Environmental and Climate Technologies
2024, vol. 28, no. 1, pp. 863–879
https://doi.org/10.2478/rtuect-2024-0066
https://content.sciendo.com

Comparative Life Cycle Assessment of Airport Ground Operations: Environmental Impact of Diesel, Biodiesel, and Electric Sources

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Received 22.10.2024; accepted 18.11.2024

Abstract **– In pursuit of the United Nations (UN) Sustainable Development Goals (SDGs), nations are growing more conscious of the importance of implementing SDGs and adopting various tools and frameworks to advance environmental and human development. Current study aims to investigate the environmental impacts of airport ground operations through Life Cycle Assessment (LCA) and was conducted on three different Ground Power Units (GPU) namely, diesel, biodiesel, and electric-powered by adopting a system boundary of cradle-to-gate, using *SimaPro* version 9.4 software and adopted a CML Baseline V3.09 EU25 characterization model. Results show that the highest environmental impact was caused by diesel-powered GPU, followed by the biodiesel-powered GPU. At the same time, the electric-powered GPU contributed to lower environmental impact in comparison. The Abiotic Depletion (AD) in the diesel, biodiesel, and electric-powered GPU in a respective manner was (in kg Sb eq, 0.196, 0.196 and 0.162), global warming (kg CO_2 eq of 1142, 1130 and 1044), Ozone Depletion Potential (ODP) (kg CFC-11 eq of 0.0003, 0.0001 and 0.0001), Human Toxicity Potential (HTP) (kg 1,4-DB eq of 516.49, 510.96 and 549.29), Freshwater Aquatic Ecotoxicity (kg 1,4-DB eq of 441.56, 463.22 and 605.91), Terrestrial Ecotoxicity (kg 1,4-DB eq of 2.74, 2.31 and 2.35), Photochemical Oxidation (kg C_2H_4 eq of 0.609, 0.70 and 0.545), Acidification (kg SO_2 eq of 11.01, 11.23 and 10.11) and Eutrophication of (kg PO_4 eq 3.432, 3.459 and 3.2311). Batteries, diesel, aluminium, wheel rims, and synthetic rubber were the main contributors to these environmental impacts. It was concluded that lead-ion batteries are a good replacement to lithium-ion batteries due to their lower impact. Similarly, switching to stationary GPUs rather than mobile, can contribute to lowering impacts as the wheel rims in mobile GPUs are the main contributors to overall environmental impact of airport ground operations.**

Keywords **– Airport operations; aviation emissions; GPUs; Life Cycle Assessment; sensitivity analysis; sustainability.**

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1. INTRODUCTION

Aviation infrastructure is a key part of modern-day transportation networks. Airports play a crucial role in facilitating the transport of people and goods in today's highly globalized society. Over 40 000 airports are located throughout the world [1]. An estimated number of more than 4.5 billion passengers were handled by over 2500 airports in 2022 [2]. This number is expected to increase in coming years and consequently, airports must invest heavily to update and renovate outdated and insufficient airport infrastructure, including airfields, terminals, and service equipment. The impact of airport operations and maintenance on the environment, including building renovations, runway, terminal lighting, aircraft maintenance, parked aircraft servicing, Auxiliary Power Unit (APU), and Ground Service Equipment (GSE) operations during aircraft turnaround time, are noteworthy and should be considered. To investigate ways to successfully reduce the aviation industry's contribution to climate change, a thorough environmental accounting of the sector should consider the Greenhouse Gas emissions (GHGs) from these operations. An estimated 5 % of the total GHGs from the aviation sector are attributed to airport operations [3]. This amount is understated because it does not account for the entire range of emissions from all airport operations, such as maintenance, engineering, and construction [4]–[7].

There are ways to lower the emissions produced by the aviation sector, such as reducing aircraft emissions, which often comprise most of an airport's operating emissions. The Airport Cooperative Research Program (ACRP) has developed best practices and support tools to help minimize climate-related impacts like rising sea levels, destructive storms and wildfires, and population displacement. Reducing an airport's facility-related emissions will also help meet the global and national GHG emission reduction targets and determine possible operational GHG mitigation options [8]. In addition to GHG emissions, air pollution from airport operations and maintenance activities includes the release of Carbon Monoxide (CO), Nitrogen Oxides (NO_x), and Particulate Matter (PM); the disturbance and destruction of natural ecosystems; the production of waste; and the use of resources like water, electricity, and energy [4].

Most of an airport's operating emissions come from aircraft; and there are multiple opportunities to mitigate these emissions within the airport perimeter and reduce emissions connected to airport facilities [8]. Identifying and quantifying the energy and raw materials used, emissions, and waste produced, as well as assessing the choices for minimizing the possible environmental effects of these factors, are essential components of Life Cycle Assessments (LCA) [9]. With 221 billion ton-km of freight and over 4.4 billion people travelling in 2018, the aviation sector is essential to the world's transport network. The sector accounts for 2–3 % of the world's emissions caused by humans [10], [11]. Still, aviation activities are anticipated to have a more considerable portion of environmental impacts as other industrial and transportation sectors decarbonize more readily [12]. Mapping the carbon footprint of aircraft operations, such as take-off, cruise, and landing, is more extensive than mapping the carbon footprint of airport operations, such as runway and terminal lighting, aircraft maintenance, and aircraft parking. Airports are thought to account for just 5 % of the GHG emissions produced by the aviation industry overall. Yet, this estimate is inaccurate since it does not account for the complete range of emissions from all operational activities, including embodied and regional impacts. A thorough environmental accounting of the aviation sector must consider emissions from all airport operations as it looks for ways to reduce its impact on climate change more effectively, to include not only aircraft but GSE as well [3], [13].

The introduction and assessment of alternative energy sources for airport GSE has led to outstanding questions that require answering through further research. The environmental performance of these alternative energy sources, and main drivers of the environmental impacts associated with each source are yet to be explored. To get insights into these aspects, the objective of this study is to investigate the GHG mitigation potential of using biofuels and electricity to replace diesel for GSE (impact assessment). The impact of 'micro level' mitigations of equipment component replacements on overall environmental impacts (sensitivity analysis) is also carried out. To answer the scoping questions, a comprehensive LCA of three energy sources was conducted, as described in the methodology part of the article.

2. LITERATURE REVIEW

The aviation industry has provided, for decades, unprecedented mobility and economic benefits to the world. It became an important mode of transport for people and goods and contributed to the expansion of trade between nations. Currently, the industry is accountable for 3 % of global GHG emissions and this figure is expected to rise as other industries move faster towards decarbonizing their operations [11], [14]. The rise in demand for air travel, coupled with fast-paced global economic growth, has led to the industry experiencing unprecedented levels of energy consumption, increased pollutant emissions, and growing pressure on airports to expand and support this growth [15]. The environmental impacts from airports are significant and spread across various sources within it, ranging from energy consumption in terminal buildings, servicing of aircraft on ground, and operation of GSE, to name a few [16]. Emissions from these sources may be produced from outdoor and indoor activities. Indoor emissions mainly include carbon dioxide emissions from passengers and airport staff. Direct outdoor emissions occur from aircraft operations, ground transportation, ground support during aircraft turnarounds (the time taken for unloading and ground handling preparation for the return journey of an aircraft), and operation of diesel generators. The airport operator directly controls emissions from fuel for airport vehicles, purchased energy, and diesel generators. However, airports do not directly control emissions from airport tenants' operations, aircraft movement in hangar areas, airline vehicles, and ground service equipment [17].

Currently, emissions associated with airports are significant, with airport operations accounting for 5 % of total aviation sector's emissions, an underestimated figure as it does not account for total airport activities [4], [18]. In recent years, several scholars have measured the impact of aviation activities within the airport perimeter and developed inventories of air pollutants and their sources [19]–[21]. These studies are however limited to "tailpipe" emissions from aircraft during landing and take-off cycles and GSE operating during aircraft turnaround operations. As of the writing of this research, there are no known publications that comprehensively assess airport emissions across various activities within the airport's perimeter. On the other hand, LCA studies conducted on airports are currently focused on airport pavement construction [22], [23], airport buildings [24], and airport waste [25]–[27]. The only LCA study known to the authors highlighting impacts of airport operations, is published by Altuntas *et al.* (2014), where a gate-to-gate method of LCA is used in comparing the environmental impacts of aircraft APU and airport's GPU [28].

In previous studies, when an APU was utilized to supply electrical power and heating/cooling for parked aircraft, the life cycle technique was utilized to estimate GHG emissions. However, GSEs were not included in the research [29]. Similarly, LCA approaches were used in other studies to quantify the exhaust (tailpipe) emissions of aircraft, ground handling activities, and the environmental impacts of these activities. However, the LCA of the APU and GSE operations during aircraft turnaround time was not specified [30]. Several other researchers [4], [31] identified the lack of research on airport emissions from APU and GSE operations, which drew attention. Their findings prove that little research has been done on how airport GSE operations affect the environment. Recently we performed a systematic literature review to assess the environmental impacts of airport operation and maintenance activities. The study identified knowledge gaps, particularly in LCA of APUs and GSE operations. It also recommended research into alternative energy sources at airports to reduce the environmental impacts of petrol- and diesel-powered GSE [2]. Greer *et al.* (2020) emphasized the need for comprehensive sustainability metrics for airports beyond greenhouse gas emissions. They highlighted research themes such as airfield pavements' GHG emissions and energy management strategies for airport buildings. They noted a disconnect between research and airport practices but suggested effective strategies for short-term sustainability goals [4]. In another study, Greer *et al.* (2023) explored the environmental and human health impacts of terminal building construction and operation in US commercial airports. The Airport Terminal Environmental Support Tool (ATEST) was developed to assess baseline emissions and mitigate climate change damage. The findings of this study revealed the significance of electricity mix and construction in determining emissions across various case-study airports [13]. Lastly, Greer *et al.* (2021) examined the potential GHG reductions and economic benefits of electrifying gate operations at global airports. Complete electrification could yield significant GHG reductions and financial savings, with the extent of reduction dependent on electricity sources and operational parameters [32]. It should be noted that while these studies concentrate on specific aspects of airport operations, the role and contribution of GSEs in the context of GHG emissions from airports is yet to be explored. This paper therefore explores a type of GSE, the GPU, and develops an understanding of its environmental impacts, and potential scope for emission reduction from these units.

3. METHODOLOGY

The International Organization for Standardization (ISO) has organized and standardized the LCA approach i.e., ISO 14040-14044 series, which serves as the foundation for further, more specialized standards like ISO 14045 (eco-efficiency) and ISO 14067 (carbon footprint). The ISO standard for carrying out an LCA adheres to a precise approach separated into four stages [33]–[35]. The first is the Goal and Scope Definition stage, the most essential phase of the LCA study, during which the analysis' goal is determined, and the assumptions, functional unit, and system boundaries are clearly stated. This phase defines and describes the product, method, or activity and the environmental burdens to be examined in the study. This is followed by defining the Functional Unit, where for this study, one GPU of each type, i.e., diesel, biodiesel, and electric- powered was selected. All the inputs and outputs data were expressed in terms of one GPU functional unit. Following that, the system boundary was set which was limited to the cradle-to-gate approach and encompassed transportation of energy resources and raw materials to the GPU site, water consumption, solid waste generation, wastewater, and environmental emissions, as depicted in Fig. 1.

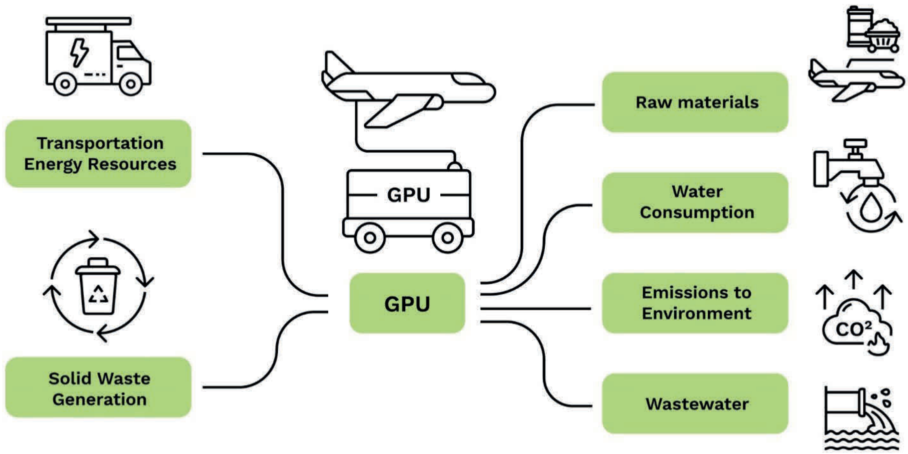

Fig. 1. Cradle-to-gate system boundary of GPUs.

The Inventory Analysis phase of the LCA study involved identifying and measuring materials, energy, water, and environmental discharges (such as air pollutants). This required gathering data to quantify the inputs of materials and energy as well as the output waste from the system, as shown in Tables 1, 2, and 3. This was followed by an Impact Assessment stage, involving: valuation, normalization, characterization, and categorization. The measurable environmental consequences are aggregated during the Inventory Analysis step to create identifiable impact categories, such as acidification, global warming, and climate change, etc. The final stage, Interpretations, involves drawing conclusions to aid in decision-making and provide data that is understandable and implementable. The information acquired is assessed here, drawing on the inventory analysis and impact assessments to provide a research conclusion [36], [37].

SimaPro version 9.4 software was utilized in conjunction with the *Ecoinvent* database. Other databases such as the United States Life Cycle Inventory (USLCI), ICAO emission databanks, government reports, and equipment manufacturers' manuals have been used. The Life Cycle Impact Assessment (LCIA) was performed using the CML V3.09 EU25 characterization model to calculate midpoint environmental impacts: Abiotic Depletion (AD), Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Eutrophication Potential (EP), Acidification Potential (AP), Photochemical Oxidation (PO), Marine Aquatic Ecotoxicity (MAE), Terrestrial Ecotoxicity (TE), Freshwater Aquatic Ecotoxicity (FAE), and Human Toxicity Potential (HTP) [38], [39]. The LCIA included the analysis of 1 kWh or MJ power generation by the GPU on different environmental components such as soil, air, and water. Contribution analysis is therefore conducted to understand the contribution of every input and output to the overall environmental impacts and to identify the hotspot inputs, outputs, and activities which accounted for major contribution to overall or some specific environmental impacts [40].

TABLE 1. LCI FOR DIESEL-POWERED GPU

Inputs	**Unit**	**Quantity**
Diesel consumption	L/h	10.1
Diesel fuel tank capacity	L	189
Engine oil/lubricating oil	L	11
Engine coolant (base oil)	L	18.9
Batteries (2)	kg	60
Transportation of diesel from gas station to GPU point	t·km	0.00015
Air filter	kg	1.814
Engine oil filter (0.3 kg kraft paper + 0.4 kg iron and steel for the outer metal case of the oil filter)	kg	0.7
Engine fuel filter (weight 3.5 kg) iron and steel metal = 2.1 kg, kraft paper = 1.4 kg	kg	3.5
Fan belts (synthetic rubber) (weight of a fan belt = 0.113 kg)	belts	0.339
Generator bearing	g	250
Wheels (aluminium rim 13.60 kg + tire (synthetic rubber) 12.24 kg)	kg	103.36
Radiator fan/alternator belt (synthetic rubber 48.96 kg)	kg	48.96
12-volt batteries	kg	30
Drive plate/clutch plate	kg	5
Screen cover (plate glass uncoated)	kg	3
Large screws (carbon steel)	kg	0.0250
Exciter cover (leather sheet/cover)	kg	1
lock washer (nylon)	kg	0.05
Spacer (steel alloyed)	kg	0.362
Outputs		
CO	g/kg	180
VOC	g/kg	54.81
NO_x	g/kg	718
SO_x	g/kg	1.89
PM_{10}	g/kg	45.36
$PM_{2.5}$	g/kg	45.36
CO_2	kg/kg	99.19
HC	g/kg	3.402

TABLE 2. LCI FOR ELECTRIC-POWERED GPU, RESULTS REPRESENTED IN KG UNLESS OTHERWISE MENTIONED

Inputs	**Quantity**
Battery	30
Input voltage/Electricity/Power = (15 A)	400–480 V (8 kWh)
Wheels (aluminium rim 13.60 kg + tyre (synthetic rubber) 12.24 kg)	103.36
Air Filter	7.256
Panel component (latch, emergency stop, etc.) metal	210 g
Panel mounting (solar panel)	20
Screws (carbon steel)	0.6
Door latch (metal)	300 g
Doors (metal)	40
Circuit breaker	0.128
Frame, mounting	4.5
Air duct (steel)	21
Cables	06.996
Wiring	0.270
Rubber, 0.875 in. I.D.	0.0009
Rubber, 1.12 in. I.D.	0.00045
Rail, component mounting (23 inches)	500 g
Fan box	17
Fan rail	800 g
Fan motor	20
Spacer	7.843
Outputs	
Trace pollutant emission levels	
Noise level	60 dB

TABLE 3. LCI FOR BIODIESEL-POWERED GPU

Input (for B100 blend WCO Biodiesel)	**Unit**	**Quantity**
Biodiesel/ Energy	Btu/lb	16.377
	Btu/gal	119.550
Biodiesel consumption	L/h	7, 10 % higher than diesel
Biodiesel fuel tank capacity (280 kg or litre = 74 gallons)	L	280 kg
Output		
CO_2	g/gal	197
HC	g/kWh	0.062
CO	122 g	32 % less than diesel
NO_x	860 g	19.7 % higher NO_x than diesel

4. Results

The following sub-sections present a comparative investigation of life cycle impacts of different GPUs considered. Each environmental impact is measured across the three units, with a presentation of the data obtained, as shown in Table 4. Similarly, Fig. 2, 3, and 4 show the environmental impacts of each type of GPU respectively.

TABLE 4. ENVIRONMENTAL IMPACTS: DIESEL-POWERED GROUND POWER UNIT (GPU)

Impact category	**Unit**	**Diesel Powered GPU**	**Biodiesel Powered GPU**	**Electric Powered GPU**
Abiotic depletion	kg Sb eq	0.19591199	0.195791662	0.162391031
Global Warming Potential (GWP100a)	kg CO_2 eq	1142	1130	1044
Ozone Layer Depletion (ODP)	kg CFC-11 eq	0.00025467	0.000130231	0.000106064
Human Toxicity Potential (HTP)	kg 1,4-DB eq	516.486662	510.955505	549.2893775
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	441.554748	463.2236653	605.910019
Terrestrial ecotoxicity	kg 1,4-DB eq	2.73960665	2.314995779	2.353128862
Photochemical oxidation	kg C_2H_4 eq	0.6086043	0.700065326	0.544951085
Acidification	kg SO_2 eq	11.0038667	11.22688672	10.11418264
Eutrophication	kg PO_4 eq	3.43277778	3.459170043	3.231101748

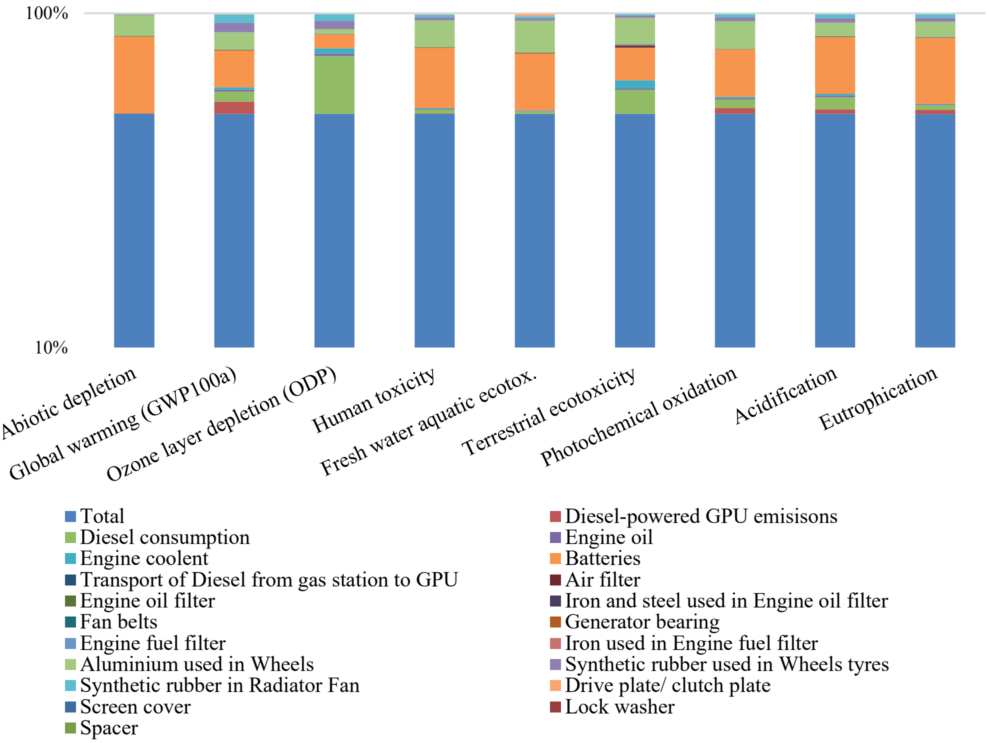

Fig. 2. Environmental impact of Diesel-powered GPU.

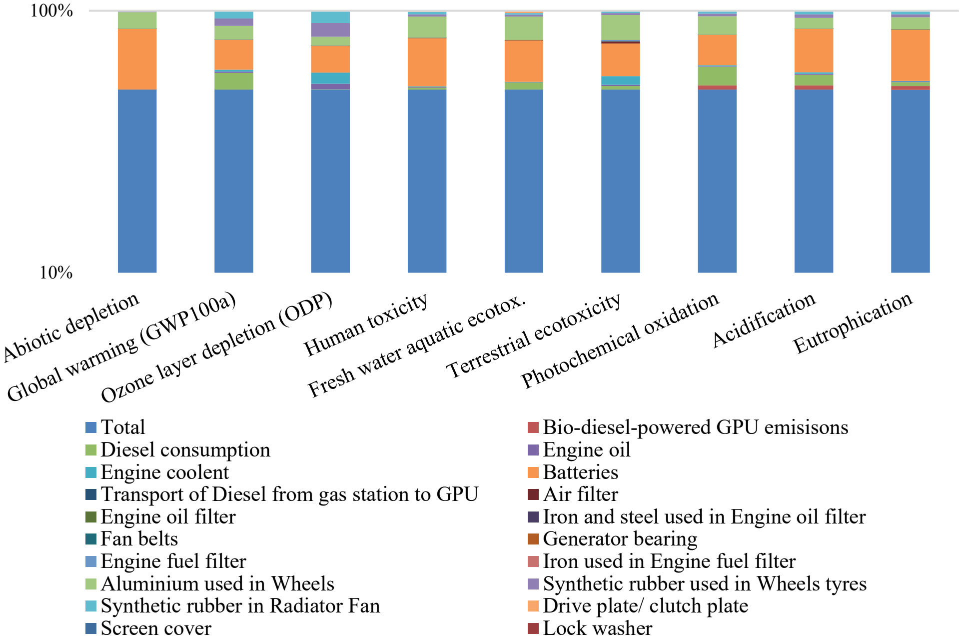

Fig. 3. Environmental impact of Biodiesel-powered GPU.

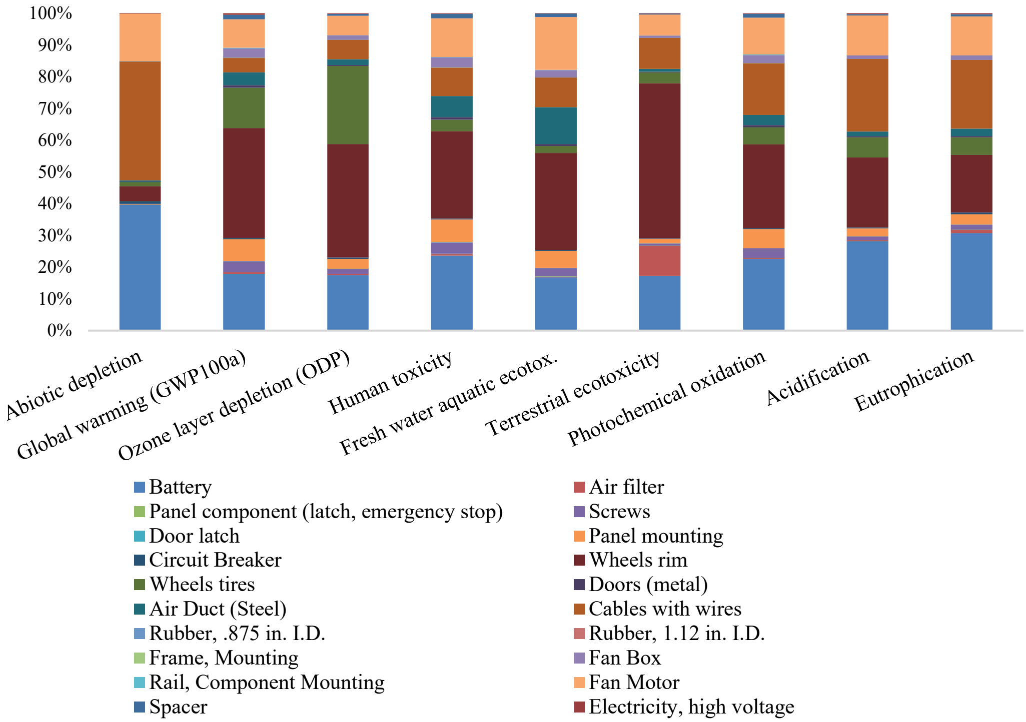

Fig. 4. Environmental impact of electric-powered GPU.

4.1. Environmental Impacts

4.1.1. Abiotic Depletion (AD)

The AD is a measure of the use of non-renewable sources for energy production. The assessment revealed that three inputs: batteries (71 %), aluminium (27 %), and synthetic rubber (1 %) are the hotspot sources of the overall AD impact category caused by the diesel-powered GPU. Similarly, biodiesel-powered GPUs have batteries (71 %), aluminium (27 %), and synthetic rubber (1 %) as hotspot sources over this impact category. However, in electric-powered GPUs, batteries (40 %), cable with wire (38 %), and fan motor (15 %), are the hotspot sources of the overall AD impact category. The overall impact of the diesel-powered GPU on AD is 0.19591199 kg Sb eq followed by biodiesel-powered GPU which is 0.195791662 kg Sb eq. The electric-powered GPU had the lowest impact of 0.162391031 kg Sb eq.

4.1.2. Global Warming Potential (GWP100a)

GWP is an index to measure the amount of infrared thermal radiation a GHG would absorb over a certain period after it has been released into the atmosphere. Results of the study show that batteries used in diesel-powered GPUs accounted for 35 %, followed by aluminium used in wheel rims with 20 % of global warming. Similarly, batteries used in the biodiesel-powered GPU are responsible for a high contribution and account for 35 %, followed by aluminium in wheel rims with 20 %, and diesel consumption accounting for 16 % of global warming. In contrast, synthetic rubbers (tires) in wheels and rubber in radiator fans account for 12 % of global warming. In addition, these three inputs: wheel rim, batteries, and wheel tires (35, 18 and 16 %, respectively) are the hotspot sources of the overall global warming impact category caused by electric-powered GPUs. The overall contribution of diesel-powered GPU is therefore 1142 kg CO_2 eq, followed by biodiesel-powered GPU with 1130 kg CO_2 eq, and electric-powered GPU with 1044 kg CO_2 eq to the GWP.

4.1.3. Ozone Depletion Potential (ODP)

Ozone depletion occurs when the natural balance between the production and destruction of stratospheric ozone is disturbed. The study shows that three inputs: diesel consumption, batteries, and synthetic rubber (49, 16 and 10 %, respectively) are the hotspot sources of the overall ODP impact category caused by diesel-powered GPUs. Similarly, these three inputs: batteries, synthetic rubber, and aluminium (31, 20 and 12%, respectively) are hotspot sources caused by biodiesel-powered GPU. In contrast, electric-powered GPUs have five inputs: wheel rim, wheel tire, batteries, fan motor, and cable (36, 25, 18, 6 and 6 % respectively) as hotspot sources of the overall ODP impact category. The overall highest impact is caused by diesel-powered GPUs is 0.00025467 kg CFC-11 eq, followed by biodiesel-powered GPUs accounting for 0.000130231 kg CFC-11 eq. In contrast, electric-powered GPU has a lesser impact of 0.000106064 kg CFC-11 eq.

4.1.4. Human Toxicity Potential (HTP)

The HTP is a quantitative Toxic Equivalency Potential (TEP) that is used to express the potential harm of a unit of chemical released into the environment. It is used to express the potential for health impact from exposure to harmful agents, both carcinogens and non-carcinogens [41]. Diesel-powered GPUs have three inputs, namely, batteries, aluminium, and synthetic rubber (54, 32, 4 %, respectively) as hotspot sources of the overall HTP impact category. Similarly, these three inputs: batteries, aluminium, and synthetic rubber, with identical individual contribution (54, 32, 4 %, respectively), are hotspot sources of the biodiesel-powered GPU. Electric-powered GPU had wheel rim, batteries, and fan motor (28, 24 and 12 %, respectively) as the hotspot sources of the overall HTP impact category. Overall highest impact is caused by diesel-powered GPUs (516.486662 kg 1,4-DB eq), followed by biodiesel-powered GPUs (510.955505 kg 1,4-DB eq). In contrast, electric-powered GPU has the least impact (549.2893775 kg 1,4-DB eq) on the impact category.

4.1.5. Freshwater Aquatic Ecotoxicity

Freshwater aquatic ecotoxicity is a measure of toxic effects of chemicals on an ecosystem i.e., freshwater causing biodiversity loss and/or species extinction [42]. The LCIA revealed that four inputs (batteries 49 %, aluminium 37 %, drive plate 4 %, and synthetic rubber 3 %) are the hotspot sources of the overall freshwater aquatic ecotoxicity impact category caused by diesel-powered GPUs. Similarly, five inputs (batteries 47 %, aluminium 36 %, diesel consumption 4 %, drive plate, and synthetic rubber 3 %) are hotspot sources caused by biodiesel-powered GPU for this category. In contrast, these four inputs: wheel rim (31 %), batteries (17 %), fan motor (17 %), and air duct steel (12 %) are the hotspot sources to the overall Freshwater aquatic ecotoxicity impact category caused by the electric-powered GPU. Ultimately, the highest impact is therefore caused by diesel-powered GPUs (441.554748 kg 1,4-DB eq), followed by biodiesel-powered GPUs (463.2236653 kg 1,4-DB eq). In contrast, electric-powered GPU has the least impact (605.910019 kg 1,4-DB eq) on the impact category.

4.1.6. Terrestrial Ecotoxicity

Terrestrial Ecotoxicity pertains to metals emitted during the life cycle of different products and substances that may generate damage to the soil [43]. In this category, five inputs (batteries 32 %, aluminium 32 %, diesel consumption 18 %, engine coolant 7 %, and synthetic rubber 3 %) are the hotspot sources of the overall Terrestrial Ecotoxicity impact category caused by diesel-powered GPU. Also, these five inputs: batteries (38 %), aluminium (38 %), engine coolant (8 %), diesel consumption (3 %), and synthetic rubber (3 %) are the hotspot sources of the overall Terrestrial Ecotoxicity impact category caused by biodiesel-powered GPU. In contrast, these five inputs (wheel rim 49 %, batteries 17 %, cable with wire 10 %, air filter 9 %, and fan motor 7 %) are the hotspot sources to the overall Terrestrial Ecotoxicity impact category caused by the electric-powered GPUs. The overall highest impact is caused by diesel-powered GPUs (2.73960665 kg 1,4-DB eq), followed by biodiesel-powered GPUs (2.314995779 kg 1,4-DB eq). Also, electric-powered GPU has the impact of 2.353128862 kg 1,4-DB eq on Terrestrial Ecotoxicity.

4.1.7. Photochemical Oxidation

Photochemical Oxidants are secondary air pollutants formed by the action of sunlight on nitrogen oxides and reactive hydrocarbons, producing components such as ozone and peroxyacetyl nitrate [44]. Four inputs (batteries 43 %, aluminium 33 %, diesel consumption 6 %, and synthetic rubber 5 %) are the hotspot sources of the overall Photochemical Oxidation impact category caused by diesel-powered GPUs. Comparably, these four inputs: batteries (38 %), aluminium (29 %), diesel consumption (18 %), and synthetic rubber (4 %) are the hotspot sources of this impact category caused by biodiesel-powered GPU. In contrast, three inputs (wheel rim 26 %, batteries 23 %, and cable with wire 16 %) are the hotspot sources to the overall Photochemical Oxidation impact category caused by the electric-powered GPU.

The overall highest impact is caused by diesel-powered GPUs (0.6086043 kg C_2H_4 eq), followed by biodiesel-powered GPUs (0.700065326 kg C_2H_4 eq). In contrast, an electric-powered GPU has an impact of 0.544951085 kg C_2H_4 eq on the impact category.

4.1.8. Acidification

Acidification is a process whereby CO_2 is absorbed by the oceans, creating a more acidic water with low carbonate ions available. In the study, four inputs (batteries 55 %, aluminium 17 %, diesel consumption 9 %, and synthetic rubber 6 %) are the hotspot sources of the overall acidification impact category caused by diesel-powered GPUs. Also, these four inputs: batteries (54 %), aluminium (17 %), diesel consumption (10 %), and synthetic rubber (6 %) are the hotspot sources of the overall Acidification impact category caused by biodiesel-powered GPU. In contrast, three inputs (batteries 28 %, cable with wire 23 %, and wheel rim 22 %) are the hotspot sources to the overall impact category caused by the electric-powered GPUs. The overall highest impact is caused by diesel-powered GPUs (11.0038667 kg SO_2 eq), followed by biodiesel-powered GPUs (11.22688672 kg SO_2 eq). In contrast, electric-powered GPU has the impact of 10.11418264 kg SO_2 eq on the impact category.

4.1.9. Eutrophication

Eutrophication is a process whereby excessive plant growth occurs resulting from nutrient enrichment by human activity in a body of water, consequently depleting the water oxygen [45]. Three inputs (batteries 61 %, aluminium 19 %, and synthetic rubber 5 %) are the hotspot sources of the overall Eutrophication impact category caused by diesel-powered GPUs. Similarly, these three inputs: batteries (61 %), aluminium (19 %), and synthetic rubber (5 %) are the hotspot sources of the overall Eutrophication impact category caused by biodiesel-powered GPU. In contrast, three inputs (batteries 31 %, cable with wire 22 %, and wheel rim 18 %), are the hotspot sources of the overall Eutrophication impact category caused by the electric-powered GPUs. The overall highest impact is caused by diesel-powered GPUs (3.43277778 kg PO_4 eq), followed by biodiesel-powered GPUs (3.459170043 kg PO_4 eq). Electric-powered GPUs have an impact of 3.231101748 kg PO_4 eq on the impact category.

4.2. Sensitivity Analysis

Sensitivity analysis in LCA is a valuable method for determining how differences or uncertainties in the input data, assumptions, or parameters may affect the outcomes of an LCA study. It is used to evaluate the impact of changes or uncertainties in input data, suppositions, or factors on the outcomes. Here, alternative versions are considered which differ from the main study's scenario, therefore influencing changed parameters on the final results. In this study, the lithium-ion battery was substituted with lead acid battery, dramatically changing the impact assessment of biodiesel-powered GPUs as depicted in Fig. 5. The percentage changes made in the impact categories in AD was reduced by 51.25 %, global warming potential reduced by 41.07 %, and ODP reduced by 17.33 %. In contrast, HTP increased by 42.84 %, Freshwater Aquatic Ecotoxicity increased by 58.95 %, and Terrestrial Ecotoxicity increased by 40.0 %. In addition to the above, the Photochemical Oxidation reduced by 30.68 % and acidification by 30.32 %. Eutrophication decreased by 21.55 % and the level of Toxicity increased by 42.84 % due to the use of acid in these batteries.

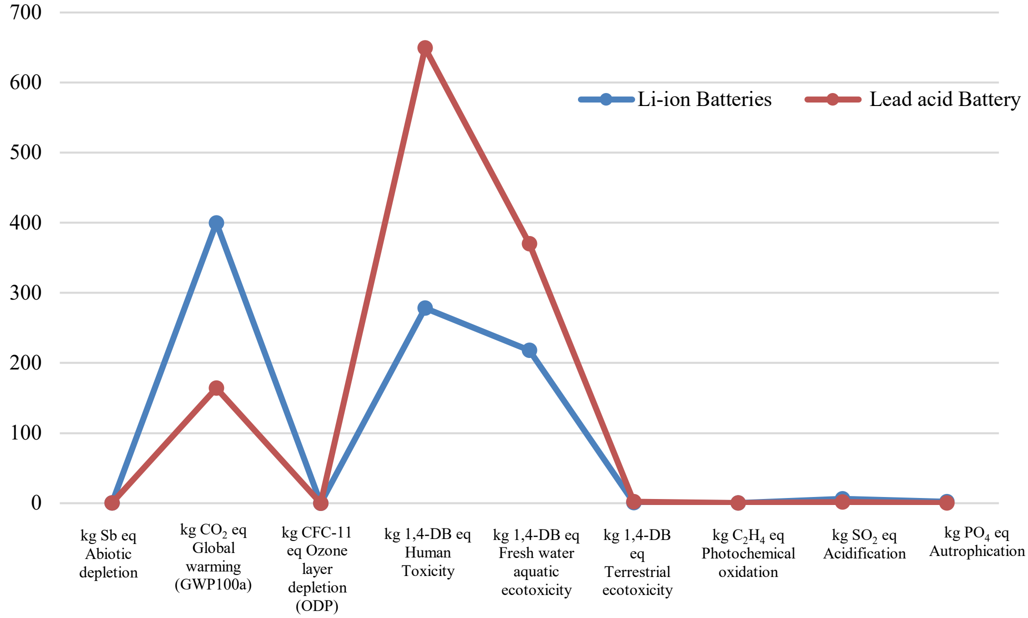

Fig. 5. Sensitivity analysis of Diesel and Biodiesel-Powered Ground Power Unit (GPU).

5. Discussion and Recommendations

It is evident from the results that the impact of ground operations and equipment mobility on air quality is very significant. In this context, factors like energy use, carbon emissions, solid waste management, and water and effluent management are significant environmental sustainability concerns within the airport industry. Considering the energy source of each equipment and what it consumes during an aircraft turnaround operation (system boundary), together with the sensitivity analysis detailed above, the results of the LCA of three GPUs were analysed.

As shown in Fig. 6, batteries, aluminium, diesel consumption, synthetic rubber, fan motor, wheel rims, wheel tires, and engine coolant were the main contributors to the environmental impacts. The highest environmental impact was on Global Warming Potential (GWP100a) followed by Human Toxicity, Freshwater Aquatic Ecotoxicity, Acidification, Eutrophication, Terrestrial Ecotoxicity, Photochemical Oxidation, and AD, whereas the lowest impact was on Ozone Layer Depletion. The environmental impact of the inputs used in diesel-powered GPU was highest followed by biodiesel-powered GPU, while electric-powered GPU had the lowest impact.

The above comparative analysis of the environmental impacts of GPU inputs found that:

- Diesel GPU inputs have the highest GWP (1142 kg CO_2 eq), highest Terrestrial Ecotoxicity (2.73960665 kg 1,4-DB eq), highest AD (0.19591199 kg Sb eq), and highest ODP (0.00025467 kg CFC-11 eq).
- Biodiesel GPU has the highest Acidification potential (11.22688672 kg SO_2 eq), highest Eutrophication potential (3.459170043 kg PO_4 eq), and highest Photochemical Oxidation (0.700065326 kg C_2H_4 eq).

– Electric GPU has the highest Human Toxicity (549.2893775 kg 1,4-DB eq) and highest Freshwater Aquatic Ecotoxicity (605.910019 kg 1,4-DB eq).

Similarly, the comparative analysis of the environmental impacts of GPU outputs found that:

– Diesel GPU has the highest CO, CO_2, HC, Pb, NO_x, SO_x, and VOC emissions between air, soil, and water.
– Biodiesel GPU has relatively lower emissions of CO, CO_2, HC, Pb, NO_x, SO_x, and VOCs.
– Electric GPU has the highest $PM_{2.5}$ (937.6263 g) and PM_{10} (858.8139 g) emissions.

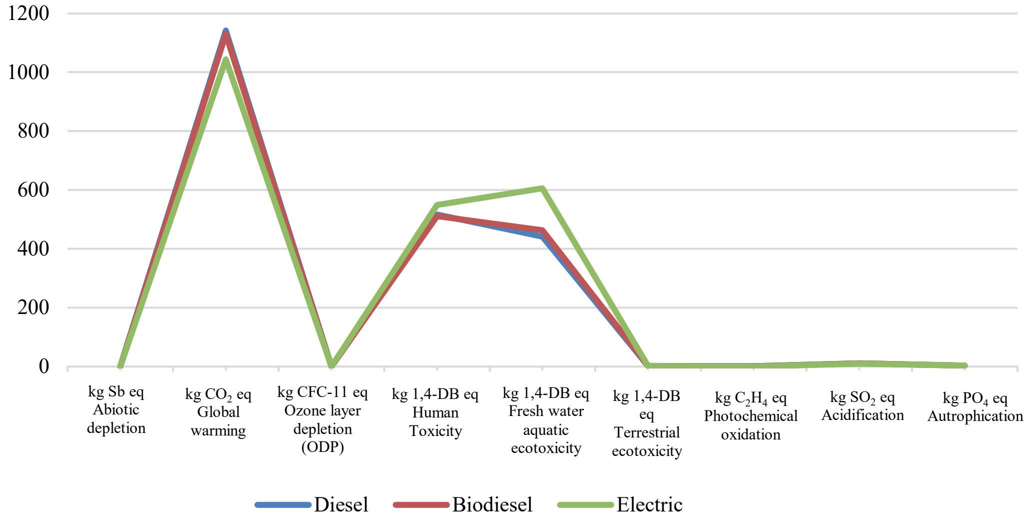

Fig. 6. Comparative environmental impacts of Diesel, Biodiesel, and Electric GPUs.

These findings indicate that out of the three energy sources, diesel-powered GPU has the greatest environmental impacts. Similar studies on the environmental impacts of diesel indicate that it is among the largest contributors of environmental problems worldwide, causing ever-increasing global emissions. Diesel emissions contribute to the development of cancer, cardiovascular and respiratory health conditions; pollution of air, water, and soil; reduction in visibility; and global climate change [46]. It also contains significantly higher concentrations of dangerous substances, such as NO_x, causing severe diseases, such as respiratory infections and asthma, and premature deaths [47].

Biodiesel GPU which has the highest Acidification potential (11.22688672 kg SO_2 eq), highest Eutrophication potential (3.459170043 kg PO_4 eq) and highest Photochemical oxidation (0.700065326 kg C_2H_4 eq) is considered the global community as a good replacement for traditional diesel due to energy security reasons, environmental concerns, and socioeconomic issues related to the rural sector. Most importantly biodiesel has become more attractive because of its environmental benefits as it is predominantly produced from bio renewable feedstocks. However, there are significant environmental impacts which include CO, CO_2, HC, Pb, NO_x, SO_x, VOCs, and particulate matter emissions into the air, water, and soil [48].

Though electric GPUs cause high Human Toxicity (549.2893775 kg 1,4-DB eq), high Freshwater Aquatic Ecotoxicity (605.910019 kg 1,4-DB eq), $PM_{2.5}$ (937.6263 g) and PM_{10}

(858.8139 g) it can safely be used inside warehouses and airport hangars, reducing the number of GSEs needed as they can be used indoors and outdoors [5]. Auxiliary equipment such as hydraulic lifts, refrigeration machinery, and pumps for various uses are more efficient when powered by electric motors. Electric GPUs are more efficient when operating under conditions that involve frequent starts and stops, frequent idling, and short-range usage [49].

This study therefore recommends electrifying aircraft gate operations and GSE to significantly reduce the airport industry's life cycle GHG emissions. An alternative is to increase industry-level penetration of renewable energy sources and use power plants that are energy-efficient and green. In addition to petrol and diesel, other fuel alternatives should be explored, for internal combustion engines, which can be adopted for GSE including compressed natural gas, liquefied natural gas, hydrogen, and liquefied petroleum gas. It is also recommended that wheel rims be removed entirely from the electric-powered GPU, and a stationary GPU should be installed on the aircraft parking stand. This can be implemented as part of a full gate electrification upgrade or simply a solar at-gate electric GPU. While dramatically decreasing life cycle impacts associated with specific equipment components, stationary electric GPUs enhance overall airport electrification efforts and maximize emission reduction benefits by eliminating fossil fuel related emissions.

6. Conclusion and Challenges

Research in the aviation industry has extensively investigated alternative energy sources for various aircraft, equipment, and operations within the airport. The goal has always been to find mitigative solutions for cost effective and environmentally friendly energy options. In this study, three GPU models were assessed through a comparative LCA analysis. In comparing the diesel, biodiesel, and electric-powered GPUs, the highest impact was of the diesel-powered GPU, followed by the biodiesel-powered GPU. In contrast, the electric-powered GPU contributes to the least number of impacts over the impact categories. Specifically, diesel consumption, batteries, aluminium, synthetic rubber, and wheel rims were found as inputs with a high number of impact-causing contributors. Through the sensitivity analysis conducted, most of the inputs were substituted with alternate materials that showed a reduction of environmental impacts. Overall, electric-powered GPUs are found the most suitable for reducing the environmental impact of airport's daily processes and activities in general and avoiding the serious impacts of diesel emissions that contribute to the development of cancer, cardiovascular and respiratory health conditions; pollution of air, water, and soil; reduction in visibility; and global climate change.

A limitation of this LCA study which presents avenues for future research lies in the unknown uncertainties of the input data and results. The input values used in the calculations here were collected from airport equipment manufacturers' manuals, government documents, international guidelines, published literature, airport reports that are reasonable and appropriate for the estimations provided. This is coupled with the difficulty concerning capturing relevant temporal dynamics of airport processes. Therefore, applying a more dynamic LCA to various airport equipment and processes may reveal more accurate comparative data and variability of LCA results.

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