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Federal Transit Administration

ASSESSMENT OF NEEDS AND RESEARCH ROADMAPS FOR RECHARGEABLE ENERGY STORAGE SYSTEM ONBOARD ELECTRIC DRIVE BUSES

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Background, Research Needs, Stakeholder and Expert Input, Research Recommendations, and Research and Technology (R&T) Roadmaps

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In support of the Federal Transit Administration (FTA) Electric Drive Strategic Plan (EDSP), this report assesses state-of-art advances in lithium-ion batteries, ultracapacitors, and related power management and control technologies for the rechargeable energy storage systems (RESS) on-board existing and emerging electric drive buses. RD&T roadmaps for near-, mid-, and long-term are developed for FTA and potential partners developing next generation electric drive buses, based on a review of technical literature, and inputs from experts and transit stakeholders regarding lessons learned, knowledge gaps, and priority RD&T needs. Illustrative projects up to 2020 are proposed based on the identified priority needs in these roadmaps. They promise to advance RESS technologies from research, development, demonstration, test and evaluation to full integration in more fuel efficient, environmentally sustainable, and cost-effective commercial electric drive transit buses.

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FOREWORD

This report assesses state-of-art advances in lithium-ion batteries, ultracapacitors, and related power management and control technologies for the rechargeable energy storage systems (RESS) on-board existing and emerging electric drive buses, in support of the Federal Transit Administration (FTA) Electric Drive Strategic Plan (EDSP). There is a need to develop Research, Development and Technology (RD&T) roadmaps for the near-, mid-, and long-term, to guide FTA, its partners, and stakeholders in developing the next generation of electric drive buses. To this end this report summarizes findings from a review of technical literature, and inputs from leading technical experts and transit stakeholders regarding lessons learned, knowledge gaps, and priority RD&T needs. Illustrative projects up to 2020 are proposed based on the identified priority needs in these roadmaps. They promise to advance RESS technologies from research, development, demonstration, test and evaluation to full integration in more fuel efficient, environmentally sustainable, and cost-effective commercial electric drive transit buses The proposed Roadmap priorities will remain valid for the next decade, since they are designed to capture and exploit the rapid advances in battery and energy storage technologies for vehicle electrification, and complement ongoing efforts to develop advanced urban buses less dependent on fossil fuels. The principal author of this report is Dr. Aviva Brecher, National Technical Expert in Energy Technology, Energy and Environmental Systems at the U.S. DOT Volpe Center. Contributions from Volpe Center colleagues Stephen Costa, Scott Lian, Karen Shilo, and Michael Kay are gratefully acknowledged. The FTA sponsors of this project are thanked for valuable guidance and review comments: Mr. Walter Kulyk, Director of the FTA Office of Mobility Innovation, and his staff: Ms. Christina Gikakis, Mr. Sean Ricketson, and Mr. Gregory Rymarz.

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List of Abbreviations

21CTP	21st Century Truck Partnership
AC	Alternating Current
AFCB	American Fuel Cell Bus
ANSI	American National Standards Institute
APU	Auxiliary Power Units
APTA	American Public Transportation Association
ARRA	American Recovery and Reinvestment Act
AZD	Azure Dynamics
BAT	Best Available Technology
BEB	Battery-electric Bus
BMS	Battery Management Systems
BUS-2010	Compound Fuel Cell Hybrid Bus
BYD	Build Your Dream
CARB	California Air Resources Board
CNG	Compressed Natural Gas
CD	Charge Depleting operation
CS	Charge Sustaining operation
CSA	Cell Stack Assemblies
CTA	Chicago Transit Authority
CTE	Center for Transportation and the Environment
CUTE	Clean urban Transport for Europe
DC	Direct Current
DoD	Department of Defense
DOD	Depth of Discharge
DOE	Department of Energy
DOT	Department of Transportation
EB	Electric Bus
ECU	Electronic Control Unit
EDLC	Electrochemical Double Layer Capacitors
EDTA	Electric Drive Transportation Association
EDV	Electric Drive Vehicle
EERE	Energy Efficiency and Renewable Energy (office of DOE)
EOL	End of Life
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
FESS	Flywheel Energy Storage System
FMVSS	Federal Motor Vehicle Safety Standards
FTA	Federal Transit Administration
FCB	Fuel Cell Bus
GE	General Electric
GFCI	Ground Fault Current Interrupter
GHG	Green-House Gases
GTR	General Technical Regulations

HARC	Houston Advanced Research Center
HEB	Hybrid-Electric Bus
HEV	Hybrid-Electric Vehicle
HIL	Hardware in the Loop
HHICE	Hybrid hydrogen internal combustion engine
HVAC	Heating, Ventilation and Air Conditioning system
ICE	Internal Combustion Engine
IEC	International Electro-technical Commission
IGBT	Insulated Gate Bipolar Transistor (an electronic switch)
I-SAM	Integrated Starter Alternator Motor
ISO	International Standards Organization
KESS	Kinetic Energy Storage System (flywheel, hydraulic)
KWh	Kilowatt-hour
LCM	Life Cycle Model
LCCM	Life Cycle Cost Model
LCO	Lithium Cobalt Oxide (cathode for lithium-ion batteries)
LFP	Lithium Iron Phosphate (cathode for lithium-ion batteries)
LIB	Lithium- Ion Battery
LIP (also LiPo)	Lithium- Ion Polymer Battery, also abbreviated LiPoly, Li-Pol, LIP, PLI or LiP)
LMO	Lithium Manganese Oxide Battery
LMP	Lithium Metal Phosphate (includes Li Iron phosphate electrodes)
LMS	Lithium Manganese Spinel (olivine-type electrode)
LTO	Lithium Titanate Battery
MBRC	Mean- Time Between Road Calls
MDOT	Michigan Department of Transportation
MESA	Modular Electronic Scalable Architecture
M&S	Modeling and Simulation
MSDS	Material Safety Data Sheets
MTS	Metropolitan Transit Systems
NAVC	Northeast Advanced Vehicle Consortium
NEC	National Electric Code
NFCBP	National Fuel Cell Bus Program
NFPA	National Fire Protection Association
NHA	National Hydrogen Association
Ni-Cad, NiCd	Nickel Cadmium battery
NiMH	Nickel Metal Hydride battery
NIST	National Institute of Standards and Technology
NMC	Nickel Manganese Cobalt (*NMC*) oxide cathode for LIB
NRC	National Research Council
NREL	National Renewable Energy Laboratory
NYCTA	New York City Transit Authority
OEM	Original Equipment Manufacturer
O&M	Operations and Maintenance
PCS	Power Conversion Systems
PEM	Proton Exchange Membrane

PHEV	Plug-in Hybrid Electric Vehicle
PHMSA	Pipeline and Hazardous Materials Safety Administration
PMS	Power Management Systems
RC	Road Call
R&D	Research and Development
RD&T	Research, Development and Technology
RDT&E	Research, Development, Test and Evaluation
RD3	Research, Development, Demonstration and Deployment
RESS	Rechargeable Energy Storage System
ROI	Return on Investment
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe Accountable Flexible Efficient Transportation Equity Act
SC&S	Safety Codes & Standards
SDU	Safety Disconnect Unit
SEI	Solid Electrolyte Interface
SHFCC	Southern Hydrogen and Fuel Cell Coalition
SLI	Starting, Lighting, and Ignition battery
SME	Subject Matter Experts
SOC	State of Charge
SSPP	System Safety Program Plans
TA	Transit Authority
TC	Transport Canada
TCRP	Transit Cooperative Research Program (under TRB)
TMS	Thermal Management Systems
TRB	Transportation Research Board
TRL	Technology Readiness Level
UAB	University of Alabama at Birmingham
UL	Underwriters Laboratory
US	United States
USABC	DOE’s Advanced Battery Consortium
USCAR	United States Council for Automotive Research
UT-CEM	University of Texas at Austin
V	Volt
V&V	Verification and Validation of modeling tools, or design predictions
WG	Working Group
Wh	Watt-hour
WMATA	Washington Metropolitan Area Transit Authority
ZBus	Zero Emission Bus
ZEBRA	Zeolite Battery Research Africa project

Summary

For over a decade FTA RD&T leadership and investments have demonstrated the potential fuel efficiency and environmental benefits of hybrid, electric drive and fuel cell buses (HEB, EB and FCB) using advanced RESS technologies. An important goal of the 5 years FTA Research Program Plan (FY2009—2013)[1] is to successfully undertake, complete and sustain the full suite of projects proposed under the FTA Electric Drive Strategic Plan (EDSP). This includes the evaluation of technology options for RESS, and the full integration with bus power and propulsion system architectures, power management electronics under realistic in-service operation, and customized mating to recharging infrastructure. Chapter 1 provides the background and overview of this study, undertaken to assist FTA in refining EDSP efforts to address the knowledge gaps and priority Research and Technology (R&T) needs related to advanced batteries.

A comprehensive review of relevant technical and trade literature was conducted on existing and emerging hybrid and electric buses, power-train architecture options, and on-board Rechargeable Energy Storage Systems (RESS). The goal was to assess the state-of-knowledge on advanced batteries, and to identify further on- board energy storage needs for hybrid and electric buses. The state-of-practice and lessons learned from early adopters of hybrid, electric and fuel cell buses were also reviewed, to reveal performance gaps and commercial deployment challenges. The findings from this literature review are summarized in Chapters 2 and 3: Chapter 2 describes the multiple existing architectures of hybrid and electric drive buses, and their respective RESS technology options, suggesting that standardization and optimization of bus and RESS platform is needed for successful commercialization. Chapter 3 discusses the comparative performance, cost and reliability of emerging lithium-ion battery chemistries, versus traditional heavy duty bus batteries, and discusses the remaining safety challenges requiring thermal monitoring systems (TMS) and Battery Management Systems (BMS) hardware and software. The need for updated standards and protocols for battery testing to ensure electric/hybrid vehicle safety and optimal performance, and the ongoing national and international standards development efforts are also reviewed.

Based on the literature assessment of deployed, ongoing national and international RD&T, and advanced lithium-ion and other RESS under evaluation for heavy duty vehicle applications, Chapter 4 identifies major lessons learned and identifies RESS research needs. These findings served as the basis for structured interviews (Appendix 1) with a representative, yet diverse set of Subject Matter Experts (SMEs) and stakeholders (Appendix 2). As summarized in Chapter 5, the SMEs provided well-informed inputs regarding the lessons learned over more than a decade of experience with the design, development, test and evaluation of HEB/FCB, current RESS technology options and respective Technology Readiness Level (TRL). Chapter 6 summarizes the recommended Next Steps to address current RESS knowledge gaps and to remove obstacles to advanced battery technology integration and commercial deployment in electric drive buses. The key R&D needs to advance RESS technologies, and to facilitate the rapid RESS integration in hybrid electric bus fleets include:

[1] "FTA Multi-year Research program Plan (2009-2013)" at http://www.fta.dot.gov/assistance/research_research.html

- Develop and apply RESS Modeling and Simulation (M&S) tools, complemented by Hardware- in- the- Loop (HIL) testing before prototype development;

- Perform comparative assessments of various lithium-ion battery chemistries to identify tradeoffs, and optimize RESS performance and safety;

- Address knowledge gaps on battery and ESS durability, and explore innovative options to deliver better battery performance at lower lifecycle cost; and

- Conduct independent Test and Evaluation (T&E) and in-service safety assessments of advanced RESS options for electric drive buses.

Chapter 7 presents two high- level strategic 2020 RD&T Roadmaps on RESS test, evaluation and integration with targets, benchmarks, and timelines, in order to address identified priority technology gaps and research needs. Major recommendations were prioritized, organized and synthesized into phased RESS RD&T Roadmaps for the near-term (3 years), mid-term (5 years) and strategic (10 years) efforts. Near- term RD&T needs focus on:

- The standards for testing bus batteries and RESS safety;

- RESS performance optimization and system integration;

- Development of a comprehensive RESS database for the FTA Technical Assistance program.

Mid-term efforts include the development of RESS Modeling and Simulation (M&S) tools for RESS performance, and their Verification and Validation (V&V) with hardware in the Loop (HIL). Longer-term RD&T targets system optimization of RESS within electric drive buses, complemented by in service demonstrations, as well as analysis of cost-effectiveness, energy and environmental benefits of advanced RESS for electric drive buses, and the removal of commercialization barriers. Tables with examples of near-, mid-, and long-term RD&T projects illustrate how these high level strategic Roadmaps will be translated into funded electric drive bus programs and projects. Such efforts will advance RESS for integration and commercial deployment in hybrid and electric drive buses.

The realization of energy, environmental and economic (E3) benefits to urban bus transit users is enabled by sustained FTA RD&T partnerships with other federal agencies, state and local transit authorities, and with industry and university consortia. Recommended RD&T efforts target advancements in energy storage options on-board hybrid and electric buses and span the spectrum from research conception, to demonstrations, evaluation and deployments.

1. Introduction

Over the past decade the FTA Office of Research, Demonstration and Innovation (TRI) has fostered the development, demonstration and commercialization of advanced electric drive bus technologies, in partnership with transit agencies, consortia, and the Department of Energy (DOE) Vehicle Technologies Program. In particular, the FTA National Fuel Cell Bus Program (NFCBP) focused on technology development and integration of electric drive power-trains, and on evaluations of electric and hybrid drive systems for bus prototypes performance and cost.

Recent American Public Transportation Association (APTA) statistics[2] indicate the largest transit fleet in the US consists of over 65,000 buses and a similar number of para-transit vehicles. Hybridization and electrification of urban and intercity buses utilizing advanced technologies and components for energy storage and recovery offers multiple benefits: improved energy efficiency, decreased tail-pipe pollution, and lower fuel and lifecycle maintenance costs. Hybridization of urban transit fleets promises to improve both fuel efficiency and environmental performance, as electrification technology and components mature, their reliability and longevity increases, and cost is reduced with economies of scale. For hybrid-electric bus applications, the battery size and weight is not as restricted as it is for personal vehicles, and the centralized maintenance and predictable routes offer additional cost advantages. Bus fleets represent an excellent niche market for early adoption and demonstration of advanced hybrid electric technologies.

Although rechargeable energy storage systems (RESS) on-board the bus, and associated power management electronics have greatly advanced in recent years, a remaining research need is to improve RESS (flywheels, batteries, ultra-capacitors, and optimized combinations thereof) capabilities and safety, as well as power monitoring and management. Rechargeable and modular RESS with improved performance (greater capacity and power delivery), reliability and durability must be further developed, demonstrated and commercialized at an affordable cost, in order to meet the public transit authorities (TA) needs for real city-bus routes. The recent FTA-funded Transit Cooperative Research Program (TCRP) Report 132[3] has evaluated the hybrid-electric bus (HEB) technologies deployed in transit fleets to date, and bus life-cycle cost models (LCCM) to provide guidance for TAs. This study confirmed that advanced batteries, integrated within the RESS with associated electronic power and thermal control, are a key enabling technology, but it still too costly and unreliable at present.

Improving batteries, ultracapacitors, and other energy storage systems is also a key RD&T priority of this Administration's, as reflected in more than $2.4 billion DOE technology funding under the American Recovery and Reinvestment Act (ARRA) awards for advanced batteries to speed up transportation electrification.[4]

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[2] APTA "*2008 Public Transportation Factbook*" (June 2008) and 2009 Appendices posted at http://www.apta.com/resources/statistics/Documents/FactBook/APTA_2008_Fact_Book.pdf

[3] TRB/TCRP Report 132 "*Assessment of Hybrid Electric Transit Bus Technology*", Dec 2009, see http://www.trb.org/Main/Blurbs/Assessment_of_HybridElectric_Transit_Bus_Technolog_162703.aspx

[4] See list of 2009 Recovery Act awards for transportation electrification at http://www1.eere.energy.gov/recovery/pdfs/battery_awardee_list.pdf

This report provides a snapshot in time of the rapidly evolving electric drive components and identifies promising opportunities for advancing on-board energy storage options for early deployment in commercial bus fleets. Project objectives were to:

- Identify, survey and obtain recommendations regarding electric drive buses energy storage system development, testing, operation, maintenance, or evaluation from qualified Subject Matter Experts (SMEs) and stakeholders;

- Summarize SMEs insights regarding priority RD&T needs for RESS, and technology forecasts; and

- Benchmark ongoing and proposed initiatives in terms of timeline, cost, and their energy efficiency and environmental benefits.

The FTA Office of Mobility Innovation (TRI-10) has supported major national research efforts for over two decades to develop, demonstrate and evaluate the next generation of fuel efficient, environmentally friendly light-weight buses. This project supports Goal 3 and objectives 3.4 and 3.5 of the FTA/TRI "*Multi-year Research Program Plan (FY2009- FY2013)*"[5] as shown in Figure 1:

Figure 1 - FTA Strategic Research Goal and Objectives for Electric Drive Buses

Goal 3: Support Improving the Performance of Transit Operations and Systems
3.4 Investigate the use of high-efficiency technologies and alternative energy sources (vehicles and facilities)
3.5 Perform research to reduce transit environmental impacts (e.g., emissions, waste streams, recycling)

Beyond the Electric Drive Strategic Plan (EDSP) projects listed in Table 5-8 of the Multi-Year Program Plan, this effort aims to help define, prioritize, and implement the Research, Development and Demonstration (RD&D) needs to improve the RESS capabilities on-board the bus. The RESS must be tailored to bus load and route profile and other operational performance requirements. By informing FTA on the state- of- art for commercial batteries and ultracapacitors, bus RESS architecture options, and related power electronics, electric motors and integrated power-train technologies, it is hoped to focus R&D resources on demonstration, test and evaluation (RDT&E) partnerships with high Return on Investment (ROI) leverage.

This report reviews findings from technical literature and other federal and international technology initiatives to advance emerging energy storage technology options for electric drive transit buses in Chapters 2-4. Recent hybrid and fuel cell bus prototypes featured advanced power trains, and RESS capable of expanded range, operating with improved fuel efficiency and environmental footprint (but not yet at affordable cost).

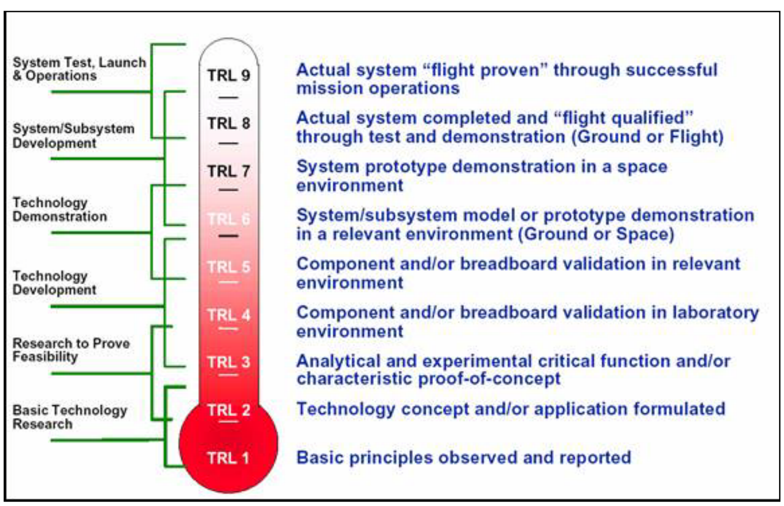
[5] Posted on the web at http://www.fta.dot.gov/documents/FTA_TRI_Final_MYPP_FY09-13.pdf

The literature reviewed highlights both the advantages and the possible downside for each RESS technology option in specific bus applications (Chapters 2 and 3).

The key RESS research issues (Appendix A-1) were identified from a comprehensive review of relevant technical literature. Initial research needs for interviews were extracted from the EDSP draft report and FTA projects. To complement the EDSP and identification of RESS needs from the literature review, informed advice and feedback from Subject Matter Experts (SMEs) was obtained to assist FTA in refining existing RD&T plans and programs, and to help prioritize and allocate program resources. The SMEs who responded (Appendix A-2) are recognized as research and technology leaders on RESS for hybrid -electric and fuel cell buses and/or relevant transit experience. These Subject Matter Experts (SMEs) represent diverse FCB/HEB/EB and RESS stakeholders segments: federal agencies, state and local transit agencies, industry, and university consortia. The goals of interviews was to collect first-hand inputs on lessons learned to date, and to identify and summarize the most promising RESS projects that address major knowledge gaps and advance bus technologies. Their recommendations regarding RD&T priorities and next steps are summarized in Chapters 5 and 6.

The Technology Readiness Level (TRL) of existing and emerging on-board energy storage options for integration in commercial electric drive buses must also be evaluated, in order to develop an appropriate R&D Roadmap for RESS, with targets, benchmarks, and timelines that address RESS technology gaps and priority research needs. The definitions of nine TRLs are provided in Figure 2, spanning the spectrum of maturity from basic research, through bench-scale and full scale prototyping, to commercial deployment – ready. Some experts warned that premature battery technology deployment (below levels 8-9) could backfire, and further delay RESS advances and integration and deployment in HEB/EB/FCB electric drive.

Figure 2 - The NASA Technology Readiness Levels (TRL) Meter



To lay a proper foundation for research planning and implementation for on-board bus energy storage technologies, an RD&T roadmap (Chapter 7) was developed based on literature findings (Chapters 2-4) and on experts inputs (Chapter 5). Such a roadmap for RESS and its building block technologies is needed to test, evaluate, optimize, and speed up the RESS integration and deployment in commercial hybrid electric buses This Roadmap aims to refine and improve not only the on-board bus rechargeable energy storage subsystem, but also its successful systems integration into energy efficient and environmentally sustainable hybrid-electric and electric drive buses. The findings are synthesized in the RESS RD&T roadmaps presented in Chapter 7, which identify promising near, mid- and long-term research goals. These roadmaps promise to systematically address knowledge gaps for on-board bus integration, optimization, and standardization, in order to accelerate RESS technology commercialization and deployment of electric drive buses in urban fleets. However, the high-level roadmaps will need to be translated into specific R&D projects, designed to enhance the capacity and reliability of on-board energy storage technologies of hybrid electric buses. Illustrative Tables with near-term, mid-term and long-term research projects are also presented in Chapter 7.

2. Rechargeable Energy Storage Systems (RESS) for Hybrid Electric and Fuel Cell Buses

2.1. RESS Components and System Integration

The 2008 National Research Council (NRC) review of the 21st Century Truck Partnership (21CTP)[6] examined the electric drive and energy storage subsystem requirements for heavy-duty hybrid vehicles with parallel or series configurations, capable of recovering and storing braking kinetic energy. A 2008 Congressional hearing on hybrid technologies for medium to heavy-duty commercial trucks examined the state of art, knowledge gaps, and commercialization challenges to hybrid electric propulsion in heavy duty vehicles, including Class 7 buses addressed by the "*21st Century Truck Partnership*" and DOE's Advanced Battery Consortium (USABC).[7] The hearing confirmed that substantial focused research efforts, combined with demonstration, test and evaluation (RDT&E) are needed to improve both batteries and hybrid power-trains for specific heavy-duty hybrid and electric vehicle applications and operational profiles, to enable their commercialization.

The national and international technology development and demonstration efforts described below, will also benefit transit and commercial bus applications, which represent a market niche less sensitive to cost and volume for the early adoption of environmentally friendly power and propulsion products.

Recent and rapid progress in the technology, chemistry, durability and performance capabilities of the on-board vehicle RESS components described below. The building blocks of a hybrid electric drive system includes not only rechargeable batteries (RESS) storing energy for traction, but also the power electronics (power switches, electronic control units- ECU, rectifiers, converters, inverters); a Battery Management System- BMS, and Thermal Management System- TMS), as well as electric machinery (electric motors). The battery pack typically consists of several modules (called "bricks"); the bricks may consist of multiple interconnected "cells", and are in turn connected electrically by inlet and outlet bus bars in series "strings" to achieve the desired s energy storage capacity, deliver needed output Voltage and traction currents and to reabsorb regenerated power. Vehicle designers and manufacturers aim to combine these electric drive subsystems and components into plug-and-play configurations. The real challenge is to integrate the subsystems as building blocks of electric and hybrid power trains, so as to optimize vehicle system operations.

The rechargeable battery is the key energy storage element in a hybrid electric power-train, to absorb and store the mechanical (braking) energy converted to electrical energy, and in turn deliver it on demand to the motor for propulsion. The state of charge (SOC) of the battery and other operational status indicators (voltage, current, temperature) must be monitored by sensors, communicated and controlled in real time to ensure its efficiency

[6] "*Review of 21st Century Truck Partnership*", NRC 2008 posted at www.nap.edu/catalog/12258.html
[7] House Committee on S&T hearing, June 10, 2008," *Hybrid technologies for medium to heavy duty commercial trucks*" at http://science.house.gov/publications/hearings_markups_details.aspx?NewsID=2216

and safety, and to detect and diagnose failures. The RESS subsystem is mated to the power conversion and conditioning elements (inverters, rectifiers, converters), and controlled by a Power Management System (PMS) or Battery Management System (BMS). If susceptible to overheating, the battery pack may also require also a Thermal Management System (TMS) for cooling it to maintain it within a safe operability window (see more details in Chapter 3).

Batteries with limited storage capacity could be complemented with an Auxiliary Power Unit (APU) for range extension, such as a Fuel Cell, or an internal combustion engine. If the battery performance is degraded when rapidly charged or discharged, an ultracapacitor ("ucap") may be used to complement it.

Most of the advanced hybrid electric and fuel cell buses discussed in this Chapter are currently in demonstration, test and evaluation stages, or in pilot fleet deployment phases, promising standardization and commercialization in the near future. In view of the diverse bus architectures described below, it is evident that there is no standard, widely applicable RESS solution as yet: both RESS and electric drive architecture must be customized to specific bus routes and climates, and to meet stringent cost, maintainability, safety, durability and environmental constraints.

The most recent annual comprehensive merit review on key enabling technologies for hybrid-and electric vehicles conducted by the Department of Energy (DOE) Vehicle Technologies Program (VTP) assessed progress in advanced battery development, and further research needed for commercial HEV/PHEV/EVs[8], including:

- Exploratory and Applied battery research;
- Battery development, testing, simulation and analysis;
- Advanced power electronics; and
- Battery technology vehicle integration and deployment.

The DOE National Labs support RD&T effort: the National Renewable Energy Lab (NREL) supports the Advanced Vehicles and Fuels Research program with projects on Advanced Power Electronics[9] and on Energy Storage, focusing on modeling and evaluating the safety and thermal management of batteries and ultracapacitors for hybrid electric vehicles[10]. Ongoing research by DOE/NREL on advanced Power Electronics and Electric Machinery (PEEM) systems for heavy duty applications (21st Century Truck Program- 21 CTP applicable to buses) has specific performance targets to overcome the technical barriers to commercialization.[11] NREL has conducted multiple evaluations of

[8] "*2008 DOE Vehicle Technologies Program Annual Merit Review 2008*" posted at http://www.1.eere.energy.gov/vehicles and fuels/resources/printable_versions/vt_merit_review-08.htm.
[9] See www.nrel.gov/vehiclesandfuels/powerelectronics/about.html
[10] See postings on energy storage and battery thermal management at http://www.nrel.gov/vehiclesandfuels/energystorage/
[11] See Advanced Power Electronics research description at http://www.nrel.gov/vehiclesandfuels/powerelectronics/about.html

demonstrations or in-service hybrid-electric and fuel cell buses[12] in support of FTA's NFCBP and hybrid bus programs, and also hosts a comprehensive Alternative Fuels and Advanced Vehicles Data Center that provides details on the manufacturers of heavy duty vehicles, including hybrid-electric and fuel cell buses.[13]

The Argonne National (ANL) and Lawrence Berkeley Lab (LBL) focus on battery chemistry advances (e.g., nano-materials and technologies for electrodes), while Sandia National Lab (SNL) conducts advanced research on RESS[14] technologies, which must be controlled with advanced power electronics (PE) and integrated with electric machinery:

- Advanced batteries that are still evolving (Lithium-Ion, Metal-Air like Zinc-Air, Sodium Sulfur; Zinc bromine, etc.);
- Battery failure modes and abuse testing protocols in support of SAE standards;
- Flywheels;
- Power electronics, typically consisting of switching devices (fast semiconductor switches, IGBT and GTO thyristors), rectifiers (AC-to-DC), inverters (DC-to-AC), boosters (DC-to-DC), and cyclo-converters (AC-to-AC);
- Electronics Control Units (ECU) which include microprocessors hardware and application specific software;
- Thermal Management Systems (TMS);
- Battery Management Systems (BMS);
- Magnetics and machinery: transformers, motors; and
- Power Conversion Systems (PCS): motor drives, load monitoring and leveling devices, programmable controllers, etc.

SNL also awarded and monitors the major ARPA-E energy storage research projects that will benefit advanced transit applications, such as the MIT/FastCAP Systems corporation award to develop "batacitors", namely enhanced ultracapacitors based on carbon nanotubes, whose energy density will be similar to batteries, but with larger power density and longer cycle life.

To advance these key RESS technologies for electric drive applications, the Department of Energy (DOE) recently awarded $2.4 billion of American Reinvestment and Recovery Act (ARRA) funds for advanced batteries, electric drive components, and electric drive

[12] E.g.: "*Hydrogen and Fuel Cell Transit Bus Evaluations*", NREL/LTP-560-42781-1, May 2008 at www.nrel.gov/hydrogen/proj_fc_bus_eval.html
[13] See www.afdc.energy.gov/afdc/vehicles/heavy/vehicles?print=1
[14] See postings at www.sandia.gov/ess/Technology/technology.html and www.sandia.gov/ess/tech_home.html

vehicle (EDV) demonstrations,[15] complementing related awards for transportation electrification. Resulting technology advances are expected to improve transportation fuel-efficiency and greenhouse gas reduction as well as speeding up the development, demonstration and commercial deployment of plug-in hybrids (PHEVs), electric vehicle (EVs) and fuel cell vehicles (FCVs). Advanced electric drive buses also stand to greatly benefit from a strong and diverse domestic industrial base for high power and energy batteries and fuel cells resulting from these awards to US battery OEMs:

- A123 Systems - for Nano-phosphate lithium-ion batteries (also called lithium iron phosphate, LFP);

- EnerDel - for lithium-ion cells and battery packs with manganese spinel/lithium titanate (LMTO) electrodes for high power applications, and manganese spinel (LMO)/amorphous carbon for high energy applications;

- Saft America, which partnered with Johnson Controls- for several types of lithium-ion cells, modules and battery packs including nickel-cobalt-metal and iron phosphate chemistries;

- Compact Power and LG Chem.- for making the lithium-ion polymer (LIP) battery cells using manganese-based cathodes for the GM Volt vehicle; and

- EastPenn Manufacturing Company- to produce the *UltraBattery*, a combination of advanced lead-acid batteries with carbon supercapacitors (or ultracapacitors).

2.2. Hybrid Electric Bus Architectures

A hybrid electric bus (HEB) usually combines an internal combustion engine (ICE) with the battery and an electric motor. The ICE can be fueled by gasoline, diesel, or other (natural gas, biofuel) and work either in series or in parallel with the electric motor. Regenerative braking capability in HEBs minimizes energy losses by recovering some of the kinetic energy used to slow down or stop a vehicle. The on-board bus RESS must be tailored to the specific electric drive architecture and bus duty cycle, with trade-offs in battery attributes tied to system optimization.

The 2009 TCRP Report 132 summarized the findings of a comprehensive assessment of hybrid-electric transit bus technologies, including scenario-based life-cycle cost-effectiveness.[16] Technologies were evaluated for series, parallel and more complex hybrid electric bus drive configurations (Figures 3, 4).

In a series hybrid configuration (Figure 3), the ICE drives a generator to feed the electric motor and recharge the battery. Braking energy can be captured and stored in the battery ("regenerative braking"). The powerful battery can enable electric-only operation for

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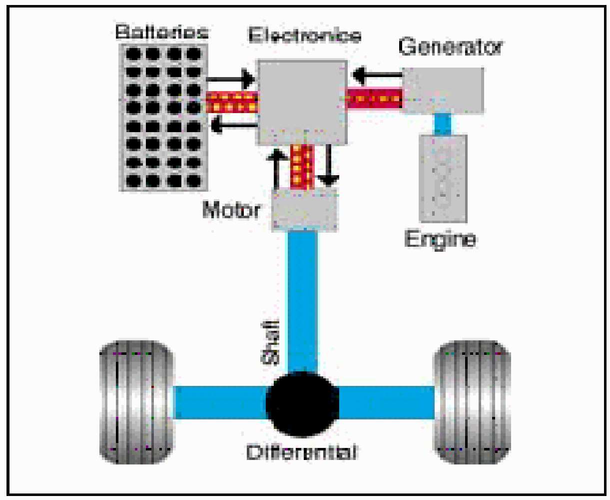
[15] DOE "*Recovery Act Awards for Electric Drive Vehicle Battery and Component Manufacturing Initiative*" – http://www1.eere.energy.gov/recovery/pdfs/battery_awardee_list.pdf

[16] Transit Cooperative Research Program (TCRP) Report 132: *"Assessment of Hybrid-Electric Transit Bus Technology," (*2009).

longer stretches and lowers the power demand on the ICE. The engine can be downsized compared to a conventional drive-train with the same performance, meaning lower ICE weight and higher energy efficiency.

Figure 3: Schematic of Series Hybrid Bus Architecture



Source: Electric Transit Vehicle Institute

The electric motor powers the drive system, using either energy stored in batteries, or from the engine, or from both as needed. There is no mechanical coupling between the engine and the wheels. The engine is more efficient at lower speeds and higher load, so the series hybrid is preferred for slow and start-and-stop city driving. However, adding a large rechargeable battery and electric motor adds weight and thereby reduces the energy efficiency. Disadvantages noted in TCRP Report 132 (Table 1.1. ibid.) include a heavier and larger engine and battery, and electrical energy losses in the battery, and motor/generator.

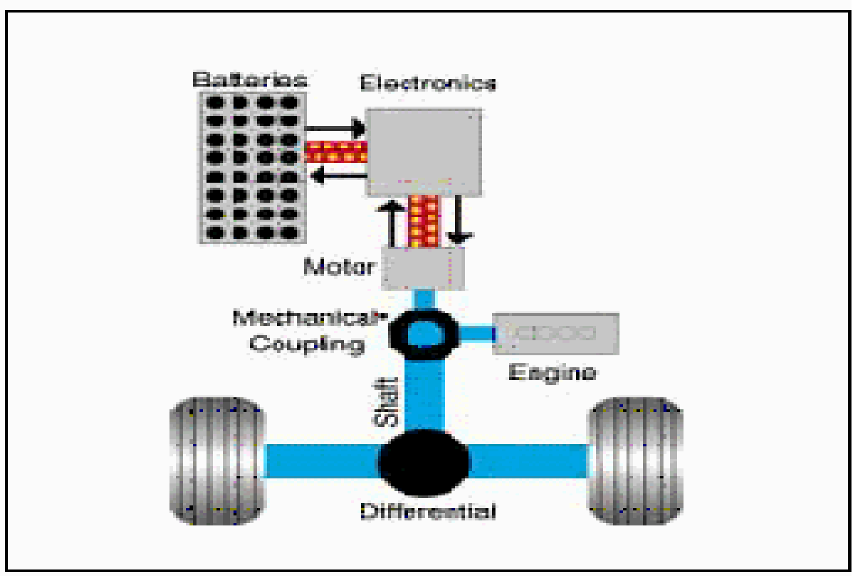
Examples of series hybrid-electric bus (HEB) configurations, further discussed below, are the Orion VII diesel electric hybrid buses using the BAE Systems *HybriDrive*; and the ISE *ThunderPower* drive in buses using the *ThunderVolt* RESS. New York City Transit (NYCT) has operated more than 500 40 ft Orion VII with BAE HybriDrive and Cummins (ISB series) engine. This engine is connected to a generator that produces or recaptures electricity from braking and recharges the lead-acid batteries. The major integrators of series hybrid bus drive, with respective RESS options, are discussed in Sec 2.2.

When the two HEB power sources (ICE and RESS plus electric motor) are arranged in parallel, either one or both can be used, depending on the traction power needed (Figure 4).The parallel hybrid bus architecture couples both power sources (electric motor and IC engine) to the wheels, either pre-or post- transmission performance is optimized by using the strengths of the engine to offset weakness of the motor, and vice versa. The batteries are connected only to the electric motor via power electronics (inverter and controller). Parallel hybrid systems can be a “drop-in” or retrofit, and offer better energy efficiency at steady over-the-road cruising speeds, but require more complex control systems and designs. Another trade-off is that a smaller and lighter engine and electric motor can be used, but less of the captured braking energy is returned to the battery, and higher emissions may result compared to the series hybrid.

In a pre-transmission design, the electric motor is located between the engine and the transmission; during braking, the electric motor works as a generator to recharge the batteries. In a post-transmission parallel hybrid configuration, the electric motor is located between the transmission and the rear axle, and can be an easy retrofit to conventional ICE buses. TCRP Report 132 (in Table 1.3) summarizes the advantages of parallel hybrid buses as better flexibility in engine operation, and higher fuel efficiency and reduced emissions, traded against the disadvantage of more complex design and control.

Both series and parallel hybrids allow for the removal and replacement of the starter and alternator components of a diesel ICE, with an integrated unit. This configuration is easier to control and more efficient at the high loads and low speeds typical of a city bus start-and-stop driving.

Figure 4: Parallel Hybrid Bus Architecture



Source: Electric Transit Vehicle Institute

Parallel hybrid buses include over 250 60-foot New Flyer articulated buses operated in Seattle by King County Transit-KCT, powered by GM Allison's EP50 parallel hybrid-propulsion system. This GM Allison complex drive-train is called a “two-mode split parallel architecture”, with both a mechanical and an electrical traction path to enable efficient operation in city stop-and-go, as well as in over-the-road long distance operations. The two electric motors of the EP50 are integrated into the automatic transmission. Each motor, which also operates as a generator, provides 75 kilowatts of continuous power and up to 150 kilowatts of peak power. This parallel hybrid system blends outputs from the 330-horsepower Caterpillar C9 diesel engine and the electric motors to provide propulsion power. The RESS relies on nickel-metal-hydride (NiMH) batteries, which are recharged by the diesel engine and by regenerative braking energy. The types of parallel hybrid buses, their variants and RESS components are discussed below in Sec 2.2.

2.3. RESS Characteristics for Hybrid Electric Buses

The RESS components are essential building blocks for viable hybrid- electric or purely electric buses, which must be configured with different sizes, weights and capacity and power capabilities depending on the specific bus power-train architecture and its service load and range requirements. Judicious selection of RESS and other hybrid drive components is essential for optimizing HEB operational efficiency.

Modular and diverse RESS components (advanced batteries, ultracapacitors, fuel cells) must be optimally mated to the traction system, including power electronics, electric motors/generators and power conditioning (inverters, converters, DC bus) must be tested and evaluated as an integrated system to improve HEB fuel efficiency and environmental performance. RESS attributes (charge capacity, power, discharge rate, size and shape) depend on the bus traction power requirements and operational profile. The size, weight, capacity and capacity rating (the "C-rate") of the chosen battery should match the power-train architecture. There are many RESS technology and battery chemistry and packaging options for hybrid and electric drive buses, as recently summarized in a CALSTART report for FTA[17]. These emerging high power RESS options, that integrate advanced batteries, ultracapacitors with power electronics in real fuel cell, electric and hybrid buses, have yet to be tested, evaluated and validated for in-service conditions. For instance:

- A hybrid-electric bus (HEB) with an internal combustion engine (ICE) that recharges the traction battery (and operates in charge sustaining CS mode) could employ a lighter and smaller battery than a battery electric bus (BEB), where the deep discharge and charge depleting (CD) operation limits the range between recharges.

- A Plug-in Hybrid Electric Bus (PHEB) might require smaller, intermediate-sized battery packs, capable of either charge-sustaining (CS) operation in the blended mode with an active ICE, or of charge-depleting (CD) operation. Batteries for PHEBs must also allow for rapid and efficient recovery of braking energy, and for fast charging/discharge cycling without excessive heating that could pose safety hazards.

- A battery electric bus (BEB) would require a larger and heavier battery pack, to provide both high energy density (specific energy) and high energy storage capacity so as to maximize the range between recharges. The BEB battery must

[17] "*Energy Storage Compendium- Batteries for Electric and Hybrid Heavy Duty Vehicles*", March 2010, posted at www.calstart.org

also accept rapid charging from regenerative braking, and provide pulses of power for acceleration, and maintain performance (current, voltage, power) when repeatedly cycled in charge-depleting (CD) operation .A large battery might also present more safety problems due to higher voltage and more caustic or toxic chemicals. Though power for acceleration could be supplied by an ultracapacitor capable of rapidly storing braking energy and supplying it on demand, this would add further weight and bulk to the RESS.

With FTA support, several Transit Authorities (TAs) have served as demonstrators, evaluators and early adopters of advanced hybrid electric and fuel cell buses promising environmental and energy-efficiency gains. Representative examples of innovative hybrid-electric drive buses evaluated in-service by TAs are mentioned below, to highlight the wide range of power-train architecture options and energy storage technologies.

A series of NREL Technology Validation reports[18] have summarized the in-service performance of several generations of fuel cell and hybrid electric bus technology demonstration programs and deriving lessons learned. Demonstration fleets in a variety of climates and routes included hybrid-electric power-train architectures capable of regenerative braking and integrating the energy storage system (primary advanced traction batteries, and secondary batteries or ultra-capacitors for high loads) with power electronics (switches and inverters), Battery Management Systems (BMS) and Thermal Management Systems (TMS) for safe operability, as well as Auxiliary Power Units (APU) that can charge the battery.

Several NREL reports[19] have benchmarked the performance of the 1st and 2nd generations of Fuel Cell Bus (FCB), to derive lessons learned and to identify research needs. Recent improvements in key technologies were evaluated over time, including RESS, capital, operational and maintenance (O&M) costs of advanced buses, as well as availability, reliability, fuel economy and environmental benefits. . A recent NREL report[20] summarized FCB demonstrations to date and showcased key technologies, highlighting progress and remaining challenges.

Although California has led the nation in demonstrating advanced fuel cell, hybrid and electric buses to improve the fleet fuel-efficiency and environmental footprint, demonstrations were conducted nationwide to assess the operational capabilities, efficiency and cost of these prototypes over a broad range of climates and routes.
The California Air Resources Board (CARB) Zero Emission Bus (ZBus) regulations (adopted in 2000 and finalized in 2006)[21] include battery-electric bus (BEB), fuel cell bus (FCB), electric trolley, and clean alternative fuel mandates. By 2011, the TAs are required to purchase ZBuses for 15% of fleets, or more than 200 units. Five Bay Area

[18] Fuel cell, hydrogen ICE and hybrid electric bus evaluation reports are posted at http://www.nrel.gov/hydrogen/proj_tech_validation.html

[19] *Leslie Eudy, NREL: "Fuel Cell Buses in US Transit Fleets: Summary of Experiences and Current Status"* at http://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/ 41967.pdf *and "Fuel Cell Bus Evaluation Results"*, TRB presentation, Jan.13-17, 2008, at http://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/ 42665.pdf

[20] NREL "*CTTransit Fuel Cell Transit Bus: 2nd Evaluation Report"* May 2009, Appendix A.

[21] See information on CARB Zero Emission Buses at www.arb.ca.gov/msprog/bus/zeb/zeb.htm

TAs are actively engaged in 12 bus technology demonstration and performance evaluations; however the demonstrations are currently behind schedule. ZBus regulations are premature and could not be implemented on the projected timetable because of overly optimistic technology forecasts. Desired in-service ZBus reliability, durability, availability and cost targets could not be reached because technologies are still evolving, and currently there are no final technology and safety standards in place to guide commercial acquisitions for deployment.

Although RESS components, subsystem manufacturers and integrators have teamed up with bus designers and transit agencies to prove the merits of various alternative HEB/EB/FCB concepts, they are currently competing for early market share while offering uncertain benefits at unaffordable costs. As shown in TCRP Report 132,[22] advanced HEB technologies have not yet undergone sufficient in-service shakedown to prove their lifecycle cost-effectiveness, reliability, safety, durability, maintainability and environmental benefits. A promising approach to the early market adoption of an integrated HEB is to form strategic alliances between the bus designer, battery and motor suppliers, RESS system integrators and bus manufacturers in order to provide complete, market-ready bus solutions.

2.3.1. RESS for Series Hybrid Electric Buses

2.3.1.1. ISE Corporation's ThunderVolt Drive

The ISE Corporation (San Diego and Poway, CA)[23] is a leading supplier and system integrator of advanced ThunderVolt series hybrid-electric drives, tailored to the specific bus architectures. ISE components for electric and hybrid drive are manufactured by Siemens (ELFA). The RESS has been optimized for bus application and routes, packaged in a cassette (usually placed on the roof of the bus) and liquid cooled; it consists of batteries and/or ultracapacitors to bank and deliver on demand energy from the Auxiliary Power Unit (APU) or from regenerative braking. ThunderVolt packs have been integrated in over 300 in- service buses, and operated for over 10 million miles cumulative.[24]

The bus RESS integrates batteries (including lithium-ion batteries for the battery-dominant hybrids) with a Thermal Management System-TMS (located on the roof of the bus), and with compact, scalable, high-energy Maxwell BoostCap ultracapacitor modules (Ultra-E 500) in the ThunderPack II. This combination enables up to a million charge/discharge cycles for rapid capture of energy (regenerative braking) at high power levels.

ISE also developed a compact ultracapacitor (360 Volts), comprised of 144 Maxwell 2600 Farad cells connected in series). Two ultracapacitors can be used in series hybrid bus drive units to provide 720V and 300 KW of power pulses for acceleration and hill climbing, although each unit can only store 0.65 KWh.

[22] TCRP Report 132, Assessment of Hybrid Electric Transit Bus Technology, 2009
[23] See postings at www.isecorp.com/hybrid-technology/overview
[24] See presentation by Paul B. Scott, ISE Corp. at CEC Hydrogen Workshop, Sept 29, 2009 posted at www.energy.ca.gov/2009-ALT-1/documents/2009-09-29_workshop/presentations

ISE has developed and deployed a full suite of modular ThunderVolt electric drive products for series hybrid-electric buses[25] manufactured by several OEMs (New Flyer, NABI and Gillig). ThunderDrives are flexibly configured (see below), so they are usable in fuel cell, diesel and gasoline hybrid electric, as well as in all electric buses, including:

- Diesel-hybrid buses, like the 50 new (60) ft articulated buses operating in Las Vegas.

- Gasoline hybrids, now installed in over 250 buses operated by more than 10 transit operators in the US, which accumulated more than 12 million in-service miles. New Flyer gasoline-hybrid (35 and 40 ft low-floor) buses using the ThunderVolt drive was purchased by the San Diego Metropolitan Transit System (MTS) in 2008. Their RESS integrates batteries (option includes lithium-ion batteries for battery-dominant hybrids) with electric thermal management systems (TMS) located on the bus roof, with compact, scalable, high-energy ultracapacitor modules (Ultra-E 500). This combination enables up to a million charge/discharge cycles for rapid capture of energy (regenerative braking) at high power levels.

- Hybrid Hydrogen Internal Combustion Engine (HHICE): The ISE/New Flyer HHICE bus, introduced in 2004 by SunLine, combined the ISE ThunderVolt integrated electric propulsion system with a hydrogen fueled ICE.

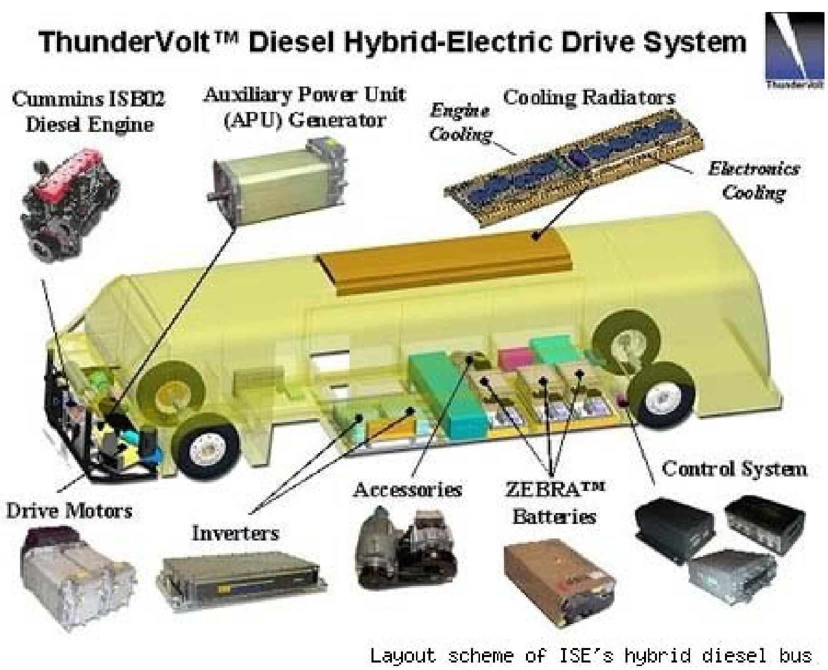
- Fuel Cell Hybrids: In 2004-06, AC Transit and SunLine demonstrated 40 ft Van Hool buses using UTC fuel cell stacks and compressed hydrogen fuel, integrated with an ISE hybrid electric drive system. The ongoing American Fuel Cell Bus (AFCB) project will demonstrate an improved ISE electric traction and power electronics system, featuring UTC fuel cells (120 KW) and a lithium-ion battery, in a lighter and quieter New Flyer 40 ft bus. This architecture will be deployed in 20 fuel cell hybrid buses for the Vancouver 2010 Winter Olympics, and for the London 2012 Summer Olympics.

The ISE RESS design has been increasingly modularized and standardized for broader industry adoption, and it includes the required programmable power control hardware and software and interfaces. ISE offers flexible RESS options to meet specific bus power cycling and loading requirements, integrating various batteries, e.g.:

[25] See hybrid-electric drive subsystems posted at www.isecorp.com/applications/transit-bus

Figure 5 – ISE Hybrid Drive Integrated in a Fuel Cell Hybrid Bus

Figure 6 – Exploded View of the ISE ThunderVolt Components



1. A 3- module ZEBRA (Sodium Nickel Chloride) batteries, each with 53 KWH of usable energy, and 95 KW charge/discharge power.

2. A Cobasys Nickel Metal Hydride (NiMH) battery (25 KWH, with 340KW power rating for 10 secs.).

3. Since 2002, ISE has entered a strategic development and supply agreement with Maxwell Technologies, a San Diego manufacturer of the PowerCache

ultracapacitors.[26] The ThunderPack energy storage system uses 150 large cell ultracapacitors to rapidly store and release 150 KW, or as a dual unit up to 300 KW of power, for hundreds of thousands of cycles.

4. Since 2007, integrated a lithium-ion battery (e.g., LFP from A123 or LTO from Altairnano).

2.3.1.2. The BAE Systems HybriDrive

BAE Systems[27] (Johnson City, NY) is a major integrator and supplier of integrated hybrid-electric propulsion for Orion hybrid-electric buses manufactured by Daimler Buses North America[28]. The BAE's HybriDrive series hybrid propulsion systems are configured optimally for start-and-stop urban driving duty cycles. For over a decade, HybriDrive was proven and improved in several generations of Daimler Orion series (diesel) hybrid-electric buses.[29] BAE has delivered 2,300 HybriDrive systems. Both NYCTA in NY City and Chicago Transit Authority (CTA) operate large Orion VI and VII hybrid-electric bus fleets. More than 3,000 Orion buses are operating in US cities (NYC, San Francisco, Boston, Chicago, Houston, Washington, Seattle and) and abroad.

The latest Orion VII (Figure 7) generation of diesel-electric hybrid buses have accumulated over 100 million miles in service, and proved to be more energy efficient, and environmentally friendly. The bus integrates a single electric motor powered by a diesel generator with the HybriDrive propulsion system[30]. Figure 8 shows an exploded view of HybriDrive components. The next generation of improved HybriDrive will enable modular RESS configurations (see Figure 9), with electronically controlled cooling and APU (fuel cells, or other options) placed on the roof, for easy access and maintenance. The Orion VII has used new LFP lithium-ion batteries (from A123 Systems) since 2007, to replace the heavier lead acid batteries. These batteries have greater energy density and power, and are 3000 lbs lighter, thus improving the bus fuel economy, as well as having a six- year design life with lower operating and lifecycle cost.

Currently, under the FTA/NFCBP funded Calstart Compound Fuel Cell Hybrid Bus for 2010 or BUS-2010, BAE is integrating HybriDrive with the air-cooled A123 Li- Ion Nanophosphate (LFP) battery, and with a fuel cell APU to extend the range of a 40 ft Orion low-floor bus. This fuel cell hybrid-electric bus will be demonstrated by the San Francisco Municipal Transportation Agency (SFMTA).

The HybriDrive is also compatible with other bus platforms and RESS options: the latest New Flyer (DE40LFQA) bus also uses the BAE HybriDrive with more advanced, lighter and longer lived nano-phosphate lithium-ion batteries with 200 KW peak power and cooled with forced air (from Lithium Technology Corp of Plymouth Meeting, PA).

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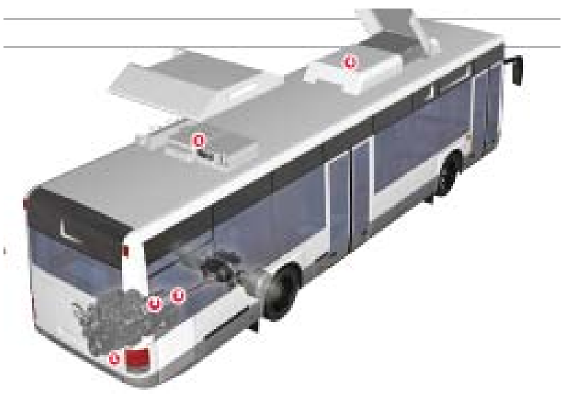
[26] See the ISE and Maxwell integrated Energy Storage systems at www.isecorp.com/energy-storage/
[27] See postings at www.baesystems.com
[28] See postings at www.orionbus.com/orion/
[29] BAE presentation "BAE Systems Hybrid propulsion Systems" by at the AB 118 Hydrogen Workshop of the California Energy Commission (CEC) on Sept. 29, 2009, posted at www.energy.ca/2009-ALT-1/documents/2009-09-29_workshop/presentations/
[30] See HybriDrive components and power specifications at www.hybridrive.com

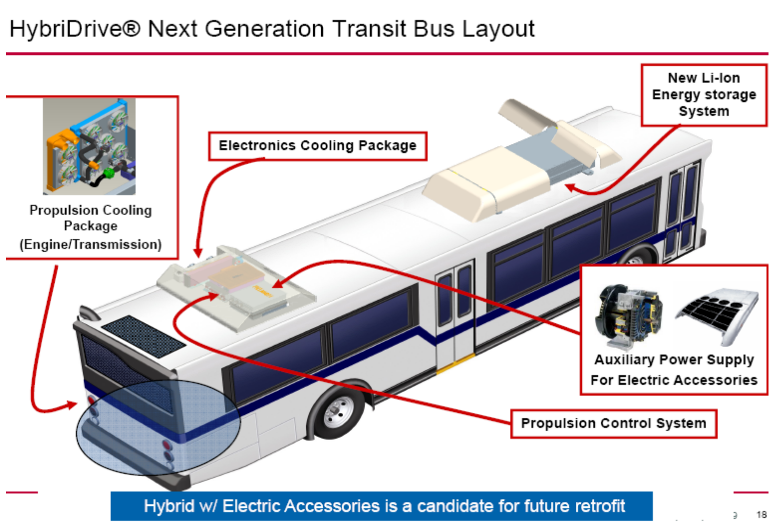
Figure 7- The Orion VII Daimler Bus with BAE HybriDrive

Figure 8- Exploded View of the BAE HybriDrive



The engine, motor and generator are in the back of the bus (1-3), while the HybriDrive RESS (4) with lithium-ion batteries and the propulsion control system (5) are roof-mounted.

Figure 9- Next Generation HybriDrive layout



2.3.1.3. Other Series Hybrid Electric Drive-trains

Ebus, Inc.[31] (of Downey, CA) has developed and integrated a diverse range of electric battery, hybrid and fuel cell buses with regenerative braking, based on a series hybrid architecture. The Ebus series hybrid uses a low-emissions Capstone micro-turbine as an APU to recharge the batteries. A 22 ft plug-in hybrid-electric fuel cell Ebus was demonstrated and was equipped with a 90 KW fast charger in case the fuel cells used to charge the battery are turned off or depleted (the Ebus uses a 19.3 KW Ballard PEM fuel cell stack an APU). This RESS uses a battery pack of 48 Saft Nickel Cadmium batteries (288 V, 200 Amp-h), which can be fast-charged, last for up to 2000 charge/discharge cycles (or a nominal 7 years of service) and has a demonstrated a range of 45 mi between recharges. The advanced power management and control electronics shares the load between battery and fuel cell power outputs to extend FC life beyond a nominal 5000 hours of operation. It was demonstrated by the Indianapolis Transportation Corporation (IndyGo) and Knoxville Area Transit (KAT) in warm temperate and cold weather operation. The Ebus and mated hydrogen infrastructure are also in testing by the Texas Hydrogen Coalition in partnership with: University of Texas at Austin, Gas Technology Institute, Houston Advanced Research Center (HARC) and CTE.

2.3.2. RESS for Parallel Hybrid Buses

2.3.2.1. The GM Allison EP Two-mode Electric Drives

Although designed as a parallel architecture, a power-split or two-mode hybrid electric bus can operate in either a series, or a parallel configuration, so that the power distribution along one or two paths is optimized as required by the operating conditions. A planetary transmission is used as a switch to distribute electrical and mechanical power. The GM Allison Transmission Electric Drive[32] unit is currently owned by Stewart and Stevenson, S&S. [33] S&S designs, manufactures and installs the EP hybrid parallel dual mode compound propulsion systems on different bus platforms:

- The EP40 is a two-mode compound split hybrid bus drive offers 209 KW continuous, and 260 KW peak, acceleration power. The RESS uses advanced NiMH batteries with six- year design cycle life and offers full regenerative braking. The EP40 system controller links a dual-power inverter module (DPIM, 430-900 VDC and 3-phase AC) and concentric AC induction electric motors.

- The EP50 is also a two-mode compound-split parallel hybrid drive architecture used for 60 ft articulated buses. The RESS uses advanced Lead Acid or NiMH batteries.

The two mode GM Allison Hybrid HyValue EP40 drive uses NiMH batteries. It has been integrated in both 40 ft and 60 ft articulated New Flyer Industries hybrid buses. The EP40

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[31] See various Ebus postings at www.ebus.com
[32] See postings at http://www.allisontransmission.com/product/electricdrive/
[33] See Hybrid Buses postings at www.ssss.com/ and http://www.stewartandstevenson.com/Products%20and%20Services/Specialty%20Products/Hybrid%20Bus/default.htm

was also integrated into two 40 ft New Flyer demonstration diesel hybrid buses for SEPTA in Philadelphia, and in converted hybrid buses operating in Portland, OR, for Orange County Transit Authority (OCTA), and for the MTA in Harrison Co., TX. Since the EP40 variable hybrid drive can automatically choose a parallel or hybrid path to maximize efficiency, and minimize environmental impacts, it was also selected by the National Park Service (NPS) for the Yosemite hybrid bus fleet.

Both parallel and series EP40 and 50 drive hybrid buses are operating in 95 cities worldwide, and in the US: Albuquerque, Aspen, Austin, Chicago, Cleveland, Houston, Minneapolis, Philadelphia, Portland, Seattle Sound Transit, and Washington DC.

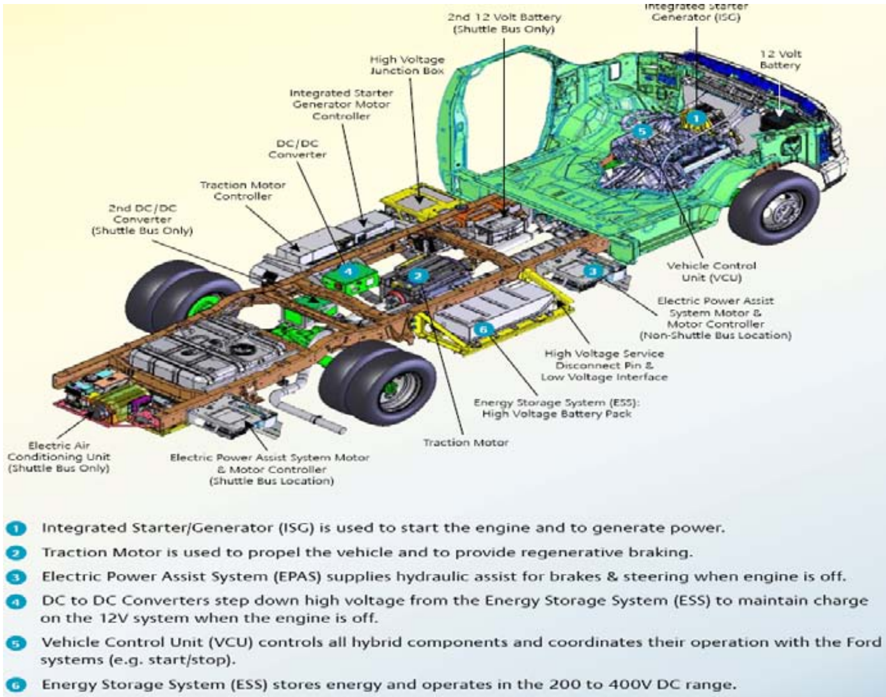
2.3.2.2. The Azure Dynamics (AZD) Balance ™ Drive-train

AZD (Detroit, MI; former Solectria of Boston, MA), developed the Balance ™ parallel hybrid electric drive train[34] for heavy duty commercial vehicles (Ford's E450 shuttle bus, CitiBus, school bus and van), as well as the series hybrid HD Senator CitiBus. The Balance RESS uses a Nickel Metal Hydride (NiMH) battery with nominal 288Volt DC, 60KW, 8.5 Ah. An electric induction motor (100KW AC) enables the regenerative braking energy to be recovered for storage and reuse. The Balance drive-train is integrated with a starter/generator, power electronics, electric motor and converters, electrically- driven HVAC auxiliary systems, and control software. (Figure 10) The Balance hybrid drive shuttle bus was tested and certified for 7 years, 200,000 mi operation at the Altoona Bus testing facility; it claims 40% fuel economy improvements, and 30% lower maintenance cost. The Michigan Department of Transportation (MDOT) has recently ordered 50 buses with AZD Balance hybrid power trains for its state fleet. Similar AZD contracts for hybrid electric shuttle buses are in process with Kentucky and Minnesota. The AZD hybrid drive is compatible with several bus body manufacturers, including Champion, StarTrans, Goshen Coach, Glaval Bus and TurtleTop.

Recently, AZD teamed up with Collins Bus Corporation to deploy NEXBUS, a hybrid electric school bus, which integrates the AZD Balance ™ hybrid electric drive-train with the Ford E-450 chassis. It will be operated by the NAPA Valley, CA school district.

[34] See products and specifications posted at www.azuredynamics.com

Figure 10- AZD Balance Hybrid- Electric Architecture



2.3.3. RESS for Other Complex Hybrid Electric Drive Systems

Several companies have developed and demonstrated more complex, versatile, and/or flexible hybrid-electric drive architectures, on order to optimize operation in both fit-and-start city operation (where series hybrids have an edge), and for highway driving at cruising speed and constant load (where parallel power trains have an efficiency advantage). These hybrid-electric drive-trains use different types of Auxiliary Power Units (APUs), including microturbines, fuel cells, and ultracapacitors, to enhance the RESS batteries and to extend the bus range.

The FTA NFCBP funded the Northeast Advanced Vehicle Consortium (NAVC) to develop, demonstrate and evaluate a broad range of fuel cells and hybrid electric drive bus architectures that promise better fuel efficiency and environmentally performance, and can be operated in all climates. Four of the six NAVC projects funded by the NFCBP[35] involve fuel cell bus development, integration demonstration and evaluation. For instance, CT Transit is operating hybrid FCBs in Hartford, CT to evaluate cold climate impacts on fuel cells and battery performance.

Specific examples of flexible hybrid electric, PHEV and fully electric drive-train and RESS options, some of which can be retrofit on existing buses, are described below.

2.3.3.1. The Enova Systems HybridPower with Fuel Cell APUs

[35] See details posted at www.navc.org/projects.php

Enova Systems[36] (of Torrance, CA) has developed a suite of proprietary HybridPower drive system, and related power conversion and management components for both series and parallel hybrid and electric bus applications.

Enova Systems also developed a battery- dominant, fuel-cell power train for hybrid-electric and plug-in hybrid buses. This drive system integrates an induction electric motor, a dual 8KW inverter, a 380V DC/DC converter, a battery care unit (BCU) with safety disconnect protection, and a digital power management system. The RESS can supply modular power (90, 120, or 240 KW) using an Energy Management System (EMS). The Enova 30 ft hybrid drive provides 120 KW of power (Figure 11) using a 20 KW Hydrogenics Fuel Cell stack. It was demonstrated 2003 at the Hickam AFB in Honolulu, HI. NREL has evaluated (2007) the performance of these battery-dominant fuel cell shuttle buses.[37] Fuel Cell (FC) hybrid electric buses currently operate in the Denali National Park, AK. Their RESS uses the Valence Technology XP-U-Charge Saphion® phosphate lithium-ion batteries for improved safety and thermal stability.

The HybridPower drive-train was recently integrated by IC Corporation[38] (a bus division of Navistar, Inc.) in both charge- sustaining (CS) and charge-depleting (CD) parallel hybrid buses. In 2009, DOE funded Enova and IC/Navistar to deploy 60 such PHEB school buses nation-wide. Enova's pre-transmission hybrid drive systems were recently delivered to First Auto Works, a large Chinese bus and vehicles manufacturer, for their Jiefang 12 meter buses (103 passenger, 85 km/hr top speed) due to deploy and operate in 13 China cities. This PHEB couples a diesel engine with an 80 KW AC induction electric motor mounted behind the transmission (post-transmission), and hybrid controller, with a battery care unit (BCU) to monitor the battery voltage, state of charge (SOC), amp-hours, kilowatt-hours and temperature. The BCU controls a Safety Disconnect Unit (SDU) to ensure the safety of the battery pack during charging, and provides surge protection and automatic disconnect in case a ground fault occurs.

Enova CD hybrid buses: There are several RESS battery options for the charge- depleting (CD) Plug-In Hybrid Electric (PHEB) school bus: Nickel Metal Hydride (NiMH), or lead acid (PbA), or a dual lithium-ion battery packs. The latter is integrated within the hybrid cooling package, and must be recharged overnight. These battery packs can be deep-discharged to about 25% SOC over the 40 mi range after overnight recharging.

Enova CS Hybrid Buses: The charge-sustaining (CS) RESS system for the latest Ze (zero emission) school-bus integrates the Enova post-transmission 80 KW hybrid drive-train with a lithium-ion battery pack and an electric motor. The battery SOC is maintained by on-board equipment and does not require grid recharge interfaces.

[36] See posted ESS and bus specifications at www.enovasystems.com
[37] "*Hickam AFB Fuel Cell vehicles early implementation experience*" NREL, Leslie Eudy, 2007 at https://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/42233.pdf
[38] See www.ic-corp.com postings

Figure 11 – Enova 120 kW HybridPower Drive System in a 30 ft bus

2.3.3.2. The Proterra Buses with TerraVolt RESS

Proterra, Inc[39] (headquartered in Golden, CO, San Diego, CA, with manufacturing in Greenville, SC) has designed a range of lightweight, composite body hybrid-electric, plug-in hybrid fast recharge, and zero-emission fuel cell assisted battery-electric transit, buses. The proprietary TerraVolt RESS integrates the NanoSafe lithium-ion Titanate (nLTO) battery pack, developed by Altair Nano (see Figures 13 a, b). The LTO Altair Nano battery was selected because of its long cycle life (16,000 cycles) under deep discharge, its low internal resistance to avoid overheating, and its fast charging capability. The TerraVolt has a warranty for 10 years of operation, or 6000 charge-discharge cycles. Proterra designed its own Battery Management System (BMS) and Thermal Management System (TMS) for safety, since the RESS requires active cooling, matched to the bus design and operational duty cycle.

Altairnano developed the NanoSafe nano-lithium titanate (nLTO) battery modules[40] for applications with a demanding charge-discharge duty cycle, long operational cycle life, and for better abuse tolerance and safety The battery pack consists of three 368 Volt parallel strings of 16 modules at 23 V, providing 54 KWh of useable energy (with a fourth string on reserve for increased power to 72 KWh and greater range). The batteries are stacked and mounted in the composite floor structure to lower the center of gravity and confer greater stability. The NanoSafe kit includes BMS software, and integrated heat sink, and the ability to measure and communicate technical and operational status.

This RESS and battery stack can be rapidly recharged (in less than 10 minutes), and is managed by the ProDrive vehicle control and energy management system (EMS). This RESS power plant requires active cooling. The TerraVolt RESS was designed to last for up to 10,000 charge/discharge cycles and to be rapidly recharged in minutes at route layovers, or plugged in overnight, or from any type of APU (e.g., an ICE powered by

[39] See postings at www.proterraonline.com/products.asp and at www.proterra.com
[40] See NanoSafe battery specifications for transportation applications posted at http://www.altairnano.com/

gasoline, or a fuel cell). The RESS supplies electric power to two UQM PowerPhase 150 KWatt electric propulsion motors. The electric motor from UQM Technologies, the PowerPhase 150 [41] is a brushless permanent magnet- PM motor/generator; it is able to recover up to 90% of the braking kinetic energy, and convert it to electrical energy. This configuration allows for flexible operation in either a battery-electric mode, or can use an Auxiliary Power Unit (APU) fuel cell for range extension.

The FTA's NFCBP has funded Proterra in 2007 to design and integrate its TerraVolt RESS in a 35 foot light-weight composite body for the Hydrogen Fuel Cell, 35 foot (HFC35) battery-dominant fuel cell hybrid electric bus. The FTA also funded demonstrations of the HFC35 light weight bus in Columbia, SC.

Figure 12 – The Proterra EcoRide BE35 Battery-Electric Bus

The Proterra hybrid electric buses have a series hybrid drive train. They are versatile and can operate in a charge-depleting (CD) battery- electric mode (BEB) for up to 20 miles; but if equipped with a fuel cell APU or an overhead canopy to recharge the battery (in deep discharge or charge- sustaining CS operation, the range can be extended up to 250 miles and/or 20 hours of operation. The Proterra Foothill Transit Ecoliner will operate as a plug-in hybrid bus (PHEB), with a rooftop FastCharging hook-up to an overhead canopy or pole catenary.[42] The NanoSafe batteries (Figures 13 a, b) can be recharged rapidly (in 5-10 minutes) at bus stops, and have a 30-40 mi range per charge.

The Proterra bus cost is high ($1.2 Million), or about 50% of the FCB cost, but twice the cost of a CNG bus. Although Foothill Transit managers deployed only three Proterra Ecoliner buses to date, a strong business case was made for acquiring more buses. Because of its expected 18-25 years life (longer than the typical 12-15 years bus life), this composite bus is more cost-effective than CNG or HEBs. Depleted batteries can be rapidly recharged from 10 to 90% SOC in less than 10 minutes from a pole catenary to its rooftop connector. The short layovers for these fast charge buses have no adverse impact, even for a 24 hrs continuous service profile. The cost of installed charging infrastructure

[41] UQM Technologies electric motors for hybrid and electric buses, see http://www.uqm.com/pdfs/PowerPhase150%20_edited_.pdf
[42] See 2009 "All American Zero Emission Electric Bus Debuts on Capitol Hill" at http://green.autoblog.com/2009/10/30/zero-emission-proterra-electric-bus-comes-to-capitol-hill/

(consisting of 2 chargers at both ends, and 1 in the middle of the line with 2 connectors for buses going and coming), is also considered affordable given the 30 mi all-electric range between the 10-15 min layovers for recharging.

A Proterra battery-dominant FCB has operated for the past 2 years in Burbank, CA logging about 100 miles per day with the original RESS, thus proving its reliability and durability. In this battery-dominant FCB, the battery can be recharged by an APU consisting of two small, 16 KW Hydrogenics PEM fuel cells (fueled by pressurized hydrogen in tanks on the bus roof).

Figure 13 a – TerraVolt Electric Drive Unit with AltairNano Lithium Titanate Battery Pack

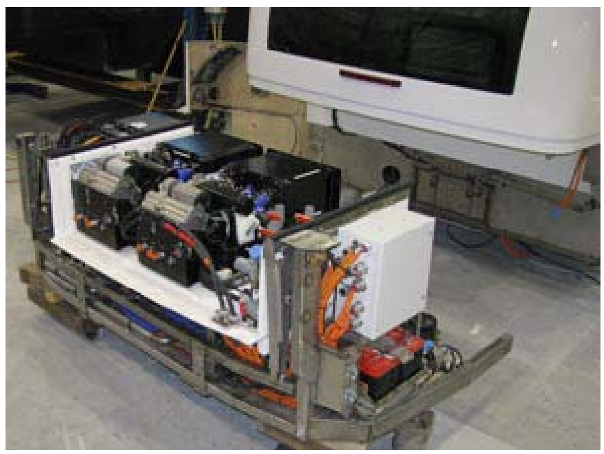
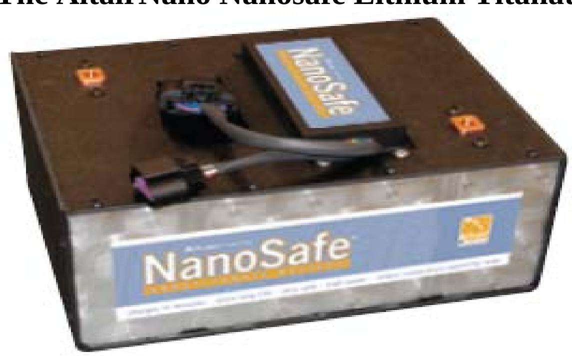


Figure 13 b: The AltairNano Nanosafe Lithium Titanate (nLTO) battery



Nanosafe™ Battery Module

2.3.3.3. The Capstone Microturbine RESS in the DesignLine ECOSaver IV Bus

DesignLine (NZ and Charlotte, NC) developed the ECOSaver IV**,** a light-weight (aluminum) hybrid-electric (series) bus with twice the fuel efficiency and half of conventional diesel bus tailpipe efficiently absorb and store braking energy. The bus remains in service as long emissions. This hybrid- electric bus uses a Capstone (30KW) micro-turbine diesel engine and generator as an Auxiliary Power Unit (APU). The micro-turbine produces AC power, and recharges via two inverters (250KW each) the

AltairNano lithium-ion batteries to extend driving range. The battery powers two 120 KW, 3-phase AC induction motors and can as fuel is provided to the APU. Bus operation is managed by an advanced Battery Management System (BMS)**,** APU controls and driver interface (Figure 14 – The ECOSaver IV at the Charlotte International Airport). This bus was successfully demonstrated in 2007 by CTA (Chicago) and is currently being evaluated in New York City. The city of Baltimore purchased in 2009 21 DesignLine ECOSaver buses, after CTA's successful demonstrations.

Figure 14 – The ECOSaver IV at the Charlotte International Airport

The Capstone microturbine is usually mounted in the back of the bus, while the batteries are placed in the bus floor, behind and between the wheels. The micro-turbine can also be used as a range extender and charge the on-board battery for Plug-in Hybrid Electric Buses (PHEB) as shown in the series hybrid architecture (Figure 15).

In 2006 FTA funded a partnership of General Electric (GE Global Research of Niskayuna, NY) and A123 battery manufacturer to develop a similar plug-in battery-dominant Ecomagination bus (Figure 16). The GE dual battery bus paired a sodium battery with a lithium-ion one to optimize energy storage and driving range (to 60-80 mi per charge). Another version will use the A123 LFP batteries with high power and long cycle life, coupled with fuel cells to extend the range to 200 miles.

Figure 15 Schematic of Plug-in Hybrid Electric Drive

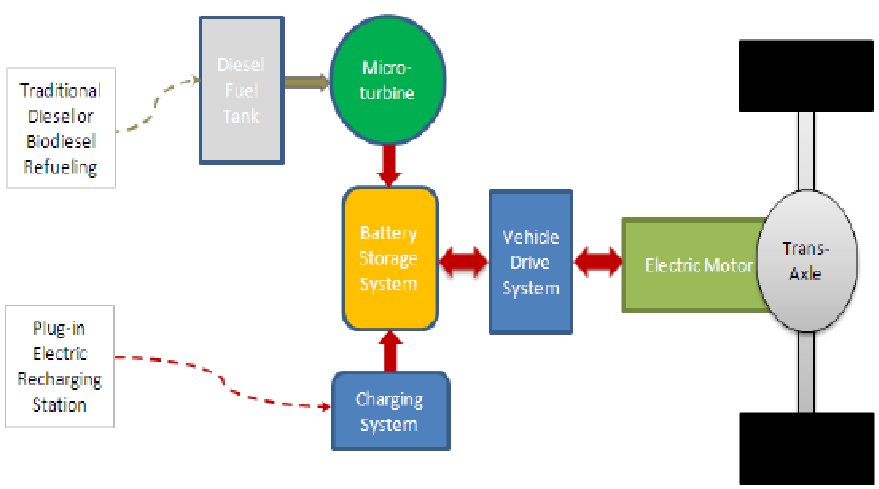


Figure 16 – The GE Ecomagination Hybrid ElectricDual Battery Transit Bus

2.3.3.4. RESS in Hybrid Electric Buses with Fuel Cell APUs

Under FTA's NFCBP, the Southern Hydrogen and Fuel Cell Coalition (SHFCC) - a regional coalition led by the Center for Transportation and Environment (CTE) - has recently initiated a University of Alabama at Birmingham (UAB) study to examine the performance and commercial viability of various fuel cell hybrid electric power-trains in transit bus demonstrations with the goal of developing and optimizing energy storage in battery-dominant designs with smaller fuel cells. The University of Texas-Austin (UT-CEM) has designed for the SHFCC a **flywheel energy storage system (FESS)** for a 40 ft. fuel cell bus. The lead acid batteries in the CARTA fleet of 12 electric buses will be recharged by fuel cells APUs. SHFCC and partners will also integrate the 3rd generation Georgetown University methanol fuel cell bus power plant using a light-weight commercial bus platform and hybrid-electric power train.

A 2008 FTA/NFCBP grant to AC Transit funded Indiana-based EnerDel Lithium Power Systems[43] to develop and integrate its advanced lithium-ion batteries for RESS in 16 advanced Van Hool fuel cell hybrid buses. This RESS features a modular array of prismatic lithium-ion cells stacked in a 700 Volt (200 KW) battery pack. The EnerDel lithium-ion batteries used feature a thermally stable chemistry of mixed oxides (titanium and manganese), which is also easier to cool and considered safer than alternatives. In combination with UTC Power fuel cells and hydrogen tanks on the roof, this integrated energy storage system will extend the bus' range to 300 miles.

2.4. International Advanced Hybrid Electric Buses

International developments of fuel efficient advanced hybrid- electric buses in development, demonstration and/or deployment (D3) are discussed below, in order to illustrate the diverse RESS architecture options undergoing technology evaluation prior to commercialization.

2.4.1. The European CUTE Fuel Cell Bus Partnership

[43] See postings regarding EnerDel Energy Storage technologies at www.ener1group.com/lithium-ion/

The European Union (EU) and the International Partnership for the Hydrogen Economy (IPHE) sponsored the European Hydrogen and Fuel Cell Technology Platform together with over 30 industrial partners. This development and demonstration program, dubbed HyFleet Clean Urban Transport for Europe (CUTE)[44] has fielded 27 hydrogen buses in 9 cities across Europe (Hamburg, London, Madrid, Luxemburg, Stuttgart and Stockholm), with associated maintenance facilities, and fueling infrastructure from fuel suppliers. The buses (see Figure 17 – The HyFleet CUTE Hybrid Fuel Cell Bus in Europe) covered over 1 million km and completed over 9,000 safe refueling operations with no major safety incidents and only 100 minor safety incidents. The CUTE demonstration is followed by "Hydrogen for Transport," that will operate 200 hydrogen buses (HyFleet) on 3 continents to test, evaluate and optimize competing hybrid power train architectures.

Figure 17 - The HyFleet CUTE Hybrid Fuel Cell Bus in Europe

2.4.1.1. The Van Hool (Belgium) Diesel Electric and Fuel Cell Hybrid Buses [45]

Van Hool has successfully developed and marketed fuel cell series- hybrid electric buses in the US (ACTransit, SunLine and CT Transit demonstrations were discussed above). A next generation of Van Hool FCBs will still use NiMH batteries and Siemens ELFA electric motors mounted in the wheelbase, but feature UTC Power PureMotion 120KW fuel cells with extended life (10,000 operation hours, 8 hydrogen tanks on the roof, and rooftop cooling. ACTransit ordered 8 new Van Hool FCBs, with option for 4 more; over 100 advanced Van Hool hybrid buses were delivered in 2008 to the US transit agencies.

2.4.1.2. The Mercedes Benz Citaro Bus

Mercedes has developed the Citaro G BlueTec- a series hybrid electric bus, using the diesel hybrid bus power train. It has roof-mounted hydrogen tanks and 2 Ballard fuel cell stacks recharging the water-cooled lithium-ion traction batteries (27 KW-h). The batteries can supply 120 KW to the water-cooled 60 KW hub-mounted electric motors for 1-2 miles without help from the fuel cells. The bus has regenerative braking and claims a

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[44] See for instance HyFLEET: CUTE newsletter issue 7, Sept. 2009 "*Project Finale: the Facts, the Future*" at http://www.global-hydrogen-bus-platform.com/News/Newsletters and the "*CUTE Summary of Achievements*" brochure.
[45] See www.vanhool.be and www.utcpower.com

30% better fuel efficiency over diesel, but only a six year service life (maintenance free for fuel cells, batteries and drive motors) compared to 12 years for conventional buses.

2.4.1.3. Volvo Hybrid Bus

The Volvo 7700 low-floor, 95-passenger parallel hybrid bus was introduced in 2009. It features an Integrated- Starter Alternator Motor (I-SAM) - a permanent magnet motor running on AC current (which also serves as a generator). I-SAM integrates the starter motor, electric motor, generator and electronic control unit (ECU) into one component. It is powered by roof-mounted lithium-ion batteries, which are recharged by captured braking energy. The electric motor is used to start and accelerate the bus up to about 20 km/h, while the diesel engine takes over at higher speeds. The small (5 liter) independent diesel engine shuts off at bus stops and traffic lights for cleaner running, turning on only when the bus reaches speeds of 20 kilometers per hour.

2.4.1.4. The Optare (UK) Hybrid Buses

Optare (UK) developed and demonstrated in London hybrid buses with two-mode Allison drives, which are also marketed in the US by Enova Systems. Optare offers both plug-in hybrid electric (PHEB), and fully electric buses (HEB). All buses use the Allison EP 40 parallel hybrid electric drives, typically integrated with NIMH batteries, battery chargers and DC/DC converters. However, the Optare Solo electric bus and the plug-in hybrid diesel electric will use lithium-ion battery packs and include on-board battery chargers. The Tempo Hybrid bus also uses Cummins engines, and has a roof-mounted dual power inverter module.

2.4.1.5. The Dutch e-Traction Bus[46]

The e-Traction Bus and the Whisper are modular, electric, light composite buses now in a 3rd generation. They feature individual electric motors in the wheel hubs (TheWheel is a permanent magnet synchronous motor), a light composite body. The RESS consists of 28 Li Ion batteries (4 strings of 7) from Valence Technologies, which can be individually monitored and controlled by the CANopen energy management and control system. They are recharged from regenerative braking and/or an APU. The batteries are housed in two air conditioned storage compartment under the seats behind the rear axle for easy access, and can be rapidly exchanged.

2.4.1.6. The German MAN Lion’s City Hybrid Bus

This is a series hybrid bus operating in several European cities (e.g., Vienna, Nuremberg), which uses a high performance ultracapacitor energy storage system The bus can run on electric power from stored braking energy, with its diesel engine shut down for 40% of the time.

[46] See postings at www.e-traction.com

2.4.1.7. The Irisbus Iveco hybrids

The Citelis and Crealis hybrid standard or articulated buses are manufactured and operate in France, Italy and Spain. They feature the BAE Systems hybrid electric traction with regenerative braking, and the latest lithium-ion batteries for RESS.

2.4.1.8. Transport Canada (TC) Hybrid Bus

The Transportation Development Center (TDC) funded development of a hybrid electric shuttle bus for airport and transit applications. [47] The bus was developed by Overland Custom Coach (OCC) and incorporates BET Services Inc. traction power modules, three 550 V ZEBRA (molten sodium salt) batteries, a Ford V8 gasoline/natural gas engine and a Siemens 150 KW generator for charging. Multi-mode OCC shuttle operation means that the traction motor can be powered by the battery, from the engine via a generator, or from the combination of both in hybrid-blended mode. The battery-only range is 36 mi using only 80% deep discharge but the hybrid operation achieves more range, exceeding 300 miles. The batteries can be fast-charged from the grid using an air-cooled dual inverter, or slow-charged overnight from a 240V AC supply.

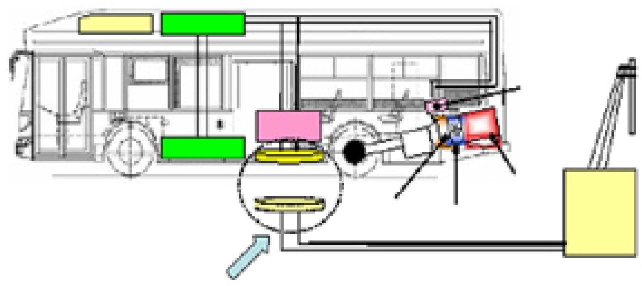
2.4.1.9. The Hino Motors (Japan) Wirelessly Charged Bus

Hino Motors, the Toyota heavy-duty vehicle division) in Japan, has developed a hybrid shuttle bus, which is equipped with lithium-ion rechargeable batteries and can be wirelessly recharged. (Figure 18 a and b) The coils embedded in the bus floor are recharged by magnetically coupled resonance from infrastructure coils embedded in pavement. The Hino bus has operated since 2008 between terminals at the Tokyo Haneda airport.

[47] See the project summary and report posted at www.tc.gc.ca/innovation/tdc/summary/14200/14240e.htm

Figure 18 a – The Hino No-Plug-In Hybrid Electric Bus at Haneda Airport

Figure 18 b – Schematic of Hino Bus in- Pavement Induction Charging System



2.4.1.10. The BYD (China) hybrid electric bus

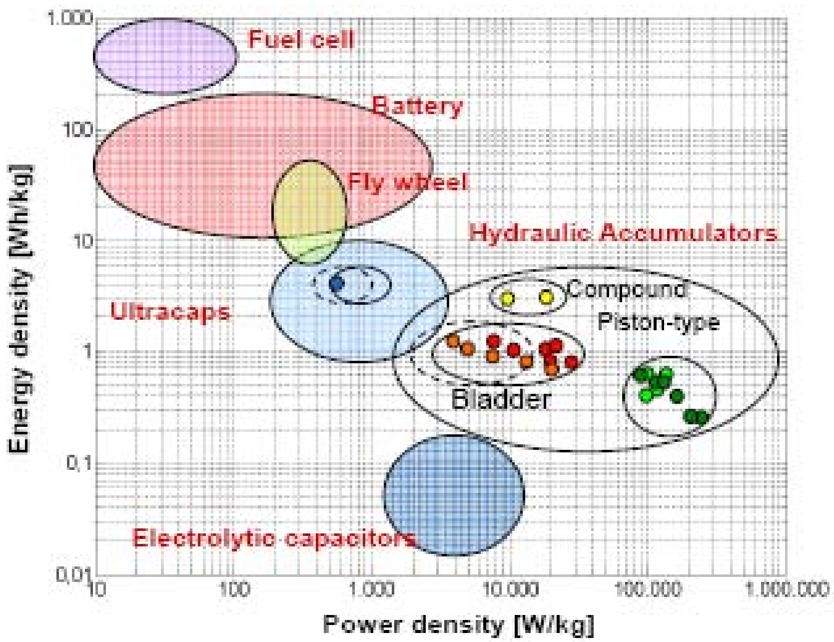
China's Build Your-Dream (BYD), a manufacturer of rechargeable lithium-ion batteries (LIB), has acquired the Shenzhen Auto Company Ltd. and Hunan Midea Coach. BYD hybrid buses were showcased during the 2008 Beijing Olympics. BYD has developed and is currently marketing a LIB-powered hybrid-electric bus and all electric buses.

2.5. Hybrid Bus Kinetic Energy Storage Systems (KESS): Flywheel (FESS) and Hydraulic Launch Assist (HLA)

Hybrid electric buses described previously use batteries and/or ultracapacitors to capture, store and release the regenerated braking kinetic energy for improved fuel efficiency. An alternative energy storage system option is offered by KESS, also called **Kinetic Energy Recovery System (KERS),** which use flywheels or hydraulic pumps as mechanical alternatives for use in hybrid bus and heavy duty applications. Mechanical hybrids prototyped in the UK and US were claimed to offer up to twice the efficiency of battery-based electric hybrid in a package that is half the size, half the weight at a quarter of the cost. Most promising are the compact electric and hydraulic retrofit kits for buses and other heavy duty applications, such as those developed and marketed by KersTech[48], an Oregon company. **Figure 19** illustrates the relative energy capacity (density) versus power density for various energy storage technology options, including hydraulic accumulators.

[48] Postings at www.kerstech.com/TechOverview.asp

Figure 19: A Comparison of Energy Storage Technologies.[49]



2.5.1. Flywheel Energy Storage

Ricardo, Inc.[50] developed a flywheel mechanical hybrid energy storage system under the KinerStor R&D project. Funded by the UK Technology Strategy Board, the FLYBUS research program, a sealed high-speed flywheel was developed to recover and store braking kinetic energy (KINERGY). FLYBUS is headed by Torotrak, Ltd[51] with Ricardo and Optare Bus as partners. Torotrak developed a mechanical, bolt-on Kinetic Energy Recovery System (KERS) to retrofit buses that provides up to 30% fuel savings. It was installed in an Optare Eco Drive Solo bus (using the Allison Transmission hybrid drive) instead of battery electro-chemical energy storage. The FLYBUS (Figure 20a) will use the Kinergy flywheel RESS (Figure 20 b) to demonstrate improvements in fuel efficiency and environmental emissions. The FTA 2006 Southern Hydrogen and Fuel Cell Coalition (SHFCC) program and Texas DOT supported the preliminary design of a flywheel RESS for a fuel-cell powered 40 ft. bus by the University of Texas-Austin Center for Electromechanics (TX-CEM)[52], along with cost and system performance analysis. This 2 KW-hr flywheel "battery" leverages a DARPA Flywheel Safety program. The flywheel rotor shown in Fig. 21 a consists of concentric rings made of high strength carbon fiber composite (CFC) impregnated with epoxy, capable of high speed operation up to 36,000 rpm, to recover and deliver braking energy, which will be integrated in the Texas hybrid fuel cell bus (Fig 21b).

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[49] Michael Conrad, Bosch Rexroth Corporation presentation: "*Hydraulic Hybrid Vehicle Technologies,*" at Sept 9, 2008 Clean Technologies Forum, Sacramento CA.
[50] See postings at http://www.ricardo.com/en-gb/About-Ricardo/
[51] See "Torotrak to present paper advocating Flywheel Hybrid System for buses at SAE Commercial Vehicle Conference", Oct. 3, 2009 at www.greencarcongress.com/2009/10/torotrak-sae-20091003.html
[52] See www.utexas.edu/research/cem/

Figure 20 a: FLYBUS Cutaway

Figure 20b- The Kinergy Flywheel

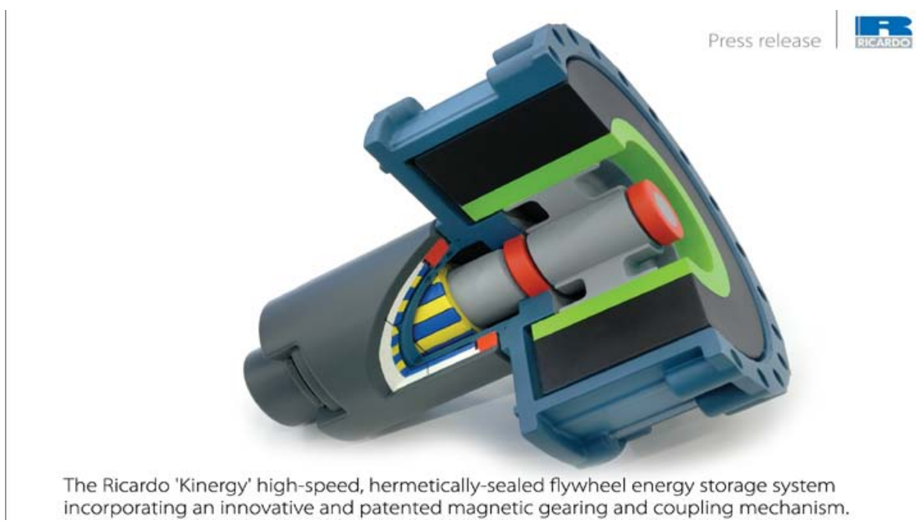


Figure 21 a- Composite Flywheel Rotor Designed by UT-CEM for the Hybrid Bus

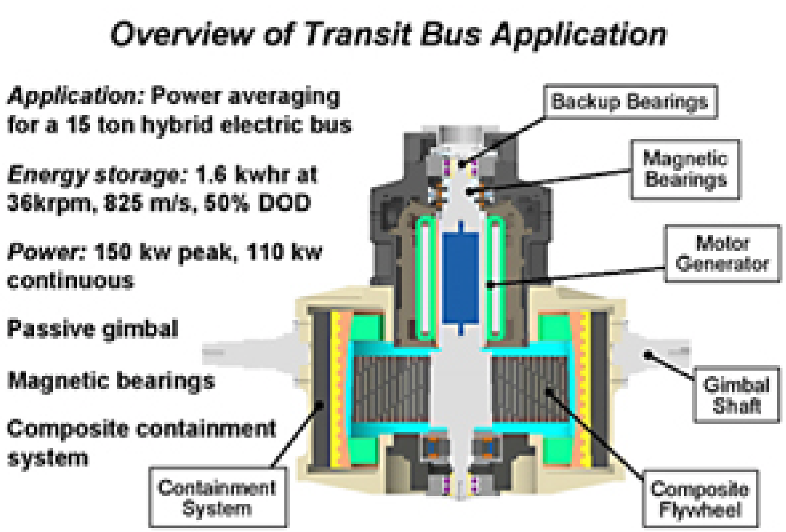


Figure 21b – Hybrid Bus Utilizing Composite Flywheel Rotor

However, use of large, high speed flywheel RESS for mobile applications present major challenges due to potential imbalances and stresses introduced by mechanical vibrations. Magnetically suspended, frictionless flywheels in stationary Trackside Energy Storage Systems (TESS) have better promise to store and supply regenerated braking energy for electrically powered rail transit and trolley buses. FTA is actively engaged with APTA in demonstration and evaluation of flywheel Wayside Energy Storage Systems (WESS) to improve the energy efficiency of trolleybuses, light and heavy rail with 3rd rail or overhead catenary systems (OCS).

2.5.2. Hydraulic Hybrid Vehicle (HHV) Powertrains

The EPA, has been developing for over a decade series hybrid hydraulic drive-trains in collaboration with industry partners (Eaton Corporation[53], Navistar, etc) to recover the braking energy of medium and heavy duty (MD/HD) vehicles with start-stop duty cycles (trucks, buses, trash compactors). These hydraulic hybrids have been demonstrated to have higher power capabilities for start and stop duty cycles. Fuel efficiency gains due to regenerated braking energy in heavy duty hydraulic hybrid vehicles were up to 70% for series hybrids, and up to 30% in parallel drive-trains.

The prototypes evaluated the use of a hydraulic pump, powered by braking energy, to transfer and store fluid from a low-pressure reservoir to a high pressure accumulator, which also holds nitrogen gas. The accumulator can release kinetic energy to the driveshaft when needed. This Hydraulic-launch-assist (HLA) technology allows for smaller and lighter batteries in RESS of trucks and shuttle buses. Up to 70% braking energy was recovered in the EPA- Eaton series hydraulic hybrid trucks and vans for UPS, and up to 40% in parallel hybrids.

[53] See the Eaton Corp. backgrounder on hydraulic Hybrids at www.eaton.com/hybrid

Figure 22a – Eaton Parallel Hydraulic Hybrid Schematic

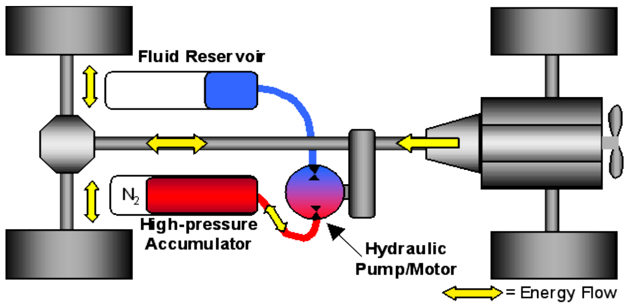
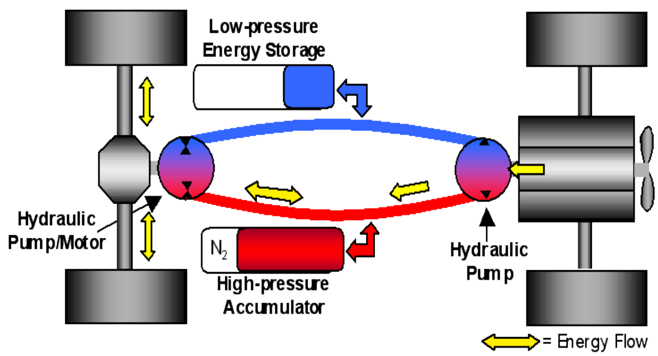


Figure 22b - The Eaton Series hydraulic hybrid drive schematic



EPA, the US Army National Automotive Center (NAC), Eaton, UPS and the International Truck and Engine Corporation have partnered to develop and demonstrate a hydraulic hybrid delivery vehicle with 60-70% improved fuel efficiency and 40% reduced GHG emissions. In 2008, the CA South Coast Air Quality Management District (SCAQMD) and the California Air Resources Board (CARB) agreed to develop a hybrid hydraulic shuttle bus with the above partners and Navistar. The CA goal was to retrofit 4000 shuttle buses and 100,000 trucks in the basin with hybrid hydraulic drive trains.[54] Eaton delivered for evaluation to the US Army in 2006 a hydraulic hybrid shuttle bus on a Ford E-450 chassis, which showed over 25% fuel economy improvement, reduced noise during acceleration and longer lived brakes in stop-start cycling. The Eaton hybrid hydraulic power systems and drive-trains are now available on trucks manufactured by International, Peterbilt, Kenworth, and Freightliner, and on delivery vehicles used by FedEx, UPS, Coca-Cola, Wal-Mart, Frito-Lay and Pepsi-Co.

Other companies that specialize in heavy duty fluid power and transmission components and systems applicable to hydraulic hybrid buses include: the Bosch Rexroth Corporation, Hydraulic Hybrid Systems (HHS), CZero and Parker Hannifin. Most promising for HEB applications are the compact retrofit kits that can be attached to existing vehicle, in order to convert them to a hydraulic hybrid that captures and reuses braking energy. For instance, CZero of Fort Collins, CO has partnered with the Colorado

[54] See www.aqmd.gov/hb/2008/July/090714a.htm

State University Engines and Energy Conversion Lab to develop the hydraulic retrofit kit it now markets.[55]

In Japan, Mitsubishi Motors developed and demonstrated a parallel hydraulic commuter bus (MB ECS-III) in 1983. In the UK, IRISBUS developed the Hynovis concept hydraulic hybrid diesel bus, with stop-start technology and a lighter engine. It entered service trials in Paris in 2008, and is being offered for the European market to meet Euro environmental standards.

[55] See "Hydraulic Hybrids: the answer for start-stop vehicles" at www.notthfortynews.com/News/200910photo_14_EFL_hydraulicHybrids.htm

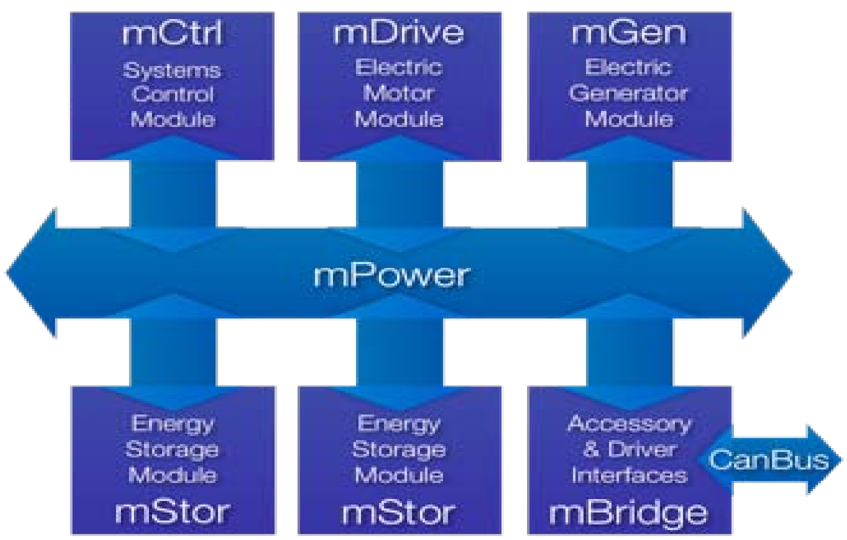
3. Batteries and Ultracapacitors RESS for Hybrid Electric Bus

3.1. Modularization and Optimization of RESS components

The diversity of RESS components, their integration and optimization in selected hybrid-electric drive-train architectures were illustrated for representative hybrid bus demonstrations in Chapter 2. Increasingly, the OEM strategy is to improve components of the RESS in a modular plug-and-play manner, and to retrofit existing buses in order to improve energy storage performance, capacity, safe operability and maintainability, as well as life-cycle cost. A recent CALSTART report[56] responding to FTA's EDSP goals lists 25 current battery manufacturers worldwide, whose cells, modules and packs specifications can match the power and energy requirements of hybrid electric drive buses. However, there is insufficient information at present on their cost, performance, durability and safety in service to enable bus integrators and designers to choose.

A modular, integrated design of the RESS within the electric drive power-train as done was successfully developed and marketed by Adura Systems (Menlo Park, CA). The Modular Electronic Scalable Architecture (MESA)[57] for hybrid-electric buses. The modular MESA architecture can be reconfigured to optimize use of several RESS mSTOR module (see Figure 23). A hybrid electric bus using the Adura MESA, with a range of 25-100 mi on battery alone, was demonstrated in China in 2009.

Figure 23: Adura System Series Hybrid Modular MESA Architecture



The DOE/USCAR Advanced Battery Consortium (USABC)[58] and the 21st Century Truck Partnership have considerably improved rechargeable batteries for heavy duty vehicles, although the knowledge base on advanced rechargeable vehicle battery options is still rapidly evolving. The goal of these RD&T partnerships is to develop modular, durable,

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[56] "Energy Storage Compendium- Batteries for Electric and Hybrid Heavy Duty Vehicles", March 2010, at www.calstart.org
[57] See http://www.adurasystems.com/Adura/Adura.html
[58] See DOE/USCAR USABC postings at http://www.uscar.org/guest/view_team.php?teams_id=12

safe batteries with high energy storage capacity while improving the ability to deliver high power for acceleration and to rapidly accept energy recovered from braking, all while reducing cost and size. R&D on end- of- life (EOL) battery recyclability aims to minimize toxic metals and electrolyte contents. The energy storage system must be tailored to bus operational requirements and meet its demanding energy storage requirements at affordable cost including: safe on-road operability, in-service abuse and durability, crash safety standards and survivability.

To help develop a domestic engineering design and manufacturing industrial base, the Department of Energy (DOE) recently awarded over $2.4 Billion of ARRA funding for electric drive vehicle battery and component manufacturing.[59] RD&T funded by DOE and the Department of Defense (DoD) aims to optimize electrochemical storage systems and the design and packaging of hybrid-electric power trains for hybrid electric and all-electric vehicles (including heavy duty applications). Transit buses will benefit from rapid advances in battery technology and serve as early test beds, as well as provide a market niche for early adopters. The use of capacitors in state- of- art vehicle energy storage devices could significantly reduce the power demand on and weight of batteries, and of fuel cells in fuel cell hybrids.

3.2. Advances in Ultracapacitors

Ultracapacitors (ucaps), or supercapacitors, are actually electrochemical double-layer capacitors (EDLC) (see Figure 24). They typically have low energy storage capacity, but high power yield. These devices are able to rapidly absorb, store, and release the recovered bus braking energy, an assist in delivering the peak power loads needed for acceleration or hill climbing. Therefore, ucaps complement well the steady- state power supplied by the battery modules, and are used primarily for load balancing and power management, in order to protect advanced batteries degraded and overheated by rapid charge/discharge cycling. Recent reviews of performance characteristics for commercial batteries and ucaps in HEB/EB/PHEBs have identified several promising options that combine these RESS elements for higher energy capacity, power delivery, and operational safety for near-term hybrid and electric vehicle applications**.**[60]

Ongoing RD&T on advanced hybrid electric and all electric power trains for buses and other (21st Century truck) heavy duty applications will improve both batteries and ultracapacitors, which are complementary RESS components in integrated power trains[61].

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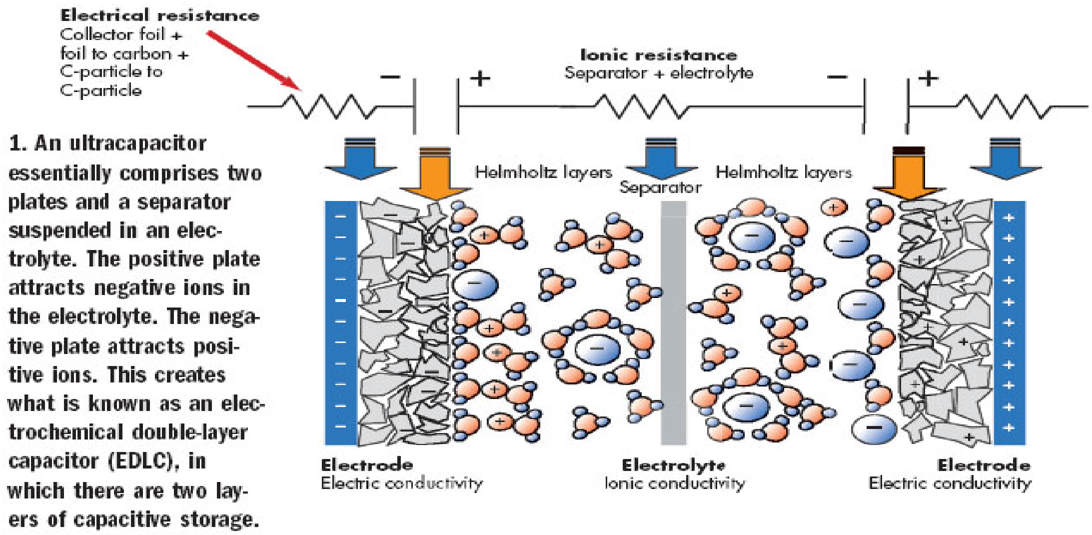
[59] "*Recovery Act Awards for Electric Drive Vehicle Battery and Component Manufacturing Initiative*" at www1.eere.energy.gov/recovery/pdfs/**battery_award**ee_list.pdf

[60] A. Burke, July 2009, UCD-ITS-RR-09-23 and International Journal of Energy Research: "*Ultracapacitor Technologies and Application in Hybrid and Electric Vehicles*" at http://pubs.its.ucdavis.edu/publication_detail.php?id=1312
and "*Performance, Charging and Second-use Considerations for Lithium Batteries for Plug-in Electric Vehicles*", July 2009 report posted at http://pubs.its.ucdacis.edu/publication_detail.php?id=1306

[61] Source: *Ultracapacitors and the Hybrid Electric Vehicle*, B. Maher, Maxwell Technologies in Alternative Energy eMagazine, Feb. 2005

Figure 24 - Schematic of an Electrochemical Double Layer Capacitor



Batteries and ultracapacitors are integrated in the Sinautec bus RESS. The Sinautec Automobile Technologies, LLC[62] developed and markets ultracapacitor buses, which can be rapidly recharged in station. They have successfully operated in Shanghai, China since 2006. Since batteries cannot discharge rapidly enough to deliver the high power loads needed for bus acceleration and hill-climbing, an ultracapacitor with high pulse-power capability is used either as standalone RESS to be recharged at short stops; or used as complement to battery in an effective integrated energy storage system for longer range. It provides short duration pulses or bursts of high power (during acceleration) to complement steady battery-supplied current loads, built into the overhead canopies at bus stops.

Figure 25 a – Hybrid Electric Power Train System and Components shows that the ucaps are placed in parallel with the batteries. These batteries store the converted kinetic energy recovered from braking, and can also be recharged by an electric motor/generator, fuel cells, or any Auxiliary Power Unit (APU), as shown in Figure 25 b – Sinautec Ultracapacitor Bus at Fast Charging Station, built into the overhead canopies at bus stops.

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[62] See Sinautec ultracapacitor bus specifications, video, news articles at www.sinautecus.com and Foton America at www.foton-america.com

Figure 25 a – Hybrid Electric Power Train System and Components for Sinautec Ultracapacitor Bus

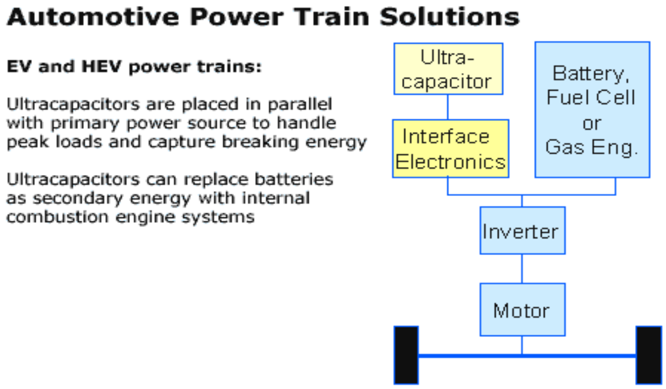


Figure 25 b – Sinautec Ultracapacitor Bus at Fast Charging Station

3.3. Battery Chemistry Options and Performance Trade-offs

This section discusses existing and emerging chemistry options for emerging bus lithium-ion and other established batteries (Lead Acid and VRLA, ZEBRA, NiMH) with modular configurations, and related trade-offs between energy capacity and power delivered. Reliable, affordable, and high capacity batteries and subsystems tailored to typical bus operating requirements are a key enabling and building-block technology for hybrid-electric, electric and fuel-cell buses. In addition to improving bus fuel economy and reduce environmental impacts, the safety, reliability, maintainability, recyclability and affordable lifecycle cost are key factors for bus battery selection and R&D efforts in the future.

Hybrid bus manufacturers and propulsion system developers are racing to integrate lithium-ion batteries with existing hybrid and hybrid-electric power trains because they are more powerful, have greater storage capacity and are lighter and more durable than established Nickel metal hydride (NiMH) batteries. Although Li-ion batteries could yield higher capacity and power for lower weight and size than established heavy duty alternatives, a recent review[63] noted the many challenges to be overcome before their widespread adoption. Challenges include: importing raw materials, developing a US production base, ensuring quality control and robust packaging, recyclability, affordable cost, safety in monitoring and controlling electric and thermal performance (cold weather operation), and durability issues.

Bus batteries are selected to meet the specific energy storage and power output (voltage and current load) requirements for typical start-stop bus duty cycles on urban routes and for peak loads during acceleration or hill-climbing. Selection of the best battery chemistry for a specific hybrid-electric bus application depends on the required bus weight, size, route characteristics and other operational requirements.

Primary traction batteries should also be able to recharge fast enough for the expected duty cycle and to absorb regenerative braking energy for fuel efficiency. Several metrics are used for battery: capacity (ampere-hours, or Ah), discharge rate (C, 2C, 3C, etc.); available energy (Watt-hour, Wh, or KiloWatt hour- KWh), specific energy density (Watt hour per kg or per liter) and discharge power (in Watt or KW). Although both high battery capacity and high specific energy density (Wh/kg) are desirable, there is a tradeoff between capacity and power density (W/kg) for the most common automotive battery chemistries**,** as shown by the Ragone plot of Figure 26a – Ragone Plot of Power Density vs. Energy Density of Batteries.

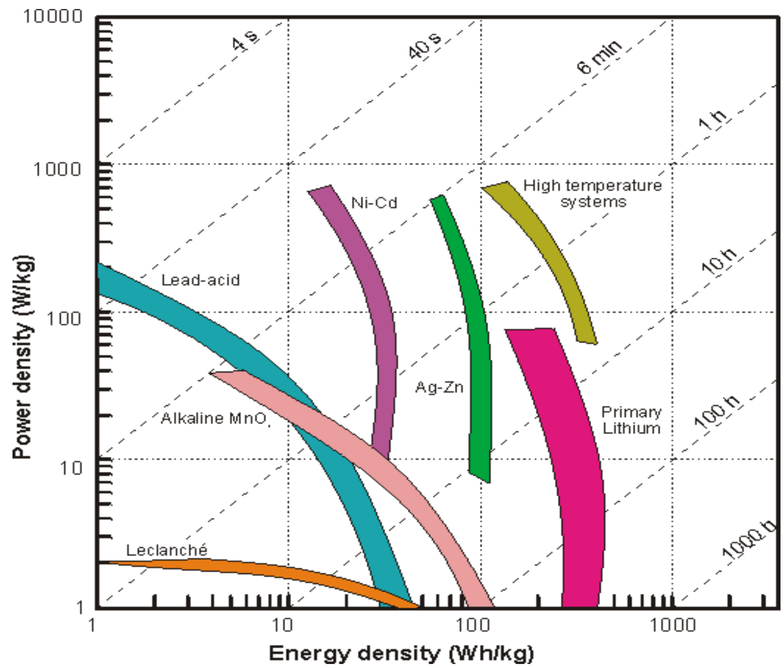
Emerging LithiumAir batteries[64] promise the highest practical energy density possible in a metal-based battery, with reasonable safety and environmental friendliness. It uses a lithium anode - an air cathode to supply the oxygen (as done with the popular Zinc-air hearing aid batteries), however low power density and currents, and performance degradation at lower temperatures may preclude their use in automotive applications.

There are trade-offs between electric drive requirements and battery attributes; there is no "one size fits all" battery solution for electric drive buses, and the battery selection depends on the specific bus application. The chosen battery chemistry, design, and materials determine RESS performance characteristics: reliability, maintainability, durability (number of cycle-life), safety for the operating temperature (hot vs. cold starts and charge decay with age and degradation of electrodes and electrolyte), shelf- life (rate of spontaneous charge decay), as well as range on battery power (electric only) and time to recharge, as tabulated for comparing options in Figures 26 a and b below.

[63] "*Move to Li-ion requires many technical changes*" in Sept 14, 2009 Automotive Engineering Online, at www.sae.org/mags/AEI/6863

[64] See ANL discussion at www.transportation.anl.gov/features/2009_Li-air_batteries.html

Figure 26a – Ragone Plot of Power Density vs. Energy Density of Batteries



Important battery features include: the operating temperature range, the rate of discharge, time to recharge during operation, shelf life (decay of charge - time vs. temperature), internal resistance (which leads to heating during discharge/charge cycling) and the degraded integrity of electrodes and electrolyte over cycle-life (or the inability to fully recharge and discharge after repeated cycling, also known as Depth of Discharge-DOD, and/or State of Charge- SOC).

The recent IBM Almaden Conference on "*Scalable Energy Storage: Beyond lithium-ion*" convened leading government, industry and university experts on electric hybrid power trains and battery electrochemistry to review the state of art in battery chemistry and highlight remaining challenges while developing a research roadmap to overcome them.[65] (see also the Ragone Plot with respect to vehicle energy/power performance targets shown in Figure 26b, Relative Performance of Electrochemical Storage Devices).

[65] Aug 26-27 IBM Almaden Institute conference "*Scalable Energy Storage: Beyond lithium-ion*."Agenda and presentations are posted at http://www.almaden.ibm.com/institute

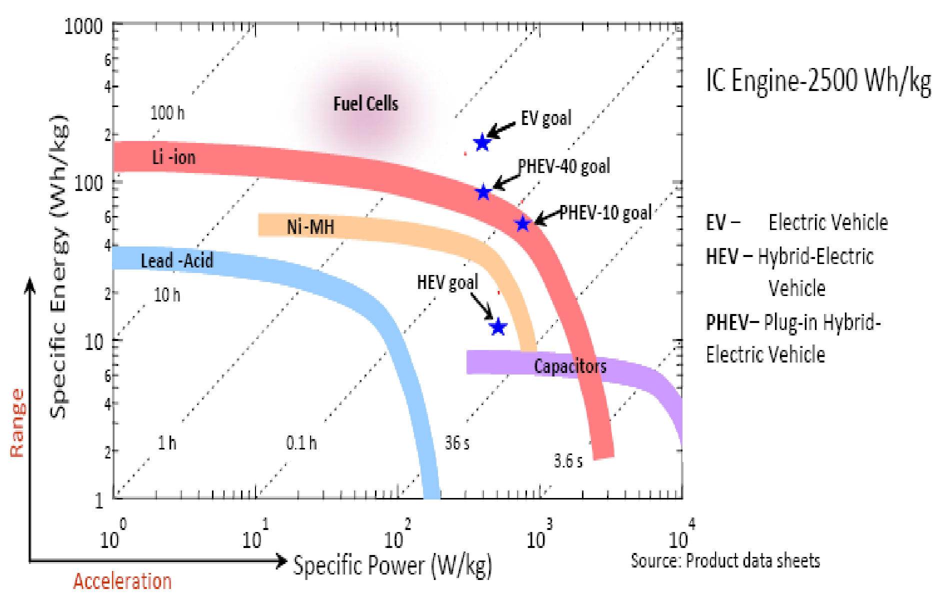
Figure 26b – Battery Chemistries, Performance, and Safety Characteristics

	Nickel-cadmium	Nickel-metal-hydride	Lead-acid sealed	Lithium-ion cobalt	Lithium-ion manganese	Lithium-ion phosphate
Gravimetric Energy Density (Wh/kg)	45-80	60-120	30-50	150 - 190	100 - 135	90 - 120
Internal Resistance in mΩ	100 to 200[1] 6V pack	200 to 300[1] 6V pack	<100[1] 12V pack	150 - 300[1] pack 100 -130 per cell	25 – 75[2] per cell	25 – 50[2] per cell
Cycle Life (to 80% of initial capacity)	1500[2]	300 to 500[3,4]	200 to 300[3]	300 - 500[3]	Better than 300 – 500[4]	>1000 lab conditions
Fast Charge Time	1h typical	2 to 4h	8 to 16h	1.5 - 3h	1h or less	1h or less
Overcharge Tolerance	moderate	low	high	Low. Cannot tolerate trickle charge.		
Self-discharge / Month (room temperature)	20%[5]	30%[5]	5%	<10%[6]		
Cell Voltage Nominal Average	1.25V[7]	1.25V[7]	2V	3.6V 3.7V[8]	Nominal 3.6V Average 3.8V[8]	3.3V
Load Current peak best result	20C 1C	5C 0.5C or lower	5C[9] 0.2C	<3C 1C or lower	>30C 10C or lower	>30C 10C or lower
Operating Temperature[10] (discharge only)	-40 to 60°C	-20 to 60°C	-20 to 60°C	-20 to 60°C		
Maintenance Requirement	30 to 60 days	60 to 90 days	3 to 6 months[11]	not required		
Safety	Thermally stable, fuse recommended	Thermally stable, fuse recommended	Thermally stable	Protection circuit mandatory; stable to 150°C	Protection circuit recommended; stable to 250°C	Protection circuit recommended; stable to 250°C
Commercial use since	1950	1990	1970	1991	1996	2006
Toxicity	Highly toxic, harmful to environment	Relatively low toxicity, should be recycled	Toxic lead and acids, harmful to environment	Low toxicity, can be disposed in small quantities		

Source: www.batteryuniversity.com and http://www.all-battery.com/batteryuniversity.aspx

Figure 27 – Relative Performance of Electrochemical Storage Devices

(Venkat Srinivasan, Almaden Conf. 2009: "*The Batteries for Advanced Transportation Technologies (BATT) Program.*")



The ZEBRA (Zeolite Battery Research Africa Project), which has been commonly used for more than 20 years as a traction battery, was integrated into the SunLine Hydrogen FCB developed by Van Hool, UTC and ISE Corporation[66]. ZEBRA is a molten salt battery (molten sodium electrode and sodium chloro-aluminate solid electrolyte). It operates at high temperature (250 degrees C) and cannot be allowed to cool down and solidify or else it must be reheated over 3 days to restore charge. The ZEBRA battery has also been used in Daimler-Orion hybrid-electric buses, since it offers both high specific energy and power (90 Wh/kg and 150 W/kg). Full size bus batteries of 10-20 cells have proven their long operating lifetimes over 3000 cycles in 8 years. State-of-charge (SOC) balancing problems due to failed (shorted-out) cells within any of the 3 parallel-linked batteries led to bus propulsion shut-downs and must be addressed. These ZEBRA traction batteries complemented the UTC Power Fuel Cell Stack Assemblies (CSA), which also degraded prematurely in power over time due to contamination (from 120KW initial to below 90 after 800-1200 hrs operation - far below the 4000 hours expected). This illustrates the need for components of on-board power storage systems operating in tandem to be optimized both individually and after integration.

Over a decade ago, a modular refuelable Zinc-Air bus battery[67] was developed at the Lawrence Livermore National Lab (LLNL). It was perfected (specific energy - 200 Wh/kg, delivering about 300 kWh at power levels up to 50 KW) and commercialized by Arotech Corporation and the Electric Fuel Corporation. The FTA's Zinc-Air Electric Bus Program between 1998- and 2004 supported its integration into a hybrid electric powertrain by General Electric (GE). The Electric Fuel Zinc-Air battery performance in a Nova Bus was evaluated in combination with other power sources (Ni-Cd auxiliary battery, ultracapacitors and the Zebra battery) and the proprietary manufacturing process of dendritic Zn pellets and special requirements for refueling and recycling of battery materials proved impractical.

Lithium-ion (Li- Ion) batteries are very promising because they are lighter, more compact, and can store more energy at sufficient power, but are also costlier. Emerging lithium- iron phosphate batteries (90–110 Wh/kg) have high storage capacity, but not as high as the more common lithium cobalt-oxide batteries (150–200 Wh/kg). However, the latter tend to overheat and may catch fire or explode due to runway oxidation reactions of the graphite electrode. Nano lithium-titanate batteries store sufficient energy and power (respectively, 116 Wh and 72 Wh/kg; 1,250 W and 760 W/kg) with greater chemical stability and improved thermal safety.

Professor A. Burke and coworkers at UC Davis have recently reviewed various commercial lithium-ion battery chemistries considered for Plug-In Hybrid Vehicles (PHEVs) and compared their broad range of performance characteristics with respective

[66] "*SunLine Transit Agency Fuel Cell Transit Bus: Fifth Evaluation Report*" by L. Eudy and K. Chandler, Aug 2009, NREL/TP-560-46346-1 and Appendix, www.nrel.gov/hydrogen/pdfs/46346-1.pdf

[67] "*Powering Future Vehicles with the Refuelable Zinc/Air Battery*", LLNL Science and Technology review, 1995; "*Zinc-Air Fuel: all Electric Hybrid Bus Program*" at www.yenra.com/zinc-air-fuel/;
"*The Zinc-Air Zero Emission Electric Transit Bus*" at www.electric-fuel.com/EV

trade-offs.[68] The Ragone plot in Figs. 26 and 28 illustrated relative advantages, and performance trade-offs for leading candidate lithium-ion batteries in HEBs due to their higher specific power and energy density relative to battery chemistries of proven longevity, reliability and affordability. A more detailed comparison of lithium-ion battery chemistries and associated performance characteristics is shown in Figure 29.

In 2009, the lithium-ion battery manufacturer EnerDel Lithium Power Systems signed a contract with Alameda contra Costa Transit (AC Transit) to supply the on-board batteries and RESS for the next generation of 16 hybrid electric fuel cell buses developed with Van Hool and UTC Power. With DOE stimulus funding (from the $2.4 Billion designated for advanced battery technologies for transportation vehicles) EnerDel was awarded $118M to evaluate the various Li Ion battery chemistry options and identify those materials best suited to hybrid electric cars, including:

- Lithium layered metal oxide cathode (e.g., NMC), with carbon anode;
- Lithium iron phosphate (LFP,) with carbon anode;
- LMO cathode, hard carbon anode; and
- More complex Lithium manganese oxide spinel (LMO) cathode, with lithium titanate ($Li_4Ti_5O_{12}$, or LTO) anode.

Although emerging lithium-ion and other (e.g., lithium-air, and zinc-air) automotive rechargeable battery systems promise both higher energy density, high power, lower weight, reduced volume, and reliable performance when integrated into advanced electric-hybrid power-trains. However, several technology challenges must still be addressed to enable commercialization at affordable cost and with proven safety.

There are pros and cons to be weighed in selecting any lithium-ion battery chemistry for a specific vehicle application. For instance, Nickel Manganese Cathode (NMC) materials are more thermally stable, cost less than the potentially flammable and toxic LCO and can be charged beyond 4.5V. Other benefits are higher capacity (more than 180Ah/kg) than LMO and than the nanophosphate (LFP) batteries manufactured by A123, Inc.

[68] A. Burke and M. Miller, "*Performance Characteristics of Lithium-Ion batteries of Various Chemistries for Plug-in Hybrid Vehicles*" presented at EVS24 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium in Stavanger, Norway, May 13-16, 2009

Figure 28 - Power/Energy “Design Spaces” for Battery Performance

RAGONE PLOT: TRADEOFFS OF HEV BATTERY ENERGY DENSITY VS. POWER

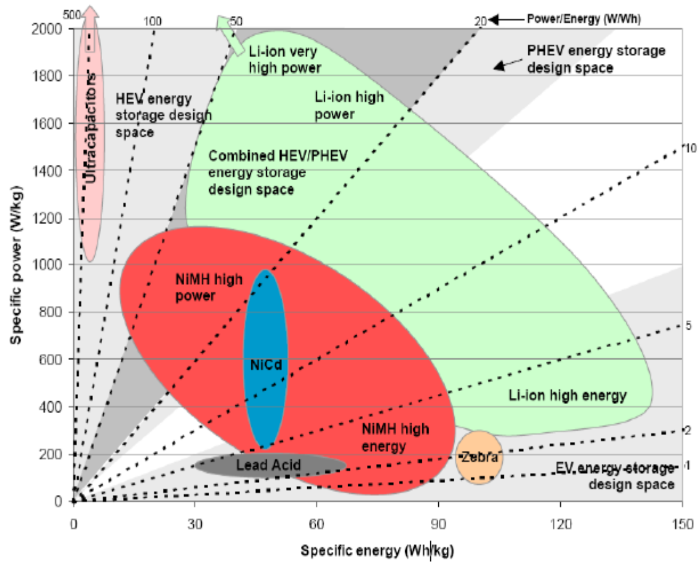


Figure 29 ranks the technology maturity, and tradeoffs in performance and safety for the major contender automotive lithium-ion battery chemistries commercialized today, most of which can be adopted and adapted to bus applications.

Figure 29 – Characteristics of Several lithium-ion Positive Electrode Chemistries

Characteristics of Lithium Ion Batteries for Automotive Applications

	Lithium Cobalt Oxide	Lithium Manganese Spinel	Lithium Nickel Manganese Cobalt	Lithium Iron Phosphate
Automotive Status	Limited auto applications (due to safety concerns)	Pilot	Pilot	Pilot
Energy	High	Low	High	Moderate
Power	Moderate	High	Moderate	High
Safety	Poor	Good	Poor	Very Good
Cost	High	Low	High	High
Low-Temperature Performance	Moderate	High	Moderate	Low
Life	Long	Moderate	Long	Long

3.4. Bus and Battery Safety Hazards and Safeguards

Early identification, prevention and mitigation of hazards associated with the battery subsystems in the design, test and evaluation stages, is essential to their commercial viability for a growing bus niche market. The likelihood of occurrence of a hazard depends on the specific battery-chemistry, size and integration within the powertrain, and is application-specific. Preliminary Hazard Analysis (PHA) is needed to identify and rank hazards due to: battery materials, size of stack, design form factor, misuse, aging and degradation, as well as the integration interfaces within the electric propulsion and control subsystems.

The internal resistance of batteries generates heat during charge/discharge cycles, so a cooling system must be provided for precise temperature control to ensure safe operation and prevent thermal runaway. Li-ion batteries can also degrade rapidly when fully discharged and recharged in charge-depleting operation; they are heavily dependent on electronic control modules to match battery lifetime to powertrain lifecycle.

An NREL Case Study report[69] on the Ebus series hybrid electric buses and trolleys in use by the Indianapolis Public Transportation Corporation (IndyGO) reported a fire due to an undetected corrosion from winter road salt of exposed cable and fuse of the battery tray. During overnight bus battery recharging in 2004, this corroded cable caused a fire, which spread and damaged the IndyGo hybrid electric buses, its chargers and parts of the garage. It led to 6 months of delays to repair the fire damage, and perform required improvements to protect and prevent future corrosion of exposed propulsion system cables and fuses under the bus floor.

The FTA Clean Air Program[70] issued in 2003 guidance to address the safety challenges of emerging electric and hybrid buses, from early design phases, as part of a series on alternative fueled buses. It provides an excellent generic blueprint for bus operators on best safety practices, but an update is needed to reflect current battery and electric power train and management technologies, system designs, and recent battery and bus safety training resources. The safety issues and applicable standards it discusses include:

- Electric shock prevention and mitigation are achieved using electrical isolation and crash-safety (per SAE[71] standard J1766[72]) of wiring, equipment and battery modules, enclosed batteries for weather and water protection, labeled and grounded high voltage circuits and components (per SAE J1673[73]), with warning signs on high-voltage wires and casings. Automatic shutdown and disconnect of

[69] "*Case Study: Ebus Hybrid Electric Buses and Trolleys*", NREL/TP-540-38749, July 2006 at http://www.afdc.energy.gov/afdc/pdfs/38749.pdf

[70] See "*Design Guidelines for Bus Transit Systems using Electric and Hybrid Electric Propulsion as an Alternative Fuel*", DOT-FTA-MA-26-7071-03-1, March 2003, found at http://transit-safety.volpe.dot.gov/Publications/order/singledoc.asp?docid=370

[71] See the Society of Automotive Engineers (SAE) list of vehicle Standards and Recommended Practices at http://www.sae.org/standardsdev/ and those specific to batteries and charging systems at http://www.sae.org/technical/standards/ground_vehicle/BATT

[72] SAE J1766, "*Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing*," April 2005

[73] SAE J1742, "*Connections for High Voltage On-Board Road Vehicle Electrical Wiring Harnesses - Test Methods and General Performance Requirements*," Dec. 2005

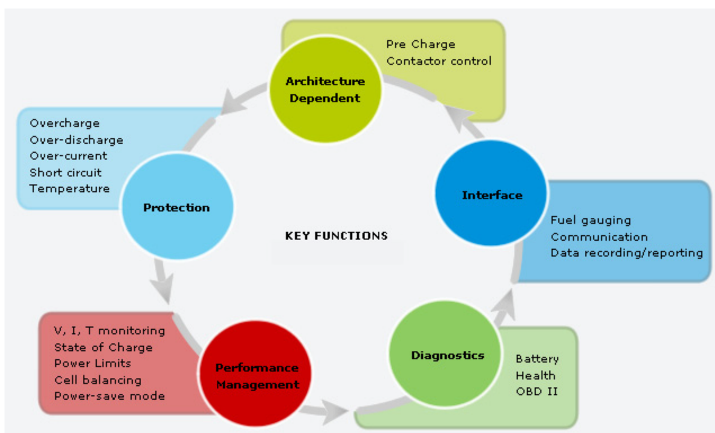
the energy storage subsystem must occur in case of short circuit, excessive current draw, in a crash, or during maintenance.

- On-board and off-board (outlet) charging safeguards and specifications regarding the recharge current or voltage tolerances to avoid overcharge or sparking; and automatic shut-off in case of full charge or detected anomaly (heat, fire, leak).

- Cut-out switches and ground fault detection per SAE wiring standards (J1654[74], J1673[75]) and connectors (J1742). A Ground Fault Current Interrupter (GFCI) must be installed to prevent any shock or harm to workers from the charger.

- Battery Management Systems (BMS) with individual cell monitoring and balancing; Thermal Management Systems (TMS) with ventilation and/or coolants to prevent overheating, or cooling below safe operability specifications; and a Power Management System (PMS)- all able to communicate with the motor control system and alert the operator of anomalous conditions. (Figure 30)

Figure 30 - Battery Management System (BMS) for Safe Operability
Source: http://www.compactpower.com/bpack.shtml



- Material Safety Data Sheets (MSDS) and maintenance and emergency response training to prevent, detect and respond to hydrogen gas leaks in fuel cell buses, fire/toxic fumes, or battery electrolyte spills.

- Training of maintenance personnel and bus operators regarding the safe off-loading, replacement, and maintenance of bus batteries and power trains as well as safe storage, recharging and handling of batteries and electrical subsystems.

- The existing 1998 APTA bus safety management program guidance[76] "*Manual for the Development of Bus Transit System Safety Program Plans*" (SSPP)

[74] SAE J1654, "*High Voltage Primary Cable*" was initiated in 2008 for voltages below and up to 600 V RMS, which exceed existing standards for lower nominal voltages (J1127, J1128, or J1560).
[75] SAE J1673, "*Requirements for 120 VAC Electrical Distribution on Medium- and Heavy-Duty Trucks*", 2002

addresses (only generically) the identification, prevention and mitigation of safety hazards due to subsystems integration. The DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program issued a generic "*Safety Planning Guidance for Hydrogen Projects*" applicable to FCBs[77].

- The Sixth International Fuel Cell Bus Workshop featured a Safety Round Table[78] and discussed safety resources for fuel-cell and hydrogen buses and fueling infrastructure, but did not focus on battery-specific safety issues or standards.

The Society of Automotive Engineers (SAE) Battery Storage Standards Committee has developed several consensus (voluntary) standards for the design, and safe operation of RESS devices[79]. Several Working Groups (WG) of the SAE Battery Storage Standards Committee are actively engaged in developing standards addressing: durability, safety, controls and interfaces with power electronics and traction subsystems. For instance:

- J1495-200506, *Test Procedure for Battery Flame Retardant Venting System*, is a test for heavy-duty vehicle SLI (starting, lighting and ignition) lead-acid batteries. It determines the effectiveness of venting systems and retardant propagation of external flaming battery gas inside the battery (where an explosive mixture might be present).

- J2464, *Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing* has just been updated to recommend battery testing to determine battery failure modes under crash or other abnormal (temperature, fire) scenarios.

- J2293 (Parts 1 and 2), *Energy Transfer System for Electric Vehicles, Part 1: Functional Requirements and System Architecture; and Part 2- Communication Requirements and Network Architecture*. These standards for the recharging system and interfaces will help ensure the safety and interoperability of vehicles and public or private charging infrastructure installations.

Resources on existing and emerging safety codes and standards (SC&S) for fuel cells and hydrogen-fueled vehicles are posted by the Hydrogen Fuel SC&S Coordinating Committee, as part of the National Hydrogen Association (NHA).[80] It coordinates standards and training activities with DOE/NREL, state safety and permitting authorities, the National Fire Protection Association (NFPA), and the International Electro-Technical Commission (IEC) Technical Committee (TC) 105, which drafted safety standards for portable fuel cell power systems. Bus power system designers, manufacturers, system

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[76] "*Manual for the Development of Bus Transit System Safety Program Plans*" (SSPP) 1998, Rev. 5/99 at http://www3.cutr.usf.edu/bussafety/documents/apta-sspp.pdf
[77] See "*Safety Planning Guidance for Hydrogen Projects*" posted at http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/safety_guidance.pdf
[78] See the conference Agenda and embedded Safety Roundtable presentation by Barry Mickela and others posted at http://www.electricdrive.org/index.php?ht=d/sp/i/11031/pid/11031
[79] See a comprehensive list of SAE standards and best practices applicable to the battery subsystem at http://www.sae.org/technical/standards/ground_vehicle/BATT
[80] See www.hydrogenassociation.org and safety information and standards for fuel cells and hydrogen tanks posted at www.hydrogenandfuelcellsafety.info

integrators and operators must also observe specific design, safe operation and maintenance standards for fuel cells. The SAE Standards Committees for FCB safety are: the Fuel Cell Safety Working Group, Fuel Systems and Hybrids, and the Truck and Bus Hybrid and Electric Vehicle committees.

System safety requirements for FCB hydrogen safety (Figure 31) include also mechanical, electrical, and chemical vehicle battery safety standards. Relevant IEC TCs developing new or updated standards for service stations and hydrogen FC refueling include: TC 22- Road Vehicles, and TC 197- Hydrogen Technologies. NIST and SAE are also developing battery safety standards, while DOT/PHMSA issued restriction for transportation lithium-ion batteries on-board aircraft.[81]

Electrical safety training is needed for operations and maintenance (O&M) personnel to implement HazOp procedures specific to the types of batteries and other RESS components, regarding battery replacement, plugs for recharging, SOC monitoring, and thermal management. Training related to RESS safety must address:

- Maintaining the physical integrity of packaging, and an optimal temperature range. An important safeguard, especially for lithium-ion batteries, is a Thermal Monitoring System able to detect overheating and to activate battery cooling (by air or water, or other coolant).

- Monitoring the State of Charge (SOC) of the battery stack and balancing of individual cells is needed to detect overcharge or undercharge, and to rebalance the voltage drop across the stack.

- Monitoring both local cell and overall battery stack temperature with a Thermal Management System (TMS), to prevent thermal runaway, flammable gas discharge, fires and explosions. (Figure 32, Lithium-ion Battery Temperature Related Hazards and Safeguards);

- Ensuring the electrical isolation of the battery subsystem from any metallic vehicle parts and the electrical separation between cells electrodes to avoid short-outs.

- Venting may be needed to prevent explosions or fire due to accumulation of any toxic or flammable gas reactants or byproducts which could rupture the packaging under pressure.

[81] See safety restriction on lithium batteries on-board aircraft at http://safetravel.dot.gov/index_batteries.html

Figure 31 – Selected Fuel Cell Safety Standards[82]

Selected Fuel Cell Standards
SAE J1766 Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing
SAE J2572 Recommended Practice for Measuring Fuel Consumption and Range of Fuel Cell and Hybrid Fuel Cell Vehicles Fuelled by Compressed Gaseous Hydrogen
SAE J2574 Fuel Cell Vehicle Terminology
SAE J2578 Recommended Practice for General Fuel Cell Vehicle Safety
SAE J2594 Recommended Practice To Design For Recycling Proton Exchange Membrane (PEM) Fuel Cell Systems
SAE J2615 Testing Performance of Fuel Cell Systems for Automotive Applications
SAE J2616 Testing Performance of the Fuel Processor Subsystem of an Automotive Fuel Cell System
SAE J2719 Information Report on the Development of a Hydrogen Quality Guideline for Fuel Cell Vehicles
SAE J2760 Pressure Terminology Used In Fuel Cells and Other Hydrogen Vehicle Applications
FMVSS 49 CFR 571 69 FR 42126 NHTSA's Four-Year Plan for Hydrogen, Fuel Cell and Alternative Fuel Vehicle Safety Research - (Proposed Rules)
ISO 23273-1 Fuel cell road vehicles Safety specifications Part 1: Vehicle functional safety
ISO 23273-2 Fuel cell road vehicles - Safety specifications - Part 2: Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen
ISO 23273-3 Fuel cell road vehicles Safety specifications Part 3: Protection of persons against electric shock
GME FCA14041 Chemical Resistance to Coolants for Fuel Cell Vehicles.

[82] Source is http://auto.ihs.com/news/gm-fuel-cell-propulsion-architecture.htm

Battery subsystem failures can be initiated by diverse causes and then propagate to interlinked power electronics and traction subsystems. Failure chains could result from the:

- Physical abuse and fracture due to mechanical vibrations, thermal cycling, physical or chemical embrittlement, or to crushing in a road crash;

- Breakage and leakage of toxic or corrosive battery electrolytes, which could lead to internal or external short-circuits);

- Chemical degradation and aging of electrodes (corrosion) or of cables;

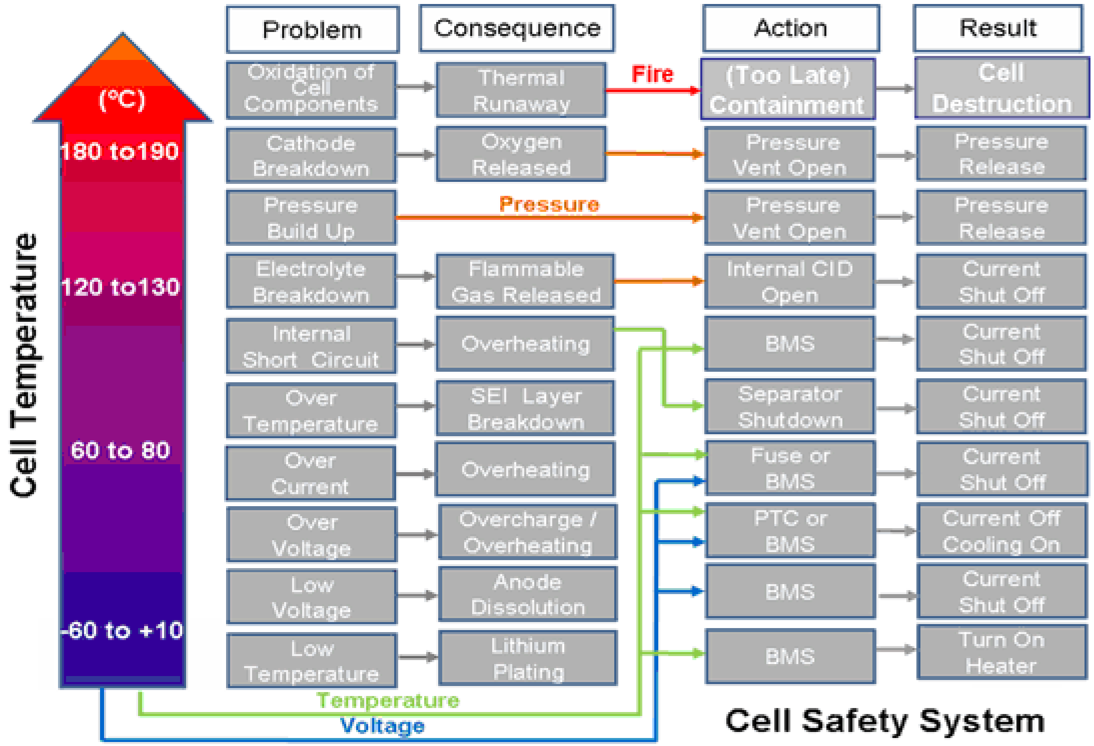
- Runaway electrode oxidation reactions which are exothermic (heat-producing), or produce oxygen and hydrogen under pressure that can ignite or explode;

- Electrical hazards which include electrocution due to improper charger/coupler interfaces, or to fast charging, or fast discharging, which could cause sparking and ignite any flammable materials.

The generic battery safety hazard categories shown schematically in Figure 32 relate to:

- <u>Battery chemistry for electrodes, electrolyte and packaging</u>: To the extent feasible, battery manufacturers should avoid the use of toxic and corrosive components or prevent accumulation of toxic reaction byproducts and flammable or corrosive gases. It should be noted that lithium metal itself is both toxic (lithium is used to treat mental disorders) and flammable. The electrodes and the electrolyte chemistry should be optimized for the application for maximum electric power and capacity, and chemical stability over the operating temperature range. Lithium cathode chemistry variants were discussed above and include electro-active oxides like Li- Cobalt oxide (though Co is also toxic), Li Nickel oxide, Li manganese oxide, and Lithium iron phosphate (currently preferred because of its stability and improved safety). Monitoring and control systems must maintain lithium-ion Cells temperature and voltage within narrow ranges for safe operability, as also shown in Figure 33 (The Lithium-ion Cell Temperature-Voltage Safe Operation Window).

Figure 32 Lithium-ion Battery Temperature Related Hazards and Safeguards



- Improper handling and maintenance: Battery manufacturers publish both cell and stack specifications sheets (nominal voltage, capacity in Amp-hours or Ah, charge and discharge condition with the peak and continuous current allowable operating temperature, cycle life, etc. In addition a Material Safety Data Sheet (MSDS) and results of safety testing and certification must also be posted. The MSDS identifies all battery hazardous components, human exposure health effects and mitigation, how to handle, store, and dispose of properly, and how to respond to accidental releases[83].

- Electrolyte Safety: Liquid electrolyte medium is conductive and usually consists of lithium salts in an organic solvent (lithium and water would react violently). Electrolyte leakage may lead to battery short-outs. In Lithium batteries with carbon anodes, a solid electrolyte interface (SEI) layer can build-up, thus increasing internal cell resistance and causing over- heating and fires. Lithium titanate (LTO) anodes do not react adversely with electrolytes to form an SEI layer and thus not degrade with cycling age or temperature. Lithium Polymer (LiPo) batteries use a gel or solid electrolytes, hence are solid-state cells, eliminating leakage hazard and enabling flat, prismatic battery cells that can be stacked and packaged in foil.

[83] Kokam America is a subsidiary of the Korean battery manufacturer Kokam, Ltd. and partner in the KD Advanced Battery Group LLC that will build a battery plant in Michigan for the Range Extended EV Chevy VOLT). It will supply the high power (180 Wh/kg) Superior Lithium Polymer Batteries (LiPo SLPB) to Smith Electric Vehicles US for heavy duty applications. Specifications and MSDS are posted at www.kokam.com/english/product/battery_main.html

- Electrical Safety: Electrocution hazards should be preventable during maintenance and recharging operations: safe handling, warning signs and wire coding, safe charging couplers and training may be required.

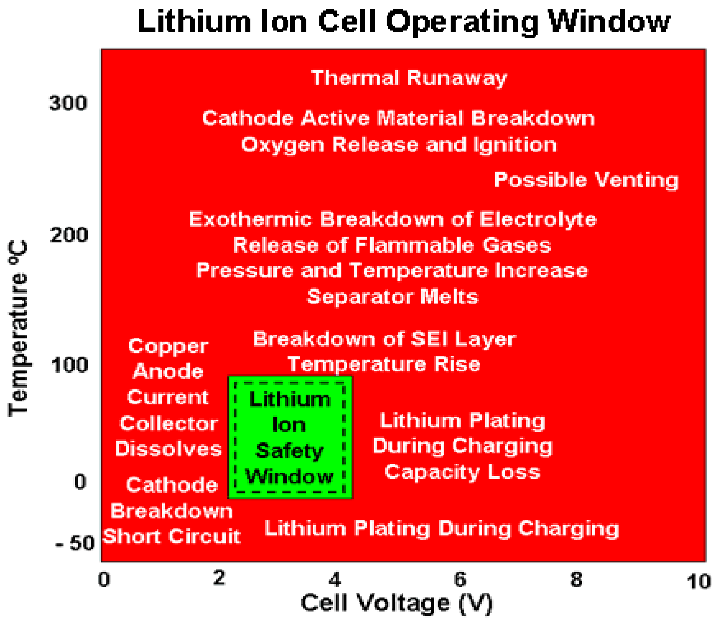
- Charge/Discharge Cycling: Safety hazards result from charging at improper rate, above/below the cell voltage or current tolerance. As shown in Figure 22, the Lithium batteries safety specifications must be maintained through many charge discharge cycles, which lead to performance degradation. The safe operability ranges must be maintained within a narrow window (Figure 23) for: charging temperature, charge voltage limits, charge and discharge current limits, reverse polarity protection, overcharge protection (above the 4.3V cell limit), and over-discharge protection (when cell voltage decays below 2.3 V). Typically, fuses are designed to open automatically when an unsafe, out-of-specification condition occurs, in order to prevent battery malfunction.

- End-of-life (EOL) safety: Manufacturers strive to select recyclable batteries, which can be safely remanufactured and reused, or safely disposed in landfills without leachable toxics.

- Fire Safety: Fire prevention requires the use of thermal management systems (TMS) with forced air or liquid cooling; and a battery management system (BMS) to regulate both current and voltage during charge/discharge cycling. Fires may occur due to either battery overheating (if the thermal management system fails or the monitoring system malfunctions). Possible fuel cell hydrogen ignition and explosion; or secondary fires may be due to sparking during battery overcharge.

- Crash and Electrocution Safety: The NHTSA Federal Motor Vehicle Safety Standards (FMVSS) are applicable to all vehicles below 10,000 lbs gross weight (including Class 7 buses) and ensure the crashworthiness of the full bus system and its subsystems. In June 2010, NHTSA updated its rule FMVSS 305 ("*Electric-powered Vehicles: Electrolyte Spillage and Electrical Shock Protection.*"), first issued in 2000. This rule will ensure the electrical and chemical crash safety performance of battery subsystems using more than 48 V batteries for propulsion power in hybrid, fuel cell, and electric vehicles. It requires separate crash-testing of the battery and electrical propulsion subsystem to prevent electrolyte spillage, and the intrusion of batteries into the passenger compartment. It also requires that the chassis be electrically isolated from the high voltage subsystem to prevent electrical shock to passengers or rescuers. To further enhance the crash safety of emerging hybrid-electric, fuel cell and hydrogen cars, NHTSA is also considering updating existing FMVSS 301 ("*Fuel System Integrity*") and 302 ("*Flammability of Interior Materials*"). The new FMVSS 305 is better aligned with the SAE J1766, Recommended practice for Electric and Hybrid Electric Vehicle battery Systems Crash Integrity Testing. These updated battery crash safety standards will also benefit FCB/ HEB safety.

Figure 33-The Safe Operability Window for Lithium-ion Battery



- International Safety Standards: NHTSA is currently working on the International Standards Organization (ISO) General Technical Regulations (GTR) ECE/TRANS/WP.29/2007/41) to develop a GTR for hydrogen/fuel cell vehicles that is performance-based, and does not restrict technologies, but ensures the safety for the fuel tanks, requires electrical isolation and integrity of the high voltage fuel cell propulsion system, and limits hydrogen leakage from high pressure tanks.

Many other applicable Recommended Practices, guidelines and safety standards[84] for high power vehicle rechargeable batteries and associated chargers and interfaces are undergoing development and/or revisions. The Standards Developing Organizations (SDO) actively engaged include the: American National Standards Institute (ANSI), National Electrical Manufacturers Association (NEMA), National Electric Code (NEC) and National Fire Protection Association (NFPA). The Underwriters Laboratory (UL) also develops battery testing and certification standards: it has recently released a new standard for safety testing of the large batteries required to mitigate battery-related fire and electrical hazards[85] for emerging electric vehicles.

[84] See posted Electropaedia Battery and Energy Technologies monitoring and safety standards posted at http://www.mpoweruk.com/standards.htm
[85] UL Subject 2580, "*Requirements to Mitigate Hazards for Electric Vehicle Batteries.*"

4. Preliminary Findings on RESS Research Needs

4.1. Bus RESS Performance- Lessons Learned and Research Needs

For over a decade, advanced bus technology demonstration and evaluation projects were sponsored by Federal agencies, in partnership with state and local transit authorities and with industry. Electric drive and fuel cell prototypes were usually over-designed for safety assurance, operated sporadically, carefully monitored and preventively maintained to avoid unsafe conditions. According to some experts consulted, the eleven fuel cell buses developed, demonstrated and evaluated by FTA and NREL to date were probably safer than future commercial fleets of fuel cell hybrids and advanced hybrid/ electric buses, because of close technical oversight and preventive maintenance. Ongoing NFCBP consortia efforts to develop and demonstrate an improved second generation of hybrid electric fuel cell buses will also put a premium on safe operability at higher cost, to enable future development and deployment of cost-effective, commercial in-service bus fleets and O&M practices.

Key lessons learned from demonstrations of fuel cell hybrid-electric buses to date are evident from the latest (October 2009) overview of all NREL/FTA NFCBP hydrogen and fuel cell bus evaluations.[86]

- The on-board energy storage capacity must be optimized within the hybrid propulsion powertrain. Energy storage subsystems have not reached the Technology Readiness Level (TRL > 6) needed to optimize, standardize, integrate and manufacture for bus fleets competitively.

- The bus weight (including battery, fuel cell stacks and hydrogen stored on-board) must be reduced to improve fuel efficiency and extend range.

- The average number of Road Calls (RCs) and the Mean Time Between Road Calls (MBRC) reported by NREL evaluations were substantially higher than for conventional diesel and CNG fueled buses.

- Standardization and quality control are needed to achieve bus lifecycle cost and performance goals. Both technical and safety standards are under development for the electrical subsystems, interfaces and associated infrastructure.

- National standards for the RESS components safety and operability test and certification must be developed and internationally harmonized;

- Commercial deployment of electric drive buses is premature until subsystems are optimized and integrated to meet specific bus operational requirements. For large scale commercialization, a 12 year bus service life in revenue operations must be

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[86] *"Fuel Cell Buses in U.S. Transit Fleets: Current Status 2009"* NREL/TP-560-46490, Oct. 2009, by L. Eudy, K. Chandler and C. Gikakis at http://www.nrel.gov/hydrogen/pdfs/46490.pdf

achieved and more affordable, reliable and accessible hydrogen production and refueling infrastructure must be deployed.

A recent review of worldwide hydrogen bus demonstrations[87] also concluded that batteries did not perform as well as expected and must be further improved. Substantial improvements are needed in both fuel cell durability and in reducing cost of stack replacements. The report findings concerning potential hydrogen and battery safety issues were encouraging and were addressed during fleet demonstrations so rigorously that service was adversely impacted due to outages for preventive maintenance. The report also recommended that complementary energy storage sub-systems capable of delivering high power pulses for acceleration (such as ultracapacitors, and flywheels) should be integrated with primary traction batteries to enhance electric drive train performance and range.

4.2. Initial Expert Inputs on RESS RD&T Priorities

To supplement the technical literature review and to ascertain that all emerging battery-related safety issues were identified, a few experts from government, university and industry were asked about priority RD&T needs to advance RESS technology. These Subject Matter Experts (SMEs) are recognized for their R&D experience and extensive publications on state-of-the-art batteries and ultracapacitor technology and safety.[88] Highlights supplementing relevant publications on how to improve energy storage systems capacity, durability, safety and affordability on-board buses with hybrid electric drive-trains, include:

- NREL evaluations of prototype technology demonstrations to date indicated that the observed operational safety of fuel cells, hybrid electric bus RESS and batteries resulted from a combination of overdesign and of over-cautious response to fault detection. Bus operation was usually stopped for inspection and preventive maintenance on warning of potential battery problems. This approach would adversely impact bus service reliability and availability of future commercial hybrid-electric drive buses. Therefore battery management systems (BMS) and thermal control systems (TMS) must be automatically, reliably and appropriately diagnose and respond to detected faults.

- NREL has not yet evaluated the safety of lithium-ion batteries in commercial hybrid electric bus operations. Usually, the energy storage or power train integrator (e.g., BAE or ISE) for a new bus selects the battery based on bus weight, size and power requirements, with safeguards (packaging, BMS, TMS) provided by the battery OEMs. Since AC Transit is presently using the A123 nano-phosphate lithium-ion (LFP) batteries in its hybrid buses, as will the NYCTA hybrid buses on-order, a safety and operability evaluation is needed to

[87] "*A Report on Worldwide Hydrogen Bus Demonstrations, 2002-2007,*" March 2009, FTA-GA-04-7001-2009.01 posted at www.fta.dot.gov/research

[88] Appendix A-2 lists the experts who provided references and oral inputs, from a set of twice as many contacted.

more fully examine battery subsystems and their integration with hybrid-electric power trains for bus service duty-cycles and for diverse climates.

- Recent battery technology reviews posted on NREL's Vehicles and Fuels Energy Storage sub-site reveal vigorous research on thermal runway modeling and analysis, aiming to improve battery thermal management. Battery chemistry, size, form factor, packaging and prevention of overcharging and over-discharging, ability to maintain pressure and vent gases, and the chosen cooling systems are all important safety factors. The integration of advanced Li Ion and other battery cells into battery packs (e.g., the control of temperature anomalies, short-circuits, voltage imbalance and rebalancing) are also very important for safe vehicle performance.

- Experts from other DOE National Labs, who have been engaged in battery safety testing and materials options research in partnership with industry, expressed the following informed opinions:

    - At present, all Li Ion batteries are still dangerous and problematic for use in buses since their optimal operation is within a very narrow temperature range and they tend to overheat when discharged or recharged rapidly due to their internal resistance. The safety of buses using lithium-ion batteries must be assured during hill climbing at peak loads, and for hot climates operations. The TMS and voltage/charge control systems are essential to both battery and bus safety: a battery cooling system for dissipating the waste heat is needed to keep temperature differences between cells very small (2-3 degrees).

    - Overcharge protection (similar to systems used for lead-acid and NiMH batteries), is required as Lithium batteries are likely to overheat from high recharge currents during regenerative braking, and thus can cause fires. Since any oxygen release from the cathode is a fire hazard, the best choice for bus batteries is to use electrodes which do not release oxygen if the cell overheats, and avoid materials that can decompose when heated.

    - The Sandia National Laboratory carried out in cooperation with the Argonne National Laboratory extensive abuse testing of lithium-ion batteries with diverse chemistries, in order to understand the effects of battery chemistry on its tolerance to physical, electrical and thermal abuse.[89] As a result, the SAE Recommended Practice for abuse testing of batteries was updated[90] with new recommended tests to prevent generic battery failure scenarios. Failure modes to be prevented and managed include: overcharge and over-discharge; high temperature effects, gas

[89] a) E.P. Roth and D.H. Doughty "*Thermal abuse performance of high-power 18650 Li-ion cells*", Journal of Power Sources 128 (2004) 308–318; b) E.P. Roth "*Abuse Response of 18650 Li-Ion Cells with Different Cathodes Using EC: EMC/LiPF6 and EC:PC:DMC/LiPF6 Electrolytes*" at Electrochemical Society (ECS) Conference, 2007; c) D. H. Doughty, *E.P.* Roth, et al., "*Effects of additives on thermal stability of Li ion cells*", in the Journal of Power Sources 146 (2005), 116–120.

[90] *"Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing," SAE J2464 (R).*

generation, electrolyte leakage, short circuits and crush on impact. Since there are no current standards for battery module designs, system level testing is needed to identify battery and power-train failure modes related to integration interfaces.

- Battery companies are striving to ensure battery operational safety with monitoring and control systems for cooling and State-of-Charge (SOA), safety valves (to vent any oxygen) and quality control (QC) packaging and stacking of cells. These technologies are still being developed and rapidly evolving, so that their shake-down is likely to continue for the next few years before reaching readiness for electric drive vehicle integration and commercialization.

- Industry experts have investigated real, in-service lithium-ion battery fires, explosions, short-outs and tested commercial batteries to understand how a thermal runaway is initiated and how it can be prevented. Cells have failed in the field during normal operation causing thermal runaway and fires due to internal shorts, and not under the abuse conditions used in tests. It is clear that quality testing procedures today, and monitoring by existing cooling and control systems, cannot ensure battery safety in the field, especially for vehicle applications. Furthermore, since battery safety is also a systems integration issue, focused RD&T is needed to optimize materials selection for Li-ion battery electrodes, electrolyte, separator, and packaging, coupled with lab testing and simulations. Improved understanding is needed to prevent or stop the propagation of internal cell short circuits that could cause fires or explosions.

- University experts have also evaluated the technology readiness and safety of diverse advanced batteries and ultracapacitors for use in EVs, HEVs and PHEVs. These evaluations indicated that battery systems safety depends on how the cells are packaged and stacked. “Prismatic” cells stack well, but may overheat if there is not enough space allowed between the stacks for efficient cooling. Sufficient hours of operation under realistic service conditions are needed to determine the proper level of safety for battery design options. Although battery components may be safe, their integration into the driveline and their position on the bus (on roof, under motor, in floor or in the back) may introduce unsafe conditions. The current overdesign for developmental hybrid-electric drive is a good strategy to prevent hazards related to the battery, until all possible failure modes over the bus operating life are identified and understood. Experts agreed that the shakedown of batteries for hybrid drive vehicles will take a few more years before maturing so that commercialization is achievable.

- Currently, a preferred RESS technology option for achieving both operational safety and reliable performance is to combine ultracapacitors with batteries, as well as to optimize RESS configuration by improving the power monitoring and control electronics for both. Although the ucaps are the safest electrical devices known, they too can blow up and/or incinerate if overcharged. Commercial ultracapacitor stacks have insufficient energy storage for urban bus operation, but can achieve sufficiently high power for acceleration, and have the capability to rapidly recharge on braking. However, novel nano-technology ultracapacitors with both high energy and high power capabilities ("batacitors") are being developed for this eventual application[91].

These preliminary findings on RESS RD&T priorities from the literature and selected experts, served as a basis for developing and conducting structured interviews with a broader and more diverse set of experts and stakeholders, including early transit authority adopters, as discussed in Chapters 5 and 6.

[91] See for instance postings at http://newenergyandfuel.com/http:/newenergyandfuel/com/2009/06/19/a-combined-capacitor-and-battery-technology-from-japan/; and "*A New Model for Regenerative Electrical Energy Storage*", Joel Schindall, 2008**,** at lees-web.mit.edu/

5. Inputs on RESS Technology Readiness from Experts and Stakeholders

5.1. Approach to Collecting Experts' Inputs

Chapter 5 summarizes inputs on hybrid and electric bus Rechargeable Energy Storage System (RESS), obtained from a representative set of informed Subject Matter Experts (SMEs) from academia, industry and Transit Agencies (TA) (see the respondents listed in Appendix A-2). They were invited to provide inputs on the technology readiness of advanced RESS components and systems, as well as share Lessons Learned, Knowledge Gaps, R&D priorities for next Steps, and commercialization challenges. The respondents' insights and suggestions for improving RESS capabilities for hybrid-electric drive bus applications are discussed below.

The 2009 TCRP Report 132 funded by FTA (*"Assessment of Hybrid Electric Transit Bus Technology"*)[92] reviewed the advantages and trade-offs for currently deployed hybrid electric bus technologies, but with a life cycle cost model (LCCM). The report's Appendices contain up-to-date information on existing Hybrid Bus architecture and technology options worldwide, on RESS components for hybrid, electric and fuel cell buses (batteries, ultracapacitors, fuel cells, and/or flywheels). In addition, the number and market share of hybrid electric buses (HEB) and their US and global manufacturers and suppliers are documented. The diversity of hybrid architectures for HEB and FCBs as of 2009 was noted: By 2006 there were 31 different types of FCBs developed or underway, in different sizes (30, 40 and 60 ft.), with various electric drive motors (DC or AC) and several classes of electric motors (asynchronous, synchronous, induction, permanent magnet, etc.) with diverse battery chemistries. Abroad, 58% of deployed HEBs had a series driveline optimal for start and stop city driving, but only 18% featured parallel drivelines more efficient for over-the-road and intercity routes. In the HEB industry, rechargeable chemical batteries were used for energy storage in 67% of the HEBs, compared with 12% ultracapacitors and 3% flywheels (see Fig A-9 and text, ibid.). In the US HEB market as of 2008, three manufacturers dominated (BAE Systems- 2536 series hybrid buses by 2007, GM-Allison- 942 parallel hybrid buses; and ISE Corporation- 280 series gasoline hybrids), with only a small number of hydraulic hybrids manufactured by Eaton Corporation, and only about 50 E-Bus electric (22 ft.) shuttle buses with Capstone micro-turbo engines.

A Research Interview Guide was developed (Appendix A-1) to structure outreach to stakeholders; it was then tailored to their specific affiliation, experience and interests. Both long and short versions of the interview guide were developed in order to secure responses from busy industry respondents.

The list of Electric Drive Strategic Plan (EDSP) projects included in the FTA Multi-Year Research Program Plan (2009-2013)[93] was the basis for structured interviews with the SMEs. The EDSP projects represented the 2008 consensus of diverse transit technology stakeholders in support of FTA's Strategic Objective 3.4, *Investigate the Use of High-*

[92] Available to download at http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_rpt_132.pdf
[93] The FTA Multi-Year Research Program Plan (2009-2013) is posted at http://www.fta.dot.gov/assistance/research_research.html

Efficiency Technologies and Alternative Energy Sources. Specifically, Figure 5-1 and Table 5-8 (ibid.) identified three of five high-priority program areas related to RESS for hybrid electric bus drives: program implementation; vehicle energy management; electrification; and bus design. Feedback from SMEs was sought in order to update RESS-related topics for several advanced bus projects listed below:

V1. Compendium of Energy Storage Technology Options for Transit (FY2010). Provide FTA and transit agencies an objective source of the most recent information available for vehicle energy storage systems.

V2. Development of Performance Interface Standards for Energy Storage Systems (FY2012). Develop and support the use of standards to improve the quality and reduce the cost of advanced energy storage systems for transit vehicles.

V3. Demonstration of Advanced Energy Storage Solutions for Transit Buses (FY2012). Facilitate the improvement and validation of advanced vehicle energy storage systems to improve capacity and reliability.

A list of leading Subject Matter Experts (SMEs) from industry, academia and Transit Agencies (TAs) with contact and background information was compiled (only respondents are listed in Appendix A-2). About 25 SMEs responded, and provided inputs on various aspects of RESS and bus electric drive design, development, cost, or operation, focusing on lessons learned and priority RD&T needs These respondents included: 9 leading university experts; 8 managers of operations and maintenance (O&M) for hybrid, electric, or fuel cell bus fleets, or managing advanced fuel cell bus prototypes and refueling infrastructure; and 8 industry representatives, including manufacturers and integrators of fuel cells, batteries and hybrid or electric drives for advanced hybrid or electric buses. The following sections summarize their views on lessons learned from design, development, test and evaluation of HEB/FCB buses to date, current RESS technology options, and suggestions for the Next Steps needed to address knowledge gaps and remove obstacles to RESS technology commercialization, integration and deployment.

5.2. Lessons Learned on RESS and Energy Efficiency

The lessons learned (LL) relevant to bus energy storage technologies varied widely among the diverse stakeholders segments (transit agencies, industry and university researchers), reflecting their experience with the design, development, test, evaluation, or operation of hybrid electric, electric, or fuel cell buses. Some LLs are generic, and some are very technology-specific, but they help refine the R&D needs and Next Steps presented below.

5.2.1. Transit Authorities (TA) Operations of HEB/EB/FCBs

A TA manager, who has been operating more than 120 MCI parallel hybrid electric buses (with GM Allison two-mode EP40 and EP50 propulsion and Cummins engines) and 130 Orion VII series hybrid buses, noted that:

- The fuel efficiency (FE) of hybrid buses was not as good as promised. The GM Allison two-mode (parallel and series) EP 40 and 50 hybrid buses were designed for efficient over-the-road operation in parallel mode, and stop-start using the series drive. They had higher in service fuel efficiency (4.4.-5.1 mpg) and better reliability than the Orion series hybrid buses. Series hybrids, designed for stop-and-start city routes, typically achieved 2.4-4 mpg in hot climates, but occasionally up to 8 mpg (in cooler locations like New York City).

- The longevity of emerging lithium-ion batteries for buses must be proven in service: it has been good (6.5-7 years) for the Ni Metal hydride battery used in GM Allison parallel hybrid buses. However, the durability and reliability of new Li ion batteries in the Orion VII is not yet proven in service, appears to be only half the life of the bus at best, and Lithium-based batteries are costly to replace (a 5-6 years warranty was available, but not purchased because of high cost).

- RESS technology applicable to electric drive buses is rapidly improving, so any repowering or retrofits for HEB buses could exploit this Best Available Technology (BAT) for traction batteries.

- The increased electrification of auxiliaries (e.g., to replace hydraulic fan drives), use of automated stop-start systems and of lighter solid-state DC-to-DC converters (also called “beltless alternators”), and the reduction of parasitic losses (e.g., electric fans) also promise to improve the efficiency of RESS. For instance, GM Allison[94] plans to use a DC-to-DC converter to replace the alternator in its new hybrid bus and truck, in order to improve its FE.

- Special electrical training and lock-out procedures were needed to ensure the safety of HEB maintenance staff dealing with the high voltage (up to 600 V) RESS and to enforce safe recharging procedures.

Another TA manager, who has operated for several years a fleet of gasoline HEBs (40 ft New Flyer buses with ISE series hybrid drive, using Siemens ELFA electric motors and power electronics) noted that:

- HEBs did not live up to their initial energy efficiency and environmental performance promise, but have improved over time.

[94] See specifications for the Allison H40 and H50 EP drives at www.allisontransmission.com/commercial/transmissions/hybrid-bus/

- It took 5 years of experience and more than 11 million hours of service for this TA operations and maintenance (O&M) staff to get up to speed on the learning curve regarding the best practices for HEB operational performance and safety.

Another TA manager with unique experience in operating and maintaining successive generations of Ebus fully electric shuttle buses, alongside with a fleet of parallel HEBs and diesel buses, offered some comparative lessons learned:

- Both hybrid and electric buses required high cost premiums, but have achieved quieter and environmentally friendly service;

- Running and maintaining an electric shuttle bus fleet on fixed routes requires dedicated, well trained staff, and continual learning;

- Both electric power costs for recharging, and bus batteries costs are still high;

- The mean time between road calls (MBRC) for Ebus were comparable to HEBs and diesel buses, but electric bus failure causes differed as follows:

    - There were some, though rare, NiCd battery outages. NiCd batteries had an acceptable average life of 7 years(still half of the bus life), but had problems with range, thermal events, and potential safety hazards (e.g., hydrogen outgassing incidents due to electrolyte leaks and plastic case cracking);

    - Nationally, as reported by Enova Bus, there are presently 10 electric buses (EBus) running in Santa Barbara, 5 in New Haven, CT, and 10 in Anaheim, CA. These start-up Ebuses used 2 NiCd batteries, of 60KWh per bus. Though the first generation Ebuses met users' expectations (e.g., in Santa Barbara, where there are no windows and no air conditioning), other users in hot climates did not have sufficient hotel power from the first generation of NiCd batteries. In Chattanooga, TN and at U. TN the Ebus operation was discontinued, because hotel power for air conditioning (A/C) drained the bus batteries. Other TAs in hot or cold climates (e.g., in Mobile, AL) have also surplused their Ebus chargers.

    - These electric shuttle buses have operated successfully by minimizing the parasitic loads on the traction battery (no HVAC; no alternator; no primary SLI battery; minimal idling; no active battery cooling, though there are 4 fans in the battery compartment for forced cooling in case of overheated batteries; use only DC to DC converter and electric motor for traction power);

    - To date there were no electric shuttle operation safety incidents due to handling the batteries, or their charging infrastructure;

- The advent of more powerful Lithium batteries and RESS would make EB shuttle viable for operations in a wider range of climates. Repowering the EB fleet with new and more advanced RESS battery subsystems is necessary, but proved to be challenging, complex and costly:

  - Older EBs buses with NiCd batteries are now being repowered with new Lithium Iron Phosphate (LIP) batteries to increase current load to 350 Amps. In order to cut costs, some transit authorities have purchased batteries in bulk: for instance, the SBMTD purchased 200 LIP cells and is doing in-house the packaging of cells and configuring them into 2 series and 2 parallel strings for the RESS battery pack. Therefore, there will be 92 LIP cells in a stack, requiring overnight recharging. These new LIP batteries will also need a Battery Management System (BMS) for cell balancing; separate contracts are needed for the complex BMS, and for the computer controlled internal resistance (R test) system;

  - Domestic Lithium Titanate (LTO) batteries were considered, but were too expensive to retrofit the existing fleet;

  - The recharging infrastructure in the depot must be mated to these new LIP batteries and requires additional funds for the design, construction and O&M staff training. Two new chargers, to be built by FerroMagnetics for the TA, will permit faster overnight recharging to 80% SoC.

AC Transit, which has unique experience operating and evaluating in service fuel cell electric drive buses (FCB), shared the lessons learned from its first 5 years of operating the first generation fuel cell buses, towards improving the next generation of FCBs:

- <u>More operational experience is needed to improve technology for RESS and the electric drive buses</u>:

  - There were only 3 Fuel Cell gasoline (ISE series) hybrid electric Van Hool buses with Siemens ELFA drives, which used large and heavy ZEBRA batteries and UTC fuel cells as APUs, but operated well;

  - There is good operational and safety experience with the H2 refueling infrastructure, which uses on site H2 production from steam reformed natural gas, and a solar compressor (the first 3 FCBs can now be refueled at the central station).

- <u>More RESS test, evaluation and improvements are needed</u>: Commercial lithium-ion batteries with diverse chemistries must be evaluated and proven in bus service for reliability, capability, maintainability and cost, while other emerging battery chemistry and configuration options (Lithium Sulfur, Lithium air) are being developed. The 12 new Van Hool FCBs now on order for five Bay Area Transit Agencies are arriving (2/month since May 2010), and 4 more for CTTransit will use RESS consisting of the UTC Power PureMotion 120 fuel cells[95] and EnerDel prismatic lithium-ion batteries.

Another TA manager, who has operated a mixed fleet of clean buses indicated that:

- CNG is now the top choice fuel for the California clean bus fleets: the cost of diesel is $2.50/gal, but only 95 cents for GGE of CNG from SCA Gas. Unfortunately, only the Cummins CNG engine is certified in CA, so there is no suppliers' competition to serve the market for alt-fueled CNG buses.

- Compared to CNG buses, the performance of Orion 5 HEBs purchased a few years ago was not as satisfactory. Even more challenging was the operation of the FCBs tested and of associated H2 fueling stations, which proved to be too expensive to buy, refuel and operate in regular service. This operator will wait for FCB technology to mature, and costs to come down to affordable levels.

Another TA manager, who has operated and evaluated the in-service performance of 250 parallel hybrid buses (out of a fleet of 1500), shared the following lessons learned to guide the planned acquisition of another 150 HEBs:

- Environmental Footprint Compliance with EPA 2010 pollutant emission standards is now assured for all types of new buses, not just for HEBs; current buses, including diesels and the 500 CNG buses, are as "clean" in service as the HEBs. Other criteria than environmental sustainability will have greater influence on bus fleet renewal choices.

- RESS and hybrid drive servicing by bus manufacturers is good: Allison contracted with 2 local companies to repair the warrantied electric drive components within 24 hrs, or as soon as possible.

- HEB Reliability: The MTBRC for parallel HEBs was good and improved over time; in 2006 it was only 7-8,000 mi, then got up to 11,000 mi, which is comparable to the best diesel buses.

- HEB Cost issues: The cost of HEBs is not yet competitive. The cost premium ($150K more per bus) is still too high, as are battery change-out costs after a few years. The CNG refueling infrastructure is costly, and the hybrids are the most expensive (now 558K/bus). Subsidies are needed to renew the fleet.

- HEB Energy efficiency: HEBs initially achieved only 3.7 mpg, but fuel efficiency improved over time to exceed 5 mpg. The latest HEB fuel efficiency was higher

[95] See 2009 news at http://www.utcpower.com/fs/com/bin/fs_com_Page/0,11491,0307,00.html and 2010 NREL update at www.nrel.gov/hydrogen/pdfs/48115.pdf

(5.3 mpg) than for clean diesel buses (3.5 mpg), and their reliability was good as well.

- Energy recovery: Regenerative braking recovery is now more aggressive, with less brake wear, but there is still need for improving it beyond the 25% average.

5.2.2 Industry Lessons Learned

The Electric Power Research Institute (EPRI), which represents electric power generation utilities, is an important industry nonprofit partner on HEB and EB development, test and evaluation projects. EPRI has partnered over the past decade in developing and evaluating several advanced electric drive bus prototypes, including the Ebus 22 ft plug-in fuel cell bus (Daimler hybrid-drive, Ballard fuel cells) and the Georgetown fuel cell bus with methanol on-board reformer. Ebus and the University of Delaware (UDE) designed and maintained the on-board RESS, which successfully used a proven NiMH water cooled battery packs in earlier hybrid electric generations. Ebus has recently replaced them with the AltairNano Lithium Titanate (LTO) batteries, which required less cooling and had longer calendar and cycle life, but lower energy density.[96] Both batteries performed well, reliably and safely (though there no formal safety assessment), including in cold weather.

Lessons learned by EPRI, Ebus and other industry respondents regarding the in-service performance reliability and safety of fully electric buses versus hybrids with range extension (e.g. APUs like fuel cells) were:

- Extended testing, evaluation and redesign is needed to resolve energy storage problems and to improve successive generation of electric drive buses, e.g.:
  - The FC bus was covered under the Ebus contract, but not under separate warranty, so there is no good data available on respective lifecycle O&M problems and costs;
  - No safety incidents occurred with the FC buses that EPRI was involved with, because the Ebus developer built in mitigation efforts, e.g., the controller of the cooling system maintaining the battery safe operation range;
  - It is expected that improved Li Ion batteries will be commercially available by 2012, given the pace of development, and emerging new chemistries (like Lithium Air batteries). The preferred chemistry for lithium-ion batteries is still unclear, though there are a lot of options being evaluated and they all may have performance, safety or cost trade-offs.

[96] See www.ebus.com for details.

- EPRI is currently co-developing a plug-in parallel hybrid drive for diesel shuttle bus, with an RESS for 10 mi range of all electric drive (good for tunnels, or short range operation between charges);

- Range is the main limitation for HEB RESS, since a bus typically consumes about 1 KWH/mile, so the challenge is to increase RESS capacity, not just the energy density for the given battery size and weight;

- A fully electric bus cannot perform as well as trolley buses with overhead catenaries. Plug-in hybrid electric buses (PHEBs) also would require costly charging infrastructure. However, hybrid electric buses (diesel or gasoline or CNG- hybrids) would have the range and power required for urban service;

- The biggest industry (OEM, supplier, integrator) challenge in developing advanced RESS and hybrid electric power trains for advanced buses is the small market size. It's hard for an innovative company to recoup the high cost of advanced bus engineering design and development.

- Upgraded Li Ion batteries for new and improved buses: The 5 electric Ebuses ordered by LYNX in central Washington State will use Lithium Titanate (LTO) batteries from AltairNano and will have an automated charging system (400Amp, 600 V) that does not require an operator to plug into the 2 chargers per charging station. A fast charging (5 min) option from an overhead canopy charger is available[97]. The new Ebus electric bus and the high efficiency HEB 40 ft bus will use Altair Nano cells, to be stacked by Ebus into battery packs of the same size and shape so as to match the old compartment.

- Range Extension needed for existing RESS: Recent electric drive architectures are also more diverse and have been updated with improved and more powerful Li Ion batteries for powerful and lighter RESS, to allow for extended range between charges and for fast charging in stations. Capacitors would not work as well as batteries. For instance, Ebus is testing a high energy density Li iron phosphate (LiFePO) batteries from China for longer range, but are not fielded yet.

- BAT for batteries: The Best Available Technology (BAT) for RESS is continually changing as the technology improves. In the HEB a small 4 cylinder engine drives a light generator (only 700 lbs for engine and generator) to recharge the battery. The high efficiency HEB with LTO battery pack is running as a prototype in Los Angeles. This LTO battery pack, together with the cooling unit and power electronics weighs only 1,500 lbs, but is costly. Though lighter and more powerful (120 KWh), they require aggressive cooling with water and use an electronic thermal management systems (TMS/BMS). The LTO pack for the 22 ft EB costs $250K per bus, which not affordable without federal subsidies.

[97] See the video posted at http://ebus.com/impactmovie

- Cost-sharing is needed: Ebus and Sacramento TA recently proposed to DOE/NREL to build and run 3 x 40ft bus CNG hybrid buses with LTO batteries (a prototype was tested and is running in San Diego). Extending the FTA-funded lessons learned to DOE-funded new hybrid power train buses would clarify the domain of applicability for emerging RESS designs.

Companies which have partnered with FTA on Fuel Cell Bus projects and developed the Fuel Cell Power Plant (FCPP) (e.g., Hydrogenics, Nuvera, and UTC Power) had a different set of lessons learned. For instance, Hydrogenics is currently a partner under 3 FTA NFCBP projects: the CTE/Proterra/Columbia bus demonstration; the NAVC/GE Global Research battery dominant bus development; and the Calstart/ BAE/SF MUNI Bus 2010 project that will use both the Hydrogenics FC APU and a lithium-ion battery for the on-board RESS. The HyPM fuel cells (FC) modules have been integrated in both new and converted buses. A New Flyer 40 ft bus used the HyPM 65 (with 189 KW power) FC power module was integrated into a ultracapacitor- FC hybrid power train and demonstrated in Winnipeg in 2006. In Europe, the Midibus electric bus has operated in 2006 for 10 hrs and 200 km range between refueling (using NiCd batteries). Specific Lessons learned are that:

- The technology developer (e.g., Hydrogenics) must also serve as integrator and battery OEM, and work closely with both the bus platform manufacturer and with the customer;

- Training (on safety and handling, refueling, etc.) is essential for quality and performance in bus applications;

- Buses with large space allowed for power plant and cooling/ventilation are a plus to allow for easy maintenance and repowering;

- Hydrogen is the FC fuel and requires dedicated refueling infrastructure. The H2 price fluctuates depending on where and how H2 is produced, so on-site production is desirable.

- A FCB fleet requires dedicated H2 refueling stations, maybe on-site production, sophisticated self diagnostics and leak detectors, and technicians training. It's more expensive, but cleaner than competing hybrid bus options.

- The FC has improved over time, with MTBF of 1000- 2000 hrs now. This MTBF is on par with gas hybrids, but worse than for electric buses, but offers the performance gains (no offline charging, no 2nd or 3rd battery needed for range).

- The FC and integrated FCPP power plant are fully warrantied to cover repairs and replacement. Quality, performance and price must be benchmarked to be competitive.

- The key criteria for selecting a bus battery and RESS integrator were:

    a. Technology Readiness Level

    b. Cost

    c. Compatibility with a particular fuel cell engine.

    d. Availability – many integrators have been changing business direction and focus away from bus applications to larger markets of Commercial Vehicles (CV) and/or personal vehicles (PV).

- The RESS choice matches power plant and FC hybrid bus needs: The RESS energy output depends largely on the duty cycle: There were changes in the on-board energy storage partners, so Nuvera is reconsidering battery selection. The initial plan was to utilize an 80kW engine with an ISE system, but a second integrator had a larger capacity battery layout, so a smaller output engine could match that system. A third integrator has a 150kW system which would require two of our engines.

- Determine the Best Available Technologies (BAT) for RESS on-board HEBs: Though lithium-ion batteries have been considered, it's not clear yet which battery type will be used, since the RESS is normally selected by the system integrator. From an efficiency and energy density standpoint, the lithium-ion would offer the most benefits vs. drawbacks, although a good battery management system (BMS) is needed. Because of the required cooling and charge monitoring systems, the new lithium-ion batteries are more challenging to integrate into an electric drive architecture than previously used batteries, especially when fuel cell APUs are also needed (like in a battery-dominant FCB). However, the lithium-ion batteries charge/discharge cycling efficiency is higher, so their adoption would be advantageous to improve energy efficiency.

- Further RESS subsystem cost reduction is needed for HEBs and FCBs: The cost of a large and powerful Li Ion battery pack is still too high to be affordable. The RESS on a typical bus must provide both traction power, and auxiliary loads (hotel power). Only a small amount of power is needed to get a FC engine going at steady state, so a RESS combining a Li Ion battery with a small Fuel Cell in the battery dominant fuel cell hybrid buses now under development and demonstration could also save money, parts, weight and space.

- Stable partners are needed to develop a new FCB prototype with efficient RESS: FTA could help facilitate and overcome this challenge: Nuvera originally partnered with ISE as drive train integrator utilizing Nuvera's FC engine. Due to funding delays, some of the original partners changed their direction, so Nuvera is now looking for a new integrator and the bus configuration is still being developed pending integrator's commitment. Also, more timely FTA funding is essential to the survival of advanced bus development and demonstration partnerships

- Shorter timetables for FCB commercialization require greater federal investments: The respondents pointed out that the time table for commercialization of an affordable fuel cell for use in an electric drive buses depends on the federal and private industry investment level. Though FC performance has continually improved over time, affordability is tied to levels of investment. Though the commercialization of FC for buses with advanced electric drive and RESS is possible in less than 5 years, it would require a huge effort and investment. The feedback loop is determined by how much government support is available.

  More focused efforts and higher funding levels are needed to further fuel cell hybrid bus technology towards US commercialization, including efforts to:

- Develop reliable power management system that balances the fuel cell and the battery capabilities as an integrated power source and minimizes first & life-cycle costs while meeting performance requirements;

- Accelerate field durability testing of fuel cells as part of a full RESS subsystem in real bus service duty cycles, in order to verify and validate (V&V) lab simulations and testing;

- Refine the first cost and lifecycle cost models (LCCM) for fuel cell hybrid buses, including the cost of H2 production and of refueling infrastructure;

- Increase current funding levels for manufacturing development to accelerate technology deployment readiness for further cost reduction of next generation FCBs.

5.2.3. University Researchers

The university researchers who provided inputs in addition to initial feedback received and reported in Section 4.2 had direct experience in evaluating and improving automotive batteries and ultracapacitors for optimal RESS components designing advanced hybrid electric and/or fuel cell bus power-trains, and/or working with bus designers, integrators and manufacturers (e.g., ISE, Proterra, Sinautec). Some experts consulted are developing novel energy storage technologies, such as the “batacitors” (a name for ultracapcitors with the high energy capacity of batteries, able to rapidly store recovered kinetic energy and provide it at peak power demand.) Notable lessons learned include:

- Technology options for bus hybridization have not yet been optimized for a specific operational profile: Although there are many hybrid-electric drive-train architectures and components choices, there is no standard platform or power-train design. None of the HEB/EB/FCBs RESS technologies are commercially competitive as yet. This fragmentation of an already limited bus market makes the fleet-wide deployment of HEBs, EBs or FCBs more difficult.

- Optimal RESS integration and performance require in-service validation: As discussed in the TRB/TCRP report 132 (2009), several competing bus hybridization options have shown performance improvements over time, but the battery technology base is evolving faster than the bus lifetime, and needs to undergo shakeout in service over the next few years to "right-size" the battery for specific bus route and climate needs and to determine the best value choice.

- Identify "winners" among competing electric drive bus technologies: Though many competing advanced buses, cleaner fuels options, and associated infrastructure have been demonstrated and evaluated over the past two decades, benchmarking is needed to select the best candidate amongst:

    - RESS subsystem and components (many battery chemistries still being improved for commercialization, same for ultracapacitors);

    - Electric motors (AC induction motors of several types);

    - Power electronics controllers and battery management systems (BMS);

    - Diverse HEB drive-train architectures (series, parallel, complex);

    - Cleaner fuels (gasoline, diesel, CNG, hydrogen, etc.) and tailpipe controls;

6. Recommended Research to Advance RESS Technology

6.1. Priority RD&T Needs

Responding SMEs identified several priority RD&T thrusts, both in order to improve the energy storage components and subsystem, and to ensure RESS integration with hardware and software for power management and control (PMC) electronics:

- Develop, Improve, and Conduct RESS Modeling and Simulation (M&S): Simulations and lab measurements of batteries and RESS are necessary, but not sufficient, in order to save money and predict vehicle performance, prior to building a full scale bus prototype to test and evaluate in service. The *ADVISOR (ADvanced VehIcle SimulatOR)* model was created in 2002, and improved since by the Department of Energy's National Renewable Energy Laboratory's (NREL) Center for Transportation Technologies and Systems[98]. It's a flexible modeling tool that rapidly assesses the performance and fuel economy of conventional, electric, hybrid, and fuel cell vehicles. The *Powertrain Systems Analysis Tool (PSAT*) model was developed by the Argonne National Lab (ANL) [99] to evaluate vehicle performance and fuel efficiency for various fuel cell (FC), hybrid electric (HEV), plug-in hybrid electric (PHEV) and electric (EV) power-train design options. This priority research need was discussed by UC Davis (UCD) experts, who have successfully used the NREL ADVISOR model and the ANL PSAT model to simulate performance of hybrid electric and electric vehicles, by adding and improving modules.

- Complement M&S with Hardware- in- the- Loop (HIL) testing before prototype development: M&S theoretical results must also be verified and validated (V&V) in lab tests and complemented with real Hardware-in-the-Loop (HIL) battery and ultracapacitors testing, in order to trust the M&S results for complex RESS systems and bus architectures. Such HIL test data are used as inputs to the models used to predict the full-scale system design and performance for a broad range of in-service and climate conditions. Battery cells and stacks should be tested together with the BMS and/or TMS for a full range of bus in-service power loads, temperature for diverse climates and operating conditions.

  For instance, UCD researchers have both modeled and tested in the lab alternative options to the Altair Nano Lithium Titanate (LTO) NanoSafe prismatic battery cells used in the Proterra electric bus RESS. Tests confirmed that the battery chosen has up to 100 mi range on a single charge, and can absorb regenerated braking power and be rapidly recharged (to 90% capacity) in less than 10 min during station stops. Modeling studies complemented by HIL lab testing indicated that LTO batteries are better for long cycle life than Li Iron Phosphate batteries (LPO), which can undergo only 1-2,000 cycles of deep discharge before performance is degraded. Though its energy density is not the best, the LTO cycle

[98] See ADVISOR model information at *http://www.nrel.gov/analysis/forum/pdfs/2004/advisor_poster.pdf*
[99] See PSAT model description at http://www.transportation.anl.gov/modeling_simulation/PSAT/index.html

life durability is good. However, both M&S and lab tests indicated that the battery stack requires a reliable Thermal Management System (TMS), using air or water cooling to maintain temperatures in the range needed for safe operability.

- Conduct independent Test and Evaluation (T&E): In service validation testing of RESS operation in real bus prototypes is also needed to extend and confirm M&S and lab testing. Independent testing and safety assessments should also be performed on each RD3 effort to develop confidence in results and robust safeguards. If even one bus or charging structure is burned down by a battery incident, this would likely set the entire vehicle electrification industry back a decade.

- Perform comparative assessments of lithium-ion battery chemistries to identify performance and safety tradeoffs: Different lithium-ion battery chemistries have trade-offs in voltage, capacity, power, safety, durability, etc. Tradeoff analysis is needed to select the best choice that satisfies RESS performance and safety requirements, constrained by lifecycle costs. Battery manufacturers usually post Materials Safety Data Sheets (MSDS) that were found to provide incomplete, inaccurate, or insufficient information to reliably predict the RESS safety performance over the full cycle life and range of environmental conditions. For instance, lab testing at UC Davis has indicated that Lithium Titanate (LTO) batteries are the safest RESS option on-board hybrid electric buses, since it's harder to get a thermal runaway event than for competing chemistries. However, since both batteries and capacitors can leak corrosive and combustible electrolytes, solid state or polymer compositions are preferred.

- Improve both lifecycle performance and safety for advanced rechargeable batteries and Fuel Cells (FC) used as Auxiliary Power Unit (APUs): To accomplish this objective, it is necessary to optimize the integration of RESS within the electric drive power management and control and with specific Thermal Management System (TMS) and/or Battery Management System (BMS) so as to avoid thermal runaway events. BMS/TMS are also needed for battery voltage monitoring, cells balancing, health assessment, and operational safety.

- Innovate and validate to deliver better battery performance at lower cost: Further R&D efforts are needed to improve HEB/EB/FCB batteries and achieve longer life and deep discharge cycling at lower cost. The RESS subsystem is a sizeable fraction of the high FCB cost ($2.5 M/bus now), which also requires expensive H2 refueling infrastructure ($6M per hydrogen station).

- Standardize and optimize simultaneously RESS and commercial hybrid bus architectures: Although RESS technologies are still evolving, the challenge is to standardize the hybrid electric configuration for optimal performance by vehicle class and duty cycle, so as to enable economies of scale and easy maintenance. The RESS for HEB drive-trains has not yet been optimized and standardized as an integrated subsystem compatible with multiple bus platforms. Standards are needed for the bus industry and their suppliers to prevent currently confusing claims of HEB and RESS capabilities that may not be accurate in a real-world operation or climate setting. Integration and optimization are needed to achieve the objectives desired by transit bus fleet operators, such as: in-service fuel efficiency, reduced emissions, proven durability, and O&M cost savings, which are best suited to bus routes and driving schedules. This lack of standardization for hybrid-electric and electric drive vehicles and the many choices of yet unproven architectures and components could cause further bus market fragmentation for suppliers and integrators, as well as higher costs of products, maintenance and operation.

- <u>Fill knowledge gaps on Battery and RESS durability</u>: The durability of RESS systems in transit bus applications is not well understood and has not matched by far the bus service life. R&D is needed to build more capable RESS life and performance models that include shelf life and ambient temperature impacts. It's desirable to integrate the RESS modules into a whole bus system performance and cost optimization framework. The "building block" modeling approach promises RESS solutions that are better rounded and more realistic. The benefit desired by TAs is a cost competitive, long-life HEB/EB/FCB fleet that leverages the best attributes of each available technology, without over-specifying (and thus increasing costs) RESS requirements.

- <u>Additional research topics suggested to advance RESS in HEB/EB/FCBs also include:</u>

    - Optimization of the power management system (PMS) considering together the RESS and Fuel Cell APU durability.

    - Understand the full spectrum of bus integrated system operating conditions, as affected by RESS, APU and power control subsystems durability and reliability for them.

    - Develop novel power management and control systems (PMS), that can leverage the degrees of freedom available from integrating other (e.g. HVAC) systems into the power management envelope. The PMS optimization requires development of associated control hardware and software for the full envelope of transit bus applications.

- <u>Exploit related technology initiatives by other federal agencies, which are applicable to bus electrification</u>: FTA could consider and exploit R&D by DOE labs (BNL, ANL, ORNL and NREL) on electrified passenger and heavy duty commercial vehicles, which focuses on electric machines and power electronics, as well as on energy storage. These efforts will also benefit HEB/EB/FCBs. For instance, Oak Ridge National Laboratory (ORNL) is working on inductive, through-the-road charging of on-board RESS. The technology seems well suited to opportunity- charging of hybrid electric buses in bus depots, shuttle bus loading areas, etc.

- Develop FCB Standards for joint Hydrogen and advanced batteries systems safety : There are several Standards Development Organizations (SDOs), such as the National Hydrogen Association (NHA) and the Society of Automotive Engineers (SAE), working on standards for hydrogen storage on-board vehicles, but state and local permitting authorities and, the Fire Marshalls, and emergency responders (EMTs) are overly cautious in allowing FCB and refueling operations. SAE, Underwriters Laboratory (UL) and others are also developing testing and safety standards for advanced Li Ion battery in hybrid-electric vehicle applications. However, there is no coordination for timely standards development. FTA and APTA could work to ensure that bus electrical and hydrogen safety standards are developed and made available soon, to enable commercial deployment of FCB/HEB/PHEB/EBs.

- Develop RESS Lifecycle Model (LCM): The TCRP Report 132 developed a Lifecycle Cost Mode (LCCM) for 3 fleets of HEBs. However, in addition to the HEB LCCM, a detailed and realistic RESS Life Cycle Model (LCM) of materials and operational performance is needed to help designers, integrators, and bus operators select among competing alternatives of batteries and auxiliary on-board power sources. Since lithium-ion battery performance degrades with age, temperature and discharge rates, the LCM for RESS should account for advanced battery materials degradation, energy density decay and battery failures over time. This LCM should address not just lithium-ion battery cost and cycle life, but also how to safely and efficiently manage the battery cooling using a TMS. The LCM should also include environmental recycling or disposal issues, and the residual value of used batteries. This is especially needed for the complex RESS in battery dominant hybrid FCBs, where both fuel cells are used as APU to complement energy stored in advanced batteries. This research will help overcome current FCB/HEB deployment challenges due to lack of experience or confidence in emerging lithium-ion and other batteries.

- Optimize the Power Electronics and Control for RESS: Power electronics are a key component for efficiently managing combined hybrid drive RESS systems for the full range of HEB/EB/FCB architectures and operations, including for example both a battery for steady state energy storage, and a capacitor for rapid capture and delivery of regenerative braking energy. Recharging the battery at a high rate may damage performance and shorten the Li Ion battery life, as well as cause thermal runaway events for high temperature operation,, unless continuously monitored and prevented by the power electronics subsytem.

- Overcome with continued R&D the technology and cost barriers limiting battery life : Current limits to Li Ion operational life prevent large scale deployment in buses, which require reliability and durability. Even battery swapping models like that proposed by A Better Place, Inc. do not address as yet the limited life cycle for rechargeable and expensive Li Ion batteries.

- Evaluate the performance of RESS combining advanced batteries with ultracapacitors (ucaps): To achieve more efficient energy recovery, storage and power management in stop and start cycles of normal daily operation, ISE and the Proterra bus architecture combined rechargeable lithium-ion batteries for steady state loads, with ucaps that rapidly absorb and deliver power bursts. However, the Maxwell ucaps cost and weigh as much as Li ion batteries packs, so combined battery and ucaps RESS power packs in a hybrid and fuel cell buses may not be the most cost-effective, and could decrease fuel efficiency due to extra weight and add complexity to power management.

- Evaluate and compare strategies to improve HEB energy efficiency when used in concert for compound impact on energy savings, including:

    - Pay more attention to the full electrification of HVAC auxiliaries, e.g., remove the hydraulic pumps to improve energy efficiency and reduce complexity;

    - Eliminate parasitic loads on the electric drive (e.g., from hydraulic pumps, fans cooling the motor, etc.) and replace them with lower power electrical equipment. For example, the EMP electric (micro-turbine) fans saved 9-11% of bus energy consumed in 2 years;

    - Rely only on the traction battery pack and eliminate unnecessary equipment, such as the alternator now recharging the 12-24 V Starting-Lighting and Ignition (SLI) primary battery;

    - Lighten all bus components and subsystems, not just the body panels and chassis;

    - Improve bus aerodynamics to reduce energy losses;

    - Retrofit buses to automate stop/start Developing new electronics retrofit kits for large scale deployment could reduce fuel and emissions due to idling. (Note that EPA idling restrictions for buses now require the motor to shut down after 20 min., but 5 minutes is feasible); and to install low power and long life (7 yrs) LED lighting;

    - Conduct RESS durability tests and develop models for transit applications: Testing by RESS suppliers has focused on classical battery cycling scenarios. The spectrum of operating conditions encountered in the field may be very different from the test protocols in the lab. Durability testing is time-consuming and some accelerated tests may need to be carefully designed. New R&D is proposed to:

        - Develop durability prediction capability for different RESS architectures, bus drive-cycles and full range of ambient temperature operating conditions; and

        - Target fielded RESS systems in addition to lab tests to narrow the expected lab-field gaps in these predictive models. This project might cost $ 4 million (if it leverages other DOE initiatives in this area) and take 4 years to complete.

- Promising strategies suggested to speed up early FCB commercial deployment include:

    - Expand scale of field tests: The FCBs have typically hybrid electric drives, with RESS consisting of both FCs and batteries. It is desirable to expand the scale of field testing and evaluation of FCBs in order to speed up bus fleet integration, encourage broader adoption and achieve economies of scale to drive down acquisition and operation costs. Easy access to refueling infrastructure in a central location is needed for smooth operation and to make FCBs visible as a public transportation option. Selection of projects in large urban areas could maximize the environmental and energy benefits of having a fuel cell hybrid system (vs. diesel systems), such as improved air quality from the zero emission system, no particulates, quiet operation etc. It's best to start with large transit fleets that have the tools, training and equipment for early service support. Also, concentrated deployments can create high H2 throughput, and sufficient fuel demand for all the vehicles, so as to make the costly H2 refueling stations more viable.

    - Improve Advanced Battery Integration into FCBs: Accelerated evaluation of Lithium-Ion batteries with multiple chemistries within a given Hybrid or Fuel Cell Electric Drive System is a promising "easy win" in the near term.

    - Develop and Validate High- efficiency Electric Drives: Develop, test and validate more durable RESS and power control electronics for hybrid-electric drive, and confirm reliability and durability in actual field tests. (The estimated cost to the new NFCBP could be $15 million over 5 years.) Key challenges are the high vibration and engine compartment volume requirements, as well as environmental factors (temperatures, humidity, etc.). There are a lot of unknowns for which reliable field data does NOT exist as yet, but could impact commercial viability of FCBs. A benefit will be to lower overall life-cycle costs

6.2. Recommended Next Steps for RESS Commercialization

Most respondents were satisfied with FTA RD&T and grants program support of advanced technology buses, and benefited from funding to develop, test or purchase them. Some SMEs hoped that more could be done by FTA to partner with federal agencies (DOE, DOD, EPA) in order to better leverage reinvestment and RD&T programs targeting the rapid prototyping and production of advanced batteries for HEV/PHEV/EVs and of related electrification infrastructure, "smart grid" initiatives.

Multiple stakeholders recommended sustained multi-year FTA RD&T programs to:

- Conduct demonstration and evaluation efforts to compare and evaluate competing and different hybrid electric drive architectures with upgraded RESS;

- Focus on RESS Systems Integration as the key to a successful commercial electric drive bus;

- Benchmark in-service RESS performance capabilities, actual battery life, and O&M costs for HEBs with advanced RESS architectures, by working with RESS system integrators and Transit Authorities (TA) partners

- Publicize findings of these RD&T efforts and maintain a database on RESS options based on periodic surveys of TAs operating HEB/EB/FCB in their fleets.

Specific R&D priorities to advance state-of-art and to fill knowledge gaps regarding RESS options and integration in diverse types of hybrid, electric and fuel cell buses are to:

- Maintain, monitor, and publicize multi-year RD&T efforts that advance hybrid and electric drive buses with reliable and powerful RESS: As an example of a successful sustained RD&T effort, the Georgetown Fuel Cell Bus team and other advanced electric drive bus designers stressed that advancing the technology of FCBs took over 2 decades of dedicated FTA RD&T funding, cost shared with multiple partners. Also, multiple stakeholders' partnerships to increase the funding pool were essential. For instance, the original Georgetown hybrid fuel cell bus used a lead-acid battery until 4 years ago. Gradual improvements of fuel cell hybrid bus technologies, including the RESS subsystem, took place for over 12 years, to exploit technology base advances, prior to optimizing a design for commercialization. BAE served as the RESS integrator for the Orion series of hybrid buses, some of which had a fuel cell used as an Auxiliary Power Unit (APU). Though BAE considered using lithium-ion batteries, it did not bid on the Generation III Georgetown FCB. The successful bidder for the current Generation III Georgetown Fuel Cell hybrid bus was Electric Vehicle America (EVA) [100], a small retrofitter and integrator of hybrid electric drives. This FCB effort is funded

[100] EV America (EVA)[100] of Wolfeboro, NH at http://www.ev-america.com/.

by FTA, EPRI, US Army TARDEC and other industry and university partners. EVA will use a Ballard methanol FC stack with on-board reformer, in a series drive train with an AltairNano lithium-ion Titanate battery and associated BMS. A 600 V battery pack consisting of 50 modules will be placed in the back of the bus, and actively cooled (unclear yet if by air, or water).

- Facilitate and initiate strategic alliances of federal, state and transit agencies with bus manufacturers, electric drive integrators and RESS suppliers: Strategic alliances have been a proven success story in the integration of components into the RESS and hybrid drive. For instance, ISE has several strategic alliances with RESS suppliers and provides "packaging", e.g. with Maxwell Ucaps for its ThunderVolt and ThunderDrive, and as Allison GM transmission did in partnering with NABI and Gillig bus platform manufacturers. Proterra has a strategic alliance with Altairnano for TerraVolt batteries, with UQM power for the drive-train and with Aerovironment for overhead canopy (catenary) fast-charger and for overnight charges. Also, Proterra bought the composite body tooling from TPI Composites, in order to make its own bus bodies.

- Facilitate and enable further HEB/EB/FCB market growth: FTA will continue to assist the hybrid bus manufacturers to demonstrate, prove value, commercialize and grow their market share, since the bus hybrid drive-trains and RESS subsystems and lessons learned are usable for hybridizing heavy duty engines (HDEs) in trucks and special use vehicles (trash collection, dump trucks, etc.) However, the US transit bus market turnover is small, only about 6000 new buses per year (1/10 of the fleet turns over). The global and the commercial bus market segments are far larger, but also more diverse. Since the school bus and intercity commercial bus market segments are larger is larger (e.g., about 100,000 school buses purchased per year) and will also benefit from electric drives and advanced RESS, FTA could encourage HEB manufacturers and integrators to target both for improved viability.

- Alleviate RESS compatibility challenges through standardization: Compatibility, durability, and cost are key to commercial success. It's best to design an electric drive that is compatible with multiple manufacturers' bus body platforms, as ISE's ThunderVolt did to grow its market share. Others (like BAE in NY City, and ISE in Chicago, and NABI with CNG buses in LA) focused on large city bus fleets.

- Help RESS suppliers meet the bus system integration challenge: Based on lessons learned It's best for a bus manufacturer to serve as its own integrator, as Van Hool is doing now (after problems in using ISE with its Siemens ELFA as integrator for the Columbia SC FCB). OEMs do not know how to integrate components into complex drive-train architectures for optimal performance.

- Conduct a comparative analysis of the on-board battery recharge, versus external charging and refueling infrastructure, as part of HEB/PHEB/EB benchmarking studies: Several experts suggested, based on lifecycle cost considerations, that on-board charging options are more desirable to avoid the additional (currently too high) cost of building and deploying charging infrastructure,. The large and powerful charger (more than 200 KW) required in stations for fast charging of the Proterra electric bus with an overhead canopy, or pole catenary could also present safety hazards and maintenance challenges. For instance, University of California Davis (UCD) modeling indicated that for electric and Plug-in hybrid electric buses, an Auxiliary Power Unit (APU) is needed as range extender to complement battery performance capability. Examples of APUs used to extend the life and range of Li Ion batteries in RESS are:

  - small diesel engines that can act as generators/motors;
  - fuel cell APUs, which can deliver steady-state power, but cannot not absorb any regenerated braking energy;
  - ucaps, now used to rapidly absorb and supply regenerated power.
  - The fuel cell APU, whether powered by compressed hydrogen gas, or from on-board methane reformer, requires further refueling infrastructure and introduces hydrogen safety training requirements, besides electrical safety training.

- Document and publicize the results of RESS Systems Integration, Test and Evaluation (T&E) Projects: There was remarkable consensus among SMEs consulted regarding the need for more integration and in-service T&E of advanced bus architecture alternatives as the key to optimizing bus performance for HEB/PHEB/EB. Although the series or parallel hybrid buses, and more complex architecture options were designed to perform best for distinct bus service profiles (stop and go, versus over the road, or hilly terrain, length of route, etc.), system integration and configuration control were not optimized in bus demonstrations, even if the components and subsystems were perfected by suppliers (e.g., as are electric motors and power electronics). At present, it's unclear how to select the best bus design, integrator and subsystem suppliers among competing options, so as to better satisfy multiple requirements and constraints. The NREL hybrid and fuel cell bus evaluations for FTA were mentioned by SMEs as a very helpful effort, but their time horizon was too short to guide TA purchases.

- Conduct focused R&D on RESS and power electronics systems integration and optimization: FTA should work with OEMs to first optimize the HEB and EB technology to verify in service benefits, and then commercialize it. Insufficient integration with matching power electronics for power management and control of RESS components has led in the past to suboptimal operation and too much downtime. For instance, bus manufacturers (like Van Hool) have initially used system integrators (like ISE), but as they gained operational experience with hybrid and fuel cell buses, they became their own integrators. Similarly, Ballard has reduced the number of subsidiaries and partners involved in producing successive generations of fuel cells, to better integrate and optimize the design and performance for large scale commercialization. There is a great deal of learning from successive generations of hybrid-electric bus designs to improve performance and safety over time, as BAE has shown with its still evolving Orion series of hybrid buses.

- Broker partnerships to lower RESS cost and enhance performance: FTA could continue to expand its partnerships with DOE labs, DOD/TARDEC, nonprofits (EPRI), state DOTs, transit agencies and battery makers on RD3 to reduce the cost of emerging batteries, power electronics and other RESS components, through bulk purchases or subsidies. For Transit Agencies (TAs) currently strapped for funds, the cost of advanced Li Ion batteries, FCs and hybrid technology is too high (about $1,500/kWh) to be affordable. Battery and RESS costs will only come down as the entire vehicles electrification market, including the bus segment, grows over the next 20 years, when competition will increase and high volume production can be achieved. To enable large scale, sustainable commercial vehicle applications, stakeholders stressed the need for cheaper and longer-lived batteries which are intrinsically safe and rugged, run cooler without complex liquid or air cooling systems, and use nontoxic and recyclable materials. Affordability was considered as important, as the battery safety, reliability and durability. Although current lithium-ion batteries have sufficient storage capacity for vehicle RESS applications, they are not yet affordable, and their performance degrades with cycling and temperature extremes, requiring frequent replacement. Given that lower cost, proven battery options are currently available for electric drive buses (e.g., NiMH, NiCd, advanced lead VRLA) the emerging lithium-ion batteries are not necessarily first choice for RESS designers. There is a lot of ongoing research on this topic, e.g., an MIT project funded by DARPA that aims to lower battery energy storage costs from the current $500-800/kWh to $250/KWh. Though FTA could explicitly require advanced bus grantees to leverage such advanced battery development efforts in bus demonstration projects, it's unlikely that bus grantees will use unproven and potentially unsafe batteries.

- Mediate with EPA an update of Bus HDE certification requirements: Some respondents suggested that FTA assist bus integrators and manufacturers by working closely with EPA on regulatory changes needed to incentivize HEB/EB deployment. The EPA now certifies only the heavy duty engine (HDE) and not the entire hybrid drive bus system under in-service test conditions. Also, there is no standardized testing protocol for bus tailpipe emissions for alternative drive-trains and fuels (though CA has interim test procedures). These outdated EPA engine certification requirements also inhibit retrofits with automatic Stop/Start engine that can improve both fuel efficiency and reduce emissions. For instance, the current EPA requirement for the bus heavy duty engine life (435,000 hours) and exhaust emissions standards compliance reporting[101], ignores the wear and tear while the engine is off but under load (2000 hrs idling, say) within this limit.

[101] See EPA heavy duty engine certification postings at http://www.epa.gov/oms/certdat2.htm and emissions standards at http://www.epa.gov/oms/standards/heavy-duty/hdci-exhaust.htm

- Conduct focused RD&T on electric drive buses that address major RESS utilization challenges:

    - Lower the cost and improve the reliability of lithium-ion Batteries: Given the low cost, proven battery choices for buses emerging lithium-ion batteries may not be chosen for fleet deployments. Since 06 through 09, the Allison hybrid drive RESS used a NiMH battery, which was proven in service to satisfy storage and power requirements. Allison and Siemens ELFA will not put in yet a Li Ion battery, until cost and reliability improve.

    - Extend the battery life to bus design life: At best, the rechargeable battery life is still only half of the bus life. Although TAs now require long term battery and RESS warranty (e.g., WMATA has a 5 years warranty on the Siemens ELFA hybrid electric drive, prorated cost or reduced percentage cost of replacement beyond 5 years. However, since a HEB bus life is now 15 years, a factor of 3 improvements in the battery durability is needed to match it, and save the costs of battery replacements, bus repowering and downtime.

    - Provide uniform and appropriate safety training for electric drive buses: Formal electrical, chemical and fire safety training programs (perhaps at the Transit Research Institute) for O&M staff are needed to prevent and mitigate the hazards due to high voltage batteries, RESS and diverse charging infrastructure. Because FCB safety training involves both hydrogen handing safety, and electrical safety, the cost of training for a complex FCB is high, even for centralized depot maintenance, and must be considered a recurring bus lifecycle cost. Georgetown FC bus consortium respondents stressed that both the safety issues and the operations and maintenance (O&M) staff training in advanced bus RD3 phases are very different from training in a commercial operational environment. The Georgetown bus generations have been only demonstrations of an advanced technology FC bus, and therefore were operated only sporadically as a campus shuttle. In a real commercial operation with 12-18 hours duty cycle, the bus RESS safety and reliability would have to be improved and verified. Unlike its fleet of diesel buses in service, the prototype FCB is not in regular service and can be preventively maintained and equipped with extra safeguards. Hydrogen gases and the use of methanol reformer both require a well ventilated garage. Over more than 12 years of RD&D, the Georgetown buses had one electrical fire, but no hydrogen or methanol spills. The high voltage RESS system safety issues were addressed by Engineering School researchers, but putting this FCB in service would require that O&M personnel, Fire

Marshalls and EMTs be trained to prevent, handle and respond to methanol and hydrogen fire safety incidents.

- Identify RD3 technology development projects that improve the on-board energy storage capability and demonstrate energy efficiency gains, such as:

    - Improve the kinetic energy recovered through regenerative braking: Only 25% recovery of regenerative braking energy has been achieved, so better braking energy recovery, storage and use is desirable;

    - Redesign the electric or hybrid or electric power train and Power Management and Control (PMC) subsystem to reduce parasitic loads, as suggested above;

    - Complete the electrification of HVAC accessories to eliminate parasitic loads and improve energy efficiency: microturbines, electric fans, air compressors to replace hydraulics;

    - Explore if smaller engines and lighter buses can further improve HEB/EB/FCB energy efficiency.

- Shorten commercialization production timetables of affordable, integrated RESS and auxiliary power units (APUs) for range extension of electric drive buses. The current experts' estimates for timeframe of energy storage subsystems to achieve technology readiness for production and deployment in commercial buses (Levels 8-9 in the TRL schematic of Figure 2) are expected to be:

    - advanced high energy and power lithium-ion batteries - 2016

    - ultracapacitors for energy storage and power boost - 2014

    - combination of battery pack and ultracapacitors in RESS - 2020

    - reliable battery management and control systems - 2018

    - use of fuel cells and hydrogen fuel for APU - 2018

    - "on the fly" bus battery chargers - 2025

    - In-station, in-depots, or public charging infrastructure - 2025

    - other range- extending technologies for electric buses (microturbines; turbocharged ICE; stop-start shut-down; other kinds of power-boosters, etc.): APUs (including a battery) for automated shutdown / startup capability for hybrid buses with IC engine are likely.

- Improve outreach, communication, and information sharing on electric drive technologies: Several stakeholders hoped that FTA could more closely coordinate outreach with trade, research and standard developing organizations (e.g., APTA, TRB/TCRP, EDTA and NHA), and partner with their transit-focused committees (e.g., the APTA Green Propulsion Technologies Committee). Jointly, they could co-sponsor regional and/or national forums to share information on in- service performance of HEB/EB/FCB, their subsystems (RESS), safety issues, and O&M best practices. For instance, a Northeast regional event might convene WMATA, Baltimore MD MTA and SEPTA; all have operated Allison drive HEBs, and could discuss best practices, problems, solutions and insights regarding the most efficient buses for commuter service, over the road (in HOV lanes at 60 mph), vs. stop and start city service. For a regional West Coast forum, for example the Foothill Transit Authority suggested an examination of the Business Case for purchasing the Proterra Ecoliner, as a topic to share with peers for mutual benefit.

6.3. RD&T Partnerships to Advance Bus RESS

Improvements in the chemistry, capabilities and cycle life of rechargeable batteries for on-board energy storage are essential to large scale deployment of energy efficient and environmentally friendly hybrid-electric (HEB) and electric buses (EB). Key goals are to ensure their safe operability, reliability and durability at affordable life-cycle cost, and to lower battery size and weight, as well as optimizing their integration into more efficient electric drive power train architectures.

To complement the higher energy capacity, but lower power delivery of automotive batteries, hybrid RESS architectures must be developed, tested and evaluated. These types of RESS will utilize APUs (fuel-cells, ultra-capacitors, or microturbines) to deliver peak power for acceleration and to rapidly absorb braking energy, and be optimized for bus duty cycle with power management and control electronics, integrated with traction motors. This strategy allows for battery peak power loads to be delivered during acceleration, even in deep discharge cycling, without degrading performance, and for regenerative brak*ing capture t*o recharge the battery and extend the operational driving range.

However, both the cost and complexity of the RESS for hybrid electric buses will increase due to battery integration with sophisticated power electronics for monitoring and control of voltage, current and temperature (inverters, controllers for voltage and thermal management, and electric motors/generators).

The key technologies for components, subsystems and the power train architectures for efficient electric buses and hybrid buses are still evolving rapidly and many options are still in the technology demonstration and evaluation phases.[102] The latest DOE/EERE review of energy storage systems for vehicle applications targets focused fundamental and applied battery research, addressing multiple cross-cutting issues. Both benchmark

[102] See DOE/EERE Vehicle Technologies "*FY 2008 Progress Report for Energy Storage Research and Development*" at http://www.eere.energy.gov/vehiclesand fuels/

testing of emerging battery technologies and full system target development and validation of in vehicle applications of advanced lithium batteries and ultracapacitors (for 42 V start/stop applications) are examined.

Upgrades in the performance of on-board RESS for hybrid-electric and electric buses so far show increasingly diverse and complex electric traction and RESS architectures. These performance enhancements promise benefits, but also introduce new and unforeseen failure chains and pathways. Complex architectures in turn pose new risks to hybrid bus safe operability. For instance, a breakdown or fire could be initiated by overheating (thermal runaway) of a battery cell or string or stack, by overcharge sparking or arcing, by internal battery short-out, or by corroded cables connecting the bus to the wall outlet during recharge cycling. These are examples of new electrical safety hazards that must be better understood, characterized, prevented and mitigated for each type of hybrid-electric architecture and for each selected battery option, and will require well trained maintenance staff and well informed bus operators.

The most pressing challenges to large scale commercialization of Li Ion batteries identified by multiple stakeholders, that need to be addressed by future RDT&E efforts include: ruggedized battery packaging able to withstand mechanical vibrations and crashes without electrocution hazards; also standardized non-conductive and fire-proof battery packaging for both shock prevention and fire protection; improved Battery Management Systems (BMS) to monitor the State of Charge (SOC) and individual stack and cell voltage, and to rebalance the load in case of cell failures or degradation; standardized battery charging infrastructure and interfaces allowing rapid recharging to reduce downtime and deployment costs; built-in Thermal Management Systems (TMS) for safe operability, and to maintain optimal operating temperatures; isolation of electrical system and components to prevent current/charge leakage and electrocution; minimum safeguards, such as a High Voltage Interlock loop for battery covers, that ensure the electrical isolation of battery strings and modules; fully integrated batteries with Power Conversion System (PCS) and power electronics, able to accept recharging from the grid, or from an Auxiliary Power Unit, store braking energy, and provide power at variable frequency via inverters or converters to electric motors, as well as interfacing with IGBT and other electronic switches;

Recommendations to expand existing EDSP projects and/or add new efforts to improve RESS for hybrid-electric and fuel cell buses include:

- <u>Updated RESS Safety Guidance and Training</u>: Conduct R&D to update, and to verify and validate the APTA 1999 "*Manual for the Development of Bus Transit System Safety Program Plans*" (SSPP), so as to include and expand the list of safety procedures and resources for electric and hybrid bus referenced in the 2003 FTA report (see Footnotes 39 and 40). The SSSP for advanced fuel cell and hybrid electric buses must address in sufficient detail the safety concerns for novel and emerging lithium-ion batteries, their battery management systems (BMS), and thermal management systems (TMS), as well as safe integration with the hybrid-electric power-train and charging infrastructure. Other potential safety hazards to be explicitly considered include: potential fires and explosions in road crashes; control system (BMS and/or TMS) failures to detect and correct charge/discharge or temperature anomalies; the safety (secondary electrocution or fire hazards) of the charge/recharge procedures and appliances, and interfaces with APUs, plugs, outlets and the recharging infrastructure.

- Participation in Technical and Safety Standards Development: Consistent with OMB Circular 11A, ensure and expand the FTA participation on SAE technical standards committees and Working groups (WG) related to the development of battery-related safety standards. FTA could also actively support the development of national and international Safety Codes and Standards (SC&S) for advanced electric bus systems and components by the IEC Technical committees (TC), and testing of RESS and capacitors in RESS by the Underwriters Laboratory (UL). This would ensure that transit industry interests are considered, and will enable FTA to monitor, adopt and adapt consensus standards relevant to the safety of hybrid electric and electric bus battery, and of the energy storage system and infrastructure.

- Peer-to-Peer Exchanges and Workshops: Provide close technical oversight of, synergy and coordination among the EDSP research projects on bus electric drive energy storage identified in the "*FTA Multi-year Research Program Plan (FY2009- FY2013*)"[103] and performers. FTA could conduct annual workshops in conjunction with APTA or TRB conferences to ensure that the lessons learned from specific projects will result in optimization of the RESS for both safety assurance, and for enhanced performance and maintainability at lower operating cost.

- RESS Technologies and Best Practices Database: Assemble, maintain and web-post a comprehensive, up-to-date database industry and university resources to assist transit agencies and bus industry stakeholders. The database should include technical references on advanced bus batteries, and RESS integrators and suppliers. Consider also inclusion of up-to-date lists of bus manufacturers, advanced hybrid electric drive-train architecture options with respective subsystems suppliers and integrators, as well as a compendium of applicable Safety Codes and Standards (SC&C) and UL- certified battery safety testing labs.

- Develop HEB/EB/FCB and RESS Acquisition Support Guidance: Transit Agencies need current guidance to assist in their acquisition of hybrid electric and fuel cell buses, with model contracts for purchase, warranties, maintenance. For instance, advice on requiring an extended warranty for the battery and RESS, including the BMS and TMS, APU and other key subsystems would protect the TA and promote reliability and durability. Similarly, the TAs could require proof

[103] See bus energy storage projects listed in Table 5-9, Objective 3.4, Investigate the use of high-efficiency technologies and alternative energy sources, bus electric drive R&D projects in the plan, posted at http://www.fta.dot.gov/documents/FTA_TRI_Final_MYPP_FY09-13.pdf

of safety testing for batteries and other components, fire-proof materials, and safety testing for charging appliances and stations.

- Expanded Partnerships: new and broader FTA partnerships with federal agencies and State/ TA/industry/university consortia could accelerate demonstrations of new RESS technologies, such as with:

    - The DOD/TARDEC/TAC on advanced hybrid/electric vehicle technologies, such as heavy duty green power-trains, and RESS applicable to buses;
    - EPA on hydraulic power-trains for hybrid heavy duty;
    - EPRI on PHEB/HEB bus and charging infrastructure options for rapid charging;
    - International partners, to foster global market applications and to capture and demonstrate the value of the new RESS technologies discussed above, including flywheel Kinetic Energy Storage Systems (KESS); ultracapacitor buses; combinations and integration of advanced batteries with high storage capacity, with high power ultracapacitors optimized for bus operational profile; and the expanded use of renewable energy sources for RESS recharging; and novel infrastructure for recharging buses on the fly, including OCS, canopies, or road-embedded induction loops.

7. Research and Technology (R&T) Roadmaps to Advance RESS for Electric Drive Buses

7.1. The Need for Strategic RD&T Roadmaps

FTA leadership in RD&T to develop, demonstrate and improve advanced RESS for hybrid/electric drive and fuel cell buses, will not only save fuel for, and reduce emissions from the existing public transit fleet of 65,000 buses, but also benefit US manufacturers, suppliers and owners/operators of more than 33,000 commercial motor coach buses, and 480,000 school buses.

An important goal of the 5 years FTA Research Program Plan (FY2009—2013)[104] is to successfully undertake, complete and sustain the full suite of projects proposed under the FTA Electric Drive Strategic Plan (EDSP). The 2008 Volpe Electric Drive Strategic Plan (EDSP) stressed the need to consider the Rechargeable Energy Storage System (RESS) technology options, not in isolation, but fully integrated with the power and propulsion systems, and energy management electronics, and well as with the charging infrastructure.

The state of art and knowledge gaps regarding RESS for hybrid and electric drive buses with diverse drive-train architectures were summarized in the Task 1 report, based on a literature review. Batteries are the key enabling technology and a key economic driver for the accelerated vehicle fleet hybridization and electrification, needed to respond to the national energy, environmental and economic imperatives. Recent international, federal and industry initiatives have targeted rapid advances in lithium-ion batteries, ultracapacitors (ucaps), and fuel cells, by addressing multiple challenges in materials, capacity, packaging, cost, reliability, weight and size, durability, safety, toxicity and recyclability. Chapters 5 and 6 summarized both general and specific inputs by transit technology experts and stakeholders, on lessons learned, key research needs, and suggested next steps to further improve RESS components next steps.

In this Chapter, the findings and recommendations were prioritized, organized and synthesized into a set of near-term (3 years), mid-term (5 years) and strategic long-term (10 years) research roadmaps only for the RESS components and subsystem on-board a hybrid electric (HEB), plug-in hybrid (PHEB), fuel cell (FCB), or electric bus (EB). The RESS R&D Roadmaps identify major thrusts to improve, demonstrate and deploy advanced RESS systems, as the entire bus fleet adopts hybrid-electric drive for improved energy efficiency and environmental sustainability. The role of FTA was differentiated from roles and responsibilities of its partners (federal, state or local agencies, industry and academia), to better leverage limited RD&T funding resources, and to ensure successful technology demonstration and implantation through shared funding and joint intellectual property (IP) ownership. Drill- down to detailed project level research was illustrated in Tables 2-4.

[104] "FTA Multi-year Research program Plan (2009-2013)" at http://www.fta.dot.gov/assistance/research_research.html

RESS integration with power-train and transmission architectures, and with the Energy Management Subsystem (EMS) requires bus performance optimization for a given bus duty cycle and route, in order to reliably and efficiently deliver power loads and store the recaptured braking energy. Also, if recharging the battery requires external infrastructure, or a fuel cell Auxiliary Power Unit (APU) for range extension, hydrogen refueling infrastructure and interfaces must also be considered. The close interdependence of related alternative technologies and architectures for hybrid-electric drive buses (including rail transit) is illustrated in Figure 34[105] which depicts the range of Electric Drive Technologies for power delivery, energy storage and energy management.

Figure 34- EDSP chart illustrating interconnected technology options for Electric Drive subsytems

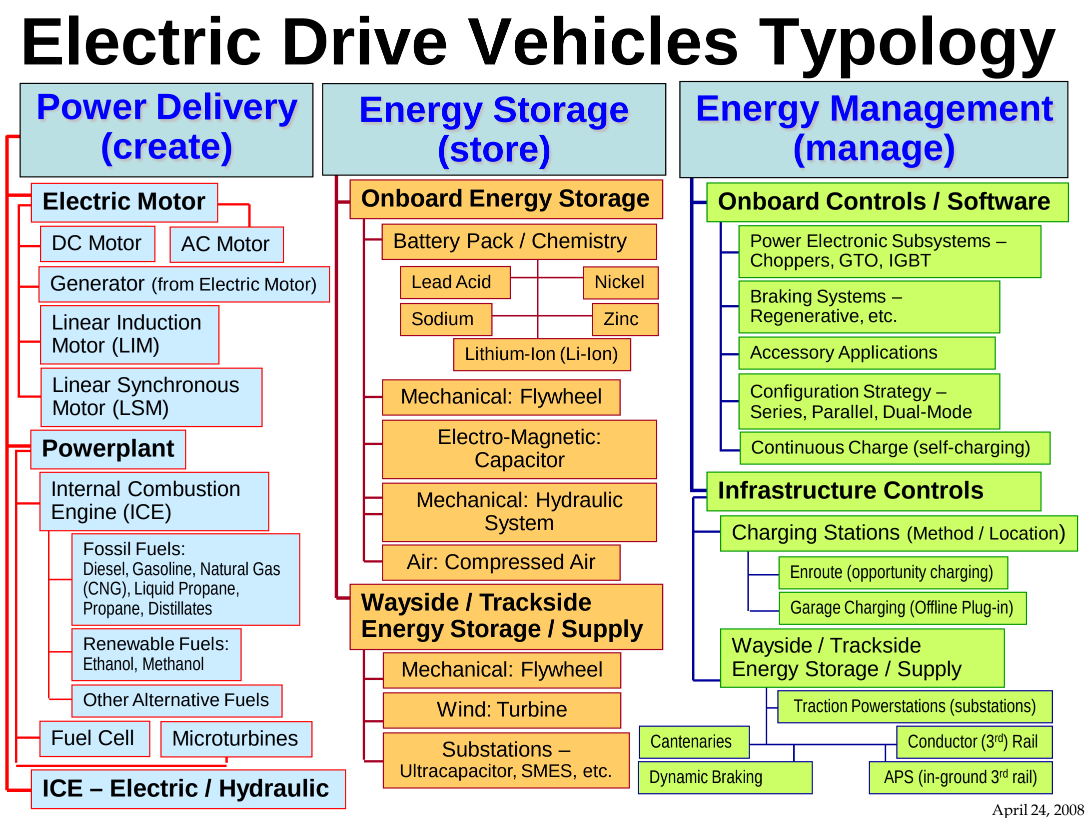


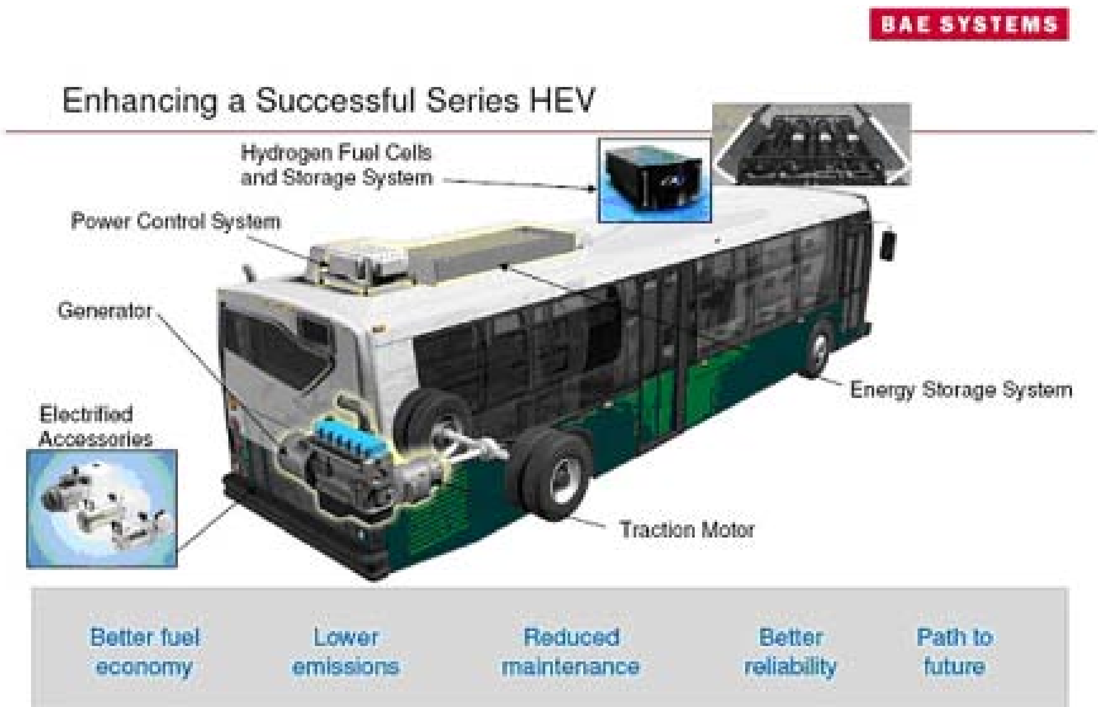
Figure 35 illustrates how this holistic approach to electric bus advances is enabled by combining advanced RESS with complementary technology modules in a specific advanced bus RD&T project. In this case, the FTA/Calstart Bus 2010 project[106] led by BAE Systems integrates advanced, large format A123 lithium-ion batteries with a hybrid fuel cell power converter and an integrated auxiliary module (IAM) for a 40 ft fuel cell bus. It will enhance the powerful A123 lithium-ion A123 batteries now used In Orion

[105] Excerpt from the Volpe Center 2008 EDSP report to FTA

[106] C. Gikakis presentation on "*USDOT Fuel Cell Bus Program*", at the International Fuel Cell Bus Working Group Meeting, June 2009; "*BAE Systems to develop Hydrogen Fuel Cell bus for SunLine Transit*" at www.greencarcongress.com/2010/03/bae-20100325.html and "*Bus 2010: Leveraging lithium-ion Technology*" at www.calstart.org/projects/low-carbon-bus-program/Publications/.

VIII buses, with a fuel cell Auxiliary Power Unit (APU) from Hydrogenics, and electrified accessories for cleanly extending bus range.

Figure 35-BAE Systems HybriDrive series hybrid propulsion system for the BUS2010 FTA/Calstart project



Ongoing USDOT/NHTSA joint rulemaking[107] with EPA and DOE to establish stricter Corporate Average Fuel Efficiency (CAFÉ) standards (2012-2016) for Medium and Heavy Duty (MDHD) vehicles include buses, and thus will speed up the hybridization and electrification of the nation's bus fleet to increase fuel efficiency and reduce GHG emissions for compliance. The recent NRC report on "*Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles*"[108] discussed the hybrid technology options for improving both fuel efficiency and environmental performance, and pointed out the tradeoffs: bigger batteries for RESS increases bus weight, which impacts adversely fuel efficiency gains. Table 1 and Figure 36 (from the NRC report) quantify the tradeoffs in weight added by batteries in hybrids. They also point to two major FTA R&D priorities: the need to develop lighter and more capable batteries, replace accessories with lighter-weight electric alternatives, and to use composite materials for reduced bus weight. Table 1-Extra weight of hybrid bus RESS reduces fuel economy benefits (NRC, 2010)

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[107] See postings on proposed MDHD CAFÉ rule at http://www.nhtsa.gov/fuel-economy and http://www.nhtsa.gov/Laws+&+Regulations/CAFE+-+Fuel+Economy/Model+Years+2012-2016:+Final+Rule

[108] National Academies Press, March 2010, download from http://www.nap.edu/catalog.php?record_id=12845

TABLE 4-8. Hybrid Technology, Benefits and Added Weight for Transit Buses

Architecture	Percent Benefit (FC)	Incremental Weight
Gasoline series	25-35[a]	2,000 lb.
Diesel series	30-40	2,600 lb.
Diesel parallel and dual-mode	22-35[b]	940-2,840 lb.

[a] Site Visits.
[b] FTA (2005), Altoona
SOURCE: TIAX (2009).

Figure 36 (excerpted from the NRC 2010 MDHD fuel efficiency technology options analysis) compares the potential bus fuel efficiency gains from hybridization, ITS enabled operational efficiencies, and weight reduction, with other MDHDVs. It is clear that bus hybridization offers the largest fuel efficiency gains – 35% on average. In turn, successful bus fleet hybridization and electrification requires major RESS improvements in capability, durability and reliability, and cost reduction for widespread commercialization.

Figure 36-Relative technology bus fuel consumption reduction (NRC 2010 report)

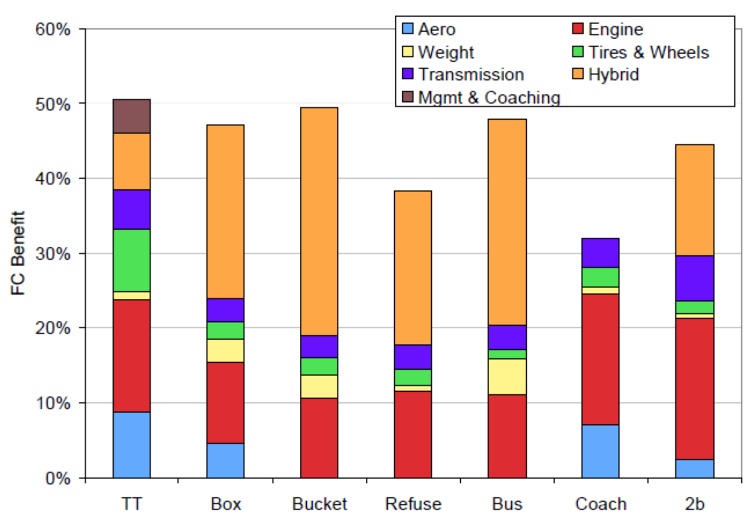

FIGURE 6-1. Comparison of 2015-2020 New Vehicle Potential Fuel Savings Technology for Seven Vehicle Types: Tractor Trailer (TT), Class 3-6 Box (Box), Class 3-6 Bucket (Bucket), Class 8 Refuse (Refuse), Transit Bus (Bus), Motor Coach (Coach), and Class 2b Pickups and Vans (2b).

7.2. Priority RESS Research Projects by Time Horizon

Chapter 5 summarized stakeholders' recommendations regarding priority RESS research needs and the next steps needed to advance existing battery and storage capabilities and performance, and to speed up bus fleet hybridization and electrification. These priorities were identified based on lessons learned by early adopters from over a decade of diverse bus hybridization and power-train electrification pilot demonstrations, and on operational experience with commercial series and parallel hybrids, electric buses, and various fuel cell buses. It is difficult for FTA to carry out all the recommendations, as a follow-on effort to the ongoing Electric Drive Strategic Plan (EDSP) research on rechargeable bus batteries and advanced energy storage subsystems. Therefore, this chapter synthesized the key enabling R&D "building blocks" and organized them by time horizon, into a logical progression:

- Near term (1-3 years) projects, as shown in the examples listed in Table 2;

- Mid-term (3-5 years) projects, with selected priorities shown in Table 3; and

- Long-term (5-10 years) sustained efforts illustrated in Table 4, to ensure the commercial viability of RESS for hybrid-electric or fuel cell buses.

These efforts must also support Goal 5 of the FTA's Multi-year Research Program Plan ("*Protect the environment and promote energy independ*ence") and its two inter-related objectives, namely:

- "*Facilitate the development of technologies to improve energy efficiency and reduce transit vehicles emissions"* (Objective 5.1); and

- "*Identify and overcome barriers to adoption of clean technologies*" (Objective 5.2).

The RESS R&D projects must be aggregated and organized into only a few targeted technology clusters, in order to achieve synergy, and also be cost-effective. To synthesize multiple recommendations on how to advance and integrate RESS into existing diverse hybrid electric bus architectures, and to ensure convergence towards a standardized and optimal platform, a phased and sustained research roadmap is needed. The roadmaps below adopt a "building blocks" approach, so that near-term R&D results enable mid-term advances in RESS; while mid-term projects remove barriers to long-term commercialization of advanced batteries and power control systems, when integrated into standardized hybrid-electric bus fleets with superior and cost-effective performance.

Examples of near-term RESS R&D projects selected amongst those suggested in Chapter 6 are shown below in Table 2. Selected mid-term projects are shown in Table 3, leading progressively to the type of larger-scale pre-commercial field demonstrations of successful hybrid and electric drive buses with advanced RESS, shown in Table T. Viable HEB/EB with advanced RESS are able to operate with the acceptable range, proven energy efficiency, durability, safety, and environmental footprint under diverse drive-cycles, over a wider range of climates and temperatures.

Table 1-Examples of Near-Term RESS RD&T Projects

Project Title	Project Description
Benchmark alternative lithium-ion battery chemistries for RESS on the same Bus platform	Using the same hybrid electric bus platform and power-train integrator for similar duty cycles, but in diverse climates, benchmark the performance, safety, durability, and cost for alternative Li Ion battery chemistries (e.g., Li iron phosphate, Li titanate, spinels).
Benchmark the performance of different HEB power-trains (series, parallel) for the same battery chemistry	Benchmark the RESS performance attributes for a leading battery chemistry and supplier (e.g., A123, or AltairNano) in alternative HEB power-trains/platforms. This will optimize integration, validate RESS applicability, and facilitate standardization and commercialization.
Standardize RESS for each HEB/EB/FCB architecture	Recommend standard RESS chemistry, size, configuration, and performance attributes, based on in-service evaluations of FTA-funded HEB/EB/FCB demonstration projects .
Analyze, evaluate and standardize high efficiency electric drive bus architectures	Evaluate and publicize results on the most energy efficient and cost effective integrated RESS with proven electric drive bus platforms for city driving, to enable and promote large scale commercialization of RESS / HEB architectures.

Table 2-Examples of Mid-Term RESS RD&T Projects

Project Title	Project Description
T&E: Test & Evaluation (T&E) of leading RESS candidate chemistries	For Technology Shakeout in diverse Hybrid-Electric Buses, select the leading lithium-ion battery chemistries (titanate, iron phosphate, manganese spinel) in cost-shared partnerships with suppliers and OEM/integrators of RESS, for T&E of performance, durability and safety on the same hybrid or electric bus platforms in several regions of the US.
M&S: Develop Modeling and Simulation (M&S) tools	Develop, verify and validate (V&V), then standardize RESS M&S software tools for advanced battery chemistries, coupled to Battery Management System (BMS) and Thermal Management System (TMS) logic, to facilitate design, development and deployment for Heb/EB applications.
V&V: Verify and Validate (V&V) RESS safety and efficiency for HEB/EB options	RESS capacity, safety and efficiency in actual in HEB/EB applications with diverse power-train design choices and operational profiles
V&V with HIL: Verify and Validate RESS designs with Hardware in the Loop (HIL) to optimize system performance, safe operability and efficiency	Use a the same hardware-in-the loop (HIL) bus platform to conduct extended V&V testing of alternative heavy-duty, large format RESS chemistries, packaging, and configurations to identify failure modes, and develop prevention and mitigation of potential thermal runaway hazards (fires, explosions) and electrical hazards (overcharge, undercharge, early discharge and short-outs).
Benchmarking: Prototype and test leading RESS candidates in bus service operations	Undertake multi-year (3 yrs) demonstration and T&E of competing RESS candidates for series and parallel HEB and EB drive-trains to benchmark energy, environmental, O&M and range- for complete performance characterization.

Table 3-Examples of Long- Term RESS RD&T Projects

Project Title	Project Description
RESS System Integration and Optimization	Integrate advanced RESS options into HEB, EB, FCB architectures to demonstrate and quantify long-term benefits (environmental, energy efficiency, safety, maintainability, and cost-effectiveness)
In Service RESS Performance Evaluation	FTA and early adopter TAs agree to multi-year test, evaluation, demonstration and safety-certification of 2-3 RESS candidates.
Analysis and Dissemination of Results	Analyze and publicize findings of long-term pilot deployments that quantify the life-cycle cost-effectiveness and energy efficiency benefits of RESS subsystem integration in HEB/EBs
Remove Commercialization Barriers	Identify and overcome O&M, safety and training barriers related to RESS and charging infrastructure, in order to achieve commercial viability of RESS in HEB/EBs commercial bus fleets.
Conduct Outreach for Tech Transfer	FTA and its partners monitor, verify and document the advanced RESS technology readiness for commercial HEB/EB/FCB applications for successful technology transfer and market development

7.3. RD&T Roadmaps to Advance RESS on-Board Electric Drive Buses

The RESS technology roadmaps presented below proceed and progress from near-term (3 years) building-block, high priority efforts identified by experts and stakeholders, to more sustained and longer duration mid-term (5 years) bus battery technology shakeout to down-select the leading candidate RESS designs and manufacturers, to long-range (10 years) urban hybrid-electric bus test-beds that capture the benefits from preceding federally funded technology transfer efforts and achieve commercial viability in urban bus fleets.

Consistent with DOT and FTA strategic goals, the key strategic objective of these R&D Roadmaps is to establish: *"Multi-year RDT&E partnerships to advance RESS technologies and related fueling infrastructure, for superior hybrid-electric bus energy efficiency, environmental sustainability, and economics."*

The underlying strategy of FTA RESS R&D Roadmaps involves partnerships with federal, state and transit agencies, and with industry nonprofits and research consortia, to better leverage limited FTA R&D funding, and to maximize the probability of successful completion and utilization of research results. Furthermore, past FTA experience with RD&T partnerships and cooperative efforts has shown that shared ownership of intellectual property (IP) can incentivize the early adoption and deployment of advanced batteries and RESS configurations and industry products in urban bus fleets.

These Roadmaps were structured to reflect the consensus among the experts and stakeholders consulted regarding desired FTA Next Steps to advance electric drive technologies, demonstrate lifecycle value for urban bus operations, and promote their commercialization , namely to:

- Continue to **conduct demonstration and evaluation of advanced RESS** options for competing hybrid-electric bus architectures;

- Focus its efforts on **RESS Systems Integration** on-board the bus and/or with external charging infrastructure, to derive full benefit from technology advances;

- **Standardize and utilize predictive Modeling and Simulation (M&S) tools** to speed up the adoption of advanced RESS at lower cost prior to testing and technology shakedown in deployment pilots; and

- **Benchmark the in-service performance capabilities** of leading RESS options, to obtain and summarize data on Life Cycle Cost (LCA), O&M training and safety issues, etc and to develop clear guidance for operators.

The RESS R&D Roadmaps shown in Figure 4 shows the top-level research thrusts responsive to the key goal stated at the top, to meet commercialization challenges for electric drive buses. The Roadmap identifies efforts suited to near, mid- and long-term objectives, and suggests FTA programmatic milestones on these time-scales, as well as specifying the roles and responsibilities for FTA, its partners, and stakeholders.

The major categories of near-term (1-3 years) R&D efforts illustrated in Table 2 and Figure 37 must address the key knowledge gaps and current safety, durability and cost issues for advanced Lithium-Ion based RESS for electric buses, which were identified by experts and stakeholders, namely to:

- Develop Standards for battery and more complex RESS test protocols, performance, interfaces and safety of operations;

- Address RESS System Integration issues, including subsystem interfaces, for proof of durability, reliability and safe operability;

- Develop and maintain for FTA’s Technical Assistance program a current and comprehensive database on RESS technology options, capability and cost pros and cons, commercial suppliers and compatibility with specific power-trains and bus platforms; and

- Continue a vigorous and diversified applied RD&T, including Modeling and Simulation (M&S) tools for RESS integration into diverse drive-train architectures and electric bus platforms.

The mid-term (3- 5 years) RD&T thrusts illustrated in Table 4 and Figure 37 show how advanced RESS subsystems will be enhanced with Verification and Validation (V&V), Hardware in the Loop (HIL) testing and Benchmarking of RESS in whole bus performance. The Longer-term (10 years) efforts outlined in Figure 37 and Table 5 will productively focus on RESS optimization, its integration and standardization on electric buses; and on RESS lifecycle and market analysis, as well as focus on technology transfer and outreach to publicize analysis findings, to remove RESS commercialization barriers.

The Roadmap in Figure 38 stresses the FTA RD&T partnerships as the preferred strategy to advance RESS technologies coupled to bus drive trains capabilities, and to address current challenges to lithium-ion battery commercialization. Figure 38 also shows the key potential FTA partners and chief R&D objectives that can be productively accomplished over the 3 timetables (3, 5 and 10 years). Again the focus is on Test and Evaluation (T&E) and demonstrations of RESS options for electric buses under real operating conditions and diverse climates.

Figure 37-FTA Research, Development, Test, and Evaluation (RDT&E) Roadmap for Rechargeable Energy Storage System (RESS) for Hybrid and Electric Buses (HEB/EB)

	Near-term (3 years)	Mid-term (5 years)	Long-term (10 years)
Major Challenges	**Goal**: Multi-year RDT&E partnerships to evaluate and improve RESS technologies and related fueling infrastructure for superior hybrid-electric bus energy efficiency, environmental sustainability, and economics.		
Components Selection	Perform R&D to fill "**Knowledge gaps**" (e.g., Safety) on advanced batteries, RESS components, packaging, and power management and control in HEB/EBs.	**M&S:** Develop Modeling and Simulation (M&S) tools to verify and validate advanced battery and RESS capacity and safety in HEB/EB applications.	**System Optimization**: Demonstrate environmentally sustainable, safe, and cost-effective advanced RESS architectures for commercial bus fleets and field test fleets.
	Standards: Characterize and standardize RESS testing protocols (batteries, ultracapacitors, power for management and control electronics).	**V&V**: Verify and Validate RESS safety and efficiency for HEB/EB power-train design choices.	**In Service RESS Evaluation**: FTA and TAs test, evaluate, demonstrate and certify RESS viability in commercial HEB/EBs.
Testing In-service Performance	**System Integration**: Characterize RESS performance, cost, durability & reliability for bus in-service profiles.	**HIL V&V:** Verify and Validate RESS designs with Hardware in the Loop (HIL) to optimize system performance, safe operability and efficiency.	**Analysis**: Demonstrate and quantify cost-effectiveness and efficiency benefits of RESS subsystem integration in HEB/EBs.
	RESS Database: Establish and maintain a comprehensive database on RESS technology options for HEB/EB bus for Technical Assistance.	**Benchmarking:** Prototype and test RESS from competing suppliers in series and parallel HEB and EB drive-trains.	**Remove Commercialization Barriers**: Identify and overcome O&M and training problems related to RESS and charging infrastructure.
RESS Operational Integration	**Applied R&D**: Develop, verify and validate (V&V) RESS Subsystem Modeling and Simulation (M&S) tools in diverse HEB/EB drive-train architectures.	**Partnerships**: Coordinate with Transit Agencies, federal agencies and State DOTs to incentivize deployment of validated HEB/EB prototypes with advanced RESS.	**Outreach for Tech Transfer**: FTA/Volpe/NREL to verify and document RESS technology readiness for commercial HEB/EB/FCB applications.
FTA RD&T Milestones	• Multi-year projects selected (2011) • MOUs/Partnerships with TAs and other agencies for hybrid-electric bus demonstration (2012) • Hardware-in-the-Loop (HIL) RESS Testing for safe hybrid/electric drive integration (2013) • RESS Modeling and Simulation Tools Available (2015)	• Validated RESS integration with power electronics and advanced propulsion for real, in-service loads (2012) • Evaluate pilot advanced RESS Demonstrations in HEB/EB architectures (2014) • Commercial viability of plug-and-play RESS is proven (2015)	

Figure 38- RDT&E Partnerships for Improved RESS Performance

<table>
<tr><td>Challenges / Milestones</td><td colspan="2">Shakeout of diverse RESS designs and bus electric drives within market constraints
Lack of Standards for RESS Test and Certification (Safety and Environmental)
Lack of Modeling, Simulations and Validation Tools</td><td>High cost of RESS and System Integration
Need for Bus RESS Performance Metrics
Funding for Transit Bus RD&D, T&E and Pilot Bus Fleet Deployments</td></tr>
<tr><th>Performers</th><th>Near-term (3 years) RDT&E</th><th>Mid-term (5 years) RDT&E</th><th>Long-term (10 years) RDT&E</th></tr>
<tr><td rowspan="4">FTA in Public Private Partnerships (P3) and Consortia
(e.g., DOD/TARDEC, DOE/NREL, USCAR, CALSTART, NAVC, EPRI, etc.)</td><td>Research on RESS Optimization: Performance, Durability, Safety</td><td rowspan="2">Perform RESS Test & Evaluation For Technology Shakeout in Diverse Hybrid-Electric Buses</td><td rowspan="2">Demonstrate Successful RESS System Integration on FCB/HEB/PHEB/EB Platforms</td></tr>
<tr><td>Develop RESS Testing Standards and Evaluation Tools for Bus Performance and Safety</td></tr>
<tr><td>Down-Select for Optimal RESS Capacity, Size, Weight, Shape, BMS/TMS hardware/Software and Power Electronics</td><td>Optimize RESS technology through: Materials/Components/Packaging Simulations, Verification & Validation Demonstration of Safety, Sustainability</td><td rowspan="2">Demonstration and Deployment of Commercial RESS for Electric Drive Bus Fleets</td></tr>
<tr><td>Develop RESS Database of Standard Types/Architectures, Suppliers, Cost and Performance</td><td>Down-select and Deploy the Best Batteries for integrated RESS with Specific HEB/EB Architectures</td></tr>
<tr><td>FTA Role</td><td>Performs RDT&E Technology Scan to Monitors RESS Progress and Facilitates Bus Integration</td><td>FTA Partners with APTA, NREL, EPRI, TAs, and UTC Consortia to Evaluate RESS System Verification & Validation</td><td>FTA Grants for Advanced RESS/HEB/BEB/PHEB and FCB Early Adoption and Deployment in Urban Fleets</td></tr>
</table>

Appendix A-1

RESS Research and Technology Status and Needs

Note: Conduct outreach to stakeholders by phone or email, to be tailored to their sector affiliation, experience, and interests.

I. Current and Past Experience with Rechargeable Energy Storage System (RESS) for Hybrid-Electric Buses, with focus on the battery, ultracapacitors, Power Electronics and Control

1. Background information:

    a. Are you a developer, supplier, manufacturer, integrator, or user of electric propulsion technologies? (please describe)
    b. Which, and how many, hybrid electric buses were tested in service, and for how long?
    c. What are your products and services relevant to hybrid-electric buses?
    d. Are you an established company, or a start-up? How large is your transit market share?
    e. What is your role in the company?

2. Are you a designer/supplier/integrator of Rechargeable Energy Storage System (RESS) and/or components? If yes, please specify which. If not, please identify your supplier.

3. RESS Battery specifics: type, size, weight, chemistry, power, energy density and energy storage capacity, life, cost, range on electric only?

4. Were lithium-ion batteries considered? Selected? If yes, which? If not, why?

5. Experience to date: Why and how was this battery selected? How satisfied are you with the safety, performance, maintainability (pros) of this rechargeable battery.

6. Please discuss specific strengths (pros) and problems (cons) with this RESS or hybrid-electric powertrain architecture. E.g., how long it takes to recharge the battery; how well it runs in hot and cold weather; how and how well are its state-of-charge (SOC) and operating temperature monitored and controlled?

7. Please discuss the best practices you adopted to optimize RESS performance to meet bus route and operational requirement.

8. Please suggest solutions to above problems, or improvements in battery and RESS for hybrid-electric buses.

II. <u>**Lessons Learned re RESS Capability and Battery Safety from Hybrid-Electric Bus (HEB) or Fuel Cell Bus (FCB) Demonstrations**</u>

1. Please describe any operational and/or safety incidents related to the RESS or battery, including electric shock, gas venting, short-outs, fires, overheating.

2. What were your responses and adopted prevention and mitigation measures?

3. How often were these advanced buses out of service because of battery malfunction, outage, or overheating; and how did this affect the bus service level?

4. Was the Mean Time Between Road Calls (MBRC) for this RESS-related failures unreasonable compared to other causes or to MBRC for conventional buses?

5. Who has been maintaining the RESS and battery?

6. How often were they hybrid-electric electric RESS and battery inspected?

7. Risk transfer strategy: How was the battery, or integrated RESS warrantied, repaired, and/or replaced? Did your supplier provide insurance/warranty; or cover repairs and replacements? Did you buy spares?

8. O&M costs: Were O&M costs for battery, inverters, power electronics, and controls systems (BMS, TMS) unreasonably high? Comparable to diesel or CNG buses?

9. Fuel and Environmental benefits: Were fuel savings and energy efficiency gains sufficient to offset higher capital and O&M costs?

10. Training needs: How and where were the RESS maintenance staff trained? How well were they able to address problems? (give examples)

11. How were the RESS suppliers and integrators chosen? What competing options did you consider, and what were the decisive factors in your selection?

12. What was the role of the RESS integrator, battery OEM, and bus manufacturer in customizing bus RESS to your specific route and climate requirements?

13. What would you do differently, or better in acquiring future hybrid-electric buses and architectures, based on your experience to date (e.g.: would you ask for extended warranty? Battery spares? Larger, smaller, lighter batteries. Different emplacement on bus top or back?)

III. <u>**Preference and Justification for Choice of Advanced Battery and/or RESS**</u>

1. Are you currently involved in any fuel cell or hybrid-electric bus Research, Development or Demonstration (RD&D)?

2. If yes to #1:

    a. Is this project one of those identified by FTA (Table 5-9 in its Multi-Year Research program Plan (FY09-13)?
    b. Please describe the effort goals and partnership.
    c. Please identify your current RD&D partners and their respective roles and responsibilities.

3. Please identify which- in your opinion- is the Best Available Technology (BAT) for hybrid-electric bus:

    a. Secondary rechargeable battery (chemistry, energy / power, safety, cost);
    b. Primary Starting, Lighting and Ignition (SLI) battery;
    c. On-board RESS architecture;
    d. Auxiliary Power Unit (APU);
    e. Designed-in battery safety features;
    f. Power monitoring, management, conditioning and control electronics (inverters, converters, switches, BMS, TMS) subsystem integration;
    g. Power train architecture and efficiency;
    h. Recharging infrastructure, if any.

4. Which are outstanding RESS-related technology and safety concerns (please rank), and how are they addressed at present?

5. What are the major RESS performance limitations (e.g., operating temperature range, effective power/energy for charge sustaining vs. charge depleting operation, shelf life, charging times)

6. What are your Top-3 criteria in selecting a battery and RESS supplier/integrator?

    a. Cost? (specify: capital, replacement, operation, maintenance);
    b. Performance characteristics (e.g.: Energy capacity; power density; electric-only range; recharge time; durability)?
    c. Safety issues (e.g., fire, explosion, toxics, high voltage safety)?
    d. Technology Readiness Level (TRL in range 4--9), and when would it be ready for large scale commercial deployment?
    e. Other R&D needs: e.g., O&M, training, infrastructure, standards development and compliance)

IV. **Advanced Bus Batteries and RESS: RD&D Needs, Priorities and Plans**

1. Are you aware of or participating in ongoing research, development and demonstration (RD&D) sponsored by FTA, DOE, DOD, NSF and other federal

agencies and industry partnerships (21st Century Truck, USCAR/DOE) to advance the technology base and improve the fuel efficiency and environmental sustainability of transit bus fleets? (If so, specify)

2. Are you benefiting from federal subsidies and/or reinvestment funding? (If so for which projects?)

3. Are all important research needs and priorities relevant to hybrid electric buses are being actively investigated? Is funding sufficient? (discuss)

4. Which battery- or RESS-related capability and performance needs are not being addressed, but should be?

5. Please give your Top-3 priority RD&D projects for near-term advanced RESS in hybrid or electric buses, and guesstimate their cost, timetable, challenges and benefits.

6. Please indicate which FTA electric drive technology development and demonstration projects are: a) most promising in the near term (easy wins), or b) have higher risk, but also high payoff in the long term (long shots). Please justify.

7. What is the best RD&D strategy to achieve early deployment of electric drive buses for transit fleets? (e.g., start with niche markets like paratransit vans? Small shuttle buses at airports and federal facilities; school buses? BRT only? Short distance? Long distance with few stops?).

8. On what timetable do you anticipate the commercial production of affordable, integrated building block technologies for electric drive buses, including:

    a. advanced high energy and power lithium-ion batteries;
    b. ultracapacitors for energy storage and power boost;
    c. combination of battery pack and ultracapacitors;
    d. reliable battery management and control systems;
    e. use of fuel cells and hydrogen fuel for APU;
    f. “on the fly” bus battery chargers;
    g. In station, in-depots, or public charging infrastructure;
    h. Other range-extending technologies that you suggest testing for electric drive buses, e.g.: microturbines; turbocharged ICE; stop-start shut-down; other power-boosters?

Appendix A-2

Subject Matter Experts (SMEs) who Responded on RESS Needs Assessment

I. DOE National Labs

1. **Lawrence Berkeley National Lab (LBNL)**
   Dr. Venkat Srinivasan, BATT team leader
   vsrinivasan@lbl.gov , 510-495-2679
   Batteries for Advanced Transportation Technologies (BATT) staff listed at:
   http://berc.lbl.gob/BATT/

2. **National Renewable Energy Lab (NREL)**
   Leslie Eudy, Senior Project Leader
   Hydrogen Technology Validation
   leslie.eudy@nrel.gov, 303- 275-4412
   Hybrid Bus and FCB evaluation reports for FTA are posted at:
   www.nrel.gov/hydrogen/proj_tech_validation.html

   Dr. Ahmad Pesaran, Team Leader, Battery Technology Evaluation
   Ahmad.Pesaran@nrel.gov, 303-275-4441
   Battery publications posted at:
   http://www.nrel.gov/vehiclesandfuels/energystorage/publications.html

   Other NREL experts consulted on advanced batteries status:
   Dr. Matthew Keiser, Matthew.Keyser@nrel.gov, 303-275-3876
   Tony Markel, Tony.markel@nrel.gov, 303-275-4478
   Dr. Robert Rehn, Group Manager for Testing and Analysis, Center for Transportation Technology 303-275-4418

3. **Argonne National Lab (ANL)**
   Khalil Amine, Group leader, Battery Technology Development
   630-252-3838, amine@anl.gov
   Dr. James Miller, Mgr. Electrochemical Technology Program
   630-252-4537, millerj@anl.gov
   Gary Henriksen, Mgr. Battery Technology Dept
   630-252-4591, henriksen@anl.gov

4. **SANDIA National Lab**
   Dr. Peter Roth (505) 844-3949, eproth@sandia.gov
   Expert on abuse and safety testing of EV batteries; updated SAE Handbook J2464 (R) Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing

II. Universities

1. **MIT**
   Prof. Donald Sadoway, John F. Elliott Professor of Materials Chemistry
   617-253-3487, dsadoway@mit.edu

   Prof. Joel E. Schindall, MIT Lab of Electromagnetics and Electronic Systems, Electrical Engineering & Computer Science (EECS) and RLE Assoc. Director at (617) 253-3934, joels@mit.edu

2. **UC Davis Institute of Transportation Studies (ITS)**
   Plug-in Hybrid Electric Vehicle Research Center
   Andrew Burke, Research Engineer, afburke@ucdavis.edu, 530-752-9812
   Marshall Miller, Sr. Development Engineer, mmiller@ucdavis.edu, 530-752-1543

3. **Georgetown University**
   FCB Program
   cpp@georgetown.edu and http://fuelcellbus.georgetown.edu/
   Charles Pritzlaff, Program Mgr, Fuel Cell Bus Program, 202-687-4503
   Viacom (Vehicle) Systems Integration (VSI) in College Park, MD:
   Don Mase, and/or Larry Long, 240-297-3730

4. **Georgia Tech**
   Dr. Tom Fuller- Georgia Tech Applied Res. Corporation (GTARC)
   Tom.fuller@gtri.gatech.edu, 404-407-6075

5. **University of South Carolina (USC)**
   Prof. Roger Dougal, Electrical Engineering and Fuel Cell Center
   803-777-7890

6. **Bowling Green State Univ. (BGSU)**
   Electric Vehicle Institute (EVI)
   College of Technology
   Jeff Major, Chief Engineer
   419-372-8391, jeffmaj@bgsu.edu

7. **West Virginia University (WVU), Morgantown, WVA**
   Center for Alternative Fuels, Engines and Emissions (CAFEE) and
   National Alternative Fuels Training Consortium
   Mechanical Eng and Aerospace Depts.
   Prof. Clark, Nigel N, 304-293-3111, nigel.clark@mail.wvu.edu
   Prof. Wayne, W. Scott, 304-293-3111, Scott.Wayne@mail.wvu.edu

III. Industry: Bus OEMs, RESS Integrators, and Battery Consultants

1. **Hydrogenics Corporation**
   Mississauga, Ontario

http://www.hydrogenics.com

Daryl Wilson
905-361-3654, dwilson@hydrogenics.com
President and CEO Advanced Hydrogen Solutions

Kevin Harris
Business Development & Sales Director,
Americas Power Systems Group
27201 Tourney Road, Suite 201
Valencia, CA USA 91355
kharris@hydrogenics.com, 661-253-2593

2. **United Technologies Corp. (UTC)**
   Judith Ann Bayer
   Director, Government Business Development
   1401 Eye St., NW Suite 600
   Washington, DC 20005
   judith.bayer@utc.com, 202-336-7436

   Kenneth C. Stewart
   Vice President, Transportation Business
   United Technologies Corp. (UTC)
   860-727-2200, Ken.Stewart@utcpower.com

   Rakesh Radhakrishnan
   Product Manager, Transportation Business Development, Lead on CTE Bus
   860-727-2754, rakeshr@utcpower.com

3. **UQM Technologies, Inc.**
   Frederick, CO
   John Lutz, VP Technology
   jlutz@uqm.com, 303-278-2002

4. **Nuvera Fuel Cells**
   Billerica, MA
   Brian Bowers and Scott Blanchet, Director, Product Development
   617-245-7500

5. **Hymotion**
   Mark Kunin,
   Manager, Sales and Dealer Support (Prius retrofits with Li Ion batteries)
   Division of A123 Systems
   mkunin@a123systems.com, 636-534-3147

6. **TIAX, LLC**
   Cambridge, MA
   617-498-5000, www.tiaxllc.com
   Dr. Brian Barnett, VP Technology and Director of Advanced Battery Practice
   Barnett.b@tiaxllc.com, 617-498-5307

7. **ISE Corporation**
   Poway, CA; San Diego, CA
   www.isecorp.com, 858-413-1720, 858-413-1752
   Paul Scott, Chief Science Officer, pscott@isecorp.com
Tavin Tyler, Director FC Bus programs, 858-413-1720 (x775)
   Andrew Worley, VP Program Development
   Rob Del Core, Director of RESS Business Development
   rdelcore@isecorp.com, 858-413-1759

8. **Proterra, Inc.**
   Golden, CO ; Greenville, SC plant
   www.proterraonline.com, 303-562-0529
   Joshua Goldman
   Director of Business Development, San Diego, CA
   jgoldman@proterra.com

9. **A123 Systems, Inc.**
   Watertown, MA
   www.a123systems.com, 617-778-5700
   David Vieau, CEO; Dr. Bart Ripley, VP R&D; Ric Fulop, VP Bus Devpt.

10. **Maxwell Technologies, Inc.**
    San Diego, CA
    www.maxwell.com, 858-503-3300
    John M. Miller, VP Systems, applications and integration

11. **BAE Systems**
    www.hybridrive.com, 760-941-1448
    John Maddox, john.m.maadox@baesystems.com
    Tom Wells, expert on HEB Orion (worked with WVU on TRB LCA report)
    Rob Lindsey, Director of Transport Systems

12. **IC Corporation LLC** (Bus division of Navistar International)
    www.hybridshoolbus.org or www.ic-corp.com
    Michael Cancelliere, VP and General Manager
    Dane Roth, R&D Facility in Fort Wayne, IN
    dane.roth@ketchum.com, 312-228-6843

13. **Enova Systems, Inc.**
    Torrance, CA
    www.enovasystems.com
    Mike Staran, CEO and Executive VP, 310.527.2800
    jbadalamenti@enovasystems.com
    Developed a hybrid drive-train Plug-in Charge Depleting System:
    A V8 Diesel Engine is coupled in parallel hybrid with 25/80 KE hybrid electric power train, the Post Transmission System

14. **GM Allison Transmission**
    Dave Mikoryak, Manager Electric Drive Programs
    317-915-2848, David.Mikoryak@gm.com

15. **Sinautec Automobile Technologies, LLC**
    Arlington, VA
    Dan Ye, CEO
    dan.ye@sinautecus.com, 202-361-0549

16. **Foton -America Buses**
    Germantown, TN
    Cliff Clare, CEO
    914-474-1152

17. **Electric Power Research Institute (EPRI)**
    Mark Duvall, Director, Electric Transportation
    mduvall@epri.com, 650-855-2591
    Marcus Alexander, Vehicle Systems Analysis
    malexander@epri.com, 650-855-2489

18. **Ebus, Inc.**
    Downey, CA
    Anders (Andy) Eklov
    eklov@ebus.com, 562-904-3474

IV. Transit Authorities (TA) and NFCBP Consortia Partners

1. **Hawaii Center for Advanced Transportation Technologies (HCATT)**
   www.honolulu.gov/dts, 808-523-4125
   Thomas Quinn, Director
   tquinn@htdc.org, 808-594-0100
   James Burke, Chief, Honolulu Public Transit Div
   Had 10 New Flyer hybrid (60ft) buses in service since 04

2. **NAVC**
   Sheila Lynch, Executive Director

slynch@navc.org
Dave Dilts, Project Director
617-482-1770 (x14), admin@navc.org
Works with Nuvera Fuel Cell Bus - and UTC Hybrid-Fuel Cell Bus - both listed in III

3. **WESTART/CALSTART**
   http://www.buselectricdrive.org
   John Boesel, President and CEO
   Tom Brotherton, tbrother@weststart.org

4. **Center for Transportation and Environment (CTE)**
   Jason Hanlin, Director of Technology Research
   Jason@cte.tv
   Southern Hydrogen and Fuel Cell Coalition (SHFCC), Atlanta, GA
   Erik Bigelow re: batteries, 678-916-4948, erik@cte.tv

5. **AC (Alameda Contra Costa) Transit**
   www.actransit.org
   Oakland, CA
   510-891-4777 (+0 for info)
   Doug Byrne, Mgr. Maintenance and Operations for FCBs, 510-628-8253
   Jamie Levin, Director AF Policy & Marketing, 510-891-7244

6. **Long Beach Transit**
   www.lbtransit.com
   Rolando Cruz, Manager-Maintenance (gasoline-electric hybrid buses)
   rcruz@lbtransit.com, 562-599-8506
   Juan Vigil, QA and Maintenance

7. **Santa Barbara MTD**
   www.sbmtd.gov
   Dale Zielinski, Maintenance Manager, 805-963-3364 (x223)
   Bill Morris, Operations Manager

8. **Houston METRO**
   www.ridemetro.org
   Frank Bucalo, Mgr of Technical Services
   James W. Blocker, Maintenance
   713-615-7240

9. **Foothill Transit**
   West Covina, CA (near Pomona)
   www.foothilltransit.org

George Karbowski, Director of Operations and Maintenance
gkarbowski@foothilltransit.org, 626-931-7209

10. **WMATA Metrobus**
Washington, DC
202-962-1234 (info)
Jack Requa, Chief Operating Officer of Metrobus, 202-962-2800
Bob Golden, Bus Engineer, 301-618-1181
Phil Wallace, Bus Maintenance Operations, 301-618-1097

11. **Sun Line Transit Agency**
Thousand Palms, CA
Bill Loper, AF technician
760-343-3456 (x335), wloper@sunline.org
Tom Edwards, Dir. Maintenance
760-343-3456 (x312), tedwards@sunline.org

Appendix A-3: Web Resources and References

"*A Report on Worldwide Hydrogen Bus Demonstrations, 2002-2007.*" (March 2009). FTA-GA-04-7001-2009.01 posted at http://www.fta.dot.gov/research
Advanced Transit Association (ATRA) at http://advancedtransit.org/

Argonne National Lab. (ANL) postings at http://www.transportation.anl.gov/batteries/index.html and Ted Bohn," *Active Combination of Ultracapcitors and Batteries for PHEV ESS"* May, 2009 DOE Merit Review, www1.eere.energy.gov/merit_review_2009/2009_merit_review_12.pdf

American Public Transportation Association at www.apta.com

California Air Resources Board, CARB Zero Emission Buses at www.arb.ca.gov/msprog/bus/zeb/zeb.htm

"*Design Guidelines for Bus Transit Systems using Electric and Hybrid Electric Propulsion as an Alternative Fuel*", DOT-FTA-MA-26-7071-03-1, March 2003, found at http://transit-safety.volpe.dot.gov/Publications/order/singledoc.asp?docid=370

DOE 2009 Recovery Act awards for hybrid-electric vehicle components, systems and infrastructure at www.energy.gov/recovery/transportationfunding.htm and battery awards at http://www1.eere.energy.gov/recovery/pdfs/battery_awardee_list.pdf

DOE/EERE Alternative Fuels and Advanced Vehicles, Heavy Duty Vehicles and Engines data base for hybrid buses and electric drive manufacturers http://www.afdc.energy.gov/afdc/vehicles/heavy/hybrid_systems

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EBus information at www.ebus.com

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