Hybrid Fuel Cell Electric Airport Ground Support Equipment Feasibility Study

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Transport Canada Transportation Development Centre
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NOTICES

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The Transportation Development Centre and the co-sponsoring agencies do not endorse products or manufacturers. Trade or manufacturers' names appear in this report only because they are essential to its objectives.

Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

This report is intended for the Project Team, client group and sponsoring agencies named on the next page. It contains commercially sensitive information and should be shared beyond these organizations only under the discretion of a Project Team member. In general, sharing with staff among sponsoring and related government entities is permitted.

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- Transportation Development Centre of Transport Canada,
- BC Clean Air Research Fund (BC Clear), delivered by the Fraser Basin Council

In-kind support was additionally provided by our client group:

- Swissport
- Air Canada
- Air North
- Vancouver Airport Authority

The Project Team and their roles consisted of:

- Ballard Power Systems, Inc.: providing project management;
- BAE Systems Inc. (BAE Systems): supplying Phase 2 and technical input; and,
- Setton Consulting Group (SCG): supplying Phase 1 and overall report editing.

EXECUTIVE SUMMARY

Ballard Power Systems Inc. (Ballard) and BAE Systems Inc. (BAE Systems) wish to bring an advanced, zero emission ground transportation solution to airports worldwide by leveraging Ballard's heavy duty 75 and 150 kW hydrogen fuel cell modules with BAE Systems' battery-electric hybridization capabilities and technology.

Trials have been successfully completed for full sized, forty foot (40') hybrid hydrogen fuel cell electric (HFCE) powered transit buses and pure hydrogen fuel cell small airport tugs, including with Air Canada in Vancouver. The ability to fuel both buses and airport ground support equipment (GSE) could ultimately result in a complete, zero emission ground transportation solution leading to a significant reduction in airport based greenhouse gas and criteria air pollution. Furthermore, by leveraging aerospace, rail and marine applications, Ballard may be able to realize economies of scale for its heavy duty fuel cell modules at an earlier point in time.

The consortium has selected Vancouver International Airport (YVR) as the ideal GSE customer launch site. Vancouver Airport Authority has distinguished itself among airports both domestically and internationally as an environmental leader and community builder. Beyond YVR, airports and airport authorities in Montreal, Los Angeles, New York, Frankfurt, London, Amsterdam, Japan and New Zealand have participated in hydrogen fuelling trials and have overcome barriers associated with introducing a new fuel.

The North American GSE market is sized at nearly 75,000 units categorized, for the purposes of analysis in this study, into six broad categories of GSE including: baggage/material tractors, ground power units (GPU), aircraft load lifting equipment, de-icing/heat and air start units, push-back tractors and utility service equipment.

Based on the results of a Market & Commercial Feasibility Study (Phase 1), the most commercially attractive initial markets for the FCVelocity® HD6 fuel cell module are aircraft load lifting equipment and GPUs which are both produced at a rate of about 1,100-1,200 units each per year in a no market growth scenario. Interestingly, baggage/material tractors were also identified as being an attractive market for fuel cells, with strong similarities to Plug Power's near-commercial materials handling trucks, employing Ballard's smaller capacity fuel cells.

Subsequent to the market feasibility study results, BAE Systems confirmed that a GPU made the most sense as a prototype unit of GSE on which to do a deeper technical analysis. A GPU is a relatively pure-purpose type of GSE without a lot of expensive ancillary equipment that would increase the expense of a prototype beyond what was necessary for quantifying the benefits of a fuel cell electric propulsion system. In addition, the GPU is an off-board power supply that connects to an aircraft, and is considered a stepping stone to an on-board auxiliary power unit. This is a market in which aircraft manufacturers have expressed interest, and which initially provided the impetus for exploring HFCE GSE.

The primary objective of the Technical Feasibility Study (Phase 2) was to identify a system architecture and technology that would provide the cleanest emission technology to fulfill the role of a GPU currently used commercially in various airports. The exercise of designing a system would inherently help determine if a hybrid fuel cell electric GPU was feasible. However, the question arises: "What does *feasible* mean?"

Feasibility spans a range from "possible" to "beneficial." The next task was therefore to place the proposed technology on that continuum and determine if it makes sense to go to the next step, which would presumably be a prototype build and demonstration.

There are inherent challenges associated with attempting to quantify the benefits of a product that does not yet exist. However, there are hybrid fuel cell electric propulsion systems operating in pre-commercial settings in different applications (i.e. buses), and in addition, there are elements of the proposed hybrid fuel cell electric system in commercial use (i.e. battery hybrid systems and pure fuel cell systems).

As such, the approach taken was to first establish the framework against which the proposed hybrid fuel cell electric system should be evaluated, as if it existed, based on factors that the client group stated as being paramount, which were:

1. **Practicality**: how readily available and in use is the technology?
2. **Effectiveness**: Is the technology mature and does it provide a cleaner emission solution compared to the incumbent fossil fuel product?
3. **Safety**: Does the technology offer the same or a higher calibre of safety than current technology?

The next step was to go through a comparison exercise that would evaluate the proposed system against existing technologies that would represent alternative ways to reduce emissions without sacrificing practicality, effectiveness and safety.

This process is called a "trade" study. Given the limitations on data for the proposed system, because it does not yet exist, this comparison had to be more qualitative than a typical trade study. However, going through the exercise identified the strengths, weaknesses and areas where more data was needed. The trade study exercise also provided enough information to come up with a preliminary design, a set of questions and conditions to consider in a demonstration of the prototype in order to evaluate the proposed system's life cycle cost, and a rough order of magnitude cost for a prototype to be used as part of a demonstration.

The three already-commercial technologies that were selected for comparison in the new GPU application were:

1. Variable speed hybrid diesel GPU: based on BAE Systems' stationary primary power unit with the HybriGen™ Primary Power System.
2. Rechargeable electric plug-in GPU: based on the HybriGen™ Grid Tie/Back-up Power system.
3. A hybrid fuel cell electric GPU (HFCE GPU): based on the HFCE transit Bus and HybriGen™ Phase I system.

Each of the technologies above represents evolutionary progress over the previous in terms of clean emissions and advances in technology. Two of these systems are known and understood, and only the third is unknown. Therefore, each of these systems was "traded" or "compared" to yield the best technical solution for a GPU that would still be practical, clean emission and safe to convert into a demonstration system at an application site.

The trade or comparison criteria included the following categories:

- Emissions;
- Retro Fit: Weight, Packaging, Refuelling;
- Reliability;
- Ease of Use;
- Service / Maintenance; and,
- Unit Cost.

The trade study revealed that the plug-in hybrid fuel cell electric (HFCE) GPU has the *potential* to be superior to the other compared technologies (variable speed hybrid diesel and rechargeable electric), while offering a practical, effective and safe solution. However, as identified in the trade study, in order to quantify the benefits, a prototype would need to be built and operated in a demonstration program.

A demonstration program is not only critical for quantifying the anticipated benefits of the HFCE GPU, but also for collecting detailed information to analyze the market viability of hydrogen fuel in an airport environment.

The rough-order-of-magnitude price for a six-month demonstration program, including all system components and the eight-month development time frame, but not including hydrogen infrastructure, is $3.5M.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Table 1: Glossary of Abbreviations, Acronyms, Symbols and Special Terms

Abbreviation/Acronym	Definition
AC	Alternating Current
ACTM	Alternating Current Traction Motor
APS	Accessory Power System
BAE Systems	BAE Systems Inc., Feasibility Study partner
Ballard	Ballard Power Systems, Inc., the Feasibility Study Lead
CAN Bus	Controller Area Network is a vehicle bus standard designed to allow microcontrollers and devices to communicate with each other within a vehicle without a host computer. CAN bus is a message-based protocol, designed specifically for automotive applications but now also used in other areas such as industrial automation and medical equipment.
CARB	California Air Resources Board
client group	Partnering agencies representing potential end-users and demonstration partners and providing in-kind support to this project: Swissport, Air Canada, Air North and Vancouver Airport Authority
CO	Carbon Monoxide
DC	Direct Current
DC PDU	Direct Current (DC) Power Distribution Unit (PDU)
DOE	[United States] Department of Energy
EPA	[United States] Environmental Protection Agency
GHG	Greenhouse Gas
ESS	Energy Storage System
GPU	Ground Power Unit, a vehicle capable of supplying power to parked aircraft.
GSE	Ground Support Equipment (for airports, in the context of this report)
HFCE	Hybrid (with battery) Fuel Cell Electric
HV PDU	High Voltage Power Distribution Unit
IC	Internal Combustion (engines)
LFL	Lower Flammability Limit (4% for hydrogen)
MCP	Mechanical Cooling Package
OEM	Original Equipment Manufacturers
PCS	Propulsion or Power Control System (PCS)
PEM	Proton Exchange Membrane
PIM	Power Interface Module (PIM)
PSR	Power Systems Research Inc., owner of proprietary engine databases
SAE	Society of Automotive Engineers
SAE J1939	Society of Automotive Engineers SAE J1939 is the vehicle bus standard used for communication and diagnostics among vehicle components, originally by the car and heavy duty truck industry in the United States .It is used in the commercial vehicle area for communication throughout the vehicle.
SCG	Setton Consulting Group, contractor to Ballard Power Systems
TBC	To Be Completed

SCP	Stack Cooling Package
Tier 2, 3, 4 engines	US Federal emissions standards established by the EPA starting in 1994 for non-road engines.
US EPA	United States Environmental Protection Agency
VALE	Voluntary Airport Low Emissions [program]
YVR	Vancouver International Airport

INTRODUCTION

This report presents results of a feasibility study looking at advanced hybrid hydrogen fuel cell electric (HFCE) ground support equipment (GSE). The feasibility study is a consortium based initiative managed by Ballard Power Systems Inc. (Ballard) and BAE Systems Inc. (BAE Systems) with support from Setton Consulting Group (SCG). The consortium worked with a client group consisting of potential end-users and included Swissport Canada, Air Canada, Air North and Vancouver Airport Authority.

The objective of the feasibility study is to understand if advancements in fuel cell electric hybrid technology, specifically BAE Systems hybrid drives utilizing Ballard's heavy duty fuel cell modules, make the use of fuel cell based propulsion systems desirable over existing pure electric airport GSE, and if so, to come up with a preliminary configuration that maximizes the benefits of such a system. The system is called a HFCE GSE.

The feasibility study was broken into three phases which have been collated into this final report:

- Phase 1: Market & Commercial Feasibility Study – sections 1 through 8
- Phase 2: Technical Trade Study – sections 9 and 10
- Phase 3: Results & Conclusions – sections 11 through 14

Phase 1 of the study looked at relevant market, commercial and regulatory information required to scope and prepare for the technical aspects of the feasibility study in Phase 2.

Phase 2 represents the technical feasibility study, conducted in the format of a Trade Study by BAE Systems.

Phase 3 presents conclusions and recommendations for BAE Systems and Ballard on how to potentially pursue commercializing a product and if so, a path forward.

BAE Systems is a global defense, security, aerospace, and commercial products company delivering a full range of products and services for air, land, and naval forces and advanced electronics, information technology solutions, and customer support services. Platform Solutions is a business sector headquartered at Johnson City, New York. Platform Solutions is the developer and integrator of the HybriDrive™ electric drive system used on conventional hybrid electric and fuel cell powered transit buses.

Ballard manufactures proton exchange membrane (PEM) fuel cell technology and provides clean energy fuel cell products, enabling optimized power systems for a range of applications. Among other products, Ballard designs and manufactures fully-integrated FCVelocity® HD6 fuel cell modules delivering 75 kW or 150 kW of power for use in the bus market and, potentially, other heavy duty markets in the future.

SCG was authorized to represent Ballard while working in the capacity as a consultant.

SCOPE AND AUDIENCE

For practical and funding purposes, the scope of the feasibility study is on airport GSE in the North American market; however, where information was available or attainable, the opportunities, challenges and market drivers in Western Europe are described. Potential exists for collaboration with European entities in future stages such as demonstration programs.

Ultimately, the client for HFCE GSE would most likely be the GSE original equipment manufacturers (OEMs); however, in the development and demonstration stages, the “client” is the end user as represented by the airlines and ground support service providers, facilitated by an airport authority.

The audience for the final feasibility study is twofold: an internal audience includes decision makers at BAE Systems and Ballard, and other potential commercial partners, while the external audience includes funding providers and potential end users.

Phase 1 – Market & Commercial Feasibility Study

1 DATA SOURCES

1.1 Power Systems Research Inc.

Aviation GSE population data was obtained from Power Systems Research Inc. (PSR). PSR has developed a proprietary database and population model called PartsLink™ that tabulates in-service population data for engine-powered vehicles and equipment in selected market countries. A mathematical model within PartsLink™ is utilized to estimate the number of engine-powered products in service in individual market countries. Included in PartsLink™ is another database called OE Link™ that tracks production data. OE Link™ was referenced indirectly through a BAE Systems Report that pulled from the database in July 2009.

PartsLink™ employs a combination of factual data and results from an on-going vehicle/equipment-user survey developed and conducted by PSR. Population values for each respective vehicle/equipment application are distributed geographically based upon selected economic factors from the United Nations Comtrade database, with vehicle/equipment imports and exports allocated by country using the eight digit Standard International Trade Classification code.

Key elements of the population data include:

- A continuing record of OEM vehicle and equipment production and factory shipment data from PSR's proprietary OE Link™ database
- Monitoring import-export activities for engine-powered vehicles and equipment in selected market countries
- Retirement rates for engine-powered products in service are determined by an attrition model that develops estimates based upon:
    - Estimated engine life
    - Annual hours of utilization
    - Intensity of utilization – load factor

These factors are utilized to calculate annual retirement rates and estimate the resulting number of vehicle/equipment remaining in operation.

1.2 Interviews

Telephone interviews were held with the client group as well as representatives from OEM vehicle manufacturers such as JBT Aerotech, TLD, Tronair and Tug Technologies. Regulatory information was obtained through interviews and e-mail with staff members of California Air Resources Board, Environment Canada and a US DOE contractor. Consultants from European airports were also approached for their perspective on market drivers.

1.3 Online Journals & Publications

Ground Support Worldwide magazine, the Aviation Industry Expo and Conference, and Ramp Equipment News e-magazine were all consulted for industry news.

2 THE INFRASTRUCTURE ISSUE

2.1 Fuelling

Hydrogen is the most abundant element on earth but it does not exist in a pure form in appreciable amounts. Like electricity, hydrogen must be produced from a primary source of energy. Hydrogen can be produced using a wide variety of means: electrolysis (i.e. running an electric current through water), reforming natural gas, or purifying by-products of existing chemical plants (e.g. sodium chlorate, chlor-akali, CO manufacture).

The bulk of the hydrogen business revolves around hydrogen's use as an industrial chemical, where hydrogen is sold and transported in very large quantities. In industrial uses, hydrogen is a key component in the production of gasoline and diesel (e.g. hydro-cracking and de-sulphuring feed stocks), food processing (e.g. hydrogenated products), ammonia production and metals processing. Worldwide, more than 36 billion kg of hydrogen were produced in 2010 (US DOE). Within this merchant hydrogen business is a smaller set of market activities where hydrogen is produced, stored and used for nonchemical and non-industrial needs. This subset of the market involves production, storage, and use of hydrogen as a fuel, capitalizing on its ability to store energy for immediate or later use.

Hydrogen gas can be produced on site or be delivered by truck or pipeline. Typically, high volumes (>283 cubic metres/month) of hydrogen consumption are required to justify the capital investment required for on-site production or pipeline hydrogen solutions. An example of this would be BC Transit's fuel cell transit bus fleet based in Whistler, British Columbia (BC) which is served by a station designed, built, operated and maintained by Air Liquide. As of 2010, it was the largest hydrogen fuelling station in the world, with the capacity to fill 23 buses per day.

For lower consumption rates, cylinder delivery, tube trailer delivery, and liquid hydrogen delivery is commonly used. For the HFCE GSE market, it is believed that the monthly hydrogen consumption rates will be similar to the established fuel cell materials handling market. More than 30 fuel cell powered material handling sites have been installed in North America, supporting more than 1,200 fuel cell drives operating for over two million hours. In this market, hydrogen is typically supplied by established gas supply companies such Air Liquide, Air Products, Linde, and Praxair. The capital cost of the fueling equipment and hydrogen storage is, in most cases, amortized into the price of fuel for reasonable consumption rates. As demand for hydrogen increases, the cost per kilogram of hydrogen reduces thereby reducing the overall operating costs.

Figure 1 shows the relationship between hydrogen required per day and the cost per kg for the commodity based on a bus station being supplied by the vendor Air Liquide in 2010, although the demand-cost curve holds true for other vendors as well. In general, at volumes of 50-100 kg/day, the cost of hydrogen may be estimated at $5 to $12 per kg.

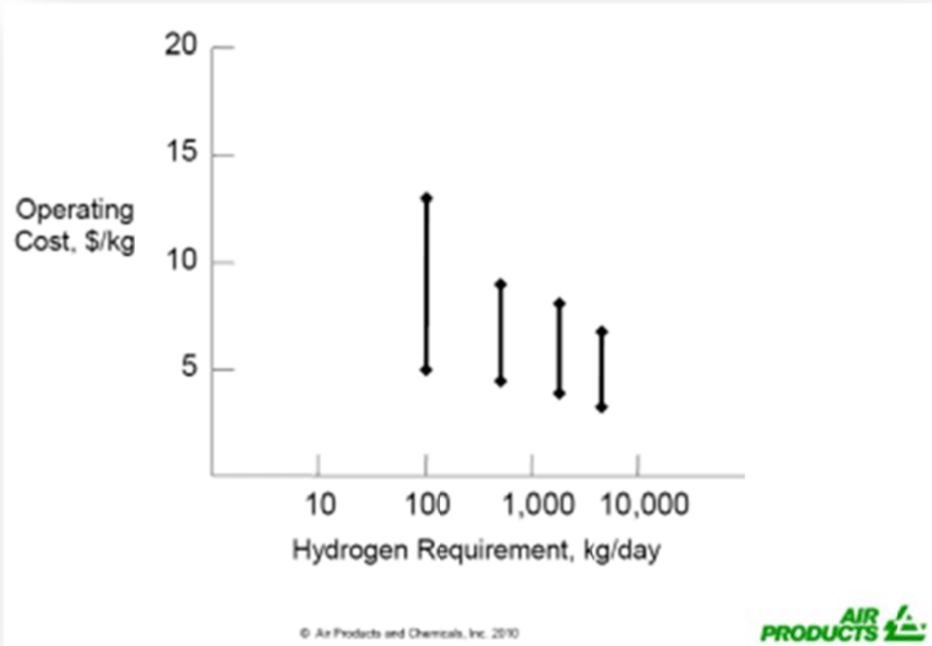


Figure 1: Hydrogen bus fuelling – range of operating costs per kg

This cost curve is relevant to a GSE installation at an airport for two reasons. First, transit buses serving as airport ground access vehicles are a means of increasing station level demand for hydrogen and bringing the cost per kg of hydrogen down for all end users. Secondly, the cost curve for buses would hold true for heavy duty GSE, if similar hydrogen demand could be attained.

As such, the target market for a pilot demonstration program as well as early commercial roll out of fuel cell GSE will be airports that are able to commit to a hydrogen demand in the 50-100 kg/day range, using a combination of applications that could include transit buses, materials handling and GSE products.

Swissport identified mobility of their fleet as a key requirement for adopting a new fuelling system. As a contracted service, they may be active at an airport one year and redeploying their equipment to other airports around the world the next year. Fleet mobility also requires that Swissport can be up-and-running within as little as 60 days from contract award at a new airport.

Turn-key, replicable fueling stations have been emerging for the fuel cell bus and materials handling markets from established gas supply companies. If required, mobile fueling solutions can be provided to facilitate fleet mobility and short fleet commissioning periods. Figure 2 shows photographs of several fuelling station configurations including, clockwise from top left: an indoor warehouse fuelling dispenser for the materials handling application; an outdoor two-pump dispenser; a mobile trailer mounted dispenser; and, an artist's rendering of a fuelling station at San Francisco Airport in California.

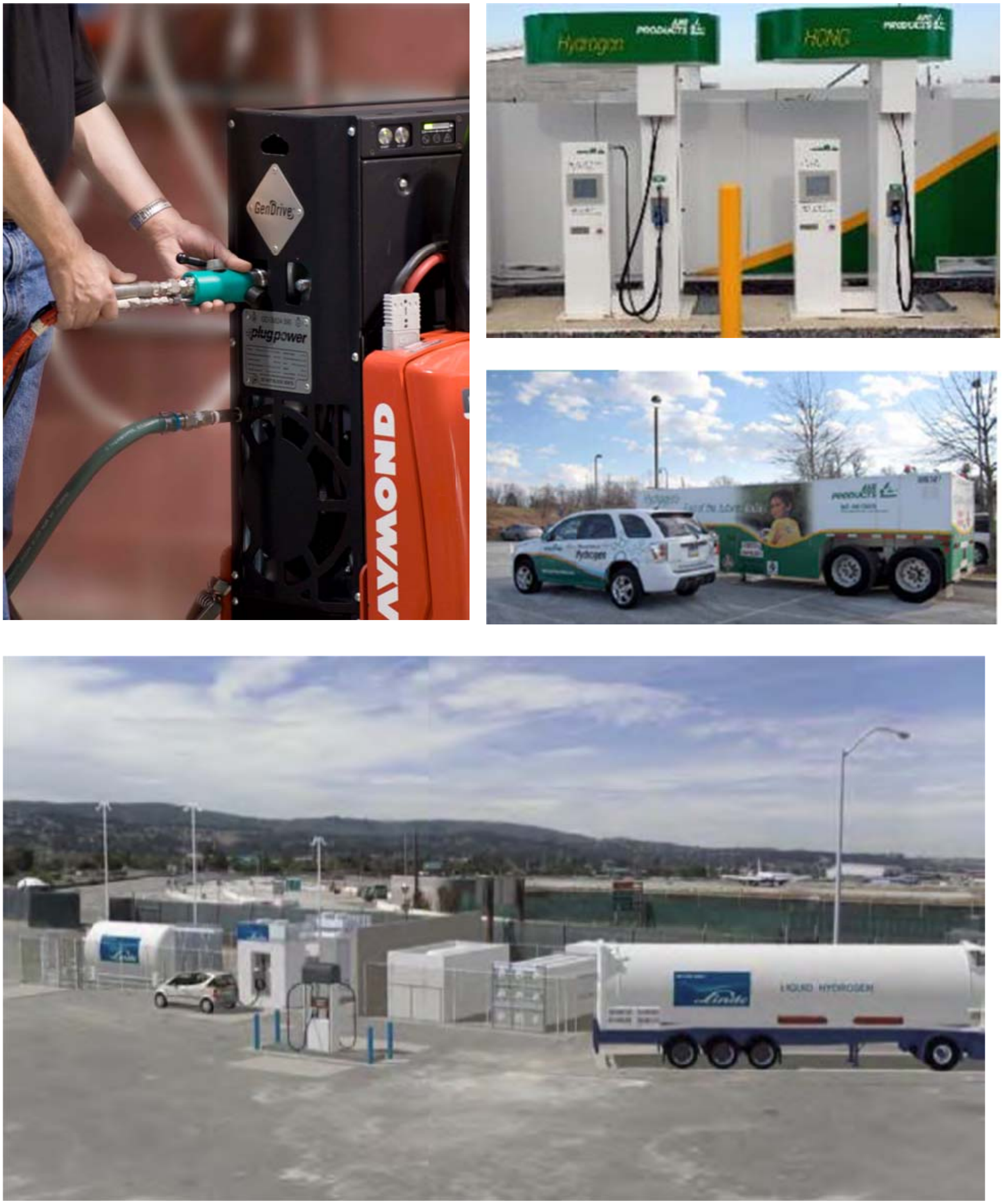


Figure 2: Fuelling station configurations

3 RISK ASSESSMENT

Like most fuels, hydrogen has a high energy density and must be handled properly to be safe. In general, hydrogen is neither more nor less inherently hazardous than other flammable fuels. However, its unique characteristics should be viewed as advantageous. Hydrogen is lighter than air and therefore it rapidly disperses in the event of a leak. This minimizes the possibility of accumulation and ignition. In the event that hydrogen does ignite, its flames generate low radiant heat due to the absence of carbon. This makes hydrogen substantially safer than conventional hydrocarbon fuels (such as gasoline) for users and first responders in the event of any accident.

Hydrogen has been safely produced, stored, transported, and used in large amounts in industry by following standard practices that have been established in the past 50 years. These practices can be adapted for non-industrial uses of hydrogen to attain the same level of safety.

In the materials handling market, the fuel cell forklifts are typically refuelled and operated indoors. The operating environments vary greatly depending on the application. Some of the fuel cell fleets are installed and operated at heavy industrial sites (e.g. Bridgestone-Firestone's Aiken County Plant, and BMW Manufacturing). Some are installed at food distribution centers operating in freezers and dry good storage areas (e.g. Wegmans, Whole foods, Coca Cola, Nestle Waters, United Natural Foods, Central Grocers, Croger, and Sysco). Materials handling fuel cell fleets are also installed at large product distribution centers (e.g. Wal-Mart, FedEx, and Defence Logistics Agency).

Refuelling is typically completed in less than five minutes. Monitoring of fugitive hydrogen emissions is integrated into the fuel cell system and the refuelling station and is hardwired into the vehicle and refuelling safety systems. Additional monitoring is occasionally required at the facility depending on the local regulatory body. In most cases, however, additional monitoring is not required.

For the GSE market, a portion of any future demonstration budget should be set aside to incorporate any additional regulatory and certifying activities relevant to the application.

4 CATEGORIES OF GSE

The market for airport GSE has been segmented into six categories with similar operating characteristics and power plants. The following six categories were consistent with available data sources and therefore used as a “first brush” approach to analysing the best application for HFCE GSE:

- Aircraft load lifting equipment (Figure 3)
- Baggage/material tractors (Figure 4)
- De-icing equipment, heat and start units (Figure 5)
- Push back tractors (Figure 6)
- Utility service equipment (Figure 7)
- Ground power units (Figure 8)

When PSR established its application and end-product categories, it was done so according to the various types of engine applications rather than what the equipment ‘chassis’ may look like or do. As such, there may be some disparate types of equipment grouped together. Alternatively, some low-volume, specialized products may be grouped within categories. Descriptions and examples of each type of equipment category are presented below, along with relevant qualitative information on duty cycles and usage.

Figure 3: Commander series, JBT Aerotech

Figure 4: Electric baggage tractor, TUG Technologies

Figure 5: Diesel air start unit, Tronair

Figure 6: Push back tractor for B747-8, JBT Aerotech

Figure 7: Multi-purpose chassis, Ground Support Specialist

Figure 8: Hobart 400 Hz GPU with Cummins engine

4.1 Aircraft Load Lifting Equipment

Container or pallet loaders, also called cargo loaders, generally have lifting capacities of up to 30,000 kg, typically in a scissor-lift configuration, with a manned control unit and roller-belt assembly for moving pallets horizontally onto the aircraft. Cargo loaders are only used for containerized cargo, and not for baggage, which is bulk loaded. As such, cargo loaders are typically applied to wide body aircraft (Boeing 767 and larger) with aft cargo compartments and freight aircraft (e.g. FedEx and DHL) with containerized cargo in North America. In Europe, narrow body aircraft such as the Airbus A320 accept containerized cargo as well.

Some manufacturers offer battery-electric versions. The duty cycle of cargo loaders—typically short duration under heavy load, limited distance traveled, and a significant amount of downtime between servicing aircraft – make it a potential candidate for electric conversion.

The lifecycle of a container loader is 20 years. Some of the more diligent customers re-build them at the 10-year mark while others may push this to 12 or 15 years.

Similar in principle to cargo lifts, maintenance platforms, or scissor lifts, are typically used indoors. They are often already electrified for this reason, and as such, compete for charging infrastructure within hangars and maintenance facilities. The data set supplied for this report by PSR only includes specialized equipment designed and built specifically for aircraft ground support. Scissors platform lifts are sold across a broad range of industry sectors and for a variety of usages.

4.2 Baggage and Material Tractors

Baggage/materials tractors, also called tow tractors or tugs, are the most common category of GSE and among the most popular choices for use with an electric power plant. The units operate at low speeds (for safety) and need to be able to go indoors, making the category well suited to electrification.

4.3 De-Icing Equipment, Heat and Air Start Units

De-icing equipment, heat and air start units have engines other than the motive force of the vehicle, to pump de-icing fluid or pressurize and pump air. Commercial airlines typically use a continuous flow air pump to pneumatically start spinning jet engines until fuel is injected and the engine is spark ignited. These air start units are not only critical to starting aircraft, they are also expensive, at over approximately $100,000 each. They are in high demand and performing high frequency starts in order to maximize use of the high capital cost equipment.

4.4 Push Back Tractors

The ground handling of aircraft with towing tractors can be divided into two usage patterns, although the same equipment may be called upon to accomplish both: pushback towing and long distance towing. The pushback tractor must be able to pull and push a large aircraft from the gate. Pushback tractors tend to perform a short high intensity task, and then are shut down until they are next needed. The average pushback takes no more than 20 minutes. Long distance towing is mainly used for gate to gate and maintenance towing. The towing is performed at higher speed and can take up to two hours. Either pushback or long-distance tractors may be configured with a towbar or else be “towbarless.”

The vast majority of tractors are tow bar equipped, with towbarless occupying devoted pockets of the market, often in general aviation arenas. While conventional towbar tractors require less maintenance, they require additional manpower on the ramp to fix the towbar on the aircraft. Furthermore, towbar equipped versions require less operator skill to drive than a towbarless model. However, towbarless tractors have higher speeds, which is a clear advantage for long distance operations and for lighter aircraft. The annual operation time of the tractors depends on the airport. Smaller airports use them for perhaps 500 hours a year, while airports like Frankfurt expect an annual operation of 5,000 hours. The overall unit lifetime may be up to 50,000 hours.

4.5 Utility Service Equipment

This category includes a wide array of motorized belt loaders, catering trucks, lavatory and water trucks, passenger steps and other specific task equipment.

4.6 Ground Power Units

A ground power unit (GPU) is a vehicle capable of supplying power to aircraft parked on the ground. Ground power units may also be built into the jet way, making it even easier to supply electrical power to aircraft. Many aircraft require 28V of direct current and 110V 400 Hz of alternating current. The electric energy is carried from a generator to a connection on the aircraft via three-phase, four-wire insulated cable capable of handling 200-600 Amps current. GPUs in the commercial aviation setting are most commonly supplying 115/220 Volt AC power at 400 Hz, with apparent power output ranging from 60 to 180 kVA. They are portable or else towed behind a truck. Most aircraft have one plug to which the GPU attaches, but some such as the Boeing 777 have two.

4.7 Other GSE Applications & Projects

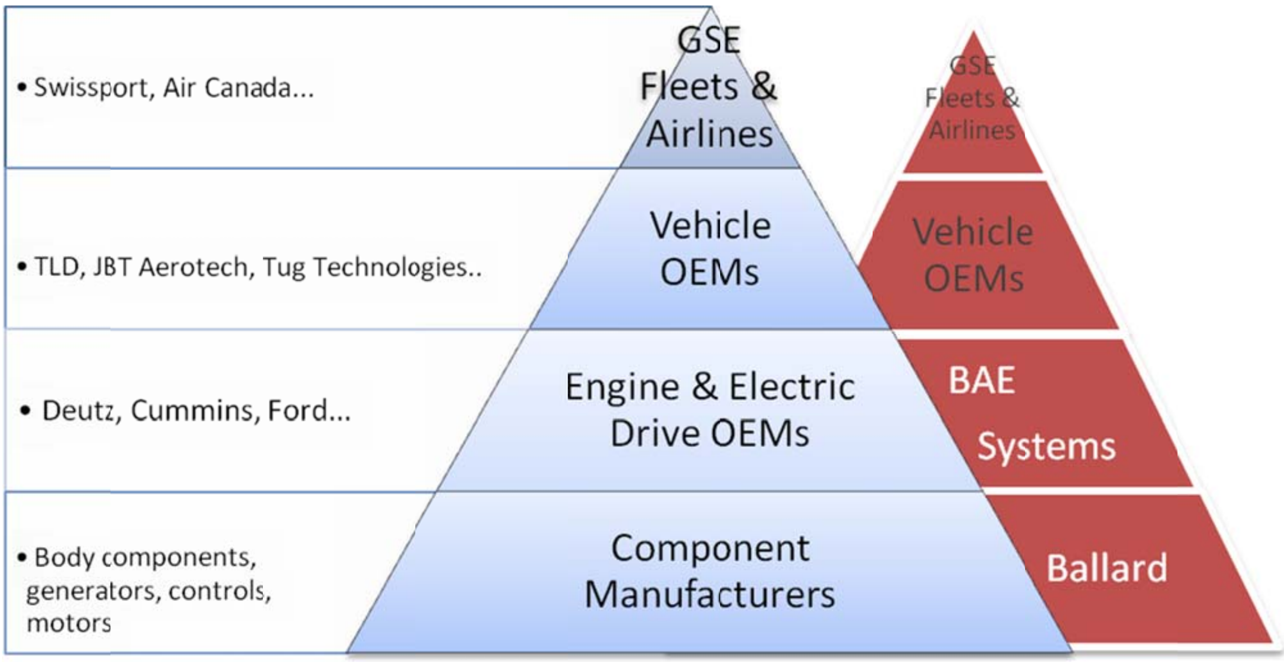
4.7.1 Hydrogen Light Stands

In March, 2011 and 2012, Lennie Klebanoff, Director, Sandia National Laboratory and Greg Moreland, representative, DOE spoke at the Cygnus Aviation Expo 2012 about development of a fuel cell powered mobile light stand, funded by Multiquip, Luxim, Stray Light, Altergy Systems and Boeing, and the marketability of hydrogen fuel cell technology in this niche. Klebanoff pointed to fuel cells as one of the more viable options for the GSE industry, which extends beyond airports to markets such as construction, as carbon reduction standards combine with rising fuel prices. Multiquip, a construction rental equipment company, intends to commercialize fuel cell powered light stands in the second quarter of 2012 (Moreland, 2012).

Figure 9 shows photographs of mobile diesel powered light stands lined up at San Francisco International Airport (left) and Multiquip fuel cell powered unit (right).

5 MARKET STRUCTURE

The market for airport ground support equipment is multi-layered, as illustrated in BAE Systems' July 2009 Market Area Plan for Aviation GSE:



The pyramids depicted in Figure 10 represent *today's* market structure for GSE vehicles (foreground) and the placement of Ballard and BAE Systems in a future scenario where HFCE are being produced (background). It is a very mature supply chain that is at risk of changing with the onset of electric power plants.

The customer for a HFCE power plant would be the Vehicle OEMs, placing BAE Systems as an electric drive OEM and supplanting some of the internal combustion (IC) engine manufacturers. The GSE vehicle OEMs would be BAE Systems' customers, and not the end users of the GSE.

While Vehicle OEMs could vertically integrate and develop their own electric power modules, it was noted by JBT Aerotech that OEMs typically take, for example, a controller from Supplier A together with a motor from Supplier B and batteries from Supplier C. They may add an onboard charger or DC to DC converter from yet another supplier. JBT Aerotech did not see a need for an integrated package, and preferred the flexibility to "mix and match" to best meet the customers' requirements because this is part of their value proposition.

5.1 GSE Fleet Operators & Airlines

The feasibility study client group includes a global fleet operator (Swissport), Canada's flagship airline (Air Canada) and a smaller regional airline (Air North). Interviews revealed that airlines and ground service suppliers take many factors into consideration when selecting an OEM vehicle vendor. At an overarching level, strategic vendors and supply agreements may guide the decision. Also, standardization of product is desirable and occurs at a station level first, and system wide as a secondary goal. The benefits of standardization are obvious, including:

1. Fewer parts on the shelves;
2. Operators can cross-utilize with minimal training;
3. Maintenance training is reduced; and,
4. Safety increases as personnel more familiar with equipment and its quirks.

However, there were also some differences between how decisions are made between the airline and ground service group. Air Canada, a representative airline, noted that they will almost always purchase a unit within the region (e.g. North America) in which the unit is destined to be used. This minimizes currency risk, keeps the competitive landscape even with other carriers, reduces initial transportation costs and improves after-sales support. However, in a 'blank state' situation, Swissport had to consider lead time as a major factor. Their decision process would consider:

1. Lead time – how much time before they have to be operational (typical contract may give 60 days);
2. Talk to vendors and see who can supply within the lead time; and,
3. If all things are equal on the supply time frame, Swissport will look at cost, history of supply, support history, and total cost of ownership for specific equipment.

Interestingly, a slightly different set of rules may apply to electric vehicles. Air Canada noted that it almost always buys straight from an OEM, even for electric. They would not, for instance, convert a unit from IC to electric purely to extend a vehicle's life. They also do not scrutinize lifecycle cost of electric vs. IC. Rather, their decision to purchase electric is driven by a requirement to do so, usually by an airport authority or other local jurisdiction.

In contrast, Southwest Airlines has found that for their business model, electric makes economic sense and rather than buy an electric vehicle from an OEM, they perform conversions of liquid fuel GSE in-house. In fact, Southwest Airlines has an ongoing conversion project for pushback tractors and belt loaders. Over more than 15 years prior to 2011, the Phoenix based crew has converted about 150 units (Haddican, 2011). The cost differential for converting versus buying new can vary by unit type. Southwest, through its continued efforts in-house, has been able to convert at about 50% of the cost of a new unit. This is the average threshold the carrier uses when evaluating projects. "We look at an asset and if we can dump 50 percent of its value into it to create a new asset, then we go for it," Waugh says. "It makes strong economic sense."

One airline that consistently appeared in literature with respect to pushing for electric GSE was Delta Air Lines. Delta's desire to reduce (and eventually eliminate) diesel emissions at the Marine Air Terminal at LaGuardia airport in Queens was a key driver that led to the development of electric push back tractors. They also participated in a demonstration at Atlanta Hartsfield International Airport, starting in 2007 with JBT AeroTech, KLS Company LLC, Southern Company and Electric Power Research Institute. This ultimately led to JBT's electric pallet loader, the Commander 15i (C15i).

5.2 Original Equipment Manufacturers (North America)

The market leaders among BAE Systems' potential Vehicle OEM customers appear to be JBT Aerotech, TLD, Tug Technologies, Tronair and Hobart Brothers. OEM profiles are provided in Table 2, which shows the market share and position of the top OEMs in each GSE category. PSR noted that market shares for individual product types should be kept in perspective. The various competitors will earn their relative positions by delivering products that meet customers' needs and solve their problems. If that includes one or several different products, it is a reflection of the OEM's market strength and resources. In addition, the data reflects an OEM's performance in conventional fossil fuel devices only. Market leaders for electric vehicles are not reflected in the data set.

Table 2: Market leaders in GSE

Category of GSE	Market position (% of 2009-2014 production market)		
	#1	#2	#3
Load lifting equipment	JBT Aerotech (34%)	TLD (25%)	Tug Technologies (20%)
Baggage/material tractors	Tug Technologies (36%)	Harlan (17%)	Tiger (14%)
De-icing, heat and start units	TLD (60%)- start units	JBT Aerotech (26%)	Tug Technologies (10%)
Push back tractors	JBT Aerotech (34%)	NMC (16%)	Mulag (14%) Tug Technologies (13%)
Utility service equipment	Stinar (65%)	Mulag (9%)	None significant
Ground power units	Hobart Brothers (46%)	TLD (30%)	Tronair (10%)

5.2.1 TLD

TLD is the North American market leader in de-icing/heat & start units (although for TLD this actually means just start units) with about 60% of the market share[1], and second in production for ground power units as well as aircraft load lifting equipment (approximately 25% market share).

With respect to the category "de-icing/heat and start units," TLD is a manufacturer of air start units and does not market de-icing equipment, whereas JBT Aerotech supplies both. As such, its dominance in the category de-icing/heat and start units for its air start units alone is even stronger.

Website: http://www.tld-gse.com

5.2.1.1 TLD's Clean Energy Products & Activities

One of TLD's most recent successes has been that of the TPX-100-E, an electric pushback that was designed and produced with an eye to the changing mood over the state of the environment. The model

[1] Based on 2009-2014 production. Source: Power Systems Research OELink database July 2009

was designed to move commuter jets to be able to cope with single aisle aircraft including the likes of the B757. The TPX-100-E relies upon a unique AC/ DC technology that is offered in this range of tractors and TLD has improved the ergonomics and maintenance procedures as well as its reliability. It now runs with the latest generation of computer controls and the installation of Can Bus has simplified the electrical harnesses and allowed the use of a logic-based interface for troubleshooting. TLD has seen between 20 and 25 push backs for an A320 performed on a single charge; charging up this model typically takes about eight hours. The most recent versions of the TLD TPX-100-E are in operation in the US, in Spain and in France. TLD is now able to produce the tractor in Sherbrooke, Quebec, for the North American market (News, 2011).

5.2.2 JBT Aerotech

JBT Aerotech is the North American market leader for both aircraft load lifting equipment and push back tractors with about 34% of the 2009-2014 production market in each, and second to TLD for de-icing/heat and start units with 26%. They have no significant presence in ground power units, utility service equipment or baggage/material tractors segments.

JBT Aerotech does not manufacture its own combustion engines. The GSE volumes are too low for vehicle OEMs to do so, with the exception of Toyota who produces a specific type of bag tractor which presumably uses a Toyota engine (Heemskerk, 2011). This airport GSE business model differs from the agricultural and construction equipment business in which Volvo, Cat, JBC and Deere all build their own engines. JBT Aerotech combines the combustion engine from one OEM supplier with a transmission from another OEM supplier and axles from yet another source. Putting a package together that best meets their customers' requirements is part of the company's value added.

Website: http://jbtaerotech.com/

5.2.2.1 JBT Aerotech's Clean Energy Products & Activities

In 2007, Delta Air Lines, JBT AeroTech, KLS Company LLC, Southern Company and Electric Power Research Institute launched the study to retrofit a diesel-powered aircraft cargo loader, the Commander 15 (C15). The C15 is used in airports worldwide to move luggage containers and other palletized cargo between ground level and cargo bins on wide-body aircraft.

The company applied lessons learned in the study to develop a commercial version of the retrofit kit for 1995–2003 model-year C15s; it is now available as a field-installable retrofit kit. The proven feasibility of the retrofit may induce other airlines to convert existing GSE to electric drive before equipment reaches end-of-life. JBT AeroTech also has since introduced a factory-built electric: the C15e.

JBT Aerotech is aware of Swissport's interest in an electric powered wide body pushback, noting that Swissport is not the only company; however, such a product is at least two years out (from 2011) in their product development schedule.

Swissport is slated for a demonstration of JBT's B400e electric powered pushback tractor for narrow body aircraft later in 2011. This demonstration could shed some light on the operational feasibility of a full electric pushback in the Swissport operation, and from this Ballard and BAE Systems could infer whether a fuel cell electric version would work (Heemskerk, 2011).

JBT Aerotech also has a bulk loader alternative to a belt loader to help staff load bags, developed in Europe in response to ergonomic requirements, which delivers bulk loaded baggage to anywhere in the aircraft belly. It is called a RampSnake and because it is a fairly expensive piece of equipment, the premium for electric was not a barrier.

Finally, at JBT Aerotech's facility in Madrid, Spain, electric transporter and passenger boarding steps are manufactured for the European market.

5.2.3 Tug Technologies

As its name may imply, Tug Technologies dominates in the baggage/material tractors production market (PSR, 2009) with 36% of the market share. Tug Technologies does not limit itself to tugs, however, billing itself as "a leading ground support equipment manufacturer providing a broad product line including air conditioners, aircraft tow tractors, air starts, baggage tow tractors, belt loaders, ground power units, and heaters, with 35 years of experience in aviation ground support equipment."

Tug technologies was the only manufacturer to place among the top three market share holders in all three categories. In addition to leading in baggage/material tractors, Tug holds third place in terms of market share to TLD and JBT in the categories of aircraft load lifting equipment and de-icing/heat and start units at 20% and 10% of the market, respectively.

Website: http://www.tugtech.com/

5.2.3.1 Tug Technologies' Clean Energy Products & Activities

Tug has been offering electric tugs for more than 20 years, with their current Model MZ powered by one 80 V battery and allowing a 2,041 kg drawbar pull. In the diesel units, Tug's Model MA baggage tractor is rated for 1.362 to 2,722 kg, while the "high speed" Model MH baggage tractor goes up to 2,268 kg and the Model MR-8 can tow either baggage or aircraft with a drawbar pull up to 3,628 kg. The MR-8 is also offered in an Interim Tier 4 (not Final Tier 4) Kubota diesel engine.

In September 2011, Tug announced on their website that a complete line electric push back tractors was coming soon, for narrow body through to wide-body aircraft.

Tug also offers two sizes of belt loader, as well as a kit for customers to convert their own belt loaders to electric. "Tug is able to offer a range of solutions from the full conversion and factory rebuild with like-new warranty to a customer conversion kit," says Brad Compton, VP sales and marketing at Tug. (Haddican, 2011)

5.2.4 Hobart Ground Power

Hobart Ground Power prides itself on being focussed. They only sell ground power equipment including solid state (electric) start units. Hobart is part of the ITW Group, a $16 billion conglomerate of over 900 companies. Manufactured in their Ohio based factory, Hobart dominates the GPU market with 46% of the production market share (PSR, 2009). Hobart has expressed an interest in furthering zero emission product offerings for their clients, who range from fixed base operators, commercial and regional airlines, ground handlers and aircraft manufacturers.

Website: http://www.hobartgroundpower.com

5.2.4.1 Hobart Ground Power's Clean Energy Products & Activities

Hobart has worked with both battery electric and fuel cells and currently offers both electric ("solid state" and diesel (producing both DC and AC power) versions of their GPU range. They noted that the most difficult requirements for solid state GPUs are as follows (Wackler, 2011):

- Transient requirements;
- Hurdle of converting and marrying AC loads for large aircraft operations (which are AC also);
- Overload portion of the specification – need 125% of the specified rating for 5 minutes, which translates into very heavy mass or high monetary cost for batteries; and,
- Torque - even gasoline has trouble meeting required torque.

5.2.5 Harlan

Harlan specializes in heavy duty tractors, built in Kansas. They are second only to Tug Technologies in market share for baggage/material tractors production. Their website has a "build your own" feature that allows users to customize how their tractor is specified.

Website: www.harlan-corp.com

5.2.6 Tiger Tractors

Tiger Tractors moved its manufacturing to Anaheim, California when it was purchased by Taylor-Dunn. They are positioned just behind Harlan in the baggage/material tractors category, offering both standard and custom vehicles - burden carriers, personnel carriers, stockchasers, electric carts and tow tractors.

Website: http://www.tigermfg.com/

5.2.7 Eagle Tugs

Products include aircraft tugs, tow tractors and push backs. Eagle Tugs has been providing commercial aviation, military, industrial and transit customers with robust, reliable and highly functional tow tractors, or tugs, for over 40 years.

Website: http://www.eagletugs.com

5.2.8 A&G Mercury

US family owned business manufacturing tow tractors, trailers and parts.

Website: http://www.agmercury.com

5.2.9 Tronair

Tronair manufactures a broad line of aviation GSE with a factory in Holland, Ohio and service centres distributed globally, reaching more than 3,500 OEM customers. In addition to having a large range of products, Tronair still manages to be among the market leaders in the categories de-icing/heat and start units as well as ground power units. Tronair tends to serve the general and corporate aviation market segment more heavily than commercial aviation. One of its signature products is the Jet Porter towbarless tug. Tronair sees their major competitor as Lektro in this category.

Website: www.tronair.com

5.2.10 NMC-Wollard

NMC-Wollard designs, manufactures, markets and services a broad line of aviation ground support equipment, industrial tow tractors, and front-end articulated loaders/tool carriers.

Website: www.nmc-wollard.com

5.2.11 Charlatte

Charlatte is the leading manufacturer of battery powered electric airport ramp vehicles throughout Europe and the United States. Products include a wide range of AC and DC powered baggage tractors, belt loaders, maintenance utility carriers, aircraft pushback tractors, and smaller tractors used for other industrial applications.

Website: www.charlatteamerica.com

5.2.12 Stinar Corporation

Stinar Corporation has been a supplier to the airline industry since 1946, offering a variety of customized products including potable water trucks/carts, lavatory carts/trucks, passenger stairs, catering and cabin service trucks, and maintenance high-lifts.

Website: no public website available.

5.3 OEM Manufacturers (Europe)

5.3.1 Trepel

Trepel is a German manufacturer of cargo high loaders for civil aviation. Next to a complete programme of cargo high loaders Trepel offers a comprehensive product range for all avenues of freight and passenger handling on the airport apron such as cargo loaders and transporters, towing tractors, catering trucks and ambulifts.

Website: www.trepel.com

5.3.2 Schopf Rofan GmbH

Germany based Schopf develops, produces and sells special vehicles for civil aviation and include a complete range of aircraft tow tractors between 5,000 and 70,000 kg operating weight, container and pallet loaders as well as passenger stairs and smaller tow tractors for airports and industry.

Website: www.schopf-gse.de

5.3.3 Mulag

Mulag provides high-tech products and special solutions for airport ground support and roadside maintenance. Mulag bills itself as the leading manufacturer in Germany.

Website: www.mulag.de

5.3.4 AXA Power

AXA Power calls itself the "leading manufacturer of 400 Hz solid-state ground power units and pre-conditioned air units for civil and military aircraft." This is a European supplier of frequency converters for aircraft, specialized 400 Hz transformers, and voltage stabilizers. Axa is part of the ITW GSE Group which also includes Hobart, Trilectron, air-a-plane, J&B Aviation and Houchin.

Website: www.axapower.com

5.4 Electric Conversions

PSR does not currently track electric GSE populations. As such, this section is a description of what is happening with the electrification trend in North America. In Europe, the trend towards electric is more aggressive due to greenhouse gas (GHG) emissions limiting airport growth in some cases (see Section 8).

Electrification of airport GSE is one way for airports and airlines to reduce operating costs and emissions. An electric-drive option exists for many GSE models, and more options are being introduced every year. However, replacing IC units with new electric-drive equivalents may not make economic sense when existing units have not yet reached end-of-life, usually about 20 years. One solution is to use a retrofit kit to convert existing IC equipment to electric drive.

Benefits include significant savings and reduced emissions: retrofitting existing equipment costs about one-fifth the cost of replacing old equipment, and electrification results in operating cost savings of approximately 80%. Additionally, electric-drive equipment aids compliance with emissions regulations.

Conversions from IC units to electric have been a largely sporadic undertaking throughout the industry. Some people, including Brad Compton of Tug, feel that interest is increasing, noting that his company has seen more interest in conversions. "I think when they look at converting a current asset, it is more economical. And then you look at all the incentives to go electric, it's going to happen," he says.

Lead acid batteries are predominant among GSE conversions. Proponents note its simplicity and familiarity to operators. Electric GSE is available for almost any platform, with the exception of a market ready wide body push-back tractor. TUG announced in September 2011 that it would be releasing a full range of electric push back tractors, so this will change in the near future. In addition, the need for electric push back tractors may diminish based on an innovation by Honeywell and Safran who plan to install an electric drive system to aircrafts starting in 2016 for push backs and taxiing (Ramp Equipment News, 2011).

Some manufacturers sell conversion kits. In addition to Tug, noted above, FMI Truck Sales has offered a kit for its Isuzu vehicles since 1999. The company offers the option of producing kits for other types of GSE, subject to demand. "To develop a kit that you put together for a specific model, generally you like to have a little bit of volume, because it's fairly expensive to design and put together for someone," owner Don Emerson explains. "We've done mostly conversions of on-road vehicles, but have the ability to do belt loaders and anything other than really heavy tugs." (Haddican, 2011)

Emerson suggests customers should evaluate the cost return for each type of unit. "A typical kit — by the time you look at something that has power steering and vacuum assist brakes and all those systems you have to convert over — it's not uncommon for the kit itself to be in the $15,000 to $17,000 range (depending on the horsepower you need)," he explains. "Then depending on what you want, you need to add for batteries and so forth, depending on your usage. A battery pack can be another $3,000 to $4,000 if you use lead-acid and more if you go with lithium. You've also got labour, which in most cases is about 100 hours for a conversion, give or take 20 on what your trying and how complicated it is."

Hercules Engine Components has also undertaken conversions for GSE, completing conversions of pushbacks, bag tugs and belt loaders and offers such services for customers (Haddican, 2011). Jack Dienes, president of Hercules Engine Components, says their conversions have averaged between 50-60% of the cost of new, which include the refurbishment of units.

There have also been fuel cell conversions on some GSE. Most relevant for this study is a demonstration conducted with Air Canada as part of BC's Hydrogen Highway in 2007. A Tug Technologies baggage tractor owned and operated by Air Canada was retrofit by General Hydrogen (which was subsequently purchased by Plug Power) using a Ballard MK9 Fuel Cell contained in General Hydrogen's high pressure 700 bar "Hydricity Pack." Fuelling was conducted using a high pressure 700-bar fuel dispenser located airside, and the demonstration (funded by Natural Resources Canada) was the first application of 700-bar storage in an industrial fuel cell application. Figure 11 shows photos of the temporary fuelling station (top left), a baggage tug getting refuelled (top right) and the fuel cell powered baggage tug in operation (bottom).

Figure 11: Air Canada operating a fuel cell powered baggage tug

5.4.1 Enabling Technologies for Fuel Cells

5.4.1.1 Lithium-Ion Batteries

Lithium-ion batteries are emerging as an alternative to lead acid batteries in leading-edge GSE. Although the up-front cost is greater, proponents argue that the recharging time is less and the output is greater. The technology has been touted as the safest battery technology in the world today (Perry, 2012).

A&V Rebuilding, in collaboration with PowerForce unveiled their L-Tug baggage tug at the Cygnus Aviation Expo 2011. The L-Tug will tow up to 50,000 pounds, according to the company. The consortium maintains that the overall cost of ownership over standard-fuelled units is about half.

6 MARKET DRIVERS FOR ZERO EMISSION GSE

Air quality, lifecycle cost and efficiency all stand to gain from electrification. However, the conservative nature of the industry and its focus on reliability may account for the repeated message that the move to electric was typically made only when mandated by a local authority or when government grants made the capital costs too attractive to ignore. As such, offering a product with improved reliability relative to pure electric GSE represents an opportunity for HFCE GSE. Interestingly, there is now concern about Tier 4 engines and their increased maintenance, which could impact reliability, increase costs, or both. Drivers of the shift to electric are discussed in more detail below.

6.1 Improved Fleet Management

An inherent advantage held all electric (solid state) technology over diesel and other IC technology is their static nature, containing no moving parts, and therefore their inherently high reliability potential. Reliability has emerged as a potential "paradigm changing" parameter that needs to be put first and foremost as a marketing feature of HFCE to offset their inevitably higher cost.

HFCE GSE could also provide improved fleet management through exceptional diagnostics and preventive maintenance. Operational availability is so essential to GSE managers, that a demonstration phase followed by a leasing option may be helpful to smooth the introduction phase (Holzinger, 2011).

6.2 Lifecycle Cost / Efficiency

Electric motors, it is well-known, can operate at more than 90% efficiency, which makes their use an attractive option in this day of escalating fossil fuel prices. Their efficiency contrasts sharply with that of the IC engine, which typically has around 40% efficiency.

Where usage is confined to slow movement and executions that rely on high levels of torque, battery power comes into its own. Moreover, an electric motor has essentially just one moving part in comparison with the IC engine which, being more complex, is also proportionately more costly to run and maintain. Taking the traditional elements of engine, transmission and gearbox out of the equation also gives the builder a free rein in terms of design, so that a fresh approach to the pushing and towing scenario can be adopted. Fuel savings and reduced component wear thus become a reality.

Another useful characteristic of electric power is that the engine does not idle, which results in an energy saving; added to that is the fact that the equipment can be designed to recycle energy into the battery through braking manoeuvres. This regenerative braking further enhances the battery's potential.

Capital cost is an issue. As one interviewee noted, there are currently not a lot of incentives to drive the growth of the market in the US. The market has relatively small numbers of units to begin with, and airlines are tied up financially. As such, they noted it was very hard to see a lot of money going towards clean energy GSE in the USA. However, in this interviewee's opinion, the situation is different in Europe (Moreland, 2011).

Ground suppliers we spoke to were motivated to use clean technologies but have very strict cost frames, and could only accept minor cost increases if the technology performed comparably or better in regard to energy consumption, carbon dioxide emissions and noise. However, improvements in reliability, maintenance and range (when compared to battery electric) rated highly. GSE managers are keenly aware of operational advantages, which impact both reliability and cost; for example, an improved fuelling situation, and need of fewer vehicles in the fleet due to hybrid solutions (Holzinger, 2011).

6.3 Air Quality

It goes without saying that running battery-powered GSE contributes to a healthier environment and that staff working around the equipment are not exposed to noxious fumes or, for that matter, high levels of noise.

GSE are classified as non-road (in US) or off-road (in Canada) vehicles. Prior to the *Canadian Environmental Protection Act 1999* (CEPA 1999), there was no federal authority for regulating emissions from off-road engines. Under the December 2000 Ozone Annex to the 1991 Canada-United States Air Quality Agreement, Canada committed to establishing emission regulations under CEPA 1999 for new off-road vehicles and engines that aligned with the US federal EPA requirements. In 2000, before the regulations were promulgated, Environment Canada signed MOUs with 13 engine manufacturers. Under the terms of these MOUs, manufacturers agreed to supply off-road diesel engines designed to meet US EPA Tier 1 standards.

The Off-Road Compression-Ignition Engine Emission Regulations were promulgated on February 23, 2005. These regulations introduced emission standards for model year 2006 and later diesel engines used in off-road applications. These regulations encompass the US EPA Tier 2 and Tier 3 standards. Alignment with US Tier 4 rules is anticipated later through a separate process.

The Off-Road Compression-Ignition Engine Emission Regulations apply to off-road engines of model year 2006 and later. As noted, compliance in Canada with US EPA Tier 1 requirements was through a voluntary agreement signing in 2000. In the US, compliance with Tier 1 requirements was mandatory as early as model year 1996, with Tier 2 as early as model year 2001 and with Tier 3 starting with model year 2006. Compliance in Canada with US EPA Tier 2 requirements was not mandatory until the 2006 model year.

While the Canadian Off-Road Compression-Ignition Engine Emission Regulations align the engine certification values with those of the US EPA Tier 2 and Tier 3 values, there are some differences, for example, the Canadian Off-Road Compression-Ignition Engine Emission Regulations do not include an optional averaging, banking and trading program as do the US EPA regulations.

The authority to regulate GSE has not been tested in a Canadian Court. Although GSE is operated in order to serve a federal undertaking, each piece is owned and managed by private entities working within the “airside” environment. As such, there is some inherent ambiguity over whether local authorities have jurisdiction over airside-only equipment. In the opinion of Metro Vancouver, their Non Road Diesel Engines Regulatory Initiative would apply to existing non-road mobile equipment at YVR. Metro Vancouver’s initiative targets existing equipment that is US EPA Tier 0 or Tier 1 emissions equivalent. Beyond this, federal regulations managing the manufacture of new equipment would effectively take over, described in more detail below.

In the United States, with the exception of California, the US EPA governs and enforces air. In most urban areas, the primary pollutants of concern are particulate matter (PM) and ozone. In interviews with airlines, GSE vehicle manufacturers and ground handlers, there was a consistent theme of local jurisdictions (e.g. airport authorities or cities) regulating emissions directly as well as indirectly through incentives or penalties. For example, the new International Terminal D at Dallas Fort Worth airport will see approximately 30% of ramp equipment be zero emission. This has been accomplished through a combination of mandates and incentives (e.g. additional ramp space).

These local actions do not receive as much attention as wide-ranging legislation described below; nevertheless, they are collectively creating a change in the market place.

6.3.1 US Environmental Protection Agency (US EPA)

In August 2004, the US EPA adopted new emission standards for non-road diesel engines with the Federal regulations “Control of Emissions of Air Pollution from Non Road Diesel Engines and Fuel – Final Rule.” Under these regulations, new engine standards began to take effect beginning in the 2008 model year, and will be fully phased in by 2015.

However, these regulations do not cover the large existing fleet of in-use engines, some of which could continue to operate for decades beyond the date of compliance. As such, the State of California, which is unique in its ability to regulate mobile sources, enacted regulations to govern the existing fleet of non-road diesel vehicles (see CARB, below). Once the US EPA “grants” California the authority to enforce its regulation, other states will essentially have the opportunity to adopt California’s regulations or use the EPA regulations.

6.3.2 California Air Resources Board (CARB)

On July 26, 2007, CARB adopted a regulation to reduce diesel PM and oxides of nitrogen (NOx) emissions from in-use off-road heavy-duty diesel vehicles in California. Such vehicles are used in construction, mining, and industrial operations including airport GSE.

In December 2010, amendments were made to the Off-Road Diesel Vehicle Regulation to make compliance easier for industry and the regulation more acceptable to the private sector. The amendments include:

1. A four year delay from the original timeline for all fleets, making the first compliance deadline January 1, 2014, for large fleets (over 5,000 hp), January 1, 2017, for medium fleets (2,501-5,000hp), and January 1, 2019, for small fleets (2,500 hp or less);
2. A dramatic reduction and simplification in the annual requirements for fleets, and fleet average structure. Fleets now have only one fleet average target to meet based on their NOx emissions. If they cannot meet the fleet average target, they are required to clean up 5 to 10 percent of their horsepower annually, as opposed to the previous requirement of 28 to 30 percent;
3. Making exhaust retrofits no longer mandatory; and,
4. Raising the low use threshold to 200 hours per year instead of 100 hours.

6.3.2.1 Impact on Airport GSE Industry:

Emissions regulations are one factor that could push the industry more toward electric in general — not only conversions, but also new builds. Electric vehicles reduce the fleet-average emissions that operators in California must comply with. Once operators become more familiar with electric, they gain comfort and experience some of the efficiency advantages. For an electric vehicle purchased on after January 1, 2007 that replaces a diesel vehicle in the owner's fleet, the horsepower of the replaced diesel vehicle may be used as the electric vehicle's horsepower.

Said Don Emerson at FMI, "I think that we're seeing much more conversation about it because of the changes that are coming with the emissions…the airlines and the service companies are desperately trying to figure out what direction to go for the long run with the new rules." (Haddican, 2011). JBT Aerotech's representative noted: "Interest levels have been very high," We're fielding questions on a regular basis. You're going to see the percentage of electric vehicles, as conversion or new production, continue to grow as money starts becoming available. With the introduction on the Tier 4 engines, customers are looking at the higher cost of Tier 4 and the maintenance involved. They are giving it more of a look to go electric." (Haddican, 2011)

6.3.2.2 Voluntary Airport Low Emission (VALE) Program

The US Federal Aviation Authority (FAA) designed the VALE program, which was authorized in the Vision 100 – Century of Aviation Reauthorization Act of 2003 (P.L. 108-176) to incent purchase of low emission vehicles. However, vehicles had to be purchased by the airport operator, who is not typically an owners or operator of GSE.

Funding programs like this, if sufficiently large, may even incent airports to venture into new lines of business. One airport, Seattle-Tacoma International, consolidated several funding sources towards subsidising the purchase of electric bag tugs, belt loaders and pushback tractors, to replace the existing petrol and diesel-powered GSE owned and operated by airlines.

6.4 Climate Change

While US airports are primarily concerned with specific air pollutants, in Europe, climate change pollutants as measured by carbon dioxide potential (CO2-e) is a much greater driver. Germany is leading the way, and, furthermore, Ballard has a long history of success in German cities.

Some airports are seeing their growth curtailed by GHG limitations. Many German airports have a goal to "grow climate neutrally," which is leading airports and ground supporters to consider alternative transport means (Holzinger, 2011). Fraport AG is an airport operator with shares or has management contracts in several airports (14 are listed on their website) around the world. Fraport has set a climate protection goal at Frankfurt Airport to reduce carbon dioxide emissions by 30% by the year 2020 relative to 2005 and also to carry out airport expansions carbon-neutrally relative to 2005. It has also become the first airport operator to receive the accreditation status of Airport Carbon Accreditation (ACA) by ACI-Europe. ACA is an institutionally-endorsed program for independently assessing and recognising airports' efforts to manage and reduce carbon dioxide emissions.

The additional carbon dioxide emissions that are expected from the traffic growth at Frankfurt Airport will be compensated for in other areas, for example, reorganization of ground power supply by replacing diesel-powered mobile ground power units, as well as energy-saving heating and lighting. Fraport is currently participating in the on-road test of electric and fuel cell vehicles.

At most North American and some European airports, ground services are subcontracted by the airport authority or airport owner. In the case of European airports, the providing a low GHG producing GSE fleet is a means of gaining a competitive advantage in the airport tendering process (Holzinger, 2011).

An overview of the GSE market potential in Germany is currently underway. The "Airport Alliance" working group, including the eight biggest airports in Germany, aims at collecting this information from the airports. (Holzinger, 2011). Table 3 shows a list of German airports that contract out at least a portion of their ground services, as represented by Swissport being active. This illustrates the importance of ensuring HFCE GSE meets the needs of contracted ground support suppliers, and not solely airline clients.

Table 3: Overview of German airports at which Swissport is active

Airport	City	Annual passengers (2010 in millions)	Swissport active?
Frankfurt	Frankfurt/Rhine-Main	53.0	YES
Munich	Munich	34.7	YES
Dusseldorf	Dusseldorf/Rhine Rurh (NRW*)	19.0	YES
Berlin	Berlin	15.0	YES
Hamburg	Hamburg	13.0	YES
Cologne/Bonn	Cologne/Bonn (NRW*)	9.85	NO
Stuttgart	Stuttgart	9.22	YES
Berlin Schonefeld	Berlin	7.30	YES
Hanover	Hanover	5.06	YES
Nuremberg	Nurenberg	4.07	YES

*NRW is the state of North Rhine Westphalia.

Canada's stated GHG priorities are first light duty on-road vehicles (in progress), heavy-duty on-road vehicles (regulations announced), marine, aviation (to go through international bodies to set standards) and rail.

However, it is recognized that GSE contributes a significant amount of GHGs to Environment Canada's annual inventory. Furthermore, Transport Canada has an MOU with the aviation industry (ATAC) in Canada to reduce GHGs. Although the existing (current) agreement clearly targets aircraft emissions, it is currently being renegotiated, and Transport Canada is expanding the list of industry representatives to include Canada's aerospace industry, the CAC (Canadian Airports Council), as well as the air service operators. Should this MOU be signed, it would provide a voluntary basis for individual airports and airlines to drive down emissions from a broader array of sources.

6.5 Tax Incentives

Stemming from climate change, the European Union's carbon tax system is an incentive for airlines to conserve fuel, including through their ground operations, and this is expected by some to expand to airports.

The Emissions Trading Scheme, which taxes companies for emitting large amounts of carbon dioxide, will take effect January 1, 2012, although airlines would not have to begin payments until January 2013. Under the scheme, airlines from countries like Canada, which do not have a carbon tax or credit-trading scheme, would pay penalties for flights to and from Europe.

6.6 Safety & Noise

Improved safety, through fewer fuelling incidents and reduced noise, is often posed as an ancillary benefit, rather than a sole driver, that contributes to the cumulative benefits offered by electric vehicles.

7 POPULATION ESTIMATES

Production data was obtained for North America (USA, Canada and Mexico), Western Europe, China and Japan, and Central/South America. It should be recognized that production values are most easily accounted for in North America, and that population data for some regions such as China are still being developed. Nevertheless, as seen in Figure 12, approximately 73,381 units across all airport GSE categories were in use in North America in 2010, and approximately 8,742 in Western Europe.

Another upcoming source of GSE inventory information will be released by the FAA's Airport Cooperative Research Program (ACRP) in 2012. The preliminary findings of their report entitled "Airport Ground Support Equipment (GSE) Inventory and Emission Reduction Strategies, Tutorial and GSE Database" state that there are 110,000 GSE units at U.S. airports, with the most common being bag tugs and belt loaders. About 75% or more of GSE are powered by conventional fuels, with 12% of GSE being electric.

These preliminary findings appear consistent with the PSR data, as the definition of GSE to ACRP may include some on-road vehicles as well as non-motorized units. The more conservative value of 73,381 units was used for this report.

Differences and trends among these markets are briefly examined in the following section.

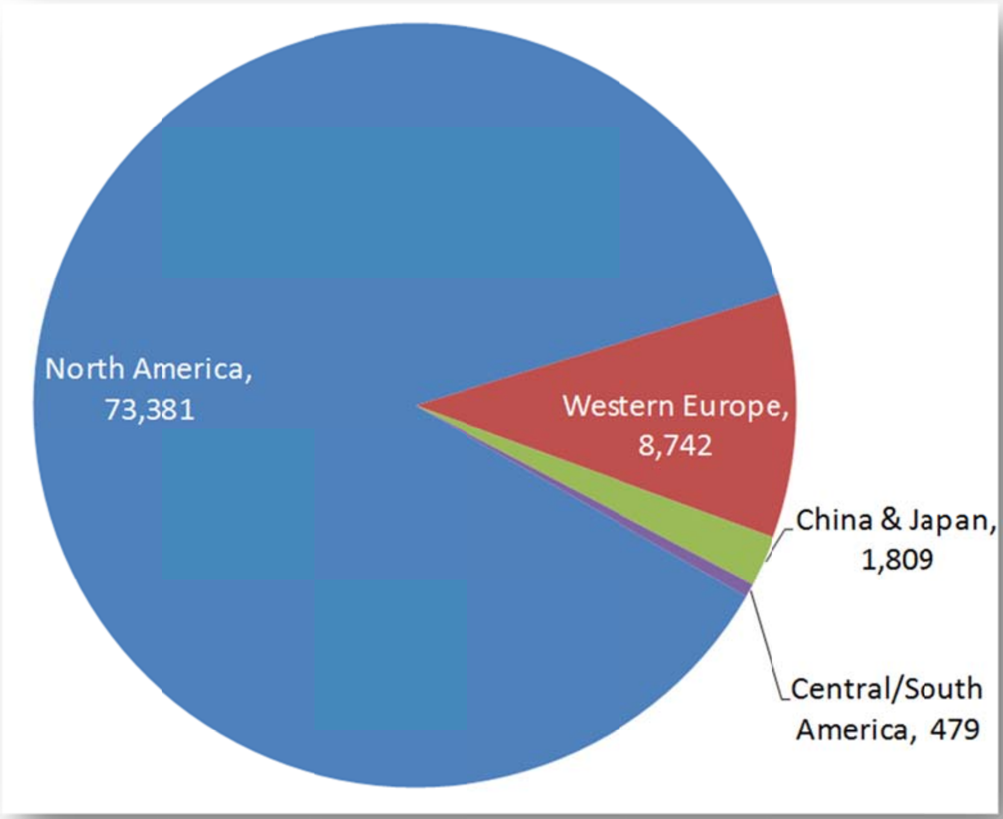


Figure 12: 2010 GSE populations by region

7.1 North America

Table 4 shows the average annual production volumes in North America since 2000 in North America.

Table 4: Average annual production in North America

Category	2000-2010
Baggage/material tractors	1,610
Ground power units	1,184
Aircraft load lifting equipment	1,095
De-Icing equipment/heat and start units	564
Push-back tractors	399
Utility service equipment	91

The average annual production data provided by PSR is the net result of all reasons for replacement of GSE, but does not include when engines are rebuilt or when GSE is repowered. Some GSE, including GPUs, can be in service for up to 35 years. Historically, engines would be re-built with no benefit to emissions. In response to CARB legislation, GSE owners have invested engineering costs to "re-power" GSE with newer engine technology that would meet CARB requirements.

Table 5 depicts the total 2010 in-service population in North America.

Table 5: Total in-service population 2010, North America

Category	2010 In Service Population
Baggage/material tractors	18,337
Ground power units	17,087
Aircraft load lifting equipment	16,695
De-Icing equipment/heat and start units	15,242
Push-back tractors	4,768
Utility service equipment	1,252
Grand total	**73,381**

Figure 13, depicting the North American GSE populations, puts the GSE categories into perspective using a pie chart. It shows that baggage/material tractors represent about one-quarter of the production population, with GPU and aircraft load lifting equipment both behind at an additional 23% each, de-icing/heat and start units at 21%, push-back tractors at 6% and motorized utility service equipment at just 6%.

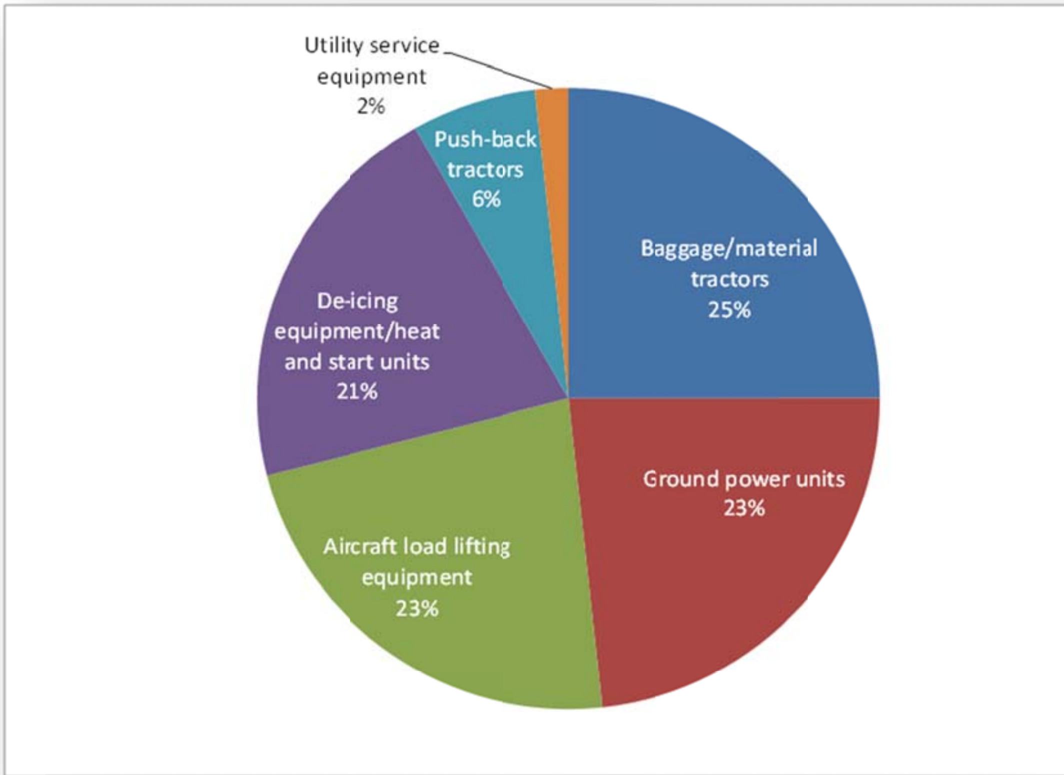


Figure 13: North American population by category

A key characteristic that will affect the age of the in-service population is the typical service life and duty cycle for each type of equipment. Some of these products experience more usage (more operating hours) than the others and may also be subject to much rougher working conditions. For example, the utility, push back and baggage tractors work considerably more annual hours and get more routine abuse than the more technically sophisticated and specialized GSE products (GPUs, load lifting and de-icing/heat and start units).

Certainly, de-icing equipment is only utilized a few months out of the year and this alone will result in a much longer service life. Even the casual observer of GSE at work at major airport will quickly see that the baggage tractors are worked hard and often, meaning that their typical life expectancy will be reduced in comparison.

Trend data is presented for each year since 1997 in Figure 14. In 2003, baggage/material tractors became the single most significant portion of the GSE market in North America. There are at least two drivers for the extended "spike" in baggage/material tractors: high cargo volumes in the early 2000's, and the impact of anticipated EPA and CARB regulations in 2008 and 2009 which drove a lot of replacements in warehouses and ramps. Swissport alone ordered 80 units at that time to meet CARB compliance mandates.

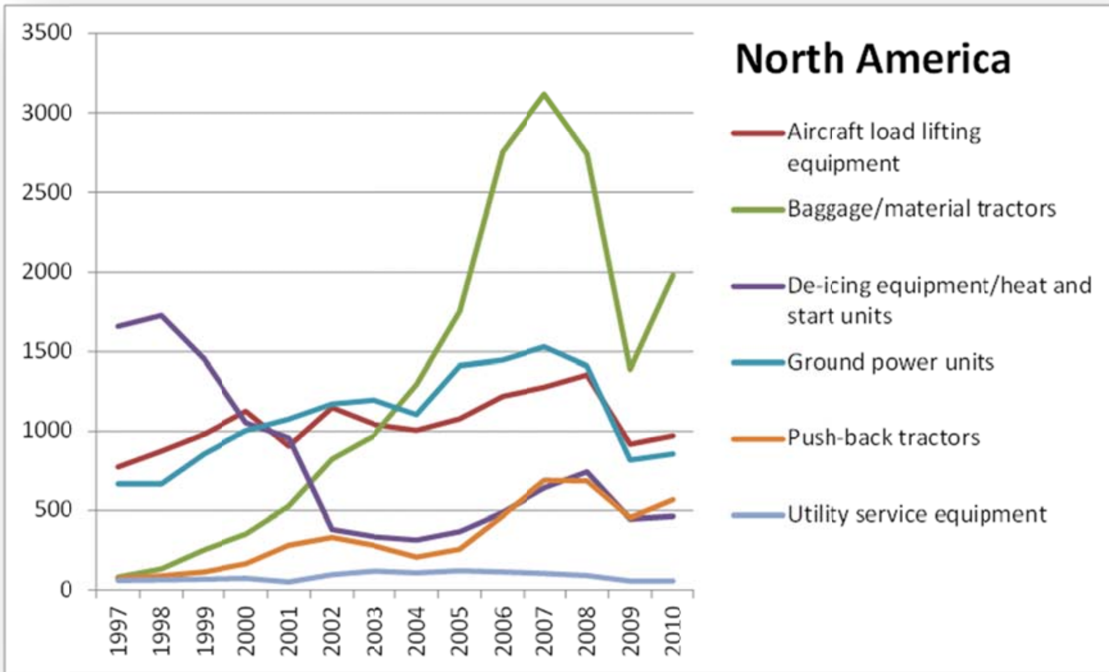


Figure 14: Trend in North America annual GSE production 1997-2010 by category

7.2 Western Europe

The profile in Figure 15 for Europe appears quite different and this may be due to regulatory drivers. For instance, the baggage/material tractors and aircraft load lifting equipment categories have been flat or even dropping in recent years. This may be due to higher penetration of electric units in Western Europe as compared to North America, where fleet operators and airlines may be more inclined to go with lower emission diesel units.

There is a higher proportion of aircraft load lifting equipment in Europe, where ramps are more highly automated. In addition, narrow body aircraft such as the Airbus A320 are containerized in Europe.

The steady rise of push back tractors remains unexplained; however, it was noted by one OEM vehicle manufacturer that towbarless tractors gained popularity more quickly in Europe, while in the US there is a stockpile of very old towbar equipped push back tractors.

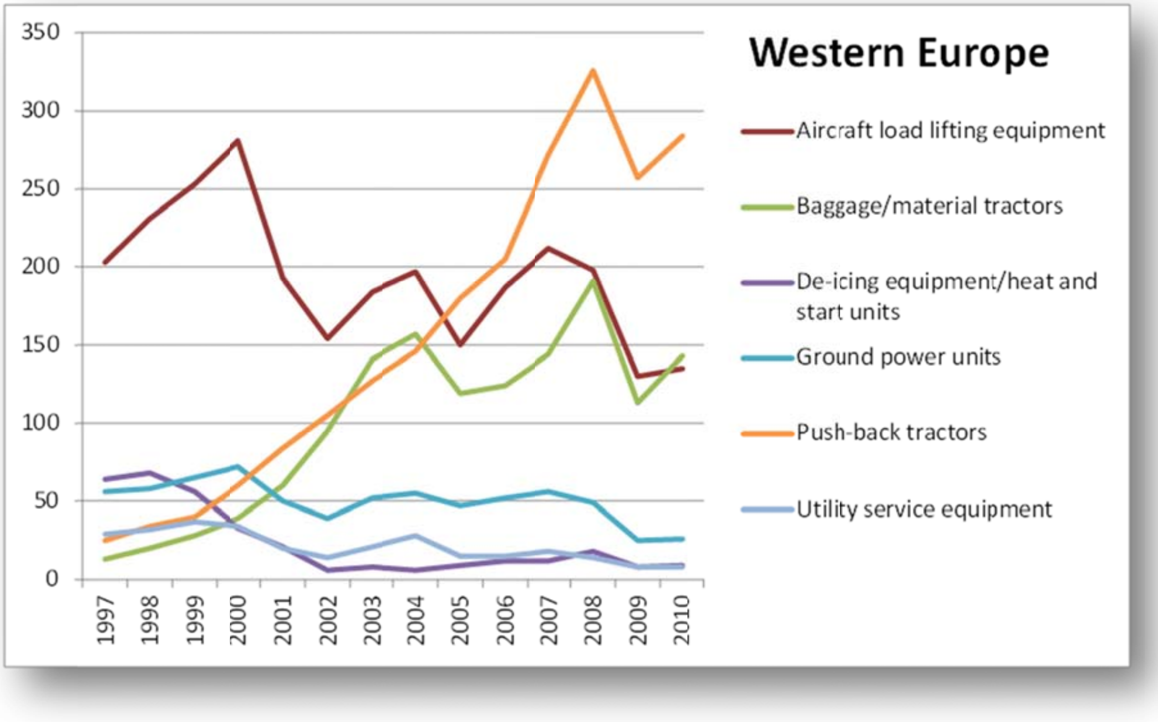


Figure 15: Trend in Western Europe annual production 1997-2010 by category

8 ADDRESSABLE MARKET

8.1 Selection of Equipment Types within Main GSE Categories

Given the population data presented in Section 9, it is possible to apply a first level of refinement to the six broad GSE categories prior to analyzing specific GSE characteristics.

As shown in Figure 13 (North American population by category) it is apparent that the most desirable early-stage equipment categories to focus on, when considering population alone, are **baggage/material tractors, ground power units** and **aircraft load lifting equipment**.

While **de-icing equipment, heat and start units** also represent a significant market segment at 21%, it does not appear to compare as favourably when broken down into the individual equipment types that are aggregated into this category. Certainly, de-icing equipment and heat units are seasonal and therefore not as numerous as air start units, but even still, overall volumes do not appear as favourable as the top three categories.

Within **utility service equipment**, belt loaders may be more ubiquitous than the population values appear, simply because airports may utilize loaders that are not classified specifically as aviation equipment. Furthermore, they have proven amenable to electrification because they do not require a lot of power, do not travel very far, and have long idle periods. However, these characteristics also leave little room for improvement by a fuel cell hybrid alternative, and their lower price point is also a detriment to innovation, relative to other potential markets.

Push back tractors are a relatively small yet high value category. TUG Technologies announced in September 2011 that three models of electric push back tractors were imminent, including a wide body version, proving compatibility with electric. However, Honeywell and French aerospace company Safran announced in June 2011 that they had signed an MOU to develop and install on *new and existing* aircraft by 2016 an electric taxiing system. Not only would this reduce emissions during runway taxi operations, but also *minimize the need for push back tractors*, as the aircraft could do ground level manoeuvring on its own. As such, this does not appear to be an attractive market entrant, as it would be competing with a strong alternative technological solution in the longer term and TUG Technologies in the shorter term.

Baggage/material tractors are known to be a good fit for electric units, although longer range was noted as being desirable by end users. Furthermore, a baggage tug retrofit with an 80V fuel cell based power pack was tested with positive feedback from Air Canada in 2007. The conclusion from this demonstration is that a smaller fuel cell/battery power pack is likely adequate, and that an opportunity exists for Plug Power, which currently manufactures fuel cell lift trucks with Ballard fuel cells, to pursue this market in the future.

In summary, **aircraft load lifting equipment** and **ground power units** appear to offer the highest potential as a suitable fit for the BAE Systems-Ballard consortium to develop a prototype piece of HFCE GSE.

8.2 Selection of GSE within Remaining Categories

The following selection criteria were used to compare GPUs and aircraft load lifting equipment:

- Vehicle population;
- Unit value/price;
- Engine as a percentage of unit value;
- Compatibility with existing fuel cell hybrid propulsion systems;
- Compatibility with electric drive;
- Energy usage;
- Fuelling events;
- Indoor use; and,
- Unmet need.

Discussion of the criteria follows, with the GSE types ranked accordingly and summarized in Table 6.

8.2.1 Vehicle Population

A higher vehicle population points to a larger potential market. Aircraft load lifting equipment and GPUs were comparable, with approximately 16,695 Aircraft Load Lifters and 17,087 GPUs in North America as of 2010. Annual production was also similar at 1,095 and 1,194 for aircraft load lifting equipment and GPUs, respectively. Hobart is reporting strong sales despite world economic challenges, in keeping with strong aircraft orders. Although close, GPUs rank first and Aircraft Load Lifters rank second.

8.2.2 Unit Value/Price

It will be easier for fuel cell technology to compete with higher value GSE. Aircraft load lifting equipment ranges from $110,000 - $650,000 USD with an average price of $230,000, making it the highest ranking category in terms of price. GPUs may be priced up to $250,000 but the bulk of equipment sold is in the $30,000-$80,000 range, with $50,000 being the “sweet spot”.

8.2.3 Engine as Percentage of Unit Value

It will be easier for hybrid electric fuel cell technology to compete with GSE whose engine value is a higher percentage of the total unit value. The percentage values provided do not take into consideration Tier 4 engine requirements. As such, across the board, the gap between diesel and electric will close. While aircraft load lifting equipment ranked highly in terms of overall price, the typical diesel drive system is only about 15% of the overall unit value (15% of $230,000 is nearly $35,000). GPU engines/motors are on average 39% of the unit’s overall value (39% of $50,000 is nearly $20,000). As such, GPUs rank slightly lower if comparing to the “old” paradigm of diesel engines powering the equipment.

8.2.4 Compatibility with Existing Fuel Cell Hybrid Propulsion Systems

This criterion looks at how power requirements compare to the existing heavy duty fuel cell hybrid propulsion systems which are in multiples of 75 KW. Aircraft load lifting equipment appears ideal, with narrow body cargo loaders typically offered at 75 kW and larger units for wide body and freighter aircraft at approximately 130 kW. A typical 400 Hz AC GPU ranges from about 50 to 180 kW, making the power output compatible; however, there is also an initial current draw that spikes up to 1600 Amps that needs to be addressed. The technical compatibility of a GPU at first glance appears to be more challenging than an aircraft cargo loader, and in addition, the GPU will be connected directly with the aircraft. For these reasons, it ranks second to the cargo loader.

8.2.5 Technical Compatibility with Electric

Some GSE is inherently more suited to electric than IC engines, for example, those with high torque/low gearing, no need for high speeds, short duration/distance activity under heavy load, and (for battery electric) a significant amount of downtime between servicing aircraft are ideal characteristics. Electric aircraft load lifting equipment has been proven, ranking first; however, some challenges remain (see fuelling events). GPUs are not widely used in an all-electric form.

8.2.6 Fuelling Events

This criterion looks at the fuelling interval for both diesel and electric versions of the GSE. Since a fuel cell consumes energy more efficiently and can stretch out fuelling events, it may give a competitive advantage. An OEM vehicle manufacturer pointed out that a challenge remains with battery electric aircraft load lifting equipment because they need to drive back to a fixed electric charging location. Not only does transporting these slow moving units take time and further draw down their energy, but they are also very large and cumbersome to fit into a charging location. Their high power also consumes a lot of charging unit time. Because this represents a potential opportunity for HFCE equipment, it is ranked highly. GPUs have an industry expectation to go at least eight hours between refuelling, and typically see a six hour per day duty cycle metered out in 30-minute events. Like cargo loaders, there may be an opportunity to offer a benefit through increased run time over diesel, but already, electric has been proven to not be a ‘show stopper’.

8.2.7 Indoor/Outdoor use

This filter rates the desirability of the GSE to be used indoors. Aircraft load lifting equipment and GPUs are thought to be similar in their need to be used indoors. Neither have a need to be driven into baggage halls or other confined spaces on a frequent basis, but there may be a benefit to their use ‘off-grid’ in maintenance bays or hangars, where shore power may be at a premium.

8.2.8 Unmet Need

This filter assesses the potential for a HFCE unit to meet some currently unmet, or poorly met, need. This filter can also rate the importance of additional features such as predictive maintenance and positional tracking. The client group did not mention aircraft load lifting equipment as an unmet need; however, an OEM manufacturer noted that a means of recharging or refuelling electric versions without having to travel back to a fixed recharging station would be desirable. Similarly, a GPU OEM manufacturer indicated that reliability is a paradigm changer with respect to ‘competing’ against diesel equipment.

Table 6: GSE categories rated by relevant characteristics

Filter	Aircraft load lifting	GPUs
Population of parent category in North America	2 Difference between categories not highly significant	1 Difference between categories not highly significant
Unit price range (US)	**1**	2
Engine/transmission as % of total unit value	2	**1**
Compatibility with existing fuel cell systems	1	2 Compatible but appears more challenging than loader
Technical compatibility with electric	1 Electric versions exist, i.e. JBT Aerotech C15e	2 All-electric GPUs not widely used
Fuelling events	1 Opportunity to improve	2 Opportunity to improve, but not a show stopper
Indoor operation	Possibly in hangars and maintenance facilities	Possibly in hangars and maintenance facilities
Unmet need 1=yes	1 Improved range	1 Improved reliability

8.3 Conclusions on Market Feasibility

Based on market parameters, as opposed to technical feasibility of a hybrid fuel cell electric system, aircraft load lifting equipment and GPUs appear to be the most attractive early markets for deployment of the proposed HFCE. Before deployment, one of the proposed unit types would be evaluated more deeply for technical feasibility followed by development of a prototype unit. This aspect of the feasibility study is explored in Phase 2, following Section 8.

Part of the market feasibility was to gather detailed inventory of the Vancouver Airport (YVR) fleet, including the duty cycle. Unfortunately, Air Canada was not able to release its inventory for YVR; however, sufficient market information was obtained to come to the conclusions about the GPU and container loaders. Sources included: Swissport (YVR) was able to provide fleet inventory information so long as it was not published; discussions with Air Canada; and, Vancouver Airport Authority's Annual Emissions Inventory which models and quantifies GSE operations at YVR.

In summary, Air Canada has 24 container loaders at YVR: six are configured for wide body aircraft and 18 are for narrow body units. Air Canada, like other carriers in Europe, load cargo onto narrow body aircraft using containers. However, many North American carriers use bulk loading (not containerized) for narrow body aircraft. Swissport has some cargo loaders at YVR, as they presently service British Airways twice a day. As of November 2011, Swissport will also add Japan Airlines to its list of customers. Swissport (YVR) is receptive to using a hydrogen powered aircraft load lifting machine. Both organizations have GPUs in service at YVR, but exact numbers were not solicited at the time of this report.

Potential demonstration opportunities are also present in Europe, and will be explored as either a back-up plan or to add further scope to any future demonstrations.

In North America, a combination of regulatory drivers and economic incentives aimed at reducing air pollutants, primarily particulate matter and oxides of n(?)itrogen in urban areas, is promoting the development of electric powered aviation ground support equipment. Electric GSE can now be found across nearly the entire spectrum of equipment types, although not all have found equal market adoption. In Europe, adoption of electric equipment is driven primarily by growth constraints dictated by greenhouse gas emissions.

Beyond regulatory and economic pressures, operators view equipment reliability as being of paramount importance. Not only is reliability operationally imperative, but in order to achieve higher reliability rates, operators will purchase new or keep additional equipment in use, adding to baseline costs.

Aircraft load lifting equipment and GPUs are relatively high-demand, high-value types of GSE that appear to stand to gain from fuel cell electric hybridization. An electric cargo loader with longer run time (than existing electric offerings) and a GPU with higher reliability are both currently unmet industry needs.

The next phase of the feasibility study (Phase 2) will better define the technical compatibility and prioritize the capabilities required for a competitively priced piece of equipment.

Subject to the conclusions of the entire Feasibility Study, Ballard and BAE Systems, ideally in conjunction with existing OEM vehicle manufacturers, will work collaboratively to develop a zero emission GPU or Aircraft Load lifter prototype that could be demonstrated at Vancouver International Airport.

Phase 2 – Technical Feasibility and Trade Study

9 TRADE STUDY INTRODUCTION

9.1 Final Down-Selection of GSE Equipment Type

Due to budget and resource limitations, a technical evaluation of *both* of the short-listed types of GSE from Phase 1, aircraft load lifting equipment and GPUs, could not be performed. As such, a GPU was down-selected from the options presented in Phase 1 based on:

1. The purity of its architecture: it is primarily a power plant without costly auxiliary parts that are not material to the evaluation of the power plant; and,
2. BAE Systems' past experience in designing a variable speed hybrid genset[2] could be leveraged in the design of a cleaner version of the incumbent diesel GPUs.

In addition to the market drivers and practical reasons for evaluating a GPU, there is a further reason that was identified during the initial concept phase of this project, in November 2010. The GPU is an off-board power supply that connects to an aircraft, and is considered a stepping stone to an on-board auxiliary power unit (Breit, 2012). This is a market that a fuel cell powered GPU could ultimately serve, as electrical power requirements for aircraft increase beyond 1 MW of demand, and was the original impetus for BAE Systems looking at HFCE GPUs based on interest from their client, Boeing.

9.2 Definition, Scope and Objective of the Trade Study

In this Phase 2 section of the Feasibility Study, BAE Systems conducted a "Trade Study" or simply, a "trade." A trade study or trade-off study is the activity of a multidisciplinary team to identify the most balanced technical solutions among a set of proposed viable solutions (FAA, 2006). These viable solutions are judged by their satisfaction of a series of measures or cost functions. These measures describe the desirable characteristics of a solution. They may be conflicting or even mutually exclusive (Wikipedia, 2011).

As a part of the trade study BAE Systems provided the following:

- Power systems architecture and hybridization strategy;
- Packaging study;
- Engineering and sourcing planning;
- PEM stack and balance of plant cost study;
- Life cycle cost analysis framework;
- Hydrogen fueling strategy recommendations;
- Program management;

Along with the trade study, BAE Systems has also estimated the cost of a demonstration program.

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[2] A genset is a combination of an engine and an electric generator. Typically, a fossil fuel engine is used to create power, which is converted to electricity by an electric generator. Other parts may include a constant engine speed regulator (governor) and a generator voltage regulator, cooling and exhaust systems, lubrication system, a battery and electric starter motor, and compressed air fed to an air driven starter motor or introduced directly to the engine cylinders to initiate engine rotation.

The primary objective of the trade study was to identify a system architecture and technology that would provide the cleanest emission technology to fulfill the role of a GPU currently used commercially in various airports. The exercise of designing a system would inherently help determine if a hybrid fuel cell electric GPU is feasible. However, the question arises: “What does *feasible* mean?”

Feasibility spans a range from “possible” to “beneficial,” subject to a number of conditions. The next task was therefore to place the proposed technology on that continuum and determine if HFCE GPUs are feasible and if so, under what conditions. As such, the approach taken was to first establish the framework against which the proposed HFCE system should be evaluated, as if it existed, based on factors that the client group stated as being paramount, which were:

1. **Practicality**: how readily available and in use is the technology?
2. **Effectiveness**: Is the technology mature and will it provide a cleaner emission solution compared to the incumbent fossil fuel product?
3. **Safety**: Does the technology offer the same or a higher calibre of safety than current technology?

The methodology for the trade study is described in Section 9.3.

9.3 Trade Study Methodology

Once the fixed elements of the comparison framework were established, the next step was to evaluate the proposed system against existing technologies that represent alternative ways to reduce emissions without sacrificing practicality, effectiveness and safety.

The three already-commercial technologies that were selected for comparison in the new GPU application were:

1. Variable speed hybrid diesel GPU: based on BAE Systems’ stationary primary power unit with the HybriGen™ Primary Power System.
2. Rechargeable electric plug-in GPU: based on the HybriGen™ Grid Tie/Back-up Power system.
3. A hybrid fuel cell electric GPU (HFCE GPU): based on the HFCE transit Bus and HybriGen™ Phase I system.

Each of the technologies above represents evolutionary progress over the previous in terms of clean emissions and advances in technology. Two of these systems are known and understood in different (non GPU) applications, and the third is partially understood because it exists without the plug in feature in a bus application, which is quite different from a GPU duty cycle. Therefore, some assumptions had to be made based on the performance of hybrid fuel cell electric propulsion systems currently operating in different *applications* (e.g. buses), and based on performance of selected *elements* of the proposed hybrid fuel cell electric system in commercial use (e.g. battery hybrid systems and pure fuel cell systems).

Going through the exercise identified the strengths, weaknesses and areas where more data was needed. The trade study exercise also provided enough information to come up with a preliminary design, a set of questions and conditions to consider in a demonstration of the prototype in order to evaluate the proposed system's life cycle cost, and a rough order of magnitude cost for a prototype to be used as part of a demonstration.

The categories that represent the variable elements of the trade study, those that could be subjectively compared, were the following:

1. Emissions;
2. Retrofit ability;
    - Weight
    - Packaging
    - Refuelling
3. Reliability;
4. Ease of use;
5. Service/maintenance; and,
6. Unit cost.

The three different technologies were compared based on the above categories. Each technology was assigned a rank of one (1) to three (3), against each of the six categories. Throughout the process, the overarching goal remained the provision of the cleanest emission solution.

The criteria applied for assigning the rank, with 1 being the best and 3 being the worst score, are summarized in Table 7. Three of the selected categories, *emissions*, *retrofit* and *unit cost*, were scored quantitatively based on the incumbent IC based GPU ("current" GPU), whereas *reliability*, *ease of use and service/maintenance* were scored relative to one another qualitatively, as data does not yet exist for the proposed system.

Table 7: Trade categories, weights and criteria

Weights	Trade Categories	Criteria
10	Emissions	Zero (1); better than current GPU (2); current GPU (3)
7	Retrofit -weight	Less than current GPU (1); current GPU (2); heavier than current GPU (3)
7	Retrofit packaging	Smaller than current GPU (1); current GPU (2); larger than current GPU (3)
7	Retrofit - refuelling	Less than current GPU (1); current GPU (2); greater than current GPU (3)
9	Reliability	Qualitative assessment
6	Ease of use	Qualitative assessment
8	Service / maintenance	Qualitative assessment
6	Unit cost	Current GPU (1); 2-4 times current GPU (2); greater than 5 times current GPU (3)

9.3.1 Emissions

Existing IC GPUs typically utilize a Tier 2 or a Tier 3 diesel engine and are run at a constant speed to provide the required power output. Each of the three compared technologies was ranked in the comparison to these existing GPUs; a score of ‘1’ reflected that the technology is a clean zero emission technology, ‘2’ reflected that the technology was better than the current GPU but still had notable GHS and CAC emissions and ‘3’ was considered the same as the current GPU.

This category was given a weight of ten (10) as this was the most important variable and represented the objective of the feasibility study.

9.3.2 Retrofit Ability

The output of the technologies and system architectures trade study could in the future displace the diesel engine based GPU, hence are required to be meet the same weight, size and refuelling needs of the current GPUs. A change in any of these retrofit needs may require change in existing vehicle infrastructure; for example, the vehicle used to tow the GPU, or available space to station the GPU between planes at the gate.

Weight, *packaging* (size) and *refuelling* are subcategories that are ranked separately in order to simplify evaluation. A score of ‘1’ indicated the technology’s capacity to be better than the current GPU, ‘2’ indicated that it met the current GPU requirements and ‘3’ indicated that the technology is larger than the current GPU.

Weight of the package includes the diesel genset, fuel tank, electronics, chassis and after treatment. Packaging is the complete enclosure and chassis. Refuelling needs pertain to the fuel refill needs of the GPU.

This category was given a weight of seven (7) as it is important in terms of retrofitting the current GPU but as the technologies traded are still fairly new, there is ample time to transition to a new configuration, and as such is not as urgent an item as clean emissions. In the long run, this category could be as critical as emissions.

9.3.3 Reliability

The technologies traded are expected to be more reliable than the current GPUs in terms of continuous operation, failure rates, availability and component life. This category was scored qualitatively by comparing the new technologies against one another and, when possible, with the current GPU unit.

The current GPU has multiple rotating components versus a static system for some of the technologies that were compared. The score was affected by increasing short life components, such as energy storage, based on duty cycle and operating environments. A score of ‘1’ in this category indicates the most reliable and ‘3’ the least reliable.

This category has been given a weight of nine (9), because reliability was reported as paramount to operators (noted in Phase 1), to the extent that it is a factor that they would pay a premium for. The client group also noted that reliability in existing conventional GPUs is low due to the number of rotating components.

9.3.4 Ease of Use

This category was evaluated qualitatively from an operator perspective, when it comes time to use the system. Features such as load-based system turn on/off, remote turn on/off capability, improved diagnostics, easy to use controls and real time system status were used to evaluate this category. Another important element considered for scoring the technologies was the training needs of the operator. A score of ‘1’ in this category indicates the most ease of use and ‘3’ offered the least ease of use to the operator.

This category was given a weight of six (6) as it is important that it be simple enough for the operators to become familiar with it quickly; however, there is ample time to transition and is not seen as urgent. This is another category that will be expected to weigh in more heavily once the technology selected becomes popular and starts replacing existing GPUs. The score can also be improved by providing the right training and support to the operator community.

9.3.5 Service/Maintenance

This category was evaluated qualitatively by comparing the technologies against each based on the required service and maintenance over the life of the unit. A score of ‘1’ in this category indicates the least service/maintenance need, whereas a ‘3’ indicated the most.

This category has been given a weight of eight (8), since the selected technologies must likely outperform the existing GPU in order to be accepted by the operator community.

9.3.6 Unit Cost

The objective of using this category was to place the technology in terms of capital cost compared to the current GPU. Though all selected technologies have a higher cost compared to the current GPUs, it was important to be able to quantify the difference. A score of ’1’ indicates the same cost as the GPU, ‘2’ indicates a cost delta of two (2) to four (4) times higher cost and a score of ‘3’ would indicate the cost delta to be five (5) times more or greater.

Since the comparison is between new emerging technologies and existing technology, the capital cost of the new technology is expected to be higher and hence a weight of six (6) was allotted to this category.

The cost is expected to improve geometrically based on large volume production of the single most expensive component, the fuel cell, in combined fuel cell markets including buses. In addition, there are existing technology programs in place at Ballard to reduce the cost of the heavy duty fuel cell module which will provide significant room for cost improvement by the time the GPU is commercially ready.

9.4 System Architecture Options

This section describes the three system architectures that are compared (traded) against one another according to the categories explained in Section 9.3.

Current GPUs are based on a diesel engine that acts as the primary source of power by spinning at a constant number of revolutions per minute (RPM) to produce the required frequency output. The units typically have a field-wound three-phase generator which is connected to some form of filtering element and a transformer (if needed) to provide the necessary AC output voltage. New GPUs and re-powered GPUs typically use an EPA Tier 2 or Tier 3 rated engine to provide emissions that are compliant with recent legislation. An example of a conventional 75 KVA GPU is shown in Figure 16, by Stewart & Stevenson.

Figure 16: 75 kVA GPU

The technology options selected for the system architecture and technology trades are the following:

1. A variable speed hybrid diesel GPU with energy storage;
2. Rechargeable electric plug-in GPU (RE GPU); and,
3. Plug-in hybrid fuel cell electric (Plug-in HFCE) GPU.

9.4.1 Option 1: Variable speed hybrid diesel GPU

The variable speed hybrid diesel GPU concept (Figures 17 and 18) is based on previous efforts by BAE Systems to develop a variable speed generator that would utilize a rechargeable battery pack to offset the engine operation at its inefficient operating points.

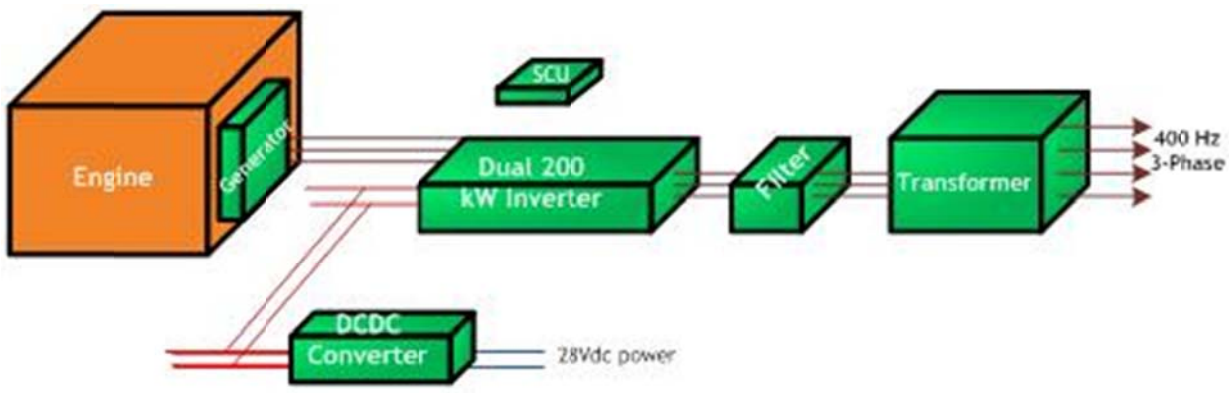


Figure 17: Schematic of variable speed hybrid diesel GPU

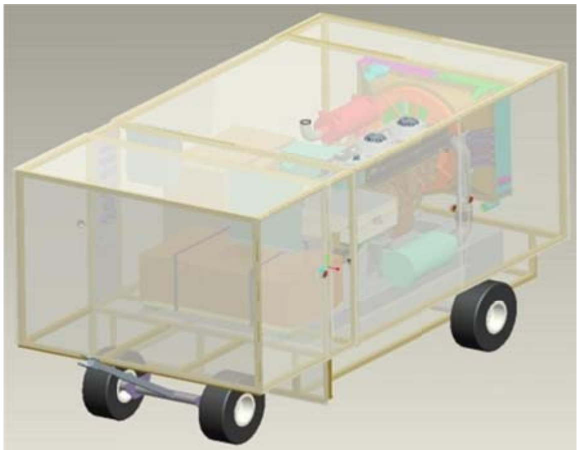


Figure 18: Potential configuration of option 1 components

The diesel engine is spun to the required speed based on the electrical loading of the system. The variable speed GPU would be designed to provide a total of 150 kW of continuous three-phase 400 Hz power. Two key operational features of this system are:

1. At low loads, up to 30% of the total rated power, the system will utilize the energy from the battery pack to sustain the load. In the event the state of charge on the battery drops below a set level, or if the load increases, the engine is spun to match the load output and to recharge the battery.
2. The engine operation is maintained at its peak continuous torque by running the engine at rpms that match the load.

The variable speed hybrid diesel GPU would provide the following benefits, based on performance of the BAE Systems genset:

- The engine operation is reduced, as the engine load is offset with energy storage at low loads, thus eliminating the inefficient operating points of the engine and reducing fuel consumption.
- By running the engine at continuous peak torque rating at a given speed, the exhaust gas temperature (EGT) of the engine is maintained higher than on conventional diesel gensets of the same size. This allows for increased burn of particulate matter in the exhaust system and reduced emissions overall.
- The run time of the engine is significantly reduced, removing failures and wear and tear of the rotating components.
- Issues related to wet stacking, caused by the running the engine under loaded at constant rpm for extended periods of time, are eliminated, increasing the life and performance of the diesel engine.
- It allows for silent operation (when the engine is off) and reduced noise (while engine is running)
- It has turn-key operation using load demand based turn-on and turn-off.
- Utilizes the energy storage in the battery pack to respond to instantaneous transient loads.
- No external charge is needed to replenish the battery pack.

9.4.1.1 Proof of Concept:

The variable speed hybrid genset concept was developed by BAE Systems as a potential offering for stationary prime power system for commercial and military ground application under the HybriGen™ Phase I program. All components used are highly reliable and are reused from BAE Systems HybriDrive® series hybrid system. The HybriDrive® series hybrid system has accumulated over 20 million hours of operation and eliminated over 250,000 tonnes of carbon dioxide emissions since being in revenue service.

9.4.2 Option 2: Rechargeable Electric Plug-in GPU

Figures 19 and 20 depict the schematic and the potential configuration of the rechargeable electric plug-in GPU (RE GPU), which would not contain a power plant of any sort. All of the energy used to provide three-phase output power would be derived from energy stored in the battery packs. High energy density lithium Ion chemistry based battery packs would be utilized and sized to deliver the necessary output power. The unit would plug-in to recharge the battery pack using other GPUs or wall power from the facility.

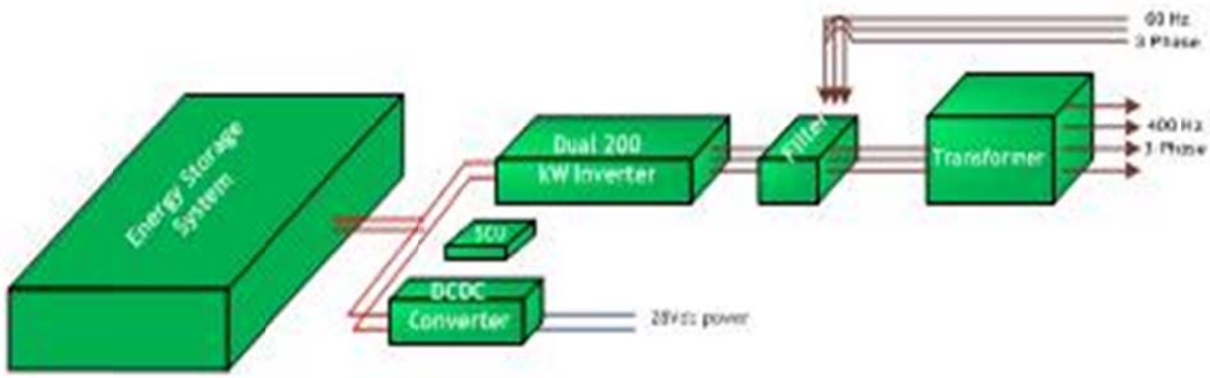


Figure 19: Schematic of renewable energy electric plug-in GPU

Figure 20: Potential configuration of option 2 components

The key operational features of the system are:

1. It does not utilize a power plant (i.e. diesel engine). All the power is derived from the battery pack and can respond instantaneously to transient loading.
2. It provides for a plug-in charge capability to replenish the battery pack energy.

The operational features provide the following benefits:

- Zero emission operation.
- The energy storage can be sized to meet a range of GPU rating and operational hours.
- Quiet operation.
- It has turn-key operation using load demand based turn-on and turn-off.
- Instantaneous load handling capability.
- Minimal wear and tear; minimal service and maintenance required.
- 28VDC output is provided as a part of the system without any additional hardware.
- Plug in feature available to support recharge using facility power.

9.4.2.1 Proof of Concept

BAE Systems has developed a similar system for uninterrupted grid-tie back-up power, as a part of the HybriGen™ Phase II program. All of the system components are borrowed from the HybriDrive® series hybrid system, providing a suite of extremely reliable components with very low failure rates and high life expectancy.

9.4.3 Option 3: Plug-in Hybrid Fuel Cell Electric GPU

The plug-in hybrid fuel cell electric (HFCE) GPU concept utilizes Ballard's FCVelocity® HD6 as the primary power plant along with a lithium ion based energy storage system as the start-up and back-up power sources. Figure 21 depicts the schematic and Figure 22 shows the potential configuration within the packaging of a conventional GPU.

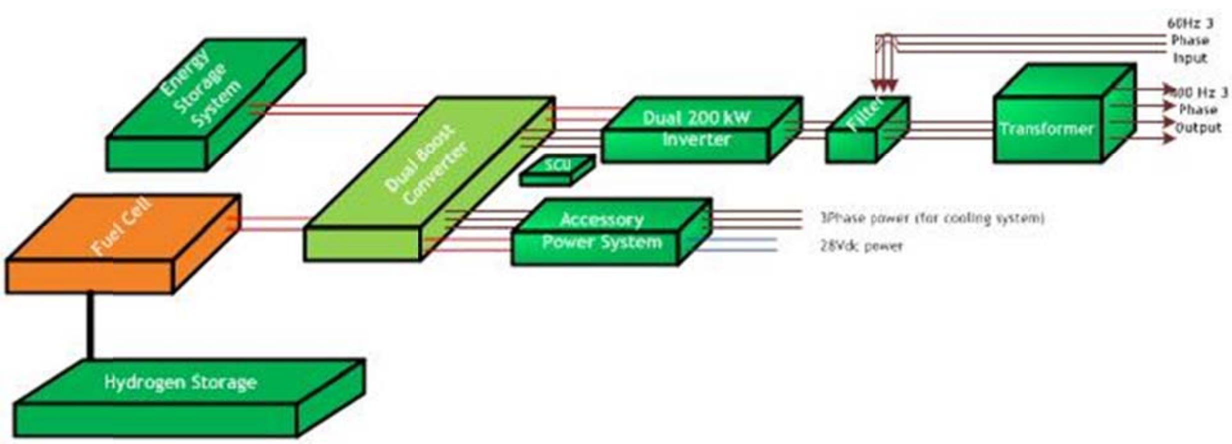


Figure 21: Schematic for plug-in hybrid fuel cell electric (HFCE) GPU

Figure 22: Proposed configuration for option 3 components

All of the power conversion is performed by solid state power electronics, from BAE Systems' HybriDrive® series hybrid system. The system is designed to provide up to a 150 kW (187 kVA) of continuous power output using power conversion electronics along with 28 VDC power output based on application. The system offers a unique plug-in feature to recharge the battery pack when needed or when the hydrogen supply has run out. The hydrogen tanks can be sized based on required power output and hours of continuous operation. The transformer unit would also be designed based on the application including total maximum power output.

The key operational features of the system are:

1. The system utilizes a hydrogen fuel cell power plant as the primary source of power generation.
2. The system consists of a battery pack that provides back-up power and can be recharged using the fuel cell power plant or through the system's plug-in feature using facility power.

The operational features provide the following benefits:

- Zero emission operation.
- Hydrogen storage that can be sized to meet a range of GPU ratings and operational hours.
- Quiet operation.
- It has turn-key operation using load demand based turn-on and turn-off.
- Instantaneous load handling capability using a battery pack
- Minimal wear and tear as there are no rotating elements in the power plant; and as such, minimal service and maintenance required.
- 28 VDC output is provided as a part of the system without any additional hardware.
- Plug-in feature that would be available to support recharging using facility power.

9.4.3.1 Proof of Concept

The plug-in HFCE GPU concept is derived from BAE Systems' effort in the transit bus market. BAE Systems took the lead on behalf of several partners, including Ballard, to build a fuel cell bus that blends energy from a fuel cell and battery electric power source, providing a zero-emission vehicle with improved fuel economy. This bus utilizes BAE Systems HybriDrive® Series transit bus propulsion system and Ballard's FCVelocity® HD6 fuel cell. The architecture improves fuel economy and allows the vehicle to operate with zero emissions. The fuel cell bus demonstrates how easily the HybriDrive® series architecture can transform from a hybrid using IC to an all-electric vehicle.

9.5 System Architecture Comparison

The three above mentioned architectures were traded off against one another based on the criteria within each of the selected categories. As described in Section 9, each technology was assigned a rank of one (best, shown in green), two, or three (worst, shown in red) for each category based on a qualitative or quantitative evaluation.

Table 8: Scored trade categories, weights and criteria

Trade Categories	Weight	Current	Variable Speed Hybrid Diesel	Rechargeable Electric Plug In	Plug In Hybrid Fuel Cell Electric
Emissions	10	3	2	1	1
Retro Fit - Weight	7	2	2	3	2
Retro Fit - Packaging	7	2	2	2	2
Retro Fit - Refuelling	7	2	1	3	2
Reliability	9	3	3	2	1
Ease of Use	6	1	1	1	1
Service/Maintenance	8	2	2	2	2
Unit Cost	6	1	2	2	3
Raw Score		127	116	118	101
Weighted Average Rank		2.12	1.93	1.97	1.68

Lowest (worst) rank	red
Middle (neutral) rank	yellow
Highest (best) rank	green

Table 8 summarizes the results of the scoring. The raw score is a weighted sum. It was calculated by multiplying the category's weight (second column) times the technology's rank (shown in each box) and then summing the results. For example, the current IC GPU achieved a raw score of 127, which is the sum of: (10x3 + 7x2 +7x2 + 7x2 + 9x3 + 6x1 + 8x2 + 6x1). The weighted average (raw score divided by 60, the sum of the weight factors) is shown in the last row, with a lower number (higher rank) being preferable.

When compared against each other, and the current GPU technology that is in service, the plug-in HFCE GPU concept stands out as the best overall value option. It is important to remember, however, that the purpose of the evaluation exercise was not to merely “prove” the value of a plug-in HFCE GPU, but also to identify the strengths and weaknesses of the system.

The other two technologies fall behind in areas of reliability, emissions, weight and refuelling. The variable speed hybrid diesel GPU (Option 1) though better than the current GPU in emissions, does not closely compare to the other two clean zero emission concepts.

The RE GPU (Option 2), offers a promising future technology concept; however, it falls behind the plug-in HFCE GPU (Option 3) in: weight, due to the use of heavy battery packages (545 kg for every 50 kWh); refuelling, limited by the size of the battery packs that can be packaged in a GPU chassis to sustain energy for a complete day operation without needing to refilled; and, reliability, due to the effect of temperature and duty cycle on the life of the energy storage cells in the battery pack.

The plug-in HFCE GPU scores significantly lower in the unit cost category, and the same in service/maintenance and ease of use, both of which are expected to be low for new technology such as hydrogen fuel cells. The score in the service/maintenance and ease of use categories could also be improved by providing the right training and support to the operator community. The score in the unit cost category will start to improve once larger volume production of the largest cost component, the fuel cell, occurs. The plug-in HFCE GPU is therefore seen as a promising and feasible candidate technology with which to work further. The next step is to perform a system sizing to determine how the components would be optimally sized in order to balance the power, operation time and packaging (size).

10 PLUG-IN HFCE GPU SOLUTION

The plug-in HFCE GPU utilizes a Ballard FCVelocity® HD6 fuel cell as the primary power plant along with a lithium ion based energy storage system as start-up and back-up power sources. The power conversion is performed using BAE Systems solid state power electronics from the HybriDrive® series hybrid system. The system is designed to provide up to a 150 kW (187 kVA) of continuous power output using power conversion electronics along with 28 VDC power output based on application. The system offers a unique plug in feature to recharge the battery pack by plugging in to a three-phase 208 VAC 60 Hz outlet when needed or it can be recharged using the power outputted by the fuel cell.

The plug-in HFCE GPU would be equipped with a data logger that continuously monitors system parameters and uploads the information to a secure server on a daily basis. This data is available to BAE Systems for analysis, advanced diagnosis of issues, and performance monitoring. The data could also be made available to the operator based on the application agreements.

The fuel cell power plant is equipped with a dedicated data logger that loads data onto a compact flash card. This card can be removed from the fuel cell and the data uploaded to the fuel cell manufacturer for analysis and diagnostics.

The plug-in HFCE system is derived from the effort BAE Systems, working with Ballard and other partners, invested in to develop the HFCE Transit Bus which currently undergoing trial runs. The system architecture is similar, except the plug-in HFCE GPU provides electrical power as output and the HFCE transit bus provides electrical and mechanical power for electrical accessory loads and propulsion load.

The system would provide a turnkey power generation system solution to satisfy the operational capabilities of the conventional diesel engine based GPUs based on written specifications from Hobart and discussions with the project client group.

10.1 Component Description

10.1.1 Fuel Cell

Based on the automotive fuel cell stack, Ballard's FCVelocity® HD6 fuel cell module offers a design ideal for integration into bus applications, which like GPUs, are one of the first heavy duty applications for fuel cells. The heavy duty power module features a control unit that can interface with a system controller, making it a plug and play product for any fuel cell or hybrid fuel cell bus platform. This next-generation module also offers significant advances in durability, power density and fuel efficiency. All of these features are what make the potential use of fuel cells in other heavy duty applications such as GPUs more feasible.

The FCVelocity® HD6 shown in Figure 23 incorporates the state of-the-art-automotive fuel cell stack with optimized balance of plant technology being used in demonstrations throughout the world. This compact and high-powered fuel cell module, when fuelled with pure hydrogen, is a zero emission energy conversion device.

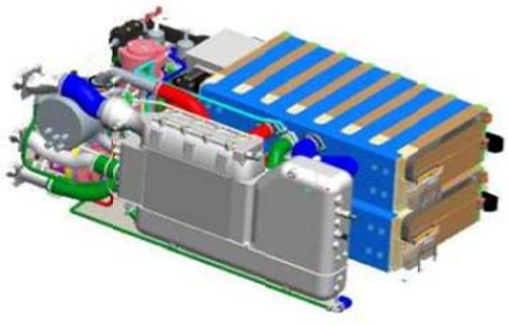


Figure 23: Ballard FCVelocity® HD6 module

The balance of plant system that is part of the module includes the following sub systems:

- Hydrogen supply, re-circulation and purge system;
- Hydrogen and air humidification;
- Condenser for water management;
- Internal cooling systems;
- CAN Bus and power supply connections; and,
- Control system.

10.1.2 System Control Unit

The System Control Unit (SCU) shown in Figure 24 is the master controller for the fuel cell system. The SCU receives inputs from the user, power electronics and all other fuel cell components and determines the power demand for the load. Based on that power demand, the SCU commands the fuel cell, high voltage batteries, and dual 200 KW inverter output to meet the desired performance. The SCU interfaces with other fuel cell system and GPU components via either hardwired input/output or J1939 communication.

There are three J1939 networks on the proposed plug-in HFCE GPU. The system network is the 256 kB network for cooling pumps and fans, and the SCU. The hybrid diagnostic network is a 1 MB network for diagnostic communication between HybriDrive® components and the system data logger. The powertrain network is also a 1 MB network for data communication between all HybriDrive® components.

Figure 24: System control unit

10.1.3 Dual 200 kW Inverter

The dual 200 kW inverter shown in Figure 25 provides the power control for the three-phase AC output and the resistive heating element. The dual 200 kW inverter also provides the switching elements for the fuel cell boost converter.

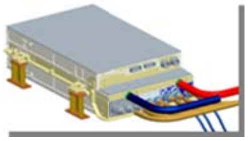


Figure 25: Dual 200 kW inverter

10.1.4 Dual Boost Converter

The dual boost converter depicted in Figure 26 is the primary high voltage junction box in the vehicle. The unit hosts the inductors for the fuel cell boost converter and the energy storage system (ESS) boost/buck converter. The dual boost converter also provides the high voltage power for the variable speed drive that controls the fuel cell coolant pump and the air compressor for the fuel cell.

Figure 26: Dual boost converter

10.1.5 Accessory Power System

The accessory power system (APS) shown in Figure 27 acts as the 28 VDC electronic alternator replacement, the 208 VAC power source for the electric accessories, and provides the switching elements for the energy storage system boost/buck converter.

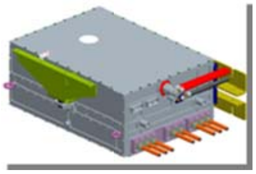


Figure 27: Accessory power system

10.1.6 Filter and Transformer

The filter and transformer are used to clean the high frequency distortions and harmonics from the three-phase output of the dual 200 kW inverter and transform the delta output to a Wye output to provide clean 400 Hz three-phase output. The filter system is designed to accommodate a plug-in feature to allow for facility power to be used for recharging the battery.

10.1.7 Energy Storage System

The battery pack or ESS acts as the secondary source of power for the plug-in HFCE system. The power from the ESS supplements power provided by the fuel cell during transient loading.

10.1.8 Electronics Cooling

The electronics cooling package (ECP) shown in Figure 28 consists of a coolant pump and two fans and provides cooling for the Dual 200 kW inverter, dual boost Converter, APS, and fuel cell air compressor inverter and motor.

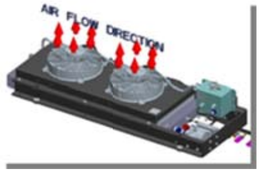


Figure 28: Electronics cooling package

10.1.9 Fuel Cell Accessories Cooling

The fuel cell accessories cooling package (FCP) consists of a coolant pump and two fans and provides cooling for the fuel cell condenser and remote commutator (rotary electric switch).

10.1.10 Defrost Cooling

The defrost cooling system consists of a single coolant pump and provides the cooling required to defrost the front windshield and generate heat inside the GPU in conjunction with the air conditioner.

10.1.11 Stack Cooling

The main cooling loop for the hydrogen fuel cell power plant is the stack cooling loop as shown in Figure 29. The loop consists of the stack cooling package (SCP), comprised of a radiator and 13 fans, as well as a three HP centrifugal pump. This loop utilizes two inch stainless steel piping, and silicone hose to maintain the high flow rate and low fluid conductivity requirements. In addition this loop is equipped with a deionization (DI) filter and specially developed coolant to maintain the extremely low conductivity requirement. The DI filter can be isolated and removed for service or replacement with minimal fluid loss. In order to maintain fuel cell performance and efficiency during cold weather operation this loop is equipped with a thermostat to ensure inlet coolant to fuel cell is of sufficient temperature. The thermostat is located on the roof and its need and configuration is currently being evaluated in combination with Ballard's cold start algorithms. This cooling loop is independent from the heating and defroster cooling loops and therefore shut-offs are not required.

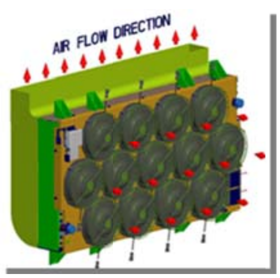


Figure 29: Stack cooling

10.2 System Sizing

For the purpose of the trade study and sizing exercise the design team opted to use a 120-150 KW rated GPU system. The packaging exercise was performed using a 120 kVA GPU unit (“120CU20”) provided by Hobart equipped with a 400Hz 120 kVA Cummins diesel engine. The reason for choosing this model was due to the fact that the data sheet available for the unit contained all the necessary data regarding packaging. The design team utilized the chassis space to package the HFCE components such that it could produce up to 150 kW (180 kVA) in the same space claim as a current GPU. A conceptual image of the plug-in HFCE GPU is reproduced next to an image of the existing Hobart GPU in Figure 30.

Figure 30: Conceptual GPU design (left) compared to actual GPU (right)

10.2.1 GPU Package Sizing

The plug-in HFCE system is composed of fixed and resizable components. The fixed components are not expected to change in physical dimensions or performance, as these components have already been developed or are in revenue service today. These components include:

1. Ballard’s FCVelocity® HD6 150 kW power plant, currently in low volume production.
2. BAE Systems’ power electronics to operate the hydrogen fuel cell power plant:
    - Dual 200 kW inverter: Borrowed from the HybriDrive® series system in revenue service.
    - System control unit (SCU): Borrowed from the HybriDrive® series system which is in revenue service.
    - Accessory power system: Borrowed from the HybriDrive® series system, in revenue service.
    - Battery pack (energy storage system): Off the shelf component.
    - Filter: Borrowed from the HybriGen™ Primary Power System.
    - Dual boost converter: Borrowed from the HFCE transit bus application.
    - Operator display and gauges: Fixed, based on current GPU system.
    - Cooling Systems: Borrowed from the HybriDrive® series system in revenue service and the HFCE transit bus.

The system will also be made up of the necessary exhaust/filter system, air compressor, cooling pump, leakage detection system and intake manifolds.

It is important to understand and consider that there are sizing limitations based on the fixed components, primarily because these are standard off-the-shelf components.

The resizable components in the system are the elements that are available in different standard sizes, ratings, and capacity and can be changed based on the application. These components are:

1. Hydrogen tanks: Size selected is based on the duration of continuous operation and required number of refills per day. For proper operation of the tank, each tank requires an electronically controlled valve, regulator and mounting frame.
2. Transformer: Sized based on maximum output capability.

10.2.1.1 Transformer Selection

The transformers are an off-the-shelf product based on the maximum current output of the generator, typically the maximum power rating. The standard transformers are packaged in National Electrical Manufacturers Association (NEMA) approved enclosures and become quite heavy, almost weighing in at 635 – 771 kg (1400 – 1700 Lbs), for a 150 to 180 KVA system. The transformer used in the 150 kW (180 KVA) plug-in package provided in this trade is a standard unit that was selected from a catalogue. Transformers are available for all sizes of GPUs; however, the transformers can be built as custom units to minimize packaging space and weight.

10.2.1.2 Hydrogen Tank Selection

Hydrogen tank selection is based on more than just the required amount of storage capacity. Tank selection will be influenced by the following:

Safety:

Tank construction includes material, wall design and layering, mounting provision, and the valve and regulation system used for tanks. These factors are critical for safety, particularly when the application will be amidst the public. Carbon fibre or custom composite tanks are recommended for the plug-in HFCE GPU application; they offer significantly improved protection and safety for a variety of applications, both stationary and mobile.

Physical size:

Tank size becomes a limiting factor in packaging; hence, different tank dimensions should be considered based on the total GPU packaging space available.

Capacity vs. weight:

Tanks can add a significant amount of weight to the overall system. Carbon fibre or custom composite technology used in tank development has helped significantly reduce the weight compared to older steel tanks while maintaining the capacity of the cylinder. Carbon fibre tanks offer a range from 0.016 - 0.025 kg of hydrogen storage per pound (0.454 kg) of tank weight. This range is dependent on the service pressure the tank is rated for.

The preliminary recommendation for the GPUs is to stay with the carbon graphite tanks that offer in the range of 0.018 -0 .022 kg hydrogen per pound of tank mass, however in the future the goal should be to use tanks that are standard in the automotive industry to leverage tank cost based on automotive market volume.

Service pressure:

Tanks are available in pressure ranges from 250-700 bar. The selection of the service pressure rating for the tank should be based on the application and the refuelling system that is available on site. The higher the service pressure is, the higher the hydrogen storage capacity will be for the same tank size, or alternatively, the smaller the physical size of the tank that is needed.

The preliminary recommendation is to use tanks that support service pressure of 350 – 700 Bar and in the future migrate to standard service pressure used in the automotive industry to leverage the hydrogen supply, refuelling stations and tank cost based on automotive market volume.

Tank size and vendor selection will be based on GPU application. The team has identified three vendors, Dynetek, Quantum, and SCI for standard off-the-shelf tanks that provide for the commercial, industrial and automotive markets. The team has also identified Lincoln Composites as a vendor for custom applications. Vendor selection in the future may vary based on the application country.

The plug-in HFCE GPU can be sized and packaged within the same chassis as the conventional GPUs. An example of this is shown above where a 150kW (180 kVA) unit is packaged on the same chassis as the 120 KVA unit. Tank selection and transformer sizing play a key role in the packaging and weight of the unit and have to be considered carefully.

10.2.2 Fuel Cell Power Plant Sizing

The key piece of information needed to perform proper sizing of the power plant is the duty cycle at which the system is typically operated. Duty cycles vary by airport and end user but were not available from the client group, as it is not something currently tracked by the end users. The design team utilized an assumed duty cycle that was vetted as reasonable by our client group for YVR.

The design team used an assumed duty cycle as shown in Table 9. It outlines a 30 minute event according to the percent loading and percent duration at that load.

Table 9: Assumed GPU duty cycle

Percent loading	Percent Duration	Run time (minutes)
0	0	0
125	1	0.3
100	10	3
25	30	9
75	9	2.7
50	50	15
Total	**100**	**30**

The duty cycle is set up based on an understanding that GPUs would typically run at an average load of 50 – 60% during each event. This allowed the team to be able to pick from two standard Ballard FCVelocity® HD6 modules that are currently in production, a 75 kW and a 150 kW unit. The size of the unit will be selected based on the average power usage.

Shown in Figure 31 is a spreadsheet model of the average power usages based on a 90 kW (120 KVA), 120 kW (150 KVA) and 150 kW (180 KVA) during a 30 minute event. All yellow highlighted areas (required total power output, event time and average daily unit usage) are data inputs to be received from the operators in specified applications.

Required Total Power Ouput	90	kw
Event time (min)	30	min
Average Daily unit usage	4	Hours
Average Hourly Usage	64%	
Average Power per Hour	57.33	KW

Required Total Power Ouput	120	kw
Event time (min)	30	min
Average Daily unit usage	4	Hours
Average Hourly Usage	60%	
Average Power per Hour	72.48	KW

Required Total Power Ouput	150	kw
Event time (min)	30	min
Average Daily unit usage	4	Hours
Average Hourly Usage	58%	
Average Power per Hour	87.63	KW

Figure 31: Average usage of GPU based on varied total power output

The sizing of the fuel cell power plant will be based on the average power usage. For instance, if a 150kW (180 kVA) rated unit is to be sized, then based on the average usage, the Ballard FCVelocity® HD6 (150 kW) unit would be selected; however the 75 kW unit can also be selected but would require that the battery pack (energy storage) be sized appropriately to provide supplemental power in addition to the power plant.

On the other hand, for units rated at 120 kW (150 KVA) and lower, the FCVelocity® HD6 (75 kW) unit will be selected. When the fuel cell plant is sized equal to or less than the average power used, the goal of the design is to compensate for the demand using the battery pack (energy storage system) in the unit.

10.2.3 Energy Storage Sizing

The energy storage in the architecture is expected to provide a minimum of 50 kWh of storage capacity. The energy storage system will provide the following functionality:

1. Provide power to the internal loads and be the main output power if the fuel cell power plant is not turned on (at initial start-up or if the loads are too low to use the fuel cell).
2. Provided supplemental power to the system output in case the hydrogen fuel cell power plant is undersized.
3. Handle any transient power demand that cannot be handled by the hydrogen fuel cell power plant.
4. Provide back-up energy storage capacity for the hydrogen stored in the system.

A 50 kWh power pack will offer 0.5, 0.6 and 0.7 hours of back-up energy capacity to a 90 kW (120 kVA), 120 kW (150 KVA) and 150 kW (180 KVA) rated system, respectively. The sustainment capacity is based on the corresponding average power usage for the three sizes of system.

The size and storage of the battery pack is intentionally kept at a minimum as it *has a profound effect on the weight of the system*. The battery pack selected for the GPU application is a 50 kWh pack that weighs 544kg (1200Lbs). The amount of energy storage can be increased if needed, however the recommendation of the design team would be to keep the ESS at the designated 50kWh and size the hydrogen storage to maximize operational sustainment period.

10.2.4 Hydrogen Storage Sizing

The design team has used the Dynetek tanks that BAE Systems used in the HFCE transit bus, for packaging reasons alone. The tanks selected in a prototype unit or in future products will be based on the application, system rating and operational time frame.

Based on testing that BAE Systems has performed on the HFCE transit bus, using the same power electronics and the Ballard FCVelocity® HD6 fuel cell power plant, it is known that the burn rate of hydrogen gas required to deliver power is 0.1 kilograms of hydrogen for every kilowatt of power delivered. Shown in Figure 32 are the results of test data based on a 150 kW rated system HFCE transit bus.

Based on test results of a 150kW total output		
Burn Rate @ total Power		
hours	Kilograms	
0.17	2.5	
1	15	kg / Hr
Burn rate is	**0.10**	**kg/kw**

Figure 32: Test data for HFCE transit bus

A burn rate of 0.10 kg/kW was obtained when running the 150 kW system over a total of 1.17 hours at total power, consuming 17.5 kg of hydrogen.

The two key elements in the sizing of the hydrogen storage system are:

1. Required operation duration

2. Number of allowed refills in a day

The burn rate of hydrogen, assumed to be approximately 0.1 kg per kW of power produced, will be used as the basis for calculating the required amount of hydrogen storage for hourly usage.

Knowing the number of hours of operation desired allows for calculation of the total amount of hydrogen required to be stored in the GPU chassis. The number of tanks may then be selected to meet the number of desired refills a day.

Shown in Figure 33 is an example of how hydrogen storage would be sized for an application. For the purpose of the trade study the packaging and sizing were based on a 150 kW (180 kVA) rated GPU unit.

The calculations are based on the three primary user inputs: total power required length of each event and average daily unit usage. Using these three inputs, and the duty cycle provided by the user, an average hourly power usage can be calculated.

Using data that BAE Systems has collected on a 150 kW fuel cell system, a burn rate of 15 kg/hour @ 150 kW can be derived, which equates to needing 0.1 kg of hydrogen for every kilowatt of power generated for an hour. Thus, if the average usage is 87.68 kW/hour, a total of 8.76 kg of hydrogen is required every hour to sustain that power output; and if the daily usage is four hours per day, the total hydrogen required is 35.05 kg.

Based on this data and the number of refills an operator would permit in a day, one can calculate the number of tanks of hydrogen and energy storage required. In the above calculations, it is shown that eight hydrogen tanks, with a capacity of 4.89 kg per tank, can provide a total of four hours at average power consumption. The tanks used in the calculations are the Dynetek w205H350G8N carbon fibre tanks that provide a total capacity of 4.89 kg of hydrogen storage per tank. The 150 kW HFCE GPU packaging concept can fit up to eight of these tanks. Based on the application need and the space available on the chassis, different tanks could be selected.

The lithium ion energy storage system, by itself, with a total capacity of 50 kWh (40 kWh usable equates to 80 kW for 30 minutes), can sustain the necessary energy supply for a half hour of average power usage. However, when combined together, the hydrogen and energy storage system can provide a total of 4.5 hours of total power.

User Input	Designer Input

Required Total Power Ouput	**150**	kw
Event time (min)	**30**	min
Average Daily unit usage	**4**	Hours
Average Hourly Usage	**58%**	
Average Power per Hour	**87.63**	KW

Based on test results of a 150kW total output		
Burn Rate @ total Power		
hours	Kilograms	
0.17	2.5	
1	15	kg / Hr
Burn rate is	**0.10**	**kg/kw**

Fuel Cell and storage Sizing		
Fuel Cell Size	150	kW
Tacnk Capacity	4.89	kG
Average Usage per Hour	58%	
Hydrogen for Hourly Average usage	8.76	Kg
Hydrogen required for daily operation	35.05	Kg
No. of Fuel Tanks	8	
Total Tank Capacity (internal)	39.12	kg
Sustainment capacity at average load with one fill	4.0	Hours

Energy Storage Sizing		
Energy Storage (total)	50	kWH
Energy Storage (usable)	40	kWH
Sustainment capacity @ Average load	0.5	Hours

Total Average load Sustainment		
Total Hours sustainable with	4.5	Hours
No. Fills to support 1 complete day operation	0.9	Fill
Assume Start of Day with filled tanks and 100% batt storage	1	Fill

Figure 33: Sample calculations to size hydrogen storage tanks

10.3 Service and Maintenance

The plug-in HFCE system is anticipated to require a similar number of maintenance and service tasks as the current diesel based gensets. However, due to the reduced wear and tear and built-in advanced diagnostics, there will be a reduction in both scheduled and unscheduled maintenance intervals as well as the intensity of labour needed to perform the maintenance and service.

Typical diesel engine based gensets require the filters and oil changed every 3 months or 4 times annually at an average cost of $160 - $200 per scheduled maintenance. This does not include the regular inspection that is required for the electrical system, nor does it include unscheduled maintenance.

The plug-in HFCE GPU system's maintenance and replacement intervals are listed in Table 10. The fuel cell module is a solid state device; therefore, maintenance costs are relatively minimal and will remain improved when compared to an IC engine. It is hypothesized that the combined maintenance requirements of the fuel cell module and the overall HFCE GPU will still be less than or equal to a conventional GPU; however, a demonstration program is required to validate this hypothesis.

The plug-in HFCE GPU maintenance and service tasks can be scheduled based on the usage of the system, reported by data logger using the stored data, rather than a calendar system. The maintenance and service activity over a period of time can be converted into a usage based trend curve, which can provide the operator with preventive maintenance information. This will reduce the time needed for maintenance and will also provide an indication of the components that might need maintenance or replacement. All system level diagnostic data can be downloaded over the CAN communication ports remotely, making maintenance needs and failure analysis simpler than with diesel engine based GPUs.

Unscheduled maintenance is expected to be reduced. Complete removal of the engine compared to the plug-in HFCE GPU system, also removes issues related to wet stacking in the engine. Wet stacking, an unscheduled maintenance and service need, is the result of running a diesel engine while being heavily under load at a constant speed (high speed). The issue arises as the fuel entering the piston does not get completely burnt and ends up causing failures and oil leaks in the injector systems and clogging of the pistons. Oil then leaks through the exhaust and reduces the performance and life of the engine. This effect is realized over the usage period and occurs sooner if the diesel engine is being used for long durations at a time. The impact is significantly higher maintenance and repair of the diesel engine along with reduced life of the engine and its components.

Table 10: Proposed maintenance and replacement intervals for the plug-in HFCE GPU

Power Electronics/ Cooling / Battery Pack	MAINTENANCE ACTION	INTERVAL
HybiDrive® System (SCU, Dual 200kW inverter, APS, Battery Pack)	Use IDS to check for latent faults	Every 3 months
ECP, FCP, SCP, Defroster	Inspect coolant levels. Refill as required. Check for leaks. Do not fill cooling system reservoirs more than 2/3 full.	Every 3 months
	Inspect all air-to-water/glycol heat exchangers to ensure they are free of debris and obstructions	2000 Hours
	Inspect water pump for excessive leakage	Every 12 months
SCU, Dual 200kW inverter, APS, Battery Pack, PIM, HV PDU	Inspect for missing or damaged High Voltage decal. Replace as required.	2000 hours
Dual 200kW inverter, APS, PIM	Inspect all external cooling system connections and seals for leaks or damage	1000 hours
SCU, PCS, APS, ACTM, ESS, PIM, HV PDU, DC PDUs	Inspect all external connectors and wiring for looseness or damage	1000 Hours
Hydrogen Storage System		
PRD Vent Caps	Inspection for presence	Daily
Tanks and Plumbing	Inspection for attachment of tank system, fittings, and any deterioration of tanks	2 weeks after placed in service
Tanks and Plumbing	General visual inspection defined by Dynetek manuals or ISO 19078	3 months or at specified maintenance intervals
Tanks and Plumbing	Detailed visual inspection defined by Dynetek manuals or ISO 19078 performed by certified inspector	36 months or 36000 miles
Hydrogen Leak Sensors	Perform calibration routine.	Every 3 months

The removal of the engine also reduces the number of components that need replacement due to thermal and mechanical wear caused by constant rotation. This includes items such as belt driven accessories, the treatment system for exhaust particulate matter reduction, the spinning field-wound electrical generator and other bearings and gear heads. The HFCE GPU does not have any moving parts and the components operate at relatively lower temperatures than they are designed for compared to the diesel engine. The components used in the system architecture also are higher life and temperature rated components and solid state controls, which are cooled with an active liquid cooling. Hence the HFCE GPU would have reduced maintenance needs compared to the diesel engine.

A demonstration program should incorporate a side-by-side run of the conventional and HFCE GPU systems and attempt to understand the mean time between unscheduled maintenance and component level repair and failures that are not covered under the scheduled maintenance activities.

Overall, the plug-in HFCE GPU may require a similar number of service and maintenance tasks as the conventional GPU, however the time required to address maintenance and the means in which it is addressed may require reduced time and effort from the user, making the system more operator friendly, as well as simpler and easier to maintain in service.

10.4 Safety

The plug-in HFCE system is designed with safety as a top priority – a criteria that cannot be compromised. The plug-in HFCE system is designed with fault detection at the components level (hydrogen system and electronics) and the system level. This multi-layered approach to safety protects the system from catastrophic failure and the user from any mishaps during operation. The system also provides for real time diagnostics that can be accessed by the user and the different control system in the unit to be able to effectively shut down instantaneously.

10.4.1 Electrical System Protection

During operation, the currents and voltages are monitored to prevent overcurrent and overvoltage faults. AC and DC ground faults are monitored to ensure the safety of the system, the vehicle, and users. The fuel cell is connected to the system in a way that prevents current from going back into the fuel cell and the system is also able to control ripple current from the fuel cell in order to increase its life. All high voltage cables are shielded and routed away from noise susceptible electronics at both the component and system levels to minimize interference. The plug-in HFCE GPU system architecture offers two forms of energy storage: hydrogen (primary) and electrical (battery pack). The system can be remotely monitored over SAE J1939 CAN bus communication ports, each system will consist of three ports, to understand and monitor real time operation and status of the system.

10.4.2 Hydrogen Leak Detection

The hydrogen leak detection system is the Amerex Vehicle Safety Net. The system consists of four hydrogen sensors:

- One sensor in each hydrogen storage system pod on the roof of the GPU(2);
- One sensor in the fuel cell interface region (1); and,
- One sensor at the top of the engine compartment (1).

The lower flammability limit (LFL) is defined as the concentration of hydrogen in air necessary to support combustion. For hydrogen, the LFL is 4%.

The system provides both “trace” and “significant” status on the operator display. The trace status is triggered at 20% LFL and issues a text warning and “yellow” trace light on the operator display. The significant status is triggered at 50% LFL and issues a text warning, red “significant” light, and audible alarm on the operator display. The alarm status also trips a fault in the hybrid system which results in a system shutdown.

The trace status is non-latching and will clear if the hydrogen concentration drops below 20% of the LFL. The significant status is latching and will remain active even if the hydrogen concentration drops below 50% LFL. A key cycle, inserting the key into the ignition and turning it on, is required to restart the GPU in the event of a significant status

10.4.3 Diagnostics and Fault Detection

The plug-in HFCE GPU would be equipped with a data logger that continuously monitors system parameters and uploads the information to a secure server on a daily basis. This data is available to BAE

Systems for analysis, advanced diagnosis of issues, and performance monitoring. The can also be made available to the operator based on the application agreements.

The fuel cell power plant is also equipped with a data logger that loads data onto a compact flash card. This card can be removed from the fuel cell and the data uploaded to the fuel cell manufacturer for analysis and diagnostics.

The system control unit in the plug-in HFCE GPU handles all fault processing for the fuel cell system and sends warnings to the operator through dash panel lights and audible alarms. Depending on the severity of the fault, the GPU either operates in a de-rated mode or has a system shutdown. The GPU chassis would be equipped with an emergency override switch that allows the chassis to be moved to safety in the event of system shutdown faults. All hybrid system and fuel cell faults are transmitted with J1939 compliant communications methodology and logged by the data logger. Fault histories and data are accessible through the diagnostic software provided by BAE Systems.

The plug-in HFCE technology, though a new technology, will be equipped with all the safety measures necessary to make it safe and reliable in operation. Lessons learned by BAE Systems, from being the integrator of the power and propulsion system in the hybrid and fuel cell hybrid transit bus market, and Ballard, from being the developer of the fuel cell power plant used in a variety of commercial and industrial application, have been incorporated in to the design of the plug-in HFCE GPU.

10.5 Plug-in HFCE GPU Technology Benefits

The benefits of the plug-in HFCE GPU system will be presented based on the trade categories and emphasis will be provided on its comparison against the conventional GPUs.

The plug-in HFCE GPU compares equally with the current GPUs in the category of retrofit and serviceability and maintenance. The concept for the 150kW (180kVA) HFCE GPU presented is packaged in the space claim of a 120kVA unit, though the weight of the unit is approximately the same if not marginally higher.

The HFCE GPU can be designed to meet the daily operational duty cycle of the current GPUs with one fill, sizing the hydrogen storage appropriately.

While maintenance issues are anticipated to be improved overall, the benefit of a plug-in HFCE GPU over the current GPUs are anticipated to be primarily in the categories of emissions, reliability and ease of use.

10.5.1 Emissions

The plug-in HFCE GPU system offers a clean zero point-source emissions product, with the potential to be zero-or near zero-emission on a life cycle basis depending on how the hydrogen fuel and electricity are produced. The combination of the fuel cell and the plug-in feature allows the unit to be as environmentally friendly as technology can provide today, while still being practical and effective.

The system eliminates the need for fossil fuels for operation. The proliferation of green and waste hydrogen sources in Vancouver, BC greatly reduce the well to wheel emissions over diesel. Ultimately, one may not need fossil fuel even for the delivery of the hydrogen, if delivery of the hydrogen fuel can be made via pipelines as is being proposed in some jurisdictions.

10.5.2 Reliability

The plug-in HFCE GPU architecture is made using the BAE Systems HybriDrive® components that have accumulated over 20 million hours of operation. The components are designed for high service life and low failure rates.

Table 11 shows the mean time between failure (in hours) of the components based on their use in the HybriDrive® system. The inverter lasts 40,000 hours, the SCU 166,667, the battery pack 25,000, the electronics cooling package/machine cooling package lasts 100,000 hours and the APS lasts 70,700 hours.

Table 11: Mean time between failures for system components

Components	Design Goal MTBF
Dual 200 kW Inverter	40000
SCU	166,667
Battery Pack-Li-Ion	25,000
ECP / MCP	100,000
APS	70700

The fuel cell eliminates any of the thermal and mechanical wear-based life expectancy issues, which are typical of diesel engine based GPUs. The fuel cell power plant and the power electronics have no moving parts that would cause mechanical wear or fatigue. The power electronics are based on solid state electronics that have been designed for significant life and high durability rates. The elimination of all moving and rotating components significantly reduces the wear and tear, and hence the need for additional maintenance.

The operating temperatures of the fuel cell and electronics are lower than typical diesel engine based systems applications, thus reducing thermal fatigue or wear at the component level. All the components in the plug-in HFCE GPU system are cooled using active liquid cooling which reduces the wear and thermal fatigue of the system and hence increasing component reliability.

Issues such as wet stacking that reduce the life and performance of the diesel engine are completely eliminated from the GPUs and are replaced with a solid state power generation and power conversion system.

The reliability of the plug-in HFCE technology is expected to be significantly better than the current GPUs. However, a side-by-side test and evaluation program is necessary to understand and collect the necessary data to evaluate the improvement and calculate the savings.

10.5.3 Ease of Use

Though the plug-in HFCE GPU and the current diesel based GPU technologies scored equally in the "ease of use" category, it is believed that the HFCE GPU system will be significantly simpler and intuitive than the current diesel based GPU.

The plug-in HFCE GPU technology's biggest hurdle in receiving a higher score in the 'ease of use' category is the level of training required for the operator, as it is a new technology. However, this is not any different from when hybrid transit buses were released in to transit authorities approximately eight years ago, which at first required significant training at the depot level; but as time has gone by, it is not uncommon to see a significant number of hybrid buses being used by all major transit organizations, where most of the training, replacement and maintenance are performed by the trained depot employees.

BAE Systems has trained multiple depots such New York City, Seattle, Toronto, Houston and London, where the workers are fully proficient in providing full service, repair and maintenance of the HybriDrive® Series hybrid systems installed on their buses. The training provided to the various airport authorities and the operator bodies in regards to the plug-in HFCE GPU would be similar, to make the entity self-reliant in providing the necessary services and maintenance tasks.

The use of the plug-in HFCE systems, once training has been received, is significantly simpler than current technology because of the following reasons:

A turnkey solution:

The technology provides for a "fire up and forget" set up. The system is fully capable of putting itself in standby mode when not in use, only running the necessary internal loads like cooling pumps, fans and other accessories. The system operates on a load demand based scenario, where the initial power is supplied from the ESS and is then transferred to the fuel cell power plant. Similarly, at instances when the power required is minimal, the fuel cell power plant is left in stand-by and the ESS provides all the power. This continues as a standard mode of operation without any intervention from the operator. The system has interlocks that allow it to recognize whether it is being connected to a load or else to facility power for recharging the battery pack.

Fault notification and management:

The system provides fault protection and lock out at all levels to provide for easier fault management failure analysis. All fault data is recorded and maintained in the unit's data loggers. The operator is notified on the units display as well as through any remote user interface that uses CAN communication of the failure. The system will be designed with de-rated mode of operation based on the severity of faults in the system. Fault histories and data are accessible through the diagnostic software provided by BAE Systems.

Diagnostics for the operator:

The system provides real-time diagnostics information remotely to the operator. The unit is capable of logging all necessary data to provide the user with insight on the system status, faults and performance. The stored data can also be downloaded using a USB flash device when needed.

Simpler maintenance:

Using the data stored in the data logger, usage and maintenance interval trends can be generated which would help reduce the maintenance frequency on the unit.

Remote usage and user friendliness:

The unit can be operated from remote locations, for example, from inside the tow vehicle, or from the jet bridge using CAN bus communication. All the data on system performance can also be transmitted to a common operator base using the wireless feature on the data loggers, allowing the number of operators required to monitor and manage a fleet of units can be significantly reduced. This feature, when implemented in the New York City depots for the hybrid transit buses, increased the availability of buses from 85% to over 95% and one fleet manager could track and manage all the buses entering and leaving the depot from the fleet.

Severe environment operation:

The system and its components are designed to operate in environments from -40 to 60°C. Unlike the diesel engine, the fuel cell power plant does not require additional heaters when forced to start operating at low temperatures.

Quiet operation:

The unit operation is significantly quieter than the diesel engines. The noise generated is typically due to the fans and pumps used for cooling.

The features listed above equate to less time and lower labour resources needed to operate and manage the system. The benefits of reduced emissions, improved reliability and ease of use, stand out in comparison to the diesel engine based GPU.

10.6 Unit Cost and Cost Reduction

Like all new technologies, the capital cost of the plug-in HFCE GPU is expected to be significantly higher than the current GPU systems. The primary cause is that the plug-in HFCE systems are currently not being produced in mass volumes. Fuel cell technology is relatively new and therefore expensive, but beginning in the next three years, and based on the increase in demand for heavy duty fuel cell usage for transit applications, and beyond this in automotive applications, this cost will reduce significantly.

A similar trend was observed in the case of hybrid diesel electric vehicles, where the cost was primarily embedded in the energy storage technologies, be it lithium ion or nickel metal hydride based chemistries. The cost of those same vehicles has dropped significantly due the reduction in the cost of the energy storage technology. Lithium ion chemistry based energy storage systems used to cost anywhere from $2.5 - $3.5 per watt-hour; in today’s market, superior chemistry and controls are available at $0.8 - $1.25 per watt-hour. The drive behind the cost reduction was primarily the improvement in technology manufacturing that was needed to meet the volume demand and the price that the market was willing to pay for it.

Similarly, Ballard is currently working on a new generation of fuel cell module with Sustainable Development Technology Canada that will realize cost reductions from manufacturing and process improvements of approximately 40 percent in the fuel cell module, as well as allow for high volume manufacturing.

As a part of this trade study, four areas of cost reduction have been identified:

1. Reduction in cost of fuel cell power plant based on next generation fuel cell module combined with increase in production volume (~50% reduction in large volume);
2. Power Electronics – a dual boost converter (~30% reduction in component cost);
3. The build and manufacturing of the HFCE GPU should be done at reduced labour charge by switching to the production house (OEMs such as Hobart) rather than development facilities like BAE Systems or Ballard (~50% reduction in labour cost); and,
4. Develop custom tanks to reduce cost based on large volumes or utilize tanks used in high volume by the automotive industry (~25% reduction in tank cost).

These cost reductions along with an increase in production volume (based on demand) will help the selected plug-in HFCE technology reduce its capital unit cost.

10.7 Life Cycle Cost

Determination of life cycle cost for any new product or technology is determined through an impact analysis. This means that the factors responsible for life cycle cost need to be collected and evaluated. Though the hydrogen fuel cell power plant technology is not new, the application of the fuel cell power plant in a GPU is new.

The HFCE technology is used in very low volumes in the automotive, transit bus, commercial truck, and industrial power sectors; in even lower quantities in the GSE application. This requires that all the factors that affect life cycle cost be properly understood and evaluated, so that an accurate comparison can be made.

There are a variety of factors that have to be accumulated and considered, along with the unit cost of the product, to be able to perform a proper life cycle cost benefit study. These are discussed in the following sub-sections.

10.7.1 Average Unit cost

Average unit cost is a factor that will change with volume. The expectation is that the unit cost of new technology at initial introduction to a market will be high and as time progresses, based on increase in volume, will decrease.

10.7.2 Operational Cost

Operational cost is the dollar per hour spent to operate the unit. This is comprised of scheduled and unscheduled maintenance, fuel, operational labour, certification and infrastructure costs.

10.7.2.1 Scheduled and Unscheduled Maintenance

As described under Section 10.3 (Service and Maintenance), the tasks required to provide service and to maintain the plug-in HFCE may be similar in number to the diesel genset; however, due to the reduced wear and tear and built-in advanced diagnostics, there will be a reduction in both scheduled and unscheduled maintenance intervals as well as the intensity of labour needed to perform the maintenance and service. This is also subject to an increase in the volume and usage of the plug-in HFCE GPU system.

Due to the removal of all rotating components and reduced thermal wear of the plug-in HFCE components, the annual repair cost is expected to be lower than that of the diesel engine base GPU. This also ties in with the higher reliability solid state power electronics components used in the architecture of the system, that significantly increase the reliability of the system and reduce repair needs.

10.7.2.2 Fuel

The annual cost of hydrogen fuel will be dependent on the quantity of the hydrogen delivered. In quantities less than 1,000 kg/day of hydrogen, the cost is substantially higher than that of delivered diesel at the point of consumption. The annual cost of fuel will be the largest hurdle that has to be overcome to reduce the operational cost of any HFCE based technology. Section 2.1 discusses the relationship between the mass of hydrogen demand per day to its unit cost.

Shown in Figure 34, for illustrative purposes, is a top level analysis that the HFCE design team performed based on a 150 kW (180 KVA) rated GPU comparison between the plug-in HFCE and conventional diesel engine GPUs. The comparison is based on the number of days of annual operation, total power output of the GPU, event times and average hours of daily usage over a given duty cycle. These parameters were used to calculate the annual cost of hydrogen needed to operate the system, in relation to the cost of diesel. The consumption of hydrogen per day (calculated in section 10.2.4) and that for a diesel genset is shown on the right hand column of Figure 34. Based on $US 10.00 / kg of hydrogen, the cost of operating the plug-in HFCE GPU as compared to a conventional GPU is approximately three times more expensive.

User Input	Designer Input

No. of days of usage in a year	365	days
Required Total Power Ouput	150	kw
Event time (min)	30	min
Average Daily unit usage	4	Hours
Average Hourly Usage	58%	
Average Power per Hour	87.63	KW

Average cost of Fuel (Commercial)	4.15	$ / Gal	
Fuel Consumption per hour			
1/4th Load	1/2 Load	3/4 load	full
3.2	6.3	9.5	12.6
http://www.hardydiesel.com/generator-fuel-consumption-calculator.html			

Percent Loading	% duration	run time	kWH
0%	0%	0	0
125%	1%	0.3	0.9375
100%	10%	3	7.5
25%	30%	9	5.625
75%	9%	2.7	5.0625
50%	50%	15	18.75
Total	1	30	37.875
Average Internal Loads (Fans, pumps, etc)			5.9
	Hourly Average Usage		87.6
	Daily Average Usage		350.5

Percent Loading	% duration	run time	Fuel Consumption
0%	0%	0	0.0
125%	1%	0.3	0.1
100%	10%	3	0.6
25%	30%	9	0.5
75%	9%	2.7	0.4
50%	50%	15	1.6
Total	1	30	3.18
Average Internal Loads (Fans, pumps, etc)			0.0
	Hourly Average Usage		6.4
	Daily Average Usage		25.4

Total Average load Sustainment		
Total Hours sustainable with	4.5	Hours
No. Fills to support 1 complete day operation	0.9	Fill
Assume Start of Day with filled tanks and 100% batt storage	1	Fill
Average Cost of 1Kg of Hydrogen Delivered	10.0	$ / kg
Cost of Hydrogen Required daily	350.52	$
Annual Hydrogen Usage	12794	kG
Annual cost of Hydrogen delivered	127940	$

Average Fuel Consumption for 30 min Run		
Average Fuel Consumption for	3.18	Gal
Diesel consumed for Daily Usage	25.4	gal
Tank Size	40	gal
No. Fills for Average Daily operation	0.6	
Annual Fuel Usage	9280	gal
Annual Cost of purchased fuel	38513	$
Annual Cost of Delivered Fuel at final point of use (assumed at 20% premium)	46216	$

Cost of Hydrogen Vs Diesel		
Hydrogen Annual Cost	127940	$
Diesel Annual cost	46216	$
Hydrogen to Diesel	2.77	
For Hydrogen to be competitive with Diesel the cost has to drop by 3x		

Figure 34: Illustration from BAE Systems' fuel cost analysis model

10.7.2.3 Operating Labour

The plug-in HFCE technology provides a simpler user interface both for normal operation as well as for maintenance. The required time from an operator could be significantly reduced with the plug-in HFCE GPU units, hence reducing the cost of labour to support the units in operation when compared to the conventional GPUs.

10.7.2.4 Certification

This is average cost over the life the conventional GPU to keep it certified for operation. Most GPUs continue to be operated beyond their initial service life, and this requires an additional cost to obtain approval based on EPA guidelines.

The plug-in HFCE GPU technology is designed to meet required standards such as SAE J2719 for fuel purity, the SAE J2600 specification for refuelling connection devices, and others. The unit will be safety certified once, prior to use. However, once in use, the HFCE GPU will not require ongoing EPA recertification because it does not produce emissions. Therefore, the plug-in HFCE may actually be less expensive in terms of certification over its life when EPA re-certification is considered.

10.7.3 Infrastructure Cost

This is the cost associated to setting up the infrastructure necessary to sustain the operation of the HFCE GPU unit. This cost is very site-specific but the elements are as follows:

- Capital investment;
- Fuel delivery;
- Facility maintenance; and,
- Operator and operator training.

Phase 3 – Trade Study Conclusions & Path Forward

11 TRADE STUDY CONCLUSIONS

The plug-in HFCE technology is a promising solution for future GSE technology, starting with the GPU. HFCE systems are mature, available, tested and effective in meeting the objectives of this trade study and are predicted to meet the performance requirements of current GPU application. The HFCE technology provides for a clean, zero emission solution which is more reliable and easier to use compared to the current GPU systems in service.

Based on the initial understanding developed in this trade study and without complete availability of data, some of which would come from a demonstration, the technology appears feasible; however the significantly higher unit cost, hydrogen fuel cost and infrastructure needs put this technology at a disadvantage.

Hardware premiums arise primarily from the low volume usage of fuel cell technology in large volume markets such as automotive and commercial transit. However, inevitable changes in technology trends in these two markets will have a significant impact on the current identified disadvantages. The increase in volume would also indicate an increase in usage rate (hours/year) leading to a reduction in the cost of hydrogen fuel based on demand.

As with all new technologies, a certain level of data needs to be collected and evaluated to accurately depict the technology's life cycle cost benefit over the current technology. A demonstration program would provide means to be able to complete this study and truly appreciate and understand the value that this future clean, zero technology can provide to the GSE market.

12 PATH FORWARD & RECOMMENDATIONS

The plug-in HFCE is a new product and competes with existing GPU technology. It is important that a well-planned demonstration program be established as the next step. A demonstration program will allow collection of data to accurately establish a life cycle cost and benefit profile for the plug-in HFCE GPU over conventional GPUs. The demonstration program would be set up to evaluate and collect data on two identically rated HFCE and conventional GPU systems side by side under similar usage cycles, at the same site of operation. The data collected for evaluation will pertain to the following categories:

- Maintenance needs for both scheduled and unscheduled issues;
- Repair cost (reliability) related to components and mean time between operational failures;
- Annual cost of fuel usage based on the usage of the two systems; and,
- Annual cost of labour based on the usage of the two systems.

The demonstration program would include the building of a new plug-in HFCE unit, rated at 150 kW (180 kVA) or smaller based on the application, with a development schedule of eight months followed by a six month on-site test program. The site for testing will be selected based on a GPU usage of at least 4 – 6 hours daily to obtain quality data as well as availability of a consistent supply of hydrogen fuel.

The cost *elements* of the demonstration program are shown in Table 12, and will be broken down at such time that a demonstration site is identified and funding pursued. The rough-order-of-magnitude cost estimate for the demonstration program, not including hydrogen infrastructure, would be $3.5M.

Table 12: Demonstration cost summary elements

Roll Up Summary	Labor Hrs	Total	% of Sell
Requirements/Specification Development			
System Engineering : Design / M&S / Analysis			
Mechanical Design (Chassis / Cooling System)			
Software / Firmware changes			
Lab Integration (Electronics)			
Chassis - Mechanical Build			
Chassis - Electrical Integration (System Int.)			
Document / Training			
Shipping to Customer			
Customer Site Support			
Program Management & Planning			
Engineering Lead			
Material & Labor Supp.			
Total			

12.1 Demonstration Program Management

BAE Systems will act as the program manager for the demonstration program with Ballard as a partner or supplier to provide the hydrogen fuel cell power plant. The team may also include an OEM, such as Hobart to support building the chassis build and integration at the site.

In the future, for large volume manufacturing, BAE Systems would prefer to partner with a GPU OEM such as Hobart, to manufacture and supply the system. The prime contractor on the production contracts would preferably be the OEM with BAE Systems and Ballard Power as partners or as preferred suppliers.

12.2 Demonstration Program Refuelling Strategy

The refuelling strategy for a demonstration program will be assessed depending on where there is interest. The ideal site would have an existing hydrogen fuelling station that would eliminate or mitigate the cost of installing a new fuelling station. There are currently several sites in North America and the European Union that have hydrogen on-site or have plans for new fuelling capabilities.

Another aspect to the ideal site would be the existence or potential for a larger hydrogen based power output demand (e.g. for back up grid, surface transportation) to increase hydrogen fuel demand and lower unit hydrogen cost. In this scenario, use of the GPU would be secondary to justify setup of a large scale hydrogen storage system.

Looking at the Vancouver International Airport as a demonstration site, the strategy would be to set up a portable dispenser on site for approximately $15,000 a month in lease from an industrial gas supplier (based on $12-15 per kg of delivered fuel). Later phases may include the utilization of locally sourced liquefied hydrogen from a sodium chlorate plant's waste stream, substantially reducing the cost of the fuel. At YVR, use of local waste hydrogen is a requirement of the Airport Authority. The local plant is anticipated to be in production of liquid and gaseous based waste hydrogen by the end of 2012.

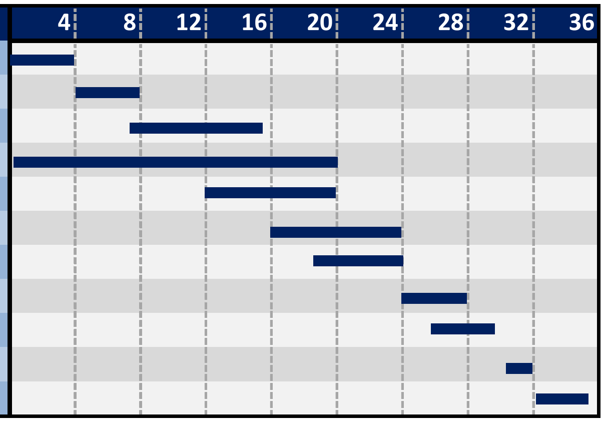
12.3 Timeline

Once funding is confirmed for a demonstration program, the technical development is anticipated to take approximately 8 months (Table 13). This would occur in parallel to site development work, including obtaining necessary permits and approvals for the demonstration; however, depending on where in the fiscal cycle the end users may be when funding is available, it may take a year to prepare for, procure and deliver any additional hydrogen vehicles (e.g. buses). Typically, one year is considered a reasonable time frame from contract award, to mobilizing and begining a demonstration project.

A demonstration should run for minimum one year, ideally two or more, and possibly involve two users or demonstration sites to capture different operating conditions and parameters.

Table 13: GPU development high level timeline

Tasks	Duration (weeks)
Requirements Development	4
Specification Development	4
Mechanical Design	8
Long Lead Material Procurement	20
Software / Firmware changes	8
Lab Integration	8
Chassis - Mechanical Build	6
Chassis - Electrical Integration	4
Document Finalization	4
Shipping to Customer	2
Customer Site Test	2



Further development work on a demonstration program could commence pending award of demonstration funding. In the meantime, BAE Systems and Ballard will further explore partnership opportunities with OEM vehicle manufacturers and simultaneously build internal capacity to pursue HFCE non-road vehicles, starting with a plug-in HFCE GPU.

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