xEV Expansion, Key Technology, and Market Development

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Presentation Outline

I. xEV Market Trends

II. Lithium-Ion Battery Technology for xEVs

III. xEV Battery Market Forecast to 2020

IV. Technology and Market Development to 2025

xEV Market Directions: High Voltage

- ***EVs:*** New EV platforms are designed for ranges of 120-300 miles (U.S. EPA) by several automakers for 2016-2019 market introduction.

- ***PHEVs:*** Most automakers are introducing a 2^{nd}-generation PHEV during 2015-2017, most commonly with an electric range of 50 km to meet Chinese regulations. GM Volt, BYD, and Mitsubishi are offering longer ranges.

- ***Full hybrids:***
  - With fuel at the current pricing, the value proposition to customers is difficult
  - Essentially no full hybrid activity by European carmakers
  - Only 4-6 companies are active: Toyota, Honda, Ford, Hyundai, and to a lesser extent, Nissan and GM

- ***Mild hybrids at >100V:*** Very little activity

EV Market potential

- As the cost of ICE vehicles that meet future regulations increases, so does the competitiveness of electrified solutions.
- The projected drop in battery price improves the competitiveness of electrified solutions.
- Some companies believe that Battery EVs can start being competitive beyond 2025, which is not that far in the future for automotive development cycles.
- What is the market potential versus vehicle range and cost? This is the (many) billion-dollar question…

xEV Market Directions: Low Voltage

- ***Stop/start vehicles:*** also called micro-hybrids
  - In Europe, new-vehicle market share is growing beyond 60%
  - Market share is growing in Japan and is low but growing elsewhere
- ***Low-voltage micro-2 to mild hybrids*** are in active development with several vehicles on the market
  - Multiple electric-system and energy-storage configurations are under evaluation/development at 14V
  - European luxury automakers will offer 48V mild configurations, driven (at least initially) by the need to power new ancillary loads
  - Chrysler will offer a Micro-2 architecture for light SUVs at 48V (2017)
  - 48V mild hybrids at high volume, maybe in the next decade

The 2021 regulation requiring 95g CO_2/km is the predominant driver. Talks of a tougher standard (70-75g) for 2025 have intensified. Post incentives, PHEV-EV market growth is not clear.

EV

- Small market for compact cars, many producers
- Probably also a small market, in the short term, for luxury long-range EVs; how small?
- Incentives in Norway, France, Holland, and to a lesser extent, Germany play a major role

PHEV

- The European Union's decision to count zero-CO_2 for electric drive and each PHEV as 1.67 vehicles ('super credit') for the CO_2 average rating (although on a sliding scale) is the key driver
- German carmakers are now introducing a PHEV option, as a premium performance package, for most platforms
- There is synergy with the Chinese market's requirement for 50 km of electric drive
- Incentives in Holland, Norway, and to a lesser extent, Germany play a major role
- Environmentally attractive only if drivers charge at least once a day
  - Will owners of expensive cars purchased for extra performance and comfort plug in daily?

HEV

- Toyota is the only active brand at high voltage. Full and moderate hybrid development by other carmakers has essentially stopped because they presumably cannot compete with Diesel
  - Will the recent difficulties with Diesel emissions reopen discussions in favor of HEVs?
- Mild hybrids at 48V in development at several automakers; Audi, Renault, Daimler, and JLR are committed to developing production vehicles

European Market – Uncertainty for 2025

Policy

- Will European regulators move toward 70-75 gm CO_2 / km as currently proposed?
- Will incentives for PHEV/EV purchases remain in place after 2019?
- Will the VW diesel emission crisis result in tougher restrictions on diesel, which would make xEVs more competitive?

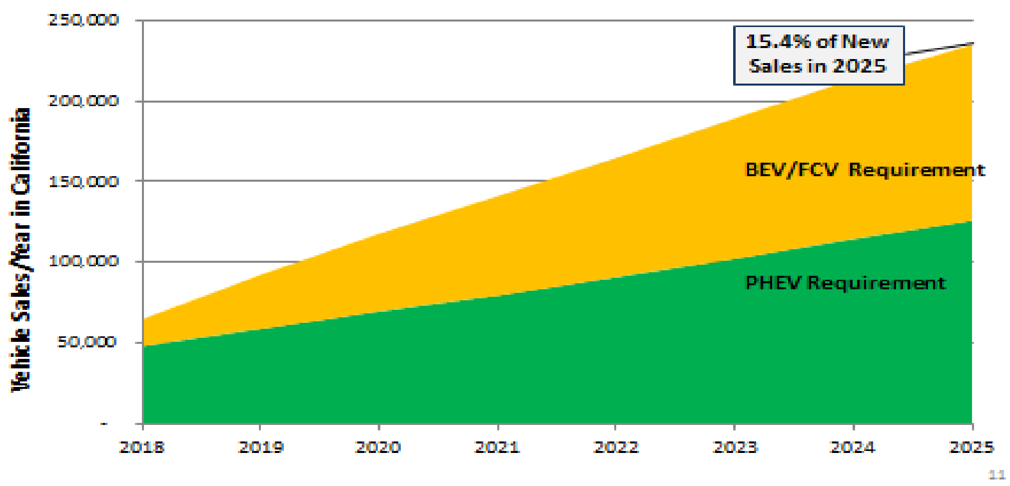
Carmakers

- Must be prepared for worst-case regulations
- Preferred solutions are segment-specific
- In the short term, most German automakers are developing a combination of 48V and PHEVs, with some EVs and essentially no high-voltage HEVs
- Development of full-battery EVs with >300km range has accelerated with the generally more positive view of market potential

The EV market share to date is very small and is predominantly due to California's CARB credits and Tesla buyers.

- Current California ARB (CARB) regulations call for a significant increase in EVs for the 2018 to 2025 period. The chart below shows an earlier prediction by CARB Staff.
- Since CARB recently modified the ZEV formula to provide more credit for longer EV driving ranges, and carmakers are increasing the vehicle range, they will be able to meet the mandate with fewer vehicles than the 15% market share initially targeted for 2025.

ZEV Mandate—BEVs/FCVs + PHEVs



U.S. Market – PHEV and HEV

PHEV

- The PHEV market share outside California is small; the CARB mandate (since 2015 also applied to other states in addition to California), access to high-occupancy lanes, and parking privileges are the key drivers. Current government subsidies pay for much of the cost differential between a full hybrid and a parallel PHEV.
- Automakers are extending the electric range in 2nd-generation vehicles.

HEV

- HEV market share has dropped from about 3% to 2%
  - Fuel cost, which has been low for the last 16 months, is the key driver.
- If we assume a cost of about $3,200 for the current (30-kW) HEV package, the (straight) payback is about 9 years with gasoline price of $2.25 per gallon.
- HEV market share is likely to increase since meeting post-2017 federal CAFE standards is more demanding. If gasoline prices do not increase, automakers will have to take a hit on the profit margin to increase sales.

Will the Republican administration reverse the tightening of fuel-economy standards?

Chinese xEVs—The Bottom Line

- China became EV market leader following rapid expansion: about 500k PHEV/EV sold in 2016
  - Government policies are the predominant driver
- Safety, reliability, and durability are not up to Western standards but the Chinese market is more tolerant
- Significant impact on Chinese battery makers and materials producers with major capacity expansion of both during 2015-2017
- Even if growth slows down, significant battery aftermarket business is essentially secured
- Government is holding back Samsung and LG Chinese plants from participating in the market but resolution is expected

Japanese Market

- Hybrid sales in 2012 to 2015 for Toyota and Honda—driven initially by a preferential tax treatment—40+% of their sedan non-K-Class offerings.
- Sales of Prius PHEVs, Nissan Leaf, and i-MiEV EVs have been slow; MMC's Outlander PHEV has fared better.
- Many carmakers are active with micro-1 and micro-2 hybrids.
- Reduced use of nuclear power makes EVs less attractive.
- Toyota is focusing on HEVs + FCEVs; Honda had the same focus but lately has appeared a bit more open to Battery EVs; Nissan is focusing on EVs.

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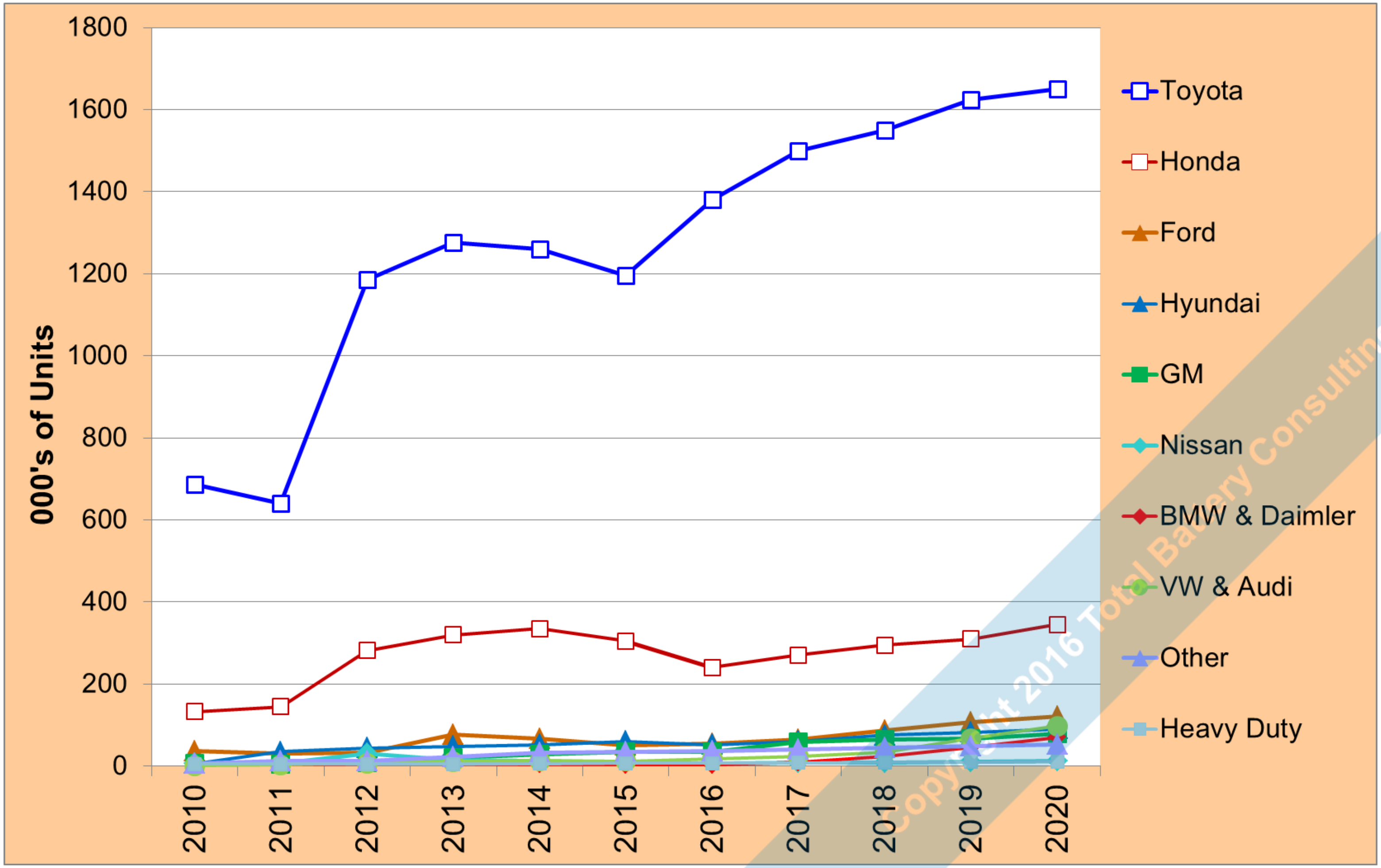
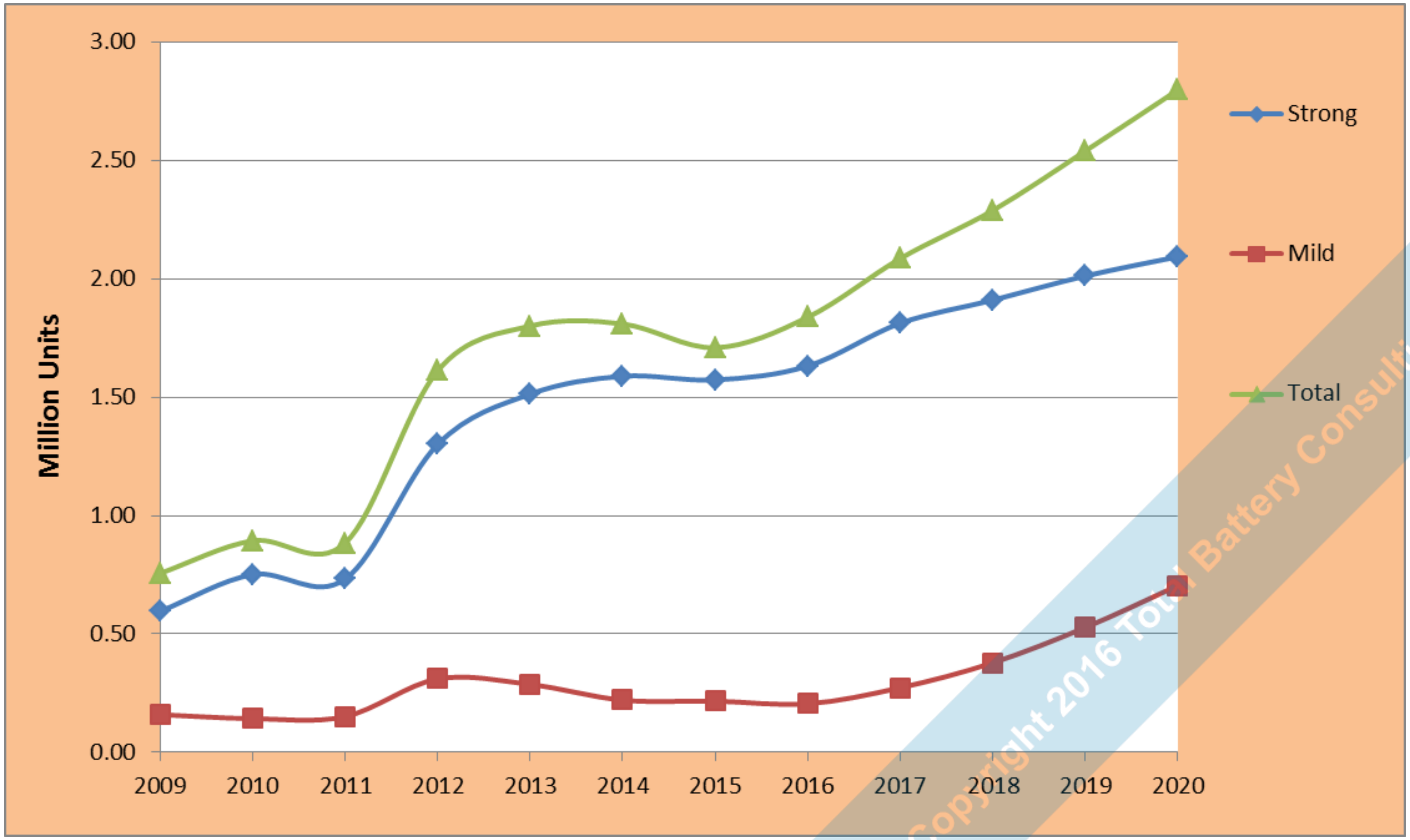
HEV Market by Vehicle Producer 2010 – 2020



HEV Market by Hybrid Category



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- Lithium Ion is now the battery of choice for essentially all new xEV architectures by all producers. The exception—Toyota, will continue to predominantly use NiMH batteries on the majority of its large full-hybrid offerings.
- Li-Ion HEV cells are proving reliable; a 10- to 15-year life in the application seems feasible.
- Li Ion introduction in PHEVs and EVs by major automakers was also generally successful with relatively limited reliability and safety issues; while durability in the field is promising, 10-12 years of life are yet to be confirmed. Efforts shifted to improving energy density and reducing cost.
- Improvement in energy density, life, and abuse tolerance of the NMC cathode makes it the preferred cathode for most applications.

Low-Voltage Hybrid Li-Ion Design

Configuration	Capacity, Ah	Key design drivers
14V single Battery	40-70	Low temperature power High temperature tolerance Voltage compatibility Voltage Compatibility
14V supporting battery	6 - 15	Charge Acceptance High temperature tolerance Cycle life Power over SOC
48V supported by 14V lead-acid	6 - 15	Power over SOC Cycle life

Small Li-Ion battery in parallel with a Lead-Acid battery

- The Li-Ion battery does most of the cycling; the Lead-Acid battery for cold start and emergency loads
- Is DC to DC necessary? Car companies are aiming to avoid it
- Battery in engine compartment is challenging; the need for a heat shield will eat into the advantages of the architecture
- Will need 5-12 Ah high-power Li Ion 150 to 250 regen amps
- Graphite LFP, or LTO-NMC chemistries for best voltage match
  - LTO is best for charge acceptance and low temperature power but is more expensive
  - Avoiding lithium plating at low temperature charge is problematic for LFP chemistry
- SDI offers an NMC-Hard / amorphous carbon design with excess negative where the carbon negative electrode is never fully charged and the operating voltage is between about 3 and 3.7V (12 to 14.8 in a 4 cell battery)
- Li-Ion battery cost potential (10 Ah 14V) under $200
- Suzuki has launched a K vehicle with a Denso-Toshiba LTO system—very high sales volumes

48V Mild Hybrids – Battery Requirements and Selection

- **48V Li Ion, 12V—most likely Lead-Acid but some automakers are evaluating a solution with two Li-Ion batteries**
- **Energy-storage requirements are being developed but 7-15 kW at 48V will require 150-300 Amps or 7-14 Ah 'HEV' cells (with even higher power-to-energy ratio)**
  - SOC swing depends on loads; e-turbo and mild hybridization most demanding
  - For e-stabilized suspension, only short (about 100 msec.) pulses—supercap can do the job
- **Multiple energy-storage systems have been selected for early programs:**
  - Supercaps
  - Carbon/NMC Li Ion
  - LTO/NMC Li Ion
  - Carbon/LFP Li Ion
- **Cost of 12-kW Li-Ion battery at moderate volumes around $350**

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Li-Ion Cells Employed in EVs 2008-2016

Cell Maker	SOP	Chemistry	Capacity	Configuration	Used in:	
	Year	Anode/Cathode	Ah		Company	Model
Li Energy Japan	2008	G/LMO-NMC	50	Prismatic	MMC	i-MiEV
AESC	2010	G/LMO-NCA	33	Pouch	Nissan	Leaf
LG	2012	G/LMO-NMC	16	Pouch	Ford	Focus
A123Systems	2012	G/LFP	20	Pouch	Chevy	Spark
Panasonic	2012	G/NCA	3.1	Cylindrical	Tesla	Model S
LG	2012	G/LMO-NMC	36	Pouch	Renault	Zoe
Litech	2013	G/NMC	52	Pouch	Daimler	Smart
Toshiba	2013	LTO-NMC	20	Prismatic	Honda	Fit
Samsung	2013	G/LMO-NMC	63	Prismatic	CFA	500
SK Innovation	2014	G/NMC	38	Pouch	Kia	Soul
Samsung	2015	G/LMO-NMC	63	Prismatic	BMW	i3
Panasonic	2015	G/NMC	25	Prismatic	VW	e-Golf
AESC	2015	G/LMO-NCA	40	Pouch	Nissan	Leaf
Panasonic	2015	Gr-Si/NCA	3.4	Cylindrical	Tesla	Model X
LG	2016	Gr/NMC	56	Pouch	Chevy	Bolt

A large variety of cell configurations and capacity with no conversion

Where is the improvement in energy density coming from?

- Eliminating LMO from cathode formulation
- Cathode with higher
  - Ni content: NMC 1.1.1 to NMC (5,3,2) → **6,2,2** → **? 8,1,1**
  - Charge voltage 4.15 → 4.25 ? → **? 4.4**
- Some Silicon in anode, better fit with NCA chemistry and for lower cycle life EVs
- Better utilization of space inside cell
- Denser/thicker electrode (when power demand can still be satisfied)

EV Cell Pricing Chevy Bolt (GM)

suggesting a path to cell pricing of $100/kWh by 2022

The industry is targeting this price level. Here are the risks:

- Is there profit at today's and tomorrow's prices?
- What is the investment level to get to tomorrow's pricing?
- Will metal pricing go up again? **Cobalt** is particularly risky
- Manufacturing subsidies: for how long?
- Will most materials need to be produced in China?

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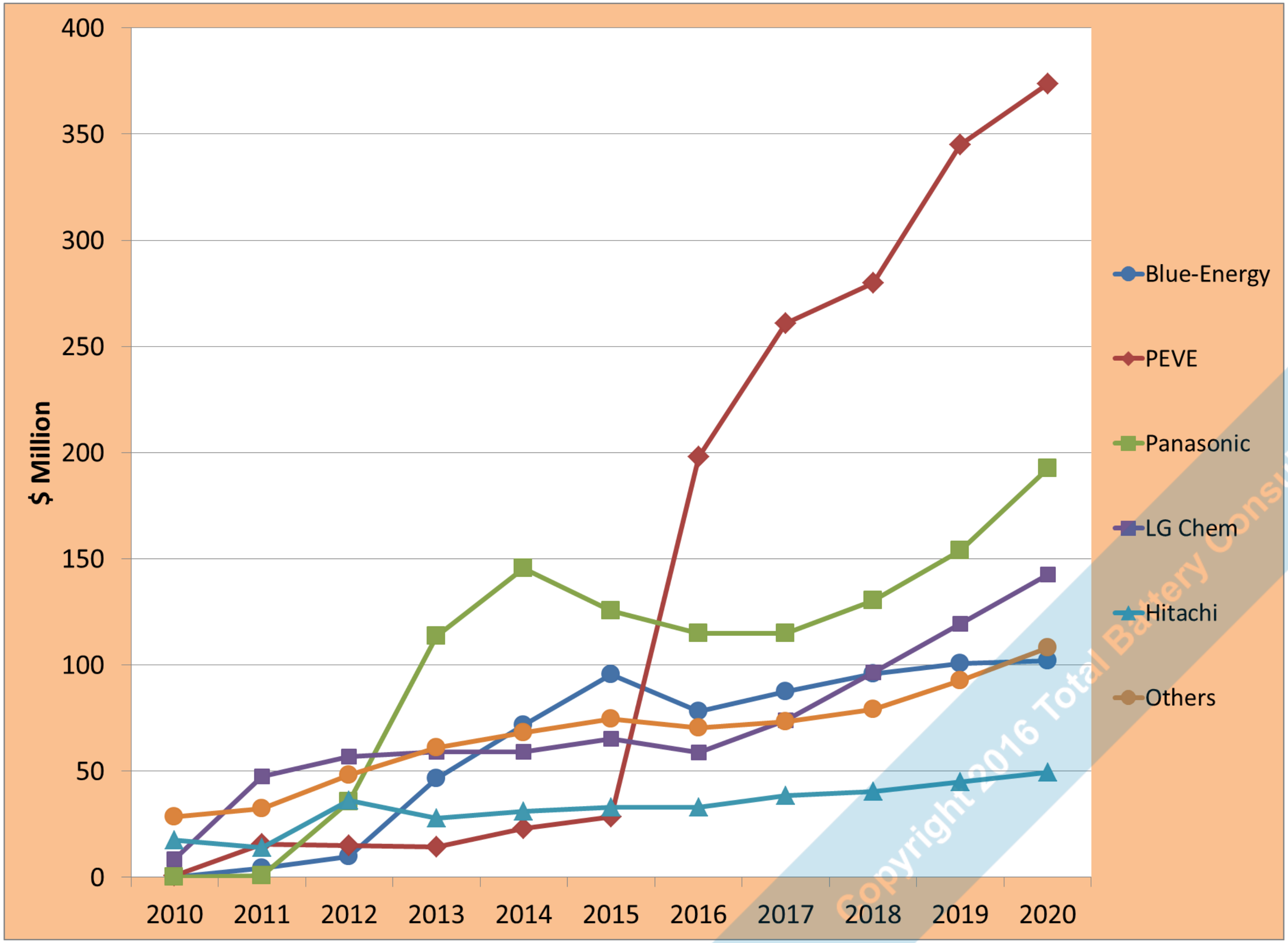
Li-Ion HEV Battery Module Market



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Lithium-Ion Projections for 2025

- Until field data on 2nd generation confirm reliability, it is a bit risky to project 3rd generation due to trade-offs in energy density, safety, and life.
- Some suppliers (predominantly Korean) project very high performance and low pricing.
- Volume will play a role but higher volume on some materials may not secure lower pricing.
- Continued high R&D and capital investments must be paid back eventually.

We believe that beyond Li Ion is… a better Li Ion

- Li Ion is a system, not a fixed chemistry. High-voltage and/or high-capacity cathodes, high-voltage electrolytes, Si-containing anodes, additives for low and high temperatures are all challenging, but are more realistic targets than most new chemistries (at least for automotive batteries)

- Li Ion offers an unusually compelling balance of energy, power, and life. Most other 'beyond' systems have no chance to match volumetric performance of Li Ion, and life at this point is minuscule

The two most 'promising' technologies are:

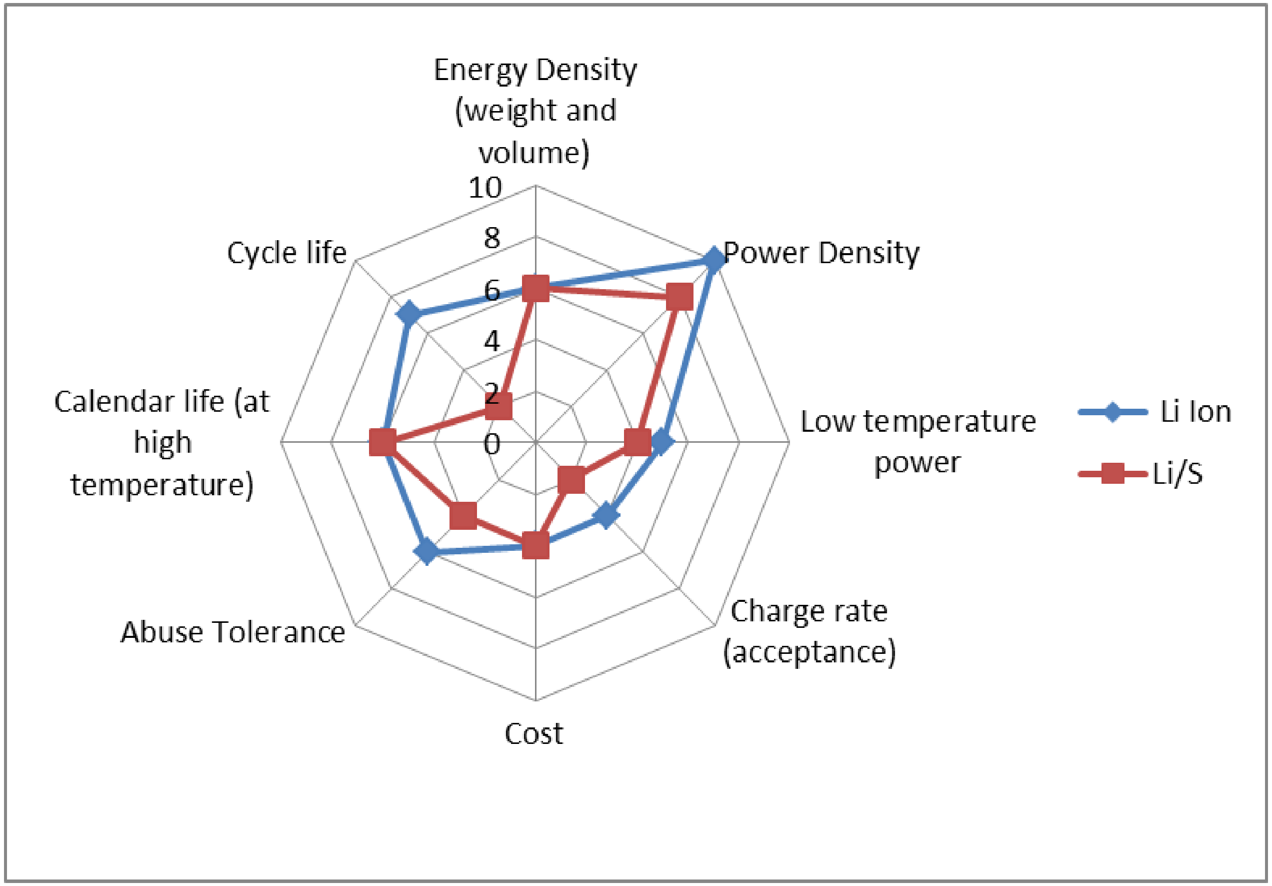
➢ Solid Electrolytes

- ✓ Could theoretically support higher energy density (with metallic Li anode) and better safety
- ❖ Have been under development for nearly 40 years
- ❖ Room temperature conductivity is not enough for automotive, need -30°C
- ❖ Consumer battery applications make more sense
- ❖ Cost of some of the new materials could be an issue
- ❖ Cyclability against Li metal is unproven
- ❖ Solid-solid interface at a porous cathode is a big challenge
- ❖ Could in fact work with Li-Ion system as well, but this would just be a Li-Ion battery with a new electrolyte system

➢ Lithium Sulfur

- Severe cycle-life issues and little potential benefit versus Li Ion
- *See next slide for spider diagram showing Li Ion versus Li Sulfur*

No single system has a chance to match Li Ion in even half of the 8 key performance attributes!



Our Projections for 2025 – EVs

- Assume a world market of between 2 and 3 million cars
  - Key question: How high will customer interest be when subsidies subside?
- Battery specific energy: 160 – 200 Wh/kg
- Average battery capacity: 55 kWh, weight 300 kg
- Battery cost: $130 to 170/kWh
- **~$8.2k for a 200-mile, 55-kWh battery**

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For More Information:

The xEV Industry Insider Report

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Based on an analysis of the major automakers' plans and regional conditions worldwide

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