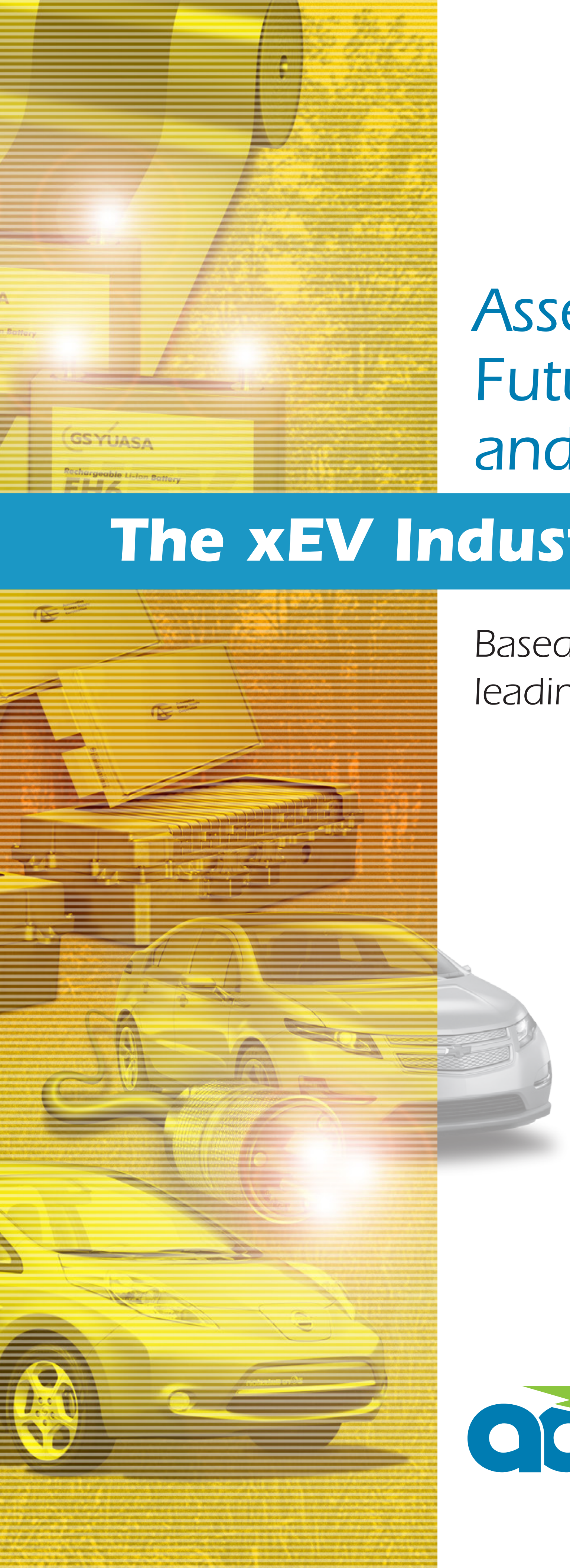

Assessing the Future of Hybrid and Electric Vehicles:

The xEV Industry Insider Report

Based on private onsite interviews with leading technologists and executives

advanced
automotive
batteries

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Executive Summary

1. xEV Vehicle Technology

a. Market Drivers

The drive to reduce fuel consumption in the transportation sector has reached unprecedented levels in the last 3-4 years. Hybrid and electric vehicles are sought after as critical technologies that can reduce fuel consumption and emission of CO_2, the increased levels of which in the atmosphere are considered a major contributor to global warming. Various governmental policies around the world are providing financial incentives for vehicle electrification, setting standards for lower fleet-average fuel consumption and even mandating the introduction of electrified vehicles.

The automotive industry is being forced to develop multiple technologies to address these governmental initiatives, but faces significant challenges. The latter include technological readiness and cost[1], product reliability and durability, and above all customer interest and willingness to actually pay for the technology. In addition to electrification, other technologies with some environmental benefits, such as ultra-efficient IC engines, clean turbo-diesel engines, and bio-fueled IC engines, are also evolving. In many cases, these alternative technologies are less expensive and less risky to the automakers, thus explaining their interest in pursuing them in parallel to, or instead of, the electrification approach. However, automotive engineers are discovering that many of the alternative solutions will also require increased electrical power, which reinforces the desirability of at least some level of vehicular hybridization.

b. Hybrid-Vehicle Architecture

Hybrid cars today cover a range of technologies characterized broadly by the extent to which electrical power is used for propulsion in an ICE vehicle. At one end of the spectrum is the ‘micro-hybrid’—a car that is not truly a hybrid as it supplies no electrical energy in support of traction, but features a “beefed-up” starter or a 2- to 4-kW belt-driven integrated-starter-alternator, in which fuel is saved during vehicle idle stop, and some mechanical energy is captured during braking. At the other end of the range is the “plug-in hybrid” (PHEV), in which a 30- to 100-kW electric motor is capable of propelling the car on its own for, say, 10 to 40 miles, and supplements the power of the internal combustion engine in most acceleration events.

Beyond the hybrids are full electric vehicles (EVs), which use a single electric motor with an all-electric powertrain powered by a battery or a fuel cell (FC). While FC-powered vehicles have been in development since the mid-1990s and are still of interest, infrastructure issues appear to limit their commercial viability for the foreseeable future.

The debate over the “right” level of electrification or hybridization has recently intensified. On the one hand a low level of hybridization provides only a small fuel-efficiency benefit but its relatively low cost facilitates high-volume introduction and can thus rapidly produce a notable impact on fleet-average fuel consumption. At the other extreme, full EVs and PHEVs offer significantly lower fuel consumption per vehicle, but their much higher cost, in addition to the limited range of the EV, reduce the market appeal and thus the environmental impact on the fleet.

Several levels of hybridization are possible as is discussed in detail in Chapter I. They are generally classified according to i) the functions they provide, or ii) the ratio of the power of the electric-drive motor to total power (the rated maximum power of the electric motor added to that of the IC engine.) Table E.1.1 describes the various hybrid-vehicle categories and the main functions they enable.

2. HEV Battery Technology

a. Cell Module and Pack Technology

The important parameters for hybrid-vehicle batteries are i) the cost of usable energy under conditions of high-

---

[1] *All cost estimates in this report are based on an exchange-rate of 90 Yen per U.S. dollar.*

	1	2	3	4	5	6	7	8
HYBRID CATEGORY:	**Micro-1**	**Micro-2**	**Mild-1**	**Mild-2**	**Moderate**	**Strong**	**Parallel Plug-in**	**Extended-Range EV (EREV)**
Main attribute	Stop/Start	Regen brake	Launch assist	Mild power assist	Moderate power assist	Limited electric drive	Extended electric drive	Largely Electric Drive
Electric machine	Regular starter or belt-driven alternator	Regular starter or Belt-driven alternator	Belt-driven or crank shaft	Crank shaft	Crank shaft	Two crank shaft	Two crank shaft	Drive Motor
Electrical power level, small to mid-size car	2-4 kW	2-4 kW	5-12 kW	10-15kW	12-20 kW	25-60 kW	40-100 kW	70-130 kW
Operating voltage	14	14-24	48	100-140	100-150	150-350	150-600	200
Example	Most new German cars	Mazda , Suzuki	In development	GM Malibu Eco	Honda Civic	Prius/Ford Fusion	C-max PHEV	Chevy Volt
Cold engine cranking	Desired							
Stop/start cranking	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Crank to idle speed	🟥	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Regen braking	🟥	🟨	🟨	🟢	🟩	🟩	🟩	🟩
Alternator assist	🟥	🟨	🟢	🟧	🟧	🟧	🟧	🟧
Torque smoothing	🟥	🟥	🟢	🟧	🟧	🟧	🟧	🟧
Launch assist	🟥	🟥	🟨	🟢	🟩	🟩	🟩	🟩
Power assist	🟥	🟥	🟥	🟨	🟢	🟢	🟩	🟩
Electric drive	🟥	🟥	🟥	🟥	🟨	🟢	🟩	🟩

Color coding:	
Full function	🟩
Moderate function	🟢
Limited function	🟨
Provides function	🟧
No function	🟥

Table E.1.1: Hybrid Vehicle Configurations

power discharge, ii) their life in the application, and iii) the volume and weight of the energy-storage device capable of delivering the required power for the required length of time, derived from the energy density (Wh/liter and Wh/kg) and power density (W/liter and W/kg). The first two parameters (cost and life), in combination, represent the economic cost of an energy-storage system capable of providing the hybridization function over the vehicle's life.

Other energy-storage system parameters include: i) operating temperature range, ii) thermal management requirements, which relate to the weight and cost of the device and the complexity of keeping it at temperatures that do not shorten the desired life, iii) charge acceptance, for effective regenerative braking, iv) electrical management requirements, v) robustness under abuse, vi) charge retention on storage, vii) availability, reliability, and long-term security of supply, and viii) logistic issues relative to shipping, storage, and recycling. In addition, a fundamental requirement for all hybrid-vehicle energy-storage systems is that they must be essentially maintenance-free.

Battery packs for xEV applications are complex systems composed of multiple modules usually arranged in series electrical configurations, together with supporting subsystems to maintain the battery cells and communicate key parameters to a higher-level vehicle controller. The modules are in turn composed of several individual cells (typically four or more) arranged in parallel, series, or a parallel/series combination with the related electronics. Modules include a thermal management system, some voltage and temperature sensors, and could also include local electronic control functions such as a cell-balancing system.

The battery pack is comprised of the modules, cooling system, mechanical enclosures and fasteners, battery controller and electrical components, including contactors, connectors, bus-bars, sensors, and fuses. Figure E.2.1 shows a general view of a liquid-cooled HEV Li-Ion battery pack.

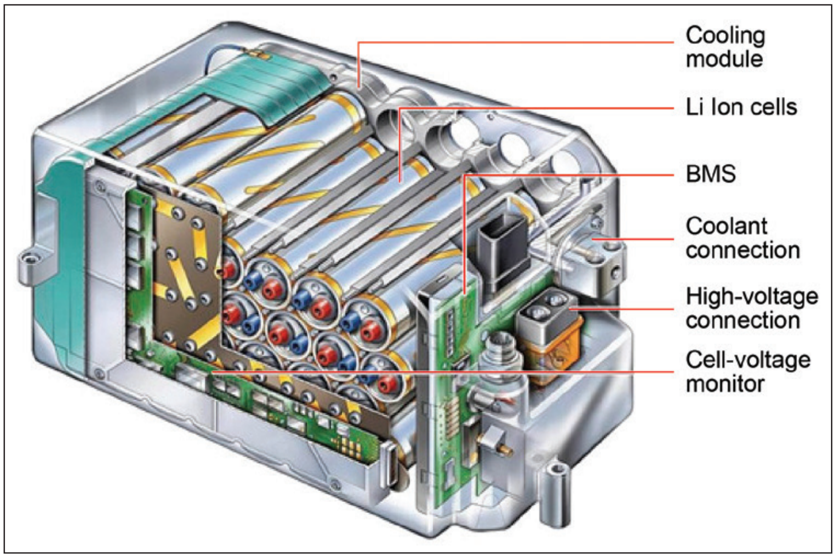

Figure E.2.1: Liquid-cooled Li-Ion Mild HEV (Cylindrical Cells) Battery Pack for Mercedes S Class Vehicle

b. Key Energy-Storage Technologies for HEVs

Four energy-storage technologies, Lead-Acid (Pb-Acid), Nickel-Metal Hydride (NiMH), and Lithium-Ion (Li-Ion) batteries as well as Ultracapacitors (UCaps) are used in current HEVs and are the only technologies of interest for the foreseeable future (10+ years). Table E.2.1 provides a generic comparison of the technologies. The table was assembled based on data from both car companies and battery developers, and should be taken as representing general “typical-to-best” characteristics of high-power devices designed for HEV applications.

Table E.2.2 compares estimated initial cost, manufacturing, and logistic issues relating to the battery and ultracapacitor technologies presented in Table E.2.1.

i) Lead-Acid Batteries

The flooded SLI (Starting/Lighting/Ignition) Lead-Acid battery has been the dominant automotive battery

Table E.2.1: Characteristics of Candidate High-Power Energy-Storage Technologies for HEV Applications (Pack level unless noted otherwise)

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Table E.2.2: Cost, Manufacturing, and Logistic Issues of Candidate Energy-Storage Technologies for HEV Applications

for over a century. Its annual sales globally amount to about $11 billion. This type of battery has been fine-tuned for the application through extensive cooperation between battery manufacturers and the automotive industry, and a major advantage is its low cost ($40-70/kWh, related to the price of lead). Recent improvements in the flooded design predominantly aim at improving cycling behavior, power density, and charge acceptance. Key design modifications in the so-called Enhanced Flooded (EFLA) designs include adding carbon to the negative electrode, a more sophisticated grid matrix, and the addition of a glass mat next to the polyethylene separator.

As the load on the micro-hybrid battery during idle stop increases, the cycling throughput requirement follows, which has prompted many European automakers to introduce a better-cycling valve-regulated (VRLA) design. However, since the pressure on automakers to keep battery prices low cannot be overstated, a continued large market share for EFLAs is assured, at least in the high-volume economy-car market in Europe, Japan, and China. While more complex designs utilizing capacitance carbon in the negative electrodes are under test, it is still too early to tell whether such designs will find market acceptance.

Lead-Acid batteries will remain the dominant 14V battery technology in automotive applications for many years to come, although in higher-voltage systems the competition from the lighter and better-cycling Li-Ion technology is strong. The immediate challenge for Lead-Acid is to enhance charge-acceptance, cycling throughput, and operating life at intermediate states-of-charge, to support its use in micro-2 vehicle configurations.

ii) Nickel-Metal Hydride Batteries

Nickel-Metal Hydride (NiMH) offers the advanced-vehicle industry a fairly rugged battery with good cycle life, good power and charge-acceptance capabilities, and excellent reliability. Its weakest points are its moderately high cost with limited opportunity for further cost reduction, marginal power at low temperatures, and significant cooling/thermal-management requirements.

Used in HEVs for 13 years, NiMH has proven to be a very reliable product with a life expectancy of more than 10 years in most installations, albeit only two companies, PEVE and Sanyo Electric (now a division of the Panasonic group), have been successful in the market place with a reliable product. Although some minor improvements in performance and reduction in cost (which is influenced significantly by the price of nickel) can still be expected, the technology is mature and close to its perceived potential. While NiMH will continue to be used in HEVs throughout this decade, their subsequent market position will depend largely on the field reliability and cost reduction achieved by competing Li-Ion batteries. Should Li Ion match the cost and reliability of NiMH HEV batteries, their advantage in power, energy density, and energy efficiency would make them the preferred choice for just about all HEV applications.

iii) Lithium-Ion Batteries

The Lithium-Ion (Li-Ion) battery technology that now dominates much of the portable-battery business entered the HEV market in 2009 and is the preferred technology for most HEV applications in the future. Its power density is 50 to 100% greater than that of existing HEV NiMH batteries, and early field data support the laboratory testing that indicates good life. For a given application, current Li-Ion technology offers a battery that is about 20% smaller and 30% lighter than existing NiMH batteries, which is a notable, if not overwhelming, advantage. In the long run, it is anticipated that Li Ion will increase its performance margin over NiMH batteries, strengthen its record for reliability, and also offer lower cost, a factor that is most critical for the market. The lower cost can be achieved by increasing manufacturing yields and simplifying pack electronics, but mainly by enhancing low-temperature power and reducing power-fading over life. This approach will substantially eliminate the current practice of using an oversized battery to meet the specifications for low-temperature power and provide sufficient margin for fading.

There are multiple cell and pack designs for HEV applications, the most critical being the cathode chemistry and the cell's physical configuration. These design variables and the performance, life, safety, and cost issues and trade-offs are discussed in detail in Chapter II.

iv) Ultracapacitors

Ultracapacitors (UCaps), a family of energy-storage devices with higher power but much lower energy density than that of batteries, are of interest for some HEV applications. They can generally be divided into two main categories: i) devices with two symmetric activated-carbon electrodes featuring electrostatic energy storage, and ii) hybrid (asymmetric) devices with one redox-storage (battery-like) electrode and one electrostatic-storage electrode. Existing applications for UCaps in vehicles are presently limited to: i) distributed power in an active or backup role, ii) engine start for heavy-duty vehicles in ultra-cold climates, and iii) micro hybrids (so far limited to PSA and Mazda), and iv) mild hybrid buses, and other heavy-duty vehicles. Future applications could include usage in mild-1 hybrids.

3. Battery Requirements and Battery Selection for Each Hybrid-Vehicle Category

a. Overview

Chapter III reviews the required performance and comparative merits of batteries (and UCaps) to qualify as power sources for the seven categories of hybrid vehicles identified in Chapter I. The electrical loads and duty-cycle requirement data were gathered from multiple sources, including field interviews, and averaged to obtain a typical profile for each category. The numerical analyses apply to a typical U.S. family vehicle of the C-D segment, a category that includes popular vehicles such as the Toyota Camry, GM Malibu, Ford Fusion, Honda Accord, Hyundai Sonata, and Nissan Altima. All of these vehicles are currently offered in the U.S. market with a hybrid-powertrain option.

While battery selection appears clear-cut in many vehicle categories, in some others, particularly the micro-2 and 48V mild-1 hybrids, several approaches may be viable, as discussed in Chapter III and noted below.

b. Micro 2

Automakers aiming to enhance the fuel economy benefits of the current micro-1 hybrid by developing micro-2 architectures are faced with selecting an energy-storage system that is either a heavy and unsatisfactory (in charge acceptance) Lead-Acid battery or one

Micro-2 - Case 2							
	Unit	*i*	*ii*	*iii*	*iv*	*v*	*vi*
Parameter		**Full VRLA**	**Li Ion**	**COMBINATIONS 60Ah EFLA + UHP**			
			HP-LFP	**UCap**	**UHP LFP**	**UHP LTO**	**NiMH**
Max charge current	*Amp*	38.4	336	225	139	225	142
Number of years	*#*	5.0	10	10	10	10	10
Rated capacity	*Ah*	80	70	1.1	4.0	3.1	6.0
Volume	*liter*	22	14.0	21	18	18	19
Weight	*kg*	31	18	27	25	25	26
Cell cost, upfront	*$*	100	337	261	94	97	98
Pack cost (excluding DC/DC)	*$*	115	604	426	228	245	187
Pack cost, 10 years	*$*	250	604	527	330	347	288

Table E.3.1: Energy-Storage Solutions for Micro-2 Profile with Existing Production Cells (Case 2); (HP = High Power, UHP = Ultra High Power)

of several systems incorporating higher performance, but also higher initial cost and some yet-to-be-resolved complexities. The results of one of the cases analyzed in Chapter III are summarized in Table E.3.1.

In practice, the automakers resolve these dilemmas by entering the market in low volumes, which permits an evaluation of costs and merits at low exposure.

c. Mild-1 – 48V Systems

Table E.3.2 displays the load profile and provides three energy-storage solutions for the mild-1 architecture.

While NiMH seems the least expensive solution, it is the largest and heaviest and has somewhat lower energy efficiency. Just as important, the calculated 10-11Ah size cell is not available commercially and there is scant incentive for the development of such a cell, considering the market risk and the momentum toward Li-Ion solutions. The latter do seem to be the most promising, but in the short term the lack of availability of 7-8Ah ultra-high-rate Li-Ion cells is a barrier. The UCap solution at an estimated cost of $1,049 is the most predictable and presents the lowest risk in the short term. However, it is difficult to see UCaps in this application for any but the highest-end European cars, as the value proposition of the architecture is not nearly sufficient to support that level of pricing for the energy-storage system.

Thus, all solutions seem problematic, making the 48V mild-1 hybrid a challenging architecture for all but the most expensive cars. Incentives for its use may well be predominantly driven by the need for extra power on board to support high-end comfort and drivability features, with the fuel-economy benefits becoming a secondary priority. To experience significant market expansion, some combination of the following must unfold:

Characteristics	***Unit***	**Li Ion**	**NiMH**	**UCap**
Max power, pulse and regen.	*kW*	7	7	7
Max current, pulse and regen.	Amp	200	200	200
Annual kwh throughput	*kWh*	192	192	192
10-year throughput	*kWh*	1920	1920	1920
Cell capacity	*Ah*	7.6	10.4	0.70
Design charge acceptance	*A/Ah*	**26.3**	**19.2**	286
Cell energy, Wh	*Wh*	27.7	12.8	1.75
Number of cells	*#*	13	38	20
Battery energy	*Wh*	361	486	**35**
Design throughput	*FOM*	**5324**	**3950**	54885
Battery weight	*kg*	9.5	13.9	8.7
Battery volume	*liter*	10.9	13.9	10.0
Cell cost	*$*	270	292	455
Battery cost	*$*	568	492	729
System cost	*$*	728	652	1049

Table E.3.2: Energy-Storage Solutions for Mild Hybrids

	14V			48V	45-120V	100-200V	200-380V		
	SLI	Micro-1	Micro-2	Mild-1	Mild-2	Moderate	Strong	PHEV	EV
SLI-FLA	🟩								
EFLA		🟩	🟨						
VRLA		🟩	🟨	🟦					
Lead Acid + UCap		🟦	🟦	🟨					
Lead Acid + Li Ion			🟨	🟨					
Lead Acid + NiMH			🟨						
Li Ion			🟨	🟨	🟩	🟩	🟩	🟩	🟩
NiMH				🟦	🟨	🟨	🟩		

Legend: 🟩 Dominant 🟨 Contender 🟦 Some prospects

Table E.3.3: Energy-Storage Technology Solutions for Advanced Vehicles by Vehicle Category

i) A significant reduction of system cost below the values calculated here
ii) A significant increase in the value of reduced fuel consumption due to increased fuel prices and/or tightened regulations
iii) A sharing of the amortized cost of the upgraded power system with additional power-hungry features that may be introduced in future vehicles

d. Energy Storage for hybrid Cars - Summary

When hybrid vehicles were first introduced in the late 1990s, NiMH was chosen for essentially all high-voltage configurations, and Lead-Acid as well as NiMH solutions were promoted for the lower level of hybridization. NiMH is still the dominant battery in the high-voltage hybrid market but its monopoly has been ended by Li-Ion technology, which started to take market share around 2009 and is expected to continually increase its share with time. Table E.3.3 (which also covers PHEVs and EVs) provides an overview of the relative prospects of energy-storage technologies to capture the various hybrid-vehicle market segments.

Table E.3.4 summarizes typical pulse-discharge requirements of the mild, moderate, and strong-hybrid architectures, and the rated capacities of Li-Ion batteries that could meet these requirements, while Table E.3.5 presents a condensed summary of the potential energy-storage solutions discussed in Chapter III, for vehicle hybridization levels ranging from micro-2 to strong.

4. Batteries for EVs & PHEVs

a. EV & PHEV Battery Cost

Chapter IV provides detailed analyses of PHEV and EV Li-Ion cell and pack design, manufacturing, and cost. Presented in Table E.4.1 is a cost estimate for a 25-Ah PHEV prismatic metal-can cell based on NMC/graphite chemistry—the most common cell used in the applica-

Table E.3.4: Load Profiles for the Various Hybrid Architectures and Li-Ion Solutions

	Discharge Pulse										Battery	
	Maximum		Average		Freq.	Average power assist energy consumption			ISS	Total	Rated	Throughput
	Load	Duration	Load	Duration	Per day	Event	Day	Per Year	Per Year	Per Year	Capacity	FOM
	kw	sec	kw	sec	#	Wh	Wh	kWh	kWh	kWh	kWh	#
Mild-1	7	10	6	3	120	5.0	600	192	84	276	0.24	11500
Mild-2	12	10	9	3	150	7.5	1125	360	198	558	0.48	11625
Moderate	18	10	12	4	200	13.3	2667	853	198	1051	0.8	13142
Strong	30	12	18	4	200	20.0	4000	1280	198	1478	1.25	11824

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Table E.3.5: Energy-Storage Solutions for Hybrid Vehicles: Key Characteristics

tion. The cost components are analyzed in detail in Chapter IV and are noted in the table. The resulting per-kWh price of $350/kWh allows for a somewhat low gross margin of 23%.

The analysis is only moderately sensitive to the choice of chemistry, with LMO-NMC blends providing lower cost (but requiring more aggressive cooling) and LFP-based cells, slightly higher cost per kWh due to the inherently lower voltage of that system. A somewhat lower cost than that calculated above could be achieved at the more recent yen-dollar exchange rate (102 yen/$ in May 2013), and also through engineering and chemistry optimization.

Table E.4.1: Cost Estimate for a 25-Ah PHEV Cell

NMC Cathode, Metal Can, 10 Million 25Ah PHEV Cells / year			
Component	$	Per kWh	%
Materials	15.6	170	53%
Factory Depreciation	5.3	58	18%
Manufacturing Overhead	1.78	19	6.1%
Labor	1.15	13	3.9%
Un-yielded COG	23.9	259	81.6%
Scrap, 4%	0.99	10.8	3.4%
Yielded COG	**24.9**	**270**	**85%**
Company Overhead	4.4	48	15.0%
Burdened Cost	**29.2**	**318**	**100%**
Warranty & Profit	2.9	32	10%
Price	**32.2**	**350**	**135%**
Gross Margin	7.3		23%

However, only chemistries with higher capacity/higher voltage would lower the costs significantly, developments which are likely to take at least another 4-5 years.

Table E.4.2 details the cost of a 36-Ah EV pouch cell for which the yielded COG amounts to $28.1, equivalent

NMC/LMO Cathode, Pouch Cell, 16 Million Cells / Year			
Component	$	Per kWh	%
Materials	16.8	126	51%
Factory Depreciation	6.0	45	20%
Manufacturing Overhead	2.40	18	8.2%
Labor	1.30	10	4.4%
Un-yielded COG	26.5	199	83.8%
Scrap, 6%	1.69	12.7	5.1%
Yielded COG	**28.1**	**211**	**89%**
Company Overhead	5.0	37	15.0%
Burdened Cost	**33.1**	**249**	**100%**
Warranty & Profit	3.3	25	10%
Price	**36.4**	**273**	**138%**
Gross Margin	8.3		23%

Table E.4.2: Cost Estimate for a 36-Ah EV Pouch Cell

to $211/kWh. Most cost factors are similar to those for the 25-Ah prismatic-wound PHEV cell. To arrive at a selling price, 15% was added for SGA, and 10% over the burdened cost (COG + SGA) for profit and warranty. The selling price of $36.4 per cell translates to $273/kWh, which is just slightly higher than that of 18650 cells, although it will clearly take the industry several years to achieve such a price level for EV batteries.

Table E.4.3 provides estimates for pack cost at two production volumes. It is assumed that the PHEV prismatic cells are liquid-cooled on their narrow side without a secondary loop, while EV pouch cells utilize a conductive heat sink on one side of each cell to remove heat to a centralized liquid-cooled plate. The numbers in the table should be regarded as a middle-of-the-line cost for the 2016-17 time-scale with large variations possible based on specific design decisions in individual programs.

Key factors that can increase cost include additional safety features such as crush protection and protection against fire propagation, more complex cooling systems, higher costs of testing, and additional electronics for safety, reliability, and diagnosis. Lower costs can be expected if developers can both amortize development/tooling costs and obtain lower piece-prices from larger-volume orders by using designs and components over multiple programs.

The analyses show that there are multiple cost drivers for Li-Ion batteries, which include cell materials, cell manufacturing, pack components, and pack integration and testing. Considering the high level of R&D in automotive Li-Ion batteries worldwide, continued improvement in performance and reduction in cost are to be

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Table E.4.3: PHEV and EV-Pack Pricing

	Cell Maker	Chemistry	Capacity	Configuration	Voltage	Weight	Volume	Ener dens	Spec Ener	Used in:	
		Anode/Cathode	Ah		V	Kg	liter	Wh/liter	Wh/kg	Company	Model
1	AESC	G/LMO-NCA	33	Pouch	3.75	0.80	0.40	309	155	Nissan	Leaf
2	LG Chem	G/NMC-LMO	36	Pouch	3.75	0.86	0.49	275	157	Renault	Zoe
3	Li-Tec	G/NMC	52	Pouch	3.65	1.25	0.60	316	152	Daimler	Smart
4	Li Energy Japan	G/LMO-NMC	50	Prismatic	3.7	1.70	0.85	218	109	Mitsubishi	i-MiEV
5	Samsung	G/NMC-LMO	64	Prismatic	3.7	1.80	0.97	243	132	Fiat	500
6	Lishen Tianjin	G-LFP	16	Prismatic	3.25	0.45	0.23	226	116	Coda	EV
7	Toshiba	LTO-NMC	20	Prismatic	2.3	0.52	0.23	200	89	Honda	Fit
8	Panasonic	G/NCA	3.1	Cylindrical	3.6	0.045	0.018	630	248	Tesla	Model S

Table E.4.4: Li-Ion Cells Employed in Current EVs

expected. However, while some of the costs calculated in this report for relatively large volumes are already being equaled in the marketplace by a number of quotes for smaller volumes, it seems likely that the latter can be regarded as loss-leading 'buy-in' prices, resulting from the highly competitive nature of the industry and the current overcapacity in large-battery production.

b. EV Cell and Pack Key Characteristics

Table E.4.4 provides the key characteristics of eight cells used in current EVs. While the first five are typical cells utilizing NMC or LMO-NCM/LMO-NCA blended cathodes versus a graphitic anode in prismatic or pouch cells, the last three are less common designs which comprise i) a Lishen cell utilizing LFP cathodes, a chemistry with somewhat lower specific energy that until recently was favored by many Chinese producers, ii) a Toshiba cell utilizing an LTO anode and thus delivering the lowest specific energy in the group, and iii) a Panasonic 18650 cylindrical cell utilizing a high-capacity computer-cell design with an NCA cathode, which delivers by far the highest energy density and specific energy.

As seen in the table, state-of-the-art Li-Ion EV battery cells are rated at 90 to 160Wh/kg and 200 to 320Wh/liter. In contrast, the best cylindrical consumer cells, as shown for the Panasonic cell (row 8), deliver 248Wh/kg and 630Wh/liter. This gap in performance is related to the design compromises made in the regular EV cells to support the more critical requirements of safety, reliability, durability, and cost. EV cell and battery performance can be expected to increase over time as confidence in the technology's durability and safety increases.

Table E.4.5 details the energy characteristics of the various packs. The specific energy ranges from 73 to 100Wh/kg, values that are approximately 50% higher than those available from NiMH batteries in the late 1990s. As noted in the last column of the table, specific energy at the pack level is only 53 to 74% of the cell's specific energy, demonstrating the significant extra weight involved in integrating cells into an automotive pack.

Table E.4.5: EV Packs Key Energy Characteristics

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The relatively poor packaging efficiency of EV batteries is due to odd pack shapes resulting from the need, in most current EVs, to fit the pack into an available space in the predesigned vehicle platform. For the same reason, effective volumetric energy densities for installed EV batteries can differ quite widely from nameplate values. Another parameter significantly affecting volumetric and gravimetric energy density is the cooling system, if there is one. While refrigerant/liquid cooling is more volume-efficient than air cooling, it is also more expensive.

c. PHEV Pack Key Characteristics

Table E.4.6 summarizes the key electrical characteristics of PHEV packs in, or close to, commercial production. The packs are listed by their rated capacity—a parameter that correlates with the vehicle's electric range. For the first four vehicles with battery capacities exceeding 10kWh, two or three cells are assembled in parallel to reach the desired pack energy capacity at optimal motor voltages (typical 300-360V). The Toyota Prius stands out as a relatively low-capacity, as well as a relatively low-voltage system. However, the Prius up-converts the battery voltage to over 600V so that motor and battery voltage are largely independent of each other. The energy density of the PHEV packs is typically 10-20% lower than that of the EV packs due to the higher-power design of the application. A very important quantity is the capacity that can be utilized over long cycle life, which is typically 55 to 75% of the initial rated capacity.

d. Life, Reliability, and Safety

The life and reliability of EV and PHEV Li-Ion batteries in the field will play a major role in the cost of ownership and thus the overall viability of these vehicles. While results in accelerated cycle-life testing support the Li-Ion battery's prospects of meeting the cycle-life requirements (at least for EVs), and provide an expectation of an adequate calendar life for batteries that do not experience temperatures above 40°C, real life in the field is obviously yet to be confirmed. This represents a significant risk factor for the industry.

The automakers' guiding principle for the use of Li-Ion batteries in any automotive application is that, regardless of what happens, no flame or burning materials should be expelled from the battery pack. A cell catching fire that does not propagate outside the battery pack is thus a reliability event rather than a safety incident. While it is the ultimate responsibility of the vehicle-engineering team to provide a vehicle that under any reasonable circumstances will not endanger

Table E.4.6: Key Characteristics of PHEV Packs

Carmaker	Model	Cell			Pack			
		Maker	Cathode Chemistry	Capacity Ah	Maker	Energy kWh	Capacity Ah	Voltage V
Fisker	Karma	A123	LFP	20	A123	20	60	333
GM	Volt	LG	LMO-NMC	15	GM	16	45	356
Mitsubishi	Outlander	LEJ	LFP	21	LEJ	12	42	286
Volvo	V60	LG	LMO-NMC	15	LG	11	30	367
Porsche	Panamera	Samsung	NMC-LMO	26	Bosch	9.4	26	362
BMW	i-8	Samsung	NMC-LMO	26	BMW	8.5	26	327
Ford	C-Max	Sanyo	NMC	24	Ford	7.6	24	317
Ford	Fusion	Sanyo	NMC	24	Ford	7.6	24	317
Audi	A3	Sanyo	NMC	24	Sanyo	7.5	24	313
Honda	Accord	Blue Energy	NMC	21	Honda	6.6	21	314
Daimler	S class	LEJ	LFP	21	Magna	6.5	21	310
Toyota	Prius	Sanyo	NMC	22	Toyota	4.5	21.5	209

the driver or passengers, engineers in all fields keep making design decisions affecting safety that are trade-offs between product requirements that allow only a small margin of cost increase or performance reduction to achieve their goal.

Lithium ion is a high-energy, high-power, flammable, and easily ignitable power source. However, so is gasoline. There are good reasons to believe that safety can be engineered into the system, even if mistakes are occasionally made in the learning process. Given the very conservative approach of automotive engineers, it seems likely that future battery-related safety incidents, at least at established western automakers, will be rare and isolated cases.

e. Technology Enhancement Roadmap

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This study revealed that PHEV-EV batteries through the end of the decade will all feature Li-Ion technology with further optimization of existing chemistries, and cell and pack designs. The largest step forward in performance will require the implementation of higher-voltage cathodes and silicon-containing anodes. Such designs are expected to support a 50% improvement in performance coupled with potential for a substantial reduction in cost. However, the main challenge for these higher performance chemistries will be to ensure that they continue to provide an adequate life and in no way compromise safety.

In recent years development work, largely supported by the U.S. government, has been directed at technologies that may supersede Li Ion, the most visible of which presently are the programs on lithium-oxygen. While some of these futuristic chemistries and approaches offer interesting prospects, replacing Li Ion with a battery of overall better value for the EV and PHEV market would be a formidable task. For the foreseeable future, it seems likely that the combination of high gravimetric and volumetric energy and power density with very high cycle life offered by the Li-Ion technology will remain unique.

5. xEV Vehicle Market

a. Market Drivers and Challenges for xEVs

The automakers' motivation for developing hybrid and electric vehicles stems primarily from the following:

i. The environmental driver: The ever-increasing pressure to reduce pollutant and CO_2 emissions that threaten the environment
ii. The energy security driver: The concern about energy supply shortages and security
iii. The customer's fuel-saving driver
iv. The customer's ancillaries driver: The promise of enhanced and new (electrically powered) customer features that improve the vehicle's functionality/efficiency and/or driving comfort
v. Industrial competitiveness driver: The national and local governments' drive to build technological competence and create jobs in future technology
vi. The image driver: The desire to project a "green" and "high-tech" image to the buying public.

Currently, the strongest global motivation to encourage the use of xEVs is the drive to reduce CO_2 emissions from the transportation sector, and it is augmented, particularly in the U.S. and China, by concerns about energy security. Figure E.5.1 shows the historical and proposed

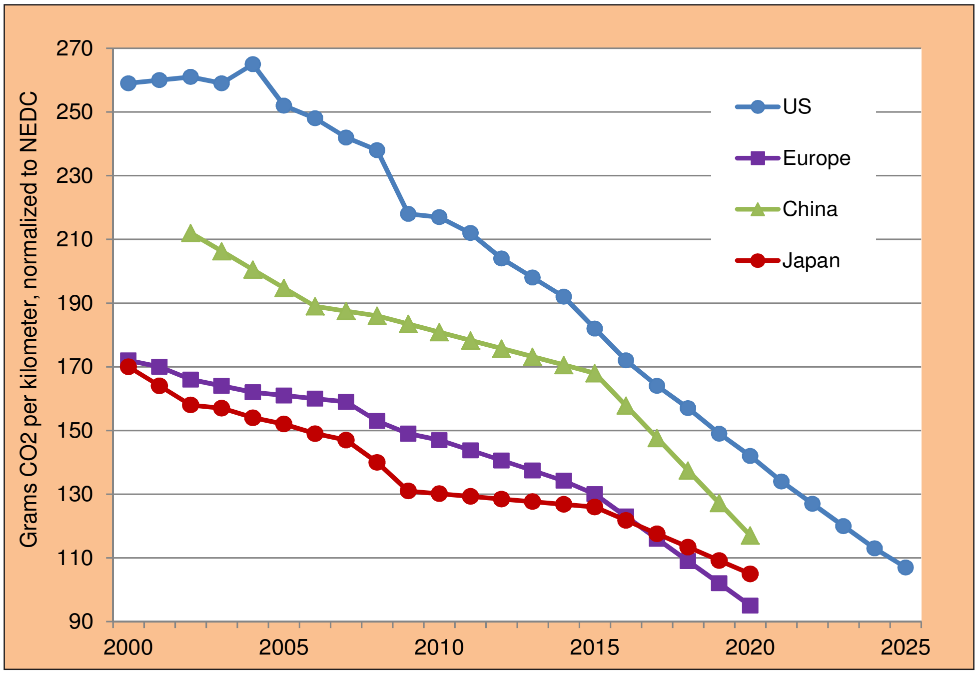

Figure E.5.1: Comparison of Global CO_2 Emission Regulations in g CO_2/km for Passenger Cars (Test Conditions Normalized to the New European Drive Cycle (NEDC)

(usually via legislation) CO_2 emissions standards in g/km in the global passenger car market. It can be seen that the reduction is quite significant, particularly for the period 2015 through 2020. Meeting these requirements at the lowest possible cost determines the direction of xEV-vehicle development at automakers.

b. Market Forecast for xEVs

The estimated growth of the micro-hybrid market by geographical region is illustrated in Figure E.5.2. Market growth in Europe shows strong momentum, which is also expected to extend to Japan; for the U.S. and China, the situation is not as clear.

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Strong and moderate (high-voltage) hybrids on the market since late 1997 showed a strong growth last year and reached market shares of 25% in Japan, and 3% in the U.S. While the global strong-hybrid market seems likely to maintain a steady growth, that of the mild-hybrid market is expected to accelerate later in the decade, predominantly in Europe and potentially at 48V, where it will be driven by the anticipated step-tightening of the CO_2 regulations in 2020. Figure E.5.3 provides historical and forecast figures for these markets by world region for the period between 2009 through 2020.

PHEV sales by world region for 2012 and projections for 2016 and 2020 are illustrat-

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Figure E.5.2: Micro-Hybrid Market by World Region ed in Figure E.5.4. By 2020, the PHEV market is projected to account for 750,000 units, or about 1% of the anticipated global sales volume for that year. Continued growth in the U.S., still predominantly driven by the CARB mandate, will be augmented by more notable growth in Europe and China as carmakers take advantage of the CO_2 test-certification, and extra credits available to the PHEV as a means to meet tightening CAFE standards.

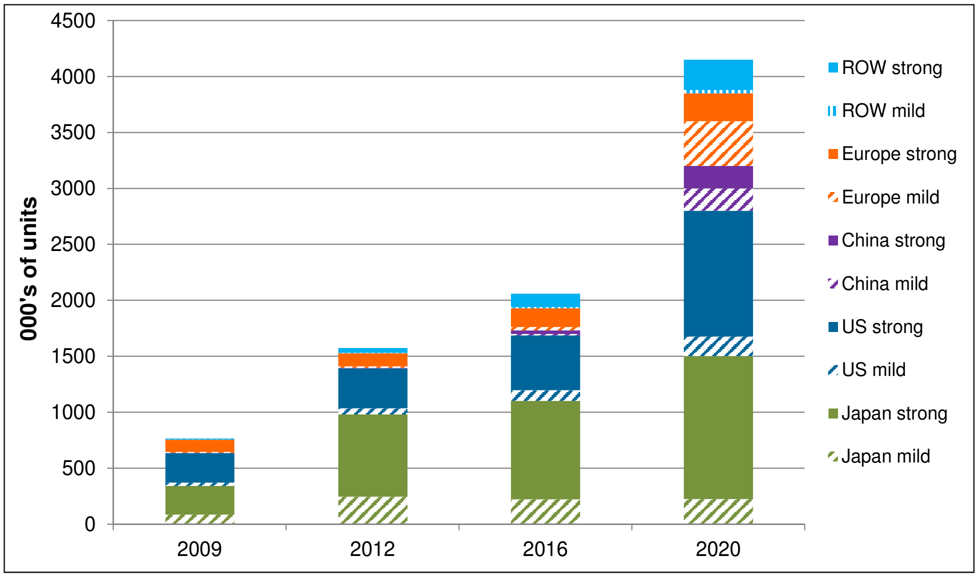

Figure E.5.3: Strong, Mild/Moderate Hybrid-Market Growth by World Region

Note that for PHEVs—as for conventional hybrids but not for EVs—the technical and economic challenges are somewhat independent of vehicle size. In fact, a mid-size vehicle, or even larger, is potentially more attractive for a PHEV powertrain since it has more space available than smaller vehicles to accommodate the larger PHEV battery. Furthermore, since a U.S. subsidy is available and is a function of battery energy capacity and not of vehicle fuel economy, the tax credits for a given fuel-economy improvement or all-electric range capability are greater the larger the vehicle.

All EVs under development at major electric-vehicle manufacturers (with the exception of Tesla) have a limited range, typically 50 to 100 miles. This handicap effectively restricts their use to urban driving. Additionally, these vehicles are typically of the mini (city), subcompact, and compact classes, which limits their market to buyers of smaller cars.

Figure E.5.5 shows the geographical distribution of EV sales in 2012 and forecasts for 2016 and 2020.

The worldwide EV market is expected to grow from about 75,000 units in 2012 to 205,000 units in 2016 and 480,000 units in 2020, showing a projected average annual growth rate of 26%. The estimate for 2020 will account for only about 0.6% of the expected total market of 74 million new vehicles in that year.

Figure E.5.6 shows historical and projected EV sales by automaker from 2009 to 2016. The Nissan-Renault alliance will continue to hold the largest share, but

Figure E.5.4: PHEV Market Growth by World Region

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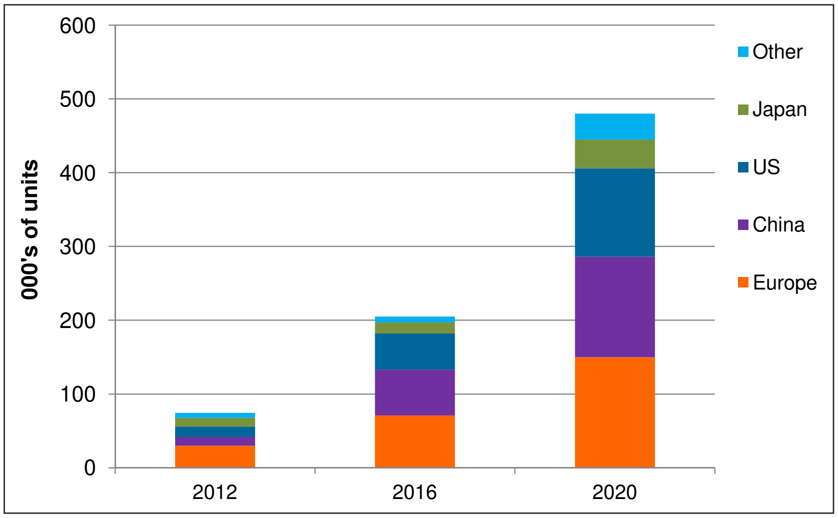

Figure E.5.5: World EV Market Growth by Region

its actual sales are likely to be a fraction of what had been anticipated. Chinese automakers, Mitsubishi Motors, luxury-car maker Tesla, and German automakers make up most of the rest of the market, while the other Japanese carmakers and the U.S. "Big Three", whose interest in EVs is largely limited to meeting the CARB requirements, are not expected to promote them heavily outside the 'CARB-states'.

c. xEV Market Conclusions

HEVs are now mainstream products in Japan and are approaching unsubsidized commercial viability in the U.S., while micro hybrids are strongly entrenched in Europe. In the absence of a market-based value proposition for EVs and PHEVs, governments are attempting to advance these technologies by issuing various mandates and subsidies (as discussed in Chapter V). Unfortunately, western governments, both federal and state, for economic, if not political reasons, may not be able to continue subsidizing vehicle electrification at the level required for them to compete with hybrids and other advanced-propulsion technologies. In fact, despite the sizeable subsidies and discounts provided by governments and carmakers respectively, PHEV and EV car sales over the past 24 months have fallen short of the carmakers' plans.

In the long term, EVs are unlikely to account for more than a small percentage of the world's new-car market until well after 2020, and they will probably be used mainly in urban driving. Despite their relatively weak value proposition in comparison with ICE and HEV powertrains, PHEVs seem to be the second most realistic (after HEVs) of the four electrified-vehicle configurations (the others being BEVs and FCVs). The PHEV's limitations of higher vehicle cost and somewhat reduced cabin space are minor in comparison with the BEV's problems of limited range and slow re-fueling time. In contrast with fuel-cell-powered vehicles, PHEVs do not require heavy upfront investment in infrastructure. It stands to reason that if governments continue to promote and subsidize the mass introduction of vehicles electrified beyond the

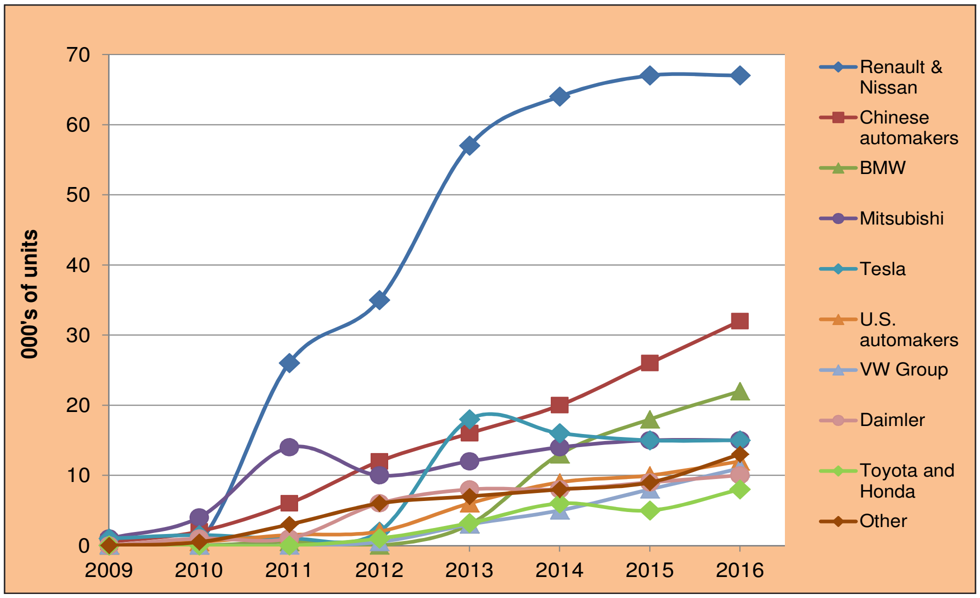

Figure E.5.6: Historical and Forecast EV Sales by Automaker

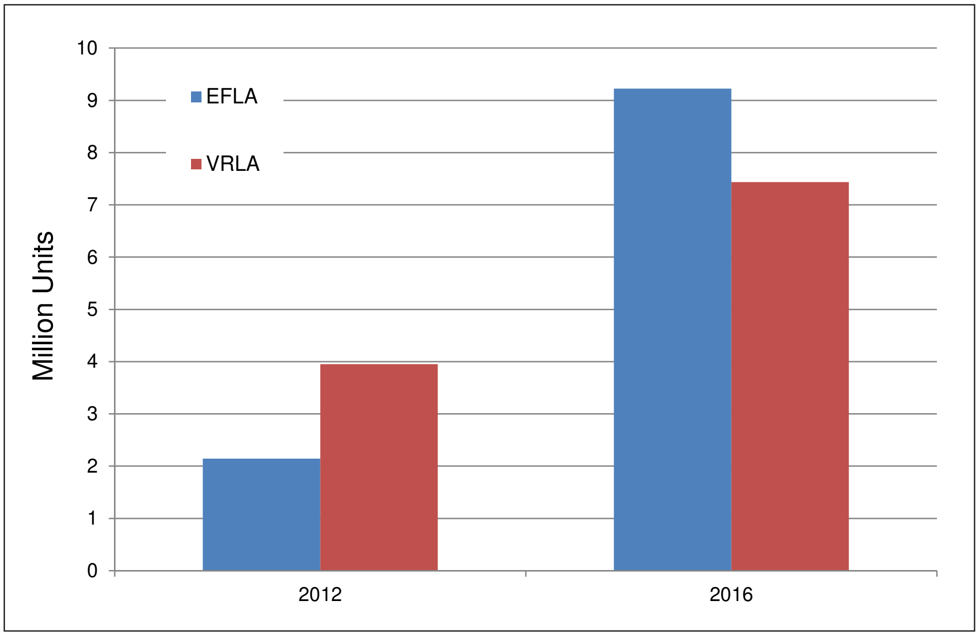

Figure E.6.1: Estimated Unit Sales of EFLA and VRLA Designs (in Million Units)

level of conventional HEVs, then PHEVs are relatively the best choice. Battery-powered EVs will remain niche-market vehicles for urban usage, while fuel-cell-powered EVs may find application in buses and other large vehicles owned and operated by governments or corporations, which are in a position to install a refueling infrastructure.

6. Battery Market for xEVs

a. Battery Markets for xEVs through 2016

i) Micro Hybrids

The cost/performance trade-offs between the two Lead-Acid technologies—EFLA and VRLA—that share the micro-hybrid market today are reviewed in Chapters II and III, while their projected market shares are presented in Chapter VI. Figure E.6.1 provides a best estimate of the unit sales of these two designs for 2012 and 2016. In the former year the major customers were European manufacturers of high-end vehicles such as BMW, Mercedes, and Audi, which prefer VRLA. In the future, as main-stream car producers such as Toyota, VW, Ford, Honda, and others expand their micro-hybrid offerings in Europe and Japan, their preference for the EFLA battery will rapidly increase its volume and market share.

ii) Strong/Mild HEVs

Figure E.6.2 illustrates the growth of the HEV battery-pack market over the past four years and includes a projection for the next four years. NiMH was the dominant technology until recently but it now seems that the NiMH HEV battery market has peaked or is about to peak. The corresponding historical and projected markets for Li-Ion HEV-cells by manufacturer are shown in Figure E.6.3. The data are based on the unit sales forecast presented in Chapter V, and combined with industry pricing information discussed in Chapter II. The total Li-Ion HEV cell business is estimated to grow from about $200 million in 2012 to nearly $570 million in 2016—a compound average growth-rate of 30%.

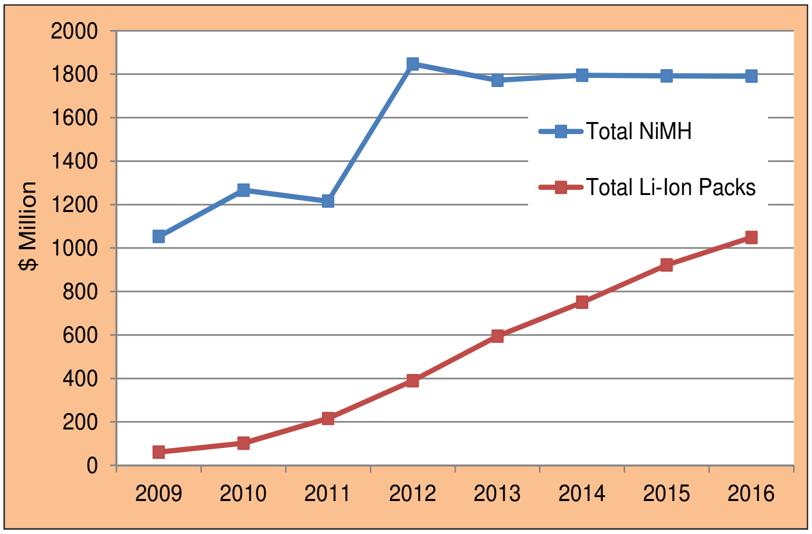

Figure E.6.2: NiMH vs. Li-Ion HEV Battery-Pack Business ($ Million)

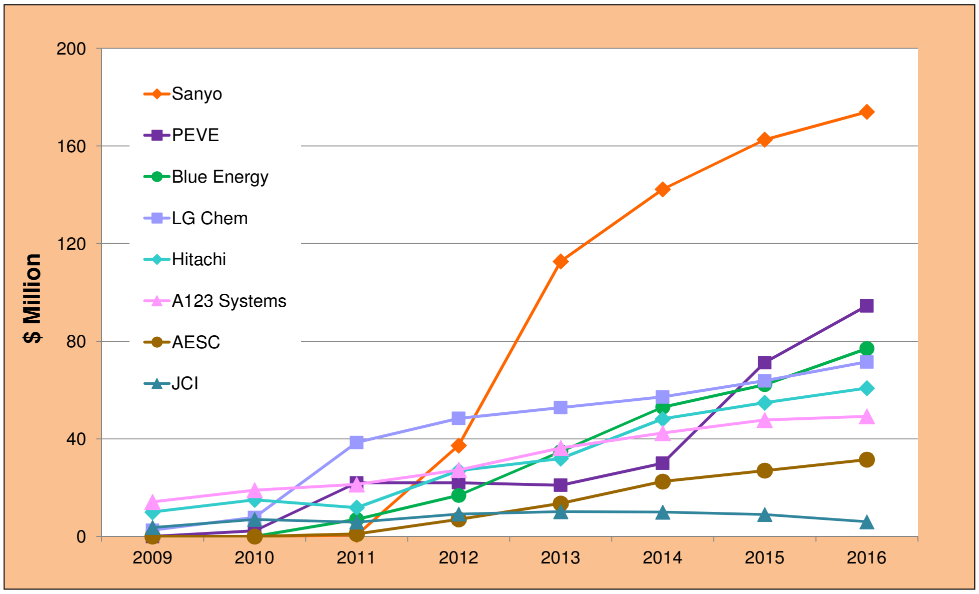

Figure E.6.3: Li-Ion HEV Battery-Cell Business by Cell Producer

iii) PHEVs

The PHEV battery-cell market, which is 100% Li Ion, is expected to increase from $9 million in 2010 to over $650 million in 2016. The corresponding PHEV battery-pack business is estimated to exceed $1 billion in 2016 (with most of the value added accruing to the automakers), since cells represent about 65% of PHEV battery-pack costs.

iv) EVs

The EV cell market—also 100% Li Ion—which grew from $41 million in 2009 to $768 million last year, is forecast to be over $1.7 billion in 2016, with the associated EV battery-pack business exceeding $2.3 billion in that year. Here again most automakers design and build their own packs. Chrysler-Fiat, for whom Bosch designs and builds battery packs, is an exception.

v) Combined Li-Ion Cell Markets

Figure E.6.4 shows the combined Li-Ion automotive battery-cell market for HEV, PHEVs, and EVs by producer. This market, which was miniscule in 2009, grew to $1.23 billion last year and is expected to exceed $2.9 billion in 2016. The eleven listed suppliers, each with annual sales forecasts ranging from $60 million to over $500 million, are projected to account for about $2.64 billion, or 90% of the business. Note that the ‘Other’ category includes some potentially significant future players, such as SK Innovation, Toshiba, JCI, Li-Tec Battery, and several Chinese producers.

vi) Combined xEV Pack Markets

Figure E.6.5 summarizes the estimated $6.2 billion advanced automotive battery-pack market in 2016 by market segment. The NiMH HEV-pack market, the dominant segment in 2009-2010, is expected to maintain its $1.8 billion level through 2016, but represents only 29% of the business in that year. The more rapidly growing

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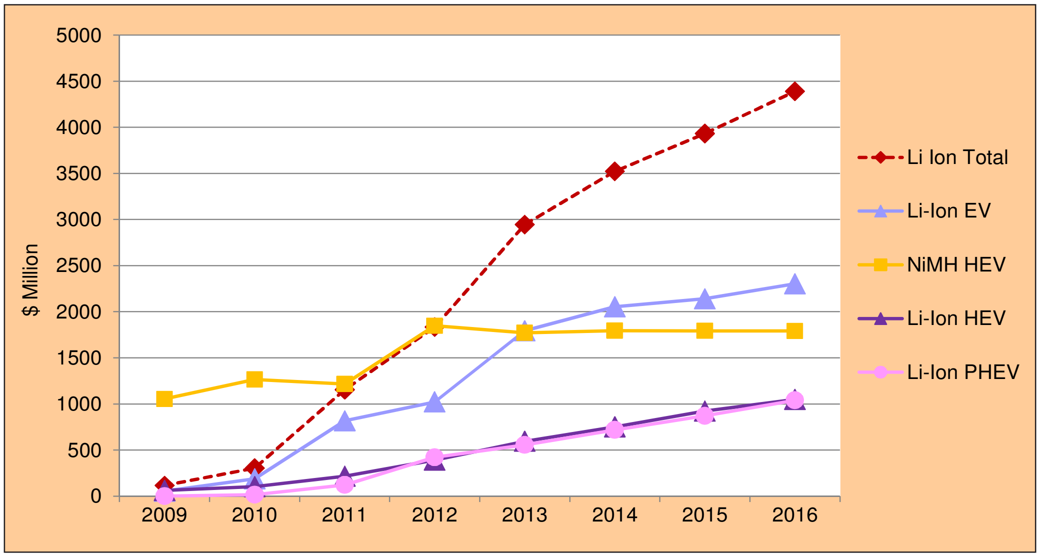
Figure E.6.4: Combined Li-Ion Automotive Cell Market for HEV, PHEVs, and EVs by Producer

Figure E.6.5: Advanced Automotive Battery-Pack Business ($ Million)



Li-Ion battery businesses account for the rest. The Li-Ion EV-pack business is estimated to exceed $2.3 billion in 2016, with Li-Ion HEV and PHEV packs topping $1 billion each. These estimates do not include any after-market and replacement business or any possible micro-hybrid Li-Ion battery-pack business, which is generally expected to be still quite small in 2016.

b. xEV Battery Market to 2020

After 2016, the growth rate of the Li-Ion HEV and PHEV battery business is expected to exceed that of the other two segments and change the relative magnitudes of the four market-segment categories. Table E.6.1 provides a projection for the 2020 world Li-Ion automotive battery market. All key assumptions are indicated in the table, including unit sales, based on data from Chapter V, average battery capacity in kWh, cell-costs per kWh, and battery-pack cost for each market segment, derived from the analyses in Chapters II & IV.

It is too speculative to suggest which battery companies will share this significant and growing market. Nevertheless, the companies with the largest shares in 2016, shown in Figure E.6.5 are the favorites, provided their cash flow turns positive by that time. Otherwise it seems clear that those which also have a significant business in consumer (portable) batteries, such as Sanyo, LG Chem, Samsung, and two or three Chinese players, will have a built-in advantage as suppliers to the demanding automotive market, because of their experience in the cost-effective manufacturing of reliable products. A factor that will greatly impact the position of some early entries, including LG Chem and AESC, is the degree to which the pouch-cell technology will be accepted by automakers that have so far avoided it.

Table E.6.1: 2020 Automotive Li-Ion Battery Market

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As noted in Table E.6.1, the total automotive Li-Ion battery production is projected to exceed 20,000 MWh in 2020. The dollar values of the key xEV-cell materials corresponding to this estimate are shown in Figure E.6.6.

c. Industry Overcapacity

Generous government subsidies have triggered the rapid and apparently premature construction of PHEV

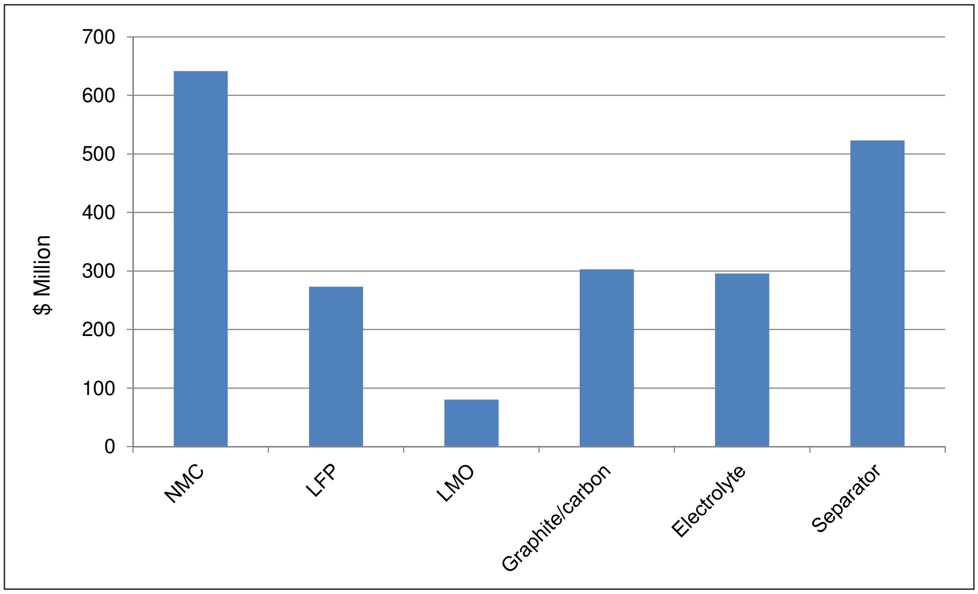

Figure E.6.6: xEV Key Cell Material Business ($ Million)

and EV battery plants. In the U.S., grants awarded by the federal and several state governments as part of the 2009 economic stimulus package covered 50 to 80% of the cost of new plants located in the automotive-industry states of Michigan and Indiana. Other grants and preferred-terms loans (in particular to Nissan-Renault) were awarded in France, the U.K., Portugal, China, and the U.S. Table E.6.2 details i) the plant capacities announced by major battery makers and scheduled to become operational by 2014, ii) an assessment of the actual installed capacity as of Q1 2013, and iii) the expected production level this year (2013). As the table indicates, the likely production volume this year will be a little over 3,000MWh, which is only 11% of the proposed 2014 plant capacity and about 21% of the capacity installed to date. This extreme overcapacity is the main reason why many xEV-battery manufacturers submit product quotations at or below cost. While the automakers benefit from lower pricing in the short term, a problem may develop in the long run since a healthy industry requires a profitable supply chain. While some plants will undoubtedly close, another likely outcome of this overcapacity is industry consolidation via mergers.

Company	**Planned Capacity for 2014**	**Estimated 2013 Status**		
		Fully Installed	**Forecasted Production**	**Capacity Utilization**
	MWh	**MWh**	**MWh**	**%**
AESC, Japan	2200	2200	500	23%
Nissan, U.S.	4000	1100	200	18%
Nissan, U.K.	2000	1100	100	9%
LG Chem, Korea	3500	2200	600	27%
LG Chem, U.S.	1200	600	150	25%
BYD, China	4000	1000	100	10%
Lithium Energy Japan, Japan	2300	1100	350	32%
Lishen, China	1400	500	150	30%
JCI, U.S.	1200	600	40	7%
Panasonic-Sanyo Electric, Japan	1000	1000	300	30%
SK Innovation, Korea	1000	500	30	6%
Dow Kokam, U.S.	600	600	20	3%
A123 Systems, U.S.	500	300	100	33%
Samsung, Korea	500	500	125	25%
Hitachi, Japan	200	100	35	35%
EnerDel, U.S.	300	0	0	0%
Blue Energy, Japan	200	200	40	20%
Li-Tec, Germany	300	300	80	27%
Other, China	2000	800	200	25%
Toshiba, Japan	300	300	80	27%
TOTAL	**28,700**	**15,000**	**3,200**	**21%**

Table E.6.2: Estimated Globally Installed and Utilized xEV Li-Ion Cell Manufacturing

The Author

Dr. Menahem Anderman, *President*
Total Battery Consulting, Inc.

Menahem Anderman has directed development programs for high-power nickel-based and Li-Ion batteries as well as electrochemical capacitors. His corporate experience ranges from materials research, cell design, and product development, to battery-product application, market development, technology and business assessment and general management. He holds a PhD with honors in Physical Chemistry from the University of California, and founded Total Battery Consulting in 1996 to offer consulting services in lithium- and nickel-based battery development and application, intellectual property issues in battery-related markets, and investment assessment.

Dr. Anderman provides technology and market assessments to international clients and government agencies including the U.S. Senate, the California Air Resources Board, the National Research Council, the U.S. Department of Energy, and others. As the world's leading independent expert on advanced automotive batteries, Dr. Anderman is routinely quoted in news and business journals including The Wall Street Journal, The Washington Post, and The New York Times.

The Vision

Reducing the harmful impact of vehicles on the environment is a vital task for the industrial world. With the introduction of advanced electrical and hybrid functions in vehicles, the automotive industry is now approaching cost-effective ways to reduce fuel consumption and emissions. Energy storage technology is the key to the commercial success of these advanced vehicles. The objective of the Report is to make available to industry professionals around the world information that will help them focus their financial and human resources on the most technologically viable and economically affordable solutions to the future needs of automotive energy storage. It will thus contribute to the development and support of more eco-friendly vehicles, a cleaner environment, and more responsible usage of our planet's resources.

Advanced Automotive Batteries

In 2000, Dr. Anderman founded Advanced Automotive Batteries (AAB) to provide up-to-date technology and market assessments of the rapidly growing field of energy storage for advanced automotive applications. Advanced Automotive Batteries published the 2002 and 2007 Advanced Automotive Battery Industry Reports, the 2005 Ultracapacitor Report and the 2010 Plug-In Hybrid and Electric Vehicle Opportunity Report.

Advanced Automotive Batteries also organizes the main international event in the industry: the Advanced Automotive Battery Conference (AABC), with Dr. Anderman serving as Chairman. For over a decade, the annual AABC has attracted professionals from the hybrid and electric vehicle world and the three tiers of the battery supply chain. Renowned as a global meeting place, AABC features presentations and discussions that address the most pivotal issues affecting the technology and market of advanced vehicles and the batteries that will power them. In 2010, to keep pace with the rapidly expanding technology and market development, AAB started hosting two conferences annually, in the U.S. and Europe, which together attracted over 1,500 participants. AABC Europe 2013 will take place in Strasbourg, France, June 24 - 28, and the International AABC 2014 will be held in Atlanta, Georgia, February 3 - 7.

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tel: 1 (530) 692 0140 ■ fax: 1 (530) 692 0142
industryreports@advancedautobat.com ■ www.advancedautobat.com