2 Green**	**Fuel Cell H_2 Industrial SMR**	**Fuel Cell H_2 Commercial**
Tank-to-Wheel (kg)	28.704	0	0	0	0	0
Well-to-Wheel (kg)	35.328	12.764	327	873	8.728	8.728
Total (t)	64	13	0,33	0,9	9	9

Table 5: CO_2 Emissions Comparison by Vehicle Technology and Fuel Source Type (kg and tonnes)[12]

In summary, both electric and hydrogen-powered tow tractors offer significant environmental and operational advantages over diesel, including lower emissions and reduced energy and maintenance costs, hydrogen-powered vehicles, particularly those using low-carbon or renewable hydrogen, stand out for their greater operational flexibility, shorter refuelling times, and higher suitability for intensive duty cycles. These features make hydrogen a compelling option for airports aiming to decarbonize operations without compromising performance or availability.

It's important to underline that incorporating the Social Cost of Carbon (SC-CO_2) into the Total Cost of Ownership (TCO) framework allows for a more holistic evaluation of the advantages offered by sustainable vehicle models. The SC-CO_2 represents the monetized value of global damages caused by the emission of one additional tonne of CO_2, including effects on health and extreme weather.

This value is essential for internalizing the environmental externalities of fossil fuel use and for guiding both public and private investment decisions toward low-emission technologies.

According to Rennert et al. (2022), the updated CO_2 is estimated at $185 per tonne of CO_2 (in 2020 USD), which corresponds to approximately €164 per tonne using average exchange rates. Their methodology integrates advanced Earth system models to simulate the long-term effects of CO_2 emissions on global warming, capturing uncertainties and a range of realistic climate scenarios. Economic impacts are assessed through empirical damage functions that quantify how climate change affects key sectors such as human health, economic productivity, agriculture, energy systems, and ecosystems. These impacts are evaluated globally over extended time horizons. Future damages are discounted using

[12] Source: authors' elaboration based on *the European Environment Agency and the GREET model by Argonne National Laboratory and IPCC* Sixth Assessment Report

lower discount rates (e.g., 2%), reflecting greater concern for intergenerational equity. Additionally, the model accounts for geographic differences in vulnerability and adaptive capacity across countries.

This integrated and transparent framework yields a significantly higher estimate of the Social Cost of CO_2 (SC-CO_2) compared to previous benchmarks, enabling a more accurate assessment of the climate-related externalities of vehicle emissions. The revised value, over three times higher than the former U.S. government estimate, reflects advances in probabilistic socioeconomic projections, updated climate modelling, refined damage functions, and consistent discounting practices. These enhancements are embedded in the open-source Greenhouse Gas Impact Value Estimator (GIVE) model, offering a solid scientific basis for policy analysis. Incorporating this updated SC-CO_2 into TCO calculations highlights the greater economic advantage of low-emission vehicles, reinforcing the long-term value of sustainable transport investments, particularly in high-emission sectors such as logistics and airport operations.

It becomes clear that the external costs associated with diesel vehicles are substantial, as illustrated in the chart below.

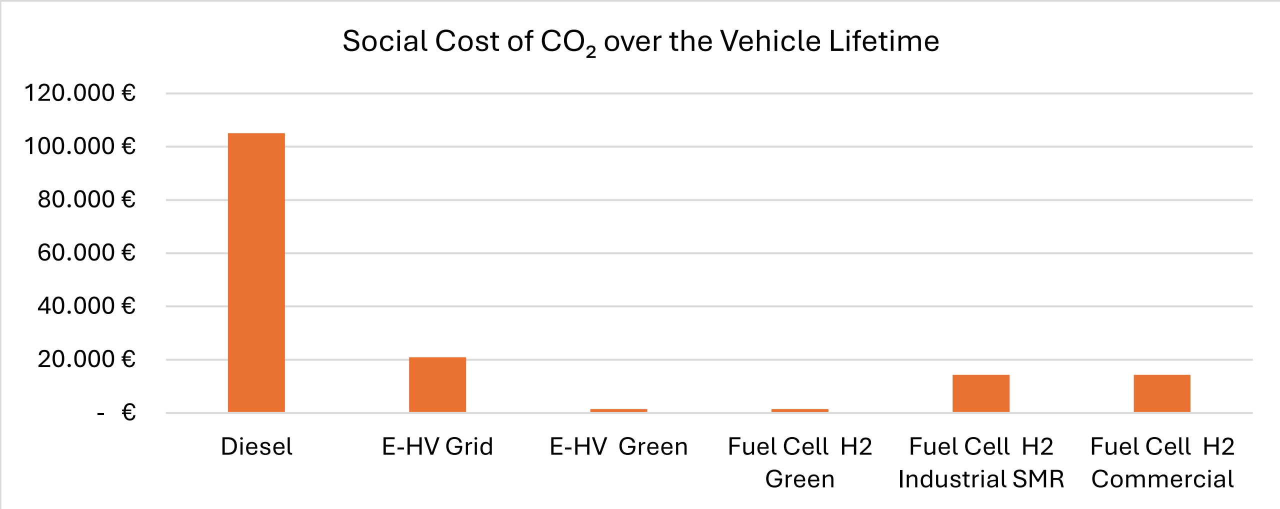

Figure 2: Social Cost of CO_2 Emissions over the Vehicle Lifetime

The environmental advantages of FCEVs are particularly evident in high-demand logistics settings, where operational flexibility and sustainability are critical. The analysis confirms that, under specific operational conditions and favourable hydrogen cost scenarios, FCEVs can represent a cost-effective alternative to both diesel and battery-electric options, especially in mission-critical and high-utilization contexts. Furthermore, FCEVs support long-term decarbonization strategies, offering strategic value that extends beyond short-term economic considerations.

Based on average emission factors per Liter of diesel, the total emissions of key primary air pollutants are estimated, including NOx, PM2.5, PM10, SO_2, NH_3, and NMVOC. These emission factors (expressed in g/l) are derived from established literature and technical databases for Euro IV–V diesel road vehicles operating in urban and peri-urban environments and are appropriately adapted to reflect the airport operational context.

Pollutant	**Emission Factor (g/l)**
NOx	2.5
PM2.5	0.05
PM10	0.07

SO_2	0.13
NH_3	0.01
NMVOC	0.17

Table 5: Emission Factors per Liter of Diesel (g/l)[13]

These values are approximations and conversions of emission factors for moderately efficient diesel vehicles, based on data from two main sources: the *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023*, which provides detailed emission factors for various vehicle categories and operating conditions, and the *EDGAR* (*Emissions Database for Global Atmospheric Research*), which offers a global inventory of anthropogenic emissions.

Multiplying these factors by the total fuel consumption, the cumulative pollutant emissions over 10 years are calculated. To quantify the associated externalities, each pollutant's total emission is multiplied by its respective social cost per kg, expressed in €2016 values (*Table* 6). These cost coefficients are obtained from the European Commission's Handbook on the External Costs of Transport (2019), calibrated for the Polish context, and include health-related damages, environmental degradation, and broader societal impacts due to air pollution exposure.

Pollutant	**Total Emissions (kg)**	**Social Cost (€/kg)**	**Total Social Cost (€)**
NOx	27,6	14,7	4057 €
PM2.5	0,55	91	502 €
PM10	0,77	16	124 €
SO_2	1,4	8	118 €
NH_3	0,11	14	16 €
NMVOC	1,8	0,7	13 €
Total			**4,830.7 €**

Table 6: Social Costs of Diesel Emissions[14]

As a result, the total social cost of pollutant emissions from a single diesel tow tractor over its 10-year lifetime amounts to approximately €4,830. This value adds significantly to the overall environmental burden of diesel technologies and strengthens the case for transitioning to cleaner alternatives, such as electric or hydrogen-powered vehicles, particularly in sensitive environments like airports.

5.5 Final Ranking and Policy Implications

To more accurately capture the societal impact of the different propulsion technologies, the TCO is expanded to include the social cost of emissions over a 10-year operational period. This component accounts for both CO_2 emissions and local air pollutants (e.g., NO_x, PM, SO_2), monetized using average European social cost values, with specific reference to the Polish context and literature-based estimates for the social cost of carbon (SC-CO_2). A discount rate of 4% was used to calculate the present value of costs.

[13] Source: databases for Euro IV–V diesel road vehicles
[14] Source: European Commission's Handbook on the External Costs of Transport (2019)

When considering the externalities associated with emissions, the Total Cost of Ownership of the diesel tow tractor increases significantly. While its base TCO amounts to €440,892 over a 10-year lifetime, the addition of environmental externalities, €105,014 from CO_2 and €4,831 from local air pollutants, raises the total to €550,736. Even when applying discounting, the present value remains substantial at €372,058.

In contrast, battery electric tow tractors powered by electricity from the grid or renewable sources exhibit markedly lower external costs. The grid-powered version results in a total discounted TCO of €396,545 and a present value of €267,892. The version powered by green electricity performs even better, with a total discounted TCO of €353,507 and a present value of €238,817, due to its negligible emissions profile.

FCEVs present competitive alternatives depending on the hydrogen production method. The FCEV operating on green hydrogen reaches a total discounted TCO of €366,619, with a present value of €247,674, comparable to the green electric option. The reforming-based hydrogen alternative shows the lowest total among the hydrogen options, with a discounted TCO of €339,103 and a present value of €229,086. However, FCEVs relying on commercially purchased hydrogen incur significantly higher costs, with a total discounted TCO of €506,512 and a present value of €342,181.

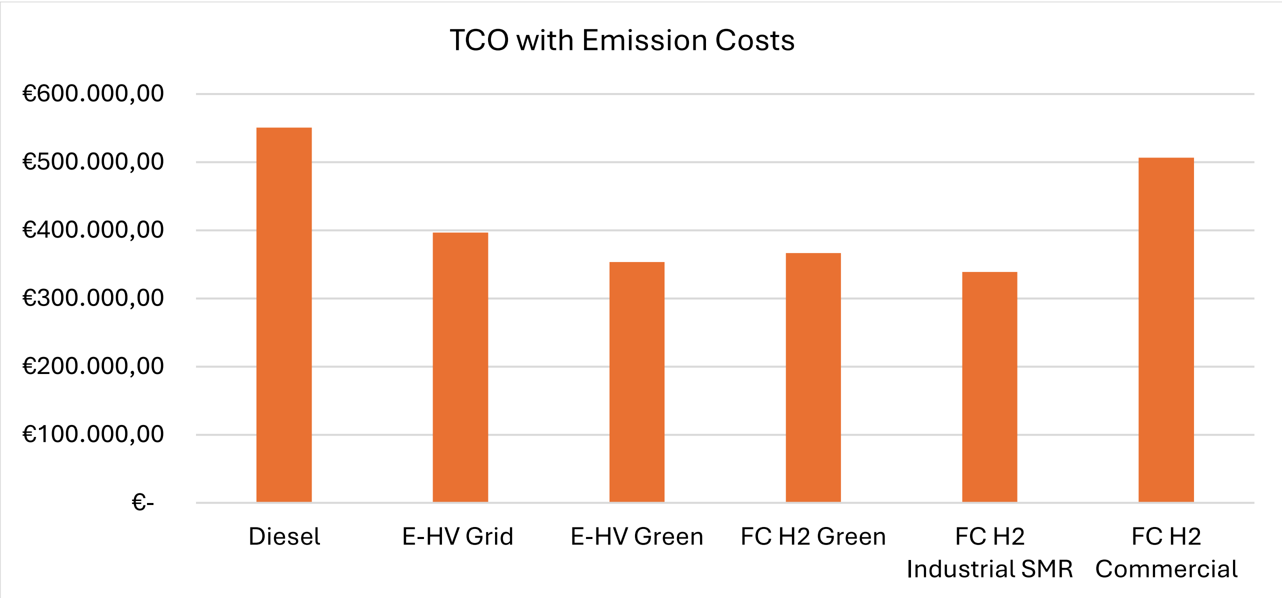

Figure 3: Total TCO with emission costs

These findings reinforce the importance of integrating externalities into cost analyses. Once emissions are accounted for, low and zero-emission technologies, especially those relying on renewable sources, emerge as economically and environmentally preferable, particularly in high-utilization sectors such as airport logistics.

The comparative analysis of BEVs and FCEVs within airport operations highlights a complex balance between economic viability and environmental sustainability. Our results corroborate existing literature indicating that, under current energy price scenarios, green BEVs and FCEVs fuelled by hydrogen produced via Steam Methane Reforming represent the most cost-competitive options over the vehicles' lifecycle.

However, a crucial differentiation arises when considering the carbon intensity of hydrogen production pathways. SMR-based hydrogen, while economically advantageous due to established infrastructure and lower immediate costs, is associated with significant upstream CO_2 emissions, unless coupled with carbon capture and storage (CCS) technologies. Conversely, hydrogen produced via renewable-powered electrolysis, often termed “green hydrogen”, aligns closely with the European Union’s climate neutrality targets, representing a truly sustainable energy vector for FCEVs (Staffell, I., et al. 2019).

Similarly, BEVs charged from the grid carry an emissions profile heavily influenced by the electricity mix (TERM 2018: Transport and Environment Reporting Mechanism). Airports located in regions with a high share of renewables in their electricity grid benefit from substantially lower life-cycle emissions compared to those relying on fossil-dominated. This underlines the importance of region-specific analyses and the integration of renewable energy sources, such as on-site photovoltaic systems, to maximize environmental benefits.

The trade-off between short-term cost savings and long-term environmental objectives poses a significant challenge for airport fleet procurement policies. While SMR hydrogen FCEVs may currently offer lower total cost of ownership, their deployment risks perpetuating fossil fuel dependency unless paired with robust decarbonization strategies. This is consistent with the framework established by the European Union Regulation (EU) 2020/852, which emphasizes the necessity to direct investments towards sustainable activities that contribute substantially to climate change mitigation and avoid ‘lock-in’ effects on fossil fuel-based technologies. Policymakers should therefore consider financial incentives, subsidies, and regulatory mechanisms that prioritize renewable energy procurement and penalize upstream emissions, aligning airport fleet investments with the EU’s long-term net-zero goals (European Commission, 2020b., ITF 2021)

Additionally, non-financial benefits, such as reduced local air pollution, noise, and improved occupational health, must be factored into procurement decisions. These co-benefits align with airports’ sustainability commitments and community relations goals, often translating into indirect economic advantages.

In conclusion, this study emphasizes that aligning airport vehicle fleets with net-zero targets requires not only technological adoption but also systemic support for renewable energy production and usage. Future research should explore integrated energy systems combining renewable generation, storage, and hydrogen production to optimize both cost and environmental performance. Moreover, comprehensive policy frameworks that internalize environmental externalities will be essential to transition airport ground support equipment towards truly sustainable operation (Franke J., 2023).

6. Conclusion

The transition to hydrogen-powered heavy-duty vehicles at airports represents not only a significant environmental advancement but also a strategic economic opportunity for the future (Testa et al., 2014). By reducing dependence on fossil fuels, lowering emissions, and improving operational efficiency, hydrogen technology aligns with both environmental sustainability goals and the need for economic resilience. While the initial investment in hydrogen infrastructure may be substantial, the long-term benefits, such as reduced operating costs, quicker refuelling times, and the potential for job creation within the emerging hydrogen supply chain, make it a financially sound decision for airports (Li et al ., 2024).

The integrated Total Cost of Ownership analysis, incorporating the social costs associated with greenhouse gas emissions and local air pollutants, provides a comprehensive and quantitatively rigorous assessment of the true economic and environmental impacts of various technologies applied to airport vehicles.

This approach represents a novel integration of environmental externalities into economic viability assessments for airport logistics, offering a replicable model for future studies.

The results demonstrate that, over a ten-year horizon, low and zero-emission solutions represent a strategically sound choice not only environmentally, but also economically once external emission costs are accounted for. Specifically, hydrogen fuel cell vehicles stand out for their ability to combine sustainability with operational performance, particularly in contexts characterized by high utilization rates and minimal downtime requirements, such as airport logistics. Unlike BEVs, which may be constrained by longer charging times and infrastructure limitations, FCEVs offer rapid refuelling and extended driving range, critical factors in environments with intensive operational demands and continuous work cycles.

The discounted cost comparison reveals that FCEVs provide a competitive TCO relative to BEVs, benefiting from significantly lower emission costs and greater operational flexibility. This positioning makes hydrogen-powered vehicles particularly suitable to support the decarbonization of the airport sector, contributing to ambitious emission reduction targets without compromising efficiency and operational continuity.

Finally, the systematic inclusion of the social costs of emissions underscores the importance of adopting an integrated, multidimensional approach in long-term economic assessments, favouring technologies capable of mitigating the overall environmental impact. The adoption of FCEVs and BEVs powered by renewable energy sources, therefore, represents a crucial lever for a sustainable and economically viable transition of the airport vehicle fleet.

Moreover, financial incentives from European funding mechanisms further enhance the economic viability of these projects. The project at Warsaw Chopin Airport serves as a concrete example of the potential of hydrogen-powered vehicles to transform airport operations, acting as a model for the large-scale adoption of sustainable and economically advantageous solutions in the aviation sector. This project not only demonstrates the feasibility of low-impact technologies but also provides a replicable model that can be extended to other airports, and potentially to other freight and mobility hubs, such as regional logistics platforms and green hydrogen corridors, contributing to the achievement of global sustainability goals and economic resilience for the entire sector.

Despite the promising results, several challenges remain. The economic competitiveness of hydrogen-powered vehicles is still strongly dependent on favourable hydrogen pricing scenarios and the availability of dedicated infrastructure, which may vary significantly across regions and airport sizes. Moreover, the analysis assumes stable technology costs and excludes long-term degradation effects that could influence real-world performance and maintenance requirements. These factors should be considered in future studies to refine the assessment framework.

Future research should explore the integration of dynamic energy pricing, infrastructure deployment models, and broader socio-environmental indicators, such as stakeholder acceptance and social life cycle impacts. Additionally, expanding the scope to include other critical logistics hubs, such as seaports, intermodal freight platforms, or regional transport corridors, could provide valuable insights to support policy design and investment prioritization.

In this regard, the HySPARK initiative offers a scalable blueprint for hydrogen deployment that aligns with both territorial decarbonization strategies and European green industrial policy objectives.

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Reference

Blanchard, J. (2020). Fuel Cell Powered Airport GSE (Ground Support Equipment) Deployment (No. DOE-Plug Power-0006093). Plug Power, Latham, NY (United States).

Bruce, S., Temminghoff, M., Hayward, J., Palfreyman, D., Munnings, C., Burke, N., & Creasey, S. (2020). Opportunities for hydrogen in aviation. Csiro.

Bubeck, S., Tomaschek, J., & Fahl, U. (2016). *Perspectives of electric mobility: Total cost of ownership of electric vehicles in Germany*. Transport Policy, 50, 63–77. https://doi.org/10.1016/j.tranpol.2016.05.012

Chong, A. T., & Pileggi, S. (2020). A Review of Hydrogen Fuel Cell Vehicle Maintenance and Operation Costs. Energy Policy, 135, 111004.

Coenen, L., Benneworth, P., & Truffer, B. (2012). *Toward a spatial perspective on sustainability transitions*. Research Policy, 41(6), 968–979.

Diercks, G., Larsen, H., & Steward, F. (2019). *Transformative innovation policy: Addressing variety in an emerging policy paradigm*. Research Policy, 48(4), 880–894. https://doi.org/10.1016/j.respol.2018.10.028

Electric vehicles from life cycle and circular economy perspectives TERM 2018: Transport and Environment Reporting Mechanism (TERM) report.

European Commission (2020). *A hydrogen strategy for a climate-neutral Europe (COM/2020/301)*

European Commission (2020b), "Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment and amending Regulation (EU) 2019/2088.

Franke, J. (2023). The power of technological innovation: Driving sustainable mobility. In Road to Net Zero (pp. 215–264).

Handbook on External Costs of Transport – European Commission (2019).

IPCC (2022). *Climate Change 2022: Mitigation of Climate Change*. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University

ITF (2021), "Decarbonising Air Transport: Acting Now for the Future", International Transport Forum Policy Papers, No. 94, OECD Publishing, Paris.

Kukutschka, R. M., & Heidenreich, S. (2019). Maintenance and Operation Costs of Electric and Hydrogen Vehicles: A Review of Published Data. Transportation Research Part D: Transport and Environment, 67, 85-99.

Li, F., Liu, D., Sun, K., Yang, S., Peng, F., Zhang, K., Guo, G., & Si, Y. (2024). Towards a Future Hydrogen Supply Chain: A Review of Technologies and Challenges. Sustainability, 16(5), 1890.

Rennert, K., Errickson, F., Prest, B.C., Rennels, L., Newell, R.G., Pizer, W., Kingdon, C., Wingenroth, J., Cooke, R., Parthum, B., Smith, D., Cromar, K., Diaz, D., Moore, F.C., Müller, U.K., Plevin, R.J., Raftery, A.E., Ševčíková, H., Sheets, H., Stock, J.H., Tan, T., Watson, M., Wong, T.E., & Anthoff, D. (2022). Comprehensive evidence implies a higher social cost of CO_2. Nature, 610, 240–245. https://doi.org/10.1038/s41586-022-05224-9

Staffell, I., et al. (2019). The role of hydrogen and fuel cells in the global energy system. Energy & Environmental Science, 12(2), 463-491.

Testa, E., Giammusso, C., Bruno, M., & Maggiore, P. (2014). Analysis of environmental benefits resulting from use of hydrogen technology in handling operations at airports. Clean Technologies and Environmental Policy, 16, 875-890.

Truffer, B., Murphy, J. T., & Raven, R. (2015). *The geography of sustainability transitions: Contours of an emerging research field*. Environmental Innovation and Societal Transitions, 17, 63–72. https://doi.org/10.1016/j.eist.2015.07.004