Life Cycle Assessment of Hydrogen Fuel Cell, Biodiesel, and Electric Ground Support Equipment at Airports

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Abstract

The aviation industry is under increasing pressure to decarbonize its operations, with ground support equipment (GSE) being a significant contributor to emissions at airports. This study presents a comparative Life Cycle Assessment (LCA) of three alternative fuel technologies—Hydrogen Fuel Cells (HFC), Biodiesel, and Electric GSE—focusing on their environmental impacts, energy efficiency, and feasibility in airport operations. Using cradle-to-grave analysis, we assess emissions, energy consumption, and ecological footprints associated with the entire lifecycle of each technology. The results indicate that while each alternative presents unique advantages and limitations, electric GSE outperforms others in emissions reduction, whereas hydrogen offers greater operational flexibility. Biodiesel, though a cleaner option than conventional fuels, faces sustainability and scalability concerns. This paper offers critical insights for stakeholders considering transitions to low-carbon airport operations.

Keywords: Life Cycle Assessment, Hydrogen Fuel Cell, Biodiesel, Electric Vehicles, Ground Support Equipment, Airport Sustainability, Emissions, Renewable Energy

I. Introduction

Airports worldwide are striving to become greener by adopting alternative fuels for their ground support equipment (GSE), such as baggage tractors, belt loaders, and tugs. Traditionally powered by diesel or gasoline, these vehicles contribute significantly to local air pollution and greenhouse gas emissions. In response, technologies such as electric, hydrogen fuel cell, and biodiesel-powered GSE have emerged as potential solutions[1].

Life Cycle Assessment (LCA) provides a systematic approach to evaluating the environmental impacts associated with all stages of a product's life. This study uses LCA methodology to compare hydrogen fuel cell, biodiesel, and electric-powered GSE in terms of emissions, energy use, and ecological impact. Understanding the full life cycle of each fuel type is essential for stakeholders making infrastructure and investment decisions for sustainable airport operations.

This research aims to guide airport authorities, environmental policymakers, and technology providers in selecting the most efficient and environmentally friendly GSE technologies. The analysis emphasizes cradle-to-grave evaluations that include production, distribution, use, and disposal phases[2].

Airports are complex ecosystems with numerous operational components that contribute to overall energy consumption and environmental impact. One often overlooked but significant source of emissions is ground support equipment (GSE), which includes vehicles and machinery used for aircraft servicing, passenger handling, cargo transport, and maintenance operations. Traditionally, GSE has been powered by fossil fuels such as diesel and gasoline, resulting in substantial greenhouse gas (GHG) emissions, air pollutants, and noise. As global efforts intensify to mitigate climate change and improve urban air quality, there is a growing demand for sustainable alternatives in aviation-related ground operations.

In response, various low-emission technologies have been introduced, including electric vehicles (EVs), biodiesel-fueled engines, and hydrogen fuel cell systems. Each of these technologies offers different benefits and limitations in terms of performance, infrastructure requirements, cost, and environmental impact[3]. To make informed decisions about adopting these technologies, stakeholders need a comprehensive understanding of their life cycle implications—not just during operation, but also across production, maintenance, and disposal phases[4]. This context underlines the importance of conducting a Life Cycle Assessment (LCA), which provides a holistic evaluation of environmental performance and guides sustainable transitions in airport operations.

II. Methodology and LCA Framework

To evaluate and compare the environmental impacts of hydrogen fuel cell, biodiesel, and electric ground support equipment (GSE) at airports, this study employs a comprehensive Life Cycle Assessment (LCA) approach. The LCA methodology is based on internationally recognized standards ISO 14040 and ISO 14044, which outline the principles, framework, and requirements for conducting an effective environmental analysis from a cradle-to-grave perspective. This means the entire life cycle of each GSE technology is considered—from raw material extraction and manufacturing to use and end-of-life disposal or recycling.

The functional unit selected for this assessment is the operation of one GSE vehicle over a 10-year lifespan or 30,000 operational hours[5]. This standardized unit allows for direct comparisons across different technologies by normalizing impacts to the same level of service. The system boundaries include: (1) fuel/energy production (e.g., hydrogen generation, biodiesel processing, electricity supply), (2) vehicle and battery manufacturing, (3) equipment use phase (including fuel combustion or electricity consumption), and (4) end-of-life treatment (such as recycling or landfilling of components and batteries).

Primary data for the assessment is sourced from peer-reviewed literature, GSE manufacturers, and life cycle databases such as Ecoinvent and GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation). The LCA considers key impact categories such as Global Warming Potential (GWP), cumulative energy demand, air pollutant emissions (e.g., NOx, PM), and resource depletion[6]. Assumptions include using the average U.S. electricity grid mix for electric GSE, B20 biodiesel made from soy oil, and hydrogen sourced from both steam methane reforming (SMR) and renewable-powered electrolysis.

Finally, sensitivity analyses are conducted to assess how changes in key variables—such as energy source, fuel feedstock, or usage patterns—affect the LCA outcomes. This step enhances the robustness of the results and ensures that the conclusions are relevant across a range of real-world conditions. By integrating these methodological components, the study aims to deliver a balanced, data-driven comparison of alternative GSE technologies for airport sustainability planning.

III. Hydrogen Fuel Cell Ground Support Equipment

Hydrogen fuel cell GSE operates by converting hydrogen gas into electricity through electrochemical reactions, emitting only water vapor. This technology offers the advantage of fast refueling times and extended range compared to electric alternatives. However, hydrogen production methods play a pivotal role in the overall environmental impact.

The LCA indicates that hydrogen produced via SMR generates high upstream CO_2 emissions, diminishing the climate benefits of the fuel cell. Electrolysis using renewable energy sources substantially reduces GWP but comes with high energy demand and infrastructure costs. Transportation and storage of hydrogen also contribute to fugitive emissions and safety concerns[7].

Despite these drawbacks, hydrogen fuel cells demonstrate superior performance in high-utilization, heavy-duty GSE applications where downtime must be minimized. The viability of this technology is closely tied to advancements in green hydrogen production and the development of airport hydrogen infrastructure[8].

IV. Biodiesel-Powered Ground Support Equipment

Biodiesel is a renewable alternative fuel derived from biological sources such as vegetable oils, animal fats, and used cooking oils. It can be used in its pure form (B100) or blended with petroleum diesel in various proportions, with B20 (20% biodiesel, 80% petroleum diesel) being the most common. One of the primary advantages of biodiesel is its compatibility with existing diesel engines and infrastructure, making it an attractive option for airports seeking a lower-emission solution without significant equipment or operational changes.

From a life cycle perspective, biodiesel significantly reduces greenhouse gas (GHG) emissions compared to conventional diesel. These reductions are primarily due to the carbon-neutral nature of biomass feedstocks, which absorb CO_2 during growth. However, the actual environmental benefit depends heavily on the feedstock source[9]. For instance, waste-derived biodiesel (e.g., from used cooking oil) tends to have a lower environmental footprint than biodiesel made from virgin soybean or palm oil. The latter may contribute to indirect land-use changes, deforestation, and food-versus-fuel debates, which undermine the sustainability of biodiesel.

In operational terms, biodiesel-powered GSE exhibits similar performance to diesel-powered equipment, maintaining reliability and fuel efficiency in most use cases. Maintenance costs may be slightly higher due to the fuel's solvent properties, which can clean and clog fuel systems, especially during initial use. Biodiesel also has higher NOx emissions than petroleum diesel, posing challenges for compliance with local air quality regulations. Despite these concerns, the use of biodiesel still results in lower emissions of particulate matter (PM), carbon monoxide (CO), and hydrocarbons, contributing to improved air quality around airport environments[10].

Economically, biodiesel is often more expensive than petroleum diesel, although this gap has been narrowing with government incentives, carbon pricing, and rising demand for renewable fuels. Its immediate deployability and low infrastructure requirements make it a favorable transitional solution for airports, particularly those in regions with limited access to electricity or hydrogen infrastructure. However, its scalability is constrained by feedstock availability, price volatility, and long-term sustainability concerns. For airports aiming for deep decarbonization, biodiesel may serve best as a short- to medium-term strategy within a broader portfolio of cleaner technologies.

V. Electric Ground Support Equipment

Electric GSE is powered by batteries that store energy from the electrical grid or on-site renewable sources. This technology is increasingly favored for its zero tailpipe emissions, low operating noise, and minimal maintenance requirements. With the rising availability of renewable electricity, electric GSE is gaining widespread adoption.

The LCA demonstrates that electric GSE has the lowest GWP among the three options when charged with a clean or partially decarbonized grid. Battery manufacturing contributes to the initial environmental burden, particularly in terms of mining rare earth elements like lithium and cobalt. However, these impacts are offset over the vehicle's lifetime due to high energy efficiency and minimal operational emissions[11].

Challenges for electric GSE include limited range, long charging times, and the need for robust charging infrastructure. Nevertheless, as battery technologies and grid decarbonization improve, electric GSE presents the most promising long-term solution for sustainable airport operations[12].

VI. Comparative Analysis and Discussion

The comparative Life Cycle Assessment (LCA) of hydrogen fuel cell, biodiesel, and electric ground support equipment (GSE) reveals distinct environmental, operational, and infrastructural trade-offs. Each technology exhibits unique advantages depending on the airport's operational scale, energy availability, and environmental priorities. This section synthesizes the LCA findings to help identify the most viable solutions for sustainable airport ground operations.

From an environmental standpoint, electric GSE demonstrates the lowest life cycle greenhouse gas (GHG) emissions**,** especially when powered by a renewable or partially decarbonized electricity grid. Battery electric vehicles (BEVs) produce no tailpipe emissions, significantly improving local air quality around airports—a critical factor in densely populated urban environments[13]. Despite the environmental burden of battery production, especially the mining of lithium, cobalt, and nickel, these impacts are largely offset over the equipment's service life due to the high energy efficiency and lower operational emissions[14].

In contrast**,** hydrogen fuel cell GSE performs well in terms of emissions during operation, emitting only water vapor. However, its overall environmental benefit is highly dependent on the method of hydrogen production. Hydrogen from steam methane reforming (SMR) is associated with high upstream carbon emissions, while green hydrogen from renewable-powered electrolysis drastically reduces the GWP. Nonetheless, green hydrogen remains costly and requires substantial infrastructure investments, including high-pressure storage, refueling stations, and safety systems[15]. Operationally, hydrogen GSE offers fast refueling and longer range, making it suitable for high-duty cycles where electric charging would be too time-consuming.

Biodiesel-powered GSE, particularly using B20 blends, provides a transitional pathway from conventional diesel, offering moderate emissions reductions and compatibility with existing engines. The LCA shows that biodiesel can reduce lifecycle GHG emissions by 50–80%, depending on the feedstock, with waste oils performing significantly better than crop-based sources. However, biodiesel may lead to increased NOx emissions and raises concerns about land use change**,** biodiversity loss, and food security when derived from agricultural feedstocks. Despite these concerns, biodiesel requires minimal infrastructure upgrades and is relatively easy to integrate into current GSE fleets.

In terms of infrastructure and cost**,** electric GSE requires upfront investment in charging infrastructure and grid upgrades but benefits from lower energy and maintenance costs over time. Hydrogen GSE demands significant capital investment and coordination for fuel delivery and storage, which may not be practical for smaller or medium-sized airports. Biodiesel, on the other hand, leverages existing fuel supply chains, making it the most immediately deployable but least scalable in the long term.

VII. Conclusion

The transition of airport ground support equipment to low-emission technologies is a vital component of aviation sector decarbonization. This LCA-based comparison underscores the environmental and operational trade-offs of hydrogen fuel cell, biodiesel, and electric GSE. While electric equipment currently offers the best lifecycle performance in terms of emissions and energy use, hydrogen and biodiesel technologies have niche applications where they may be more suitable.

Future airport sustainability initiatives should prioritize electrification while supporting R&D in green hydrogen and advanced biofuels. Policy measures, infrastructure development, and supply chain improvements will play a decisive role in accelerating the adoption of cleaner GSE technologies. A data-driven, lifecycle-based approach remains essential for informed decision-making in the pursuit of net-zero airport operations.

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