COMPARISON OF FOUR FUEL CELL BATTERY HYBRID POWERTRAINS IN BUS APPLICATIONS

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Abstract
Over the years, buses have provided an excellent platform to test and demonstrate the capabilities and benefits of hydrogen fuel cell technology. There are multiple technology drivers of powering buses with fuel cells which include the need to improve urban air quality, increase energy independence, mitigate climate change, and minimize noise. Yet certain barriers to meaningful commercialization still exist, namely cost of acquisition, and durability (lifetime) which leads to high maintenance costs.

In order to determine the preferred commercialization pathway for buses, Hydrogenics has been involved with four different fuel cell hybrid bus projects ranging from fuel cell dominant to battery dominant. The various architectures of this range of fuel cell hybrid power trains are discussed, along with the respective global demonstrations that have taken place, or will take place, in Hawaii, Manitoba, and North-Rhine Westphalia (Germany), Alabama, South Carolina, and Connecticut. Experiences and anticipated outcomes of each project are discussed.

To date, Hydrogenics' experience has indicated that buses with smaller fuel cells show significantly lower upfront costs, with promise of lower operating and maintenance costs. In one scenario, the anticipated lifecycle costs of a fuel cell battery dominant hybrid bus are shown to be less than that of a conventional diesel bus.

Keywords: hydrogen, fuel cell, plug-in, hybrid, bus

1. Why Fuel Cells in Transit Buses?
Since the 1990s, transit buses have shown to be a small but consistent and slowly growing pull market for fuel cell technology. There are several factors that contribute to this:

- Urban air quality; fuel cell transit buses contribute to the reduction of criteria air contaminants in urban setting where pollution is usually at its worst
- Centralized refueling; transit buses refuel at a common point, and do not require a network of refuelers as passenger cars do

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- Storage space; buses because of their size provide enough volume for an adequate amount of hydrogen storage and therefore can provide enough range
- Community involvement, public education, and marketing; orders of magnitude more people can experience the technology by riding the bus as opposed to test-driving a car, the size of the bus allows for itself to be a moving billboard to further educate non-riders.
- Noise issues; fuel cell buses are relatively quiet
- Climate change; fuel cell buses are zero-emission and thus do not contribute to greenhouse gases
- Energy security; fuel cell buses allow for domestic fuels to be employed
- Government controlled or influenced; perhaps the most significant factor in creating a market for fuel cell (zero-emission) buses is that governments take into account the value of the societal benefits of lower air and noise emissions, and can more easily justify the purchase of a fuel cell bus

1.1 Challenges

Although the above factors have helped in creating a market for fuel cell transit buses, several challenges have impeded their rapid deployment. These challenges primarily lie in the overall cost of the bus, the reliability and durability of the fuel cells, the cost of the hydrogen, and the refueling time of the hydrogen tanks.

Typically, fuel cell buses have been either fuel cell only or fuel cell dominant in a hybrid configuration, resulting in a relatively large (e.g. 100+ kW) and costly fuel cell power plant. These type of buses have been priced at greater than $2 million. However, in the relative recent past, bus projects involving smaller fuel cells (e.g. <75kW) with relatively more battery power have been conceived and demonstrated.

The primary goal of zero-emissions is still achieved, but the battery dominant powertrain directly addressing many if not all of the above noted challenges, which leads to the belief that the battery-dominant-fuel-cell-hybrid architecture is more conducive toward the commercialization of practical, zero-emission buses.

Four fuel cell bus projects with powertrain architectures ranging from fuel cell dominant to battery dominant are described in this paper.

2. Who is Hydrogenics?

Hydrogenics Corporation is a leading global developer of clean energy solutions, advancing the Hydrogen Economy by commercializing hydrogen and fuel cell products. The company has a portfolio of products and capabilities serving the hydrogen and energy markets of today and tomorrow.

Hydrogenics' three core areas of business include:

- Onsite Generation - turnkey hydrogen generation systems for a full range of hydrogen applications.

- Power Systems - fuel cell power products, with particular focus on fully integrated power modules and fuel cell hybrid power packs.
- Test Systems - standardized and customized fuel cell test systems and test services.

The Power Systems division has deployed its proton exchange membrane fuel cell technology into numerous mobility based applications including forklifts, buses, aircraft and baggage tow tractors, neighborhood electric vehicles, military vehicles, delivery trucks, utility vehicles, and has worked with leading original equipment manufacturers (OEMs) such as General Motors, Deere & Company, Toro, Linde, NACCO, Mobile Energy Solutions, New Flyer, and others.

Hydrogenics' initial experience in bus applications was in late 2002 when it was awarded a grant from Natural Resources Canada to build a 40 foot fuel cell hybrid transit bus employing 180 kW of fuel cell power, and ultracapacitors (supercapacitors) for energy storage. Today, Hydrogenics' experience includes several projects that involve over a dozen fuel cell buses in several countries in North America and Europe.

3. Description of the Bus Projects

The four bus projects described in this paper include the following in chorological order of contract award:

1. Natural Resources Canada (NRCan) Bus (Figure 1)
2. Hawaii Center for Advanced Transportation Technologies (HCATT) Bus (Figure 2)
3. North-Rhine Westphalia (NRW) Midibus (Figure 3)
4. Federal Transit Administration (FTA) & California Air Resources Board (CARB) buses (Figure 4)

Figure 1: NRCan Bus

Figure 2: HCATT Bus

Figure 3: NRW Midibus

Figure 4: FTA/CARB Bus

The four bus projects are summarized in Table 1.

Table 1: Comparison of Four Fuel Cell Bus Projects

Bus Project →	**NRCan Hybrid Bus**	**HCATT Hybrid Bus**	**NRW Hybrid Midibus**	**FTA/CARB Hybrid Buses**
Powertrain architecture	Fuel Cell Dominant Hybrid	Battery Dominant Fuel Cell Hybrid	Fuel Cell–Battery Balanced Hybrid	Battery Dominant Fuel Cell Hybrid
Bus make	New Flyer	ElDorado	Tecnobus	Mobile Energy Solutions
Length of bus (ft)	40	30	17	35
No. of seats	34	23	8	37
Top speed (mph)	60	60	20	60
Demonstration site and start date	Winnipeg, MB August 2006	Honolulu, HI Feb 2004	NRW, Germany Dec 2005	Columbia, SC Summer 2008, Burbank, CA Fall 2008
Power of fuel cell system (kW)	180	20	12	32
Size of motor, continuous power rating	170	120	25	123
Amount of on-board hydrogen (kg)	45	10	6	29
Range (miles)	250	125	125	300 (est'd)
Type of on-board electrical energy storage	Ultracapacitors	Lead Acid Batteries	Nickel Cadmium Batteries	Lithium Titanate
Batteries rechargeable from grid power, i.e. Plug-in hybrid	No	Yes	No	Yes

4. Discussion

It is interesting to note that with the exception of the HCATT Bus which was a military-based, pioneering project in the battery dominant hybrid architecture, the trend is from fuel cell dominant hybrid to balanced hybrid to battery dominant fuel cell hybrid. This has been the trend in other fuel cell bus projects over time as well.

Generally speaking, fuel cell buses started as fuel-cell-only (i.e. non-hybrid) (e.g. CUTE program), changed to fuel cell dominant hybrid (e.g. AC Transit/Oakland), and now we are seeing in addition to the Hydrogenics projects, battery dominant fuel cell hybrid buses (e.g. University of Delaware).

Furthermore, in the automotive field, both General Motors and Ford have built cars (the Volt and the Airstream, respectively) which employ a fuel cell plug-in hybrid architecture which is essentially the same as a battery dominant fuel cell hybrid architecture.

Figure 5 shows the different levels of "hybridity" of the four bus projects where *fuel cell power* hybridity is defined as fuel cell continuous rated power over motor continuous rated power. Similarly, the *hydrogen energy* hybridity is defined as the electrical equivalent energy capacity of the hydrogen tanks over the total electrical energy capacity of the bus (which includes the energy storage capacity of the batteries or ultracapacitors).

It should be noted that the HCATT and FTA/CARB buses are not only battery dominant, fuel cell hybrids, but are also *plug-in* hybrids (BDFCPH). That is, these buses, because their batteries are more significant in terms of energy capacity than the batteries (or ultracapacitors) in a *fuel cell dominant* hybrid system, provide justification for and have the capability of being recharged directly from grid power when parked. In fact, these buses are designed to be battery charge depleting and thus allowing for a smaller, more cost-effective fuel cell. The reason you cannot get rid of the fuel cell altogether is you cannot get the range from the batteries alone. For this reason, some refer to the fuel cell in this kind of powertrain architecture as a range extension device. Figure 5 clearly shows that most of the energy is derived from the hydrogen and fuel cell combination. The batteries or ultracapacitors account for less than 25% of the energy content (in reality, this will be somewhat higher, depending on the duty cycle, considering the batteries can provide additional energy in the form of recaptured energy from braking).

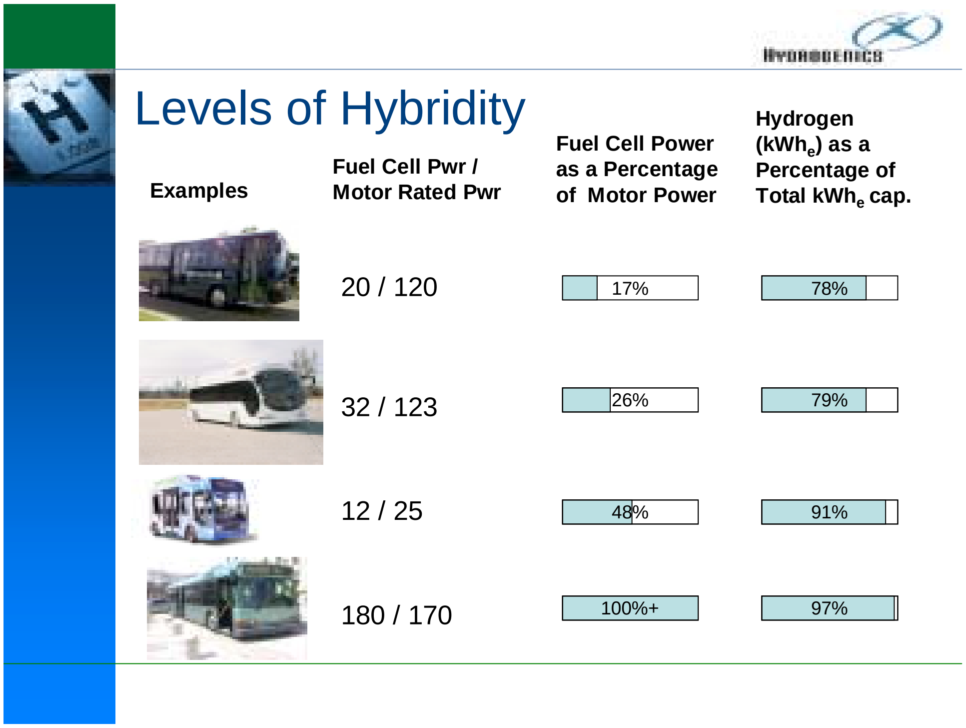

Figure 5: Measure of "hybridity" level for both fuel cell power and hydrogen energy

Further examination of the BDFCPH powertrain architecture shows other significant benefits especially over a fuel cell dominant configuration. The benefits are listed here:

- Reduction of the cost of fuel cell power module development for technology provider because iterating on a smaller fuel cell, e.g. 16kW, requires less investment dollars than iterating on a larger fuel cell, e.g. 100+ kW
- Reduction of capital costs of bus; less kilowatts of fuel cell means less dollars of capital
- Reduction of fueling costs, because of the
    - relatively low cost of electricity (at \$0.05 to \$0.10/kWh, this equates to \$1.67 to \$3.33 per gasoline gallon on an *energy* equivalent basis)
    - high round trip efficiency of batteries (at say 80+% roundtrip efficiency for the batteries compared to ~20% of a gasoline internal combustion engine, the \$1.67 to \$3.33 per gge(energy) converts to \$0.42 to \$0.83 per gge on a *distance* basis, which is how customers calculate their expenses)
- A smaller fuel cell means not as much hydrogen is required; less hydrogen means less hydrogen to purchase (and less time needed to refuel), and less hydrogen tanks to carry, thus reducing operating costs and further reducing capital costs, respectively.
- The steadier state of load on the fuel cell contributes to its increased operating lifetime, i.e. durability (which contributes to lower operating costs since stack replacement will be less frequent)

All of the above benefits contribute toward overcoming the challenges listed in the previous section (i.e. bus capital costs, cost of hydrogen, lifetime issues, and refueling time) which leads to the belief that time to commercialization would be reduced.

Through our analysis, we have calculated that a BDFCPH architecture is generally always going to be more cost effective on a lifecycle and initial capital cost basis than a fuel cell dominant hybrid bus, and in one case has the potential to be more cost effective than a standard diesel bus on a lifecycle basis. Table 2 lists some of the major assumptions for the latter case.

Table 2: Assumptions for BDFCPH Transit Bus to Beat a Standard Diesel Bus Based on Life Cycle Costs

Parameter	**Assumption**
Lifetime of fuel cell stack (operating hours)	10,000
Price of fuel cell power module ($/kW)	1000
Battery life (years)	5
Price of battery ($/kWh)	300
Diesel price ($/gal)	4.25
Hydrogen price ($/kg)	4.50
Cost of Electricity ($/kWh)	0.10
Bus lifecycle (years)	12

5. Conclusion

From our experience and calculations with four types of fuel cell hybrid powertrains, we believe that a battery dominant, fuel cell, plug-in hybrid architecture makes the most sense in terms of commercializing a practical, affordable, zero-emission bus. The BDFCPH powertrain architecture essentially uses the best of both power generating technologies: batteries for peak power needs (minimizing the size of the most expensive component, i.e. the fuel cell) and to capture braking energy, and fuel cells with hydrogen to meet overall energy (i.e. range) requirements.

Future planned deployments of buses using the BDFCPH powertrain architecture will indeed be very educational, but it is also important to note that further demonstration sites are needed to validate the system in various duty cycles and ambient conditions and to increase production volume, decrease costs, and implement improvements.

6. Author

Kevin Harris is the author of the paper and is employed by Hydrogenics Corporation as its Business Development and Sales Director for North America. He was previously an Account Executive at Cummins Engine Company. He graduated with honors from the University of Waterloo with a BASc in Mechanical Engineering, and earned his MBA from the Richard Ivey School of Business at the University of Western Ontario. He is an active member of the US Fuel Cell Council, the National Hydrogen Association, and the California Stationary Fuel Cell Collaborative.