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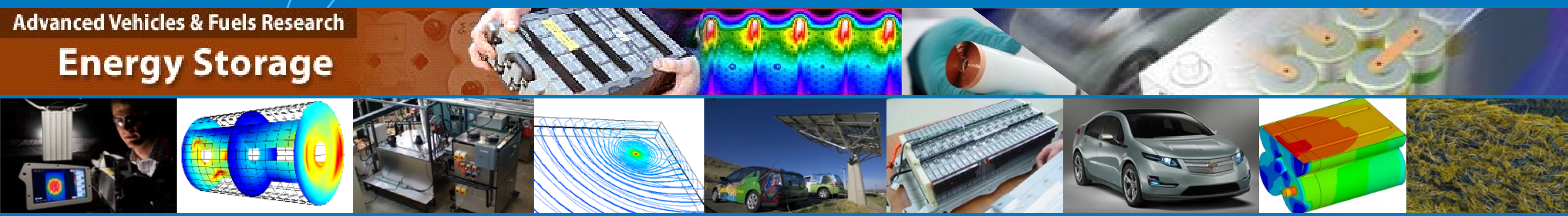
December 2015 Milestone Report

Battery Ownership Model

Medium Duty HEV Battery Leasing & Standardization



Milestone Report: Simulate MD HEVs with standardized batteries and evaluate economics of leased and owned battery scenarios

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Foreword

In summer of 2014, principals at Eaton discussed with DOE VTO that standardization and leasing batteries could make the medium duty HEVs more cost attractive and perhaps revive the USA market. DOE VTO provided guidance to NREL to focus its Battery Ownership subtask to investigate the economics of leasing standardized battery packs for medium duty HEVs. Over the last 15 months, we performed preliminary analysis and interacted with industry to collect necessary information for assessing the merit of leasing standardized batteries for MD HEVs. We found that economics of leasing may be better than owning batteries but depending on how much standardization could reduce the incremental cost of HEVs compared to conventional diesel vehicles. We then started to identify battery standardization strategies and how it could impact cost.

The focus of the work in this report was to further quantify cost benefits of standardized batteries for MD HEVs. We decided to draw on experience of Ricardo experts that have done a battery standardization study for the California Energy Commission. Interim results of the joint effort by Ricardo and NREL were shared with DOE and Eaton via web meeting on December 23, 2015. Subsequent to the web meeting, additional total cost of ownership analysis was added for this final milestone report.

This work was performed by the members of Energy Storage and the Vehicle Simulation Teams in the Transportation and Hydrogen Systems Center and members of Vehicles Analysis Team in Ricardo Inc. We appreciate the support provided by Brian Cunningham of the Vehicle Technologies Office at the U.S. Department of Energy.

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Key Findings – 1 of 4

- Incremental Costs of Hybrid Electric Drive Systems Varies by Manufacturer and Vehicle Type and ranges from \$12,000 to \$35,000 for Class 5 delivery vehicles relative to a conventional MD vehicle
- US New Vehicle Registrations of Class 4-6 HEV Step Vans are Projected to be Less than ½ of all US Step Van New Vehicle Registrations through 2020 and are expected to range from 1k - 4k per year
  - At 1k batteries/year, no value to standardization
  - At 5k batteries/year, only 2% value to standardization (communications interface)
  - At 10k batteries/year, there is 7% cost benefit with standardization (Standardizing module housing & bus bars are most beneficial)
  - At 50k and 100k batteries/year there is a 13% to 16% cost benefit to standardization
- Only one of the identified standardization strategies resulted in cost decreases at low production volumes.
- The primary cost impact of standardization is to extend the range of applications and thus increase production volumes.
- There is a steep decrease in per battery price for volumes between 1k and 10k per year (50% reduction).
- The potential Class 5 MD HEV market is not large enough to reach the benefit of 10k batteries/year
- Greater value may be obtained by applying strategies across a wider range of products such as other medium-duty vehicle platforms, full electric vehicles, and light-duty HEV
- The ideal battery for Class 5 MD delivery trucks
  - Has approximately 45 kW peak power and 1.8 kWh energy (1.5 to 2.5 acceptable)
  - Uses 5Ah to 7.5Ah Li-ion cells with peak power to energy ratio of 25 hr^{-1}
  - Uses forced air thermal management
  - Would be produced at annual production volumes greater than 10,000 units/year
  - Lasts the life of the vehicle

Key Findings – 2 of 4

- Leasing looks better than direct ownership over a short 3 year time horizon
  - Shifts expenses from capital to operating expenses, favorable in the short term, but always increases total cost of ownership over the long term
  - May be attractive to some fleet operators with constraints on capital expenses for purchasing new vehicles
  - Bottom limit for battery lease price to fleet operator is $177/month
- Strongest factors affecting total cost of ownership and payback period are
  - Fuel prices
  - Annual mileage driven
  - Incremental cost of HEV
  - Incremental fuel savings benefit of HEV
- Compared to the baseline scenario with ~15 year payback, a low-cost MD HEV scenario was identified with less than 1 year payback period by modifying the following baseline assumptions
  - HEV incremental cost reduced from $22,800 to $10,000 per vehicle
  - Government incentives increased from $3,000 to $7,500 per vehicle
  - Battery life greater than the life of the vehicle, increased from 10 years to greater than 12 years
  - Vehicle residual value at end of 12 years increased from $24k to $28k

Key Findings – 3 of 4

- Key recommendations for HEV Class 5 HEVs:
  - Continue to focus efforts on reducing incremental cost of HEV technology
    - Battery standardization is one pathway
    - Cost reductions in motor, controller, and power electronics costs will also be required
  - Improve HEV incremental benefit beyond present 17% fuel savings (drive-cycle dependent)
    - Light duty gasoline-fueled HEVs achieve 25-40% incremental fuel savings
    - Improve efficiency of energy recovery during deceleration events
    - Evaluation of powertrain performance requirements over a wider range of vehicle vocations and duty cycles and search for common components.
    - Cost impact of downsizing diesel engine (including engine availability)
  - Analysis of TCO across a range of powertrain configurations including PHEVs and EVs with the goal of defining the minimum total cost of ownership.

Key Findings – 4 of 4

- Suggested next steps:
  - Expand analysis beyond Class 5 delivery vehicles to Class 4-7 vehicles and additional vocations
  - Expand design space beyond HEV to also include PHEV and EV
  - Perform analysis of HEV powertrain with goal of minimizing cost while maintaining or improving performance. This may include the use of COTS components.
  - Employ TCO model to investigate impact of a wider range of parameters on total cost of ownership (e.g. maintenance cost reduction, use of synthetic lubricants and fluids, battery second life application impacts on residual value).
  - Identify common battery requirements across Class 4-7 PHEV, EV, HEV vehicle platforms in order to increase MD battery annual sales to greater than 10,000 batteries per year
    - Total Class 4-7 market segment is 150k vehicle per year annual sales, 10k HEVs per year is a reasonable 7% of this segment
  - Extend analysis to include other powertrain components for which a cost reduction might result from a broader range of applications.

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Project Overview

Objective:

- The overall objective of this project is to investigate if standardization and leasing of batteries for medium duty (MD) hybrid electric vehicles (HEVs) could improve the economics of MD HEVs leading to increase of their market share, which has been declining in recent years

Approach:

1. Perform a preliminary scoping analysis to estimate the potential value of standardization and leasing;
2. Build an industry coalition to collect necessary data on leasing, vehicle usage, vehicle requirements, and battery specification data.
3. Identify battery standardization strategies and quantify the associated costs.
4. Simulate performance and degradation of standardized batteries in medium duty HEV roles, and
5. Evaluate the economics of standardized batteries under leasing and direct-ownership scenarios in search of cost-optimal strategies

Progress:

- NREL has completed steps 1 through 3 and have previously reported on the results
- For Steps 4 and 5, we decided to leverage recent work by Ricardo experts on EV battery standardization and total cost of ownership. The joint effort by Ricardo and NREL focused on three areas
  - Battery standardization strategies and quantification of associate
  - Simulation of the performance and degradation of standardized batteries in medium duty commercial vehicles
  - Evaluation of the economics of standardized batteries under leasing and direct-ownership scenarios in search of cost-optimal strategies.
- This final report provides the results of the analysis and final conclusions.

Focus is on Class 5-6 Commercial HEVs

NREL 19821

NREL 18568

Standardization and leasing of batteries for medium duty hybrid electric vehicles (HEVs) has been proposed as a means to reduce the payback period of MD HEVs and to increase their market share, which has been declining in recent years. In this project, NREL and Ricardo are working together with industry partners to investigate solutions and quantify the economics of medium duty HEVs in the presence of standardized and leased batteries.

Objective:

Quantify the economics of medium duty HEVs in the presence of standardized and leased batteries. Answer the question: Will standardization strategies reduce battery costs?

Project Enhancements November-December 2015

Additional tasks were added to the scope of work during November and December, including:

1. A copy of the beta issue of Argonne National Laboratory's BatPaC (Battery Performance and Cost) modeling tool was obtained. The updated version contains many more features and capabilities than previous versions (a public release of Version 3 is scheduled before the end of December). These additional features provided an opportunity to confirm and enhance earlier calculations involving the cost impacts of standardization strategies.

2. Additional BatPac simulations were completed to evaluate the cost impact of varying the number of cells per module as well as the cell capacity (Ah), including the number of cells per pack.

3. Additional research was completed to determine the cost of battery packs to vehicle OEMs, including warranties and integration of thermal management systems (air cooling for MD HEV packs).

4. A more detailed evaluation of cost components was completed for the identified standardization strategies and range of production volumes, including fixed, variable, and investment costs.

5. Additional interviews were conducted with vehicle OEMs, hybrid component suppliers, and fleet managers to confirm vehicle specifications and operational costs associated with the total cost of ownership (TCO) model.

Contents

Analysis Approach

Fleet DNA Database

- Leverage real-world vehicle data from Fleet DNA database
- Hybrid Vehicle Incentive Program (HVIP) HEV vehicle data

Duty Cycle Analysis

- NREL's DRIVE model used to develop representative drive cycle
- NREL FASTSim model used to extract battery power profile

Battery Life Model

- Apply BLAST using vehicle duty cycle and battery specifications
- BLAST feeds battery sizing, life cycles, and fuel economy impacts to Cost of Ownership Model

Standardization Benefits Analysis

- Select Standardization Strategies
- Apply Ricardo Total Cost of Ownership (TCO) and ANL BatPaC models
- Evaluate the Cost impacts of standardization strategies

The Project Includes Use of Modeling Tools Developed by NREL and Ricardo

Tools utilized to define duty cycle, HEV system specifications, battery life, battery cost, and TCO

Data base: MD delivery van data logger (HVIP Study)

Utilize NREL DRIVE model to generate **composite duty cycle**

Determine **vehicle specifications** for MD delivery van

Utilize NREL FASTSim tool to perform parametric analysis of 61 vehicle powertrain and control set points.

Define effective **HEV system specifications:** battery capacity and power, motor size, engine size, vehicle weight, and allowable SOC range for the selected composite duty cycle

Select 1 cell size (Ah and dimensions), and one or two standard module configurations that address the power and voltage of medium duty HEV delivery trucks.

Utilize NREL BLAST tool to define **battery life** and **battery capacity as a function of accumulated vehicle miles** for MD delivery van operating under defined composite duty cycle

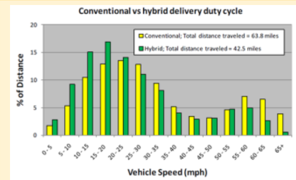
Duty Cycle

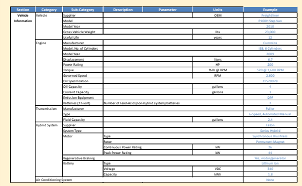
Vehicle Specifications

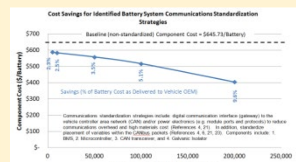
HEV System Specifications

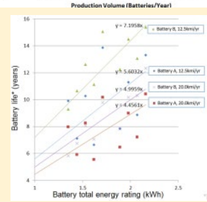
Battery Life

TCO Input

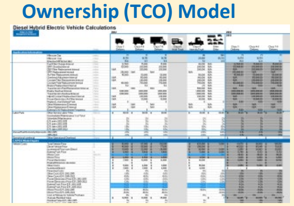








Ricardo Total Cost of Ownership (TCO) Model



Define battery standardization approaches.

Utilize ANL BatPaC tool to evaluate impact of battery standardization approaches on **battery cost**

Incorporate **battery lease and direct ownership models** into TCO model

Evaluate the **economics of standardized batteries** under leasing and direct-ownership scenarios in search of cost-optimal strategies.

Determine **residual value of battery at end of first life**.

Battery Cost

Battery Lease and Direct Ownership Costs

Battery Residual Value

TCO

TCO Output

Battery Standardization/Leasing Impacts on TCO

Standardization recommendations/alternatives that incorporate design standardization aspects

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Applying Fleet DNA Database

Fleet DNA Database

- Leverage real-world vehicle data from Fleet DNA database
- Hybrid Vehicle Incentive Program (HVIP) HEV vehicle data

Fleet DNA Project

FleetDNA is NREL's central repository of real-world duty cycle data collected from medium and heavy-duty collected from a wide variety of vehicle vocations and driveline technologies

The database includes second-by-second vehicle and component performance data from a series of medium-duty HEV vehicles collected as part of the California Air Resources Board Hybrid Vehicle Incentive Program (HVIP)

Fleet DNA Medium-duty HEV Data by Vocation

- NREL's Fleet DNA Project has collected substantial data from vehicles in the California Hybrid Vehicle Incentive Program (HVIP), summarized below

Table 2. Data Channels Collected by Vocational Vehicle Group

	Beverage			Food		Linen				Parcel			All
	H		C	H	C	H		C		H	C		
	F	L	L	L	L	F	L	F	L	F	F	L	
Vehicle Count	22	17	7	9	2	10	4	1	15	26	3	9	125
Total Hours	1,052	840	371	1,133	227	748	156	70	1,103	1,435	90	441	7,667
Driving Hours	809	605	279	901	200	380	128	39	597	1,111	62	339	5,450
Idle Ratio	23.1%	27.9%	24.6%	20.5%	12.1%	49.2%	18.0%	44.7%	45.9%	22.6%	31.4%	23.2%	28.9%
Total Distance (mi)	25,348	16,652	8,825	31,548	8,575	10,241	3,891	1,218	18,575	21,859	1,011	7,109	154,852
Total Fuel (gal)	3,167	2,547	1,430	1,825	1,328	1,058	349	179	1,912	2,398	173	238	16,604
Average (mpg)	8.0	6.5	6.2	17.3	6.5	9.7	11.2	6.8	9.7	9.1	5.8	29.8	9.3
Stops	30,534	31,196	11,847	20,780	2,619	21,070	6,524	2,132	27,068	86,745	5,154	25,824	271,493
Stops / mi	1.2	1.9	1.3	0.7	0.3	2.1	1.7	1.7	1.5	4.0	5.1	3.6	1.8
Stops / hr	29.0	37.1	32.0	18.3	11.5	28.2	41.7	30.6	24.5	60.4	57.1	58.6	35.4
avg KI (1/mi)	0.39	0.74	0.56	0.39	0.22	0.66	0.50	0.42	0.48	1.73	3.65	1.88	0.94
avg DPF Out Temp [C]	253					216		251		215	243		231
avg SCR Out Temp [C]	219					185		224		173	196		193
avg Nox SCR In [g/kWh]	4.60					6.80		4.57		7.92	5.11		6.37
avg Nox SCR Out [g/kWh]	0.88					3.15		0.67		3.56	1.93		2.42
avg Nox SCR In [g/mi]	7.32					6.39		8.43		8.28	8.23		7.40
avg Nox SCR Out [g/mi]	1.39					2.96		1.24		3.59	3.11		2.56
Total Work [kWh]	40,017					9,569		2,247		23,863	1,666		
Driving Work [kWh]	39,896					9,538		2,163		23,640	1,537		
avg Driving Power [kW]	49.3					25.1		56.1		21.3	24.8		

"H" = hybrid, "C" = conventional, "F" = full data set, "L" = limited data set

HVIP Data Collection by Technology

	Automated Manual		Automatic		
	Eaton Hybrid	Eaton UltraShift	Aisin	Allison	Grand Total
Diesel		**5**	**8**	**27**	**40**
Day Cab - Cummins ISX		3			3
Day Cab - International / MaxxForce				5	5
Day Cab - Paccar MX		2			2
Step Van - Cummins ISB				15	15
Step Van - International / MaxxForce				6	6
Step Van - ISUZU			8		8
Straight Truck - Cummins ISB				1	1
Diesel/Electric HEV	**86**		**2**		**88**
Day Cab - Cummins ISB	14				14
Day Cab - International / MaxxForce	3				3
Reefer Truck - HINO			2		2
Step Van - Cummins ISB	40				40
Straight Truck - Cummins ISB	27				27
Straight Truck - International / MaxxForce	2				2
Diesel/Hydraulic HHV	**1**				**1**
Step Van - Cummins ISB	1				1
Grand Total	**87**	**5**	**10**	**27**	**129**

Medium-duty HEV Duty Cycle

NREL's Drive Cycle Rapid Investigation, Visualization and Evaluation Analysis Tool (DRIVE) was used to develop a representative drive cycle from the FleetDNA field data.

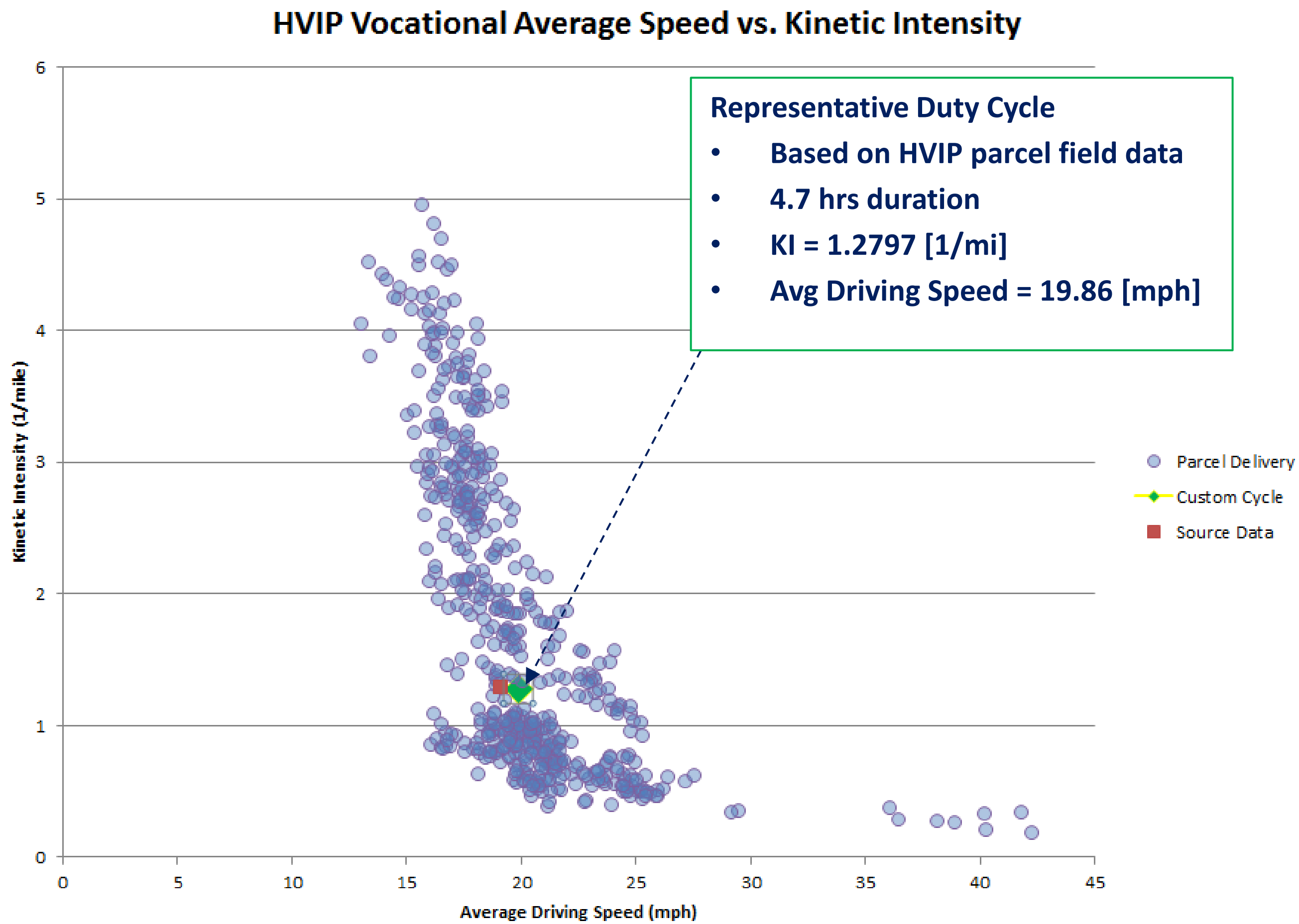
Duty Cycle Analysis

- NREL's DRIVE model used to develop representative drive cycle
- NREL FASTSim model used to extract battery power profile

NREL's FASTSim model was used to extract battery power profile duty cycle from a HEV over a range of battery design characteristics. The power profiles were fed into BLAST.

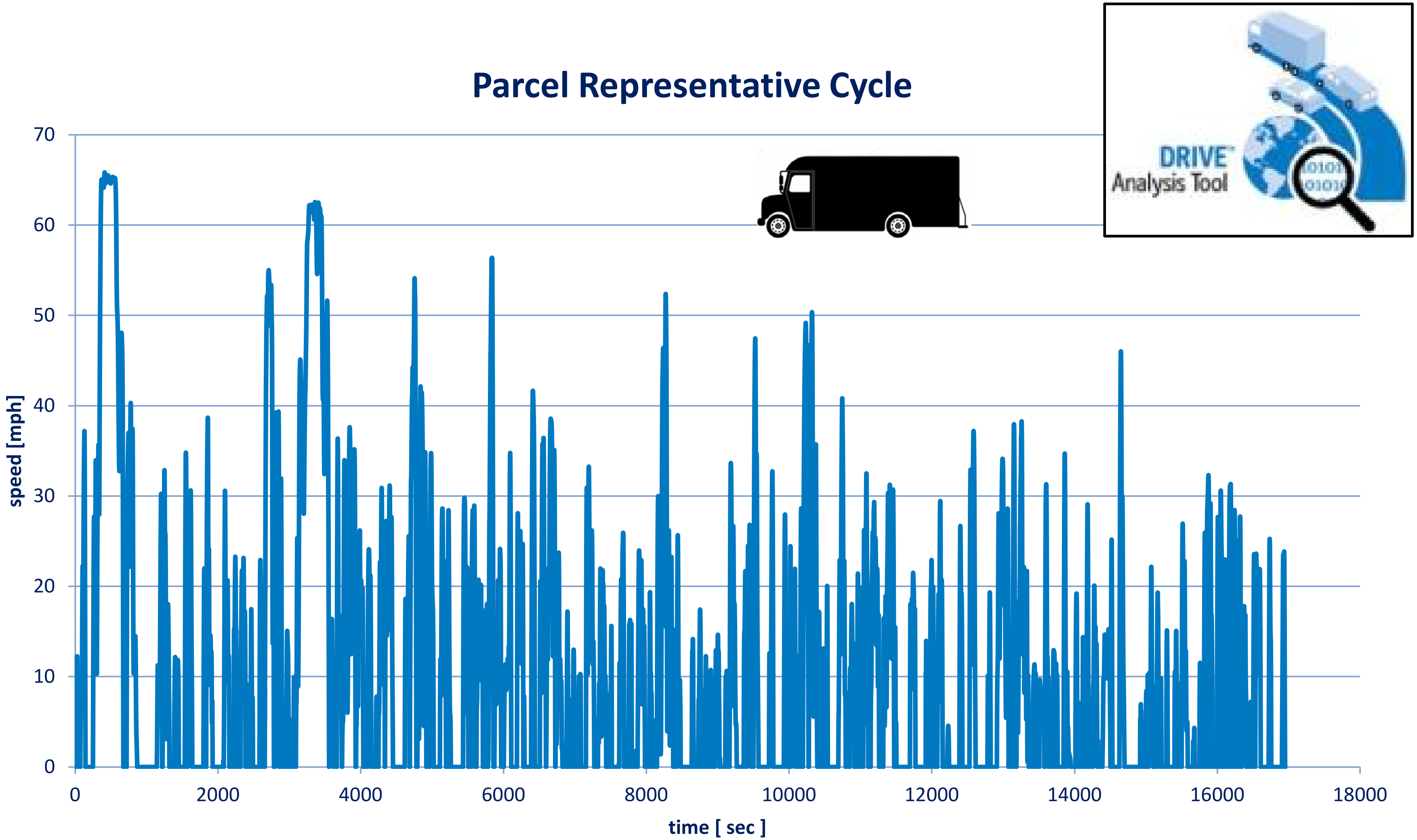
FASTSim model of parcel delivery vehicle was previously validated with chassis dynamometer testing

Custom Drive Cycle derived from HVIP Fleet DNA Data



The duty cycle selection for the parcel delivery vocation was based on data logging from 40 vehicles from three locations in the LA area. For this vocation, the standard duty cycles that matched the observed activity (and were chosen for chassis testing for this vocation and vehicle set) were the CARB HHDDT with 65 mph variant and EPA GHG rule weightings; the New York City Composite (NYCC); the UDDS (Figure 4); and the Hybrid Truck Users Forum Class 4 Parcel Delivery Driving Schedule (HTUF4) (Figure 8). These cycles plotted against the observed activity data (kinetic intensity) for this vocation.

Representative Cycle : Time-Speed Trace



FASTSim used to Sweep the Design Space

Baseline Vehicle Inputs (P100)

- Motor Size : 26 kW
- Battery Power : 26 kW continuous
- Battery Capacity : 1.8 kWh
- Battery Specific Energy : 44 kWh/kg
- Minimum SOC : 0.4
- Maximum SOC : 0.8

Simulated 62 Hypothetical Designs

- Degree of Hybridization
- Battery total energy (kWh)
- Battery rated power (kW)
- Control set points

maxEssKw	maxEssKwh	essKgPerKwh	assistKwPerI	chgKwPerPe	maxMotorKw	maxFuelConvK	mpge	FeP_LifeYrs	NCA_LifeYrs
16.9	1.8	44.0	0.2	0.5	16.9	158.2	9.0	10.9	12.9
19.5	1.8	44.0	0.2	0.5	19.5	149.1	9.1	13.0	13.5
19.5	1.8	44.0	0.2	0.5	26.0	149.1	9.2	10.0	12.6
20.8	1.8	44.0	0.2	0.5	20.8	149.1	9.2	12.8	13.5
20.8	1.8	44.0	0.2	0.5	26.0	149.1	9.2	10.6	11.4
22.1	1.8	44.0	0.2	0.5	22.1	149.1	9.2	8.9	12.0
22.1	1.8	44.0	0.2	0.5	26.0	149.1	9.3	8.2	10.3
23.4	1.8	44.0	0.2	0.5	23.4	149.1	9.2	7.1	10.0
23.4	1.8	44.0	0.2	0.5	26.0	149.1	9.3	7.5	12.8
24.7	1.8	44.0	0.2	0.5	24.7	149.1	9.3	11.2	13.3
24.7	1.8	44.0	0.2	0.5	26.0	149.1	9.3	7.5	12.8
26.0	1.4	44.0	0.2	0.5	26.0	149.1	9.3	5.3	9.4
26.0	1.4	44.0	0.2	0.5	26.0	149.1	9.3	7.3	10.7
26.0	1.5	44.0	0.2	0.5	26.0	149.1	9.3	6.9	11.6
26.0	1.6	44.0	0.2	0.5	26.0	149.1	9.3	9.8	11.8
26.0	1.7	44.0	0.2	0.5					
26.0	1.9	44.0							

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Battery Life Model

- NREL's Battery Lifetime Analysis and Simulation Tool Suite (BLAST) was used to evaluate the battery cycle life for 2 battery designs and 2 annual vehicle mileage scenarios.

- Power profiles from the FASTSim HEV models were used as inputs

- The BLAST analysis provided life cycle information to the next Total Cost of Ownership Model

Battery Life Model

- Apply BLAST tool suite using vehicle duty cycle and battery specifications
- BLAST feeds battery sizing, life cycles, and fuel economy impacts to Cost of Ownership Model

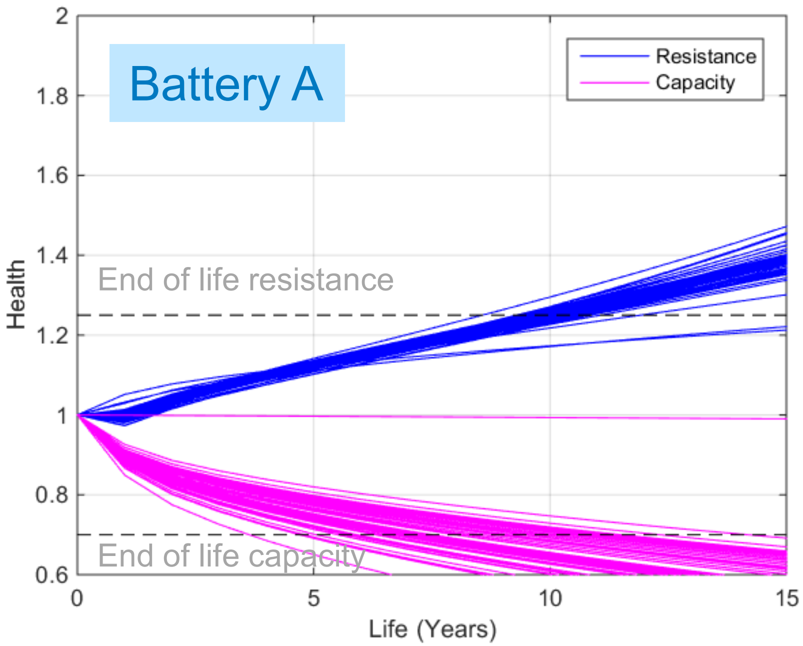
… with Four Scenarios for Battery Lifetime

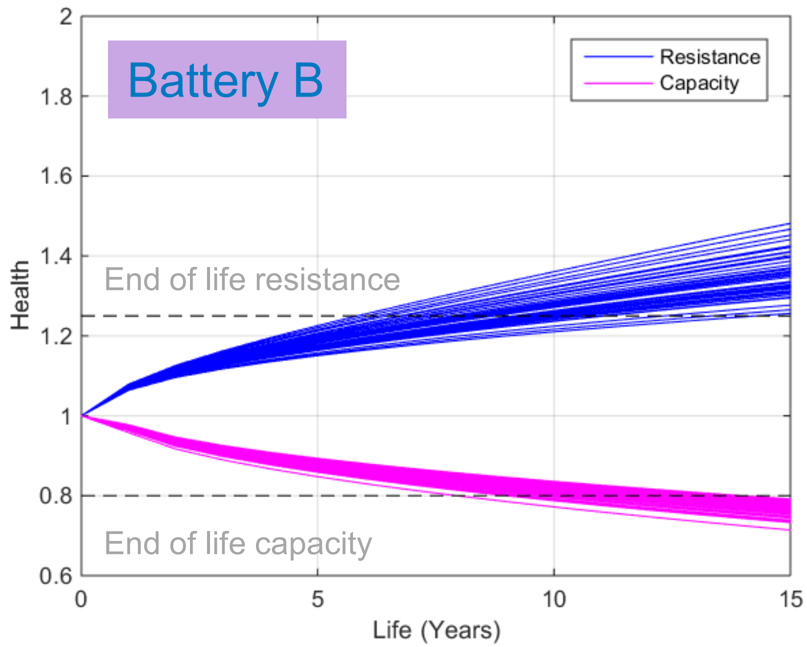
12,500 miles/year X **20,000 miles/year**

Battery A – Short Life
- Based on A123 2.3 Ah cell (iron-phosphate)
- Life ranges from 5-12 years

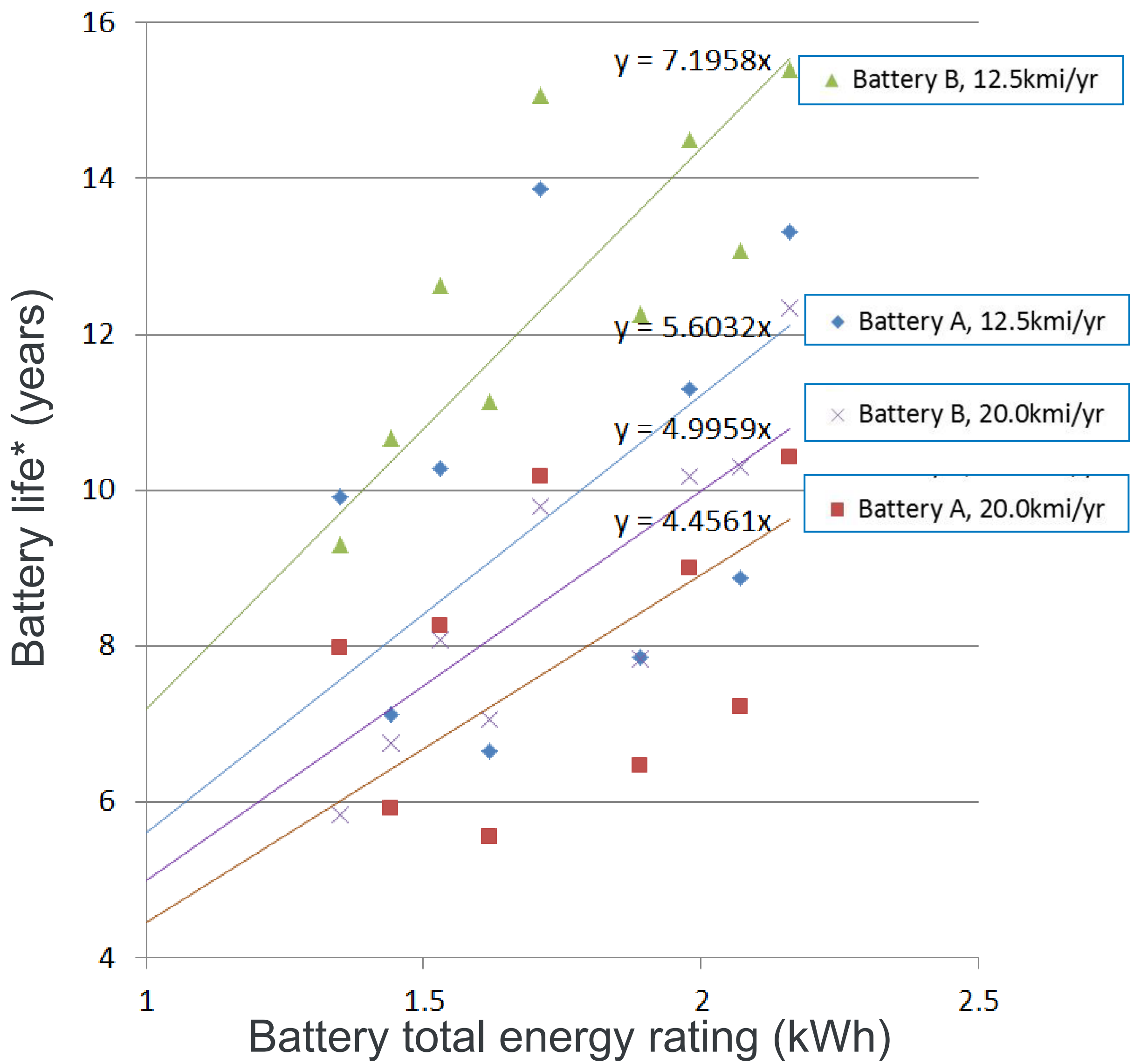
Battery B – Long Life
- Composite of Saft 6 to 40Ah cells (NCA)
- Life ranges from 7-15 years

Example life simulations of 62 vehicle/battery designs (20,000 miles/year)





Battery Life Mainly Depends on Battery Total Energy

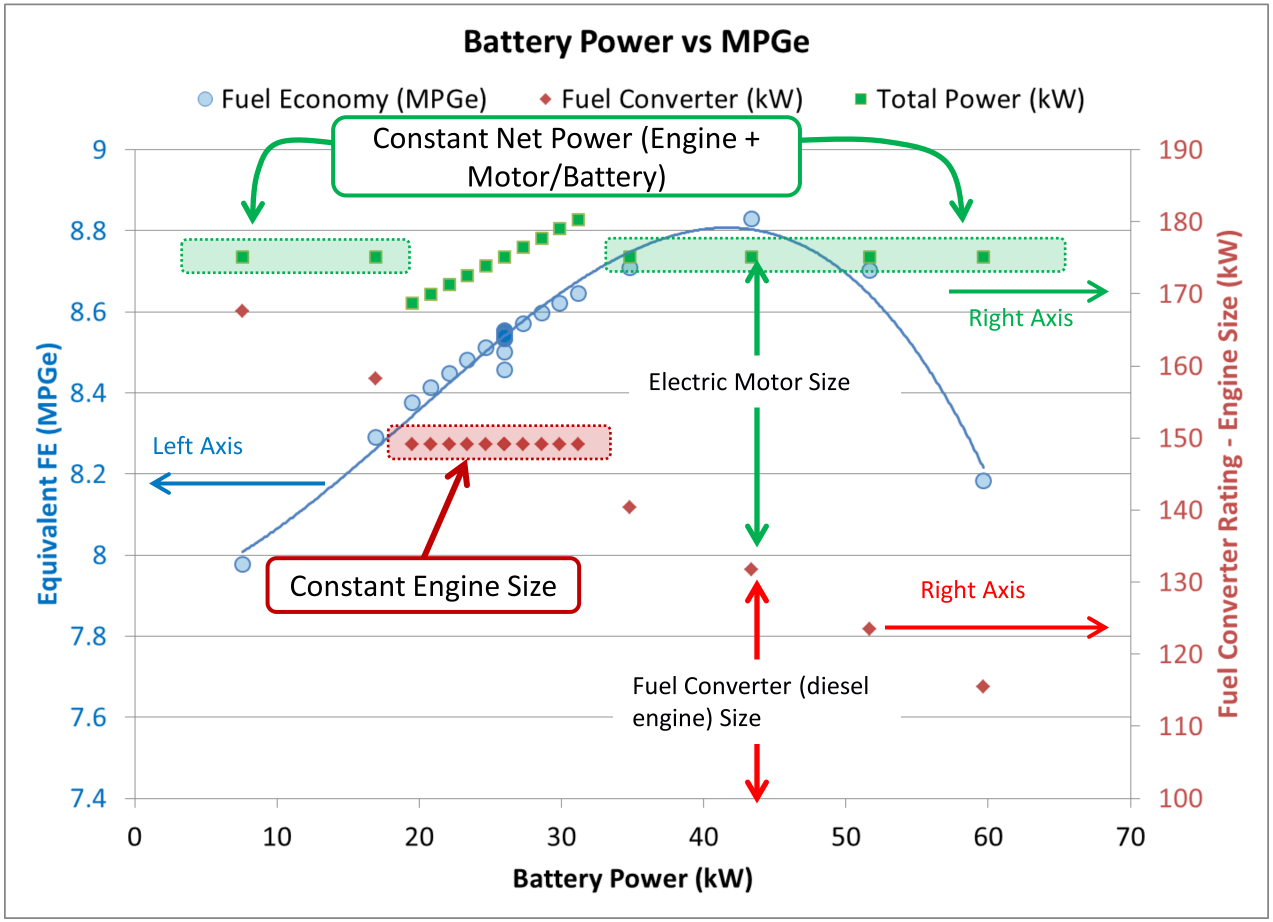


*Phoenix, AZ climate

- **Battery life increases with increasing total energy**
  - Individual cases vary due to different control set-points
  - Lifetime could be optimized with knowledge of drive cycle

Fuel economy depends on battery/motor power

Battery power rating has strong impact on fuel economy but little impact on life. (Battery energy rating is opposite. Total energy has little impact on fuel economy but strong impact on life.)



- Searched component design space with design of experiments using NREL FASTSim vehicle simulator.
- 45kW battery provides optimal fuel economy when vehicle net power (engine & battery) held constant at 175kW.
- Current Eaton system is near optimum fuel economy for package delivery duty cycle
- For battery/motor power ratings greater than 45 kW, fuel converter is not well matched to duty cycle, resulting in negative impacts on fuel economy.

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Standardization Benefits Analysis

- NREL and Ricardo teamed to identify a list of candidate battery standardization strategies based on industry consultations during phase I of this project and leveraging Ricardo experience and information from previous battery standardization projects and industry additional interactions
- Cost of ownership, incremental component costs, and vehicle market data for relevant to the medium duty parcel delivery application were gathered and incorporated into Ricardo's TCO model
- A cost analysis was conducted for each of the identified strategies using the ANL BatPaC
- TCO analysis conducted and with interim conclusions provided

Standardization Benefits Analysis

- Select Standardization Strategies
- Apply Ricardo Total Cost of Ownership (TCO) and ANL BatPaC models
- Evaluate the Cost impacts of standardization strategies

Battery Standardization and Costs

Define optimum battery specifications & costs (FASTSim analysis)

Specifications: Hitachi Li-Ion Battery (as employed in Eaton hybrid system):

Parameter	Units	Specification
Power (pack)	kW	26 continuous and 44 peak
Energy Storage Capacity (total and useable)	kWh	1.8
Cell and Pack Capacity	Ah	5.5
Cell Dimensions, Type, Weight	L x W x H (mm), kg	Prismatic Cell: 120 mm x 80 mm x 12 mm, Weight:240 g/cell
Pack Dimensions	L x W x H (mm), kg	1250 mm x 508 mm x 300 mm, 84 kg
Pack Voltage	vdc	340 (nominal range 270 – 400)
Cell Output (Power) Density	W/kg	5,000
Cells (voltage, capacity, internal resistance)	v, Ah, ohms	3.54 v, 5.3 Ah, 4mOhms
Cells/module, modules/pack, configuration	12 cells/module, 8 modules/pack = 96 cells in series	
Chemistry	Lithium-Ion: NMC cathode, hard amorphous carbon anode	
Adjoining vehicle systems, including communications protocols: Proprietary CAN link to Eaton control module		
Impact of charge/discharge cycles on power	At 80% DOD	95% of original power at 100,000 cycles
Hitachi BMS System: Functions include individual battery voltage detection, temperature detection, overcharging/over-discharging/over-temperature detection, balancing, and communications. SOC range 20% to 50%. Integrated to Eaton control module.		
Cooling system, min and max battery operating temperatures : Active air cooled -30 ^{0}C to +60 ^{0}C 1 Temp sensor per every 4 cells		

Battery Standardization Strategies were Combined into Eight Categories, each Involving Multiple Components

The twelve identified standardization strategies were divided into eight categories and ranked in order of their impact on cost reduction. A brief description of these categories and affected battery components/systems is presented in the following table. Additional details for each strategy, including impact on individual components/systems are included in the appendices of this report.

Standardization Approach	Description
Module Housings, Bus Bar, Attachments	1. Adoption of common cell and/or module sizes (outside packaging dimensions) for prismatic cells and standard housing manufacturing processes (References 10, 11, 14, 15): Allows common tooling for cells and module enclosures without restrictions on chemistry. Although not currently practical for light duty vehicle applications, common cell and module sizes are appropriate for MD HEVs due to wider ranges of installation options., 2. Common bus bar connectors (References 14, 15, 16): Provides common interface for a) power electronics and b) energy transfer; bus bars vary with battery power-to-energy ratio and are currently sized to each application, 3. Adoption of common module housing attachment method for cells, cell housing mounting attachments. (References 14, 15, 16, 28): Commodity item for future battery systems. Cells do not typically incorporate mounting features.
Module Voltages	Standardize module voltages: Allows use of common module components and reduces material handling requirements. (References 4, 6, 13, 28). Impacts module packaging: 1. Cell Group Interconnects: Standardized design (copper), including design for manufacture. Maintaining module voltages to less than 60 volts increases safety during assembly without affecting currents. 2. Module SOC Regulator: Balances SOC across cells. 3. Terminals and Other Module Materials: common size and materials.
Electrode Dimensions	Positive electrode (carbon) and negative electrode (lithium metal oxide): Material preparation, coating, calendaring, slitting, drying. Allows common processing and assembly equipment with no restrictions on variations in cell chemistries. Also allows standardization of materials and joining techniques.
Communications	1. BMS would require redesign and reprogramming to accommodate microcontroller and revised module communications, including CAN drivers. 2. Eliminates microconrollers and CAN interface at each module with single microcontroller/CAN transceiver. 3. Interface for Controller Area Network (standard set of input/output signals, protocols defined by vehicle OEM), modifications to communications interface. 4. Galvanic isolation insulates functional sections of electrical systems to prevent current flow between the sections while permitting energy or information to be exchanged between the sections to achieve safety isolation, voltage level shifting and ground noise mitigation.
Current Collectors	Material joining methods; welding; adhesives. Allows common processing and assembly equipment.
Safety Systems	1. Burst disks: commodity item to be defined by standards organization. Standardized, off-the-shelf burst discs would reduce design requirements. 2. Battery disconnect (automatic + manual): commodity item to be defined by standards organization. Provides first responders with common system.
Module Stack Interface, Heating/Cooling, Heat Conductors	1. BMS connectors: standard interface, 2. Module connectors: commodity item for future battery systems, 3. Module switching circuits: allows custom configuration of battery characteristics using a wide range of modules (power to energy ratios, voltages, etc.), 4. Air cooling components (fan, plenum, ducts): focus is on air-cooling and air-heating of HEV battery packs for commercial vehicles. Heating presents challenges (currently, resistance heaters are employed), 5. Thermal conductors, heat transfer foam: allows common interface from cells/modules to battery heat removal system. Heat-conducting foams are typically utilized to move heat away from cells. High-power-delivery events can cause rapid rise in cell temperature. Goal is to maintain constant operating temperature.
Interface for Power Transfer	1. BMS: the BMS will interface with the cell-switching circuit; the cell-switching circuit will provide the interface to the power electronics: variety of circuit interfaces, 2. Cell switching circuit: the cell-switching circuit allows dynamic configuration of cells to meet load and storage demands and isolation of abnormally-operating cells. Note standard for high voltage connector, 3. High voltage connectors: module terminals: the high voltage connectors will be a standardized design and produced in large quantities.

References 4, 6, 12, 13, 14, 15, 16, 17, 18, 23, 28

Affected Battery Components and Manufacturing Processes were Identified for each Standardization Strategy

For each of the eight battery standardization strategies, the affected components and manufacturing processes were identified. These are summarized in the following tables.

Affected Battery System	Standardization Strategy (and references)	Affected Components and/or Systems	Component Manufacturing Processes
Communications	Standardize digital communication interface (gateway) to the vehicle controller area network (CAN) and/or power electronics (e.g. module ports and protocols) to reduce communications overhead and high materials cost (References 4, 21, 28). In addition, standardize placement of variables within the CANbus packets (References 4, 6, 21, 23).	1. BMS	1. Printed Circuit Board and Integrated Circuit Manufacture
		2. Microcontroller	2. Purchased item + microcontroller programming
		3. CAN transceiver	3. Purchased Item
		4. Galvanic isolator	4. Purchased Item
Electronics	Standarized interface for power transfer to the power electronics, cell switching circuit: High Voltage connection from modules (Reference 4, 22, 28)	1. BMS	1. Modify to facilitate communication with cell-switching circuit
		2. Cell switching circuit	2. Printed circuit board and integrated circuit manufacture
		3. High voltage connectors (20-22 gauge): module terminals	3. Metal stamping
	Standardize module voltages: Allows use of common module components and reduces material handling requirements. (References 4, 6, 13, 28). Impacts module packaging.	Modules.	1. Cell group interconnects
			2. PCB and IC: Module SOC regulator
			3. Terminals (aluminum and copper stampings) and other module materials

Affected Battery Components and Manufacturing Processes were Identified for each Standardization Strategy

For each of the eight battery standardization strategies, the affected components and manufacturing processes were identified. These are summarized in the following tables.

Affected Battery System	Standardization Strategy (and references)	Affected Components and/or Systems	Component Manufacturing Processes
Current Collectors	Standardize positive (aluminum) and negative (copper) current collectors and terminal dimensions (References 6, 12, 13).	Current collectors, manufacturing techniques (material joining methods).	Material joining methods; welding; adhesives.
Electrodes	Standardize electrode dimensions (References 12, 13, 28)	Positive Electrode (carbon) and Negative Electrode (Lithium metal oxide)	Material preparation, coating, calendaring, slitting, drying.
Safety	Standardize 1) burst vent (OPSD - Over Pressure Safety Device), 2) automatic battery disconnect (CID - Circuit Interrupt Device) (References 6, 17)	1. Purchased item: burst disks	1. Frangible aluminum disk
		2. Purchased item: automatic battery disconnect + manual battery disconnect	2. Relay contactor (automatic), switch (manual)

Affected Battery Components and Manufacturing Processes were Identified for each Standardization Strategy

For each of the eight battery standardization strategies, the affected components and manufacturing processes were identified. These are summarized in the following tables.

Affected Battery System	Standardization Strategy (and references)	Affected Components and/or Systems	Component Manufacturing Processes
Modules	Adoption of common cell and/or module sizes (outside packaging dimensions) for prismatic cells and standard housing manufacturing processes (References 10, 11, 14, 15)	Cell containers	Fabricated metal housing (stamped, welded)
		Module housing	Fabricated metal housing (stamped, welded)
	Common bus bar connectors (References 14, 15, 16)	Bus bar and bus bar connectors	Copper bar stock: stamping, pressing, machining
	Adoption of common module housing attachment method for cells, cell housing mounting attachments. (References 14, 15, 16,	Module housing attachment hardware.	Stampings (clamps, crimped connectors), adhesives
	Standardize modules to stack level interface: 1. BMS Low Voltage, LV, connector (e.g. master/slave BMS and module interface), 2. Ability to connect any combination of arbitrary battery modules. 3. Reconfigurable for second life applications (References 4, 6, 16)	1. BMS connectors	1. Stamping, crimped connectors
		2. Module connectors	2. Aluminum stamping
		3. Module switching circuits	3. PCB and integrated circuit (power switching)
	Mechanical: standardize structural heating/cooling interfaces, thermal enclosure (forced air cooling for HEVs) (Reference 4)	Air cooling components: fan, plenum, ducts	Injection Molding
	Heat transfer system: Standardize conductor and heat transfer foams (Reference 12, 28)	Aluminum thermal conductor, heat transfer foams	Stamping: aluminum conductor, compressible heat-conducting foam

Market Analysis Indicates Production Volumes of MD HEVs Will Remain Relatively Low through 2020

Cost analysis for each identified battery standardization strategy

Because battery manufacturing costs are related to production volumes, an evaluation of the potential market for these batteries was completed. The market analysis was focused on vehicles that are primary candidates for hybrid electric drive systems and incorporate lithium ion battery packs in the 1.5 kWh to 2.0 kWh range. Particular focus was placed on Class 6 delivery vehicles.

Parameter	Value	References
2015 projected US full-year new registrations of Class 6 trucks (all vocations), based on sales through 30 June 2015	51,900	31
New step van registrations per year for US (based on 2013 sales data)	5,800	32
Number of hybrid MD trucks (all vocations) manufactured each year (based on 2013 sales data)	900	33
Number of HEV MD trucks (all vocations) manufactured each year (based on 2013 sales data): equal to 83% of all MD hybrid trucks.	747	33
Number of Eaton HD and MD hybrid drive systems produced (2007-2013): includes all hybrid architectures and represent world-wide sales.	6,500	34, 35
Number of hybrid trucks (all architectures) sold in North America through 2012:	4,500	41
Number of MD parallel hybrid electric drive systems produced by Eaton (2007-2011)	1,500	34, 35
Number of hybrid electric step vans in major fleets: UPS (2008 to 2015) FedEx (2003 to 2015)	400 350	34, 35, 36, 37, 38, 42
Number of parcel delivery vehicles purchased in conjunction with California Hybrid Voucher Incentive Program - HVIP, 2009-2015	621	39, 40
Cost of 1.8 kWh Lithium-Ion battery pack for Eaton Drive System	\$5,100 to \$5,400	Interviews with four industry stakeholders
Number of Hitachi 1.8 kWh battery packs produced (for Eaton hybrid drive system and other applications) over 4 year time period.	≈5,000	Interviews with four industry stakeholders
Number of battery types (manufacturers) employed in the Eaton MD hybrid drive system	2	Interviews with four industry stakeholders
Number of Hino MD (Class 5) hybrid electric trucks sold within the US since 2012:	400	33

Incremental Costs of Hybrid Electric Drive Systems Varies by Manufacturer and Vehicle Type

Cost analysis for each identified battery standardization strategy

Incremental cost of hybrid electric drive system: range of incremental costs obtained from literature search and interviews with industry stakeholders:

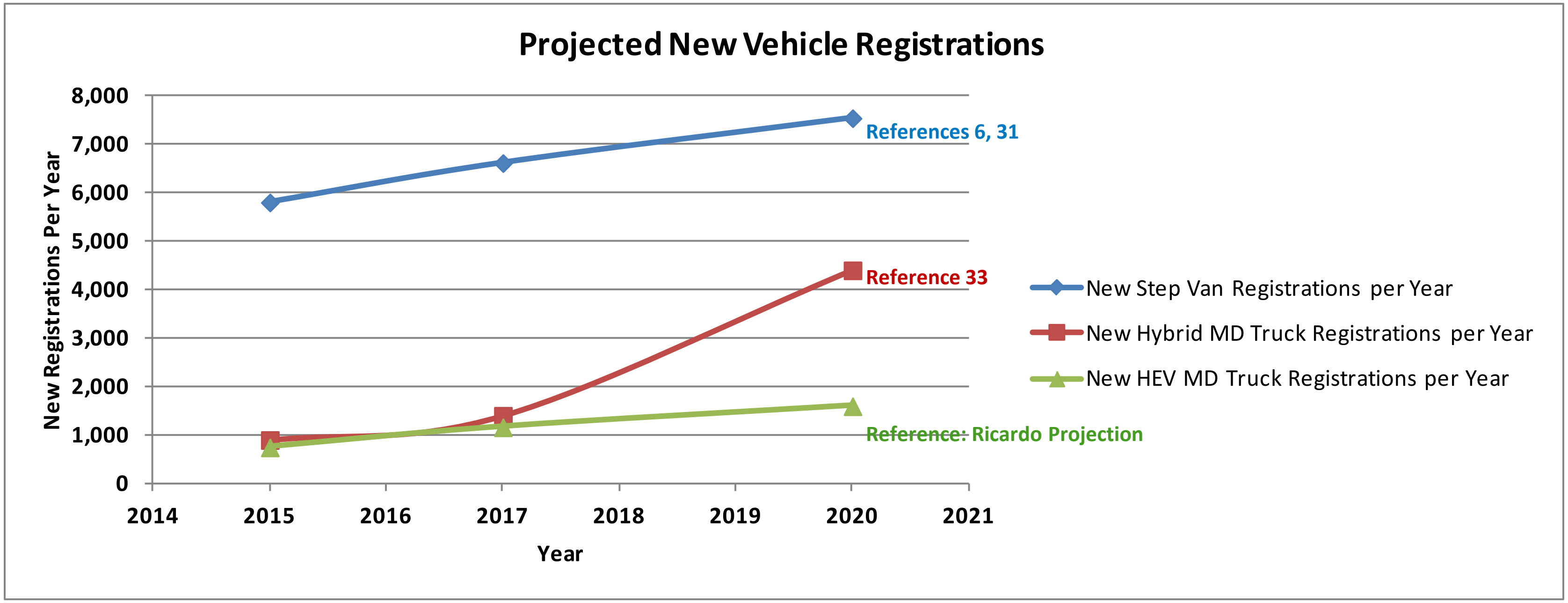
Application	Incremental Cost	Battery Type	Typical Incentive Funding/Voucher	References
Class 6 Package Delivery Truck (HEV)	$35,000	Li-Ion	$15,000	43
Class 6 Package Delivery Truck (HEV)	$21,000	Li-Ion	$15,000	44
Class 5 Package Delivery Truck (HEV)	$12,000	Nickel Metal Hydride	$18,000	33, 45
Class 6 HEV	$12,000 - $40,000	Li-Ion	$15,000 - $30,000	33

US New Vehicle Registrations of HEV Step Vans are Projected to be Less than ½ of All US Step Van New Vehicle Registrations through 2020

Cost analysis for each identified battery standardization strategy:

Because battery manufacturing costs are related to production volumes, an evaluation of the potential market for these batteries was completed. The market analysis was focused on vehicles that are primary candidates for hybrid electric drive systems that incorporate lithium ion battery packs in the 1.5 kWh to 2.0 kWh range. Particular focus was placed on Class 6 delivery vehicles.

Sales projections for U.S. Class 4-6 delivery vehicles (candidates for hybrid electric drive systems), hybrid MD trucks (all hybrid architectures) and HEV MD trucks:



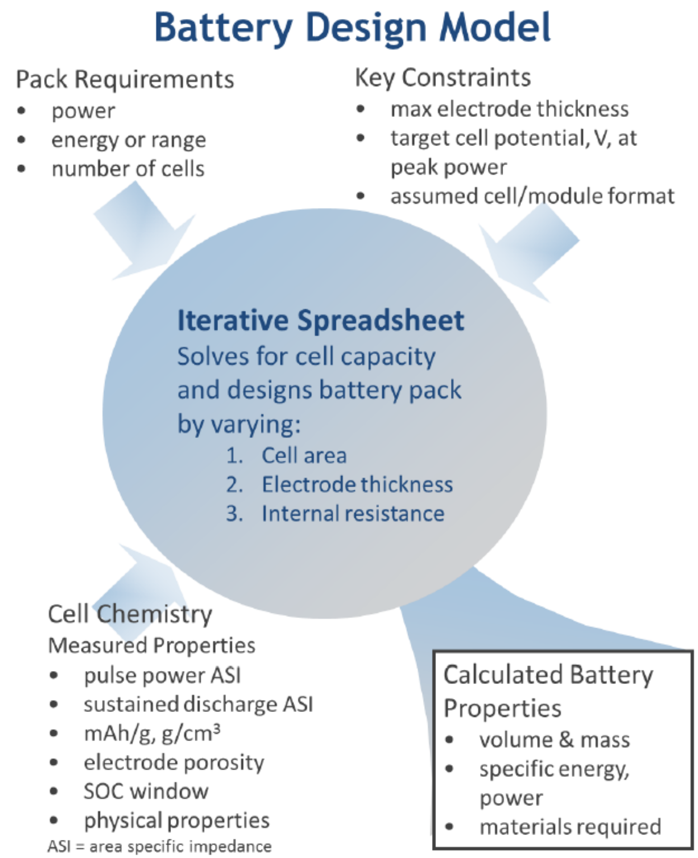
Conclusion: Battery production requirements for new HEV MD trucks will range between 1,000 per year and 4,400 per year between 2015 and 2020.

References: 6, 31, 33, Ricardo Analysis

ANL's BatPaC Model was Employed to Determine the Impact of Standardization Strategies on Battery Manufacturing Costs

A number of resources were utilized to evaluate the impact of battery standardization strategies on manufacturing costs including:

1. Ricardo component manufacturing cost data base for a) metal stampings, b) printed circuit boards and power electronics, c) injection molded parts, d) cell manufacture, and e) machined parts.
2. Argonne National Laboratory BatPaC battery performance and cost analysis spreadsheet-based modeling program (References 12, 30).



Overview of Battery Performance and Cost model (BatPaC)

- The model can be utilized to design lithium-ion batteries for a specified power, energy, and type of vehicle battery.
- The cost of the designed battery is then calculated by accounting for every step in the lithium-ion battery manufacturing process.
- The assumed annual production level directly affects each process step.
- The total cost to the original equipment manufacturer calculated by the model includes the materials, manufacturing, and warranty costs
- BatPac is the only publically available model that performs a bottom-up lithium-ion battery design and cost calculation.
- Version 3 of BatPaC is scheduled for release prior to the end of December 2015.

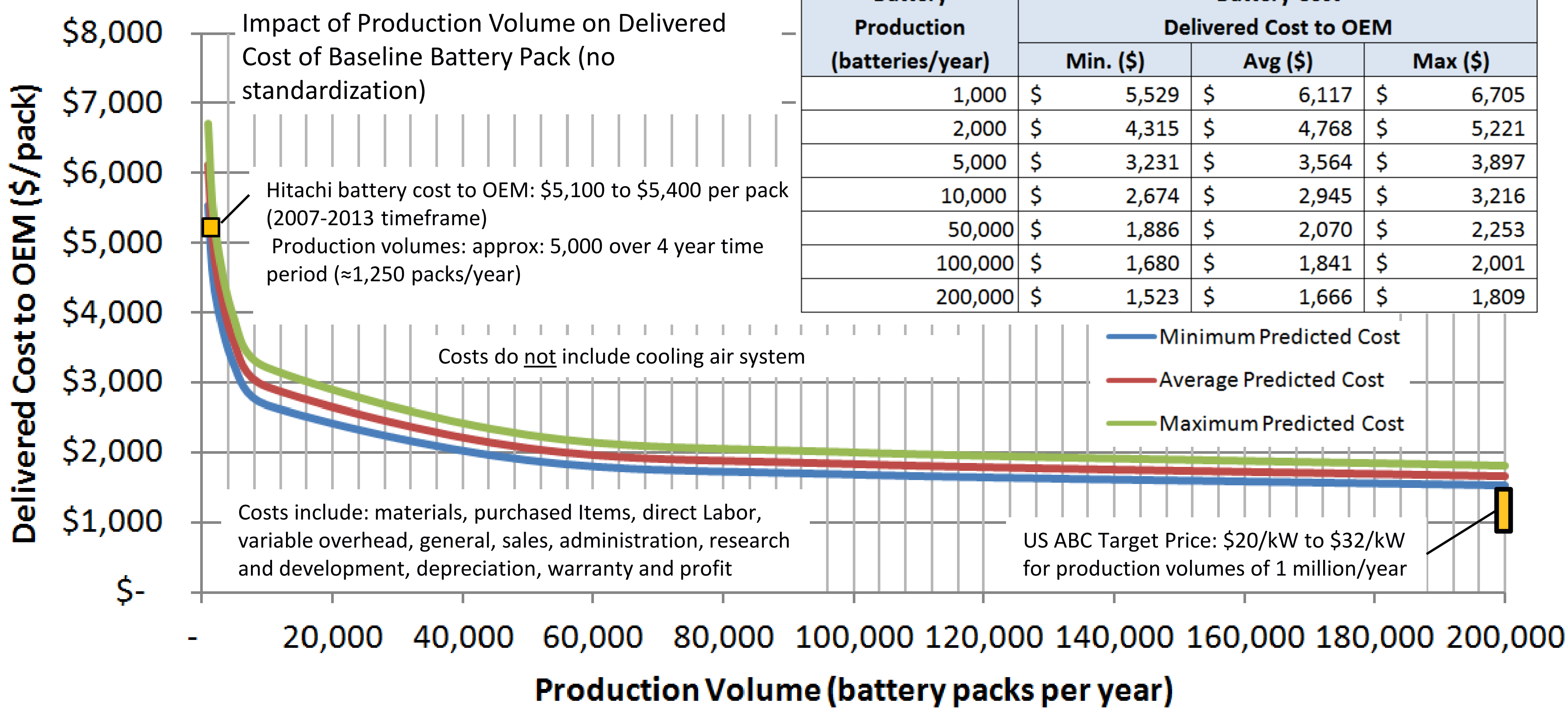
References: 12, 30, Ricardo Analysis

Impact of Production Volume on Delivered Cost of Baseline Battery Pack - w/o standardization strategies

Ricardo utilized the Argonne National Laboratory BatPaC Model to evaluate the impact of production volumes on the delivered cost of the baseline Hitachi battery pack

The BatPaC simulations were performed using the baseline battery specifications: 12 cells/module, 8 modules per pack, cells and modules in series, air cooled, NMC chemistry, 1.8 kWh:

Battery Production (batteries/year)	Battery Cost Delivered Cost to OEM		
	Min. ($)	Avg ($)	Max ($)
1,000	$ 5,529	$ 6,117	$ 6,705
2,000	$ 4,315	$ 4,768	$ 5,221
5,000	$ 3,231	$ 3,564	$ 3,897
10,000	$ 2,674	$ 2,945	$ 3,216
50,000	$ 1,886	$ 2,070	$ 2,253
100,000	$ 1,680	$ 1,841	$ 2,001
200,000	$ 1,523	$ 1,666	$ 1,809



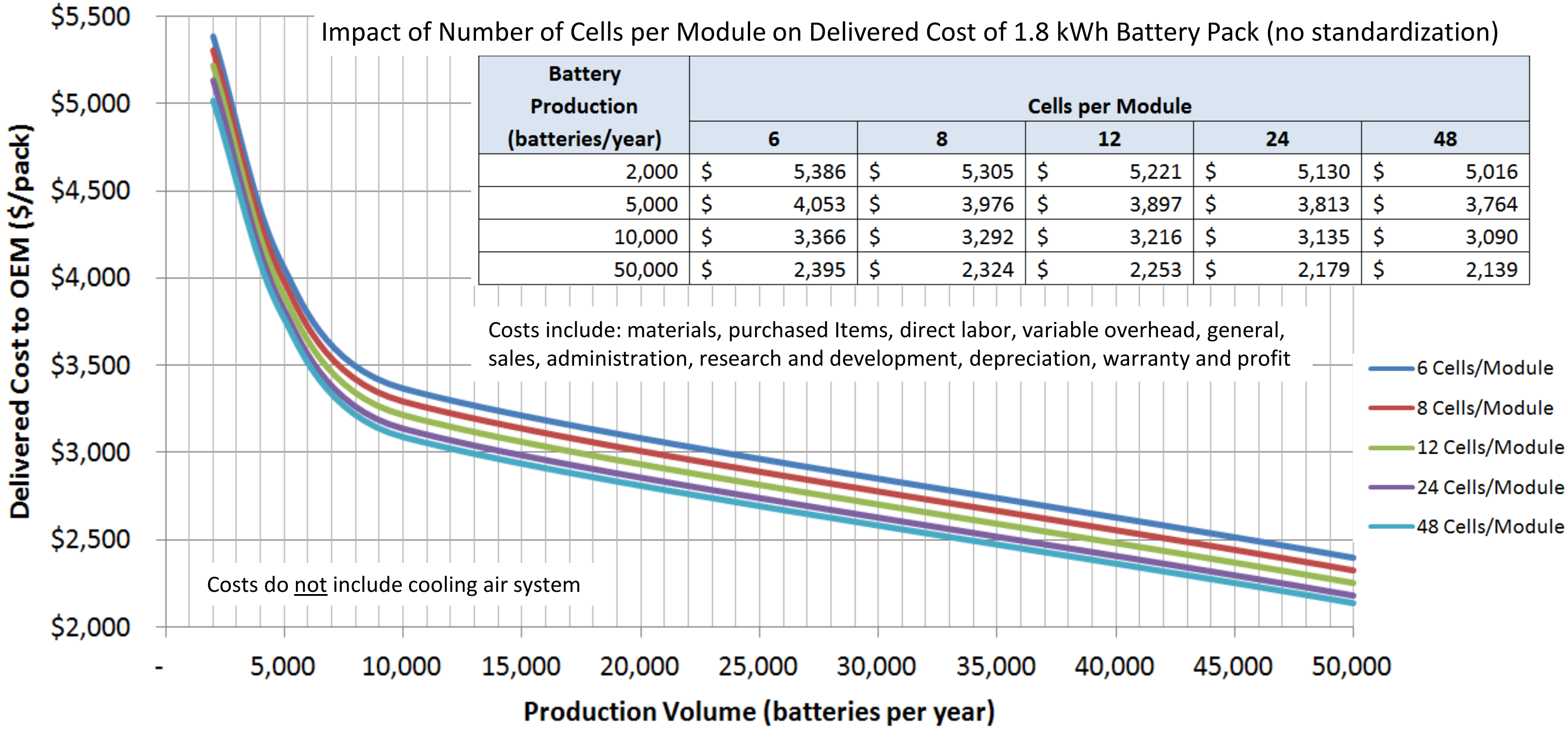
Conclusion: BatPaC model prediction matches reported battery pack production cost quite well. Note that BatPaC does not include cost of thermal management and electronics associated with system as installed with Eaton hybrid drive.

References: 12, 30, Ricardo Analysis

Impact of Number of Cells per Module and Production Volume on Delivered Cost of Baseline Battery Pack - w/o standardization strategies

Ricardo utilized the Argonne National Laboratory BatPaC Model to evaluate the impact of number of cells per module on the delivered cost of the baseline Hitachi battery pack

The BatPaC simulations were performed using the baseline battery specifications: 96 cells per pack, cells and modules in series, air cooled, NMC chemistry, 1.8 kWh:



Battery Production (batteries/year)	Cells per Module 6	8	12	24	48
2,000	$ 5,386	$ 5,305	$ 5,221	$ 5,130	$ 5,016
5,000	$ 4,053	$ 3,976	$ 3,897	$ 3,813	$ 3,764
10,000	$ 3,366	$ 3,292	$ 3,216	$ 3,135	$ 3,090
50,000	$ 2,395	$ 2,324	$ 2,253	$ 2,179	$ 2,139

Conclusion: BatPaC model suggests increasing the number of cells per module will decrease price up to 5.0% depending upon production volume.

References: 12, 30, Ricardo Analysis

Battery Standardization and Costs

The following procedure was applied to determine the impact of identified standardization strategies on price of battery delivered to vehicle OEM:

Identify battery standardization strategies appropriate for MD HEV delivery vans.

↓

Identify battery components impacted by each standardization strategy.

↓

Determine impact of production volume on cost of components identified for each standardization strategy

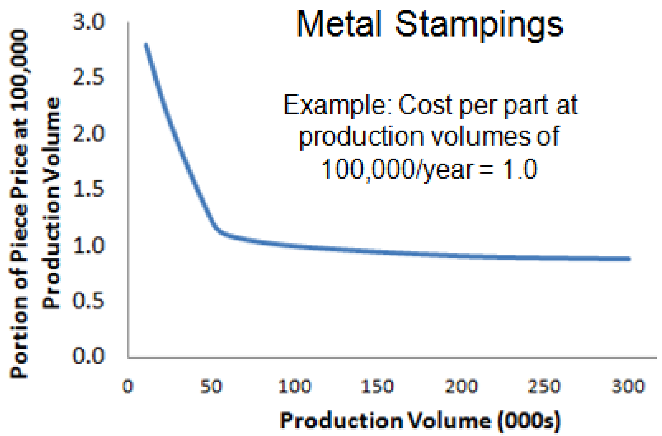
↓

Determine impact of standardization on baseline (non-standardized) battery cost as function of production volume.

↓

Determine impact of identified standardization methods on price of battery delivered to OEM as function of module production volume (1,000 units/year to 200,000 units/year)

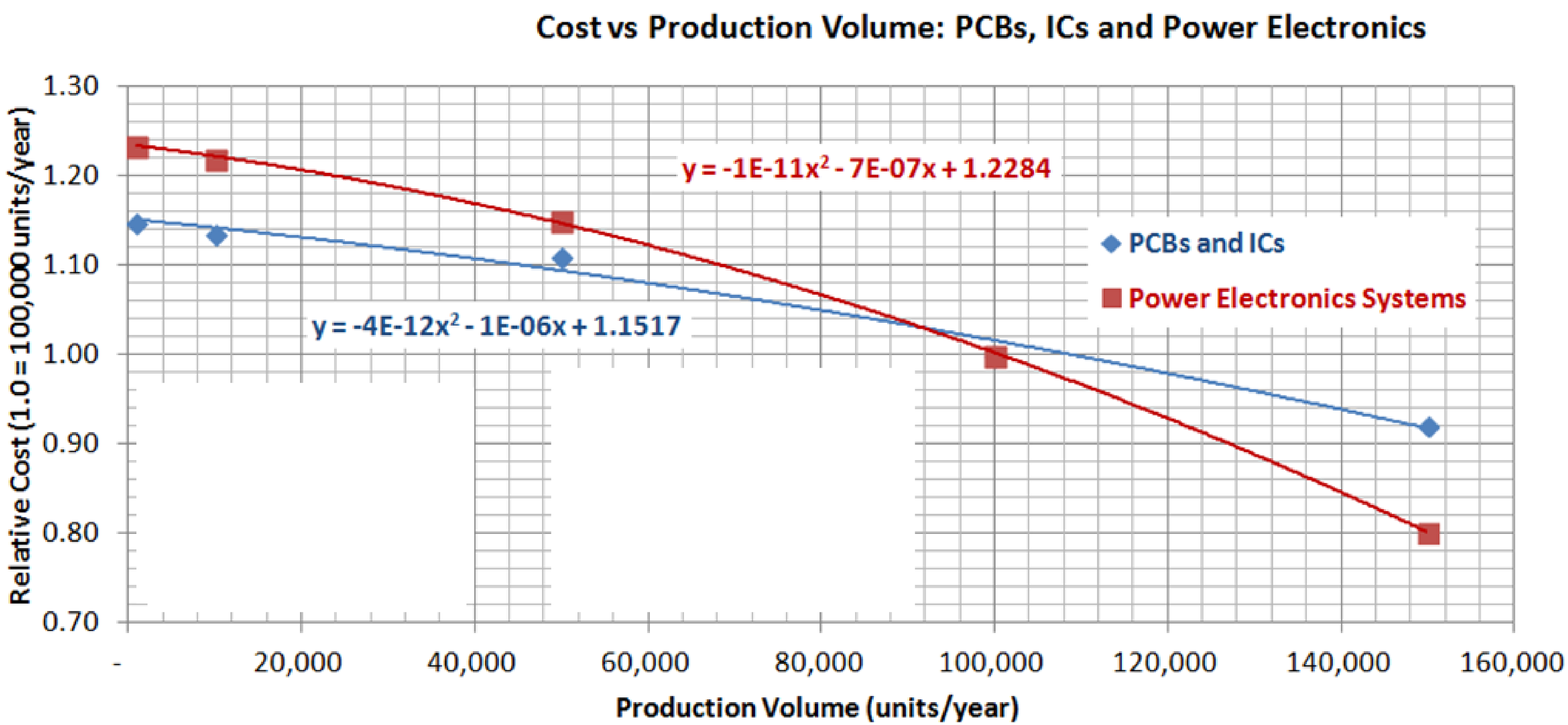
← Generate spreadsheet-based calculation procedure based on ANL BatPaC model results, including production volume impacts.



Example of low volume vs high volume manufacturing costs

A study was completed to determine the impact of manufacturing volume on individual battery component costs

Example: Impact of manufacturing volume on component costs

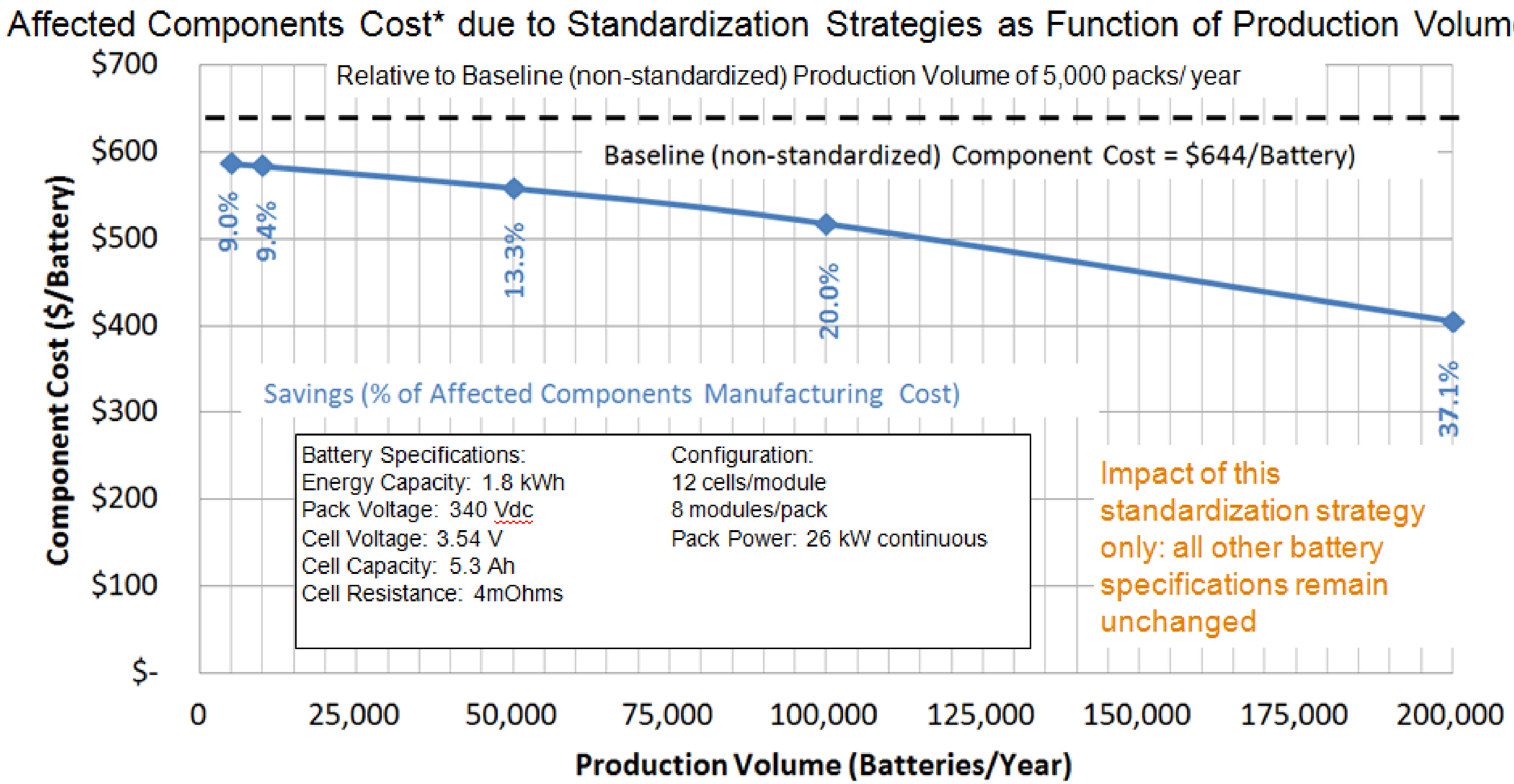


Impact of manufacturing volume on other battery components, including metal stampings, cell and module manufacture, and injection molded parts is included in Appendix B.

Reference: Industry price quotes for battery components (in volumes from 5,000/year to 200,000 per year

The impact on battery component manufacturing costs was determined for each identified standardization strategy

Cost savings for communications standardization strategies: contribution of strategy to manufacturing cost reduction as a function of production volume. Example below is for **Battery Systems Communications** standardization strategies. Similar graphs have been prepared for the other standardization strategies.



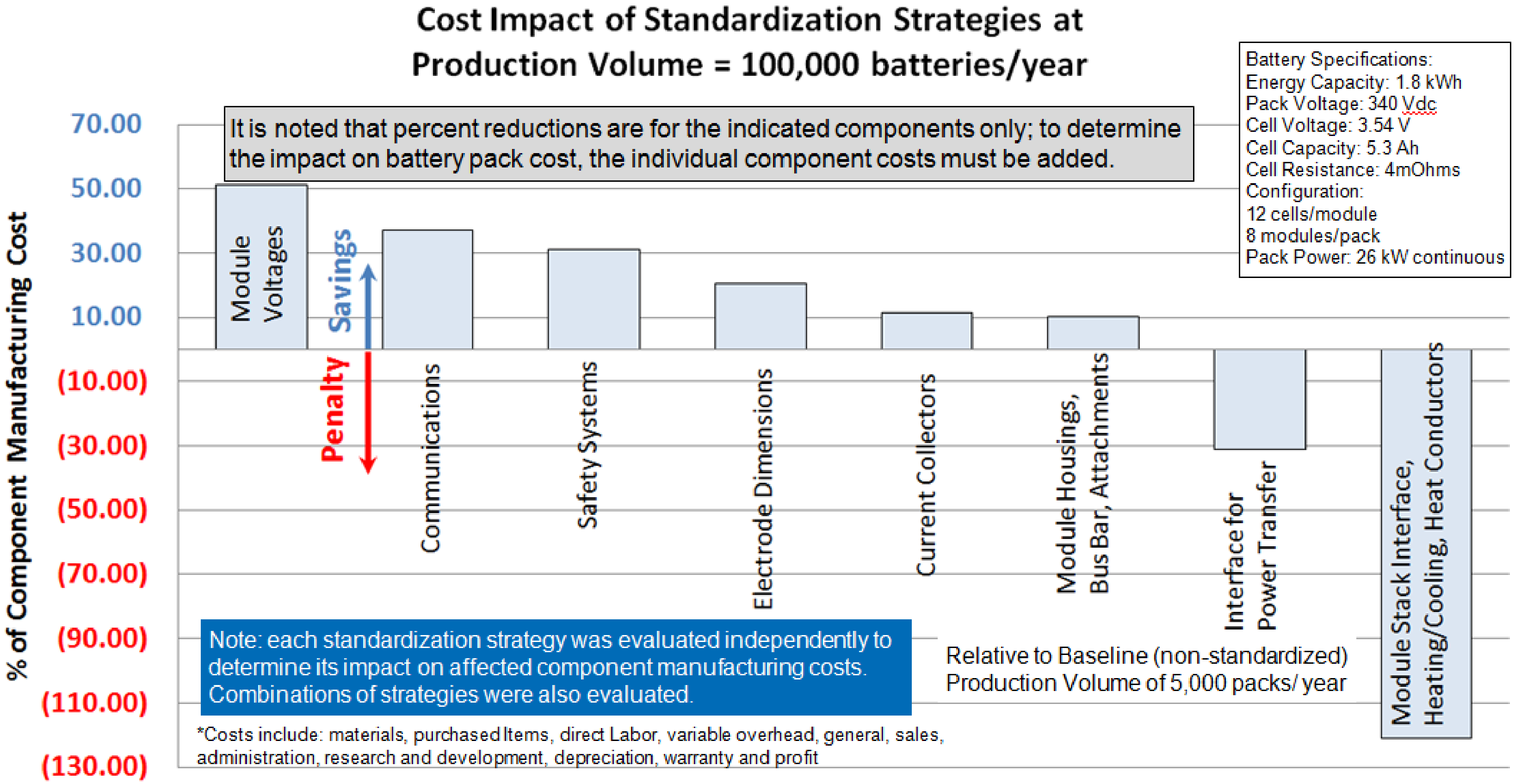
Communications standardization strategies include: digital communication interface (gateway) to the vehicle controller area network (CAN) and/or power electronics (e.g. module ports and protocols) to reduce communications overhead and high materials cost (References 4, 21). In addition, standardize placement of variables within the CANbus packets (References 4, 6, 21, 23). Components include: 1. BMS, 2. Microcontroller, 3. CAN transceiver, and 4. Galvanic Isolator

*Costs include: materials, purchased Items, direct Labor, variable overhead, general, sales, administration, research and development, depreciation, warranty and profit

References: 12, 13, 29, 30, Ricardo Analysis

Cost impacts of indentified battery standardization strategies were ranked by percent of cost reduction for a range of production volumes

The impact of standardization strategies and production volumes on affected component costs was determined using ANL's BatPaC and Ricardo's manufacturing cost analyses. The chart below shows the affected components cost* reductions (%) for a production rate of 100,000 batteries/year. Similar graphs for other production volumes have been prepared.



At production volumes of 100,000 batteries/year, all but two of the standardization strategies results in a battery production cost decrease.

References: 12, 13, 29, 30, Ricardo Analysis

Note: this graph indicates the percent reduction in component costs associated with each of the eight standardization categories. The component savings can then be added to determine the impact on battery pack cost.

Cost reductions associated with identified battery standardization strategies vary with production volumes

- The primary cost impact of standardization is to extend the range of applications and thus increase production volumes.
- Only one of the identified standardization strategies resulted in cost decreases at low production volumes.
- The results of the standardization strategy investigations are summarized in the following table and are plotted on the following page:

Production Volume (battery packs/year)	Cost savings or penalty (affected components manufacturing cost $) due to identified standardization strategies, as a function of production volume, relative to nominal production volume of 5,000 packs/year							
	Module Housing, Bus Bars, Attachments	Module Voltages	Electrode Dimensions	Communications	Current Collectors	Safety Systems	Module Stack Interface, Heating & Cooling, Heat Conductors	Interface for Power Transfer
5,000	$ (0.75)	$ (4.75)	$ (10.71)	$ 57.69	$ (5.81)	$ (0.97)	$ (452.33)	$ (445.75)
10,000	$ 3.63	$ 110.33	$ 35.25	$ 60.40	$ (4.91)	$ 0.75	$ (442.33)	$ (373.35)
50,000	$ 13.59	$ 248.20	$ 132.53	$ 85.76	$ 6.06	$ 3.06	$ (405.25)	$ (261.45)
100,000	$ 17.42	$ 290.89	$ 170.68	$ 126.67	$ 29.26	$ 4.34	$ (366.53)	$ (173.31)

Legend
Standardization Strategies that Produce a Cost Savings
Standardization Strategies that Produce a Cost Increase

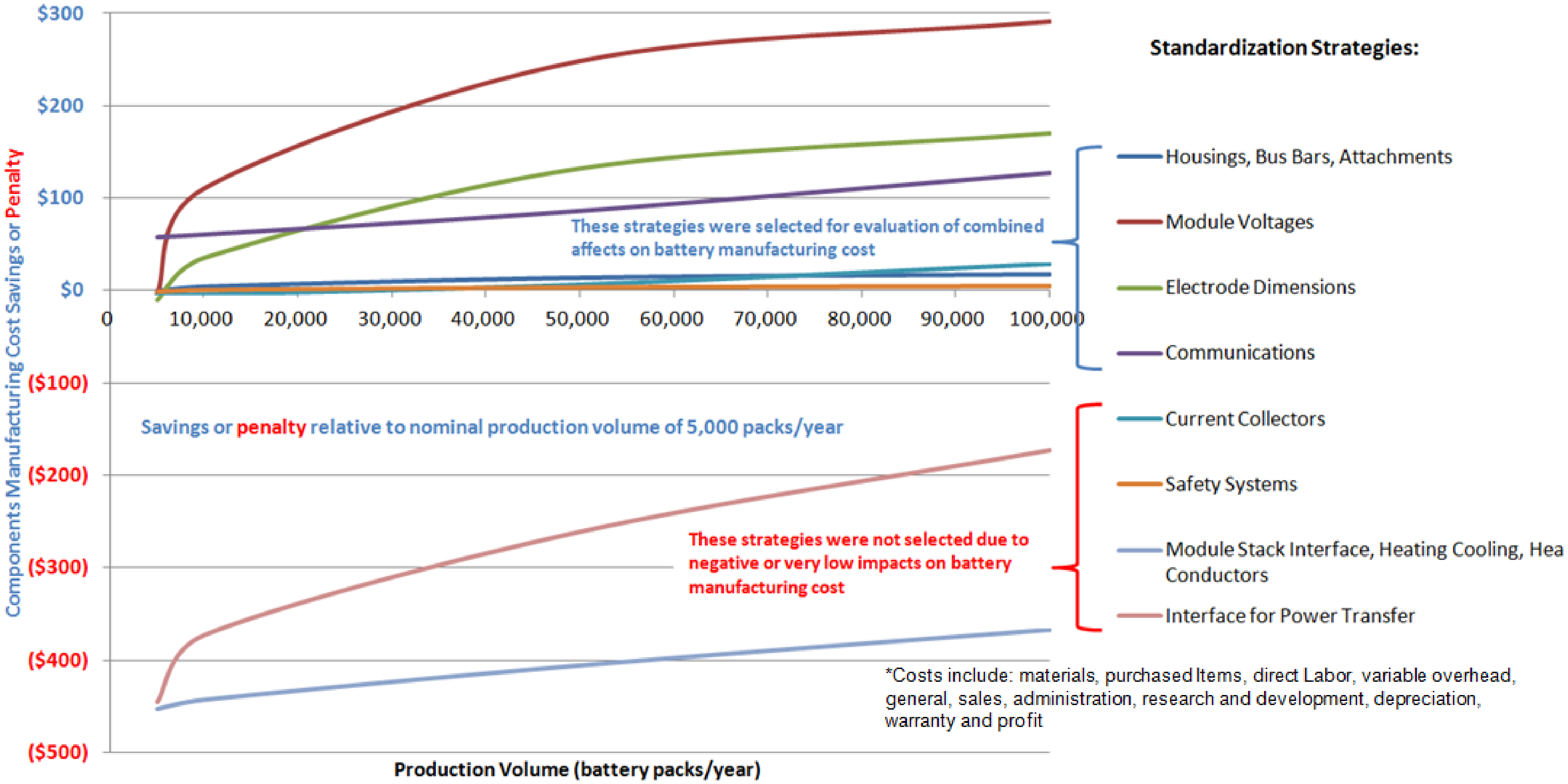
*Costs include: materials, purchased Items, direct Labor, variable overhead, general, sales, administration, research and development, depreciation, warranty and profit

The entries in the above table are not additive because several components are included in multiple standardization strategy categories (e.g. BMS is included in the Module Voltages, Module Stack Interface, and Interface for Power Transfer standardization strategies). Thus, it was decided to determine the impact on battery cost due to a combination of standardization strategies.

References: 12, 13, 29, 30, Ricardo Analysis

Four of the identified standardization strategies were selected for additional analysis based on component cost reduction effectiveness

The results of the standardization strategy investigations are summarized in the following graph:



The entries in the above graph are not additive because several components are included in multiple standardization strategy categories (e.g. BMS is included in the Module Voltages, Module Stack Interface, and Interface for Power Transfer standardization strategies).

References: 12, 13, 29, 30, Ricardo Analysis

Four standardization strategies and two design changes were evaluated in combination to determine the maximum attainable cost reduction over a range of production volumes

Standardization Approach:
Standardization increases capital costs due to the requirement for high production volume tooling and thus amortization costs per battery can be quite high at low production volumes. The study indicates production volumes must exceed 10,000 batteries per year to achieve significant savings due to implementation of standardized designs.

Evaluation of combined strategies:
Four of the identified standardization approaches were selected for additional analysis based on results of the individual manufacturing cost impacts. In addition, battery design changes (cells per module and cell capacity) shown to have a favorable impact on battery cost as determined by modeling using BatPaC were also included. Ranked in order of impact, the combined strategies are:

1. Standardization of module housings, bus bars, and attachments
2. Standardization of module voltages
3. Standardization of electrode dimensions
4. Increasing the number of cells per module
5. Increasing cell capacity (Ah/cell) and decreasing the number of cells per pack
6. Consolidation and standardization of communications system components

The cost impact of combined standardization strategies was determined

The top four standardization strategies, based on cost reduction impact, were combined with two battery design changes (increasing number of cells per module and increasing the cell capacity) to determine the impact on delivered battery cost to the vehicle OEM*.

Cost Category	Included in Category	Units	Battery Configuration	Production Volumes					
				1,000	2,000	5,000	10,000	50,000	100,000
Investment Costs	1. Equipment (including installation), 2. building, land, utility connections, 3. launch costs, and 4. working capital	$ million	Baseline	$ 9.8	$ 14.4	$ 24.9	$ 38.4	$ 112.1	$ 179.8
			Combined Standardization Strategies	$ 10.5	$ 15.4	$ 26.6	$ 41.1	$ 119.9	$ 192.4
Variable Costs: Materials and Purchased Items	1. cell materials, 2. cell purchased items, 3. module materials, 4. module purchased items, 5. pack materials, 6. pack purchased items	$/pack	Baseline	$ 985	$ 952	$ 913	$ 888	$ 839	$ 822
			Combined Standardization Strategies	$ 889	$ 858	$ 822	$ 712	$ 582	$ 539
Variable Costs: Direct Labor and Overhead	1. electrode processing, 2. cell assembly, 3. formation cycling, testing and sealing, 4. module and battery assembly, 5. cell and materials rejetion and recycling, 6. receiving and shipping, 7. control laboratory, 8. variable overhead (= 40% of direct labor + 20% of depreciation)	$/pack	Baseline	$ 1,612	$ 1,153	$ 750	$ 547	$ 271	$ 203
			Combined Standardization Strategies	$ 1,570	$ 1,119	$ 727	$ 516	$ 249	$ 185
Fixed Costs	1. general, sales, administrative, 2. research and development, 3. depreciation	$/pack	Baseline	$ 2,486	$ 1,825	$ 1,238	$ 938	$ 516	$ 406
			Combined Standardization Strategies	$ 2,517	$ 1,825	$ 1,237	$ 939	$ 521	$ 409
Additional Costs	1. profit, 2. warranty, 3. air cooling thermal management system, 4. pack integration (BMU and disconnects)	$/pack	Baseline	$ 1,154	$ 958	$ 784	$ 693	$ 564	$ 530
			Combined Standardization Strategies	$ 1,187	$ 973	$ 792	$ 694	$ 557	$ 520
Cost to OEM for Complete System (does not include air-cooled thermal management system)		$/pack	**Baseline**	**$ 6,237**	**$ 4,888**	**$ 3,685**	**$ 3,066**	**$ 2,190**	**$ 1,961**
			Combined Standardization Strategies	**$ 6,163**	**$ 4,775**	**$ 3,578**	**$ 2,861**	**$ 1,909**	**$ 1,653**

References: 12, 13, 29, 30, Ricardo Analysis

Impact of Combined Standardization Strategies and Production Volumes oı Battery Cost

Includes the following combinec standardization strategies:

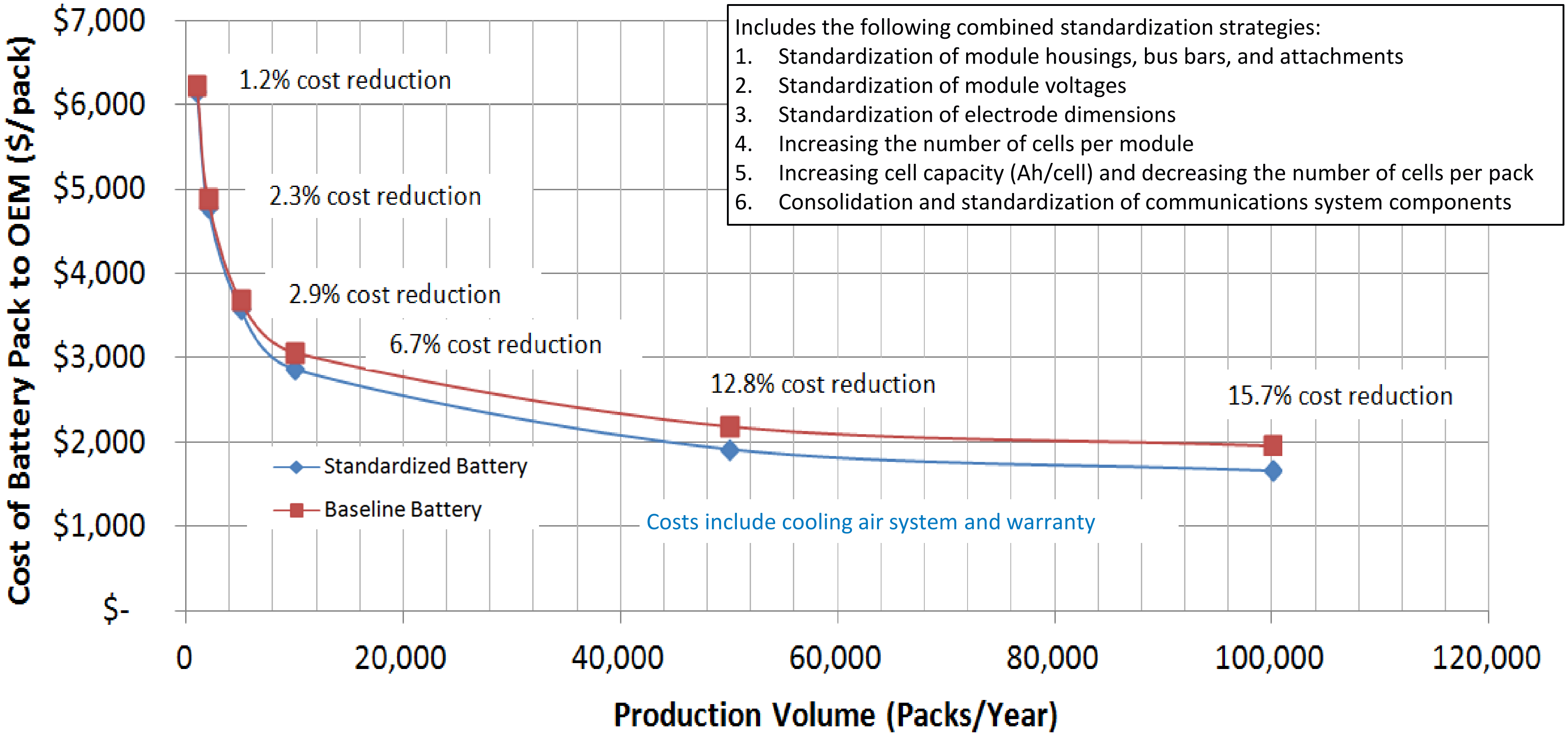
1. Module housings, bus bars, attachments
2. Module voltages
3. Electrode dimensions
4. Communications
5. Increasing the number of ce per module
6. Increasing cell capacity (Ah/cell) and decreasing the number of cells per pack.

*Costs do not include cooling air system

Increasing Production Volume has a Greater Impact on Cost than does Standardization Strategies

Conclusion: The biggest impact of standardization on cost is to extend the range of applications for a given battery pack design. Increased production volume has a larger influence on battery pack cost than does individual standardization strategies. The cost per pack for the baseline 1.8 kWh HEV battery can be reduced by 54% if production volumes are changed from 5,000 per year to 100,000 per year, while the largest impact of the identified standardization strategies is 16% at volumes of 100,000 packs per year and less for lower production volumes.

Impact of Combined Standardization Strategies and Production Volumes on Battery Cost



References: 12, 13, 29, 30, Ricardo Analysis

Optimal Cell, Module & Thermal Selection

Multiple cell and module designs can meet battery pack requirements of 45kW and 1.8 kWh. To reach high production volumes, the selected cell and module should be widely used across other applications.

- **Cell: Power/Energy > 25kW/kWh peak at min SOC ~ 30%**
- **Cell: Capacity = 5.0 to 7.5 Ah***
  - Higher cell capacity reduces cell count and lowers pack cost, however it also reduces pack voltage and must be weighed against system requirements. Pack voltage must be matched to motor/inverter. Higher voltage is ideal for reducing copper cable diameter.
- **Module: Up to 14 cells/module* based on $50V_{max}$ safe handling limit**
  - Higher number of cells per module reduces cost. Module cell count must also be matched to commercially available slave BMS chipsets. Packs will sometimes combine modules with different cell counts, e.g. 14+14+12 cells to reach 50 cells total.

Example designs:*

Cell capacity	# cells	Pack voltage	Example module config.
5 Ah	96 cells/pack	340 V_{nom}	8x12-cell modules
6 Ah	80 cells/pack	283 V_{nom}	8x10-cell modules
7.5 Ah	64 cells/pack	227 V_{nom}	8x8-cell modules
8.6 Ah	56 cells/pack	198 V_{nom}	4x14-cell modules

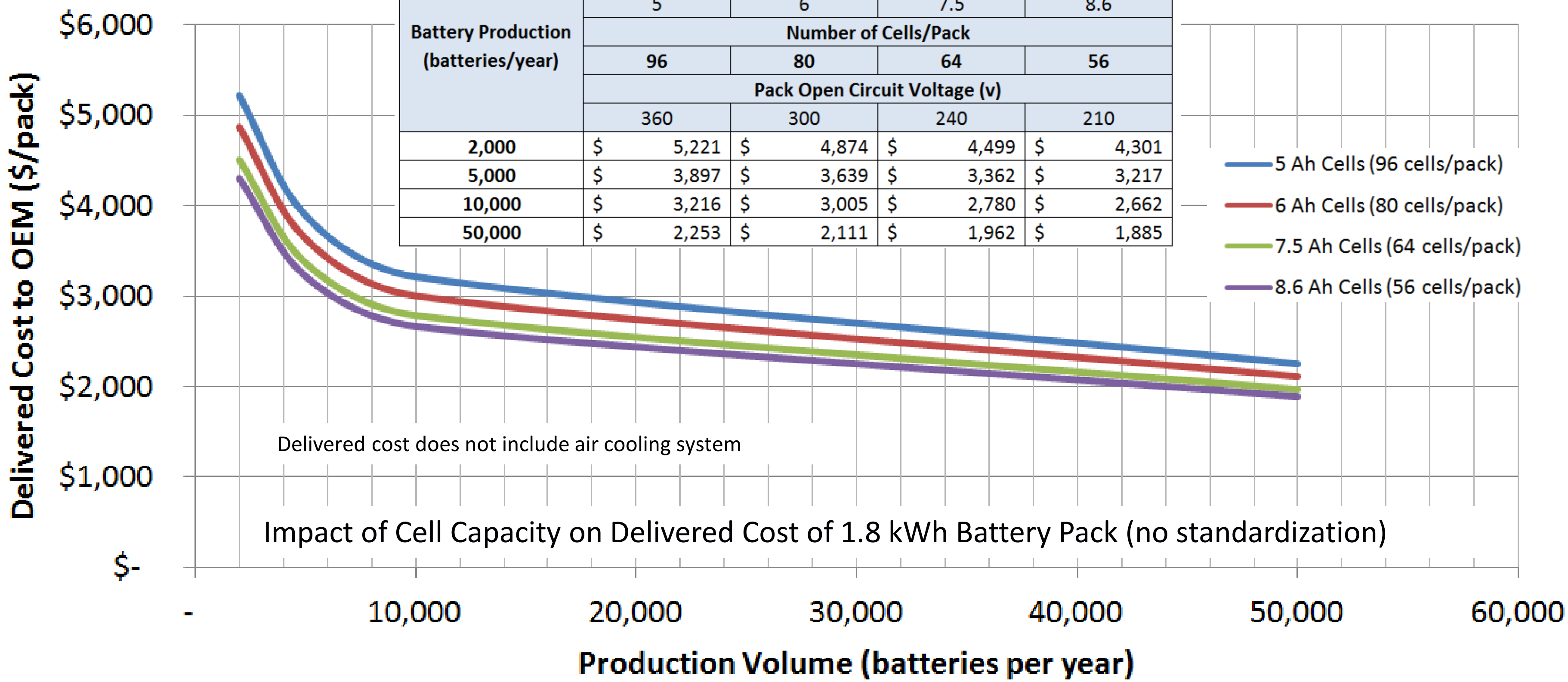
- **Thermal management: Forced air cooling**
  - For power applications such as HEV, the requirement for to maintain a small cell-to-cell ΔT is less important than for energy applications such as EV. For selected cell power/energy ratio and drive cycle, cooling system should be capable of keeping all cell temperatures below 45°C during steady-state operation with 30°C ambient air.

* Assumes $3.54V_{nom}$ NMC/hard carbon cell chemistry

Impact of Cell Capacity on Delivered Cost of 1.8 kWh Battery Pack (no standardization)

BatPaC was utilized to evaluate the impact of higher capacity cells on the delivered cost of the battery. The analysis was based on maintaining a pack energy capacity of 1.8 kWh, cells and modules in series, air cooled, NMC chemistry:

Cost of Battery Pack Delivered to OEM (does not include air cooling system)				
Battery Production (batteries/year)	Cell Capacity (Ah)			
	5	6	7.5	8.6
	Number of Cells/Pack			
	96	80	64	56
	Pack Open Circuit Voltage (v)			
	360	300	240	210
2,000	$ 5,221	$ 4,874	$ 4,499	$ 4,301
5,000	$ 3,897	$ 3,639	$ 3,362	$ 3,217
10,000	$ 3,216	$ 3,005	$ 2,780	$ 2,662
50,000	$ 2,253	$ 2,111	$ 1,962	$ 1,885

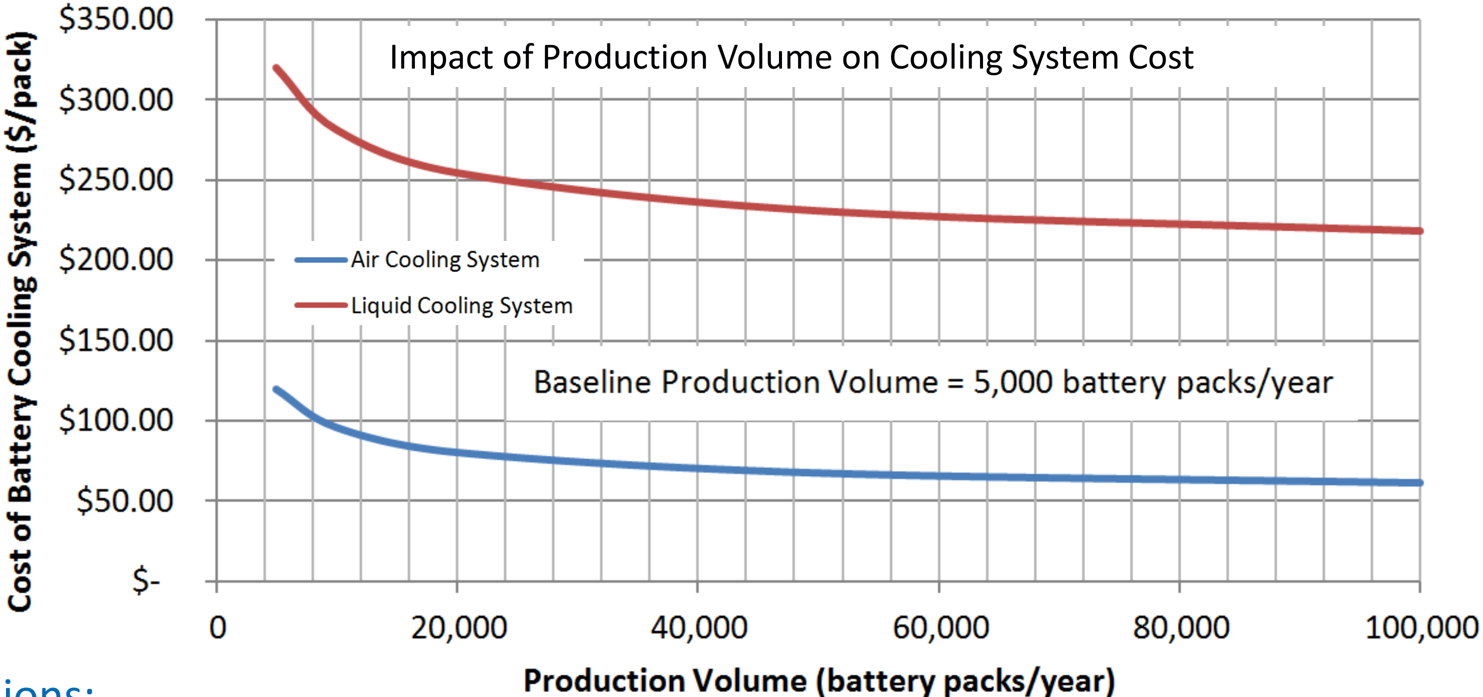


Conclusion: BatPaC model prediction indicates delivered cost reductions ranging from 6.6% to 12.3% due to increase in cell capacity. The cost reduction is a function of cell capacity increase and production volume.

References: 12, 30. and NREL/Ricardo Analysis

Battery Standardization and Costs: research on battery cooling strategies and associated costs

The impact on battery system costs due to cooling system design was investigated and include both air and liquid cooled approaches.



Conclusions:

- Air cooling systems, particularly those that do not remove heat from the air stream are the least expensive option for MD truck battery systems.
- The use of ambient air for cooling during extreme temperature conditions can lead to reductions in battery life.
- Liquid cooling modules enables size-efficient packaging
- Air cooling increases cost of module assembly and battery jacket design, which decreases savings

References: 12, 30, 57, 58, 59, 60, 61, Ricardo analysis, and interviews with industry stakeholders.

Battery Standardization and Costs

Selection of one cell and one or two module configurations that address power and voltage requirements

Based on the information from interviews with battery developers, passenger vehicle OEMs, commercial vehicle OEMs, literature searches, a cell and module selection process was initiated to define a standard cell/module design for medium duty hybrid electric vehicles (primarily for parcel delivery trucks).

Design Guidelines:

- Energy must be ≥ 1.8 kWh for reasonable life (1.5-2.5 kWh acceptable)
- Power must be ~45 kW for optimal fuel economy (25-50 kW acceptable)
- A range of cell and module solutions can produce a 1.8 kWh, 45 kW pack
- Life characteristic similar to Hitachi system (10 yr, 200k miles for composite duty cycle)
- Battery thermal management: air-cooled
- Market scale needs to be considered, particularly the total market size that can be addressed across multiple vehicle vocations with a standardized battery approach. Due to varying technical requirements, this space could prove small.
- Low cost

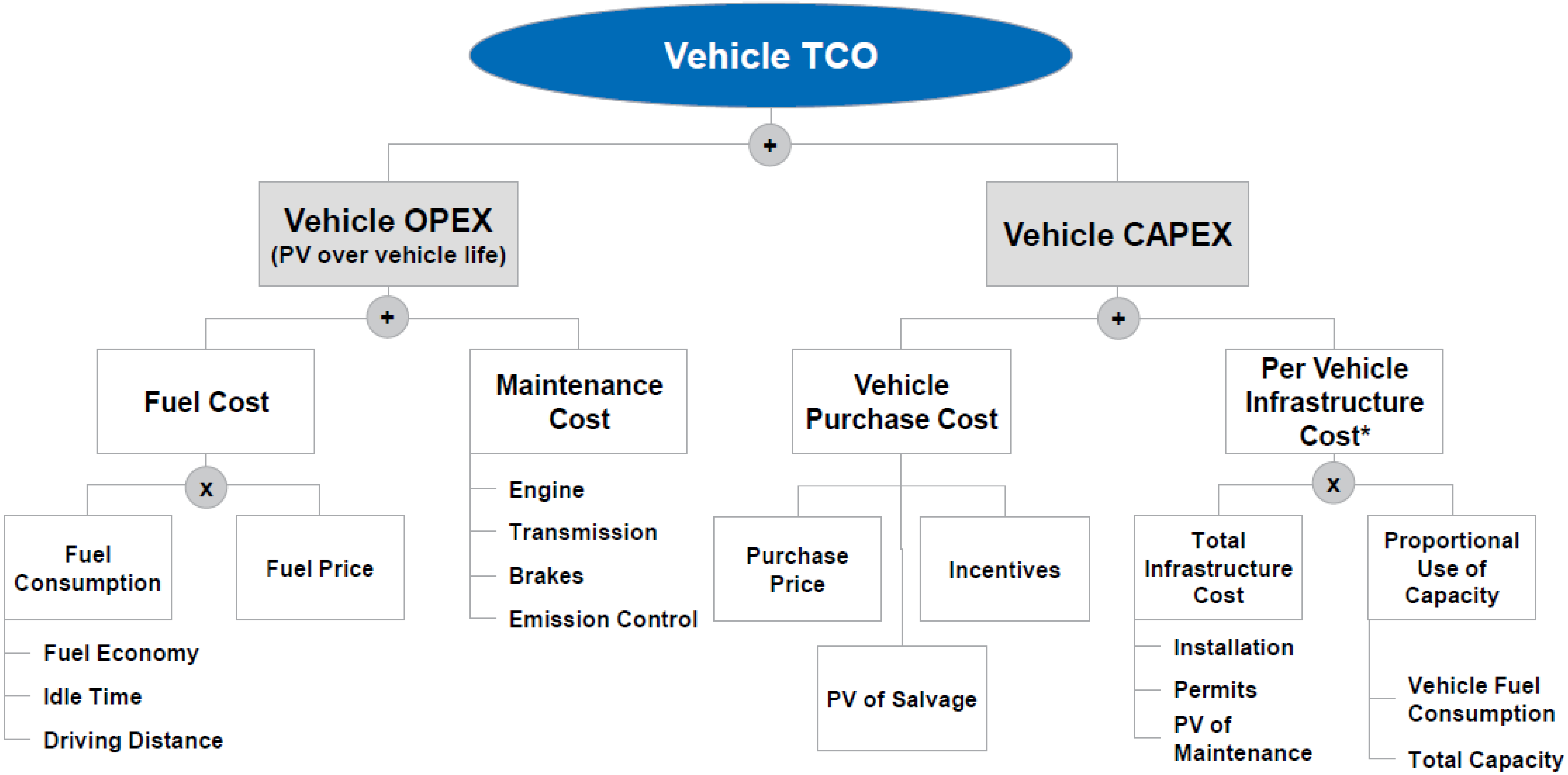
Battery specifications are included in the total cost of ownership analysis. This information is expected to be shared with Eaton, BAE, and others MD HEV OEMs for feedback.

Reference 4. 13, 18, 19, 20, and NREL/Ricardo Analysis

Contents

Economics of Standardized Batteries

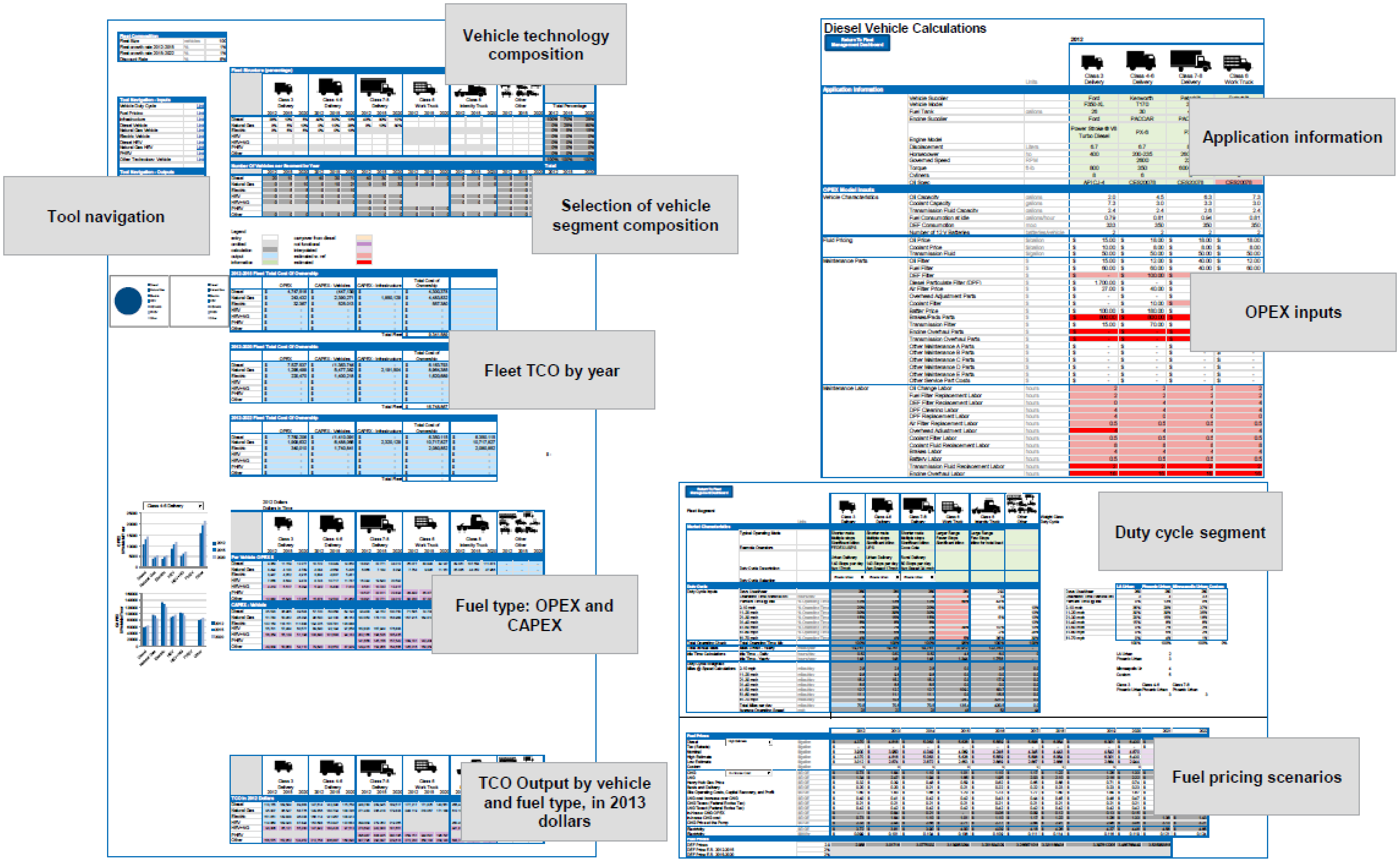
Ricardo employed its ***total cost of ownership*** model to determine impact of battery standardization and leasing



Vehicle TCO is modeled as the PV of the sum of both CAPEX and OPEX for that vehicle within its first ownership period

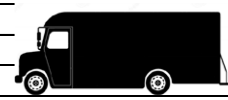
Economics of Standardized Batteries

The TCO analysis is a spreadsheet-based model which can be used for conducting further scenario analysis



TCO Model Inputs

A variety of sources were employed to verify the MD HEV delivery van specifications, including technical papers, manufacturer data sheets, and interviews with industry stakeholders.



Section	Category	Sub-Category	Description	Parameter	Units	Example
Vehicle Information	Vehicle	Supplier			OEM	Freightliner
		Model				P100H Step Van
		Model Year				2010
		Gross Vehicle Weight			lbs	23,000
		Useful Life			years	12
	Engine	Manufacturer				Cummins
		Model, No. of Cylinders				ISB, 6 Cylinders
		Model Year				2009
		Displacement			liters	6.7
		Power Rating			HP	200
		Torque			ft-lb @ RPM	520 @ 1,600 RPM
		Governed Speed			RPM	2,600
		Oil Specification				CES20078
		Oil Capacity			gallons	4
		Coolant Capacity			gallons	3
		Emission Equipment				DPF
		Batteries (12-volt)	Number of Lead-Acid (non-hybrid system) batteries			2
	Transmission	Manufacturer				Fuller
		Type				6-Speed, Automated Manual
		Fluid Capacity			gallons	2.4
	Hybrid System	Supplier				Eaton
		System Type				Series Hybrid
		Motor	Type			Synchronous Brushless
			Rotor			Permanent Magnet
			Continuous Power Rating		kW	26
			Peak Power Rating		kW	44
		Regenerative Braking				Yes; motor/generator
		Battery	Type			Lithium Ion
			Voltage		VDC	340
			Capacity		kWh	1.8
			Energy Density		kWh/kg	44
			Minimum State of Charge			0.4
			Maximum State of Charge			0.8
	Air Conditioning System					None

References: 3, 4, 5, 27, 42, and interviews with industry stakeholders.

Economics of Standardized Batteries

Evaluate various battery standardization strategies using Ricardo TCO model

Inputs to the TCO model are based upon the defined duty cycle for the MD parcel delivery van:

OPEX: Fuel and Fluid Costs

Fuel Cost	Fuel-Consumption	Duty Cycle	Description		Delivery Composite Cycle 1
			Vehicle Use	days/year	245
			Operating Time (vehicle on)	hours/day	8
			Speed Histogram	% of Operating Time	Idle: 20%
					1 - 5 mph: 3%
					5 - 10 mph: 7%
					10 - 15 mph: 15%
					15 - 20 mph: 17%
					20 - 25 mph: 14%
					30 - 35 mph: 11%
					35 - 40 mph: 4%
					40 - 45 mph: 1.5%
					45 - 50 mph: 1.7%
					50 - 55 mph: 2.1%
					55 - 60 mph: 2%
					60 - 65 mph: 1.2%
					65 + mph: 0.5%
			Annual Miles (data check):	miles/vehicle/year	15,683
		Fuel Tank Capacity		gallons	30
		Efficiency	Fuel Economy	miles/gallon	7
			Fuel Consumption at Idle	gallons/hour	0.1
	Fuel Price	Diesel	Pump Price (including taxes)	$/gallon	EIA Reference Value: $2.66/gal
		Tax	Fuel Rebate	$/gallon	($0.32)
		Private fuel system OPEX, capital recovery, profit		$/gallon	$0.10
		Diesel Emissions Fluid	DEF Price	$/gallon	$2.80
			DEF Consumption	miles/gallon	350
Fluids	Fluid Pricing	Engine Oil		$/gallon	$18.00
		Coolant		$/gallon	$8.00
		Transmission Fluid		$/gallon	$20.00

References: 28, 32, 44, 57, 63, 65, 66

Economics of Standardized Batteries

Evaluate various battery standardization strategies using Ricardo TCO model

Inputs to the TCO model are based upon the defined duty cycle for the MD parcel delivery van:

CAPEX: Vehicle and Infrastructure

Incremental Cost of Hybrid Drive System

CAPEX	Vehicle	Hybrid vehicle purchase price (nominal)		$	$87,800
		Diesel vehicle purchase price (nominal)		$	$65,000
		Battery	Nominal Price	$	$5,400 *
			Price per kWh	$/kWh	$3,000
		Motor + Inverter	Nominal Price	$	$5,350
			Price per kW	$/kWh	$206
		Other Hybrid System Components, including Power Electronics		$	$10,000
		Engine and Emission System Downsize Savings		$	$1,500
		Other CAPEX	Hybrid System Components	$	$4,500
		Incentives or Grants		$	$3,000
		Financing Costs	Vehicle Loan	% of CAPEX	4%
			Cost of Money for Vehicle Purchase	%	6%
		Residual Value	Vehicle	$	$19,500
			Battery	at $100/kWh	$180
	Infrastructure		No additional infrastructure required for HEV	$	$0

*Represents low-volume price over 2007-2013 time frame

References: 28, 32, 44, 57, 63, 65, 66

Economics of Standardized Batteries: Battery Lease Economics

We can combine the **customer (lessee, vehicle operator)** and **battery leasing company (lessor)** requirements to obtain the following relationship, which defines the acceptable ratio of battery mark-up factors as a function of time value of money for both customer and lessor:

[Lease price required by lessor] ≤ [Lease price required by lessee]

$$\frac{M_L B}{1-t}\left(\frac{1}{R}-\frac{t}{l}\right) \le \frac{M_{DO} B}{1-t}\left(\frac{1}{D}-\frac{t}{l}\right) \longrightarrow \frac{M_L}{M_{DO}} \le \frac{\left(\frac{1}{D}-\frac{t}{l}\right)}{\left(\frac{1}{R}-\frac{t}{l}\right)}$$

R = aggregate IRR

$$R = \sum_{i=1}^{l}(1+r)^{0.5-i}$$

D = aggregate discount factor:

$$D = \sum_{i=1}^{N}(1+\delta)^{0.5-i}$$

Variable	Description
r	internal rate of return
T_i	tax payments over life of battery
M_L	battery mark-up to battery leasing company, lessor (e.g. 1.3)
B	battery price
t	tax rate (e.g. 39.3%)
L_i	lease payment (price) as function of lessor's battery cost, tax rate, IRR, etc. lease price is set by the lessor
l	battery life (e.g. 7 years)
R	aggregate internal rate of return (IRR)
M_{DO}	battery mark-up to vehicle owner (e.g. 1.4)
D	aggregate discount factor
δ	discount factor (rate)

References: 2, 63, 65, 66, 67, 68

Economics of Standardized Batteries

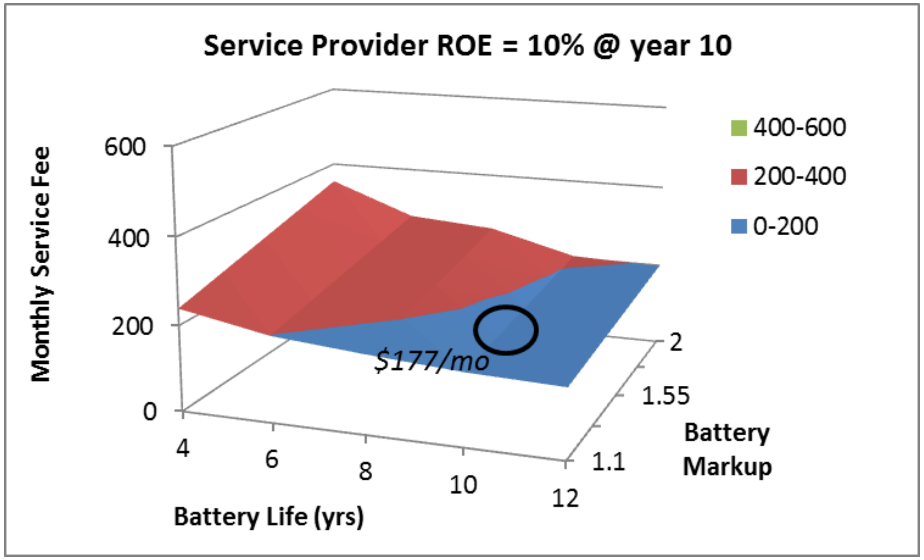
Battery Lease Economics: Lease vs Direct Ownership Model Input Parameters

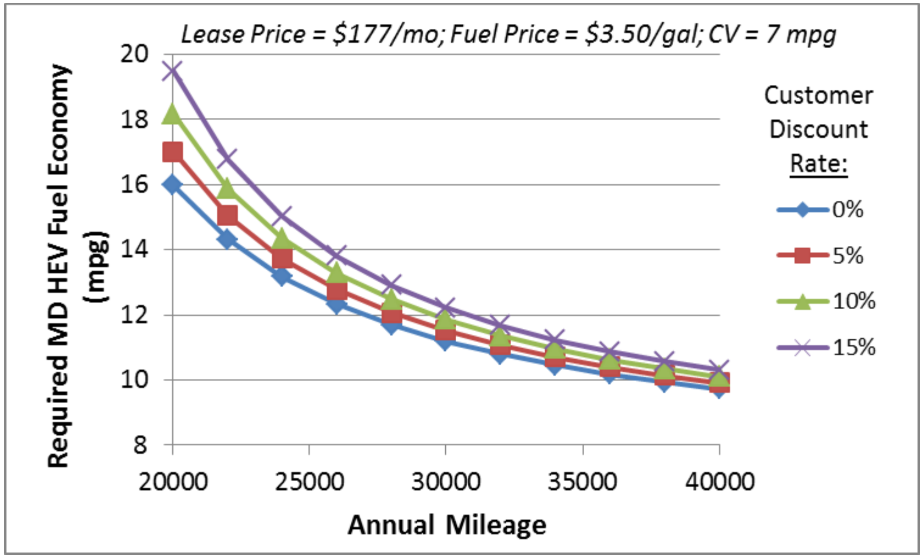
Variable	Description	Range of Values	References
B	battery cost (delivered cost to hybrid drive system manufacturer)	$1,800 to $5,400	43, 44, 63, 65, 66, current study
MI	motor + inverter cost to hybrid drive system manufacturer	$4,800 to $8,000	43, 44, 65, 66
ΔTr	incremental cost increase in transmission for HEV system	$1,000 to $5,000	44, 65, 66, industry interviews
L_i	lease payment (price) as function of lessor's battery cost, tax rate, IRR, etc. lease price is set by the lessor	$130 to $260/month	63, 65, 66, current study
G&A	general & administrative costs incurred by battery lessor	$75 to $125/battery/year	63, 65, 66
F	Fuel price: No. 2 diesel	$2.00/gal to $4.50/gal	US DOE EIA AEO
M_L	battery mark-up to battery leasing company (also known as lessor or service provider)	1.0 (no mark-up) to 1.5	63, 65, 66
M_{DO}	battery mark-up to vehicle owner = $M_{HS} * M_{OEM}$	1.0 (no mark-up) to 1.5	63, 65, 66
M_{HS}	battery mark-up hybrid system manufacturer to vehicle OEM	1.2 to 1.5	43, 44, 65, 66
M_{OEM}	battery mark-up vehicle OEM to vehicle owner	1.2 to 1.5	43, 44, 65, 66
M_{RC}	replacement battery mark-up: vehicle OEM to vehicle owner	1.2 to 1.4	65, 66
M_{RL}	replacement battery mark-up: battery manufacturer to battery leasing company	1.1 to 1.5	65, 66
P	customer, lessee, payback period	1 year - 3 years	66, stakeholder interviews
t	tax rate on net revenues	39.0% to 39.3%	63, 64, 65, 66
δ	discount factor (rate required by customer, lessee)	5% to 10%	63, 65, 66
r	internal rate of return for battery leasing company, lessor	10% to 20%	63, 65, 66
l	battery life, function of duty cycle	4 years to 15 years	Current study
FE_B	fuel economy for baseline vehicle	6.8 – 7.2 miles/gallon	3, 4, 5, 63, 65, 66
FE_{HEV}	fuel economy for hybrid vehicle (maximum)	8.2 - 8.6 miles/gallon	current study

MD HEV battery leasing – preliminary economic analysis

The preliminary lease analysis was reviewed in the January Milestone Report:

- Leasing looks better than buying on a short 3 year time horizon
- Bottom-up lease cost calculations suggest a floor of $177/mo for a 5 kWh MD HEV battery
- Analysis of vehicle performance and customer economics suggest that it is not possible to achieve a 3 year payback at this cost

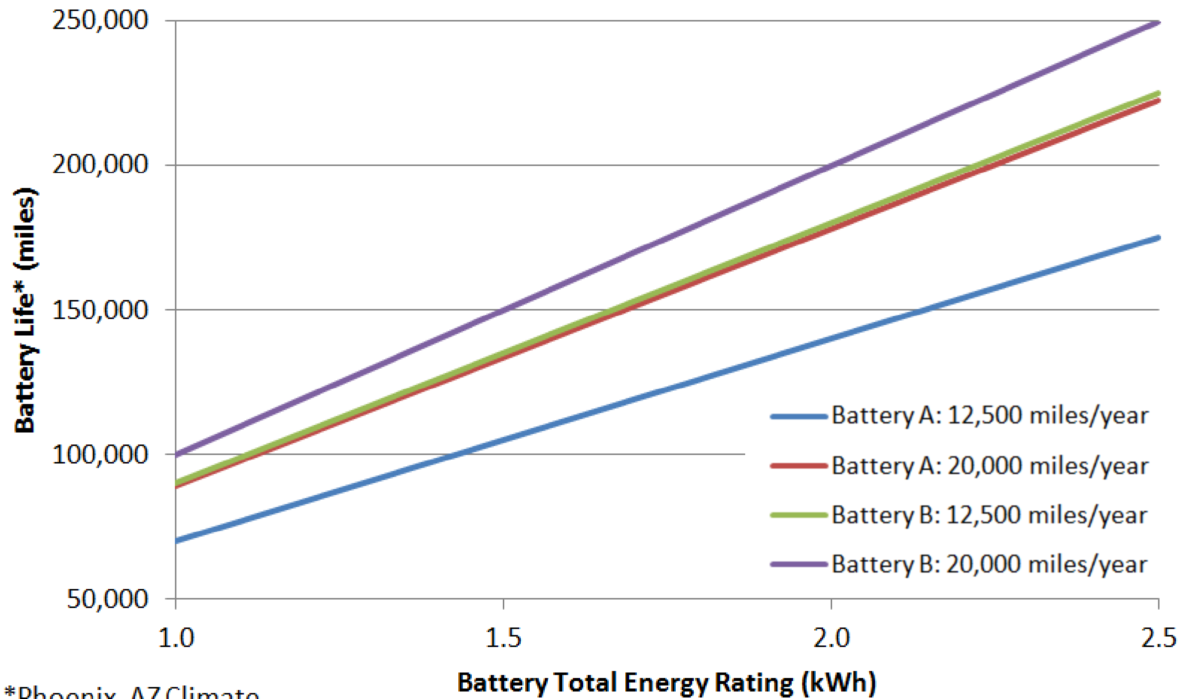




Performance and Degradation of Standardized Batteries in Medium-Duty Applications

Utilize BLAST model to provide battery life estimate for selected MD package delivery van and composite duty cycle

Battery	Miles/Year	Battery Total Energy Rating (kWh)	Battery Life (miles)
A	12,500	1.0	70,040
		1.5	105,060
		1.8	126,072
		2.0	140,080
		2.5	175,100
	20,000	1.0	89,122
		1.5	133,683
		1.8	160,420
		2.0	178,244
		2.5	222,805
B	12,500	1.0	89,948
		1.5	134,921
		1.8	161,906
		2.0	179,895
		2.5	224,869
	20,000	1.0	99,918
		1.5	149,877
		1.8	179,852
		2.0	199,836
		2.5	249,795



*Phoenix, AZ Climate

Battery A – Short Life

- Based on A123 2.3 Ah cell (iron-phosphate)
- Life ranges from 5-12 years

Battery B – Long Life

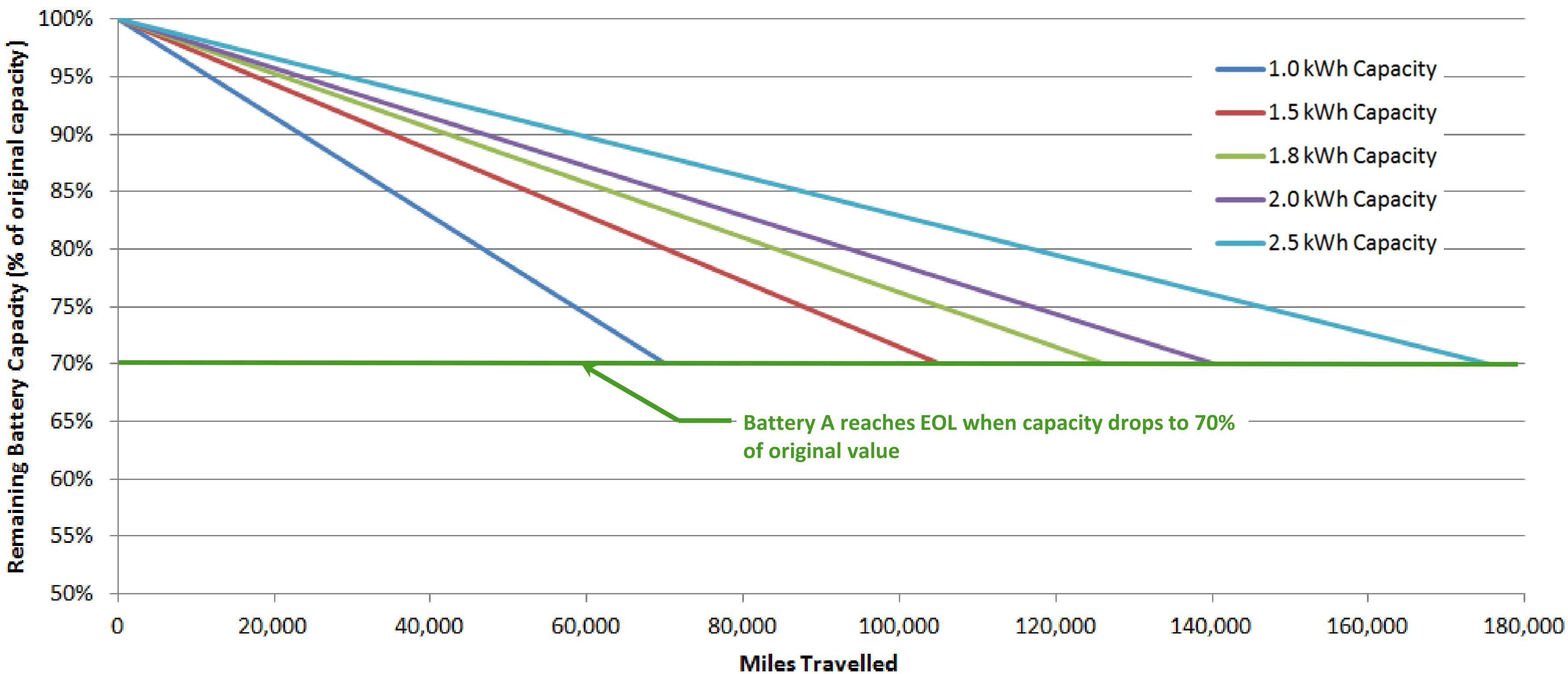
- Composite of Saft 6 to 40Ah cells (NCA)
- Life ranges from 7-15 years

References 47, 48, NREL Analysis

Performance and Degradation of Standardized Batteries in Medium-Duty Applications

Utilize BLAST model to provide battery life estimate for selected MD package delivery van and composite duty cycle

Example of Assumed Remaining Capacity Calculations: for Battery A (Short Life)



$$\left[\text{Remaining Capacity (kWh)}\right] = EOL + P\left[\frac{\left[\text{Battery Life (miles)}\right] - \left[\text{Miles Travelled}\right]}{\left[\text{Battery Life (miles)}\right]}\right]$$

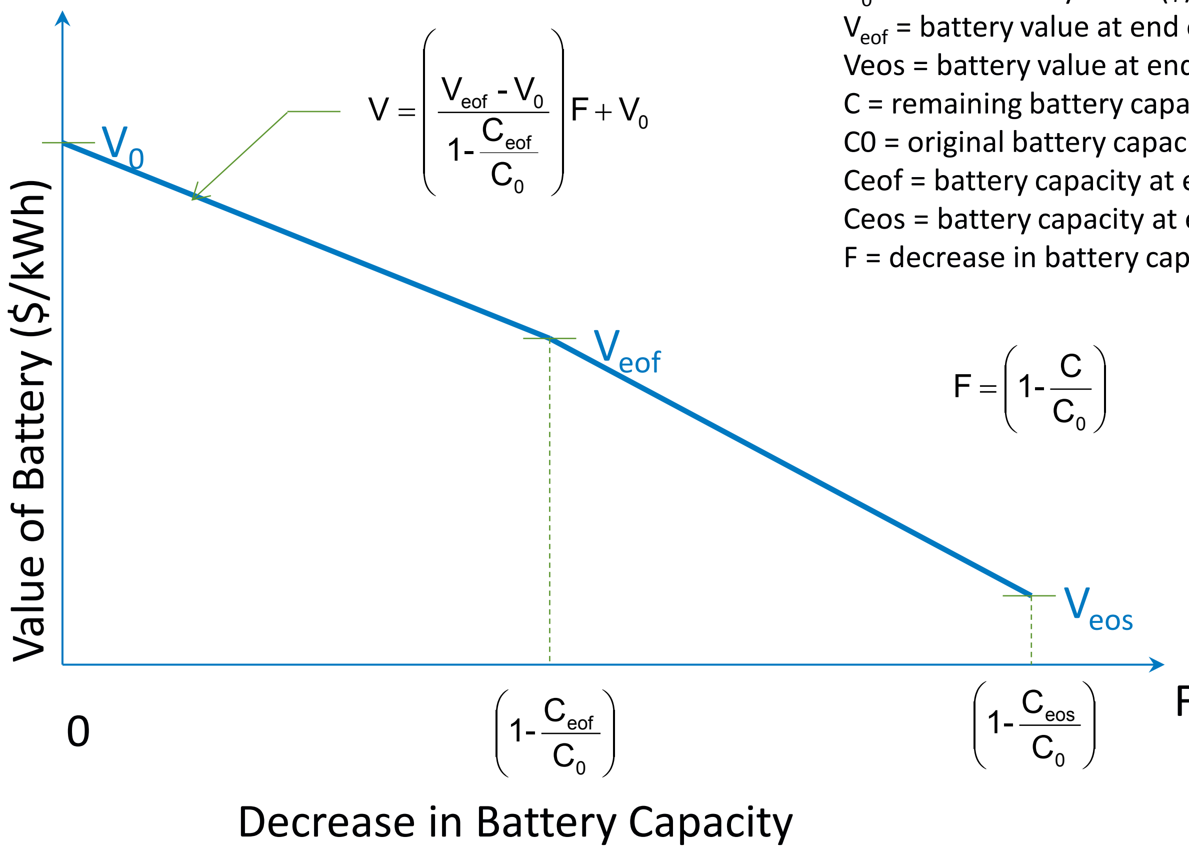
Battery A – Short Life

- Based on A123 2.3 Ah cell (iron-phosphate)
- Life ranges from 5-12 years

References 47, 48, NREL Analysis

Battery value versus remaining capacity

V_0 = initial battery value ($/kWhr)
V_{eof} = battery value at end of first life
Veos = battery value at end of second life
C = remaining battery capacity
C0 = original battery capacity
Ceof = battery capacity at end of first life
Ceos = battery capacity at end of second life
F = decrease in battery capacity



Remaining capacity determined using NREL BLAST model and correlated to vehicle mileage:

$$C = \boldsymbol{f}(M) \quad \text{where } M = \text{cumulative vehicle miles}$$

NREL has developed procedure for calculating remaining capacity as a function of cumulative miles

Economics of Standardized Batteries

Evaluate various battery standardization strategies using Ricardo TCO model

Inputs to the TCO model are based upon the defined duty cycle for the MD parcel delivery van:

CAPEX: Vehicle and Infrastructure

Incremental Cost of Hybrid Drive System

System	Included Components	Component Costs		Comments
		High Value	Low Value	
Battery Cost from Battery Manufacturer:	Battery pack	$ 6,000	$ 5,100	Represents historical low volume prices
Motor+Inverter Cost:	Motor/generator, motor inverter/controller	$ 8,350	$ 4,200	Industry interviews: low value is $3k motor +$1,200 inverter
Transmission incremental cost:	Eaton Fuller automated manual transmission	$ 1,000	$ -	High value includes modification to match motor
Other hybrid system components	Hybrid control module, battery box	$ 2,500	$ 1,200	Based on manufacturing analysis
Markup:	Hybrid system manufacturer to vehicle OEM	1.5	1.2	Eaton has provided estimates ranging from 1.25 to 1.4
Markup:	Vehicle OEM to vehicle owner/operator	1.5	1.2	Eaton has provided estimates ranging from 1.25 to 1.4
	Total Cost Delta for HEV:	$ 40,162.50	$ 15,120.00	
	Cost Delta for HEV w/o Battery:	$ 26,662.50	$ 7,776.00	
	Effective Battery Cost to Vehicle Owner/Operator:	$ 13,500.00	$ 7,344.00	

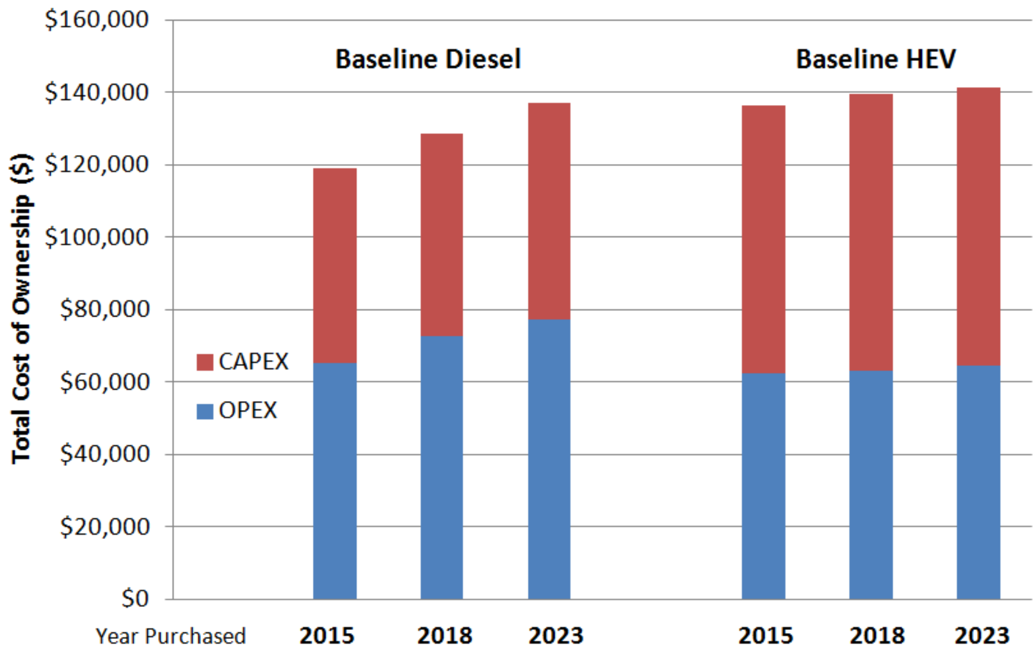
Replacement Battery Market	Mark-Up/Cost	
	High Value	Low Value
Replacement Battery Markup to Consumer:	1.5	1.0
Replacement Battery Cost to Consumer:	$ 9,000.00	$ 5,100.00
Replacement Battery Markup to Service Provider*:	1.5	1.25
Replacement Battery Cost to Service Provider*:	$ 9,000.00	$ 6,375.00

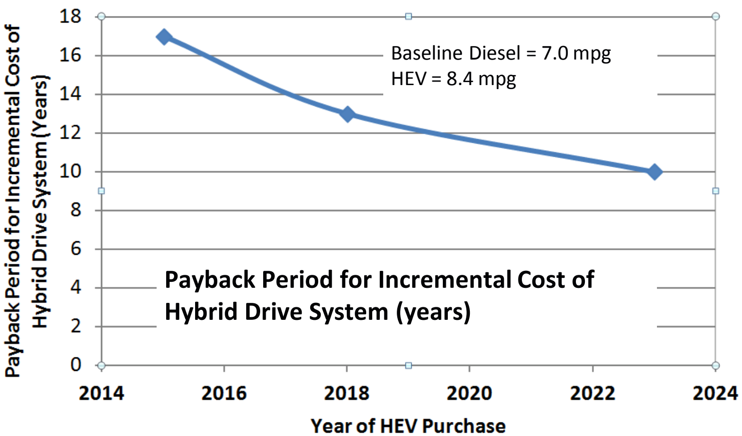
*Service Provider is the battery leasing company

Economics of Standardized Batteries

Evaluate various battery standardization strategies using Ricardo TCO model

Results of Baseline Diesel and Baseline HEV Total Cost of Ownership Models





OPEX includes: fluids, maintenance parts, maintenance labor, operational overhead

CAPEX Includes: vehicle cost (vehicle+hybrid drive components+battery) minus residual value of (vehicle+hybrid drive components) minus (residual value of battery)

TCO is present value based model; comparisons are shown in dollars valued at year of vehicle purchase.

For example, a conventional diesel vehicle purchased during 2015 can be compared directly with an HEV purchased during 2015 (2015 dollars); A conventional diesel vehicle purchased during 2023 can be compared directly with HEV purchased during 2023 (2023 dollars).

For baseline vehicles purchased during 2015 and 2018, payback period for incremental cost of hybrid drive components exceeds the useful life of the vehicle (12 years).

Total Cost of Ownership Over Life of Vehicle				
Powertrain	Year Purchased	OPEX	CAPEX*	Total
Diesel	2015	$ 65,130	$ 53,856	$ 118,986
	2018	$ 72,694	$ 56,086	$ 128,780
	2023	$ 77,197	$ 60,008	$ 137,205
HEV	2015	$ 62,434	$ 74,033	$ 136,467
	2018	$ 63,103	$ 76,573	$ 139,676
	2023	$ 64,443	$ 76,937	$ 141,380

*Includes residual value of vehicle

Assumptions:

Parameter	Units	Diesel	HEV
Useful life of vehicle	years	12	12
Battery life	years	n/a	10
Number of battery replacements		n/a	1
Incremental cost of hybrid drive system	$	n/a	$ 22,800
Vehicle purchase price	$	$ 65,000	$ 87,800
Vehicle residual value (includes battery)[1]	$	$ 19,900	$ 24,584
Battery use contract		n/a	Direct ownership
Battery cost to hybrid system supplier	$	n/a	$ 5,400
Battery residual value (80% of orig. capacity)[2]	$	n/a	$ 180
Battery lease payment (per month)	$	n/a	n/a
Diesel fuel price: EIA Reference Value: 2015: $2.66/gallon and 2020: $3.11/gallon			

[1]Vehicle residual value: 30.5% for baseline diesel, 28.0% for baseline HEV

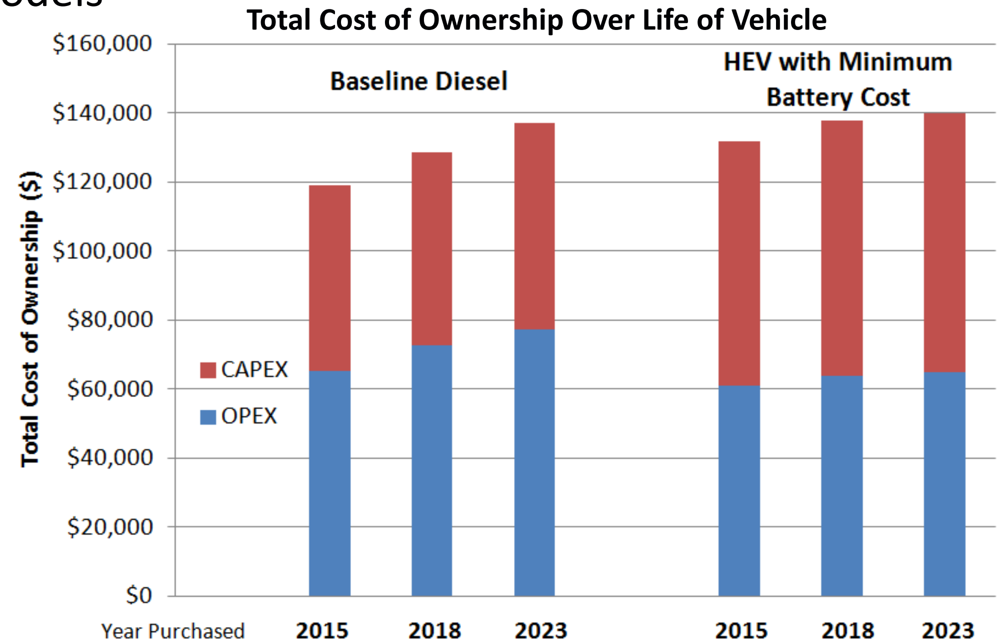
[2]Battery pack value at end of first life = $100/kWh

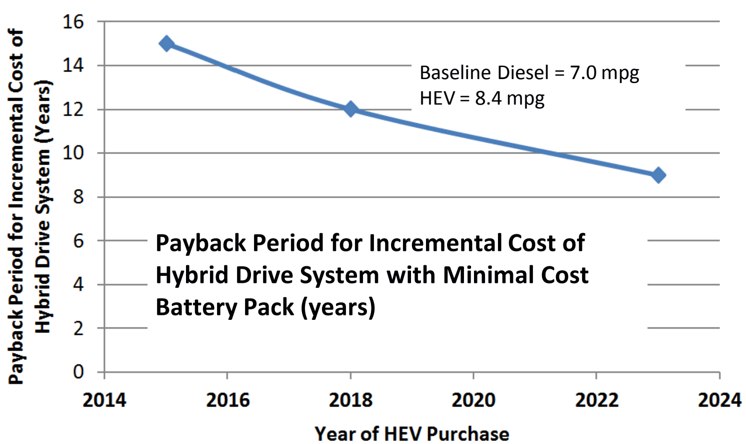
References: 28, 32, 44, 57, 63, 65, 66

Economics of Standardized Batteries

Evaluate various battery standardization strategies using Ricardo TCO model

Results of **Baseline Diesel** and **HEV with Minimal Battery Cost** Total Cost of Ownership Models





OPEX includes: fluids, maintenance parts, maintenance labor, operational overhead

CAPEX Includes: vehicle cost (vehicle+hybrid drive components+battery) minus residual value of (vehicle+hybrid drive components) minus (residual value of battery)

TCO is present value based model; comparisons are shown in dollars valued at year of vehicle purchase.

Minimal Cost Battery: $1,800 delivered cost to hybrid system supplier (vs. $5,400 for baseline battery cost)

For baseline vehicles purchased during 2015 and 2018, payback period for incremental cost of hybrid drive components exceeds the useful life of the vehicle (12 years).

Total Cost of Ownership Over Life of Vehicle				
Powertrain	**Year Purchased**	**OPEX**	**CAPEX***	**Total**
Diesel	2015	$ 65,130	$ 53,856	$ 118,986
	2018	$ 72,694	$ 56,086	$ 128,780
	2023	$ 77,197	$ 60,008	$ 137,205
HEV	2015	$ 60,985	$ 70,997	$ 131,982
	2018	$ 63,715	$ 73,989	$ 137,704
	2023	$ 64,936	$ 74,994	$ 139,930

*Includes residual value of vehicle

Assumptions:

Parameter	Units	Diesel	HEV
Useful life of vehicle	years	12	12
Battery life	years	n/a	10
Number of battery replacements		n/a	1
Hybrid drive system incremental cost: battery price reduced from $5,400 to $1,800	$	n/a	$ 19,200
Vehicle purchase price	$	$ 65,000	$ 84,200
Vehicle residual value (includes battery)[1]	$	$ 19,900	$ 23,576
Battery use contract		n/a	Direct ownership
Battery cost to hybrid system supplier	$	n/a	$ 1,800
Battery residual value (80% of orig. capacity)[2]	$	n/a	$ 180
Battery lease payment (per month)	$	n/a	n/a
Diesel fuel price: EIA Reference Value: 2015: $2.66/gallon and 2023: $3.11/gallon			

[1]Vehicle residual value: 30.5% for baseline diesel, 28.0% for baseline HEV

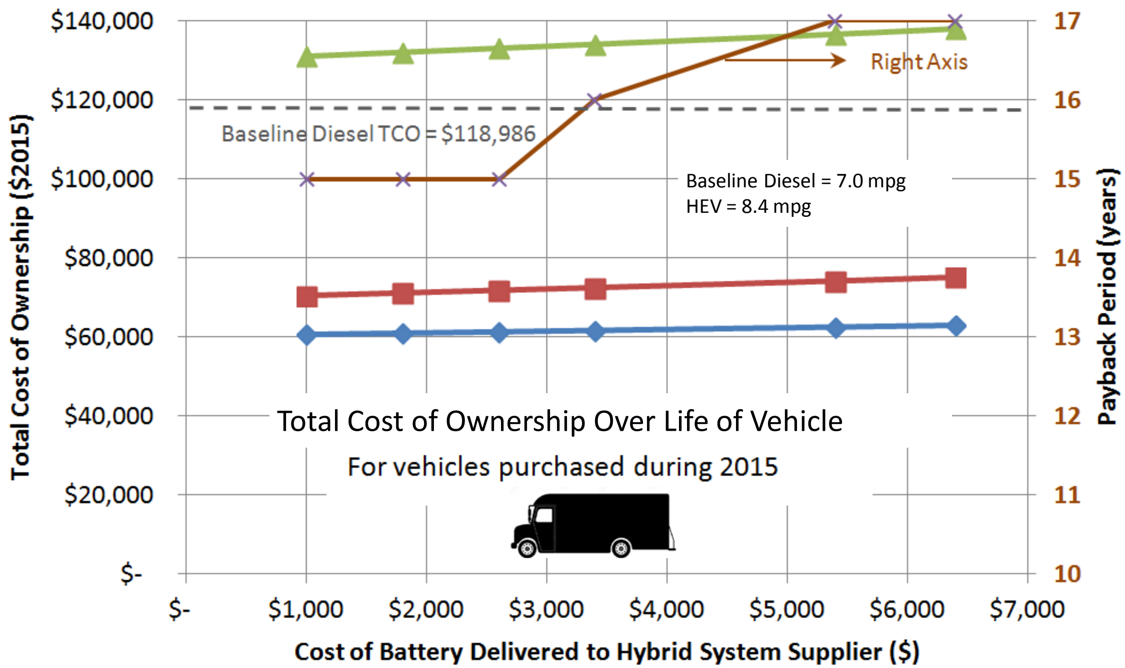
[2]Battery pack value at end of first life = $100/kWh

References: 28, 32, 44, 57, 63, 65, 66

Economics of Standardized Batteries

Evaluate various battery standardization strategies using Ricardo TCO model

Results of Battery Cost on Total Cost of Ownership



OPEX includes: fluids, maintenance parts, maintenance labor, operational overhead

CAPEX Includes: vehicle cost (vehicle+hybrid drive components+battery) minus residual value of (vehicle+hybrid drive components) minus (residual value of battery)

Assumptions:			Impact on TCO: Battery Cost to HEV System Supplier					
Parameter	**Units**	**Diesel**	**Max**	**Baseline**	**1**	**2**	**3**	**Min**
Useful life of vehicle	years	12	12	12	12	12	12	12
Battery life	years	n/a	10	10	10	10	10	10
Number of battery replacements		n/a	1	1	1	1	1	1
Hybrid drive system incremental cost: battery price reduced from $5,400 to $1,800	$	n/a	$ 23,800	$ 22,800	$ 20,800	$ 20,000	$ 19,200	$ 18,400
Vehicle purchase price	$	$ 65,000	$ 88,800	$ 87,800	$ 85,800	$ 85,000	$ 84,200	$ 83,400
Vehicle residual value (includes battery)[1]	$	$ 19,900	$ 24,864	$ 24,584	$ 24,024	$ 23,800	$ 23,576	$ 23,352
Battery use contract		n/a	Direct Ownership					
Battery cost to hybrid system supplier	$	n/a	$ 6,400	$ 5,400	$ 3,400	$ 2,600	$ 1,800	$ 1,000
Battery residual value (80% of orig. capacity)[2]	$	n/a	$ 180	$ 180	$ 180	$ 180	$ 180	$ 180
OPEX	$	n/a	$ 62,836	$ 62,434	$ 61,629	$ 61,307	$ 60,985	$ 60,663
CAPEX	$	n/a	$ 74,977	$ 74,033	$ 72,347	$ 71,672	$ 70,997	$ 70,323
Total	$	n/a	$137,813	$136,467	$133,976	$132,979	$131,982	$130,986
Payback Period	years	n/a	17	17	16	15	15	15

[1]Vehicle residual value: 30.5% for baseline diesel, 28.0% for baseline HEV

[2]Battery pack value at end of first life = $100/kWh

TCO is present value based model; comparisons are shown in 2015 dollars for a range of HEV battery costs.

Battery cost reductions alone are not sufficient to reduce the total cost of ownership for HEVs below the TCO of diesel vehicles (for vehicles purchased during 2015).

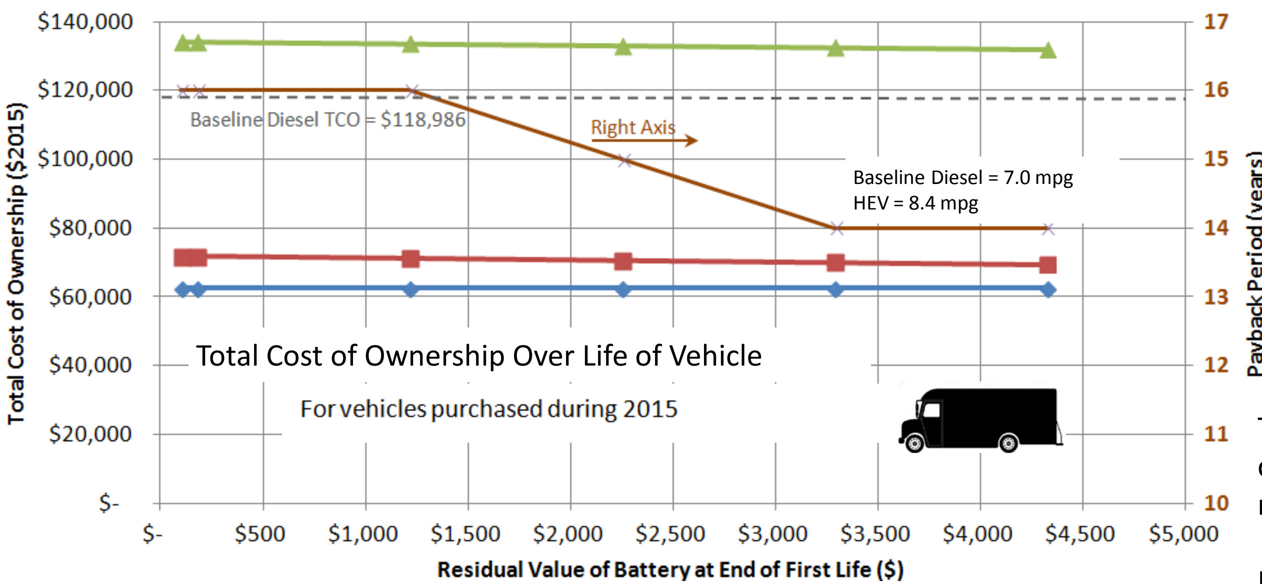
Payback periods for the incremental cost of the HEV systems are greater than the life of the vehicle (12 years).

References: 28, 32, 44, 57, 63, 65, 66

Economics of Standardized Batteries

Evaluate various battery standardization strategies using Ricardo TCO model

Results of Battery Residual Value on Total Cost of Ownership



OPEX includes: fluids, maintenance parts, maintenance labor, operational overhead

CAPEX Includes: vehicle cost (vehicle+hybrid drive components+battery) minus residual value of (vehicle+hybrid drive components) minus (residual value of battery)

Assumptions:			Impact of Battery Residual Value on TCO					
Parameter	Units	Diesel	Min	Baseline	1	2	3	Max
Useful life of vehicle	years	12	12	12	12	12	12	12
Battery life	years	n/a	10	10	10	10	10	10
Number of battery replacements		n/a	1	1	1	1	1	1
Battery use contract		n/a	Direct Ownership					
Hybrid drive system incremental cost: battery price reduced from $5,400 to $1,800	$	n/a	$ 22,800	$ 22,800	$ 22,800	$ 22,800	$ 22,800	$ 22,800
Vehicle purchase price	$	$ 65,000	$ 87,800	$ 87,800	$ 87,800	$ 87,800	$ 87,800	$ 87,800
Baseline vehicle residual value (includes battery)[1]	$	$ 19,900	$ 24,584	$ 24,584	$ 24,584	$ 24,584	$ 24,584	$ 24,584
Battery cost to hybrid system supplier	$	n/a	$ 5,400	$ 5,400	$ 5,400	$ 5,400	$ 5,400	$ 5,400
Battery residual value (80% of orig. capacity)	$	n/a	$ 100	$ 180	$ 1,215	$ 2,250	$ 3,285	$ 4,320
Change in first battery residual value from baseline[2]	$	n/a	$ (80)	$ -	$ 1,035	$ 2,070	$ 3,105	$ 4,140
Residual value of second battery at vehicle end of vehicle useful life[3]	$	n/a	$ 4,320	$ 4,320	$ 4,320	$ 4,320	$ 4,320	$ 4,320
Change in second battery residual value from baseline	$	n/a	$ 4,140	$ 4,140	$ 4,140	$ 4,140	$ 4,140	$ 4,140
Net change in vehicle residual value (including battery)	$	n/a	$ 4,060	$ 4,140	$ 5,175	$ 6,210	$ 7,245	$ 8,280
Residual value of vehicle (including battery)	$	n/a	$ 28,644	$ 28,724	$ 29,759	$ 30,794	$ 31,829	$ 32,864
OPEX	$	n/a	$ 62,434	$ 62,434	$ 62,434	$ 62,434	$ 62,434	$ 62,434
CAPEX	$	n/a	$ 71,759	$ 71,715	$ 71,135	$ 70,555	$ 69,976	$ 69,396
Total	$	n/a	$134,193	$134,149	$133,569	$132,989	$132,410	$131,830
Payback Period	years	n/a	16	16	16	15	14	14

[1]Vehicle residual value: 30.5% for baseline diesel, 28.0% for baseline HEV

[2]First battery removed from vehicle after 10 years when it reaches 80% of original capacity

[3]Value of second battery is linear to remaining capacity

TCO is present value based model; comparisons are shown in 2015 dollars for a range of HEV battery residual values

Residual value of second (replacement) battery is assumed to be linearly related to remaining capacity.

Increases in battery residual value alone are not sufficient to reduce the total cost of ownership for HEVs below the TCO of diesel vehicles (for vehicles purchased during 2015).

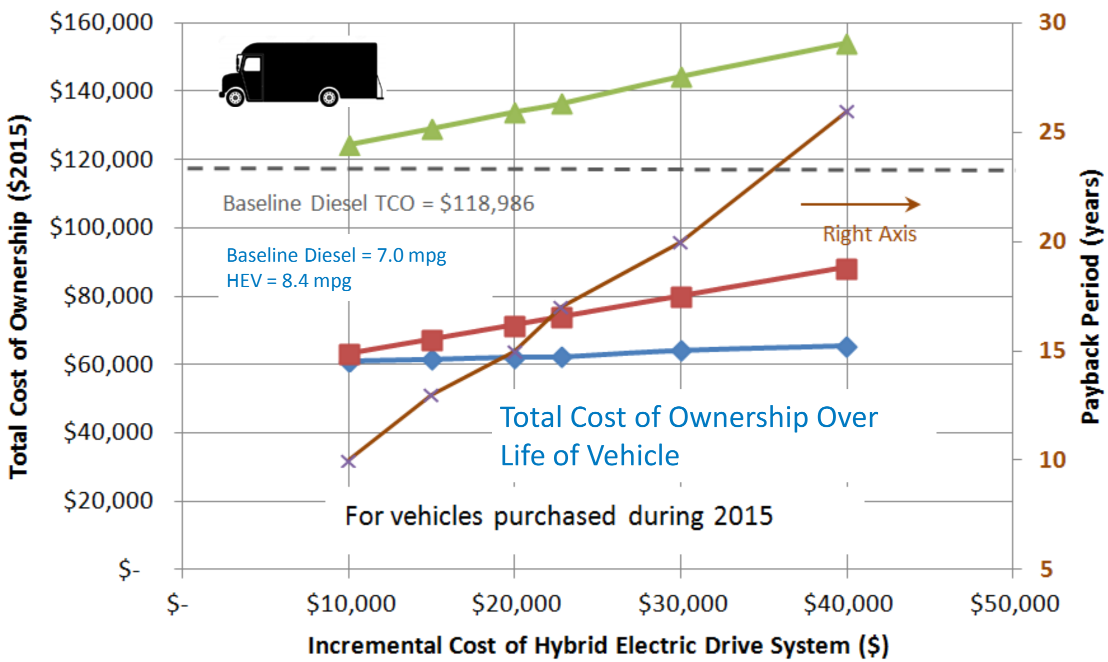
Payback periods for the incremental cost of the HEV systems are greater than the life of the vehicle (12 years).

References: 28, 32, 44, 57, 63, 65, 66

Economics of Standardized Batteries

Evaluate various battery standardization strategies using Ricardo TCO model

Results of HEV System Incremental Cost on Total Cost of Ownership



OPEX includes: fluids, maintenance parts, maintenance labor, operational overhead

CAPEX Includes: vehicle cost (vehicle+hybrid drive components+battery) minus residual value of (vehicle+hybrid drive components) minus (residual value of battery)

TCO is present value based model; comparisons are shown in 2015 dollars for a range of HEV incremental costs.

Battery residual value assumed to be $100/kWh.

Decreases in the incremental cost of the hybrid drive system alone are not sufficient to reduce the total cost of ownership for HEVs below the TCO of diesel vehicles (for vehicles purchased during 2015).

The incremental cost of the hybrid system must drop below $14K for the payback period to be less than the life of the vehicle (12 years).

Assumptions:			Impact on TCO: Incremental Cost of HEV System					
Parameter	**Units**	**Diesel**	**Max**	**3**	**Baseline**	**2**	**1**	**Min**
Useful life of vehicle	years	12	12	12	12	12	12	12
Battery life	years	n/a	10	10	10	10	10	10
Number of battery replacements		n/a	1	1	1	1	1	1
Incremental cost of hybrid system	$	n/a	$ 40,000	$ 30,000	$ 22,800	$ 20,000	$ 15,000	$ 10,000
Vehicle purchase price	$	$ 65,000	$ 105,000	$ 95,000	$ 87,800	$ 85,000	$ 80,000	$ 75,000
Vehicle residual value (includes battery)[1]	$	$ 19,900	$ 29,400	$ 26,600	$ 24,584	$ 23,800	$ 22,400	$ 21,000
Battery use contract		n/a	Direct Ownership					
OPEX	$	n/a	$ 65,692	$ 64,284	$ 62,434	$ 62,313	$ 61,669	$ 61,166
CAPEX	$	n/a	$ 88,536	$ 80,104	$ 74,033	$ 71,672	$ 67,456	$ 63,240
Total	$	n/a	$ 154,228	$ 144,388	$ 136,467	$ 133,985	$ 129,125	$ 124,406
Payback Period	years	n/a	26	20	17	15	13	10

[1]Vehicle residual value: 30.5% for baseline diesel, 28.0% for baseline HEV

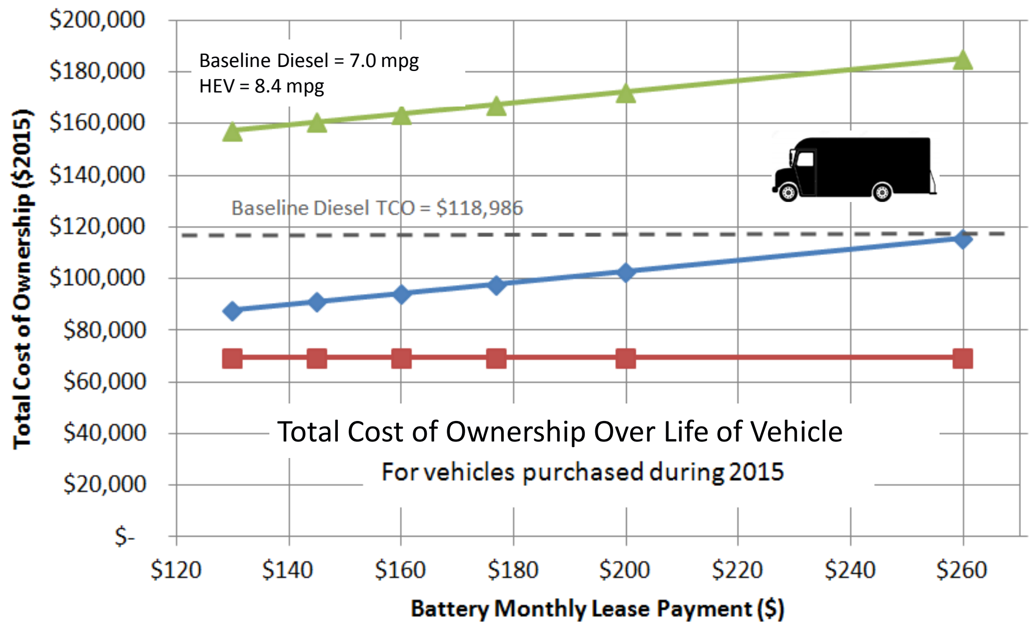
[2]Battery pack value at end of first life = $100/kWh

References: 28, 32, 44, 57, 63, 65, 66

Economics of Standardized Batteries

Evaluate various battery standardization strategies using Ricardo TCO model

Results of Battery Lease Cost on Total Cost of Ownership



OPEX includes: fluids, maintenance parts, maintenance labor, operational overhead, and **battery lease payments**

CAPEX Includes: vehicle cost (vehicle+hybrid drive components w/o battery) minus residual value of (vehicle+hybrid drive components) **without battery**

Payback period is greater than 30 years for range of lease payments shown

Assumptions:			Impact on TCO: Battery Lease vs Direct Ownership					
Parameter	Units	Diesel	Max	3	Baseline	2	1	Min
Useful life of vehicle	years	12	12	12	12	12	12	12
Battery life	years	n/a	10	10	10	10	10	10
Number of battery replacements		n/a	1	1	1	1	1	1
CAPEX Reduction (baseline battery cost)	$	n/a	$ 5,400	$ 5,400	$ 5,400	$ 5,400	$ 5,400	$ 5,400
Vehicle purchase price[2]	$	$ 65,000	$ 82,400	$ 82,400	$ 82,400	$ 82,400	$ 82,400	$ 82,400
Vehicle residual value (excludes battery)[1]	$	$ 19,900	$ 23,072	$ 23,072	$ 23,072	$ 23,072	$ 23,072	$ 23,072
Battery use contract		n/a	Lease arrangement with battery service provider					
Battery Lease Rate (monthly payment)	$	n/a	$ 260	$ 200	$ 177	$ 160	$ 145	$ 130
OPEX	$	n/a	$ 115,499	$ 102,702	$ 97,796	$ 94,170	$ 90,971	$ 87,772
CAPEX	$	n/a	$ 69,480	$ 69,480	$ 69,480	$ 69,480	$ 69,480	$ 69,480
Total	$	n/a	$ 184,979	$ 172,182	$ 167,276	$ 163,650	$ 160,451	$ 157,252
Payback Period	years	n/a	>30	>30	>30	>30	>30	>30

[1]Vehicle residual value: 30.5% for baseline diesel, 28.0% for baseline HEV

[2]HEV purchase price = baseline HEV ($87,800) minus battery cost ($5,400)

TCO is present value based model; comparisons are shown in 2015 dollars for a range of HEV battery lease rates.

Monthly lease price range based analysis of battery leasing company rate of return.

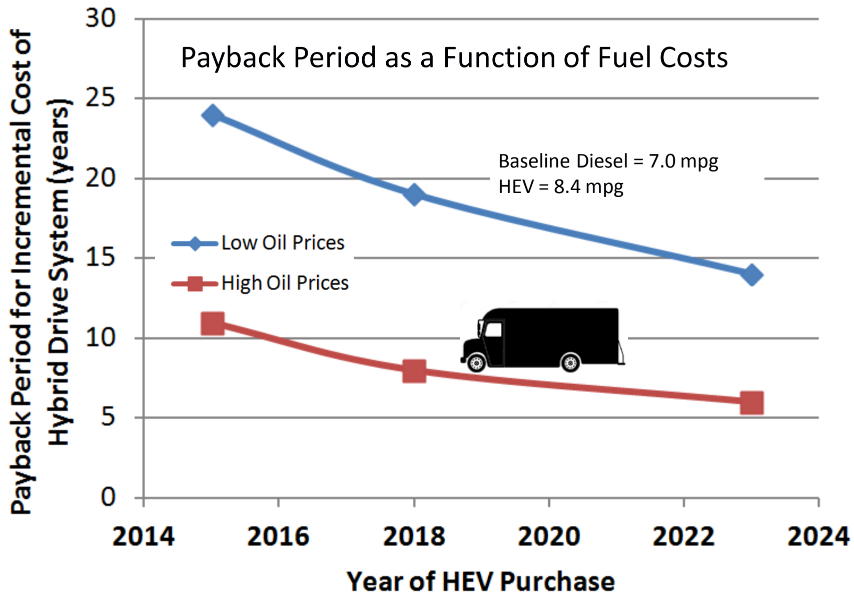
Lease payments during the entire vehicle ownership period result in a significant increase in TCO compared to the baseline battery direct cost of ownership approach (for vehicles purchased during 2015), despite the reduced CAPEX and elimination of battery replacement costs (OPEX increases, residual value decreases).

References: 28, 32, 44, 57, 63, 65, 66

Economics of Standardized Batteries

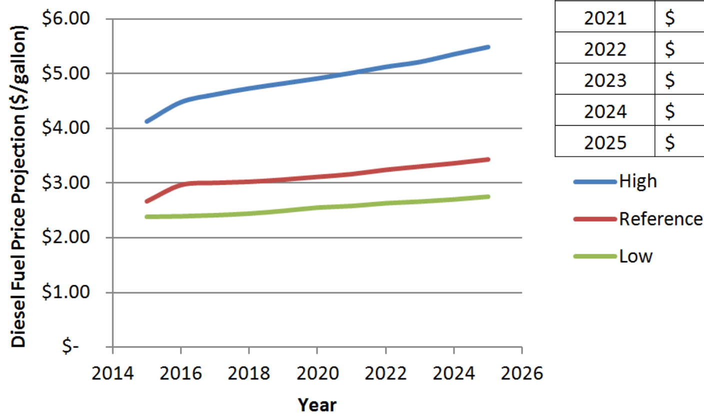
Evaluate various battery standardization strategies using Ricardo TCO model

Results of Diesel Fuel Price on Total Cost of Ownership



EIA AOL Diesel Fuel Price Projections: (reference 62) includes high, reference, and low values. These were included in the TCO to determine impact on HEV TCO and payback periods for incremental cost of hybrid components.

Year	High	Reference	Low
2015	$ 4.13	$ 2.66	$ 2.38
2016	$ 4.48	$ 2.96	$ 2.39
2017	$ 4.62	$ 3.00	$ 2.41
2018	$ 4.73	$ 3.02	$ 2.44
2019	$ 4.82	$ 3.06	$ 2.49
2020	$ 4.91	$ 3.11	$ 2.55
2021	$ 5.01	$ 3.16	$ 2.58
2022	$ 5.12	$ 3.24	$ 2.63
2023	$ 5.21	$ 3.30	$ 2.66
2024	$ 5.35	$ 3.36	$ 2.70
2025	$ 5.48	$ 3.43	$ 2.75



Low Fuel Prices

Total Cost of Ownership Over Life of Vehicle				
Powertrain	**Year Purchased**	**OPEX**	**CAPEX***	**Total**
Diesel	2015	$ 57,021	$ 53,856	$ 110,877
	2018	$ 58,404	$ 56,086	$ 114,490
	2023	$ 62,084	$ 60,008	$ 122,092
HEV	2015	$ 57,778	$ 74,033	$ 131,811
	2018	$ 53,989	$ 76,573	$ 130,562
	2023	$ 55,286	$ 76,937	$ 132,223

High Fuel Prices

Total Cost of Ownership Over Life of Vehicle				
Powertrain	**Year Purchased**	**OPEX**	**CAPEX***	**Total**
Diesel	2015	$ 97,313	$ 53,856	$ 151,169
	2018	$ 109,299	$ 56,086	$ 165,385
	2023	$ 116,594	$ 60,008	$ 176,602
HEV	2015	$ 86,877	$ 74,033	$ 160,910
	2018	$ 89,971	$ 76,573	$ 166,544
	2023	$ 91,770	$ 76,937	$ 168,707

*Includes residual value of vehicle

OPEX includes: fluids, maintenance parts, maintenance labor, operational overhead
CAPEX Includes: vehicle cost (vehicle+hybrid drive components + battery) minus residual value of (vehicle+hybrid drive components) minus (residual value of battery)

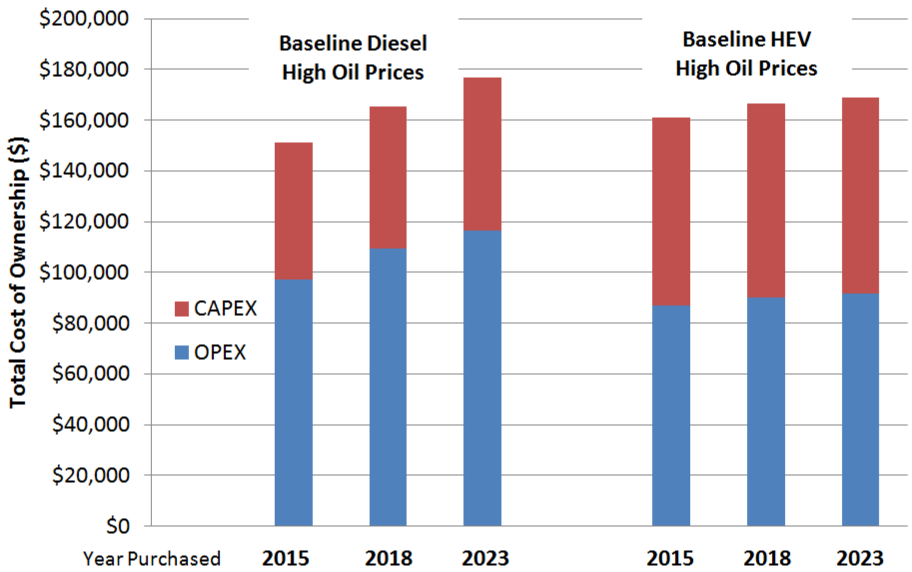
References: 28, 32, 44, 57, 62, 63, 65, 66

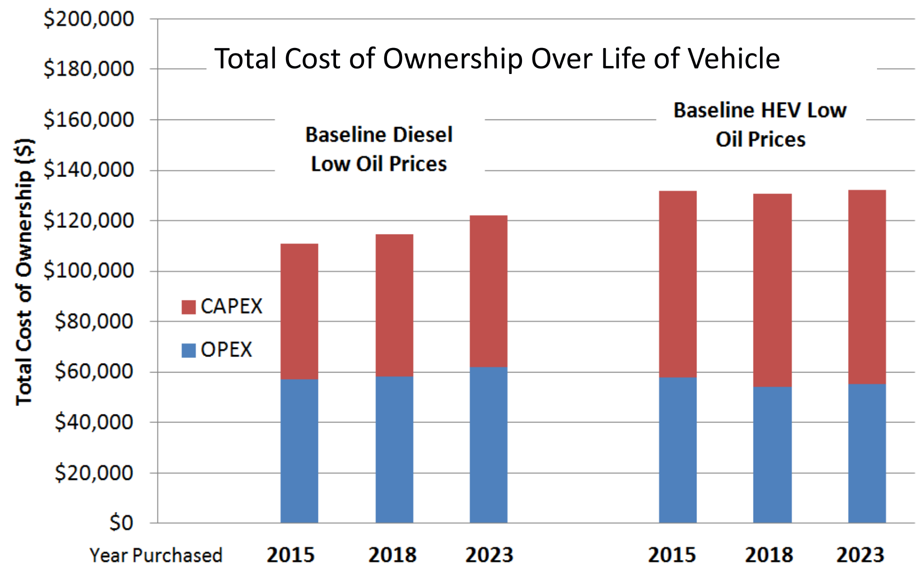
Economics of Standardized Batteries

Evaluate various battery standardization strategies using Ricardo TCO model

Results of Diesel Fuel Price on Total Cost of Ownership

Baseline Diesel = 7.0 mpg
HEV = 8.4 mpg





Assumptions:

Parameter	Units	Diesel	HEV
Useful life of vehicle	years	12	12
Battery life	years	n/a	10
Number of battery replacements		n/a	1
Incremental cost of hybrid drive system	$	n/a	$ 22,800
Vehicle purchase price	$	$ 65,000	$ 87,800
Vehicle residual value (includes battery)[1]	$	$ 19,900	$ 24,584
Battery use contract		n/a	Direct ownership
Battery cost to hybrid system supplier	$	n/a	$ 5,400
Battery residual value (80% of orig. capacity)[2]	$	n/a	$ 180
Battery lease payment (per month)	$	n/a	n/a
Diesel fuel price: EIA "High Oil Price" Value: 2015: $4.13/gallon and 2020: $4.91/gallon			

[1]Vehicle residual value: 30.5% for baseline diesel, 28.0% for baseline HEV

[2]Battery pack value at end of first life = $100/kWh

OPEX includes: fluids, maintenance parts, maintenance labor, operational overhead

CAPEX Includes: vehicle cost (vehicle+hybrid drive components + battery) minus residual value of (vehicle+hybrid drive components) minus (residual value of battery)

TCO is present value based model; comparisons are shown in dollars valued at year of vehicle purchase.

Fuel costs have a significant impact on TCO. At high fuel prices (per EIA projections), TCO of HEV becomes equivalent to TCO for conventional diesel during 2018 and is 4.5% lower than the TCO of conventional diesel for vehicles purchased during 2023.

At low fuel prices (per EIA projections), TCO for HEV remains greater than TCO for conventional diesel through 2025.

References: 28, 32, 44, 57, 62, 63, 65, 66

Economics of Standardized Batteries

Evaluate various battery standardization strategies using Ricardo TCO model

Impact of **Incentives** on Total Cost of Ownership: Identified Incentive Programs

Incentive Program	Region	Description
California HVIP Base Hybrid Voucher	California	GVW(lbs) 6,001-8,500 (plug-in hybrids only): $8,000 8,501-10,000 (plug-in hybrids only): $10,000 10,001-19,500: $15,000; 19,501-33,000: $20,000 33,001-38,000: $25,000; >38,000: $30,000
California HVIP Base Zero-Emission Voucher	California	GVW(lbs) 5,001-8,500: $12,000; 8,501-10,000: $18,000 10,001-14,000: $30,000; 14,001-19,500: $35,000 19,501-26,000: $40,000; >26,000: $45,000
San Joaquin Valley APCD HVIP Plus-Up Voucher	San Joaquin Air District	Hybrid Vehicle: +$15,000 Zero-Emission Vehicle (<8,500 lbs): +$12,000 Zero-Emission Vehicle (<8,500 lbs) manufactured in San Joaquin Valley: +$18,000 Zero-Emission Vehicle (>8,500 lbs): +$20,000 Zero-Emission Vehicle (>8,500 lbs) manufactured in San Joaquin Vally: +$30,000
California HVIP Voucher Adders	California	**The first three vouchers received by a fleet are eligible for additional funding:** $2,000/vehicle <8,501 GVWR $5,000/vehicle 8,501 - 10,000 GVWR $10,000/vehicle >10,000 GVWR **Hydrogen Fuel Cell Vehicles:** 5,001-19,500 lbs: +$20,000 19,501-33,000 lbs: +$30,000 >33,000 lbs: +$40,000

Incentive Program	Region	Description
California HVIP Voucher - ePTO	California	Aerial Boom Vehicles with ePTO: Can get voucher without hybrid driveline, Must be >26,000 GVWR. Lithium batteries $20,000 Lead-acid batteries $14,000
Incentives for Evs in New York State	New York State	Class 3-8 electric trucks. $9 million in incentives. Vouchers for 80% of incremental cost up to $60,000 per eligible vehicle. For 30 non-attainment counties. CMAQ funding from NY State DOT. For vehicles ordered after July 1, 2012. Expected spring 2013 launch.
Alt Fuel Vehicle in New York City	New York City	Class 3-8 CNG, hybrid, electric trucks. $6 million in incentives. Vouchers for 80% of incremental cost up to $40,000 per eligible vehicle. Private fleets only. Must domicile in NYC. CMAQ funding from NY City DOT. Will launch in 2013.
Metro Chicago	Chicago	Electric trucks. Launches spring 2013. Voucher amount based on battery size. Targets 60% of incremental cost. Private and public fleets. $15 million in CMAQ funds. Targets 250 vouchers.
Bill SB359	California	Saves the CA CVRP Rebate Program and provides additional funding to last through June 2014
Bill AB8	California	$2 billion for long-term state alternative fuels funding, including significant funding for EV related projects

Incentive Program	Region	Description
California HVIP Hybrid Voucher Adders	California	GVW(lbs) 6,001-10,000 (plug-in hybrids only): School Bus $5,000 10,001-14,000: Plug-in or Hydraulic Hybrid $5,000, School Bus $5,000 14,001-33,000: Plug-in or Hydraulic Hybrid $10,000, School Bus $10,000, ARB Certification (full vehicle) $15,000 >33,001: Plug-in or Hydraulic Hybrid $10,000, School Bus $10,000, ARB Certification (full vehicle) $20,000
California HVIP OBD Voucher Adders	California	Vehicle GVWR (lbs) 14,001 - 26,000: Total Number of Hybrid-Related Deficiencies 10+ (2013/2014 MY): $12,000 <10 (2013/2014 MY): $16,000 9-14 (2015 MY): $8,000 5-8 (2015 MY): $12,000 <=4 (2015 MY): $16,000 Vehicle GVWR (lbs) >26,001: Total Number of Hybrid-Related Deficiencies 10+ (2013/2014 MY): $16,000 <10 (2013/2014 MY): $20,000 9-14 (2015 MY): $12,000 5-8 (2015 MY): $16,000 <=4 (2015 MY): $20,000

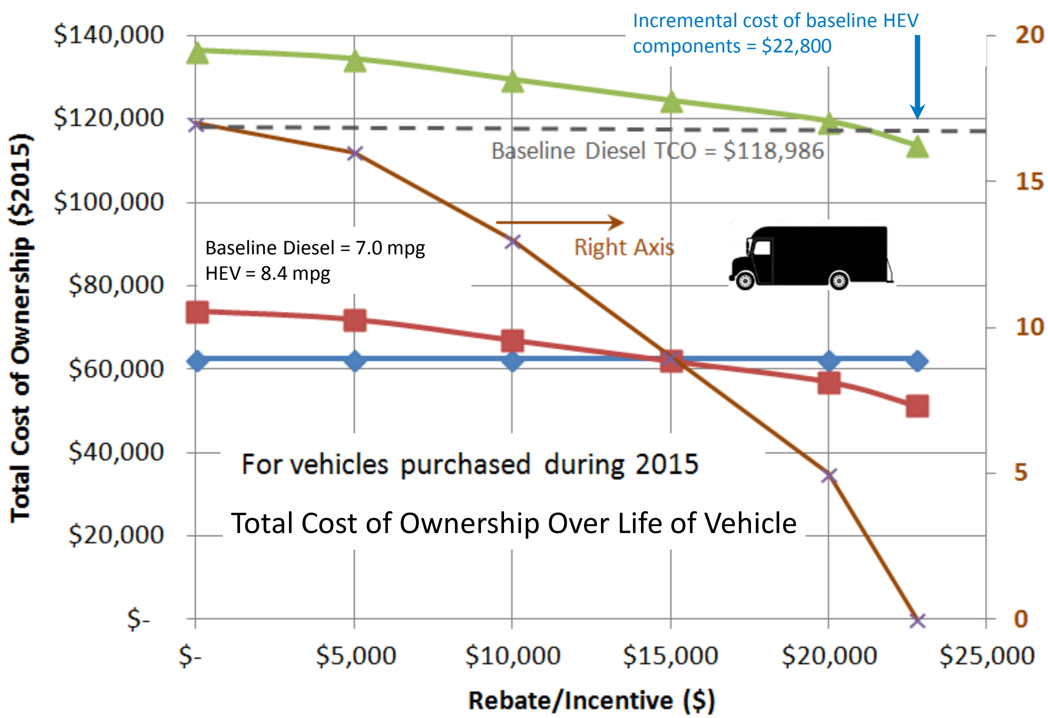
The U.S. Department of Energy, Energy Efficiency & Renewable Energy Division, Alternative Fuels Data Center, maintains an extensive data base of all current laws, incentives, regulations, funding opportunities, and other initiatives related to alternative fuels and vehicles, advanced technologies, or air quality. The data base is accessible through the following link: http://www.afdc.energy.gov/laws/all?state=

For the current analysis, incentives and rebates ranging from $0 to the full incremental cost of the hybrid drive system were evaluated for their impact on total cost of ownership for a MD package delivery vehicle.

Economics of Standardized Batteries

Evaluate various battery standardization strategies using Ricardo TCO model

Impact of **Incentives** on Total Cost of Ownership



OPEX includes: fluids, maintenance parts, maintenance labor, operational overhead

CAPEX Includes: vehicle cost (vehicle+hybrid drive components + battery) minus residual value of (vehicle+hybrid drive components) minus (residual value of battery)

TCO is present value based model; comparisons are shown in 2015 dollars for a range of rebates/incentives.

Incentives have a significant impact on TCO and payback period for the incremental cost of hybrid system components.

Incentives/rebates impact CAPEX, but do not affect OPEX.

Assumptions:			
Parameter	**Units**	**Diesel**	**HEV**
Useful life of vehicle	years	12	12
Battery life	years	n/a	10
Number of battery replacements		n/a	1
Incremental cost of hybrid drive system	$	n/a	$ 22,800
Vehicle purchase price	$	$ 65,000	$ 87,800
Vehicle residual value (includes battery)[1]	$	$ 19,900	$ 24,584
Battery use contract		n/a	Direct ownership
Battery cost to hybrid system supplier	$	n/a	$ 5,400
Battery residual value (80% of orig. capacity)[2]	$	n/a	$ 180
Battery lease payment (per month)	$	n/a	n/a
Diesel fuel price: EIA Reference Value: 2015: $2.66/gallon and 2020: $3.11/gallon			

[1]Vehicle residual value: 30.5% for baseline diesel, 28.0% for baseline HEV

[2]Battery pack value at end of first life = $100/kWh

Total Cost of Ownership Over Life of Vehicle For Vehicles Purchased During 2015				
Incentive Amount	**OPEX**	**CAPEX***	**Total**	**Payback Period (years)**
$ -	$ 62,434	$ 74,033	$ 136,467	17
$ 5,000	$ 62,434	$ 72,033	$ 134,467	16
$ 10,000	$ 62,434	$ 67,033	$ 129,467	13
$ 15,000	$ 62,434	$ 62,033	$ 124,467	9
$ 20,000	$ 62,434	$ 57,033	$ 119,467	5
$ 22,800	$ 62,434	$ 51,233	$ 113,667	0

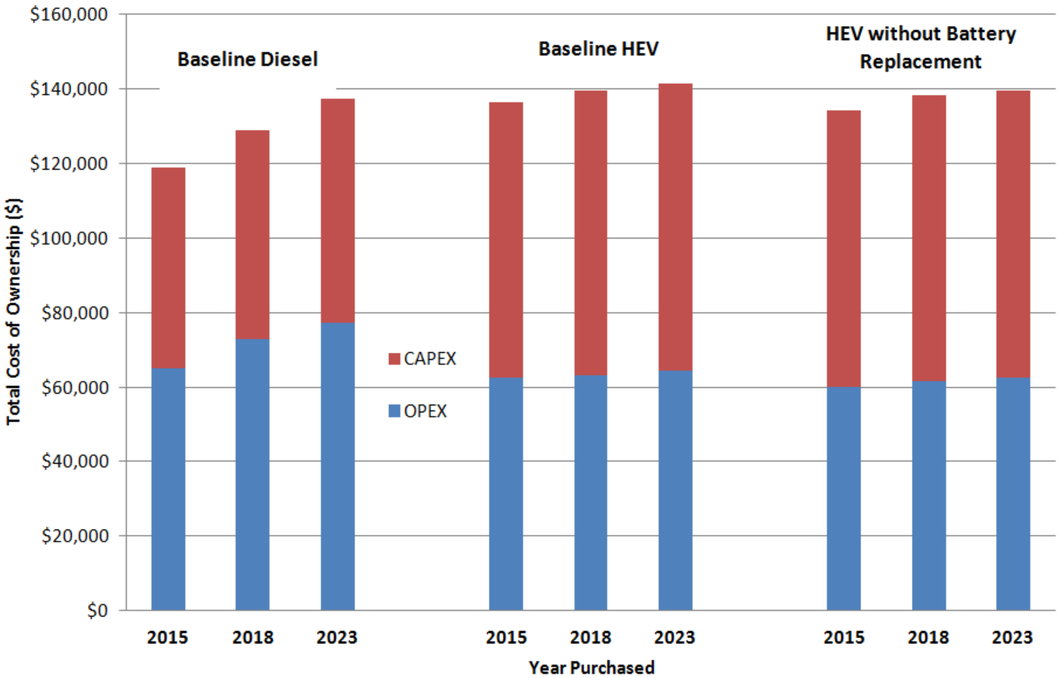
*Includes residual value of vehicle

References: 6, 28, 32, 44, 57, 62, 63, 65, 66, 70

Economics of Standardized Batteries

Evaluate various battery standardization strategies using Ricardo TCO model

Results of Eliminating Battery Replacement on Total Cost of Ownership



TCO is present value based model; comparisons are shown in dollars valued at year of vehicle purchase.

Battery replacement cost is included in operating expenses.

Elimination of battery replacement alone is not sufficient to reduce TCO below that of baseline conventional diesel.

Baseline Diesel = 7.0 mpg
HEV = 8.4 mpg

Total Cost of Ownership Over Life of Vehicle				
Powertrain	Year Purchased	OPEX	CAPEX*	Total
Diesel	2015	$ 65,130	$ 53,856	$ 118,986
	2018	$ 72,694	$ 56,086	$ 128,780
	2023	$ 77,197	$ 60,008	$ 137,205
Baseline HEV	2015	$ 62,434	$ 74,033	$ 136,467
	2018	$ 63,103	$ 76,573	$ 139,676
	2023	$ 64,443	$ 76,937	$ 141,380
HEV without Battery Replacement	2015	$ 60,045	$ 74,033	$ 134,078
	2018	$ 61,627	$ 76,573	$ 138,200
	2023	$ 62,589	$ 76,937	$ 139,526

*Includes residual value of vehicle

OPEX includes: fluids, maintenance parts, maintenance labor, operational overhead

CAPEX Includes: vehicle cost (vehicle+hybrid drive components+battery) minus residual value of (vehicle+hybrid drive components) minus (residual value of battery)

Assumptions:

Parameter	Units	Diesel	HEV
Useful life of vehicle	years	12	12
Battery life	years	n/a	>12
Number of battery replacements		n/a	0
Incremental cost of hybrid drive system	$	n/a	$ 22,800
Vehicle purchase price	$	$ 65,000	$ 87,800
Vehicle residual value (includes battery)[1]	$	$ 19,900	$ 24,584
Battery use contract		n/a	Direct ownership
Battery cost to hybrid system supplier	$	n/a	$ 5,400
Battery residual value (80% of orig. capacity)[2]	$	n/a	$ 180
Battery lease payment (per month)	$	n/a	n/a
Diesel fuel price: EIA Reference Value: 2015: $2.66/gallon and 2020: $3.11/gallon			

[1]Vehicle residual value: 30.5% for baseline diesel, 28.0% for baseline HEV

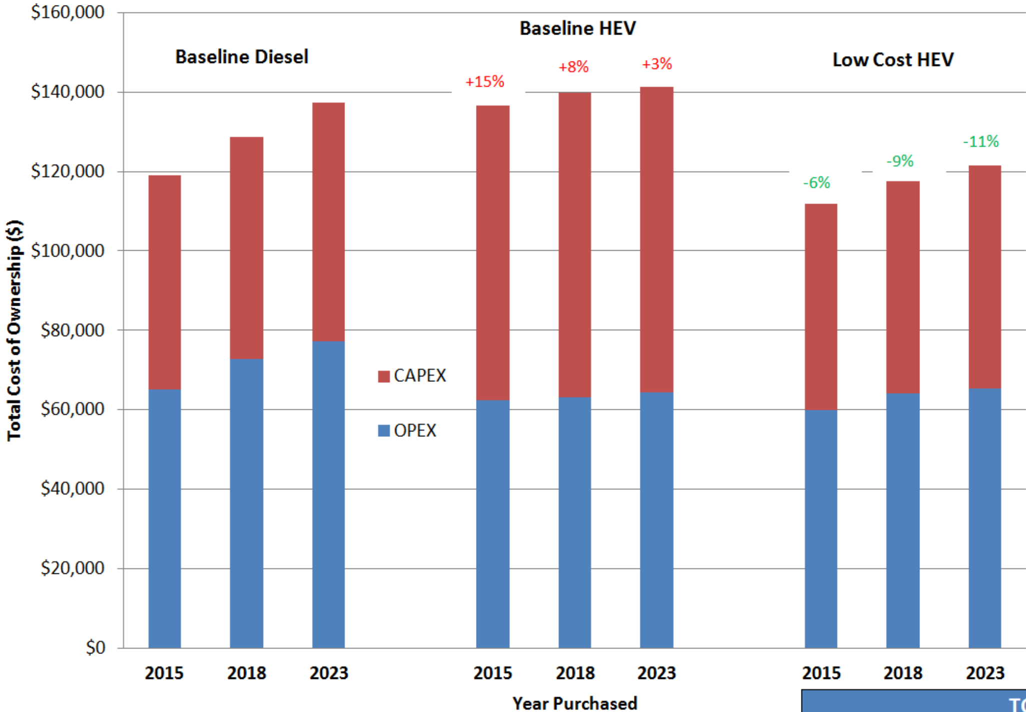
[2]Battery pack value at end of first life = $100/kWh

References: 28, 32, 44, 57, 63, 65, 66

Economics of Standardized Batteries

Evaluate various battery standardization strategies using Ricardo TCO model

Results of Combination of HEV Cost Reductions on Total Cost of Ownership



Baseline Diesel = 7.0 mpg
HEV = 8.4 mpg

TCO is present value based model; comparisons are shown in dollars valued at year of vehicle purchase.

Low-Cost HEV includes:

1) incremental cost of hybrid drive system = $10K
2) battery life greater than useful life of vehicle
3) vehicle residual value = $28K
4) incentive/rebate = $7.5K per vehicle

TCO reduction relative to baseline conventional vehicle ranges from 6% to 11% from 2015 to 2023.

OPEX includes: fluids, maintenance parts, maintenance labor, operational overhead

CAPEX Includes: vehicle cost (vehicle+hybrid drive components+battery) minus residual value of (vehicle+hybrid drive components) minus (residual value of battery)

Total Cost of Ownership Over Life of Vehicle

Powertrain	Year Purchased	OPEX	CAPEX*	Total	Change Relative to Diesel (%)
Diesel	2015	$ 65,130	$ 53,856	$ 118,986	
	2018	$ 72,694	$ 56,086	$ 128,780	
	2023	$ 77,197	$ 60,008	$ 137,205	
Baseline HEV	2015	$ 62,434	$ 74,033	$ 136,467	15%
	2018	$ 63,103	$ 76,573	$ 139,676	8%
	2023	$ 64,443	$ 76,937	$ 141,380	3%
Low Cost HEV	2015	$ 60,045	$ 51,820	$ 111,865	-6%
	2018	$ 64,127	$ 53,382	$ 117,509	-9%
	2023	$ 65,290	$ 56,245	$ 121,535	-11%

*Includes residual value of vehicle

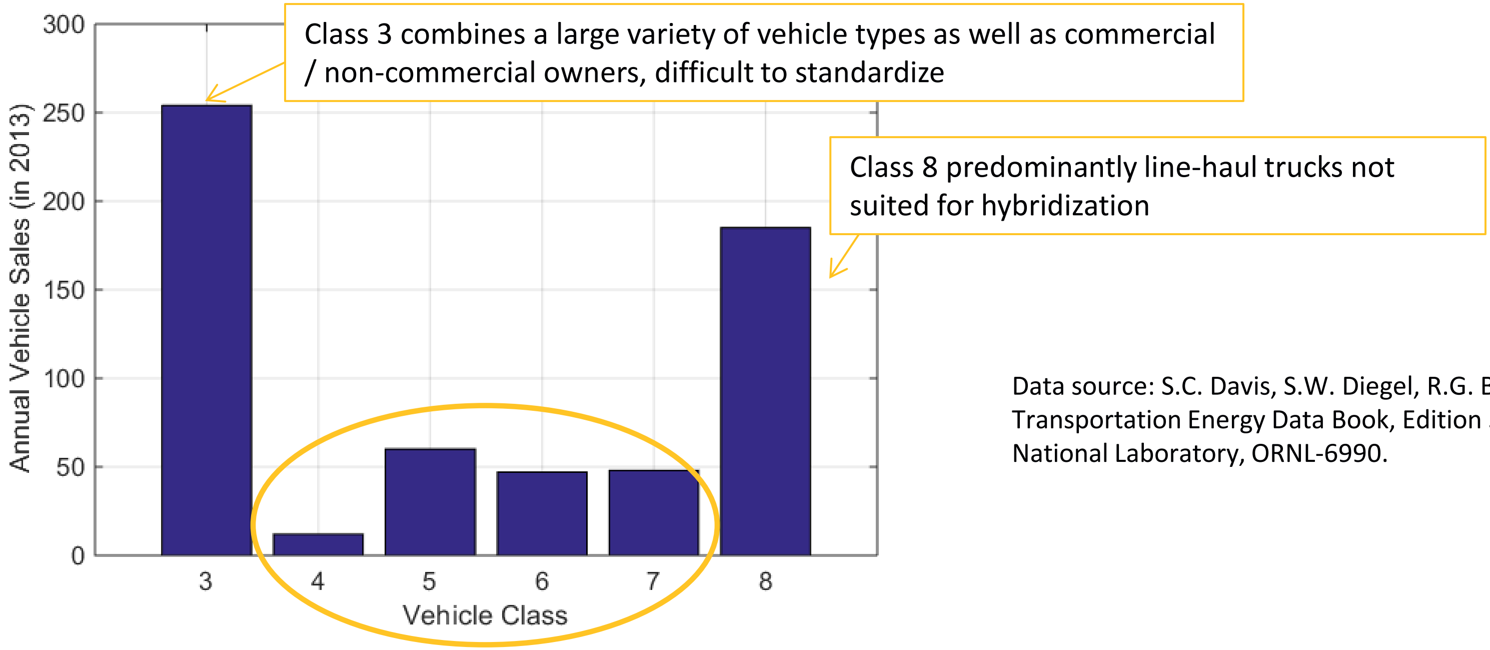
TCO Input Parameters: Combination of HEV Cost Reductions

Parameter	Units	Diesel	Baseline HEV	Low Cost HEV
Useful life of vehicle	years	12	12	12
Battery life	years	n/a	10	>12
Number of battery replacements during vehicle useful life		n/a	1	0
Incremental cost of hybrid drive system	$	n/a	$ 22,800	$ 10,000
Vehicle purchase price	$	$ 65,000	$ 87,800	$ 75,000
Vehicle residual value (includes battery)	$	$ 19,900	$ 24,584	$ 28,000
Battery use contract		n/a	Direct Ownership	Direct Ownership
Battery cost to hybrid system supplier	$	n/a	$ 5,400	$ 1,800
Battery residual value (80% of orig. capacity)	$	n/a	$ 180	$ 540
Incentive/rebate	$	n/a	$ 3,000.0	$ 7,500.0
Diesel fuel price: EIA Reference Value: 2015: $2.66/gallon and 2020: $3.11/gallon				

References: 28, 32, 44, 57, 63, 65, 66

Battery Standardization Across MD Vehicle Classes

- **What vehicle classes might be combined to increase annual production volume of a standardized battery to >10k batteries per year where significant cost reduction can be achieved?**



Data source: S.C. Davis, S.W. Diegel, R.G. Boundy, Transportation Energy Data Book, Edition 33. Oak Ridge National Laboratory, ORNL-6990.

- **Recommend to standardize battery requirements across classes 4-7**
  - 150k vehicles/year total
    - Estimate 64% of these vehicles have single purpose vocations suited for hybridization
  - Achieving battery production of 10k batteries/year requires that 7% of the 150k vehicles/year total be hybridized
    - 7% is a reasonable penetration rate to expect. It is only modestly greater than today's penetration rate of HEVs in the U.S. Class 5 parcel delivery fleet

Contents

Conclusions – 1 of 4

- Incremental Costs of Hybrid Electric Drive Systems Varies by Manufacturer and Vehicle Type and ranges from $12,000 to $35,000 for Class 5 delivery vehicles relative to a conventional MD vehicle
- US New Vehicle Registrations of Class 4-6 HEV Step Vans are Projected to be Less than ½ of all US Step Van New Vehicle Registrations through 2020 and are expected to range from 1k - 4k per year
  - At 1k batteries/year, no value to standardization
  - At 5k batteries/year, only 2% value to standardization (communications interface)
  - At 10k batteries/year, there is 7% cost benefit with standardization (Standardizing module housing & bus bars are most beneficial)
  - At 50k and 100k batteries/year there is a 13% to 16% cost benefit to standardization
- Only one of the identified standardization strategies resulted in cost decreases at low production volumes.
- The primary cost impact of standardization is to extend the range of applications and thus increase production volumes.
- There is a steep decrease in per battery price for volumes between 1k and 10k per year (50% reduction).
- The potential Class 5 MD HEV market is not large enough to reach the benefit of 10k batteries/year
- Greater value may be obtained by applying strategies across a wider range of products such as other medium-duty vehicle platforms, full electric vehicles, and light-duty HEV
- The ideal battery for Class 5 MD delivery trucks
  - Has approximately 45 kW peak power and 1.8 kWh energy (1.5 to 2.5 acceptable)
  - Uses 5Ah to 7.5Ah Li-ion cells with peak power to energy ratio of 25 hr^{-1}
  - Uses forced air thermal management
  - Would be produced at annual production volumes greater than 10,000 units/year

Conclusions – 2 of 4

- Leasing looks better than direct ownership over a short 3 year time horizon
  - Shifts expenses from capital to operating expenses, favorable in the short term, but always increases total cost of ownership over the long term
  - May be attractive to some fleet operators with constraints on capital expenses for purchasing new vehicles
  - Bottom limit for battery lease price to fleet operator is $177/month
- Strongest factors affecting total cost of ownership and payback period are
  - Fuel prices
  - Annual mileage driven
  - Incremental cost of HEV
  - Incremental fuel savings benefit of HEV
- Compared to the baseline scenario with ~15 year payback, a low-cost MD HEV scenario was identified with less than 1 year payback period by modifying the following baseline assumptions
  - HEV incremental cost reduced from $22,800 to $10,000 per vehicle
  - Government incentives increased from $3,000 to $7,500 per vehicle
  - Battery life greater than the life of the vehicle, increased from 10 years to greater than 12 years
  - Vehicle residual value at end of 12 years increased from $24k to $28k

Conclusions – 3 of 4

- Key recommendations:
  - Continue to focus efforts on reducing incremental cost of HEV technology
    - Battery standardization is one pathway
    - Cost reductions in motor, controller, and power electronics costs will also be required
  - Improve HEV incremental benefit beyond present 17% fuel savings (dependent on drive cycle)
    - Light duty HEVs achieve 25-40% incremental fuel savings (though this is for gasoline, not diesel HEVs)
    - Improve efficiency of energy recovery during deceleration events
    - Evaluation of powertrain performance requirements over a wider range of vehicle vocations and duty cycles and search for common components.
    - Cost impact of downsizing diesel engine (including engine availability)
  - Analysis of TCO across a range of powertrain configurations including PHEVs and EVs with the goal of defining the minimum total cost of ownership.

Conclusions – 4 of 4

- Suggested next steps:
  - Expand analysis beyond Class 5 delivery vehicles to Class 4-7 vehicles and additional vocations
  - Expand design space beyond HEV to also include PHEV and EV
  - Perform analysis of HEV powertrain with goal of minimizing cost while maintaining or improving performance. This may include the use of COTS components.
  - Employ TCO model to investigate impact of a wider range of parameters on total cost of ownership (e.g. maintenance cost reduction, use of synthetic lubricants and fluids, battery second life application impacts on residual value).
  - Identify common battery requirements across Class 4-7 PHEV, EV, HEV vehicle platforms in order to increase MD battery annual sales to greater than 10,000 batteries per year
    - Total Class 4-7 market segment is 150k vehicle per year annual sales, 10k HEVs per year is a reasonable 7% of this segment
  - Extend analysis to include other powertrain components for which a cost reduction might result from a broader range of applications.

Contents

References

1. Lipman, T.E., Williams, B.D., Strategies for Transportation Electric Fuel Implementation in California: Overcoming Battery First-Cost Hurdles, California Energy Commission, Public Interest Research Program, Report Number CEC-500-2009-091, February 2010.
2. International Federation of Accountants, Project Appraisal Using Discounted Cash Flow, New York, June 2008.
3. Thornton, M., et. al., Data Collection, Testing, and Analysis of Hybrid Electric Trucks and Buses Operating in California Fleets, NREL Technical Report NREL/TP-5400-62009, June 2015.
4. National Renewable Energy Laboratory, Milestone Report, Milestone Title “Create Standardization Strategies and Calculate Costs”, for DOE-NREL AOP Project with WBS 1.1.2.409, Battery Ownership Model, Medium Duty HEV Battery Leasing and Standardization, May 29, 2015.
5. Lammert, M., and Walkowicz, K., Eighteen-Month Final Evaluation of UPS Second Generation Diesel Hybrid-Electric Delivery Vans, National Renewable Energy Laboratory, Technical Report NREL/TP-5400-55658, September 2012.
6. Paul, J., Bogen, M, Liss, J, Holmes, J, Sohnen. 2014. The Market Impact of Standardized Design in PEV Commercial Battery Pack Purchase and Disposal. California Energy Commission. Public Interest Energy Research (PIER) Project Number CEC-PIR-12-005, Publication Number: Expected Publication Date: September 2015.
7. Wilson, K., Automotive Industry Standards for the Safe Use of Lithium-Ion Battery Packs, SAE International, NTSB Lithium Ion Battery Safety Forum, 11 April 2013.
8. American National Standards Institute, Progress Report: Standardization Roadmap for Electric Vehicles, Version 2.0, November 2014.
9. American National Standards Institute, ANSI EVSP (Electric Vehicle Standards Panel) Roadmap Standards Compendium, Spreadsheet Format, Updated November 2014.
10. Timmons, A., Development of ISO/IEC PAS 16898:2012: Electrically Propelled Road Vehicles – Dimensions and Designation of Secondary Lithium-Ion Cells, Society of Automotive Engineers, Electric Vehicle Battery Cell Size Standardization Symposium, 29 October 2015.

References

11. Maguire, N., Accelerating Technology Adoption through Standardization, Society of Automotive Engineers, Electric Vehicle Battery Cell Size Standardization Symposium, 29 October 2015.
12. Nelson, P.A., Gallagher, K.G., Bloom, I., and Dees, D.W., Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles, Second Edition, Chemical Sciences and Engineering Division, Argonne National Laboratory, Report ANL-12/55, December 2012.
13. Interview: Argonne National Laboratory, Paul Nelson and Shabbir Ahmed, 18 July 2014.
14. Muller, B., and Meyer, G., Electric Vehicle Systems Architecture and Standardization Needs, *Reports of the PPP European Green Vehicles Initiative*, Lecture Notes in Mobility, Heidelberg, Springer Cham, 2015.
15. International Standards Organization, Publicly Available Specification (PAS), ISO/PAS 16898 (2012), Electrically Propelled Road Vehicles – Dimensions and Designation of Secondary Lithium-Ion Cells.
16. Warner, J., Energy Storage System Integration of Common Cell Formats, Society of Automotive Engineers, Electric Vehicle Battery Cell Size Standardization Symposium, 29 October 2015.
17. Lauinger, J., Factors Driving Size (VDA & Non-Standard) of Metal Containers for Li-Ion Cells, Society of Automotive Engineers, Electric Vehicle Battery Cell Size Standardization Symposium, 29 October 2015.
18. Namiki, F., et. al., Lithium-Ion Battery for HEVs, PHEVs, and EVs, *Hitachi Review*, Vol. 63, No. 2, 2014.
19. "Hitachi Automotive Systems Supplying 5 kW/kg High-Power Density Prismatic Li-Ion Cells for MY 2016 Malibu Hybrid", *Green Car Congress*, 20 May 2015, http://www.greencarcongress.com/2015/05/20150520-hitachi.html
20. Shibata, T., et. al., Energy Storage Solutions Utilizing Lithium-Ion Batteries, *Hitachi Review*, 2011, http://www.hitachi.com/rev/pdf/2011/r2011_01_102.pdf

References

21. Thiyagarajan, V., and Puhan, S., Monitoring Stack of Batteries for EV through Controller Area Network Gateway, *International Journal of Engineering Sciences & Emerging Technologies*, Vol. 4, Issue 1, Dec. 2012, pages 100-107.
22. Kim, T., Qiao, W., and Qu, L., Power Electronics-Enabled Self-X Multicell Batteries: A Design toward Smart Batteries, *IEEE Transactions on Power Electronics*, Vol. 27, No. 11, Nov., 2012, pages 4723-4733.
23. Alfano, D., Galvanic Isolation Enhances EV/HEV Safety, Performance, and Reliability, Silicon Labs, Accessed 18 September 2015, http://components-asiapac.arrow.com/file_system/intranet/NEWS/TIME/id_90/Silicon_Labs_feb2013.pdf
24. Anderson, D.L., An Evaluation of Current and Future Costs for Lithium-Ion Batteries for Use in Electrified Vehicle Powertrains, Nicholas School of the Environment, Duke University, May 2009.
25. Sakti, A., et. al., A Techno-Economic Analysis and Optimization of Li-Ion Batteries for Light-Duty Passenger Vehicle Electrification, Journal of Power Sources, 273, (2015) pages 966-980.
26. Julien, C.M., et. al., Comparative Issues of Cathode Materials for Lithium-Ion Batteries, *Inorganics*, Vol. 2, 2014, Pages 132-154.
27. Higashimoto, K., et. al., Automotive Lithium-Ion Batteries, *Hitachi Review*, Vol. 1, 2011, Pages 17-21.
28. Interview with Isobel Sheldon, Business Manager, Hybrid and Electronic Systems, Ricardo UK Ltd, Cambridge Technical Centre, Cambridge, 18 September 2015.
29. Bubna, P., Munday, A., Paul, J., and Wiseman, M., Reducing Automotive CAPEX Barriers through Design, Manufacturing, and Materials, Final Report, Volume 2, 6 September 2015.
30. Nelson, P., Gallagher, K., and Bloom, I., BatPaC, Battery Performance and Cost Model, Argonne National Laboratory, Version 2.0, 2014.

References

31. Clinton, P., Commercial Truck Registrations, *Work Truck Magazine*, 3 September 2015.
32. Americas Commercial Transportation Research Company, LLC., *State of the Industry: Classes 5-8 Vehicles*, May and Year-to-Date Data, June 19, 2013.
33. Lyden, S., The Latest Developments in Hybrid-Electric Medium-Duty Trucks, *TruckingInfo*, March 2014.
34. Cornils, H., Hybrid Solutions for MD Commercial Vehicles, *ERC Symposium*, University of Wisconsin, June 10, 2009.
35. Busdiecker, M., Technology Potential of Commercial Vehicle Transmissions, Heavy Duty Vehicle Efficiency Technical Workshop, San Francisco, October 22, 2013.
36. UPS: A Pioneer in Hybrid-Electric Vehicles, *BlueGreen Alliance*, http://www.bluegreenalliance.com, accessed 23 September 2015
37. Scheer, R., and Moss, D., The Greening of UPS and FedEx, *The Ridgefield (Connecticut) Press*, September 19, 2013.
38. United Parcel Service Press Release, UPS Expands Hybrid Electric Fleet, September 9, 2015, https://www.pressroom.ups.com, accessed 23 September 2015.
39. California Air Resources Board, Hybrid Truck & Bus Voucher Incentive Project (HVIP), https://www.californiahvip.org/about-the-project, accessed 23 September 2015.
40. Thornton, M., *et. al.*, Data Collection, Testing, and Analysis of Hybrid Electric Trucks and Buses Operating in California Fleets, Final Report, National Renewable Energy Laboratory, Technical Report NREL/TP-5400-62009, June 2015.
41. Parish, R., *et. al.*, *Demand Assessment of First-Mover Hybrid and Electric Truck Fleets*, CALSTART High Efficiency Truck Forum (HTUF), October 2012.

References

42. U.S. Department of Energy, Energy Efficiency & Renewable Energy, Vehicle Technologies Program, Project Overview: United Parcel Service's Second-Generation Hybrid-Electric Delivery Vans, November 2011.
43. California Air Resources Board, Hybrid Truck & Bus Voucher Incentive Project (HVIP), Making the Case for Hybrid and Electric Trucks and Buses, https://www.californiahvip.org/making-the-case, Accessed 12 September 2015.
44. Interviews with Vehicle OEMs (step vans), battery manufacturers (lithium-ion), government vehicle purchase incentive program administrators, and hybrid-electric drive system component manufacturers and suppliers 2-28 September 2015.
45. California Air Resources Board, Hybrid Truck & Bus Voucher Incentive Project (HVIP), Hino Motors Model 195h Delivery Truck with Parallel Hybrid System, Package Delivery, California HVIP Voucher Amount, https://www.californiahvip.org/docs/HVIP_Year4_EligibleVehicles.pdf, accessed 17 September 2015.
46. Ramroth, L., Gonder, J., and Brooker, A., Assessing the Battery Cost at which Plug-In Hybrid Medium-Duty Parcel Delivery Vehicles become Cost-Effective, prepared by National Renewable Energy Laboratory, Society of Automotive Engineers, SAE 2013-01-1450, 8 April 2013.
47. National Renewable Energy Laboratory, Transportation Research & Energy Storage, Battery Lifetime Analysis and Simulation Tool Suite, http://www.nrel.gov/transportation/energystorage/blast.html, accessed 5 September 2015.
48. Neubauer, J. and Wood, E., The Impact of Range Anxiety and Home, Workplace, and Public Charging Infrastructure on Simulated Battery Electric Vehicle Lifetime Utility, *Journal of Power Sources*, Volume 257, 1 July 2014, Pages 12–20.

References

49. Brooker, A., Gonder, J., Wang, L., Wood, E., Lopp, S., and Ramroth, L., FASTSim: A Model to Estimate Vehicle Efficiency, Cost, and Performance, Society of Automotive Engineers, Paper Number 2015-01-0973, 14 April 2015.
50. National Renewable Energy Laboratory, DRIVE: Drive-Cycle Rapid Investigation, Visualization and Evaluation Analysis Tool, http://www.nrel.gov/transportation/drive.html, accessed 11 September 2015.
51. Hu, J., Lithium-Ion Battery Manufacturing, NSF Energy Manufacturing Workshop, Georgia Institute of Technology, Atlanta, Georgia, January 2011.
52. UPS Battery Center, Thin-Film Rechargeable Lithium-Ion Battery, Oak Ridge National Laboratory, http://www.upsbatterycenter.com/blog/thin-film-rechargeable-lithium-ion-battery/, 19 May 2014.
53. Hassan, F., Batmaz, R., Li, J., Wang, X., Xiao, X., Yu, A., and Chen, Z., Evidence of covalent synergy in silicon-sulfur-graphene yielding highly efficient and long-life lithium ion batteries, *Nature Communications*, Vol. 6, Article 8597, 11 February 2015.
54. Croft, J., 787 Batteries OK to Fly with ‘Burst Discs’, *Aviation Week*, 25 June 2013.
55. Low Voltage Disconnect Installation and Users Manual, Lite-Power Solutions, http://www.elitepowersolutions.com/docs/LVD.pdf, 2015
56. United States Council on Automotive Research (USCAR), Energy Storage System Goals, http://www.uscar.org/guest/article_view.php?articles_id=85, December 2015.
57. Eaton Corporation, *Eaton Hybrid Drive Systems Troubleshooting Guide*, October 2015.
58. Gallagher, K., Dees, D., and Nelson, P., PHEV Battery Cost Assessment, Thermal Management, US Department of Energy, Project ID ES111, Vehicle Technologies Program, Annual Merit Review and Peer Evaluation Meeting, Washington, DC, 14-18 May 2012.

References

59. *Electric & Hybrid Vehicle Technology International,* Thermal Interface Inroads, July 2015, page 217.
60. *Electric & Hybrid Vehicle Technology International,* Battery Cooling Solutions, July 2015, page 209.
61. Cunningham, B., Automotive Li-Ion Battery Cooling Requirements, U.S. Department of Energy, Hybrid and Electric Systems Team, Vehicle Technologies Program, 21 March 2012.
62. U.S. Energy Information Administration, *Monthly Energy Review*, November 2014, DOE/EIA-0035(2014/11). Projections: AEO2015 National Energy Modeling System, runs REF2015.D021915A, LOWPRICE.D021915A, and HIGHPRICE.D021915A.
63. Neubauer, J., Pesaran, A., FY15 Milestone: Medium-Duty Hybrid Electric Vehicle Battery Leasing Scoping Analysis, December 2014, NREL-DOE Milestone Report, DOE-NREL AOP WBS 1.1.2.409.
64. *Trading Economics*, United States Corporate Tax Rate 2000-2015, http://www.tradingeconomics.com/united-states/corporate-tax-rate
65. Neubauer, J., Is Leasing Better than Buying? Bottom-Up Lease Price Calculations, Vehicle Performance Requirements, Medium-Duty Hybrid Electric Vehicle Battery Leasing Scoping Analysis, DOE-NREL AOP WBS 1.1.2.409, March 2015.
66. Neubauer, J., and Kelly, K., Battery Ownership Model: Medium Duty HEV Battery Leasing and Standardization, May 2015 Milestone, Create Standardization Strategies and Calculate Costs, DOE-NREL AOP WBS 1.1.2.409.
67. New York University, Stern School of Business, Operating versus Capital Leases, http://pages.stern.nyu.edu/~adamodar/New_Home_Page/AccPrimer/lease.htm

References

68. McConnell, J., and Schallheim, J., Valuation of Asset Leasing Contracts, *Journal of Financial Economics*, Vol. 12, 1983, pages 237-261.
69. EuClaire, M., Joining Forces, a Look at the Work Being Done by OEMs and Component Suppliers to Bring Hydraulic and Electric Hybrid Technology to On-Highway Trucks, *OEM Off-Highway*, March 2008, http://www.eaton.com/ecm/groups/public/@pub/@eaton/@hyd/documents/content/ct_144836.pdf
70. U.S. Department of Energy, Energy Efficiency & Renewable Energy Division, Alternative Fuels Data Center, *Laws and Incentives: State Incentives, Utility/Private Incentives, Laws and Regulations*, http://www.afdc.energy.gov/laws/all?state=
71. S.C. Davis, S.W. Diegel, R.G. Boundy, Transportation Energy Data Book, Edition 33, Oak Ridge National Laboratory, ORNL-6990.