Joint Fuel Cell Bus Workshop

Summary Report

Prepared for:

U.S. Department of Energy (DOE/EERE)

U.S. Department of Transportation (DOT/FTA)

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June 7, 2010
8:00 AM – 12:00 PM

Washington Wardman Park Marriott Hotel

Washington, DC

News Alert distributed May 20, 2010

The U.S. Department of Energy (DOE) and the U.S. Department of Transportation (DOT) will hold a Fuel Cell Bus Workshop on June 7, 2010 at the Washington Marriott Wardman Park in Washington, DC in conjunction with the DOE Hydrogen and Fuel Cell Program Annual Merit Review (http://www.annualmeritreview.energy.gov/).

DOE invites the fuel cell bus community and other stakeholders to participate in a discussion of the most relevant research and development topics relevant to fuel cell buses for government funding. Specific emphasis will be placed on fuel cell stack components and fuel cell system balance of plant, excluding infrastructure, demonstration, drive-train, and non-fuel cell related bus components. Plenary speakers include fuel cell manufacturers, fuel cell bus integrators, and end users as well as government funding agency representatives.

Executive Summary

A Fuel Cell Bus Workshop was held June 7, 2010 from 08:00 to 12:00, prior to the 2010 DOE Hydrogen and Fuel Cell Program Annual Merit Review held June 7 through June 11, 2010 in Washington, D.C. The Workshop Plenary and Breakout Session brought together technical experts from industry (fuel cell manufacturers and bus integrators), end users, academia, DOE national laboratories, and other government agencies to address the status and technology needs of fuel cell powered buses. The workshop was jointly sponsored by the Energy Efficiency and Renewable Energy office of the DOE and the Federal Transit Administration of the DOT.

The workshop began with formal presentations from government and industry representatives, who addressed the current state-of-the-art and technology gaps hindering full commercialization. After the presentations, a brainstorming session was held to discuss the status of fuel cell bus technology and to identify critical R&D needs.

Perspectives were presented by the DOE, the DOT, the California Fuel Cell Partnership (CaFCP), the National Renewable Energy Laboratory (NREL), UTC Power, Ballard Power Systems, Proterra LLC, and BAE Systems.

Although the focus of the workshop was restricted to fuel cell sub-system technology, the industry speakers provided technology and manufacturing overviews identifying the critical issues for cost reductions, performance and durability enhancements, and pathways to commercialization for the complete propulsion system. The consensus of the group was that the fuel cell technology is close to commercial readiness but that development of fuel cell powered bus must be done at the overall system level, including fuel cell sub-system, balance-of-plant (BOP) and power electronics (PE). Individual sub-systems should not be addressed in isolation. System performance (efficiency, power, and emissions) is a function not only of the fuel cell but also of the BOP, PE, and interactions between the sub-systems.

Specific technology gaps and barriers to commercialization were identified during the Brainstorming Session:

- Optimize the entire power train including fuel cell, BOP, and PE
- Durability must be significantly greater than that required for light duty vehicles
- Performance and durability must be demonstrated over the entire range of operating conditions and cycles
- Cost (manufacturing, capital, operations, and maintenance)
- Complex systems (maintenance, including remote monitoring and troubleshooting)
- Power plant volume and weight
- Cost of H_2 (safety, volume, footprint, weight, infrastructure)
- BOP components development and manufacturing
- Demo programs too small (>3 buses per demo and more projects)
- Methanol and natural gas reforming
- Public awareness/education
- Regulations/policy factors

The following critical R&D needs were offered to address the technology barriers. Some of the R&D needs overlap effort currently being funded by DOE/EERE and many of the R&D needs pertain to "non-fuel cell" issues in spite of the stated charter of the workshop.

- Develop and implement accelerated stress test (AST) protocols and testing
- Establish performance and durability over the entire range of operating conditions and cycles
- Perform demand and benefit studies of drive cycles with a mix of routes and projections
- Develop non-FC hardware and BOP with low cost, high performance and durability
- Address air quality tolerance/filtration
- Reduce parasitic load of BOP and PE
- Perform pre-commercial design validation
- Undertake "fast-track" development to satisfy impatient customers

The recommendations developed at this workshop create a foundation for solving the critical technology barriers and gaps that can help accelerate market penetration of fuel cell powered buses.

Table of Contents

Introduction and Purpose

The purpose of the workshop was to gather the fuel cell bus community and other stakeholders to participate in a discussion of research and development topics relevant to fuel cell buses for possible government funding. Specific emphasis was to be placed on fuel cell stack components and fuel cell system balance of plant, excluding infrastructure, demonstration, drive-train, and non-fuel cell related bus components. Government funding of fuel cell bus RD&D should not be inferred from this workshop. The opinions expressed during the workshop do not necessarily reflect the position of the DOE or DOT.

Summary of Presentations

The following are summaries of the plenary presentations. The complete presentations are included as appendices.

Fuel Cell Bus Workshop Overview and Purpose, Dimitrios Papageorgopoulos, U.S. DOE

An overview of the workshop purpose was presented in the context of the DOE targets and the overall industry status with emphasis on the fuel cell sub-system. At this time, DOE is not funding any RD&D specific to fuel cell buses.

DOT/FTA National Fuel Cell Bus Program Overview, Leslie Eudy on behalf of U.S. DOT

The DOT bus program was originally funded at $49 million for fiscal years (FY) 2006 to 2009 with 50% non-federal cost sharing required. Current demonstration projects are running in CA, CT, MA, NY, and TX. Data collection and analysis is being performed in partnership with NREL.

Important conclusions so far include:

- The potential of fuel cell buses has been proven but larger volumes are needed to lower capital costs and demonstrate critical mass
- Federal assistance facilitates commercialization
- Partnering with industry, government, and transit companies is beneficial
- The transit market is small but important to demonstrating value to wider heavy duty market

An additional $13.5 million was made available in FY 2010 for new projects and/or extensions of existing projects. Emphasis will be on innovative and improved components and technologies and different fuel cell technologies as well as commercialization and market penetration aspects of fuel cell buses.

User Perspective on Advanced Fuel Cell Bus Technology, Leslie Eudy, NREL

Fuel cell buses should match conventional bus performance, durability, and reliability as summarized below:

- Operate 7 days/week, up to 20 hr/day
- One tank of fuel per service day
- Meet required duty cycle
- Similar time to fuel and prep for service
- Availability >85%
- Powerplant life > 6 years
- Miles between road calls >4,000 for all calls and >10,000 for propulsion-related calls

Additional non-technical challenges include:

- Capital and operating cost
- Infrastructure for fueling and servicing

Progress and Challenges for PEM Transit Fleet Applications, Thomas Madden, UTC Power

UTC Power has been involved with fuel cell buses since the 1998 Georgetown University phosphoric acid fuel cell bus program. Since 2002, UTC has employed PEM 60-120 kW fuel cells in several buses. UTC currently has 5 buses operating in the United States and Belgium. There are 16 additional buses being delivered in 2010. For the past 12 months, there have been no fuel cell stack-related issues affecting availability. Overall fuel cell power system availability was 95%. The 2010 fleet leader had achieved 6,300 in-service hours as of April 9, 2010. Performance decay and materials failure modes through 7,000 hours have been addressed.

UTC is pursuing accelerated testing and hybridization issues, including evaluation of multiple battery technologies and tailored strategies.

Fuel Cell Buses – Current Status and Path Forward, Greg James, Ballard Power Systems

Ballard has been involved in fuel cell buses since 1991. Between 2002 and 2009, Ballard undertook "Phase 5 Serial Production" and deployed 39 buses in Australia (3), China (3), Europe (30) and the US (3). The Whistler deployment comprises 20 buses which have accumulated >340,000 km and >18,000 hours. The current Ballard HD6 fuel cell bus power plant (75 or 150 kW) is offered with a 12,000-hour or 5-year warranty, including air, fuel, and water management systems.

The Ballard presentation described cost as the primary commercial barrier – capital cost, operating (fuel) cost, and maintenance. Ballard estimates that capital cost must be reduced by a factor of about 3, fuel cost by a factor of about 1.8, and maintenance by 2-3. Maintenance costs are dominated (85%) by bus issues other than fuel cell BOP component issues (14%) and fuel cell stack issues (1%). Cost reduction can be realized by higher volumes and component development for higher performance and better durability.

Ballard's thoughts on where government support can help commercialize fuel cell buses:

- System analysis across coach, integrator, and fuel cell provider
- Development of low-cost, high-reliability, durable components for the entire system

- Bus-level design validation (Beta) testing with new components, designs, and control systems before releasing larger fleets into revenue service
- Larger-scale bus deployments

Furthermore, the fuel cell bus industry needs to look at cost opportunities across the whole spectrum and act as a collaborative group to get the most out of research. Finally, fuel cell bus users/operators are different than fuel cell light duty vehicle users and their environmental and topology factors need to be taken into consideration. Buses are driven differently than cars and experience different drive cycles so the technology solutions might be different.

Powering a Full-Size Transit Bus with Two 16-kW Forklift Fuel Cells, Dale Hill, Proterra

Proterra, LLC was formed about 6 years ago.

Proterra's platform is designed and built from the ground up (not a diesel retrofit). It is a battery-dominant (55 kWh) PHEV supported by two 16-kW PEM fuel cells with a 300-mile range.

The fuel cells are used to maintain battery charge. The battery includes a lithium titanium oxide anode. The system can be fully charged in less than 10 minutes and has an estimated efficiency of >55% at 32 kW.

The bus is currently undergoing extensive performance, durability, and fuel economy testing, culminating in acceptance testing by BC Transit.

As of April 6, 2010, >2,200 miles had been logged. Experience has shown that failures of the fuel cell or battery are rare compared to failures of the power converter and other BOP components.

The average cost of a fuel cell bus is about $1.75M.

HybriDrive Propulsion System – Cleaner, Smarter Power for Transit, Bart Mancini, BAE Systems

BAE has been involved as an integrator in fuel cell buses since 1998 with a phosphoric acid system and since 2000 with a PEM bus. Thereafter, BAE maintained awareness but withdrew from the manufacturing aspects of the fuel cell bus industry until 2008 when they began participation in a CalStart fuel cell APU demonstration. Recent developments, especially in Europe, have renewed BAE's interest in fuel cell buses.

BAE's next generation fuel cell bus is in the initial design phase and involves a partnership with SunLine Transit Agency, CalStart, bus manufacturer ElDorado National (California) Inc., Ballard Power Systems, and the U.S. Federal Transit Administration. This bus uses a 130-kW Ballard fuel cell operating on compressed hydrogen, hybrid propulsion, and electric accessories.

BAE presented well-to-wheels efficiency for several scenarios. A fuel cell powered by hydrogen from reformed natural gas achieves an efficiency of 24% and a fuel cell using hydrogen from electrolysis achieves 6-11% depending on the source of electricity.

BAE pointed out that true zero emissions can be achieved only if the hydrogen is an industrial "waste product." Otherwise, the emissions should be based on the electric/hydrogen production method and the source fuel.

BAE's cost and emissions analysis shows a substantial initial capital cost premium for fuel cell bus propulsion relative to diesel (~5X). The additional cost corresponds to about $15,000 per % reduction in CO_2. The premium for fuel cell APUs is much less, making them the most economically viable for emissions reduction and mass fuel cell commercialization in the transportation context.

BAE proposes moving away from a "one-size-fits-all" architecture to two or three different broad duty cycle categories to address different applications such as city/urban low-speed buses and long-haul, high - speed tour buses.

Fuel cell vehicle integration issues noted by BAE include:

- Weight and volume of the system need to be reduced, including hydrogen storage and large cooling and air handling systems to accommodate the bus drive and duty cycles
- Power processing equipment is heavy and costly
- Slow response time of the fuel cell adversely affects regenerative energy recovery potential and efficiency

Barriers to full fuel cell bus commercialization include:

- High initial procurement cost
- High lifetime fuel cell stack and hybrid battery replacement cost
- High bus weight including storage, and power conversion equipment. The fuel cell and BOP are approximately equivalent in weight to a diesel power plant.

The primary critical R&D need is a top-down systems approach to define and optimize vehicle and component requirements to ensure compatibility of the sub-systems. For example:

- Increasing fuel cell temperature by 5-10ºC would reduce heat exchanger size by 20-40%
- Reducing fuel cell stack voltage to be always below the DC link of the hybrid propulsion system would reduce cost, weight, and complexity of the power conditioning equipment

Breakout Session

Commercialization Barriers

Specific technology gaps and barriers to commercialization:

- Optimize the entire power train including fuel cell, BOP, and PE
- Durability must be significantly greater than that required for light duty vehicles
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Additional discussion representing the opinions of the participants follows. The discussion can be summed in the following quote: "We must also make them affordable, make the fuel available, and make sure they're usable. If they don't work, they're out of service."

The primary barrier is not the fuel cells. Fuel cell durability increases have been realized and costs have come down. Although durability and cost targets have not been met, the major remaining barriers are the integration of the sub-systems and the BOP ancillary equipment cost and reliability. Some of the earlier vehicle systems were hindered by battery technology, but, as a result of the interest that hybrid vehicles have received, significant R&D funding has been applied to battery technology and batteries have achieved commercialization, at least in the light-duty vehicle propulsion market. In one participant's opinion, the battery technology hasn't changed in years.

Now that system manufacturers are experiencing system durability that is thousands of hours long, anything that can be done to simulate actual performance in the laboratories will help the fuel cell developers, the system integrators, and the manufacturers. The market is getting impatient. Remaining fuel cell durability issues can not be identified and understood in a timely manner through field data. Development and implementation of accelerated stress tests (ASTs) are needed for the fuel cell to help convince transit operators of fuel cell bus reliability. ASTs also provide valuable input to fuel cell bus integrators in committing to warranties.

Cognizance and correlation of the current FCV advances could influence and inform the fuel cell bus R&D. Currently, there is no quantitative correspondence between auto and bus fuel cell advances. Analysis results from post-test degraded components from auto testing would be very useful for bus developers.

The number one barrier is money. The fuel cell bus market could be a $100+ billion market. Significant additional funding is needed to develop the market. This includes R&D funding as well as support to transit companies for field trials. Such funding should be outside of normal government support and would encourage field trials without economic impact on the transit company's normal revenue.

Regulations are also needed to help promote specific performance criteria, emissions, fuel efficiency, and economy. We can't assume that the government will be subsidizing the technology forever.

Discussion of fuel cell development for buses tends to include propulsion and APUs without distinction. In fact, operating requirements and duty cycles may be quite different so development issues may not be the same. Hybridization philosophy may also change fuel cell operating and development requirements.

Specific fuel cell components needing additional advancement include platinum loading reduction to minimize current and future costs.

Issues may arise when operating and maintenance responsibilities are transferred to transit personnel. Successful deployment would benefit from an "on star"-like system to keep trained technicians in contact with the operators and allow for real-time trouble shooting.

There needs to be a greater level of investment at the manufacturing level to enable the high volume manufacturing process. Each fuel cell and bus manufacturer is developing its own fuel cell with proprietary technology and they are not willing to distribute their R&D.

At least 3 buses are required in a demo project to replicate using these buses in revenue service. The goal is not to demonstrate the operation of a single bus, but to demonstrate that they can be integrated into the market and maintain an operator's revenue stream.

If fuel cell buses life cycle costs were consistent with diesel or hybrid costs, fuel cell market penetration would be facilitated. However, this does not recognize and credit the environmental benefits. An approach to change the grading scale to include these benefits and costs that aren't typically seen by operators or passengers would encourage transit operators.

There is insufficient public awareness and demand. There is an awareness of the dangers of diesel power and emissions, especially in school buses. The advantages of clean hydrogen fuel need to be broadcast. A broader awareness of hydrogen safety also needs to be developed.

Fuel storage has a significant impact on system/bus size and weight. To get the weight down, the efficiency of the vehicle must improve to reduce the amount of storage required. Roof space is an issue (hydrogen storage). The fuel cells themselves are not an issue with respect to size and weight.

Critical R&D Needs

The following critical R&D needs were offered to address the technology barriers. Some of the R&D needs overlap effort currently being funded by DOE/EERE and many of the R&D needs pertain to "non-fuel cell" issues in spite of the stated charter of the Workshop.

- Develop and implement accelerated stress test (AST) protocols and testing
- Establish performance and durability over the entire range of operating conditions and cycles
- Perform demand and benefit studies for drive cycles, competition, and service with a mix of routes and projections
- Develop non-FC hardware and BOP with low cost and high performance and durability
- Address air quality tolerance/filtration
- Reduce parasitic load of BOP and PE
- Perform pre-commercial design validation
- Undertake "fast-track" development to satisfy impatient customers
- Identify applications (such as national parks) that take advantage of the fuel cell's environmental benefits

Additional comments follow. Many are not specifically related to just fuel cells but are relevant to advancement of fuel cell bus technology.

In addition to striving for market penetration and acceptance by decreasing costs and increasing durability, consideration of increasing the value proposition of fuel cell buses to early markets like national parks or other organizations that are interested in zero emission vehicles is desirable. In other words, should the focus of the bus program(s) be on simply developing and deploying fuel cell buses or should the focus be on government goals relative to energy security and emission reductions and emphasize fuel cell bus R&D on reducing fuel consumption?

A barrier to commercialization is the relatively low number of fuel cell buses deployed. A need would be to deploy a "critical mass" of fuel ell buses to achieve statistical significance and to increase customer acceptance. A sample in the 1,000s of buses was proposed.

Because of the differences in fuel cell bus technologies such as the operating temperatures and degree/philosophy of hybridization, BOP components are not necessarily the same across all manufacturers. A suggestion was made to "get all the part manufacturers together to optimize all the parts together" in a collaborative effort.

Current efforts to improve the fuel cell sub-system are worthwhile but it is imperative that more "breadboard and integrated systems that represent the operating system of the bus" be tested to optimize compatibility and performance of the power plant.

Optimization of the electrical accessories could reduce overall power requirements, thus reducing cost, size, and weight and improving efficiency.

It would be useful to survey transit agencies with respect to current routes and duty cycles compared to what they predict for the future (>5 years).

Codes and standards for fueling stations must be developed.

Target and Status Tables

Two status/target tables were presented and discussed at the end of the brainstorming session. Table 1 contains a comparison of fuel cell and diesel bus technology from 2007. Table 2 is a summary of recent information from NREL and the presenters at this workshop. The tables have not been modified to reflect comments at the workshop but the comments must be addressed in future versions of table 2. A summary of comments related to targets and current status follows

A target for efficiency should be included but none was proposed. Efficiency targets for both the fuel cell sub-system alone and for the entire power plant might be appropriate. The automotive OEMs are moving away from efficiency targets and toward a heat rejection parameter, Q/ITD (heat rejected per degree of initial temperature difference).

Availability of the bus, power plant, and fuel cell sub-system should be differentiated.

The cost and technical targets should be set on a par with existing diesel technology, hybrid, or electric trolley technologies. On the other hand, DOE's goal is market acceptance so meeting technical and cost status of incumbent technologies is not essential to early adopters.

Bus manufacturers claim a life of 10-12,000 hours but buses have not demonstrated such lifetimes. NREL reports 6,000 hours in Table 2.

The emissions target should be removed because, as BAE pointed out, well-to-wheels analysis reveals that there are indeed upstream emissions even if tailpipe emissions are zero. Furthermore, only hydrogen buses are "zero emissions." For example, buses operating on reformed methanol or natural gas can have emissions.

The number of fuel fills per day is less important than the time-to-fill (<10 minutes). Also important is the location, number, and capacity of fueling stations.

The total platinum group metal (PGM) content does not need to be specified as long as the total power plant cost meets the target.

Start/stop issues are not addressed specifically in the table. Although bus requirements are less severe than automotive, it is still an issue and should be recognized.

Table 1. Comparison of Fuel Cell and Diesel Bus Technology

Attribute	Fuel Cell Technology	Conventional Diesel Technology
Fuel Economy	2 times higher than conventional buses	3 – 4 miles per gallon (diesel)
Reliability (measured in "miles between road call," or MBRC)	919 – 1,600 MRBC	10,000 MBRC
Availability	58-77%	85%
Capital Cost	$2 – $3 million	$328,000
Fuel Cost	$8.90 to $18.80 per diesel gallon equivalent	$4.72/gallon*

Source: L. Eudy, et al., *Fuel Cell Buses in U.S. Transit Fleets: Summary of Experiences and Current Status* (September 2007), NREL/TP-560-41967, http://www.nrel.gov/hydrogen/pdfs/41967.pdf, accessed May 2008.
* Energy Information Administration, Weekly On-Highway Diesel Prices, 07/07/08, http://tonto.eia.doe.gov/oog/info/wohdp/diesel.asp, accessed July 2008.

Table 2. Proposed Fuel Cell Bus Targets and NREL 2010 Status

Parameter	Units	2015 Target	NREL 2010 Status	Comments
Bus Life	yrs/hrs	12/36,000		At 3,000-4,000miles per year
Fuel Cell Life	yrs/hrs	6/18,000	NA/6,000	According to appropriate duty cycle
Bus Availability	%	85	66	
Fuel Fills	Per day	1 (<10 min)	1	Time to fill is important (<10 min)
Bus Cost	$	<1,000,000	2,270,000	
Power Plant Cost	$/kW			Compare to existing diesel, hybrid, e-trolley?
Road Call Frequency (all/propulsion/FCS)	miles between road call	4,000/10,000	1,936/2,393	Differentiate between the bus, the power plant, and the fuel cell
Operation time	hours per day/ days per week	20/7	19/7	
Operating cost	$/mile	0.44 (1.16)		Including fuel
Range	miles	300	>300	
Total PGM	grams			Could be any value as long as meets total bus cost
Emissions	gram/mile	0 tailpipe	0 tailpipe	constrains technology (e.g. no reformed fuel)
Value per Ton CO_2	$			How much cost premium is required to eliminate emissions?

Conclusions

The primary consensus of the workshop is that the fuel cell stack is nearing commercial readiness as evidenced by several on-road deployments. Remaining power plant issues are cost, performance, and durability of the overall power plant and the individual sub-systems; most failures are unrelated to the fuel cell sub-system. Further development of fuel cell bus power plants must consider the power plant as a whole. No specific sub-system should be developed in isolation of the others.

Acknowledgments

Workshop organizers wish to acknowledge the support of the DOE Office of Energy Efficiency and Renewable Energy and the DOT Federal Transit Administration for their support and participation.

Appendix A

Agenda

Joint Fuel Cell Bus Workshop

Department of Energy (EERE)
Department of Transportation (FTA)

June 7, 2010
8:00 AM – 12:00 PM
Washington Wardman Park Marriott Hotel
Room Maryland C

08:00	Fuel Cell Bus Workshop Overview & Purpose	DOE – Dimitrios Papageorgopoulos
08:10	DOT/FTA National Fuel Cell Bus Program Overview	DOT – Venkat Pindiprolu
08:20	Users Perspective on Advanced Fuel Cell Bus Technology	CaFCP - Nico Bouwkamp NREL - Leslie Eudy
08:30	Progress and Challenges for PEM Transit Fleet Applications	UTC - Tom Madden
08:45	Fuel Cell Buses – Current Status And Path Forward	Ballard Power Systems - Greg James
09:00	Powering a Full-Size Transit Bus with Two 16-kW Forklift Fuel Cells – The Proterra Story	Proterra – Dale Hill
09:15	HybriDrive Propulsion System – Cleaner, smarter power for transit	BAE Systems – Bart Mancini
09:30	Break	
09:45	Brainstorming: Technical Barriers R&D Needs, Technical Targets & Timeframes	DOE – Papageorgopoulos
11:45	Summary & Wrap-Up	DOE/DOT – Papageorgopoulos/Pindiprolu
12:00	Adjourn	

Appendix B
Fuel Cell Bus Workshop Attendees

Organizers
Dimitrios Papageorgopoulos (DOE)
Tom Benjamin (DOE/ANL)
Donna Ho (DOE)
Kristen Nawoj (DOE-Sentech)

Signed-In
Jacob Spendelow (DOE/LANL)
John Garbak (DOE)
Lisa Callaghan Jerram (Fuel Cells Today)
Keith Wipke (DOE/NREL)
Bob Rose (USFCC)
Charlie Pritzlaff (Georgetown U)
Ajay K. Prasad (U of Delaware)
Adam Kinzey (U of Delaware)
Larry Long (Vehicle Systems Integration)
Don Mase (Vehicle Systems Integration)
Mahesh Murthy (W.L. Gore)
Brian Bowers (Nuvera Fuel Cells)
Silvia Wessel (Ballard)
Nancy Garland (DOE)
Greg Kleen (DOE/Golden Field Office)
Kim Cierpik (DOE-Navarro)
Shaun Onorato (DOE-Navarro)
Wahid Nawabi (Altergy Systems)
Gerald DeCuollo (Treadstone)
Kathi Epping-Martin (DOE)
Greg Moreland (DOE-Sentech)
Joe Stanford (DOE-Sentech)
Sunita Satyapal (DOE)
Peter Devlin (DOE)

Speakers
Venkat Prindiprolu (DOT/FTA)
Leslie Eudy (NREL)
Nico Bouwkamp (CAFCP)
Tom Madden (UTC Power)
Greg James (Ballard Power Systems)
Dale Hill (Proterra)
Bart Mancini (BAE Systems)

Email RSVP Received but not Signed-In
Ken Howden (DOE)
Wei Zhang (ORNL)
Brent Ritzel (Equitech Int’l)
Jinichi Tomuro (Eng’ing Adv Assoc of Japan)
Kay Kimberly Siegel (H2Safe)
Dennis J. Kountz (Dupont)
Benjamin Deal (CARB)
Elvin Yuzgullu (DOE-Sentech)
Brianna Pinson (ETA International)
Bill Elrick (CAFCP)
Geoff Bromaghim (NHA)
Chris White (CAFCP)
Siyu Ye (Ballard)

Appendix C
Fuel Cell Bus Workshop Overview and Purpose
Dimitrios Papageorgopoulos, U.S. Department of Energy

Appendix D
DOT/FTA National Fuel Cell Bus Program Overview
Leslie Eudy on behalf of U.S. Department of Transportation

Appendix E
User Perspective on Advanced Fuel Cell Bus Technology,
Leslie Eudy, National Renewable Energy Laboratory and
Nico Boukamp, California Fuel Cell Partnership

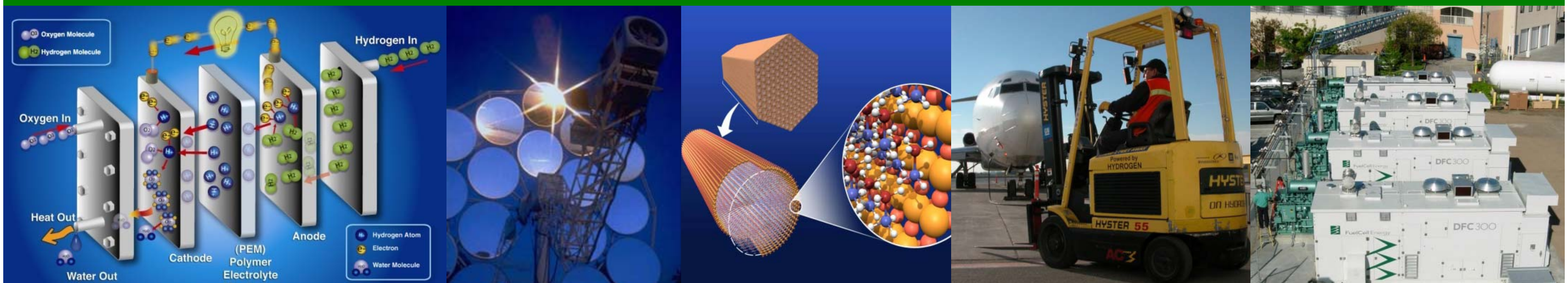
Appendix F
Progress and Challenges for PEM Transit Fleet Applications
Thomas Madden, UTC Power, LLC

Appendix G
Fuel Cell Buses – Current Status and Path Forward
Greg James, Ballard Power Systems

Appendix H
Powering a Full-Size Transit Bus with Two 16-kW Forklift Fuel Cells
Dale Hill, Proterra, LLC

Appendix I
HybriDrive Propulsion System – Cleaner, Smarter Power for Transit Bart
Mancini, BAE Systems

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Fuel Cell Bus Workshop

Overview and Purpose

Dimitrios Papageorgopoulos

Fuel Cell Technologies Program

DOE and DOT Joint Fuel Cell Bus Workshop, Washington DC

June 7, 2010

Fuel Cells - *Addressing Energy Challenges*

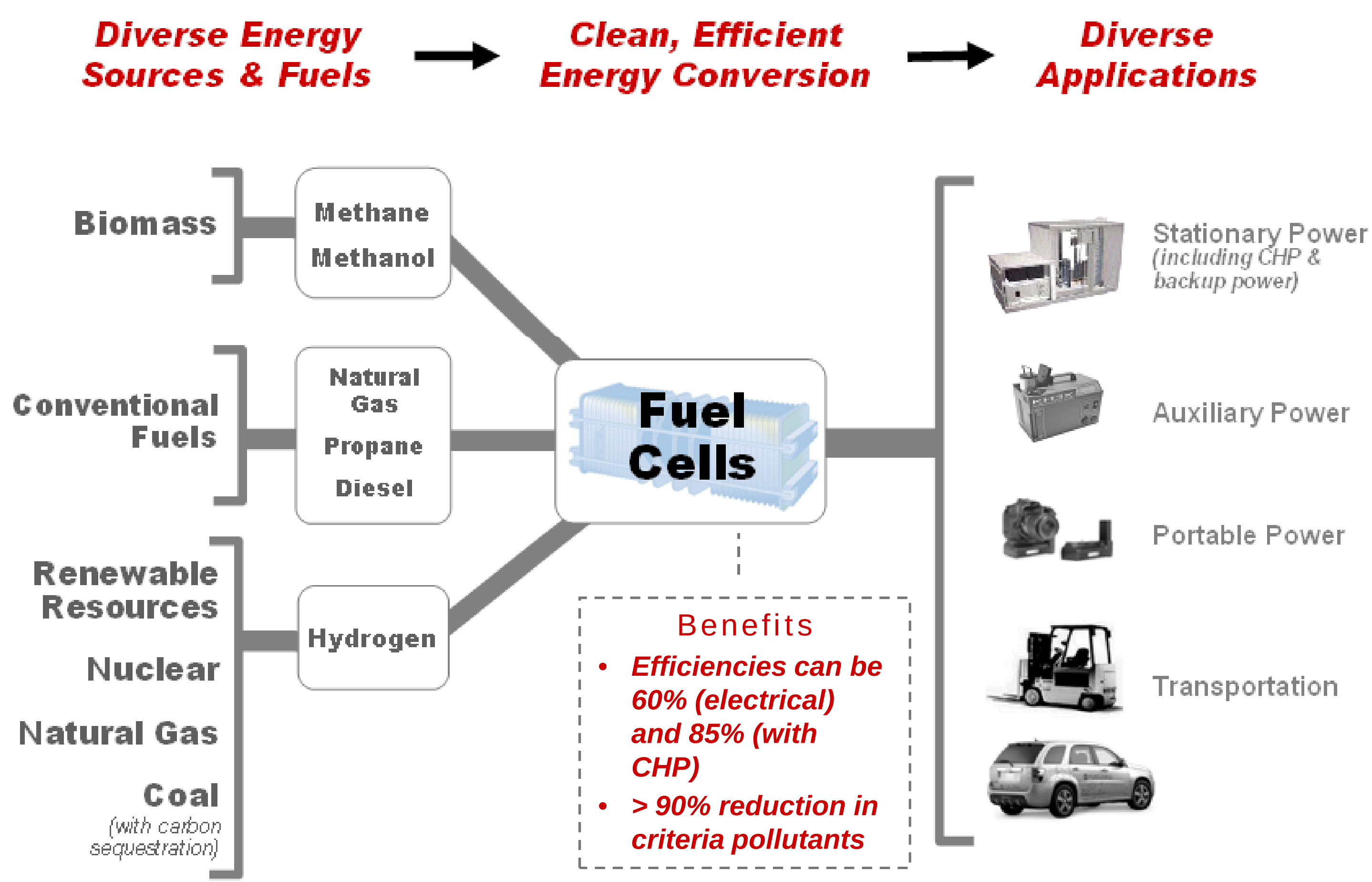
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Energy Efficiency and Resource Diversity

- ***Fuel cells offer a highly efficient way to use diverse fuels and energy sources.***

Greenhouse Gas Emissions and Air Pollution:

- ***Fuel cells can be powered by emissions-free fuels that are produced from clean, domestic resources.***

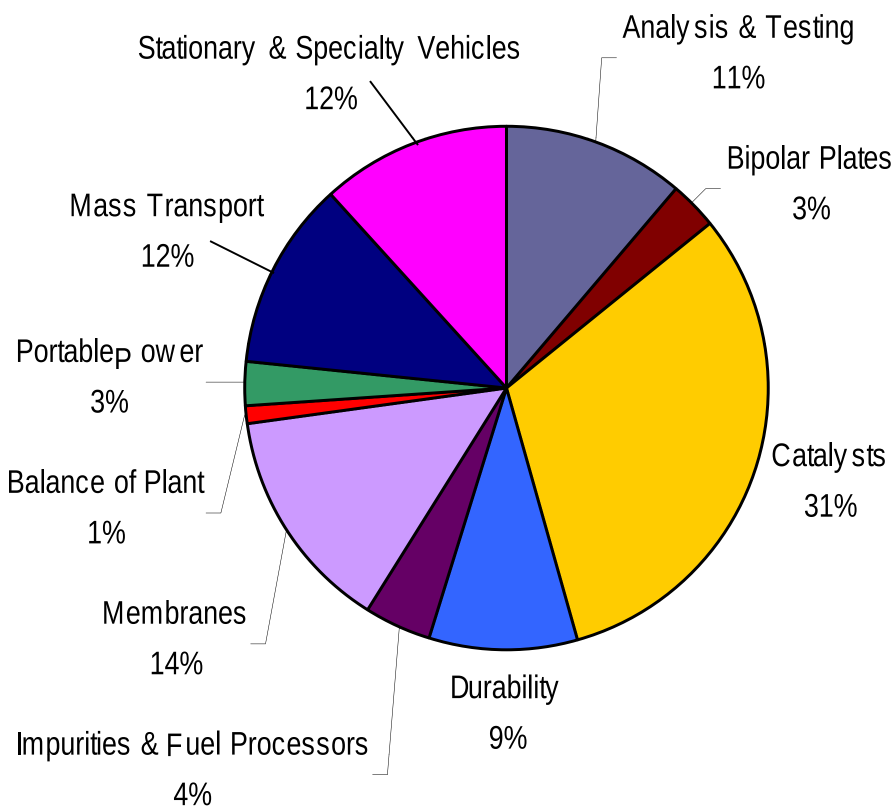


Fuel Cell Systems R&D

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY 2010

APPROPRIATION = $77.4M



FY 2010 Emphasis

R&D of materials, stack components, balance-of-plant subsystems, and integrated fuel cell systems targeting lower cost and enhanced durability

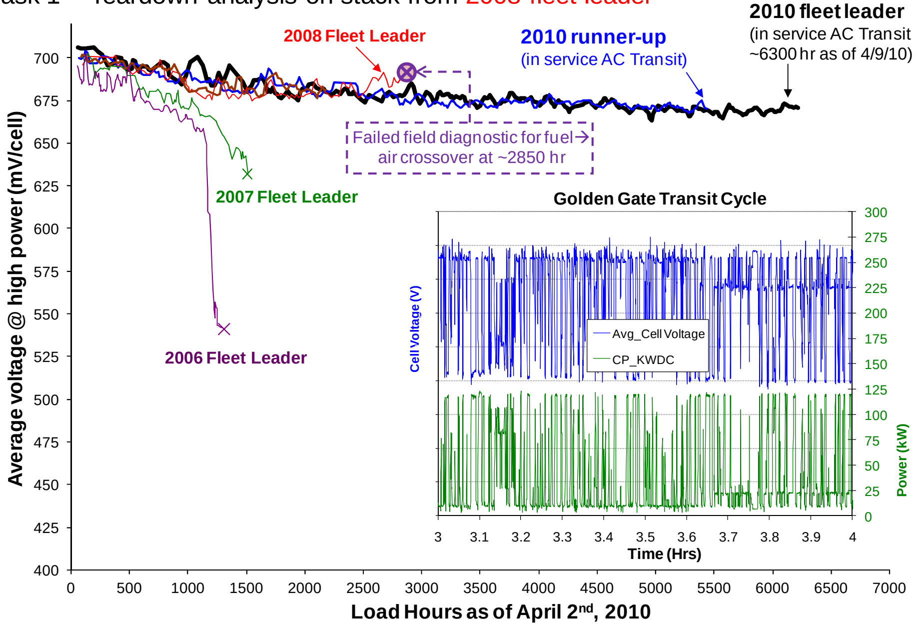
- Develop improved fuel cell catalysts and membrane electrolytes
- Characterize and optimize transport phenomena improving MEA and stack performance
- Optimize fuel cells and systems for early market applications
- Develop innovative concepts leading to a new generation of fuel cell technologies

Applications include: transportation, combined heat and power (CHP), auxiliary power units (APUs), direct methanol fuel cells for portable power, and backup power for critical infrastructure.

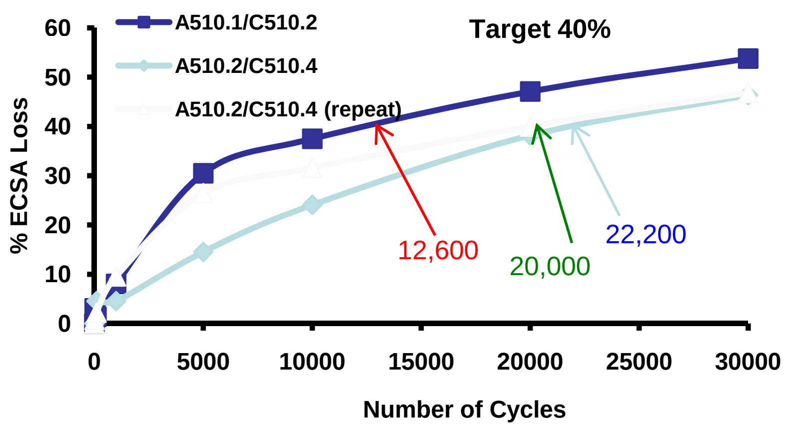
UTC, Ballard, and LANL are studying durability and developing improved ASTs

UTC: demonstrating long lifetime in real-world bus operation

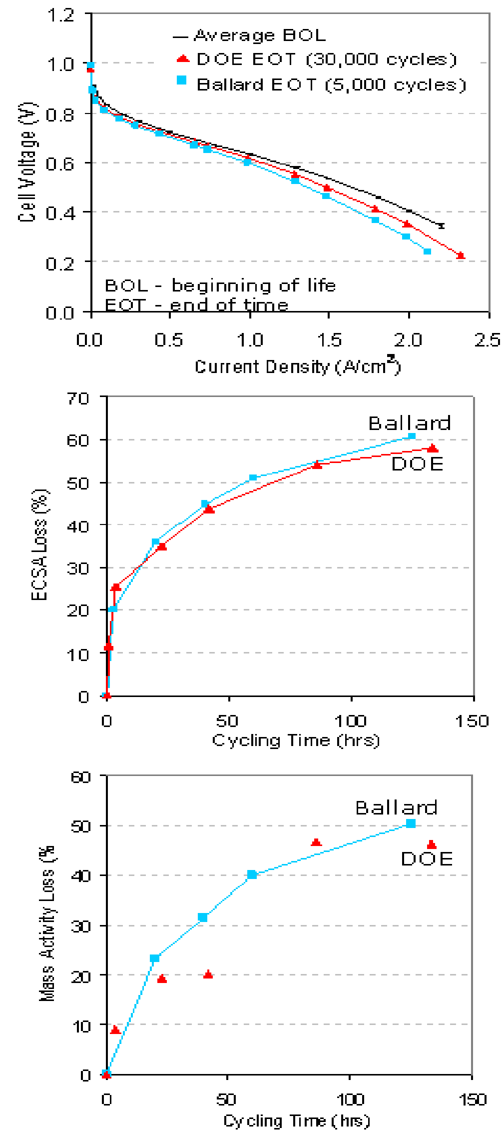
Task 1 - Teardown analysis on stack from 2008 fleet leader



LANL: improved ASTs using materials from Gore and Ballard



Ballard: developing strategies to mitigate degradation



Fuel Cell Bus Evaluation

DOE (FCT-Tech .Val.), NREL, and FTA are working closely to evaluate fuel cell technologies in transit applications

A comparison to conventional bus technology *

Attribute	Fuel Cell Technology	Conventional Diesel Technology
Fuel Economy	2 times higher than conventional buses	3 – 4 miles per gallon (diesel)
Reliability (measured in "miles between road call," or MBRC)	919 – 1,600 MRBC	10,000 MBRC
Availability	58-77%	85%
Capital Cost	\$2 – \$3 million	\$328,000
Fuel Cost	\$8.90 to \$18.80 per diesel gallon equivalent	\$4.72/gallon*

Source: L. Eudy, et al., *Fuel Cell Buses in U.S. Transit Fleets: Summary of Experiences and Current Status* (September 2007), NREL/TP-560-41967, http://www.nrel.gov/hydrogen/pdfs/41967.pdf, accessed May 2008.
* Energy Information Administration, Weekly On-Highway Diesel Prices, 07/07/08, http://tonto.eia.doe.gov/oog/info/wohdp/diesel.asp, accessed July 2008.

*** DOE's 2008 Fuel Cell School Buses Report to Congress (http://www.hydrogen.energy.gov/congress_reports.html)**

Technology Validation: Fuel Cell Bus Evaluation (L. Eudy, NREL), Poster TV 008, Thursday 6/10

Fuel Cell Bus Workshop: Purpose

DOE and DOT have invited the fuel cell bus community and other stakeholders to participate in a discussion of the most relevant research and development topics to fuel cell buses for government funding.

Specific emphasis will be placed on:

- Fuel cell stack components
- Fuel cell system balance of plant
  (excluding infrastructure, demonstration, drive-train, and non-fuel cell related bus components)

Plenary speakers include:

- Fuel cell manufacturers
- Fuel cell bus integrators and end users
- Government funding agency representatives

Fuel Cell Bus Workshop: Agenda

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

08:00 **Fuel Cell Bus Workshop: Overview and Purpose**

DOE – Dimitrios Papageorgopoulos

08:10 **DOT/FTA national Fuel Cell Bus Program**

DOT – Venkat Pindiprolu

08:20 **Users Perspective on Advanced Fuel Cell Bus Technology**

CaFCP - Nico Bouwkamp NREL - Leslie Eudy

08:30 **Progress and Challenges for PEM Transit Fleet Applications**

UTC - Tom Madden

08:45 **Fuel Cell Buses – Current Status and Path Forward**

Ballard Power Systems – Greg James

09:00 **Powering a Full-Size Transit Bus with Two 16kW Forklift Fuel Cells – The Proterra Story**

Proterra – Dale Hill

09:15 **HybriDrive Propulsion System – Cleaner, Smarter Power for Transit**

BAE Systems – Bart Mancini

09:30 **Break**

09:45 **Brainstorming: Technical Barriers, R&D Needs, Technical Targets & Timeframes**

DOE – Papageorgopoulos

11:45 **Summary & Wrap-Up**

DOE/DOT – Papageorgopoulos/Pindiprolu

12:00 **Adjourn**

BAE SYSTEMS

HybriDrive® Propulsion System

Cleaner, smarter power for transit

DOE/FTA Fuel Cell Research Priorities Workshop

Washington, DC

7 June 2010

Bart W. Mancini

Sr. Principal Systems Engineer

BAE Systems

Ph: 607-770-4103 bart.mancini@baesystems.com

Overview

- BAE Systems FC Experience / Deployments
- Technology gaps/barriers to ***full commercialization*** of fuel cell buses
  - Well-to-wheels energy efficiency and emissions
  - Cost metrics
  - Bus integration issues
- Fuel cell bus R&D needs
- Future plans

BAE Systems FC Experience / Deployments

- 1998 - Georgetown/FTA/DOE Fuel Cell Bus #1 (still serviceable)
  - UTC 100 kW Phosphoric Acid FC using on-board Methanol Reformate, Hybrid propulsion & Electric accessories
- 2000 - Georgetown/FTA/DOE Fuel Cell Bus #2 (retired)
  - Ballard 120 kW PEM FC on-board Methanol Reformate, Hybrid propulsion & Electric accessories
- 2008 - CalStart/FTA Fuel Cell APU Demonstration (this Summer)
  - Hydrogenics 2 x 12 kW FC APU units using compressed H_2, supplementing ICE-Hybrid propulsion & Electric accessories
- 2010 - Sunline/FTA American Fuel Cell Bus (initial Design phase)
  - Ballard 130 kW PEM FC using compressed H_2, Hybrid propulsion & Electric accessories

Technology Gaps & Barriers to

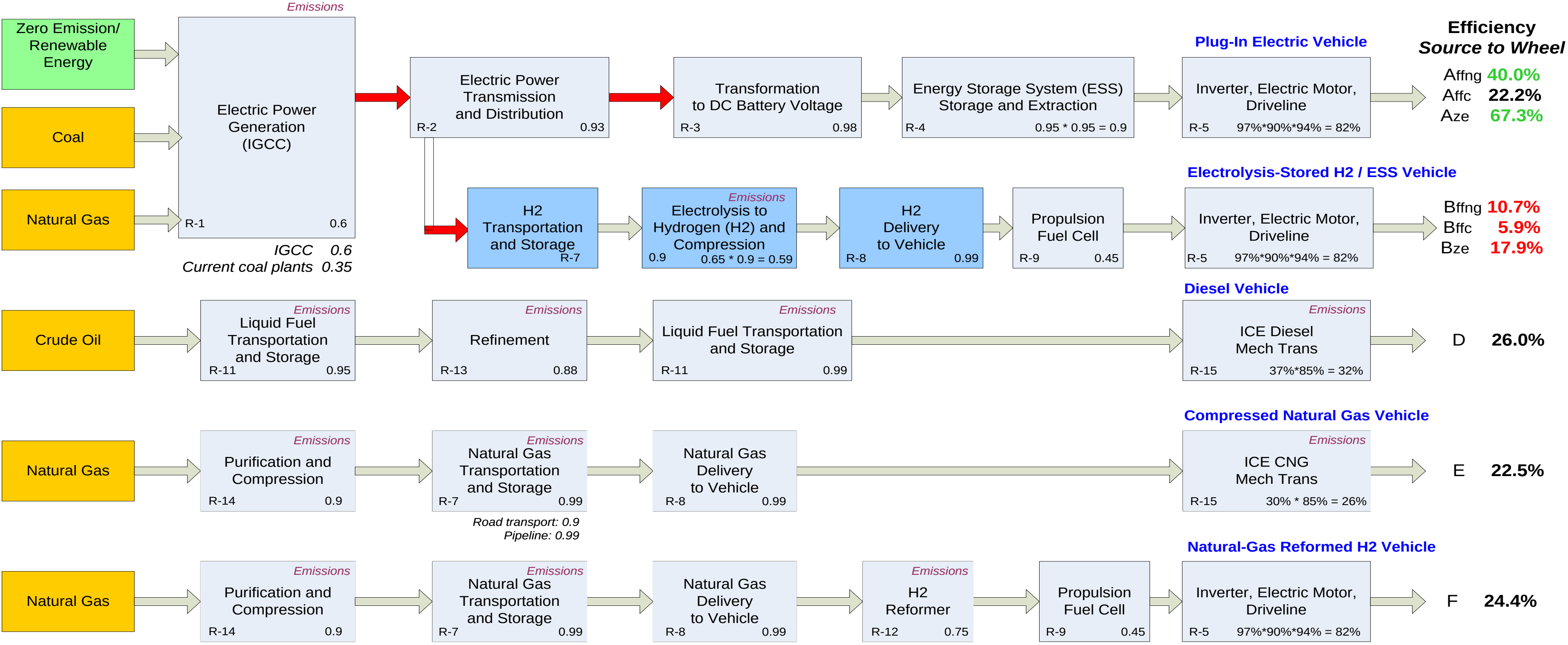
Full Commercialization of

Fuel Cell Buses

BAE SYSTEMS

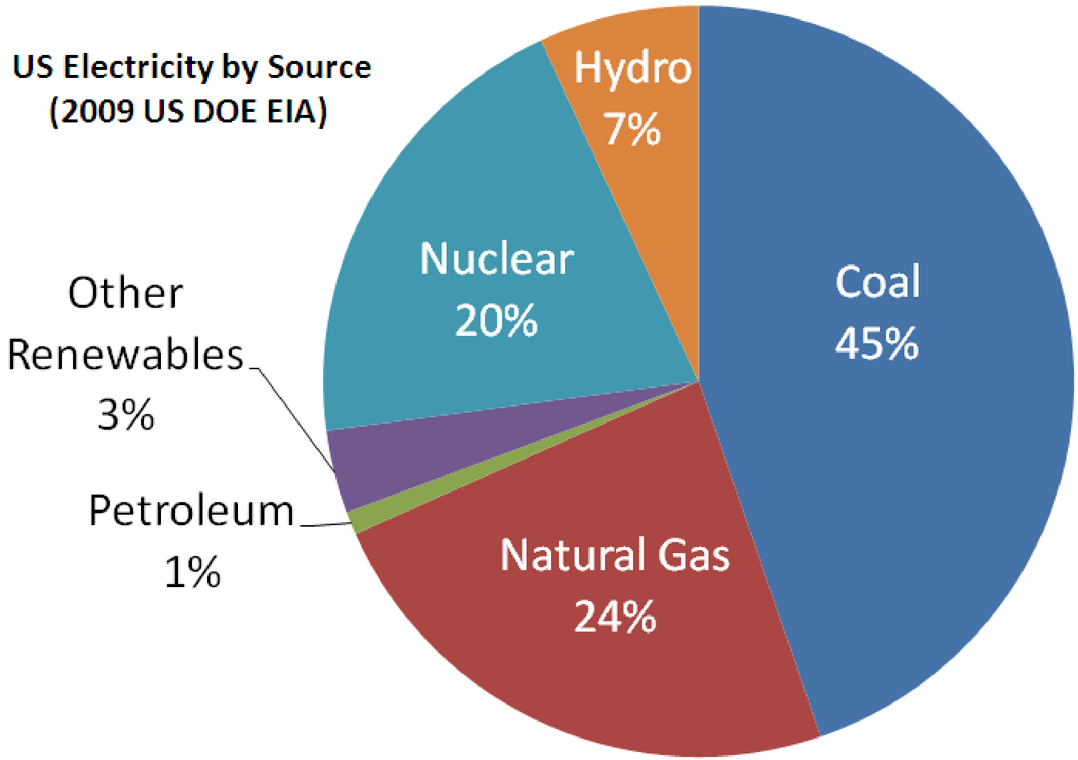
Well-to-Wheels Efficiency

- **Battery EV is best at 40% from NG or 22% from Coal**
- **Diesel ICE is best fuel burner at 26%**
- **Fuel Cell with H_2 from reformed NG 24%**
- **CNG ICE is 22%**
- **Fuel Cell with H_2 from electrolysis has efficiency at 6%-11%**



What Does Zero Emission Vehicle Really Mean?

- True ZEV only if Hydrogen is industrial “waste product” (relatively insignificant amount) or if electric energy source for electrolysis is “clean” Zero Emission.
  - 30% US electricity is “clean”: Nuclear, Hydro, Wind, Solar, Geothermal, etc.
    - Only 10% if Nuclear is not considered “clean”
- Otherwise, emissions same as electric generation fuel source or reformate fuel source
- Electrolysis will need to be conducted at off-peak times and stored so as not to over tax an already stressed daytime power generation network



Cost Metrics

Architecture	Vehicle CO_2 Reduction	Bus Premium** ∆ to $325k Dsl	$ per % CO_2 Reduction	Infrastructure Requirement
Propulsion Fuel Cell	100%	$1,475k	$14.8k /%	H_2
Battery EV	100%	$575k	$5.8k /%	Electric
FC APU [Dsl (CNG)]	50% (68%)	$375k ($425k)	$7.5k/% ($6.3k/%)	H2 (H2 & CNG)
Hybrid /EA [Dsl (CNG)]	33% (48%)	$225k ($275k)	$6.8k/% ($5.7k/%)	No (CNG)
Conv / EA [Dsl (CNG)]	15% (33%)	$50k ($100k)	$3.3k/% ($3.0k/%)	No (CNG)
CNG Conventional	18%	$50k	$2.8k /%	CNG

** Bus Only, Not including H_2/CNG fueling or battery charging infrastructure, or battery/FC replacements

- Hybrid/EA w/CNG is optimal for carbon reduction & fueling infrastructure maturity
- FC-APU provides substantial CO_2 reductions at affordable (capital) & sustainable (O&M) costs
- Conventional w/Electric Accessories and/or CNG fuel most cost effective approaches
- Battery EV looks good, but range & performance is still too limited to be broadly viable
- Propulsion FC, high initial cost plus significant O&M (FC replacements over 12 yr /50khr life)

FC- APU Architectures are currently Most Economically Viable Path to Emission Reductions and Mass FC Commercialization

Propulsion Fuel Cell Vehicle Integration Challanges

- Weight / Passenger Capacity & Cost
  - Hydrogen Storage
    - Long Range, High Endurance, sub-optimal accessory systems and sub-optimal propulsion power path drive large and heavy fuel capacity
  - Cooling System
    - Low FC coolant temps dictate large / heavy and higher power consumption cooling systems
  - FC / including Balance of Plant
    - Go-Anywhere capability, sustained highway speeds, high-speed gradeability drive larger heavier fuel cells, more cooling & air handling
- Efficiency and Power Processing
  - DC-Buss voltage dynamics & management
    - Propulsion fuel cell voltage is same as hybrid propulsion 600 Vdc typ.
    - They cannot co-exist on same DC-Link without powerful, heavy & costly conversion/regulation devices in-between, hampering efficiency
  - Slow FC time constant limits regen energy recovery potential & efficiency

Summary of Gaps / Barriers to Full Commercialization

- FC Buses need to have a lower procurement cost to support purchase in commercial quantities.
  - Example: Hybrid buses currently pose acquisition challenges at ~$500k-$600k.
- Lifetime FC planned stack replacement costs need to be reduced
  - Example: Hybrid buses currently have a planned mid-life (6-year) battery replacement at ~$40k that is taxing TAs O&M budgets.
- FC Bus weight reductions need to be addressed (thru efficiency & less tankage)
  - FC & balance of plant is good, about equivalent to diesel engine
  - Propulsion power arrangement optimization & FC response
  - Accessory loads, including balance of plant, optimization
- Unless above challenges are addressed, realizing acquisition & operation of FC buses in full commercial scale will remain a difficult challenge.

FC- APU Architectures are currently Most Viable Path: Economically, Technically, and Operationally to Mass FC Commercialization

BAE SYSTEMS

R&D Needs – Architectural & Organizational

- Develop optimized design guidelines for "Cost Effective" propulsion architectures
  - Appropriate sizing & proper application of power sources "Prime" and "APU" will make FC buses more cost-effective and commercially viable
    - Transit Bus average/intermittent power ~40 kW / 200 kW (160 kW delta)
    - $/kW for power source: ICE ~$75/kW, Fuel Cell ~$5,000 to $8,000/kW
- Develop Fleet Management guidelines for Fuel Cell and other Advanced Propulsion technologies to maximize benefit of investment
  - Procurement and O&M cost savings can be realized if buses are designed for 2-3 specific broad duty-cycle categories vs. the current "one size fits all" approach
    - Example: European "city/urban" buses with 45 mph top speed and lesser gradeability result in significantly smaller, lighter more efficient engines and higher fuel efficiency

"Remember, advanced technology cannot overcome the laws of physics" FoMoCo

BAE SYSTEMS

R&D Needs – Vehicle Technical

- Top-down systems approach to define & optimize vehicle & component requirements
- Optimization of vehicle accessory systems, including balance of plant
  - At 40 kW average power, 1 kW reduction in accessory load results in a 2.5% efficiency improvement
- Optimized self-contained fuel cell APU at 20-60 kW net power output class
  - Requires only hydrogen supply, single cooling loop, and 28V power
- Increase fuel cell operating temperature by 5-10C
  - Will reduce heat exchanger size by 20% to 40%
- Ensure all "balance of plant" thermal requirements are consistent: same or escalating (serial) cooling temperature
- Reconfigure FC stack of higher power FCs so that voltage is ***always*** below DC-Link of hybrid propulsion system
  - Eliminate one DC/DC converter and its losses, improving cost weight and efficiency proposition - - allows implementation of simple FC boost converter
- Life - - Increase operational life of FC to minimum 6-years, 25k hrs

BAE SYSTEMS

Users Perspective on Advanced Fuel Cell Bus Technology

Leslie Eudy – NREL

Nico Bouwkamp – CaFCP

DOE/FTA FCB Workshop

June 7, 2010

Transit Agencies FCB Demonstrations

Reasons for participation

- Government regulations to reduce emissions
- Public pressure
- Agency desire to be ‘green’
- Funding opportunity
- Learn about the newest technology

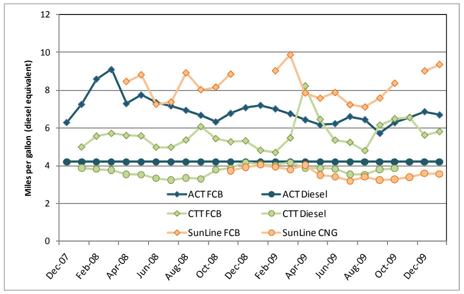
Challenges: Performance

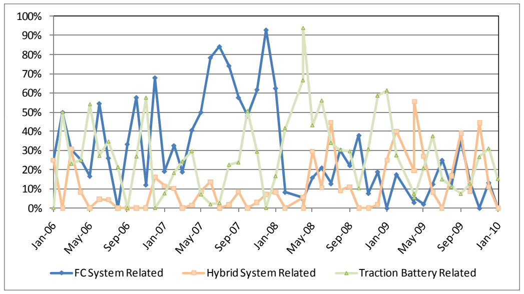
Bus should match conventional bus performance

- Operate 7 days/week, up to 20 hr/day
- Complete day of service with one tank of fuel
- Keep up with duty-cycle
- Similar time to fuel and prep for service

Challenges: Reliability & Durability

- 12 year bus requirement for FTA funded buses
  - Approx. 20,000 hrs
- Availability of 85% or more
- Miles between roadcalls
  - >4,000 for all roadcalls
  - >10,000 for propulsion related roadcalls
- Powerplant that lasts for at least ½ bus life





Challenges: Implementation into Fleet

- Facilities for maintaining and fueling FCBs
- Ability to transfer maintenance to transit agency staff
- Availability of parts
- Integrate operator training into current process

Challenges: Cost

- Capital cost of bus
- Infrastructure mods/additions
  - H_2 station capable of fueling multiple FCBs back-to-back
  - Garage/maintenance bay
- Parts cost, especially for fuel cell replacement
- Resources to manage project

Thank you.

Questions/comments?

Leslie Eudy

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Progress and Challenges for PEM Transit Fleet Applications

Tom Madden
UTC Power

2010 DOE AMR Joint DOE / DOT Bus Workshop

June 7th, 2010

This presentation does not contain any proprietary information.

UTC Power
A United Technologies Company

Agenda

- Brief company history in area of fuel cell buses
- Current fuel cell bus deployments
- Performance and life status, including reasons for forced outages
- Technology gaps/barriers to full commercialization of fuel cell buses
- Fuel cell bus R&D needs
- Future plans

UTC Fleet history

• 14+ yr experience integrating fuel cell technology into buses

1998

<u>Georgetown University</u>

40 Foot NOVA Bus

100 kW Phosphoric Acid

Methanol

FC/battery hybrid

2002

<u>SunLine, AC Transit, LAMTA, Chula Vista</u>

30 Foot Thor "Thunder Power" Bus

60 kW PEM

Hydrogen

FC/battery hybrid

2004

<u>EMT Madrid, ATM Turino</u>

40 Foot Irisbus

60 kW PEM

Hydrogen

FC/battery hybrid

2005

<u>AC Transit/Sunline</u>

40 Foot Van Hool Bus

120kw PEM

Hydrogen

FC/battery hybrid

UTC Fleet summary

- This report involves a total of six buses operated in California, Connecticut and Belgium.
- All buses are 40 ft A330 models manufactured by VanHool except DeLijn. DeLijn is a 43ft dual rear axle bus manufactured by VanHool.

Fuel Cell Hybrid Bus Fleet		#	Passenger Service	Total Fleet Hours Miles
	Total Fleet	**6**	**-**	**43,188** **434,720**
	AC Transit Oakland, CA ISE Corporation	**3**	March 20, 2006 to Present	24,120 241,505
	SunLine Transit Palm Desert, CA ISE Corporation	**1**	December 16, 2005 to Present	7827 99,775
	CT Transit Hartford, CT ISE Corporation	**1**	April 11, 2007 to Present	6791 44,359
	DeLijn Antwerp, BE VanHool & Siemens	**1**	June 18, 2007 to December 16, 2009	4451 49,081

Operating Data Through April 30, 2010

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UTC Fleet outlook

- Additional 16 buses slated for delivery through 2010

Current Programs

Power Plant	**PureMotion® Model 120**	
Bus OEM	Van Hool (Belgium)	
Customers:		
AC Transit	3 Buses	2 Running; 1 bus decommissioned
SunLine Transit	1 Bus	Running
CT Transit	1 Bus	Running
DeLijn	1 Bus	Retired; end of contract 12/2009

2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015

New Programs

Power Plant	**PureMotion® Model 120**	
Bus OEM	Van Hool (Belgium)	
Customers:		
AC Transit	12 Buses	May- December 2010 bus delivery
UTCP/NAVC	4 Buses	May- August 2010 bus delivery

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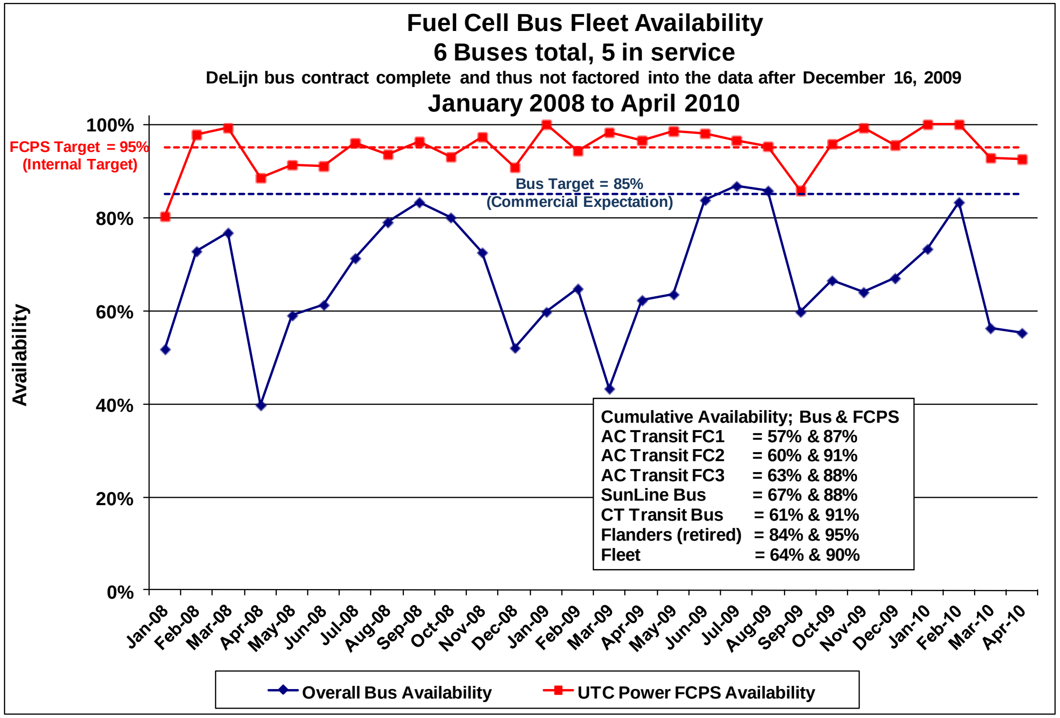
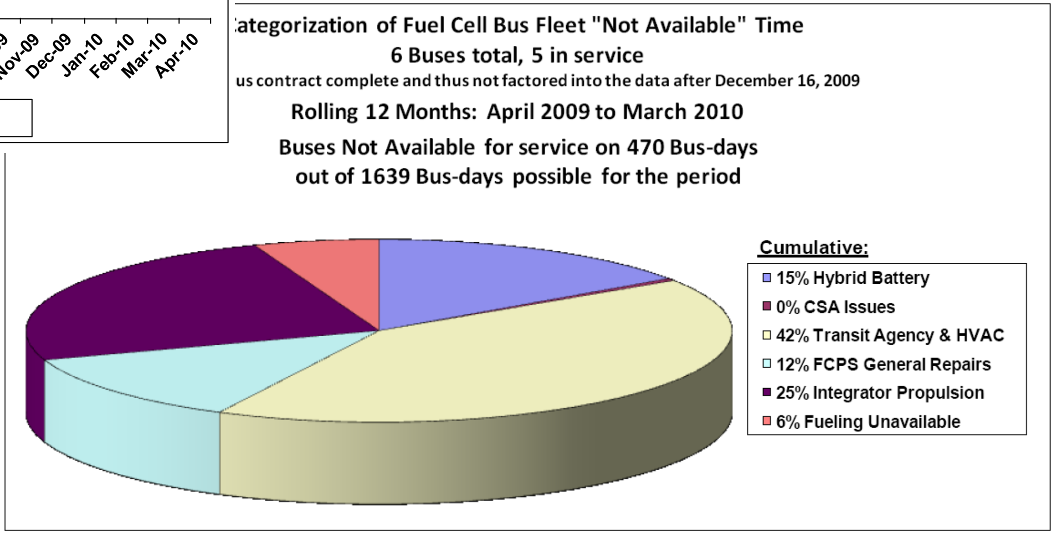
UTC Fleet availability

- Fuel cell power system (FCPS) roughly 95% available across fleet
- No cell-stack assembly (CSA) related causes for unavailability in the past 12 months



Operating Data Through April 30, 2010

Operating Data Through April 30, 2010



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UTC Fleet performance

- 2010 fleet leader and runner-up have original stacks with no intervention or recovery procedures
- Performance decay and materials failure modes through 6500+ hrs addressed

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Key gaps for fleet implementation

- Need concerted effort to drive to targets tailored for bus fleet FCV technology

Area	**Auto Target** **(2007 RD&D plan)**	**UTC Bus fleet target** **(*preliminary)**
Durability with cycling	5,500 load hrs	18,000+ load hrs
Drive schedule	- FUDS - High S/S per load-hr - Low idle time	- Golden Gate transit cycle - Low S/S per load-hr - High idle time
FCPS Cost (stack, BOP, PCS)	$30 / kW at 500,000 units / yr	- $200-350 / kW* at 1000's / yr -Need $/kW at 10's – 100's / yr
Pt loading	0.1 – 0.2 mg PGM / cm^2 total	0.3 mg PGM / cm^2 total*

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Fuel cell bus R&D needs

Area	UTC Bus fleet target (*preliminary)	Required areas for technology development
Durability with cycling	18,000+ load hrs	Accelerated life tests - Need to fund additional efforts to accelerate field failure modes in breadboard units
Pt loading	0.3 mg PGM / cm^2 total*	Low Pt-loading durability - Need to fund TRL maturation of approaches to preserve high power performance at low PGM loading
Drive schedule	- Golden Gate transit - Low S/S per load-hr	Optimize hybridization - Need to fund optimizing hybridization strategy for minimizing combined CSA and battery life-cycle costs
FCPS Cost (stack, BOP, PCS)	\$200-300 / kW * at 1000's / yr	Designs for cost, manufacturing -Need to fund new cell designs that incorporate cost-effective designs (design-for-manufacturing, improved processes for high cost components, e.g. porous bipolar plates) -Need to generate opportunities where 100's of units can be deployed to learn out cost effective designs

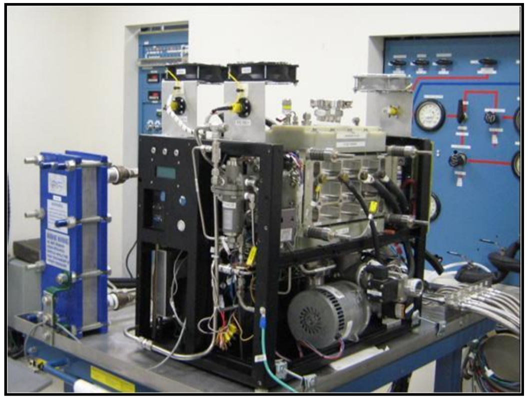
Future plans

Accelerated Life Test (ALT)

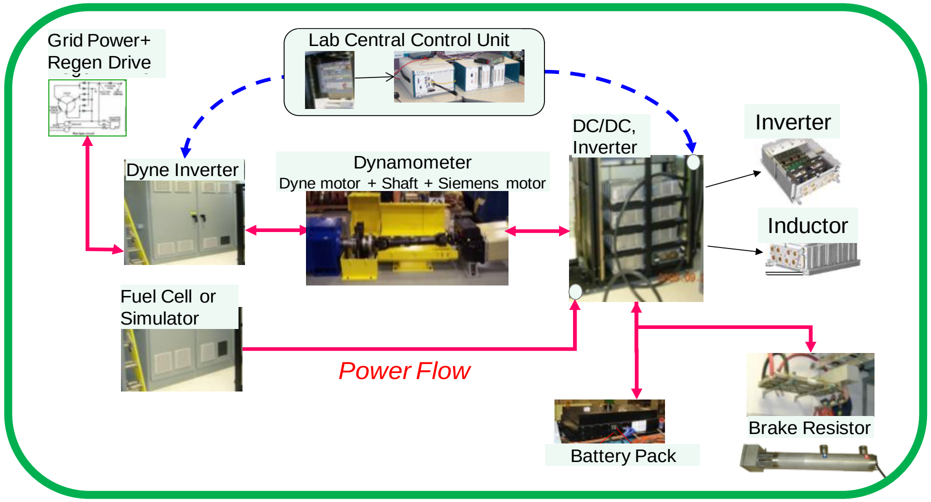
Field validation of 18,000 hr life is impractical / impossible

System effects and interactions on lifetime are significant

Mid-June 2010 start validation durability test



Full Scale Fleet Hybrid Integration and Test Facility



Hybrid Integration Lab at UTRC

Funded internally

Have completed characterization of hybrid battery

Awaiting integration of FCPS into lab

Would like to explore multiple battery technologies and tailored strategies

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BALLARD

power to change the world

Fuel Cell Buses: Current Status and Path Forward

BALLARD POWER SYSTEMS

BUILDING A CLEAN ENERGY GROWTH COMPANY

WWW.BALLARD.COM

2010

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DOE Bus Workshop – Outline of Presentation

- Ballard's fuel cell bus history.
- Ballard's current fuel cell bus deployments
- Targets for capital, maintenance and fuel costs for commercial fuel cell buses
- Definition of key areas to enable commercial targets
- Summary of Ballard's request for DOE support for commercializing fuel cell buses

Previous Ballard Bus Programs

BALLARD

	1991 - 1992	1993 - 1995	1996 - 1999	1999 - 2002	2002 – 2009
					
	Phase 1 Proof of Concept	Phase 2 Commercial Prototype	Phase 3 Fleet Demonstration Alpha Sites	Phase 4 Fuel Cell Engines Beta Sites	Phase 5 Serial Production
Power	90 kW / 125 HP	205 kW / 275 HP	205 kW / 275 HP	205 kW / 275 HP	205 kW / 275 HP
Location(s)	Vancouver	Vancouver	Chicago (3) Vancouver (3)	California	5 Continents Europe (30), Perth (3) California (3) Beijing (3)
Lessons Learned	Proof of concept	Full-size bus integration	Field service Site homologation	System optimization Cost reduction - single motor concept	International homologation Reliability growth Real world usage

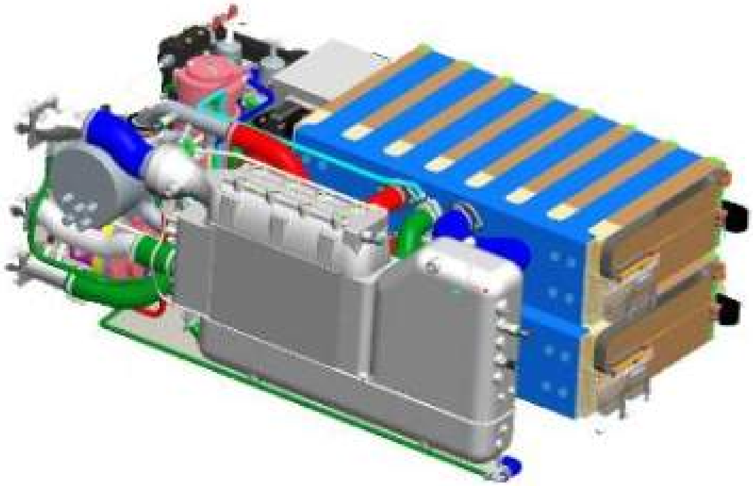
Ballard's Current Bus Product - FCvelocity™-HD6

BALLARD

- FCvelocity™-HD6 fuel cell module:
  - Greater power density and durability while maintaining some of the time tested components of previous design.
  - Featuring state of the art automotive fuel cell stack technology
  - Offered with a 12,000 hr, or 5 yr warranty

HD6 Module

- Includes:
  - air humidification system
  - hydrogen re-circulation
  - condenser for water management
  - CAN and power supply connections
  - control system
  - 150 or 75 kW configurations



Integration into a Hybrid Drive

BALLARD

Courtesy of ISE Corp.

BC Transit Fuel Cell Bus Fleet

BALLARD

- **BC Transit Fuel Cell Bus Fleet at Whistler Canada**
- **20 buses operational – main source of public transit**
- **Vehicles have now accumulated to date:**
  - > 340,000 km’s
  - > 18,000 hrs
  - Positive feedback from the drivers & transit riders

BCTransit

NEW FLYER

ISE

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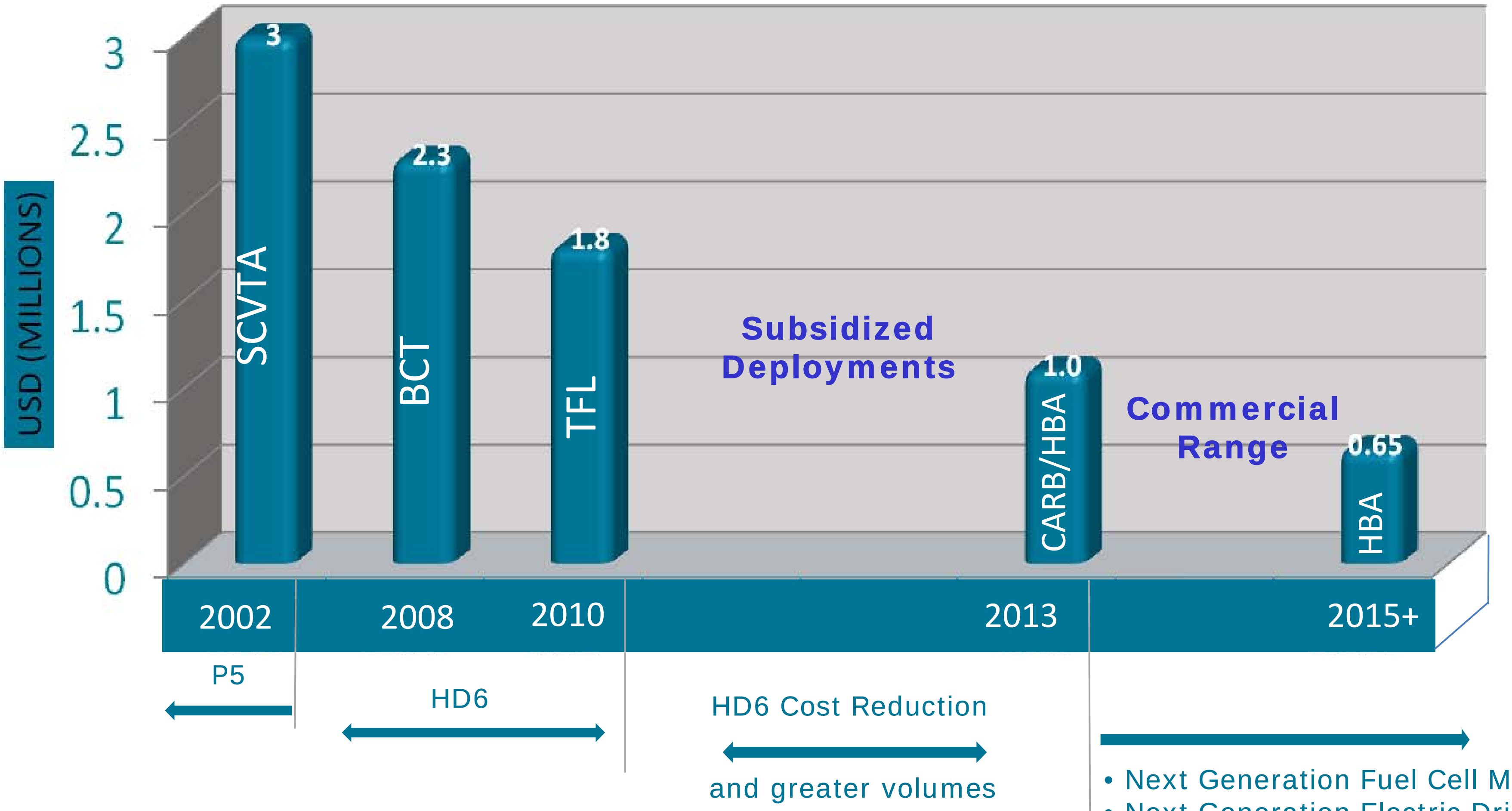
power to change the world®

HD 6 Bus Programs:

BALLARD

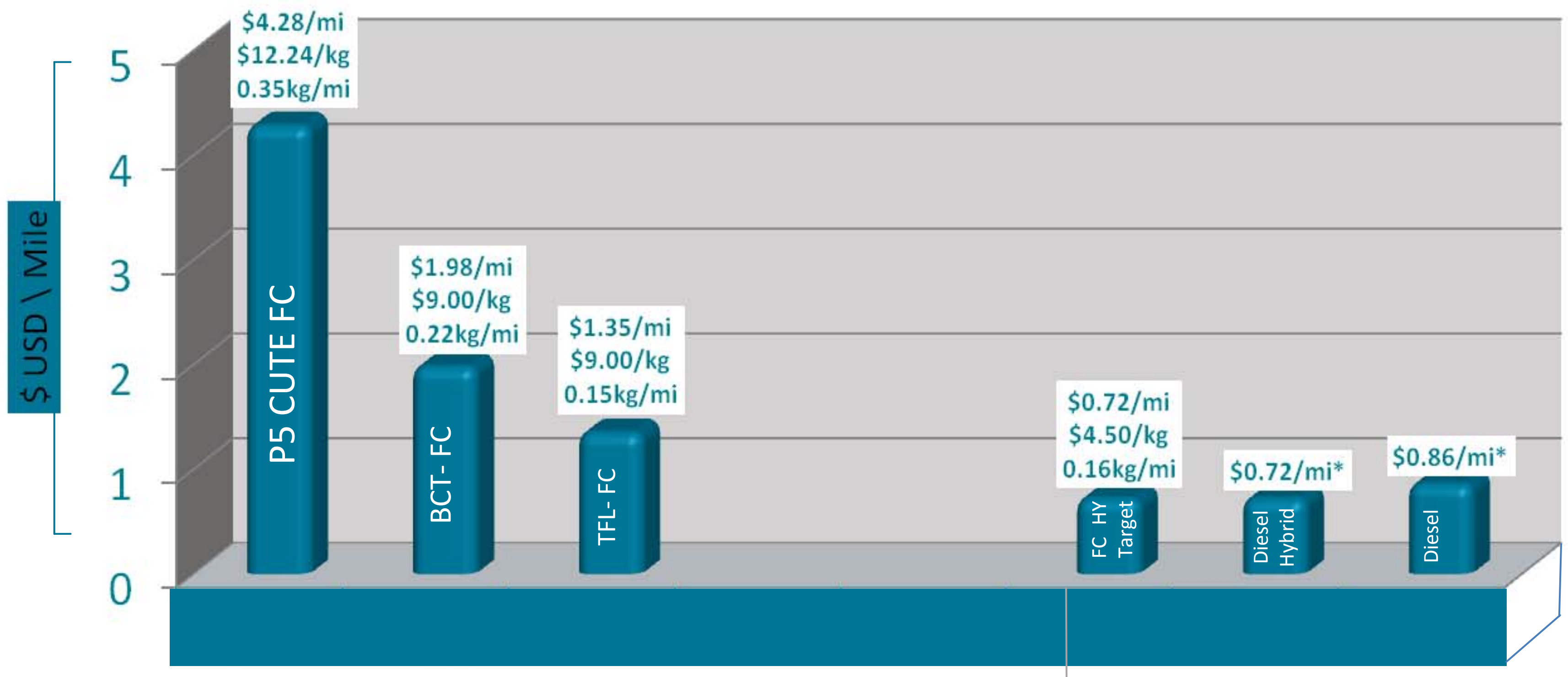
	London Bus Fleet	UNDP Sao Paulo	Palm Springs	Cologne / Amsterdam
				
	2010	Phase 2 2010	2010 2012	2010
Fleet Size	5	3	2	4
Transit Agency	Transport for London	EMTU	SunLine Transit Agency	KVB GVB
FC Power	75 kW	150 kW	150 kW	150 kW
Transit Bus OEM	The Wright Group	Marcopolo	New Flyer ElDorado National	APTS Advanced Public Transport Systems bv
Systems Integrator	ISE	tuttoTrasporti	ISE BAE SYSTEMS	vossloh

Commercial Barriers - Capital Cost



- Next Generation Fuel Cell Module
- Next Generation Electric Drive
- Next Generation Energy Storage, Electric & H2
- Production of 100's plus

Commercial Barriers - Operating Cost, Fuel Only

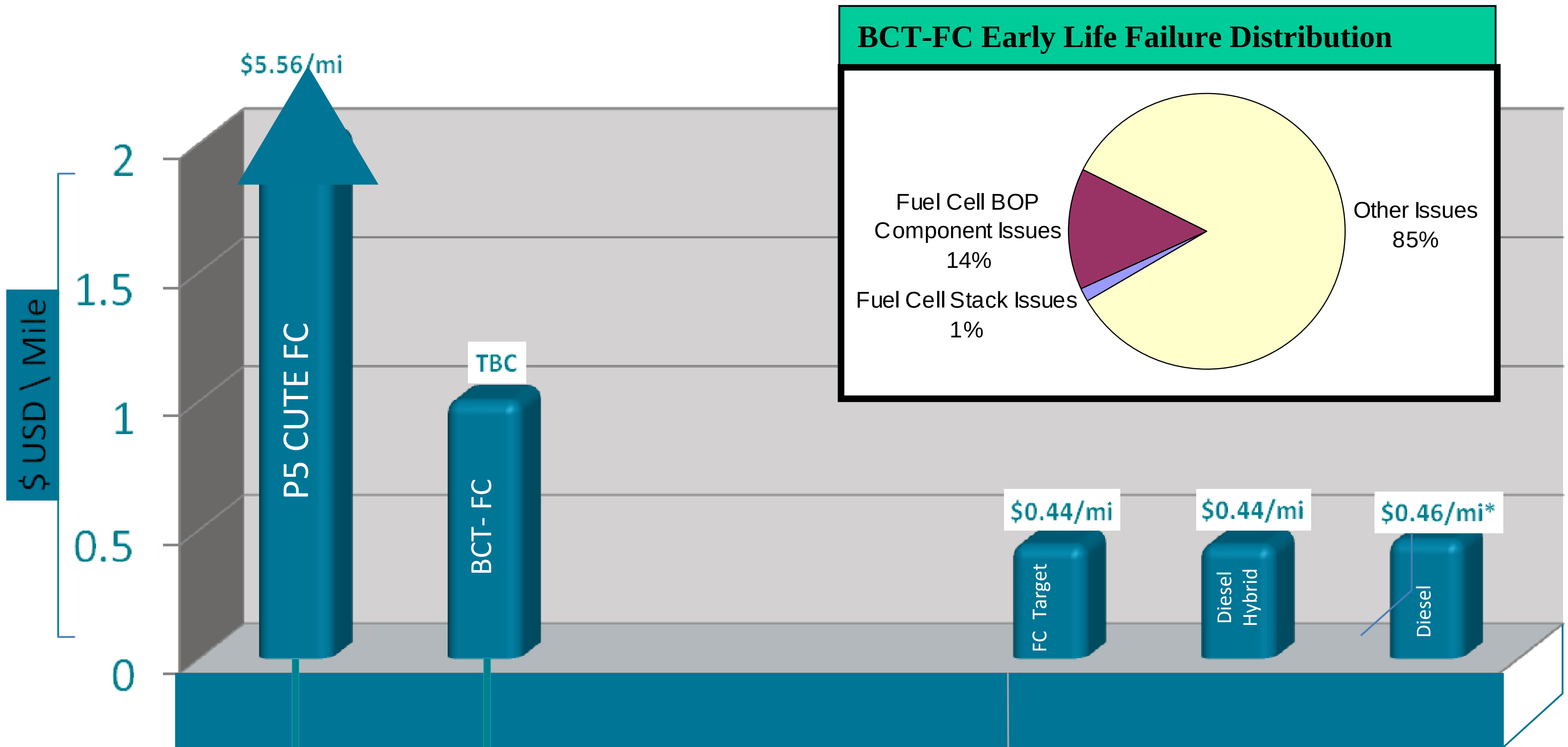


- Modest improvement of FC module efficiency
- Considerable improvement of hybridization strategy
- Considerable reduction of H2 cost at the pump

*Note: FTA-wv-26-7006.2008.1 diesel fuel @ $2.27/gallon

Commercial Barriers - Operating Cost, Maintenance Only

BALLARD



- Regular site support
- Longer stack life
- Leveraging Diesel Hybrid technology

- Intensive site support
- Short stack life
- Complex immature technology

Continuous improvement of Coach integration, System Integration and FC Module life and reliability

Next Generation System Integration & FC Module

Further improvement of Hybrid architecture for FC application

*Note: FTA-wv-26-7006.2008.1

Cost Reduction Opportunities through Volume

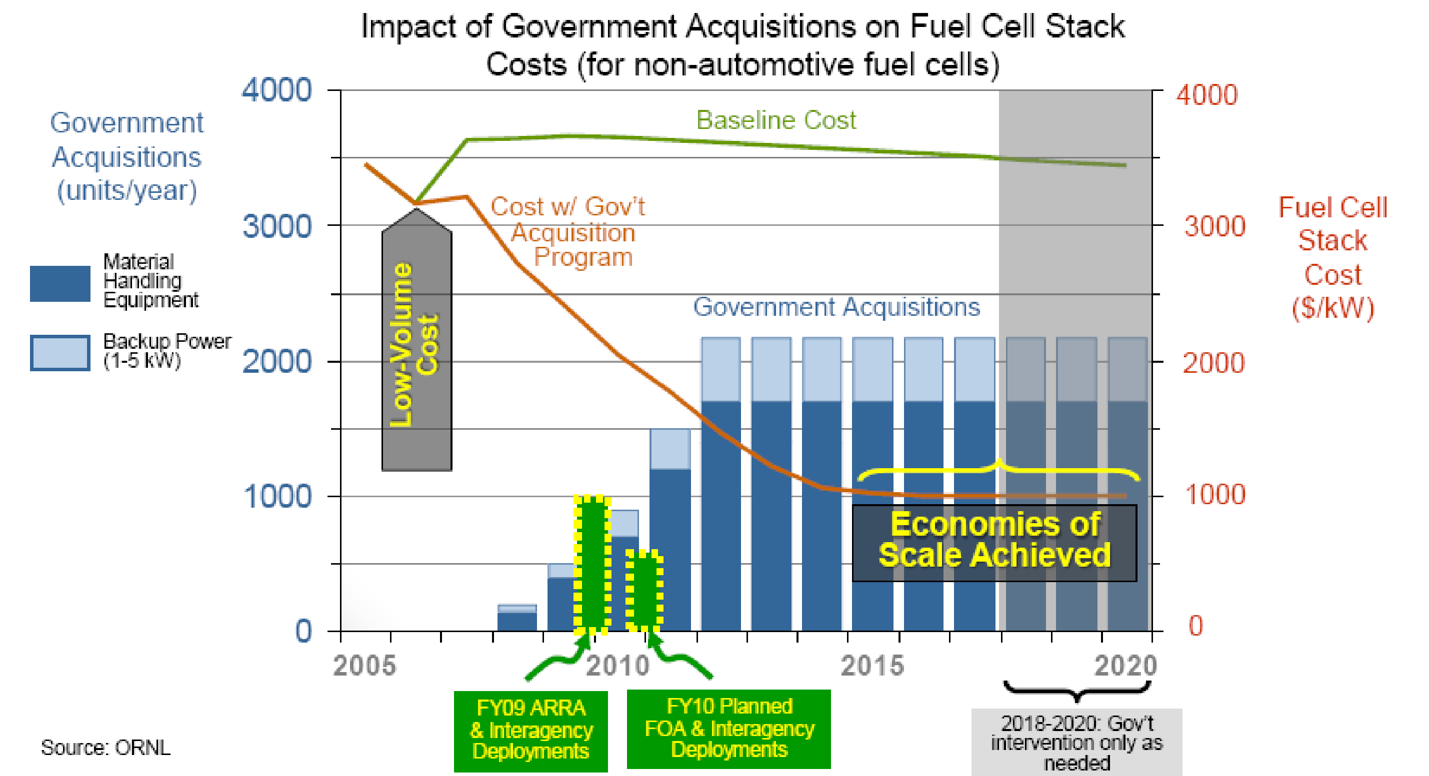
BALLARD

Market Transformation

U.S. DEPARTMENT OF ENERGY

Government acquisitions could significantly reduce the cost of fuel cells through economies of scale and help to support a growing supplier base.

Key Market Transformation Goals: Enable cost reductions from ~$3500/kW to ~$1000/kW for backup power and lift-truck power and from ~$5500/kW to ~$3000/kW for CHP systems

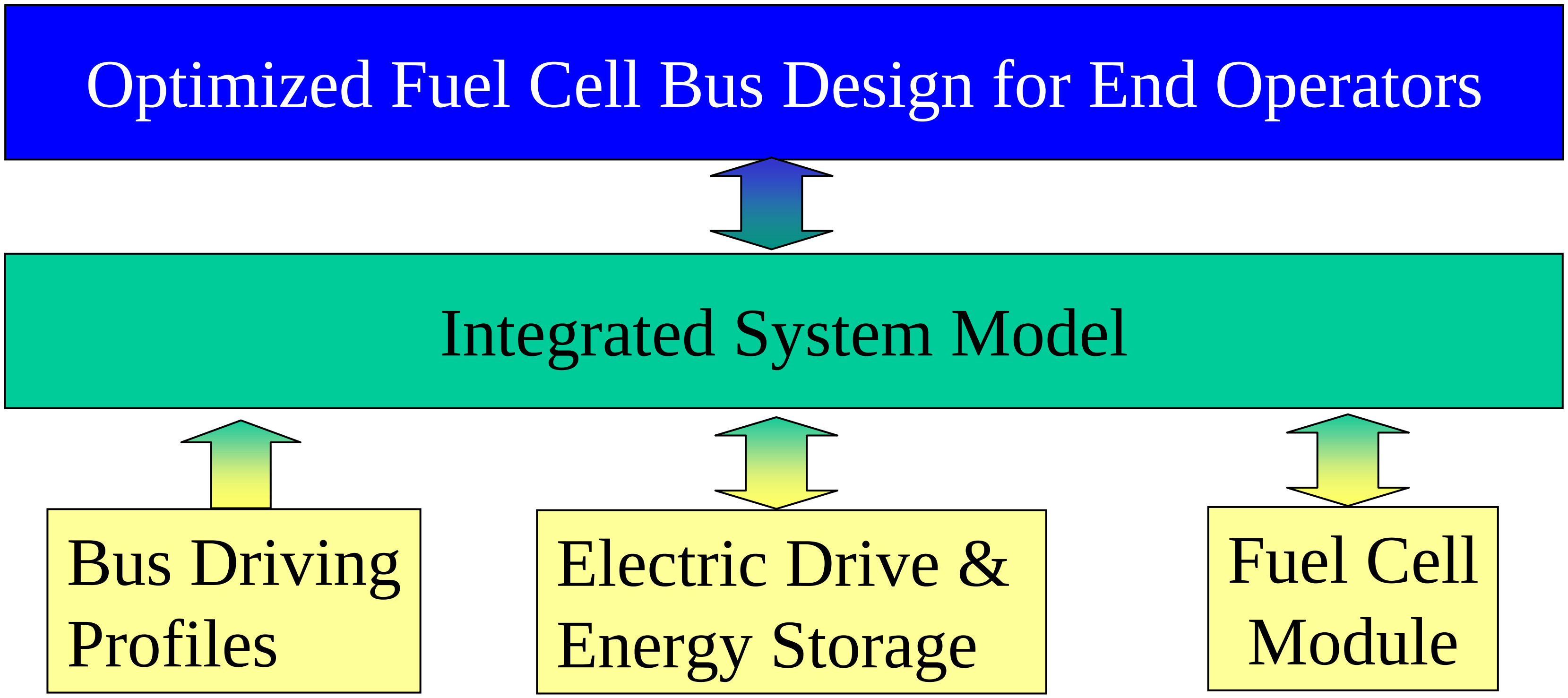


Driving volume through subsidies and/or purchases can have a big effect on achieving commercial cost targets.

Suggest similar study as done in Material Handling & Back-up Power

Source: WHEC Conference May 20, 2010
US Hydrogen and Fuel Cell Policy and Analysis Review
Michael Mills

Additional Key Tool for Cost Reduction



Drive for holistic integrated system approach across operators, integrators, energy storage suppliers and fuel cell module suppliers

- Model drives both capital, operating (fuel) and maintenance costs
- Focus capital & development money in highest value areas
- Derive optimum hybridization strategies
- Validates commercial fuel cell business and defines key targets for supply base

Capital Cost Reduction Via Component Development

BALLARD

Component Development	Component Testing	Validation Under Bus Operation
Electric Drive Energy Storage – H_2 & Electric Fuel Cell Module -Non Stack a) Air & Fuel pumps b) Electric motors c) Hydrogen Sensors d) Humidifiers e) etc Fuel Cell Stack a) Low cost materials b) Improved MFG processes c) 2-3X life improvement d) Maintain current performance level	Develop detailed test plans a) Functional tests b) Robustness tests c) Accelerated test Design & Build Test Equipment a) Purpose built b) Multi sample testing for statistics Perform detailed failure analysis a) Root cause determination b) Measurement of wear	Build components into operational bus and test under actual bus route conditions a) Catch component interaction issues b) Allows opportunity to maximize benefits of new components c) Works out infant mortality to allow for smooth transition to larger fleet operation Note, this is one of the most critical yet underfunded part of fuel cell bus development

Select components with biggest impact on fuel efficiency, capital cost & maintenance cost

Summary of Areas Where DOE Can Help Commercialize Fuel Cell Buses

BALLARD

- **Funding for system analysis across coach, integrator, and fuel cell provider**
  - Holistic approach across all elements of the bus including driving profiles, energy management, electric drive and fuel cell module options
- **Funding for development of low cost, highly reliable, long lasting components**
  - Fuel cell stack and module components
  - Energy storage – fuel and electrical
  - Electric drive systems
- **Funding for bus level "Design Validation" testing before releasing larger fleet sizes into revenue service**
  - Critical step in typically underfunded part of development cycle
  - Sets up commercial adoption of fuel cell buses due to ease of integration into normal bus service
- **Subsidies for larger scale bus deployments**
  - Allows for capital cost reduction across the bus through higher volume manufacturing processes
  - Provides incentive for supply base to engage (from coach manufacturer through component manufacturing though hydrogen supply companies)

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Thank you!




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