THE COST OF VEHICLE ELECTRIFICATION: A LITERATURE REVIEW

Lynette Cheah and John Heywood, Sloan Automotive Laboratory, Massachusetts Institute of Technology

The Electrification of the Transportation System: Issues and Opportunities

MIT Energy Initiative Symposium, April 8, 2010, Cambridge, Massachusetts.

The objective of this review is to assess the cost of manufacturing hybrid electric vehicles (HEVs, PHEVs) in the U.S. These vehicles are expected to be added to automakers' vehicle portfolios as they strive to meet the 2016 Corporate Average Fuel Economy (CAFE) mandate. These costs are intended to be compared against the cost of other approaches to reducing vehicle fuel consumption, e.g. vehicle lightweighting. This cost comparison will later be used to assess various CAFE compliance strategies.

Only more current references from 2005 onwards have been included in this review. Given the rapid rate of technology advancements in energy storage systems, cost estimates prior to 2005 have been excluded.

We are interested in the additional cost of the overall hybrid system over a comparable conventional vehicle utilizing an internal combustion engine. This should also account for the cost reduction in using a downsized engine and transmission in PHEVs.

Most of the literature only report the cost of manufacturing lithium-ion (Li-ion) battery systems for hybrid vehicles in terms of dollars per kilowatt-hour of energy storage ($/kWh). The battery is the most expensive component in an electric vehicle. Around 80% of the cost of a PHEV-40's drive system is due to the battery pack. [F&S 2009a] Other components include the electric motor, inverter, power control unit, and generator.

The battery's cost is not only due to the material, but also capital investment in battery manufacturing. This cost depends much on the battery production volume, and less so on the lithium chemistry. [Barnett 2009] The figures are expected to decline once batteries are mass produced.

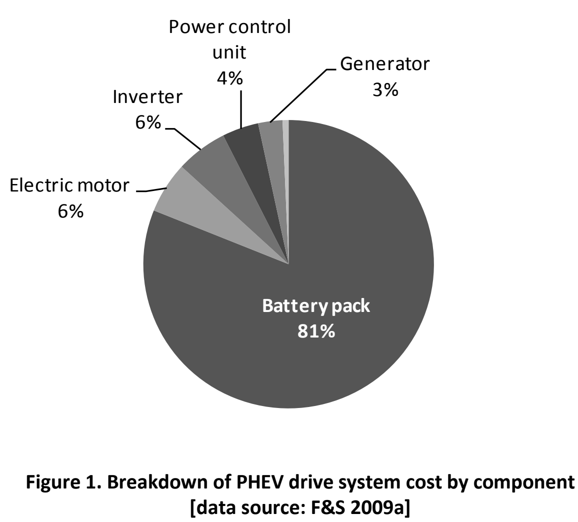

Figure 1. Breakdown of PHEV drive system cost by component [data source: F&S 2009a]

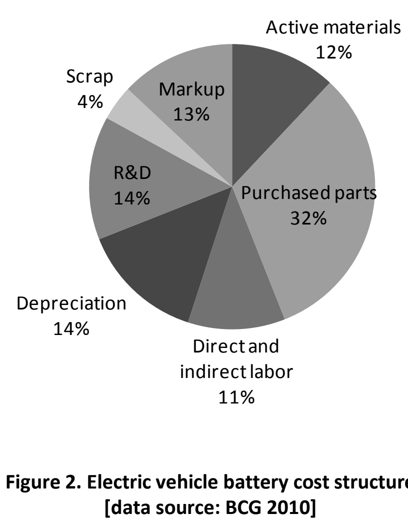

Figure 2. Electric vehicle battery cost structure [data source: BCG 2010]

The incremental vehicle system cost and battery cost numbers found in the literature are summarized and plotted in the next few tables and figures below. Estimates for both categories vary widely. Within the next 5-10 years (2015-2020), PHEVs are projected to cost an additional $6,000-16,000 more than a conventional IC vehicle. Even today, battery cost estimates vary widely from $260-$1,300/kWh. None of the battery cost estimates meet the U.S. Advanced Battery Consortium's goal of $200-300/kWh by 2016. It is noted that some of the estimates are likely to have been cross-referenced, so greater frequency of estimates need not necessarily indicate greater accuracy.

Reference	Vehicle type	Year	Cost premium over conventional vehicle[1]
Simpson 2006 (NREL)			Retail price increase:
	PHEV10	"Long-term"	+$6,300
	PHEV40		+$11,450
Bandivadekar et al 2008 (MIT)	HEV car	2007	+$3,500
	HEV light truck	2007	+$4,500
	HEV car	2035	+$1,800
	HEV light truck	2035	+$2,300
	PHEV30 car	2035	+$4,200
	PHEV30 light truck	2035	+$5,900
Frost & Sullivan 2009a			Cost of EV drive system:
	PHEV40	2009	$11,300-14,800
	BEV100	2009	$16,900-22,300
Plotkin & Singh 2009 (Argonne)[2]	HEV car	2015	+$1,450
	PHEV10 car	2015	+$2,350
	PHEV40 car	2015	+$6,250
	HEV car	2030	+$1,110
	PHEV10 car	2030	+$1,770
	PHEV40 car	2030	+$4,370
EPA/NHSTA 2009	HEV car	2016	+$2,740
	PHEV20 car	2016	+$16,140-16,220
	HEV light truck	2016	+$3,280-3,460
	PHEV20 light truck	2016	+$14,590
NRC 2010	PHEV10	2015	+$5,200
	PHEV40	2015	+$14,200
	PHEV10	2020	+$4,500
	PHEV40	2020	+$12,200

Table 1. Hybrid/electric vehicle system cost estimates from literature. All are production cost, unless otherwise stated.

[1] To convert to retail price equivalents, multiplication factors of 1.4-1.5 have been used in the literature.

[2] Cites Kromer, M. and J. Heywood, 2007. Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet, Laboratory for Energy and the Environment, Massachusetts Institute of Technology, LFEE-2007-03 RP, co-authors of Bandivadekar et al 2008.

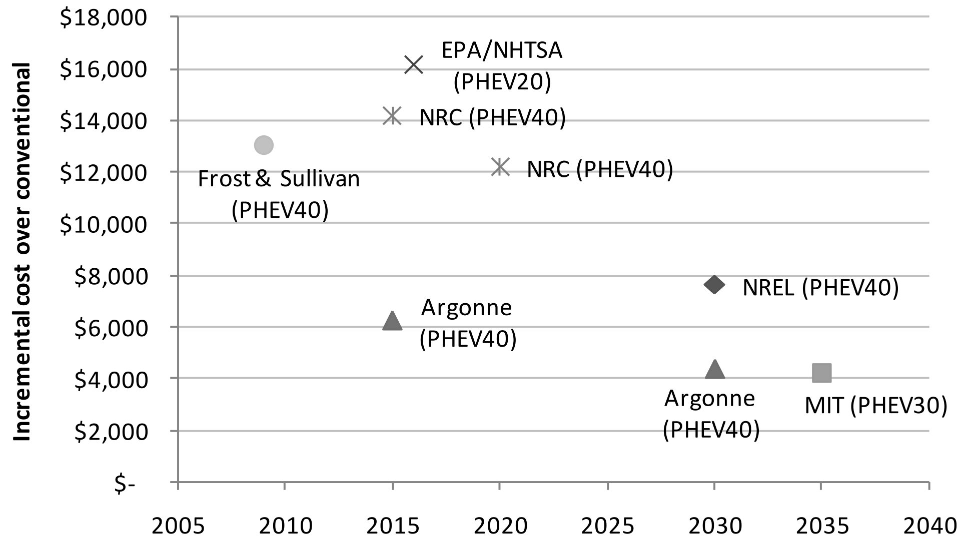

Figure 3. Estimates of plugin hybrid vehicles' incremental manufacturing cost over conventional vehicles

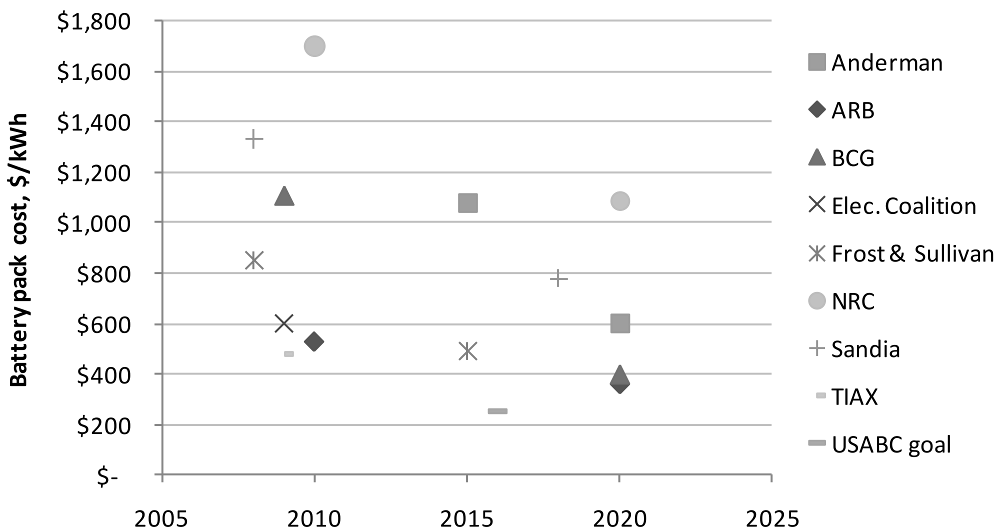

Figure 4. Estimates of PHEV Li-ion battery pack cost. Only mid-points of ranges, if any, are plotted.

Reference	Li-ion battery application	Year, or timeframe indication	Cost[3]
USABC (via Pesaran et al 2007)	For PHEV10	2016 goals, for reference only	$300/kWh, or $1,700
	For PHEV40		$200/kWh, or $3,400
Pesaran et al 2007 (NREL)[4]	High energy batteries	2007	$800-1,000/kWh
Kalhammer et al 2007 (for ARB)	For HEV	Low volumes (500MWh/yr)	$800/kWh, or $2,400
		High volumes (2,500MWh/yr)	$550/kWh, or $1700
	For PHEV10	Low volumes (500MWh/yr)	$575/kWh, or $3,300
		High volumes (2,500MWh/yr)	$400/kWh, or $2,200
	For PHEV40	Low volumes (500MWh/yr)	$380/kWh, or $7,100
		High volumes (2,500MWh/yr)	$260/kWh, or $4,900
Ton et al 2008 (Sandia)	Li-ion battery	2008	$1,333/kWh
		2018	$780/kWh
ARB 2009[5]	For PHEV10	Low volumes (500MWh/yr)	$480-600/kWh
		High volumes (2,500MWh/yr)	$340-400/kWh
	For PHEV40	Low volumes (500MWh/yr)	$450-560/kWh
		High volumes (2,500MWh/yr)	$320-370/kWh
Frost & Sullivan 2009b	Li-ion battery	2008	$700-1,000/kWh
		2015	$470-510/kWh
Electrification Coalition 2009	Li-ion battery	2009	$600/kWh
Barnett 2009 (TIAX)	Li-ion battery	2009	$260-700/kWh
NRC 2010	For PHEV10	2010	$1,650/kWh
		2020	$1,050/kWh
	For PHEV40	2010	$1,750/kWh
		2020	$1,120/kWh
BCG 2010	Li-Ni-Co-Al (NCA) battery	2009	$990-1,220/kWh
		2020	$360-440/kWh
Anderman 2010	For PHEVs	2015	$900-1,260/kWh
		2018-2020	$675-900/kWh
	For EVs	2015	$500-700/kWh
		2018-2020	$375-500/kWh

Table 2. Battery cost estimates from literature

[3] Assuming that the energy requirement for a PHEV-40 is 16 kWh, the cost of the battery can be calculated accordingly.

[4] Collaborates with TIAX, LLC.

[5] This is a review and update of Kalhammer et al 2007.

REFERENCES

Air Resource Board, State of California (2009) Summary of Staff's Preliminary Assessment of the Need for Revisions to the Zero Emission Vehicle Regulation, Attachment A: Status of ZEV Technology Commercialization (Technical Support Document), November 25, 2009.

Anderman, M. (2010) Feedback on ARB's Zero-Emission Vehicle Staff Technical Report of 11/25/2009 including attachment A: Status of EV Technology Commercialization, Advanced Automotive Batteries, January 6, 2010

Bandivadekar, A., K. Bodek, L. Cheah, C. Evans, T. Groode, J. Heywood, E. Kasseris, M. Kromer, M. Weiss, (2008) On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions, MIT Laboratory for Energy and the Environment, Cambridge, Massachusetts.

Barnett, B. et al (2009) PHEV battery cost assessment (slides), TIAX LLC, es_02_barnett, May 19, 2009.

Boston Consulting Group (2010) Batteries for Electric Cars – Challenges, Opportunities, and the Outlook to 2020

Electrification Coalition (2009) Electrification Roadmap – Revolutionizing Transportation and Achieving Energy Security, November 2009

U.S. Environmental Protection Agency and the National Highway Traffic Safety Administration (2009) Draft Joint Technical Support Document – Proposed Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards, EPA-420-D-09-901, September 2009

Frost & Sullivan (2009a) Strategic Analysis of North American Passenger Electric Vehicle Market, N598-18, May 2009

Frost & Sullivan (2009b) World Hybrid Electric and Electric Vehicle Lithium-ion Battery Market, N6BF-27, Sep 2009

Kalhammer, F., B. Kopf, D. Swan, V. Roan, M. Walsh (2007) Status and Prospects for Zero Emissions Vehicle Technology, Report of the ARB Independent Expert Panel, Prepared for State of California Air Resources Board, April 13, 2007.

National Research Council (2010) Transitions to Alternative Transportation Technologies--Plug-in Hybrid Electric Vehicles.

Pesaran, A., T. Markel, H. Tataria, D. Howell (2007) Battery Requirements for Plug-In Hybrid Electric Vehicles – Analysis and Rationale, Presented at the 23rd International Electric Vehicle Symposium (EVS-23) Anaheim, California, December 2-5, 2007, NREL/CP-540-42240.

Plotkin, S., M. Singh (2009) Multi-Path Transportation Futures Study: Vehicle Characterization and Scenario Analyses, Energy Systems Division, Argonne National Laboratory, ANL/ESD/09-5, July 22, 2009.

Simpson, A. (2006) Cost-benefit analysis of plug-in hybrid electric vehicle technology, Presented at the 22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition (EVS-22), Yokohama, Japan, October 23–28, 2006, NREL/CP-540-40485, November 2006

Ton, D., C. Hanley, G. Peek, J. Boyes (2008) Solar Energy Grid Integration Systems –Energy Storage (SEGIS-ES), Sandia Report SAND2008-4247, July 2008