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THE FUTURE OF GROUND HANDLING IN THE FORM OF ELECTRIC GROUND SUPPORT EQUIPMENT

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Abstract: The research aims to find out how the adoption of Electric Ground Support Equipment (eGSE) in the future can provide efficiency and emission reductions in every flight operation at airports. The problem of the research is the environmental impact and cost inefficiency of using fossil fuel-based GSE in the aviation industry. To resolve the problem, the research will use quantitative methods with cost-benefit analysis, where the data is collected from secondary sources, specifically price comparison data for electric GSE and fossil fuel GSE and their respective maintenance costs. The result is that the transition from conventional fossil fuel-based Motorized Ground Support Equipment to electric Motorized GSE in the aviation sector offers a viable solution for companies driven by both economic and environmental factors. This transition is expected to lead to significant reductions in emissions and operational costs.

Keywords: Ground Support Equipment, Electric Vehicle, Cost Comparison, cost-benefit analysis, Aviation

1 Introduction

In recent years, every industry has shown attention in estimating the negative influence (pollution and waste) it has on the environment, in particular, the transportation industry is a major polluting industry. Air transportation occupies a special place because of the rules of movement in high elevation (Nešić, Čavka, and Čokorilo, 2015) and the Industry has accounted for 2.4% of all human-caused CO2 emissions, accounts for 12% of total annual transportation emissions and 4% of the human-caused global warming that has been observed to date (Klöwer, 2021), and in practice according to Creutzig in (Klöwer et al. 2021) Aviation can produce up to 100 times more emissions per hour than rail, bus or shared car travel. This corresponds to the increasing global demand for aviation, for example in 2023 (measured in RPK kilometers) up 36.9% compared to 2022. Globally, traffic throughout 2023 reached 94.1% of pre-pandemic (2019) levels. December 2023 total traffic was up 25.3% compared to December 2022 and reached 97.5% of December 2019 levels. Fourth quarter traffic reached 98.2% of 2019, reflecting a strong recovery towards the end of the year (IATA, 2024).

With the increasing demand for air transportation, the aviation industry is expected to continue to grow. As a result, greater investment and funding will be required for the development, improvement and maintenance of airports, which must continue to be maintained (Sameh and Scavuzzi, 2016). According to Graham in (Sari, 2022) Airport managers have an obligation to provide facilities and services that support the air transportation industry. Their duties include terminal services, ground transportation facilities, provision of rail terminals, as well as management of cargo transportation between flight terminals and passenger terminals. In addition, they are also responsible for the management of commercial airports, ground transportation or hub airports, parking infrastructure, access to the airport, and various other related aspects outside the airport terminal boundaries.

Air transportation support service facilities that are vital to flight operations include ground support equipment. GSE is support equipment found at airports, usually on the

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apron, a service area near the terminal. This equipment is used to service aircraft between flights. As the name suggests, GSE exists to support aircraft operations while on the ground. The role of this equipment generally involves ground electrical operations, aircraft mobility, and cargo/passenger loading operations and GSE ensures smooth operation in air transportation(Ur Rahman and Akbar, 2023).

However, the use of GSE at the airport as a means of supporting flight operations still uses a lot of fossil fuels which are the main cause besides APU and aircraft engines in air pollution in the airport environment. GSE produces emissions such as nitrogen oxides (NOx), volatile organic compounds (VOC), polycyclic aromatic hydrocarbons (PAH), sulfur dioxide (SO2), and other materials (Koch, 2012.) and causes two categories of environmental effects. The first is local effects, which are felt in the area near the airport, in the form of noise, decreased air quality, land damage. Although there are efforts to mitigate the effects that occur, it has not been able to overcome some local effects such as noise. Then there are global effects that affect general living conditions on planet Earth, such as the use of non-renewable natural resources non-renewable natural resources (especially oil and some metals), the use of air space and radio spectrum space, and contributions to global warming that can increase climate change climate change and have a major impact on public opinion (ICAO,2002) in (Sznajderman, 2022).

Electric GSE is here to be the solution for airport operators to reduce emissions within the airport environment. Electrification in GSE and the aviation industry is driven by several key factors. First, it is in line with the global push for sustainability and carbon emission reduction. Given that the aviation industry makes a significant contribution to greenhouse gas emissions and air pollution, efforts to reduce environmental impact are critical. Electrification provides a cleaner alternative to diesel-powered equipment, thereby reducing carbon footprint and air pollution.

Therefore, within the airport, Ground Support Equipment plays an important role in reducing emissions through the transition to electrification of Ground Support Equipment (Aerospace, 2012) in (Sari, Mohamed, and Jalil 2022).

In this research we would like to discuss the future and sustainability of ground support equipment through GSE electrification.

2 Literature Review

2.1 Previous Research

Table 1
Previous Research

Title, Researcher, Year	Research method	Result
"The Optimization Using Electric Ground Support Equipment in Aviation Industry", Sari, 2022	Quantitative	The study finds that the options, diesel-powered GSE shows the highest NPV, making it a more profitable investment compared to electric-powered GSE over 25 years

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"Electric vehicle (EV) and driving towards sustainability: Comparison between EV, HEV, PHEV, and ICE vehicles to achieve net zero emissions by 2050 from EV", Veza, 2023	Quantitative	EVs produce higher NOx and N2O emissions of more than 70 %, indicating a dependence on fossil fuels for electricity generation. Air quality-related emissions, including SOx and PM10, are 90 % and 85 % higher in EVs, emphasizing the need for enhanced emission control technologies and the adoption of renewable energy sources. Despite their higher selling price and emission costs, EVs possess the lowest maintenance costs among the evaluated vehicles

2.2 Pollution

According to Manisalidis (2020) pollution is defined as the introduction into the environment of substances harmful to humans and other living organisms. Pollutants are harmful solids, liquids, or gases produced in higher than usual concentrations that reduce the quality of our environment.

Air pollution has various health effects. The health of susceptible and sensitive individuals can be impacted even on low air pollution days. Short-term exposure to air pollutants is closely related to COPD (Chronic Obstructive Pulmonary Disease), cough, shortness of breath, wheezing, asthma, respiratory disease, and high rates of hospitalization (a measurement of morbidity).

2.3 Emission

According to Giuffre and Grana in (Sari, 2022) Airports cause significant environmental harm through emissions generated during both airport operations and surrounding activities. This pollution can endanger the health of nearby residents. Airport management is increasingly recognizing their contribution to climate change through construction, daily operations, and maintenance.

According Talib in (Sari, 2022) The number of harmful pollutants and greenhouse gases emitted by ground support equipment (GSE), excluding electric models, is primarily determined by engine size (measured in brake horsepower), fuel type (diesel or gasoline), engine operating time, and workload. Workload refers to the average energy demand compared to the equipment's maximum capacity. Air pollution largely stems from vehicles, and levels of nitrogen oxide (NO) and carbon monoxide (CO) significantly decreased during the COVID-19 pandemic due to reduced traffic.

2.4 Airport

According to Wei and Gosling (2013) Airports serve as the main hubs in the passenger transportation network, connecting local and regional transit systems with national and international travel. Additionally, airports play a role in transferring air cargo between ground transportation and air travel, and sometimes act as key sorting and distribution centers for freight transported solely by land.

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Definition of airport according to Annex 14 in (Standards, 2009) from ICAO (International Civil Aviation Organization), "An airport is a specific area of land or water (including buildings, installations and equipment) designated either in whole or in part for the arrival, departure and movement of aircraft".

2.5 *Ground Handling*

Ground handling is a series of activities carried out by airlines related to passenger handling and services, including baggage, cargo, post, and aircraft equipment on the ground, both on arrival and departure (Evi and Sutarwati, 2022).

Ground Handling operations encompass and play an important role in all activities that take place on the airside of the airport (Fitouri-Trabelsi et al. 2015). This activity covers a wide range of essential services required by the aircraft during the period between landing and take-off. These services can be classified into three main categories: ramp services, on-ramp services, and on-board services. Each category includes several sub-services, such as aircraft parking services which comprise of directing, supervising, parking and push-back.

To ensure effective execution of ground handling operations, several key parameters must be observed. Primarily, for delays to be avoided or minimized, the performance of ground handling operations must reach optimal standards. Efficient resource management and proper assignment of personnel to operate vehicles, considering the route and schedule constraints, are crucial factors in the success of these operations.

2.6 *Ground Support Equipment*

According to IATA (2015) GSE is the equipment located at an airport, typically on the apron near the terminal, used to service aircraft between flights. As indicated by the name, GSE supports aircraft operations while they are on the ground. Its functions generally include providing ground power, facilitating aircraft movement, and handling cargo and passenger loading.

2.7 *Regulation & Policy*

In the context of implementing electric GSE at airports, the regulations contained in (Presidential Regulation No 79, 2023) regarding the acceleration of the battery electric vehicle program can significantly affect the adoption and use of electric-based equipment. This regulation aims to accelerate the transition from the use of fossil fuel vehicles to electric vehicles through various government supports, both in the form of fiscal and non-fiscal incentives.

One of the main effects of this regulation is the provision of incentives for the electric vehicle industry and its supporting components, which also includes electric GSE. Under

Article 17, the Central and Local Governments will provide incentives that encourage innovation and development of electric vehicle technology, including incentives for the development of electric charging infrastructure. This is particularly relevant in the context of airports, where GSE equipment requires access to efficient charging stations to support sustainable operations. Public Electric Vehicle Charging Stations and Battery Exchange Stations are regulated as part of the electric vehicle support ecosystem.

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Furthermore, this regulation also encourages the development of domestic components through the Domestic Component Level policy, which means that industries producing electric GSE must comply with local content requirements, which will increase over time. By 2027, for example, electric vehicles with four or more wheels adopted for GSE are required to have a minimum of 60% domestic components, which increases to 80% by 2030. This policy aims to strengthen local industries and reduce dependence on imported components, which is in line with economic and technological sustainability goals.

In addition, this regulation supports the acceleration of electric GSE implementation through the provision of convenience in charging infrastructure, as stated in Article 26. Airports as dense operational hubs will benefit from the ease of customization of electrical installations and the development of SPKLUs in public places, which includes public facilities such as airports. This will enable wider use of electric GSE in the airport environment with adequate charging infrastructure.

Overall, the regulations in Presidential Regulation No. 79 of 2023 strengthen the legal basis and provide significant incentives for the development and use of electric ground support equipment at airports. Good implementation of this regulation is expected to reduce carbon emissions from airport operations, improve energy efficiency, and support national targets in accelerating the adoption of electric vehicles in Indonesia.

3 METHODOLOGY

This research examines the practicality of switching to electric GSE in the aviation industry by comparing costs and benefits. The study uses a quantitative approach, analyzing existing data from previous research to evaluate the financial feasibility of this transition. Specifically, the research will employ financial analysis techniques such as Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (BCR) to assess the long-term profitability and sustainability of electric GSE compared to traditional fuel-powered equipment.

Quantitative methods are particularly suitable for this research due to their ability to provide objective and numerical data.

3.1 Data Collection

The Data for the study was gathered from operational records of both gasoline/diesel and electric ground support equipment. Key factors considered include the initial purchase costs, ongoing expenses like maintenance and energy use, and the advantages of reduced pollution and improved operational efficiency.

3.2 Cost & Benefit Analysis

The study analyzed the costs of using electric ground support equipment (e-GSE). Costs were divided into upfront expenses for buying and ongoing costs like maintenance and refueling/charging cost.

$$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+r)^t} - C_o$$

Where:

NPV = Net Present Value

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Bt = Benefit in year
Ct = Cost in year
r = Discount rate
t = Time in year
n = total number of years
Co = Initial investment cost

Net Present Value (NPV) is the total current worth of a project's future earnings minus its costs. To calculate NPV, we subtract the cost from the benefit for each time period. Then, we adjust these future values to account for their timing using a discount rate. If the final NPV is positive, the project is potentially profitable.

$$IRR = R_1 + \frac{NPV_1 \times (R_2 - R_{1)}}{NVP_1 - NPV_2}$$

Where:
R1 = Lower Discount Rate
R2 = Higher Discount Rate
NPV1 = NPV using R1
NPV2 = NPV using R2

The Internal Rate of Return (IRR) is a financial metric used to evaluate the performance of an investment or project by calculating its annualized rate of return, IRR represents the rate at which an investment grows (or declines) over time, considering both the timing and magnitude of cash inflows and outflows(Mellichamp, 2017).

$$BCR = \frac{PV\ of\ Benefits}{PV\ of\ Cost}$$

Benefit-Cost Ratio is a financial metric used to evaluate the feasibility of a project or investment by comparing the present value of all benefits generated from a project/asset to the present value of all costs(Pannell, 2024).

Interpretation:
BCR > 1: Indicates that the project has more benefits than cost, making it financially profitable.
BCR = 1: Indicates that the project has a balanced benefits and cost, with no clear profit or loss.
BCR < 1: Indicates that the project is more costly with fewer benefits, making it unprofitable.

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4 Result and Discussion

Table 2
Rough Estimates of Cost Between Diesel and Electric

No	Name of GSE	Initial Cost		Annual Maintenance Cost		Refueling/Charging Cost per Hour	
		Diesel	Electric	Diesel	Electric	Diesel	Electic
1	Aircraft Tow Vehicle	$ 200,000	$ 275,000	$ 3,500	$ 1,500	$ 6.50	$ 2.75
2	Belt Loader	$ 75,000	$ 90,000	$ 2,250	$ 1,000	$ 6.50	$ 1.25
3	Baggage Tractor	$ 45,000	$ 60,000	$ 1,750	$ 1,000	$ 3.25	$ 1.25
4	Ground Power Units	$ 60,000	$ 75,000	$ 2,000	$ 1,000	$ 3.25	$ 1.25
Total		$ 380,000	$ 500,000	$ 9,500	$ 4,500	$ 20	$ 7

Sources: Various Ground Support Equipment Manufacturer & Ground Handling Companies

Table 1 above provides a comparative analysis of different GSE based on their initial purchase cost, annual maintenance cost, and refuelling/charging cost per hour for both diesel and electric-powered models. The initial cost highlights the upfront investment required for each type of GSE, while the annual maintenance cost reflects the recurring expenses to keep the equipment operational, the refuelling/charging cost per hour compares the ongoing fuel or energy expenses between diesel and electric options.

The rough estimate is based on data sourced from various ground support equipment manufacturers and ground handling companies, providing an overview of the potential expenses associated with operating different types of GSE.

4.1 *Initial Cost*

One of the primary challenges facing the adoption of electric GSE is the higher upfront cost compared to traditional diesel GSE. The price of the battery is a significant influence due to the costs of raw materials like lithium, cobalt, and nickel to make these batteries large enough to provide adequate power for Ground Handling operations thus adding to the initial expense (Bubeck, Tomaschek, and Fahl, 2016). Another factor is that diesel powered GSE has been the industry standard for many years, as a result has large scale manufacturing. Electric GSE, being relatively new, lacks the same level of mass production, which keeps manufacturing costs high.

In conclusion, these factors contribute to the overall higher price of electric GSE, making it approximately 24% more expensive to purchase than diesel-powered GSE.

4.2 *Annual Maintenance Cost*

In maintenance electric GSE has a lower cost compared to diesel GSE. Some of the factors that influence it is electric GSE has fewer moving parts compared to internal combustion engines (ICE) found in diesel GSE that consist of numerous components such as pistons, crankshafts, fuel injectors, and exhaust systems, which require regular maintenance and replacement to ensure optimal performance and prevent overheating, emissions issues, and engine wear (Veza, 2023). Electric GSE eliminates the need for these systems, thereby reducing maintenance requirements and associated costs.

Which results in a lower annual maintenance cost than diesel GSE, approximately 52%.

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4.3 *Refuelling/Charging Cost*

Electric GSE offers substantial cost savings in refueling or charging compared to traditional diesel-powered GSE. From Table 1, electric GSE can be up to 65% cheaper to charge than its diesel counterparts. This significant difference is driven by several factors such as lower electricity prices due to it being less volatile and is often subject to long-term rate agreements, providing more predictable energy costs. In contrast, diesel prices can fluctuate significantly due to market conditions and geopolitical factors, leading to higher and less predictable fuel expenses.

4.4 *Net Present Value*

Tabel 3
Data

Parameters	Diesel	Electric
Initial Cost	\$380,000	\$500,000
Annual Maintenance Cost	\$9,500	\$4,500
Refueling/Charging Cost/Hour	\$20	\$7
Annual Operating Hours	5760	5760
Lower Discount Rate	5%	
Higher Discount Rate	10%	
Annual Income	\$390.2 billion	
Analysis Period (Years)	10	10

Table 3 presents a comparative NPV analysis with data from table 2 between a diesel-powered GSE and an electric GSE over a 10-year period. The analysis considers the initial purchase cost, annual maintenance costs, and fuel or energy costs with a discount rate of 5% and 10% with an estimate annual income of \$390.2 billion and annual operation of 5,760 hours.

Table 4
Cash Flow Calculation

Year	Diesel Annual Operating Cost	Electric Annual Operating Cost	Annual Income	Discount Factor (5%)	Discount Factor (10%)	Discounted Cash Flow (Diesel)		Discounted Cash Flow (Electric)	
						5%	10%	5%	10%
0	\$ 380.000	\$ 500.000	-	1,000	1,000	\$ -380.000	\$ -380.000	\$ -500.000	\$ -500.000,00
1	\$ 124.700	\$ 44.820	\$ 390.200.000.000	0,9524	0,9091	\$ 371.626.361.236	\$ 354.730.706.635	\$ 371.626.437.313	\$ 354.730.779.254,14
2	\$ 124.700	\$ 44.820	\$ 390.200.000.000	0,9070	0,8264	\$ 353.911.286.897	\$ 322.461.176.948	\$ 353.911.359.348	\$ 322.461.242.960,75
3	\$ 124.700	\$ 44.820	\$ 390.200.000.000	0,8638	0,7513	\$ 337.054.652.284	\$ 293.157.166.313	\$ 337.054.721.284	\$ 293.157.226.326,73
4	\$ 124.700	\$ 44.820	\$ 390.200.000.000	0,8227	0,6830	\$ 321.017.437.409	\$ 266.506.514.830	\$ 321.017.503.127	\$ 266.506.569.387,94
5	\$ 124.700	\$ 44.820	\$ 390.200.000.000	0,7835	0,6209	\$ 305.721.602.298	\$ 242.275.102.574	\$ 305.721.664.884	\$ 242.275.152.171,26
6	\$ 124.700	\$ 44.820	\$ 390.200.000.000	0,7462	0,5645	\$ 291.167.146.949	\$ 220.267.829.607	\$ 291.167.206.555	\$ 220.267.874.699,11
7	\$ 124.700	\$ 44.820	\$ 390.200.000.000	0,7107	0,5132	\$ 277.315.051.376	\$ 200.250.576.004	\$ 277.315.108.146	\$ 200.250.616.998,38
8	\$ 124.700	\$ 44.820	\$ 390.200.000.000	0,6768	0,4665	\$ 264.087.275.603	\$ 182.028.241.827	\$ 264.087.329.666	\$ 182.028.279.091,47
9	\$ 124.700	\$ 44.820	\$ 390.200.000.000	0,6446	0,4241	\$ 251.522.839.618	\$ 165.483.767.115	\$ 251.522.891.109	\$ 165.483.800.991,84
10	\$ 124.700	\$ 44.820	\$ 390.200.000.000	0,6139	0,3855	\$ 239.543.703.447	\$ 150.422.051.928	\$ 239.543.752.485	\$ 150.422.082.721,89
Total						\$ 3.012.966.977.117	\$ 2.397.582.753.781	\$ 3.012.967.473.918	\$ 2.397.583.124.604

Table 4 presents a comparison of the total NPV of electric GSE and diesel GSE, highlighting their cost-effectiveness over time. The NPV for electric GSE is \$

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3.012.967.473.918 & $ 2.397.583.124.604, while the NPV for diesel GSE is significantly lower at $ 3.012.966.977.117& $ 2.397.582.753.781. The higher NPV for electric GSE suggests that it's a more cost-effective option in the long run despite its higher initial purchase cost as the reduced operational expenses, particularly in maintenance and energy costs, make it a financially more sustainable option over time.

4.5 Internal Rate Of Return

Table 5
IRR

Equipment Type	IRR
Diesel	7,45%
Electric	7,45%

Table 5 shows that electric GSE has an equal IRR compared to diesel GSE, indicating it offers the same return on investment over the 10-year period.

4.6 Benefit-Cost Ratio

Table 6
BCR

Equipment Type	Discount Rate	Benefits	Costs	Benefit-Cost Ratio
Diesel	5%	$ 3.012.966.977.117	$ 1.342.884	2243655
	10%	$ 2.397.582.753.781	$ 1.146.219	2091732
Electric	5%	$ 3.012.967.473.918	$ 846.082	3561082
	10%	$ 2.397.583.124.604	$ 775.396	3092074

Table 6 indicates that while both have high BCR, electric GSE has a higher BCR compared to Diesel GSE, suggesting that it is more financially beneficial.

4.7 Discussion

The transition from diesel-powered Ground Support Equipment (GSE) to electric GSE presents both challenges and opportunities for the aviation industry. A significant barrier to the adoption of electric GSE is the higher initial purchase cost. As outlined, electric GSE can be approximately 24% more expensive than diesel GSE, primarily due to the high cost of batteries and the relatively small scale of current manufacturing. The price of batteries is influenced by the costs of raw materials like lithium, cobalt, and nickel, which are necessary to produce batteries large enough to provide adequate power for ground handling operations. Additionally, diesel-powered GSE benefits from having been the industry standard for many years. In contrast, electric GSE is relatively new and lacks the same level of mass production, which keeps manufacturing costs elevated.

Despite the higher upfront costs, electric GSE offers notable advantages in terms of operational costs, particularly in maintenance and refueling/charging. Electric GSE has fewer moving parts compared to the ICE in diesel GSE, which consist of numerous components such as pistons, crankshafts, fuel injectors, and exhaust systems. These components require regular maintenance and replacement to ensure optimal performance and prevent issues such as overheating and engine wear. By eliminating the need for these systems, electric GSE significantly reduces maintenance requirements and associated costs. As a result, electric GSE has a lower annual maintenance cost, approximately 52% less than diesel GSE.

In addition to maintenance savings, electric GSE provides substantial cost savings in refueling or charging. According to data presented in Table 2, charging electric GSE can be up to 65% cheaper than refueling diesel counterparts. This cost difference is driven by the lower and more stable price of electricity, which is less volatile and often subject to long-term rate agreements, providing more predictable energy costs. Conversely, diesel prices can fluctuate significantly due to market conditions and geopolitical factors, leading to higher and less predictable fuel expenses.

The NPV, IRR, and BCR analysis highlights that, although electric GSE has a higher upfront cost, its lower annual operating costs result in a higher NPV and BCR compared to diesel GSE with the exception being an equal IRR. This suggests that the electric GSE may be a more financially sustainable choice over the 10-year period.

Given the rising emphasis on sustainability and potential future incentives for electric vehicles, the actual financial performance could improve if these factors were considered. Further analysis could include sensitivity testing to assess the impact of varying discount rates, fuel costs, and maintenance costs on the NPV results.

5 Conclusion

The transition from diesel-powered GSE to electric GSE presents both challenges and opportunities for the aviation industry. While the higher initial purchase cost of electric GSE is a significant barrier, driven largely by the cost of batteries and the smaller scale of production, there are substantial long-term advantages. Electric GSE offers lower operational costs, particularly in maintenance and refuelling, due to the simplicity of its components and the stability of electricity prices compared to diesel. Although electric GSE requires a larger upfront investment, the potential for reduced ongoing expenses makes it a financially sustainable choice over time. As the industry moves toward greater sustainability, and with the possibility of future incentives for electric vehicles, the adoption of electric GSE could become even more advantageous.

6 Implications

The transition from diesel-powered Ground Support Equipment (GSE) to electric GSE has significant implications for the aviation industry, particularly in terms of cost management, sustainability, and industry practices. The higher initial purchase cost of electric GSE presents a challenge that could slow adoption rates, especially for smaller or budget-constrained ground handling companies. However, the long-term advantages of electric GSE, including lower operational costs in maintenance and refuelling, suggest that these barriers may be offset over time by financial savings.

For industry stakeholders, these findings imply the need to reconsider the total cost of ownership when evaluating equipment purchases. Companies may need to adjust their investment strategies, taking into account not only the upfront cost but also the potential for reduced operational expenses and the benefits of more predictable energy costs associated with electric GSE.

From a policy perspective, the shift toward electric GSE could drive the development of new incentives or subsidies to encourage adoption, particularly in the

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context of increasing regulatory pressure to reduce carbon emissions. Policymakers might also consider the implications for infrastructure development, as the widespread adoption of electric GSE will require significant investment in charging facilities and energy supply management.

Furthermore, these findings underscore the importance of continuing research and development in battery technology and manufacturing processes to reduce costs and improve the feasibility of electric GSE. As the industry moves toward greater sustainability, these advances could make electric GSE an increasingly attractive option, potentially accelerating the transition away from diesel-powered equipment.

In summary, the implications of this transition extend beyond immediate financial considerations, influencing long-term industry trends, regulatory frameworks, and technological innovation, all of which will shape the future of ground support operations in aviation.

7 Research Limitation

While this study provides valuable insights into the transition from diesel-powered to electric GSE in the aviation industry, several limitations should be acknowledged. First, the sample size was relatively small and focused on a limited number of GSE manufacturers, which limit the generalizability of the findings to other regions. Additionally, the study relied on cost data provided by manufacturers and ground handling companies, which may not fully account for all potential operational variables, such as unexpected maintenance issues or fluctuations in energy prices over time.

Another limitation is the study's reliance on current technological capabilities and cost structures. As battery technology and electric GSE production methods continue to evolve, the costs associated with electric GSE may decrease, potentially altering the cost-effectiveness of these options in the future. Furthermore, the study did not consider potential future regulatory changes or environmental incentives that could impact the financial viability of electric GSE.

Finally, the time frame considered in the NPV analysis was limited to ten years. While this period provides a reasonable estimate for long-term cost analysis, the actual lifespan of GSE equipment can vary, and longer-term studies could yield different results. Future research could address these limitations by expanding the sample size, including a broader range of operational environments, and considering longer time frames and evolving technologies.

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