Aviation Infrastructure

HIGHLIGHTS

■ **TECHNOLOGY STATUS –** This brief covers energy consumption and greenhouse gas emissions of aviation infrastructure, including runways and taxiways, airport buildings and services, and ground support equipment. Runways are tarmac or asphalt-paved surfaces for aircraft take-off and landing; taxiways are non-runway paved surfaces for aircraft taxiing, loading and storage, with lower specification than runways. In cold conditions, airport surfaces and aircraft require de-icing, currently achieved using de-icing fluid that is a major airport consumable for airports above certain latitudes. Airport terminals have similar construction and operational needs to offices and shopping centres. Ground support equipment (GSE) provides power, mobility and loading/unloading to aircraft at the terminal, and is a significant source of airport operational energy consumption. Current GSE is mainly fuelled by gasoline or diesel internal combustion engines. Moving to alternative fuels and powertrains is a major option to improve GSE efficiency.

■ **PERFORMANCE AND COSTS –** Aviation infrastructure contributes a modest proportion of the total GHG emissions from aviation, estimated at around 3.2% of the total emissions per passenger-km. Around two-thirds of these emissions arise from operation of the infrastructure, with the remaining third mainly originating from its construction. The largest single source of aviation infrastructure emissions is the ground support equipment (GSE), which account for 51% of the life cycle infrastructure emissions per passenger-km travelled. These emissions primarily occur because GSE are powered by fossil fuel combustion engines; moving to GSE powered by low emission fuels or electricity is therefore a key mitigation measure. Construction of runways and tarmacs (taxiways) is also a major contributor to infrastructure life cycle emissions, with 8% and 22% respectively. Improving the airport traffic management has the potential to reduce emissions by 6-12% per trip. Connecting aircraft to the terminal providing centrally generated electricity ("fixed gate" energy supplies) during service operation and maintenance - in place of using aircraft's auxiliary power unit or mobile generators - is another measure to improve energy efficiency, reduce emissions and costs.

■ **POTENTIAL AND BARRIERS –** There is significant potential to improve energy efficiency of aviation infrastructure, but investment costs and the physical layout of existing airports can be a barrier to changes and improvements. In addition, in developed countries, expansion projects for airport infrastructure have often to face public opposition. For example, replacing mobile power units (typically diesel) and/or the aircraft's auxiliary power unit with fixed gate supply offers a significant efficiency potential, but in many airports the physical layout is a barrier as the transmission over distance of the 115/200V, 400 Hz electricity needed for commercial aircraft involves relatively high losses, and more generation capacity would be needed to provide power to a number of aircraft docked at any time.

TECHNOLOGY STATUS

This briefing note highlights the more notable technologies which could increase the efficiency of aviation infrastructure and will contribute to the reduction in greenhouse gas intensity of aviation as a whole. The International Energy Agency in its baseline scenario [1] projects aviation to be the fastest growing transport sector in the future, with the number of *passenger-km* travelled anticipated to increase by a factor of four between 2005 and 2050. This future increase in aviation demand will involve a considerable increase in energy consumption and place a burden on aviation infrastructure, including communications, navigation, surveillance, air traffic management and related infrastructure, such as airport terminals and runways. In 2008, aviation fuel was the single largest cost item for the airline industry, representing over 30% of operating costs, up from around 12% at the start of the decade [3]. Therefore, a lot of emphasis is placed on measures for reducing aircraft fuel consumption and greenhouse gas emissions (airframe and engine improvements and radical innovation, alternative fuels, novel air traffic management approaches, see ETSAP T12). The aviation Infrastructure is responsible for only a small proportion of overall aviation GHG emissions (3.2% per passenger-km, see Figure 1), but emissions of air pollutants from airports are a major concern, particularly for airports located in urban areas, and provide an additional motivation to improve energy efficiency in aviation infrastructure. The Intergovernmental Panel on Climate Change (IPCC) estimated in 1999 that there was 12% inefficiency in air transport infrastructure. Since then, the IATA estimates that efficiency has improved by 4% in aviation infrastructure, but there is still scope for significant improvement [2]. The following sections provide an overview of technologies, performance and costs of aviation infrastructure.

■ **Components of the Aviation Infrastructure – Airport terminal buildings** can be likened to office buildings and shopping centres as far as design specifications and construction are concerned. The types of flights and airlines served at an airport determine the design features of a terminal, including

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airport services, baggage handling, areas for passengers, cargo loading/unloading, gate design and retail spaces [11].

Runway design, construction and material selection are highly influenced by quality and reliability requirements dictated by aircraft take-off and landing operation. In the United States, the top 50 airports average 3 to 4 runways which are all designed for landing of most demanding aircraft [9]. The two primary materials used for runways construction are concrete and asphalt. Asphalt offers more flexibility making it less likely to crack under pressure but is less able than concrete to withstand high temperatures. A combination of the two materials based on their different properties is often the best option to be used at different parts of an airport, including **taxiways and other tarmac surfaces** (non-runway paved surfaces for aircraft taxing, loading, parking, close to runways, terminals and support facilities), which have less demanding design specification than runways. An important element of the runway construction is the **runway lighting system** which typically consists of four different types of lights, i.e. approach lights, centreline lights, touchdown lights and edge lights. The use of the lighting systems varies seasonally and according to the daily hours of darkness of the runway location.

Ground support equipment (GSE) are technical facilities and systems to carry out airport technical services, including services to aircraft, ensuring mobility, passengers and freight loading/unloading during airport operation and maintenance. They also provide energy and electricity for the services. GSE are mainly fuelled by either gasoline or diesel and consume significant amounts of energy. The Federation of Aviation Administration (FAA) has estimated that about 72,000 GSE are in operation in the US airports alone. Although a comprehensive global inventory of GSE in operation does not exist, a study estimates that 30-40% operate on diesel fuel, 50-60% on gasoline and around 10% on alternative fuels. Using alternative fuels such as liquefied petroleum gas (LPG), compressed natural gas (CNG) and electricity can significantly reduce the airport greenhouse gas emissions. Among GSE, **ground power units** (GPU) are vehicles which supply power to an aircraft when it is on the ground. They must be quickly moveable to supply power to different aircraft. GPU are the most used pieces of GSE, typically being operational for 2,240 hours per year [13]. **Fixed gate power supply** is an alternative to GPU that offers a reduction of either GHG emissions and the use of aircraft auxiliary power units. They provide an electrical connection between aircraft and gate, which enables centrally generated electricity to be used to provide auxiliary power. Airports are not yet required to install boarding gates that provide electricity to the parked aircraft, but the FAA reports that some airports in the United States have been proactive in investing in electric gates to reduce energy consumption and emissions.

In terms of maintenance and operation, a peculiarity of the airport infrastructure is the need for de-icing of runways and aircraft in cold-weather conditions. De-icing is currently achieved using a de-icing fluid, which is a major consumable for airports above certain latitudes and which production and use involve significant GHG emissions. In the United States, 35 million gallons (160 million litres) of de-icing fluid are used each year during low temperature periods [9]. The large majority of airports use an ethylene or propylene glycol-based fluid which can impact water quality by reducing dissolved oxygen levels. Investment in appropriate precautions to manage the process is essential.

A key aspect for the airport operation is the use of advanced Air Traffic Management (ATM) systems which can drastically reduce fuel consumption and emissions from aviation transport as a significant part of aircraft fuel consumption occurs during take-off. It has been observed that an important synergy exists between the use of advanced ATM and the design and layout of airport taxiways and tracks. Changes in the airport infrastructure can relieve congestion in high density traffic areas and therefore increase the overall efficiency, with relatively low additional investment. An IPCC study [4] suggests that the improvement of the ATM systems alone for the worldwide aircraft fleet operation could reduce fuel burn per trip by 6-12%, with a positive effect on GHG emissions (assuming that relieving infrastructure congestion does not lead to more traffic and flights).

PERFORMANCE

The breakdown of GHG emissions per passenger-mile travelled from the different components of the aircraft life-cycle components are provided in **Figure 1,** where 78.3% of the emissions are attributed to the aircraft directly and only 3.2% are attributed to the aviation infrastructure. **Figure 2** provides the breakdown of this small percentage of emissions attributed to the infrastructure. More than 50% of the infrastructure emissions are from the operation of ground support equipment (GSE), about 30% from runways and taxiways construction, 11% for runways lighting, 6% for de-icing, and about 2% for buildings construction. All these figures are based on a study by the University of California at Berkley [9]. The following sections discuss these components in more detail.

■ **Ground Support Equipment –** With certain assumptions regarding typical aircraft lifetime (30 years) size, and passenger capacity, Figure 2 shows that GSE is by far the largest contributor to GHG emissions per passenger-mile travelled from aviation infrastructure. Energy consumption and GHG emissions from

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infrastructure and GSE operation can also be given as energy per aircraft-life, as energy per vehicle-mile travelled, and as energy per passenger-mile travelled. The GSE operation is attributed between 15,000 and 170,000 GJ per aircraft life [9] (with corresponding GHG emissions of 1,100-13,000 tCO_{2e}). This large range is due to the difference in both typical aircraft lifetime and size, taking figures from three aircraft types: Embraer 145, Boeing 737 and Boeing 747. A significant range also occurs when the energy use in given as energy per vehicle-mile (1,100-5,100 kJ/v-m, with corresponding emissions of 82 to 390 gCO_{2e}) and as energy per passenger-mile (28-34 kJ/p-m, with corresponding emissions of 2.1 and 2.6 gCO_{2e}) [9]. In comparison, the average direct aircraft emissions per passenger mile travelled are 113 gCO_{2e} [9]. The GSE operation is attributed about 4 $kgCO_{2e}$ per landing/take-off cycle. Among GSE, the Ground Power Units (GPUs) are the most used pieces of the equipment, typically being operational for 2,240 hours per year [13]. They have an economic life of 8 years and are typically either diesel or gasoline vehicles. Annual energy consumption of GPUs vary between 2,2 GJ/year for diesel and 2,9 GJ/year for gasoline [13]. Annually, an aircraft tug (for wide body aircraft) is the most energy-consuming piece of the GSE. A diesel-fuelled tug can consume about 6,2 GJ annually whereas the gasoline alternative carrying out the same role will typically consume 31% more, 8,1 GJ. Where practical, GPU can be replaced with a fixed gate electricity supply, in which electricity is generated from an off-airport power source (e.g. utility-scale electricity generators). These sources have a greater control over emissions and a higher efficiency than GPUs or on-board Alternative Power Units (APU). The US Environmental Protection Agency states that the cost of the fuel saved using fixed gate electricity supply is greater than the cost of electricity, meaning that this measure can reduce overall operating costs [13].

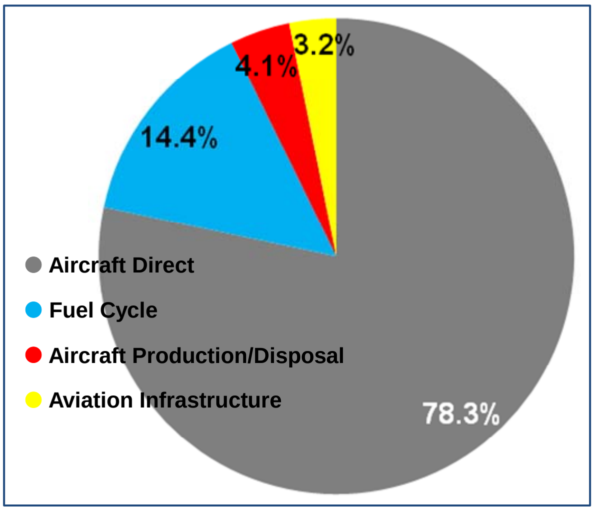

Figure 1 - Percentage of GHG emissions per passenger-mile from different aircraft life-cycle components [9]

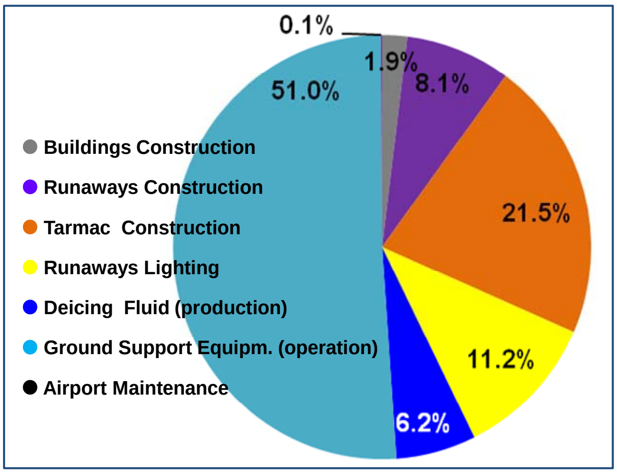

Figure 2 - Percentage of GHG emissions per passenger-mile from aviation infrastructure [9]

■ **Airport Buildings –** The energy used to construct airport buildings is estimated at 5.9 GJ/m^2, with about 460 $kgCO_{2e}$ of GHG emissions for every m^2 constructed [9]. This is based on the assumption that airport buildings are similar to shopping centres. If the energy used in the construction is given as energy used per passenger-mile travelled, this leads approximately to an energy consumption of 1.1 kJ/passenger-mile travelled and to the emission of about 0.09 gCO_{2e}/passenger-mile travelled [9]. The impact of the airport maintenance is estimated as 5% of airport construction per year [9], but there is a lack of data on airport maintenance, and on the environmental effects of yearly material replacement and processes.

■ **Runway and Tarmacs –** Runways and tarmacs are the most important elements in terms of energy use for the construction of the aviation infrastructure. Runway construction is an energy-intensive process which requires about 1.5 GJ/m^2 of energy input, with the emission of about 110 $kgCO_{2e}/m^2$ [9]. This is four times less than the energy use and the emissions involved in the construction of the airport buildings. If the energy for runway construction is given as energy use per vehicle-mile travelled, it ranges between 180-860 kJ (depending on assumptions), whilst in terms of energy used per passenger-mile travelled it is estimated at 4.7-5.7 kJ/passenger-mile, with related GHG emissions of 0.34-0.41 gCO_{2e} [9]. This value is 4 to 5 times higher than the corresponding value for airport building construction. This is due to the larger area of runway/tarmacs than buildings, and fact that, unlike airport buildings, runways need frequent maintenance and renewal of surface layers, therefore increasing the CO2e when looked at in a passenger-mile context. Using a similar estimation approach and assumptions, the energy use for construction of taxiways and tarmacs ranges between 12kJ and 25 kJ per passenger-mile-

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travelled [9], with typical emissions of about 1 gCO_{2e}/passenger-mile. These figures are extrapolated from a study based on the Dulles Washington-DC airport (which has 57 ha of taxiways and 130 ha of tarmacs) and involve an estimated energy consumption for taxiway/tarmac construction of 1.0 GJ/m^2 [8], with related emissions of 70 $kgCO_{2e}/m^2$.

It should be noted that the energy use for taxiways construction is lower than the energy use for runway construction when it is given as energy/m2 while it is higher in terms of energy/passenger-mile. This is due to the fact that the taxiway/tarmac surface (m^2) is significantly larger than the runways surface. It should also be noted that moving from energy/m2 to energy/vehicle-mile or to energy/passenger-mile), one finds larger variation ranges for both energy use and emissions because different aircraft have different size, capacity, lifetime and mileage. For example, considering the life-cycle emissions of three different aircraft (Embraer 145, Boeing 737 and Boeing 747) produces ranges of 460-5500 tCO_{2e} per vehicle, 34-160gCO_{2e} per vehicle-mile and 0.88-1.1gCO_{2e} per passenger-mile [9].

■ **Runway Lighting –** In 2002, a US study [5] of runway lighting inventoried the electricity consumption of airport lighting systems. It estimated that the approach, centreline, touchdown and edge light systems consume 57, 120, 160, and 140 GWh per year respectively across all US airports. The energy consumption associated with the operation of runway lighting infrastructure is also estimated in [9] based on average energy consumption of the US airports. Depending on the aircraft size, the study estimates 1200–3400 GJ per vehicle, 86–400 kJ per vehicle-mile-travelled and 2.2–2.7 kJ per passenger-mile-travelled.

■ **De-icing Fluid Production –** The production of de-icing fluid contributes to energy consumption and GHG emissions per aircraft-life by 1,800-22,000 GJ and 140-1,600 tCO_{2e}. Per vehicle-mile-travelled this equates to 140-640 kJ and 10-47gCO_{2e} whist per passenger-mile travelled this is 3.5-4.2 kJ and 0.26-0.31gCO_{2e}, respectively [9]. Per litre, the production of de-icing fluid consumes 17 MJ of energy and produces 1.3 $kgCO_{2e}$ of GHG emissions. For the United States alone, the 160 million litres of de-icing fluid produced annually therefore gives rise to around 210 $ktCO_{2e}$.

Costs

■ **Airports & Runways –** The cost of constructing aviation infrastructure depends on a range of factors including design, materials used, labour cost, airport size, etc. For runways, concrete and asphalt are the main primary material options. The construction of a 20-30m-width concrete-based runway is estimated to cost between US$ 4,400 and 7,200 per linear metre, whereas using asphalt the cost is about $3,900 per linear metre. A similar cost difference is also relevant for taxiways and tarmacs, though the specific cost is significantly lower, in both cases due to the lower performance requirements [10].

Estimates of the overall airport terminal infrastructure cost typically comprise five main components, with specific typical costs as follows:

- Internal/external structures - $1,870/m²
- Furniture and sanitary/disposal fittings - $178/m²
- Space heating and air temperature - $614/m²
- Electrical, communications and protective installations - $1016/m²
- Preliminaries and contingencies - $896/m²

The total construction cost for the terminal buildings is estimated to be $4,576/m² [11].

The maintenance cost of the runway infrastructure is influenced by the construction materials. Replacing a 23m^2 concrete slab costs between US$2,200 and US$4,500. In contrast, the cost of resurfacing a 23-m^2 area of asphalt runway (typically, 1 linear metre) costs around $400-$700.

A typical cost for the de-icing fluid is between US$4.7 and US$5.0 per gallon [9].

■ **Ground Support Equipment Costs –** Typical costs for GSE are outlined in Table 5 for the most expensive and energy-intensive equipment. Aircraft tugs for wide-body aircraft are the most expensive pieces of GSE (US$19,000 for tugs using conventional fuel and $25,000 for electricity-powered alternatives). In all cases, the capital costs of electric powered alternatives for GSE - where available and feasible – are higher than conventional options. However, their maintenance and operation costs per year are typically lower for equipment lifespan of over 8-10 years.

Potential and Barriers

Significant reduction of energy consumption, GHG emissions and operational costs of GSE may be achieved by replacing diesel mobile generators with a centrally generated fixed gate supply or using less carbon-intensive energy supply [13]. Providing power supply (115/200V, 400 Hz) for aircraft services and maintenance while the aircraft is parked via the airport infrastructure may also have a positive impact. Mobile generator units, gate-based converters, and centralized 400 Hz generators serving a number of gates are technology options to meet this need [13]. In existing airports and gates, barriers to the use of fixed and centralised power supply systems are the gate layout and the power distribution losses that are associated with the low voltage the high frequency required by the aircraft. The latter requires power generation to occur as close as possible to the point of use (gate). On the other hand, public acceptance can be a barrier to the development of new aviation infrastructure, e.g. adding

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greater capacity rather than improving the existing facilities. The construction of new runways in existing airports may also be limited by the surrounding environment and social acceptance. For example, plans for the construction of a third runway at London's Heathrow airport were met with widespread criticism, leading to the plans being scrapped in 2010 [7]. Therefore, in developed areas, meeting increasing demand for air travel is limited by the environmental and social implications of airport expansion.

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Table 1 – Typical Energy Usage for Aviation Infrastructure (ranges based on different aircraft types) [8, 9][2]

Life-Cycle Component	GJ per aircraft-life,	kJ/vehicle-mile	kJ/passenger-mile	GJ/unit
Construction – Airports	500 – 6,200	37 – 210	1.1	5.9 GJ/m^2
Construction – Runways	2,500 – 30,000	180 – 860	4.7 – 5.7	1.5 GJ/m^2
Construction - Tarmacs	6,400 – 77,000	480 – 2,200	12 – 15	1.0 GJ/m^2
Infrastructure Operation – Runway lighting	1,200 – 3,400	86 – 400	2.2 – 2.7	1.7 PJ/yr[3]
Infrastructure Operation – Deicing Fluid Production	1,800 – 22,000	140 – 640	3.5 – 4.2	16.7 MJ/litre
Infrastructure Operation – Ground Support Equipment	15,000 – 170,000	1,100 – 5,100	28 – 34	47 MJ/LTO
Infrastructure Maintenance - Airports	25 – 310	1.8 – 10	0.057	300 MJ/m^2

[2] Imperial units converted to metric using factors of 0.092903 m^2/ft^2, 1.609344 km/mi, 4.546092 l/gal; [3]Total for all US airports

Table 2 – Typical GHG Emissions from Aviation Infrastructure (ranges based on different aircraft types) [8,9][2]

Life-Cycle Component	tCO_{2e}/aircraft-life	$grCO_{2e}$/vehicle-mile	$grCO_{2e}$/passenger-mile	CO_{2e}/unit
Construction – Airports	39 – 480	2.9 – 16 g	0.089 g	460 kg/m^2
Construction – Runways	180 – 2,100	13 – 61 g	0.34 – 0.41 g	110 kg/m^2
Construction - Tarmacs	460 – 5,500	34 – 160 g	0.88 – 1.1 g	70 kg/m^2
Infrastructure Operation – Runway lighting	240 – 2,900	18 – 85 g	0.47 – 0.56 g	758 g/kWh
Infrastructure Operation – Deicing Fluid	140 – 1,600	10 – 47 g	0.26 – 0.31 g	1.3 kg/litre
Infrastructure Operation – Ground Support	1,100 – 13,000	82 – 390 g	2.1 – 2.6 g	4 kg/LTO
Infrastructure Maintenance - Airports	1.9 – 24	0.14 – 0.81 g	0.0045 g	20 mt/m^2

[2] Imperial units converted to metric using factors of 0.092903 m^2/ft^2, 1.609344 km/mi, 4.546092 l/gal

Table 3 – Typical Costs for Aviation Runway Construction [10][2]

Runway construction costs	Concrete	Asphalt
Runway Construction (75' to 100' width)	$1350-2200/linear ft	$1200/linear ft
Taxiway Construction	$18-28/square ft	$16/square ft
Ramps/Apron Construction	$18-28/square ft	$16/square ft
Concrete Slab Replacement (Standard 12.5' x 20' slab)	$2200-4500/slab	NA
Asphalt Runway Resurfacing	NA	$200-360/linear ft
Total Cost of runway construction by runway type	Concrete	Asphalt
General Aviation (2000 to 4000 foot runway, typical length: 3,700 ft. 8" depth, 75 ft width)	$4,995,000	$4,440,000
Reliever (5000 to 7999 foot runway, typical length: 5,000 ft. 18" depth, 100 ft width)	$9,000,000	$8,500,000
Commercial (8000 to 13,000 foot runway, typical length: 13,000 ft. 22" depth, 100 ft width)	$28,600,000	$26,000,000

[2] Imperial units converted to metric using factors of 0.092903 m^2/ft^2, 1.609344 km/mi, 4.546092 l/gal

Table 4 – Typical Costs for New Terminal Construction [11]

Terminal infrastructure component	Cost	$\$/m^2$	%
Internal/external structures	$46,760,960	$1,870	40.9
Furniture and sanitary/disposal fittings	$4,447,200	$178	3.9
Space heating and air temperature	$15,377,440	$614	13.4
Electrical, communications and protective installations	$25,406,080	$1,016	22.2
Preliminaries and contingencies	$22,480,320	$896	19.6
Total construction cost (building only)	$114,472,000	$4,576	100

Table 5 – Typical Energy Consumption and Costs for GSE [12] [13][4]

Ground Support Equipment	Economic Life (yr)	Use per year (h)	Energy Use, MJ/yr		Conventional replacement		Electric replacement	
			Diesel	Gasoline	Capital Cost US$	Maintenance Cost	Capital Cost US$	Maintenance Cost
GPU	8	2,240	2,177,229	2,955,113	$32,000	$10.44/hr	-	$7.83/hr
Van	8	1,987	-	1,046,574	$22,000	$10.09/hr	-	$10.09/hr
Pickup	8	1,722	-	906,996	$18,000	$9.65/hr	$27,000	$7.24/hr
Aircraft Tug	10	1,721	6,152,726	8,072,619	$190,00	$26.41/hr	$250,000	$19.71/hr
Bus	8	1,678	1,051,054	883,820	$110,000	$9.58/hr	-	$9.58/hr
Lift	8	1,357	-	795,653	$45,000	$13.73/hr	$54,000	$10.30/hr
Cargo Loader	10	1,250	445,421	513,041	$150,000	$9.84/hr	$180,000	$7.38/hr
Fuel Truck	8	1,117	699,659	588,336	$65,000	$16.83/hr	-	$16.83/hr
Air Start Unit	8	181	759,006	248,335	$80,000	£33.76/hr	-	$25.32/hr

[4] Calculations of average operational fuel consumption calculated from [13] (Load factor % x BHP x Gallons fuel per BHP/hour x Hourly use per year x MJ conversion ratio – 1 MJ = 0.007589 gallons gasoline or 0.006825 gallons diesel)

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