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EXTRACT

The xEV Industry Insider Report

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Chapter Outline



I. xEV Market Trends

1. Overview
2. Vehicle Markets by Region
   - China
   - Europe
   - US
   - Japan
   - Rest of the World
3. Vehicle Market Forecast to 2020
   - By xEV category
   - By world region
   - By carmaker
4. Vehicle Market Forecast Beyond 2020
5. Directions of Individual Carmakers

Market Drivers

- Complying with government regulations at the lowest possible cost is the ultimate driver for automakers.
  - Since worldwide regulations, mandates, and incentives are changeable, the preferred electrified architectures also change.
  - The preferred solutions for individual automakers in specific markets also depend on their vehicle types (light, heavy, and premium) and technological strength.
- Lower CO_2 emissions in the longer term are the most important driver for society and governments; the average reduction target from 2015 to 2025 is 40%, with Europe possibly going even further.
- Industrial competitiveness in the technology of the future and a “green” progressive image are important factors.
- Customer benefits:
  - Government-given perks
  - Lower fuel cost
  - Electric drive: high torque at low speed
  - High-tech profile
  - Enhanced comfort features

Mild to Advanced Micro-HEVs (MHEVs)
Main Development and Direction

- 48V mild hybrids are gaining momentum in Europe but the main driver is power from enhanced power supply and the functions it enables, not hybridization.
- Low-voltage micro-2 (advanced 14V) vehicles are in active development. Multiple electric-system and energy-storage configurations.
- Europe's premium car makers are the leaders.

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- Some are projecting 48V fuel-economy savings of 15%+, but real values are 6-9%.
- 48V power requirements range from 7 to 25kW but 10-15 seems most common and viable in the near term.
- Most designs include a 12V lead-acid battery.
- LFP or LTO chemistries are preferred at 14V, and NMC at 48V.

Powertrain Electrification and Impact on CO_2 Emissions

Tank-to-Wheel fuel consumption / Reduction of CO_2 Emissions

	Micro-1 Hybrid	Micro-2 Hybrid	48V Mild Hybrid	Full Hybrid	Plug-in Hybrid	Battery EV
WLTP:	3-4%	4-6%	8-13%	25-40%	50-70%	100%
Real Life:	1-3%	2-4%	5-9%	25-40%	35-70%	100%
Real Life: Well-to-Wheel	1-3%	2-4%	5-9%	25-40%	30-70%	30-100%

Real Life: Well-to-Wheel fuel consumption / Reduction of CO_2 Emissions

Increasing Cost

The matrix for CO_2 reduction has a major impact on results!

Worldwide Sales of Top Electric Vehicles (2018)

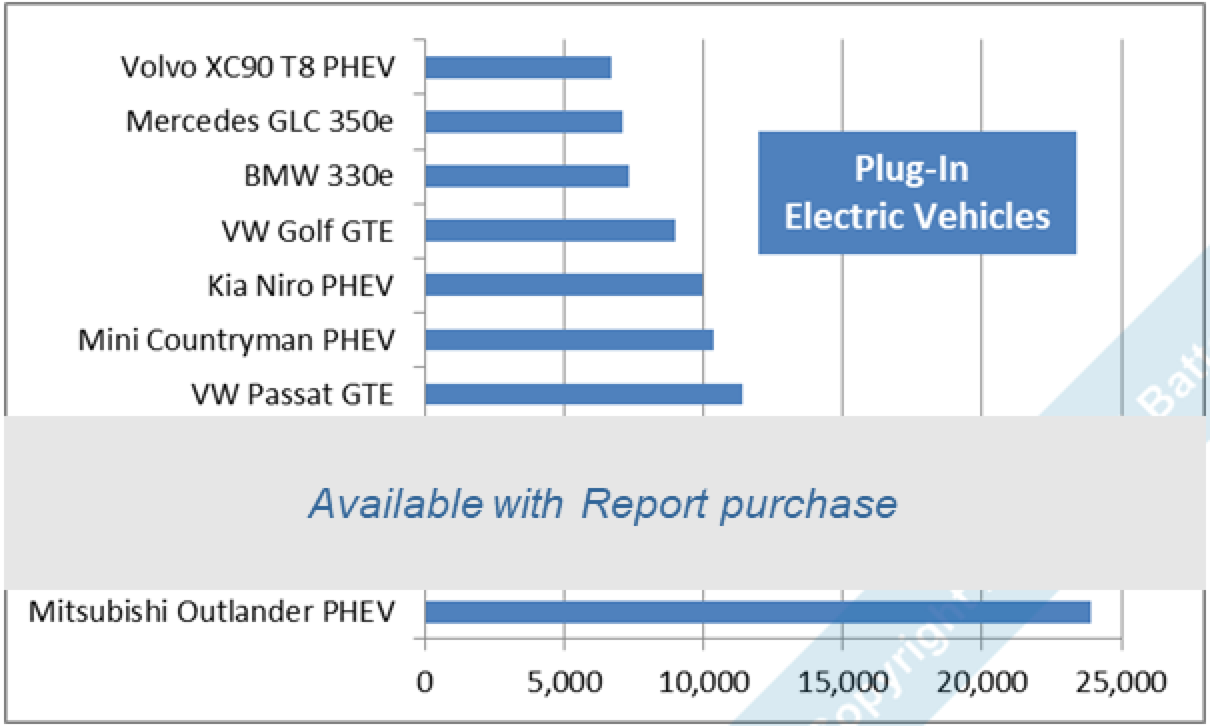
Chinese NEV (PHEV + EV) Market, 000 units

Cars	2013	2014	2015	2016	2017	2018
EVs						*Available with Report purchase*
Cars	9	25	148	257	410	
Buses	6	20	90	135	105	
Logistic Vehicles	0	0	10	17	137	
Total Evs	15	45	248	409	652	
PHEVs						
Cars	3	30	74	79	111	
Buses and Logistic	0	0	10	19	14	
Total PHEVs	3	30	84	98	125	
Total xEVs	18	75	331	507	777	

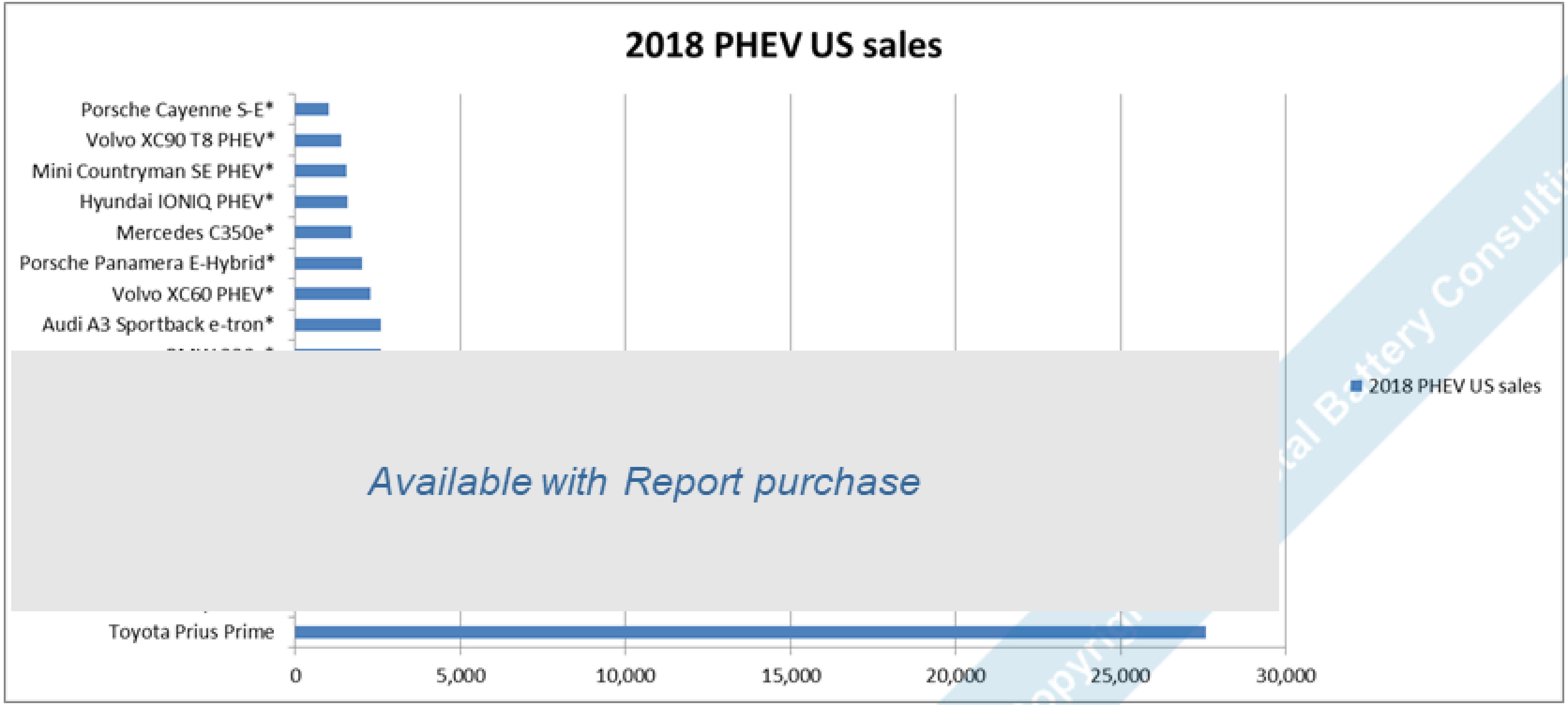
Chinese xEVs – The Bottom Line

- **China became EV-market leader following rapid expansion.**
  - Governmental policies are the predominant driver.
- **Significant growth for the EV and PHEV markets started in 2014.**
  - From 75k units (EVs and PHEVs combined) in 2013 to 507k for 2016 and over 1,180k for 2018 (all including buses).
- **Current target is for 2 million EV/PHEV sales in 2020 and 7 million in 2025.**
- **Significant impact on Chinese battery makers and material producers with major expansion of capacity for both during 2015-2019.**
- **Reliability and durability are improving but are not up to Western standards the Chinese market is more tolerant.**
  - Many local battery suppliers, some already being weeded out as the leaders continue to invest and improve their technologies, and since Korean and Japanese battery makers are now allowed to participate in the market under equal terms.
- **Significant battery aftermarket business is essentially secured even if growth slows down.**
- **Government has lifted the blacklisting (April 2018) of the Chinese plants of Samsung, LG Chem, and SKI, which prevented them from participating in the market.**

European Sales of Top Plug-In Electric Vehicles (2018)

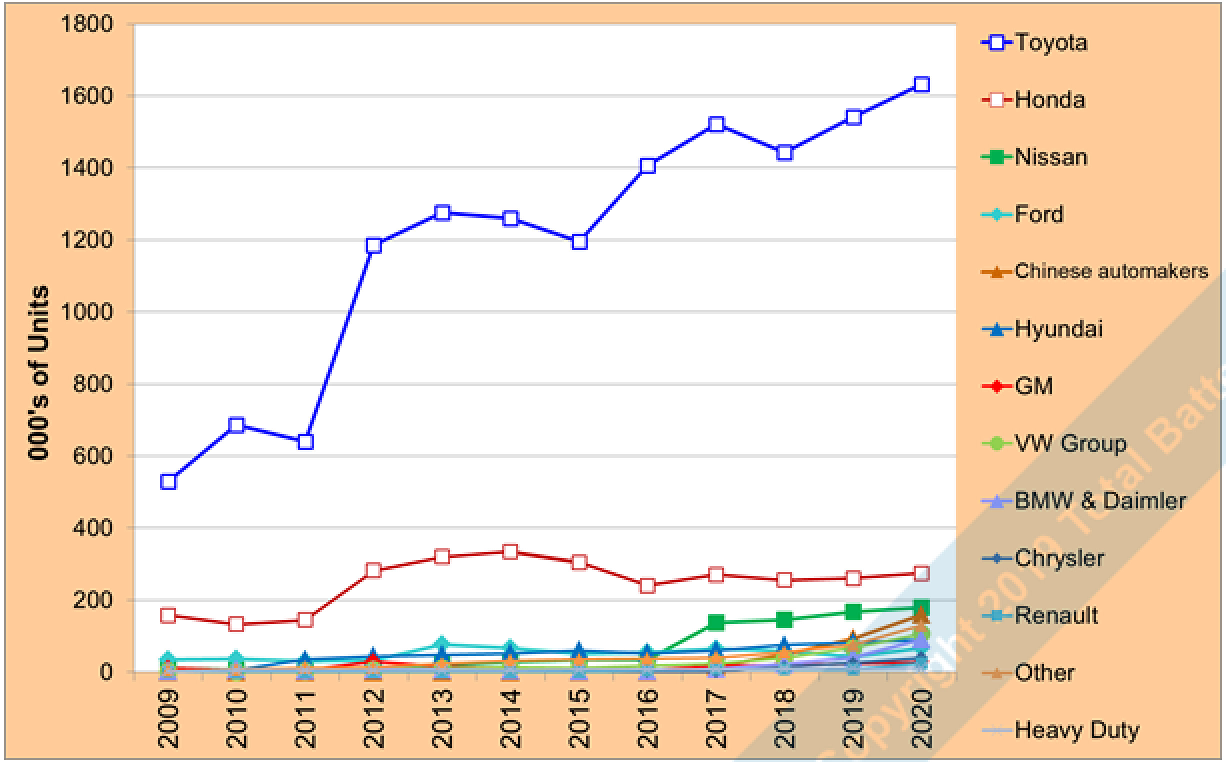


2018 PHEV US Sales

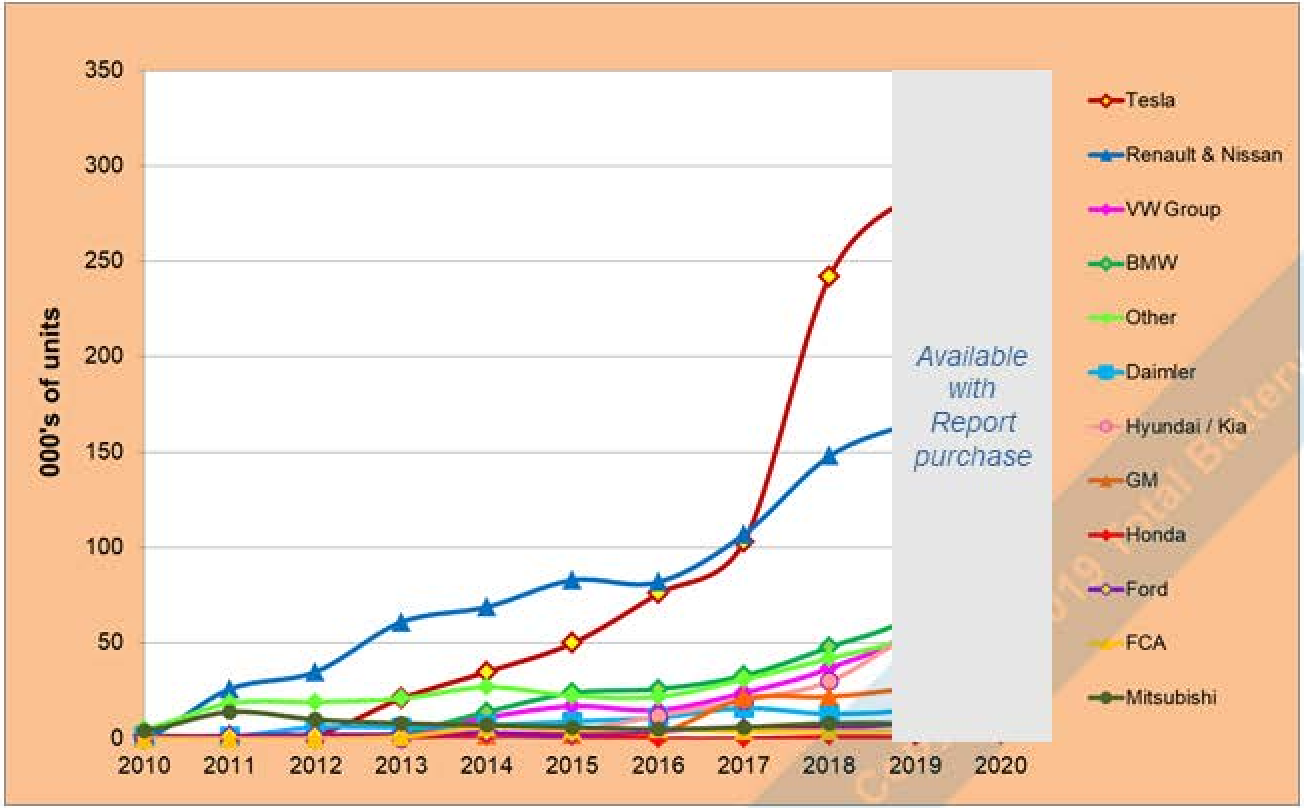


- The market depends largely on government policies: subsidies, other incentives, and regulations
  - Which also affects the type of xEV, HEV, PHEV, or BEV
- Key markets in this group: Korea, Canada, Hong Kong (shrinking after cancelation of subsidy), and India (growing)
  - From the group above, only Korea and India make xEVs and only Korea makes xEV batteries, so there is no industrial incentive to promote xEVs
  - India is interested in making Li-ion cells at some point

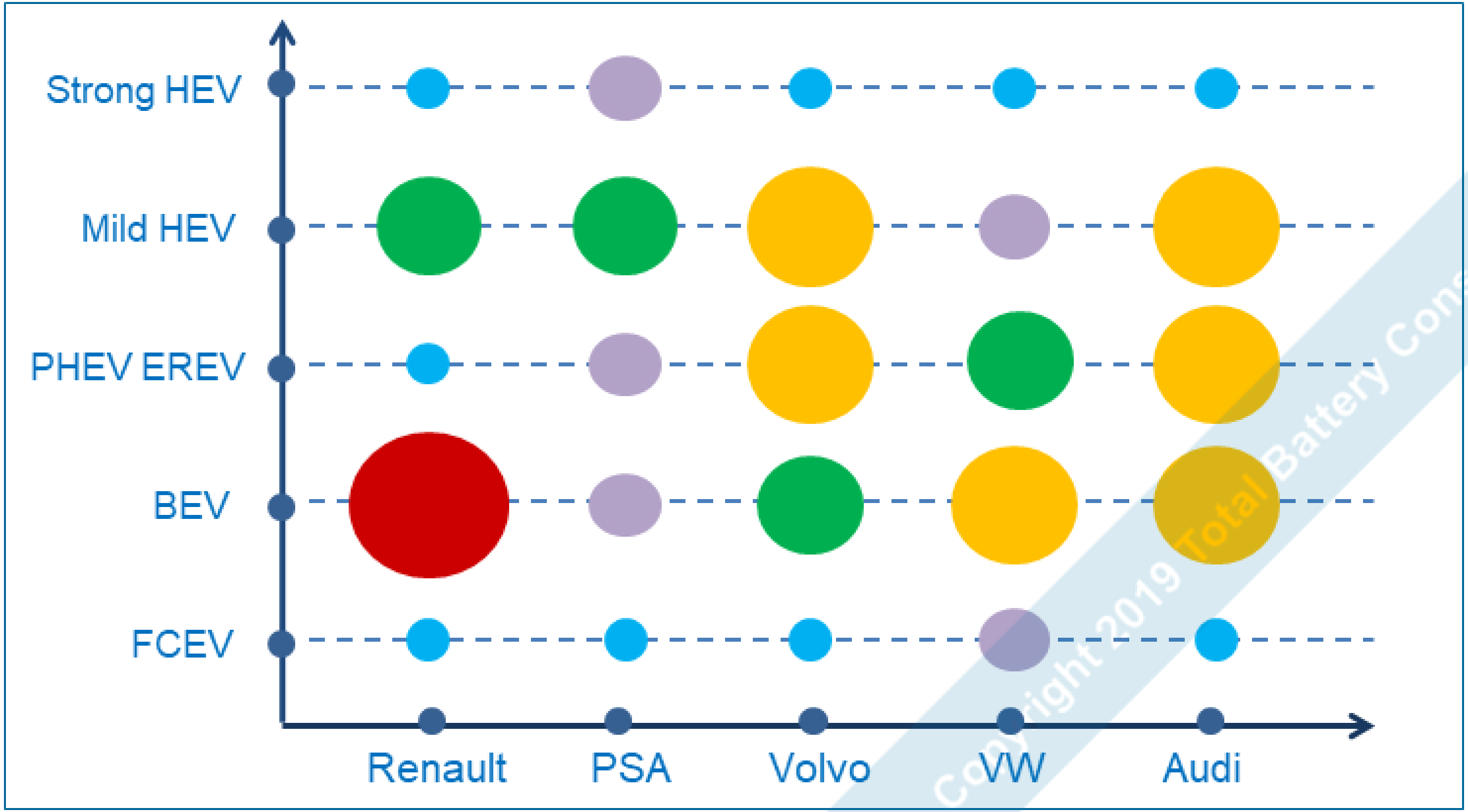
HEV Market by Vehicle Producer 2010 – 2020



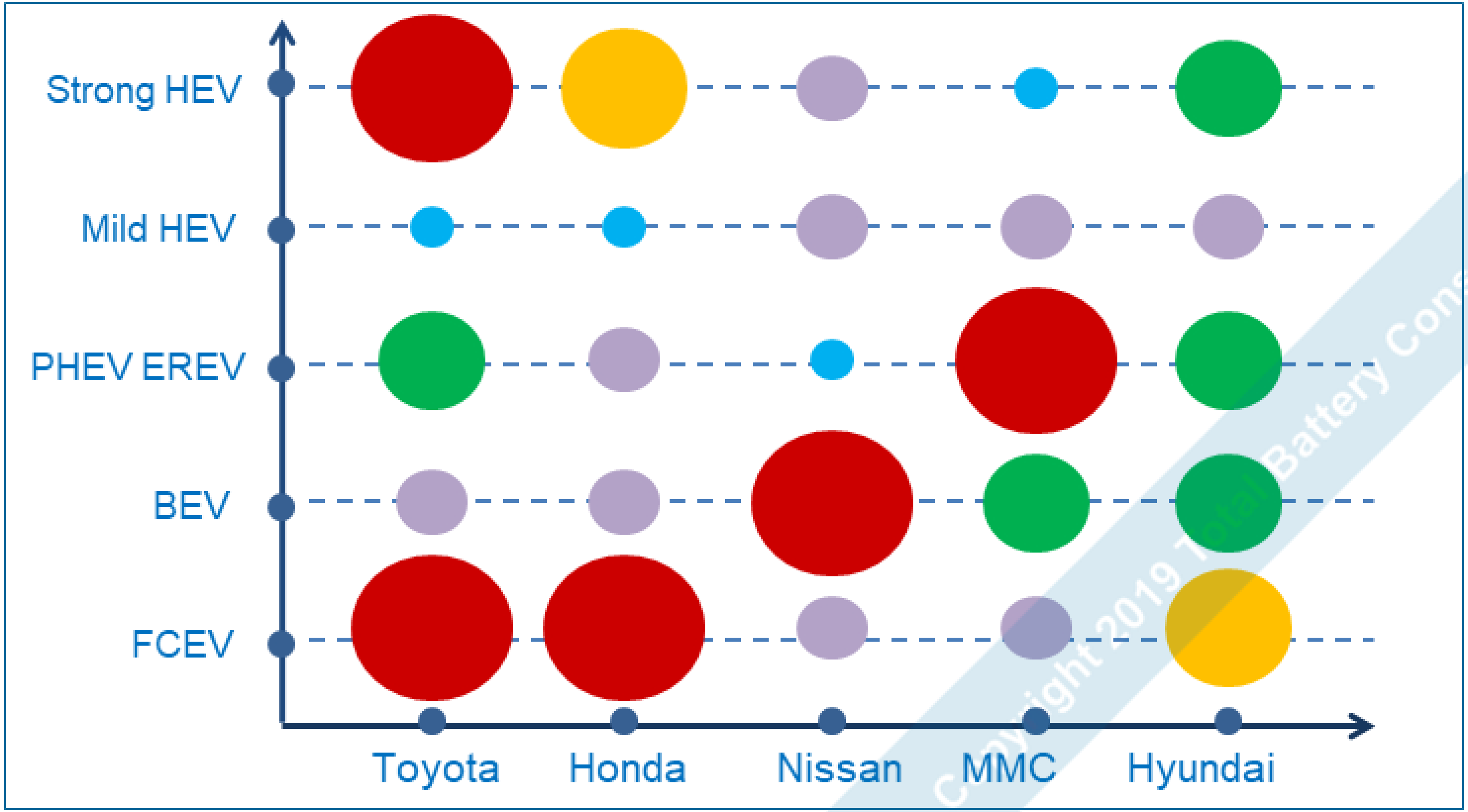
EV Market Forecast
Excluding Chinese Automakers



Direction of Key European Carmakers



Direction of Asian Carmakers



General Motors

- EV Chevy Bolt with 238 miles was introduced at the end of 2016
  - LG Electronics makes the battery pack and many of the other vehicle components
- Second-generation EREV (series PHEV) Chevy Volt with 50-mile electric range was introduced in September 2015, has experiencing steady sales but is discontinued

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- Low-cost mild hybrid 'e-assist' with Li-ion battery has been introduced in several platforms but sales have been low and some models discontinued
- Offering full-size pick-up trucks in 88V (very) mild hybrid
- LG Chem is the battery-cell supplier for PHEVs and EVs, Hitachi for HEVs
- Late with 48V and advanced micro-hybrids

Renault

- Renault has introduced four EVs since 2011. Sales were initially well below plan but picked up in 2015.
- Renault increased battery capacity from 22 to 41 kWh for the 2017 Zoe, and sales improved.
- The company chose LG Chem as battery supplier for its latest EVs and for the 48V vehicle (LTO chemistry)
- No high-voltage HEVs or PHEVs

ESS Parameter	12-13	14-16	2017
Pack Integrator	Renault		
Configuration	96s2p		
Voltage (V nominal)	360		
Peak Power (kW)	80		
Energy (kWh)	25.6 (total) 22 (usable)	25.6 (total) 23.3 (usable)	45 (total) 41 (usable)
P/E Ratio (kW/kWh)	3.6	3.4	1.95
Mass (kg)	280	280	300
Specific Energy (Wh/kg)	78.6	83.2	136.7
BMS Type	Distributed		
Thermal System	Air		
Enclosure Material	Metallic		

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Current lineup:

- **BMW i3** (third generation, 120 Ah)
- **BMW i3s**
- **BMW i8 Coupe** (2nd generation PHEV)
- **BMW i8 Roadster (PHEV)**

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- **BMW X1 xDrive25Le** (EV, Chinese market only)

2019 Introduction:

- **MINI Electric**
- **BMW 3 Series Sedan PHEV** – new plug-in hybrid variant (2nd generation)
- **BMW X5 PHEV**

Main takers

- Market success requires designing the car for the customers, not for the regulators.
- Range matters; 75 miles is not enough, 200 miles is attractive.
- Many people in the high-end market like the feel of electric drive; some of them also care about the environment.

Because of Tesla, carmakers are now:

- Developing or at least reconsidering dedicated EV platforms to allow for a larger battery and longer range.
- Significantly expanding driving range for existing platforms.
- Implementing EV in high-end vehicles.
- Driving their battery suppliers to reduce pricing to compete with Tesla.

Carmakers have evaluated but largely rejected the Tesla battery approach…

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II. Lithium-Ion Battery Technology for xEVs

1. **Key Battery Design Parameters**
2. **Mild and Strong Hybrid Batteries**
   a) Requirements
   b) Cell and Pack Design
   c) Cost
3. **EV & PHEV Battery Technology**
   a) PHEV Battery Technology Evolution
   b) EV Cell & Battery Design, Energy & Power Density
   c) Life and Safety
4. **EV & PHEV Battery Cost**
   a) Cost of Materials
   b) Cell and Battery Cost
   c) Cost Reduction Trajectory

Cell Design & Casing : Pouch, Cylindrical, or Prismatic

- No consolidation since 2010
- Cylindrical and pouch designs have the advantage at the cell level but less so at the module level
- The module's thermal management design is a key distinction; prismatic is the easiest design but new pouch designs are emerging
- Cylindrical designs are judged less reliable at the module level but more versatile
    - Little field data on 21700 cells yet
- Cylindrical cells will be used by major automakers if:
    - Volume/shape constraints of battery pack are a hindrance for utilizing larger cells
    - Increased energy density of larger cells hits a safety snag
- Differences in long-term reliability/durability and safety, which will not be confirmed for several years, could shift the advantage between the three approaches
- It is more difficult to accommodate high-nickel cathodes in pouch cells


Cathode: NMC is the Focus for Large-Cell EV Batteries

- The industry has just moved from NMC1,1,1, (through 5,3,2) to 6,2,2
    - Specific cathode capacity is up from about 145 to 175 mAh/gram
- The next step is being introduced this year: NMC 8,1,1 and related compounds
- Higher nickel content provides higher energy density + lower cost of raw materials
- More intense development in the direction of < 5% cobalt content, some including Mg
- However, higher nickel content brings some challenges:
    - Cathode manufacturing: More stringent sintering environment
    - Cell manufacturing: Higher moisture sensitivity
    - Safety: Higher energy release
    - Life: Structural and surface deterioration

Anode: Graphite-Based

- **Graphite is almost an ideal anode!**
  - Operates 3V negative of H2 electrode potential, well negative of thermodynamic stability of the electrolyte
  - Protected by a relatively stable solid electrolyte interphase (SEI)
  - Specific capacity around 350 mAh/gram, double that of the cathode
  - Volumetric capacity around 720 Ah/liter, similar to cathode
  - Excellent cycle life
  - Good power
  - Inexpensive raw material possible
  - Cost impact $5-8/kWh: about 1/7th that of the cathode
- **Areas of desired improvement**
  - Faster charge at low temperatures
  - Higher capacity density
  - More stable SEI at intermediate temperatures
  - Lower processing cost is always nice

Si-Blend Anode

- ✓ Si possesses high gravimetric and volumetric capacity: around 3500 Ah/kg and 2,200 Ah/L.
- ➢ Si stores lithium islands internally, not intercalation into a dimensionally stable structure.
  - High irreversible capacity is a drawback
  - Significant swelling
- ✓ Small, 3% to 6% Si with > 1,800 mAh/gram cyclable can be added to graphite anode and still support acceptable cycle life.
- ✓ At 3-6% Si, designers can match the anode's irreversible capacity with that of the high-nickel cathode.
- ✓ 6% silicon at 50% utilization (ca. 1750 mAh/gram), brings the blend's capacity to ca. 440 mAh/gram.
- ➢ For more than 10% silicon, pre-lithiation is currently needed as well as cell engineering that can accommodate the large expansion/contraction of the material upon cycling.
- ➢ High silicon can make sense for low-cycle-life applications if pre-lithiation is affordable.

Solid Electrolyte/Separator?

There is much excitement in the press regarding the future replacement of both separator and electrolyte with a solid electrolyte (inorganic or polymer).

However, the challenges are currently bigger than the benefits:

- ✓ Solid electrolytes do not burn as easily
- ? Solid electrolytes are not necessarily more (electro-)chemically stable
- ! Solid electrolytes are likely to occupy more space
- ! Solid electrolytes are heavier
- ! Solid electrolytes are more expensive
- ! Solid electrolytes complicate cell manufacturing
- ! Making a cyclable solid electrolyte/electrode composite is a challenge

Li-Ion HEV 5-Ah Cell Price

250-MWh plant, 2018 timescale
5-Ah, 500-W HEV Cell

5Ah 500W HEV Cell Price				
NMC/graphite, Metal Can, 12 Million HEV Cells / year				
Component	**$/cell**	**Per kWh**	**Per KW**	**%**
Materials	4.6	255	9.3	66%
Factory Depreciation	1.25	69	2.5	18%
Manufacturing Overhead	0.50	27	1.0	7.1%
Labor	0.36	20	0.7	5.1%
Un-yielded COG	6.75	371	13	96%
Scrap, 4%	0.28	15	0.56	4.0%
Factory COG	7.03	386	14	100%
SG&A + R&D	1.24	68	2.5	15%
Burdened Cost	8.3	454	17	115%
Warranty & Profit	0.8	45	1.7	10.0%
Price	**9.1**	**500**	**18**	125%
Gross Margin	2.07			23%

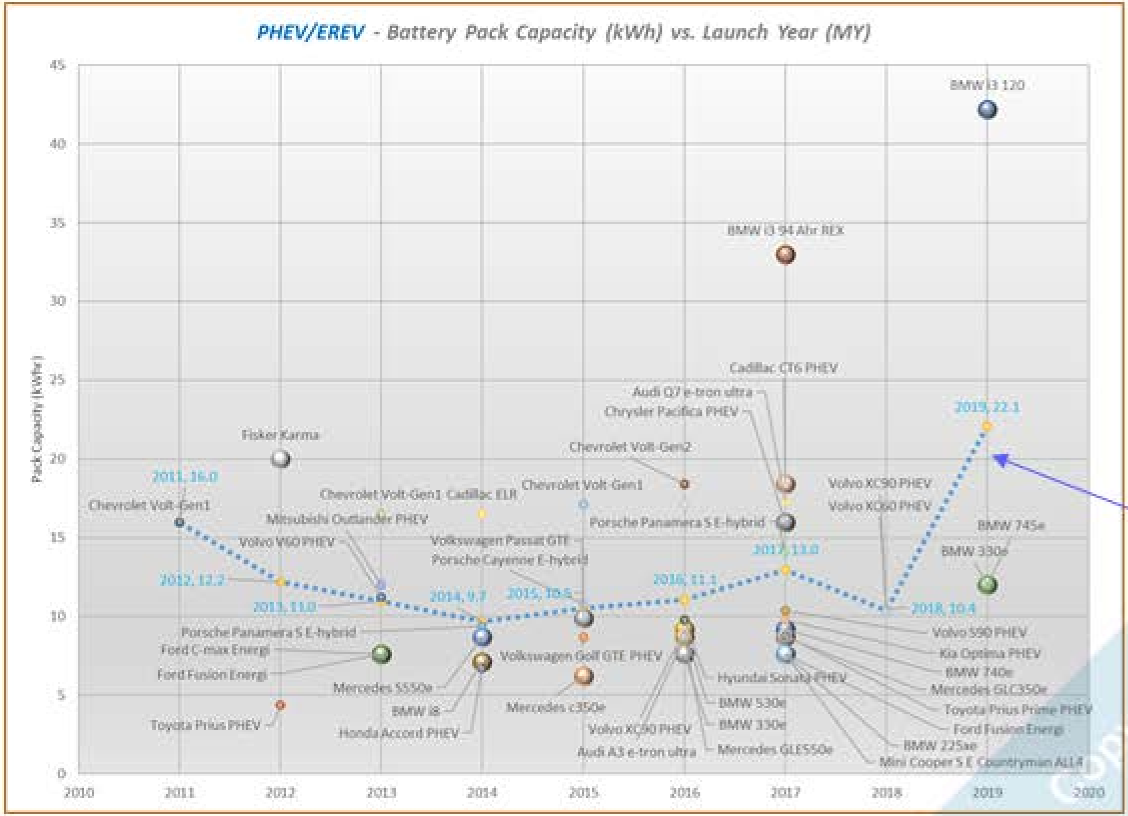
10-Ah MHEV Cell Price 2020

10Ah, 1167W, 32W/Wh, HEV prismatic Cell price				
NMC/graphite, Metal Can, 12 Million HEV Cells / year				
Component	**$/cell**	**Per kWh**	**Per KW**	**%**
Materials	7.34	202	6.3	66%
Factory Depreciation	2.13	58	1.8	19%
Manufacturing Overhead	0.72	20	0.6	7%
Labor	0.46	13	0.4	4%
Un-yielded COG	10.64	292	9.1	96%
Scrap, 4%	0.43	12	0.4	4%
Factory COG	11.07	304	9.48	100%
SG&A + R&D	1.51	41	1.29	12%
Burdened Cost	12.6	345	10.8	114%
Warranty & Profit	1.0	28	0.9	8.0%
Price	**13.6**	**373**	**11.6**	122%
Gross Margin	2.52	0	0	23%

Small Li-ion battery in parallel with a Pb-acid battery

- The Li-ion battery does most of the cycling; the Pb-acid battery is used 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 graphite 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!
- Audi is launching a vehicle with SDI 14V battery.

PHEV Battery Pack – Capacity vs. Launch Year



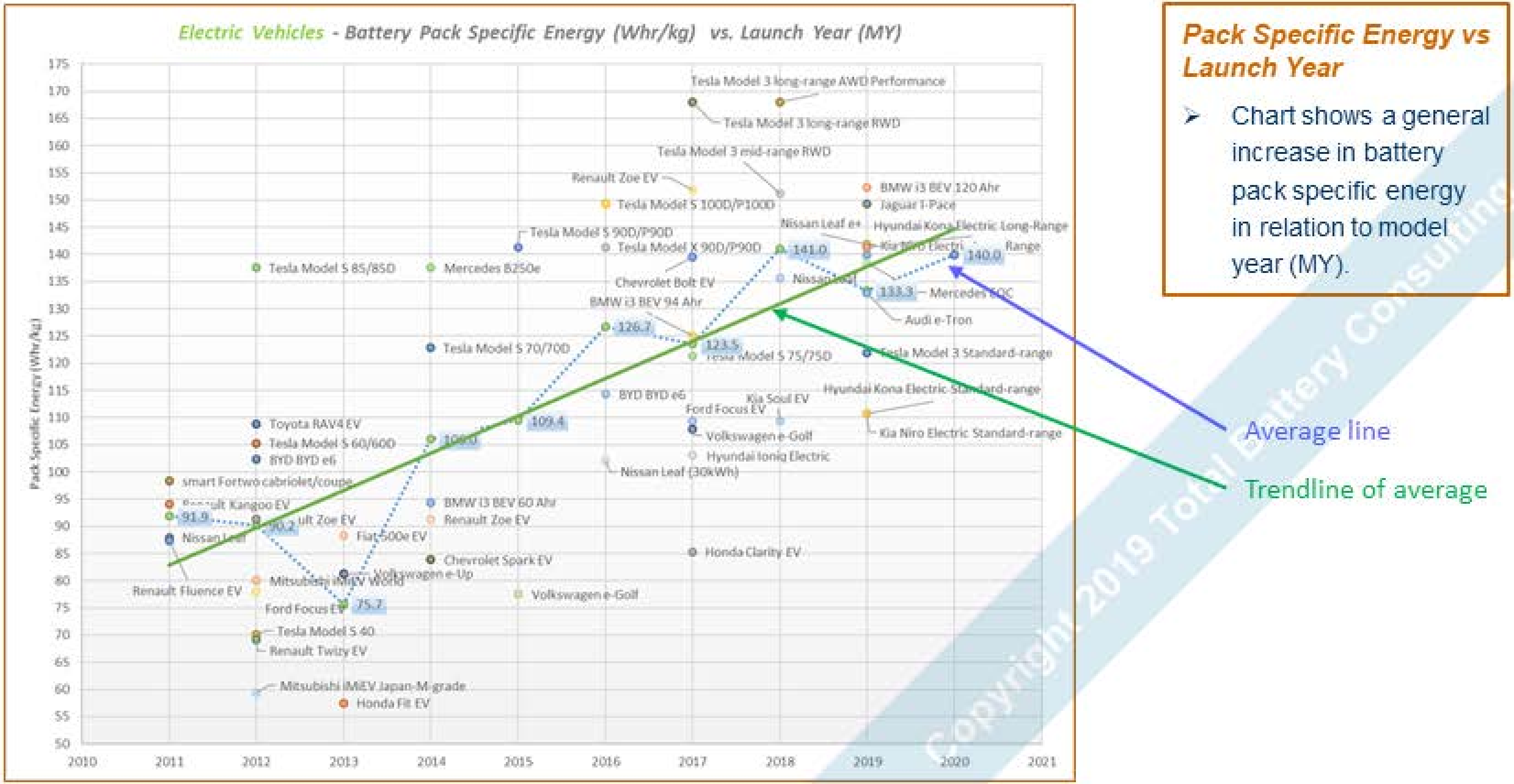
Pack Capacity vs Launch Year

- Chart shows a scattered relationship in battery pack capacity in relation to model year (MY)

EV Pack Key Characteristics since 1996

Year	Annual Production Packs/year	Carmaker	Vehicle	Battery Capacity, kWh	Battery Technology	Cell Casing	Estimated Battery Pack Parameters		
							Energy Density		Cost
							Wh/kg	Wh/liter	$/kwh
1996	1,000	GM	EV1	18	Lead Acid	Prismatic	25	90	250
2000	1,000	GM	EV1 (Gen2)	28	NiMH	Prismatic	50	130	1500
2011	30,000	Nissan	Leaf	23	Li Ion	Pouch	88	180	550
2013	25,000	Tesla	Model S	80	Li Ion	Cylindrical	130	320	325
2014	15,000	BMW	i3	23	Li Ion	Prismatic	94	150	425
2016	20,000	GM	Bolt	60	Li Ion	Pouch	140	300	240
2017	25,000	BMW	i3	32	Li Ion	Prismatic	124	275	275
2017	40,000	Renault	Zoe	45	Li Ion	Pouch	137	300	225
2018	100,000	Tesla	Model 3	78	Li Ion	Cylindrical	150	350	180
2019	100,000	Various	Li Ion	60	Li Ion	Pouch	150	325	175
2019	100,000	Audi/VW	E Tron	95	Li Ion	Pouch or Prism	170	350	175

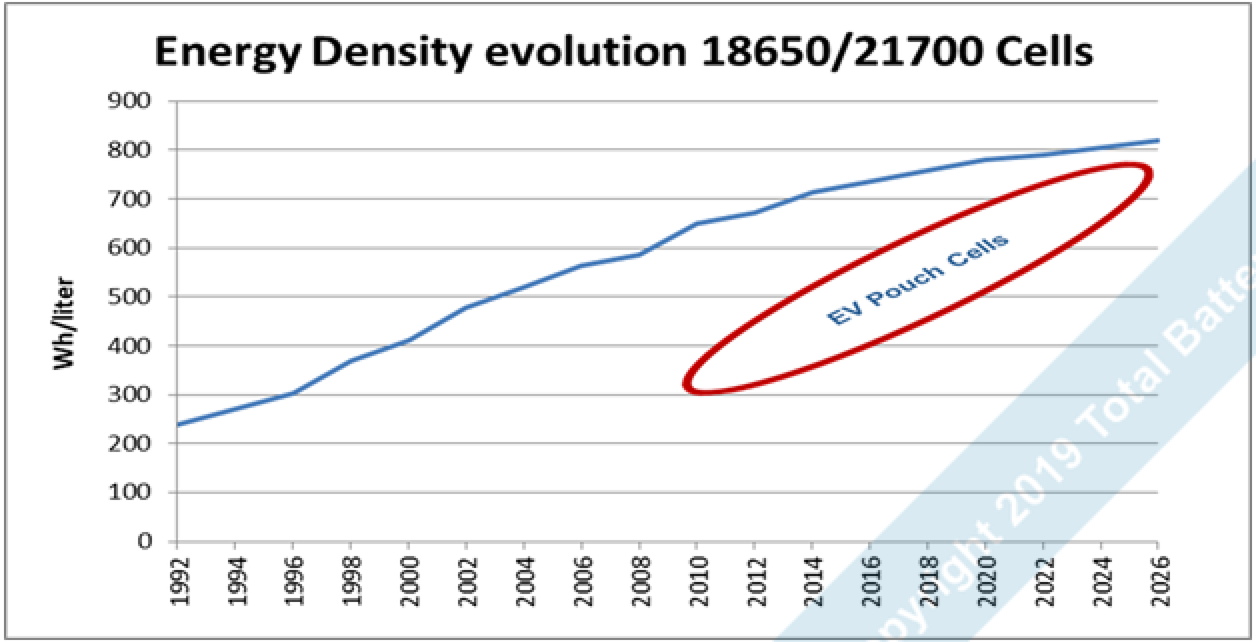
Battery Packs for EVs
Specific Energy vs. Launch Year



Pack Specific Energy vs Launch Year

- Chart shows a general increase in battery pack specific energy in relation to model year (MY).

Li-ion technology has seen 27 years of evolution but no revolution.



Safety at Module and Pack Levels

- **Avoiding fire propagation is a vital module- and pack-design challenge.**
  - If a single cell fire from an internal short occurs, it should not propagate.
- **Crush protection requirements impact battery location and shielding.**
- **As the battery gets larger and more energy-dense, the above issues become more trying.**

Safety concerns are the biggest challenge to increasing energy density!

Fast Charge & Battery Design

- **Fast-charge requirement drives cells and battery to designs with higher power-to-energy ratios (KW/kWh), to reduce current rate per electrode unit area (mA/cm^2).**
  - For discharge, a 2kW/kWh design (120kW on a 60-kWh battery) is sufficient for most EVs.
  - A continuous 12 to15-minute charge is equivalent to 4C-5C and 4-5kW/kWh.
  - A battery designed for 12 to15-minute charge time will require a cell design half-way between EV (2-3kW/kWh) and PHEV (5-8 kw/kWh), with higher cost and weight implications over standard EV batteries with normal charge.
- **If fast charge occurs after long-range driving when the driver intends to return to the highway, battery overheating is a serious concern.**
  - Thermal management will have to be sized to keep the battery from overheating.
- **Fast charge will speed up battery fading, and in turn an aged battery will be more susceptible to damage from fast charge (higher impedance and cell divergence).**
  - OEMs will apply stringent voltage and temperature control to limit battery fade.
  - Will have to consider the frequency of fast charge in their battery life predictions and/or adapt the battery design to worse-case usage.
- **Fast charge at low temperature brings the risk of lithium plating.**

NMC (6,2,2) Cost Estimate

TBC Estimate for 2019-2020

NMC, 6,2,2	Metal kg/kg of NMC	Raw Metal	Processed Metal			
Element	Wt. %	$/kg	$/kg	$/kg cathode	*$/kWh, net	*$/kWh, yielded
Ni	34.1%	13.5	18.0	6.1	9.8	**10.6**
Co	11.8%	35	37	4.4	7.0	**7.6**
Mn	14.6%	4	4.20	0.6	1.0	**1.1**
Li*	7.2%	**81**	89	6.5	10.3	**11.2**
O	32.5%	0	0	0.0	0.0	**0**
Total	**100.1%**	N/A		**17.6**	**28.1**	**30.6**
Add Cathode production cost G&A and profit				7.0	11.2	**12.2**
Subtotal price				**24.6**	**39.3**	**42.7**
* Based on Li_2CO_3 at:		13.5	$/kg	*Kg/kWh	1.60	1.74

$42.7 per kWh based on intermediate assumptions

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37-Ah PHEV Cell Price

1.4-GWh plant, 2018 time scale

37 Ah PHEV Cell Price			
NMC 6/2/2 Cathode, Metal Can, 10 Million 37Ah PHEV Cells / yea			
Component	$	Per kWh	%
Materials	16.5	120	75%
Factory Depreciation	2.7	20	12%
Manufacturing Overhead	0.91	7.0	4.2%
Labor	1.10	8.0	5.0%
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Price	**26.2**	**191**	**119%**
Gross Margin	4.2		19%

21700 Cell Price, 2020

5 Ah 21700 Cylindrical, 22 GWh			
NCA 90,5,5 Cathode, Annual Volume, 1260 Million cells			
Component	$	Per kWh	%
Materials	1.46	79	75%
Factory Depreciation	0.25	14	13%
Manufacturing Overhead	0.10	5	5%
Available with Report purchase			
Burdened Cost	2.16	117	110%
Warranty & Profit	0.138	7	6.0%
Price	2.30	124	122%
Gross Margin	0.35		15%

78Ah EV Pouch Cell Price Estimate, 2025

78 Ah EV Pouch Cell Materials Cost, 34 GWh production			
NMC 8,1,1 Cathode, Pouch, 120 Million Cells / Year ; 3W/Wh			
	$	Per kWh	%
Materials	17.5	62	**76%**
Factory Depreciation	2.8	10	**12%**
Manufacturing Overhead	1.13	3	**4%**

Available with Report purchase

Warrantee	0.77	3.3	3.0%
Profit	0.77	3.3	3.0%
Price	**26.7**	**96**	**114%**
Gross Margin		15	**15.3%**

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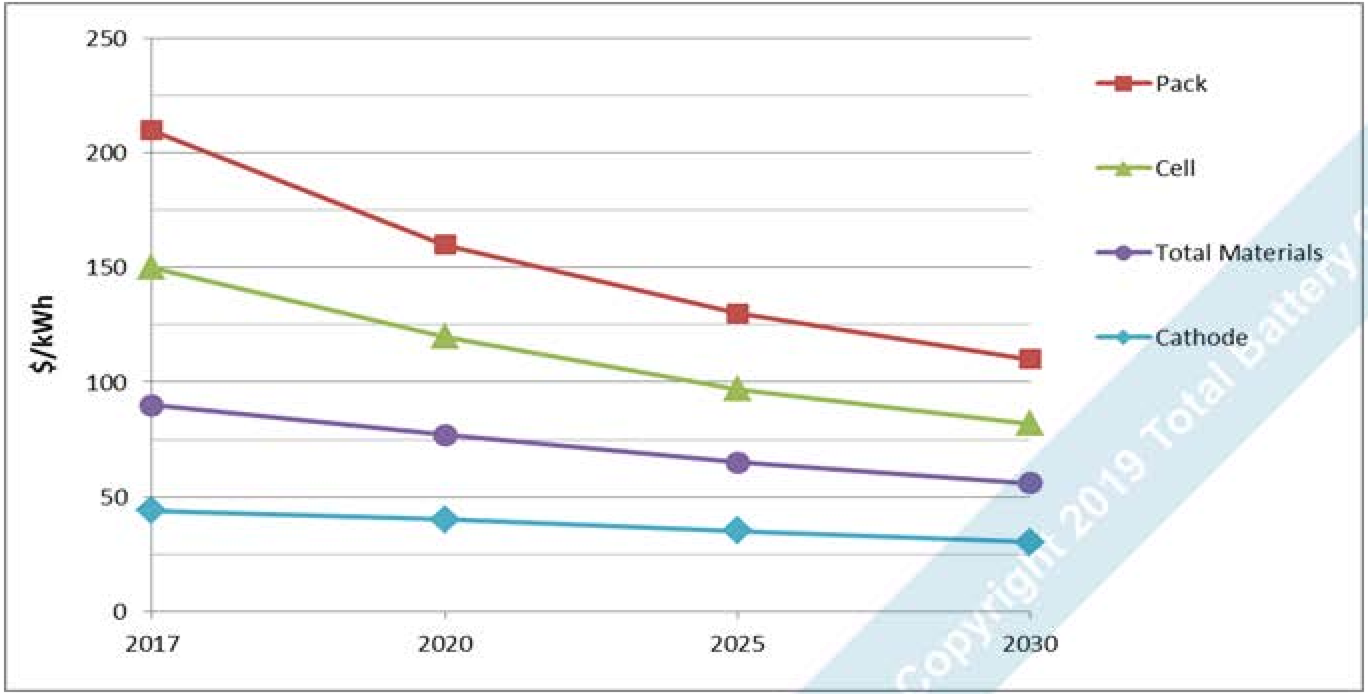
(Pouch technology, approx. 50-Ah cell, 60-kWh pack)



III. Battery Technology: Is There a Future Beyond Lithium Ion?

1. **xEV Batteries' Desired Attributes and Characteristics of 2025 Li-Ion Batteries**
2. Anode Opportunities: Silicon and Metallic Lithium
3. Solid Electrolyte: Promise and Challenges
4. Li/SE versus C-Gr/LE; Energy Density and Cost
5. Cathode Development: Is There a Future Beyond High-Nickel NMC?
6. Future EV Battery Technology Synopsis

Automakers' Expectations for Key Performance Values of Battery-EV Li-Ion Cells

- Cost at \$75-\$100/kWh
- Energy density of 675-800 Wh/liter
- Meet VDA minimum safety level 4
- Charge from 10 to 90% SOC in 12-20 minutes
- Cycle life to exceed 1,000 full cycles at > 80% of original capacity
- Calendar life: 15 years at 30°C; > 5 years at 45°C
- Specific energy > 260 Wh/kg
- > 700 W/liter (C rate) at – 20°C
- Key raw materials available with no risk of significant price hike
- Recycling established
- No use of toxic materials or materials that are mined or processed unethically

Fast-Pace Expansion History of Li-Ion Batteries

- **Invented in the early eighties**
- **Commercially introduced in 1991 (Sony)**
- **Key advantages**
  - High energy density, good specific energy
  - Long cycle life
  - Good calendar life
  - High discharge rate
  - High voltage ~ 3.7 average
  - Low self discharge
  - Extensive R&D effort due to future potential
- **Downsides are safety (at cell level), temperature performance, and cost**

- 1992 – Camcorders
- 1996 – Laptops
- 1998 – Cellphones
- 2002 – Power tools
- 2004 – Tablets
- 2005 – Space
- 2009 – (P)HEVs
- 2010 -- Robotics
- 2011 – EVs
- 2012 – LEVs
- 2014 – Grid storage
- 20XX – SLI

Since Li-ion technology became commercial, no other new rechargeable battery technology has entered the market. Li-ion technology (graphite-based anodes) was (and is) the solution to safely cycling lithium.

1. Reduce Cost

2. Increase Volumetric Energy Density

3. Increase Charge Acceptance Rate

4. Expand operating temperature range
5. Improve specific energy
6. Ensure availability of materials and price stability (reduction)

While maintaining or enhancing:

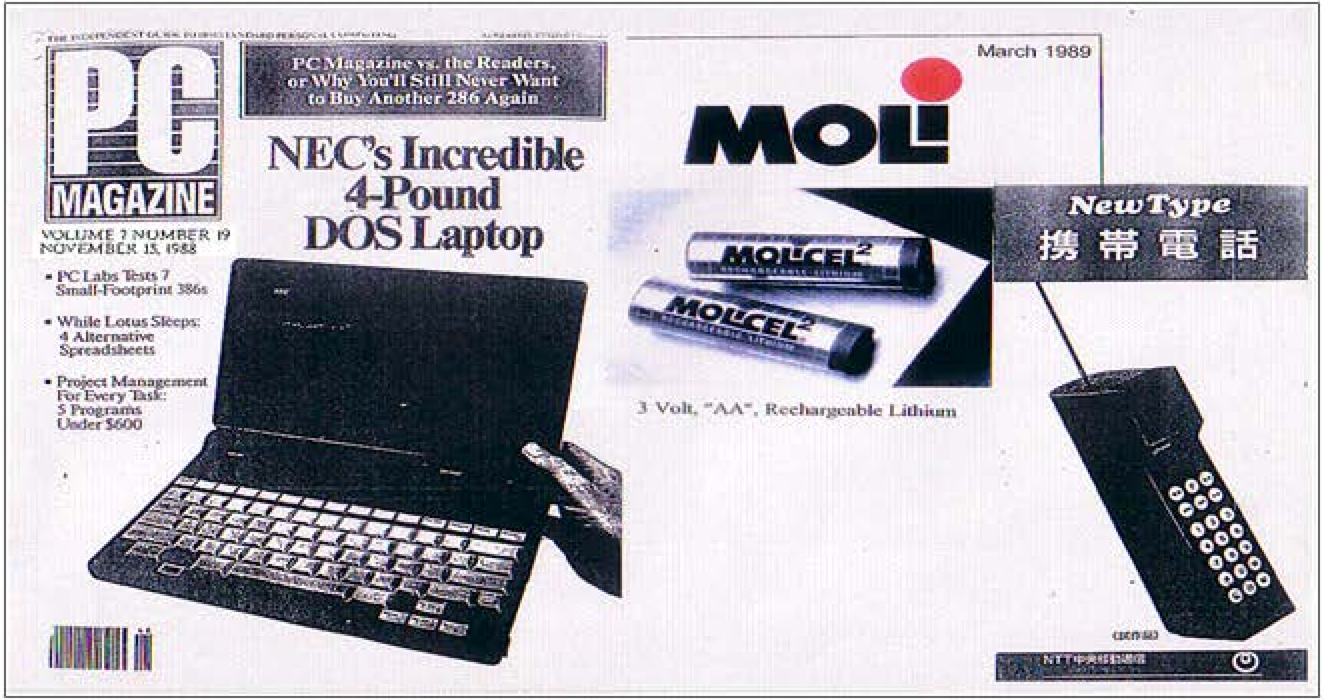
- ✓ Safety
- ✓ Durability
- ✓ Manufacturability

Silicon Anode Pre-Lithiation

- Silicon has very high initial capacity: around 3,600 mAh/gram.
- However, within a few cycles, the capacity may drop to below about 2,400 mAh/gram.
- The delta, 1,200 mAh/gram or so, corresponds to lost storage capacity.
- The lithium used on first charge to lithiate the anode, which is partially lost, requires extra sacrificial cathode material (with a capacity of 150-200 mAh/gram).
- To overcome this, it is necessary to partially pre-lithiate the silicon.
- It is possible to pre-lithiate the Si powder, the electrode prior to assembly, or the electrode in an assembled cell.
- In all three cases, there is the added cost of the lithium itself, on the order of $15-30 per kWh of cell capacity. For the first two approaches, there are additional costs associated with:
  - The pre-lithiation process
  - The impact of utilizing partially charged and water-sensitive anode in electrode processing and cell assembly.

1986-1990: Li/MoS_2 Rechargeable Cells – Moli Energy

PC-based electrolyte!



Moli introduced cells with ca 200 cycles into the computer and camera market around 1989. Several devices caught fire at customers' hands. Total recall after a few months, followed by bankruptcy.

Cause:
Dendrites

Lithium Foil Pricing

- **Lithium carbonate**: Raw material for LIB
- **Production route:** Li_2CO_3 to LiCl to Li Metal

Prices:

- Battery grade $Li_2CO_3 \approx 1.25$ x technical Li_2CO_3
- If we use Li_2CO_3 at $12/kg (low end), EV battery grade will be: > $15/kg
- Li cost (1kg of Lithium in 5.3kg of Li_2CO_3): > $80 / kg
-
- *Available with Report purchase*
-
- Foil thickness <15µm: > $800/kg, Li vapor deposition technique will be cheaper than rolling

$300/kg Lithium cost translates to $21/kWh net, or $27/kWh with 30% excess lithium, (versus $6-8/kWh for graphite); perhaps too high for EV-battery applications…

Solid Electrolytes – High-Level View

- ✓ Could theoretically support higher energy density (with metallic Li anode) and better safety.
- But long-term cyclability against Li metal is unproven for most systems.
- Under development for over 37 years, which is longer than Li ion, but recent advances in room-temperature conductivity show some promise.
- Room-temperature conductivity is not enough for automotive; needs to be proven at -20°C. Some solid electrolytes show promise.
- **Providing a solid electrolyte, solid active mass composite cathode with zero porosity, and maintaining solid/solid interface during cycling between powdery cathode and powdery solid electrolyte is a significant challenge…**
- Consumer-battery applications make more sense.
- The cost of the new materials could be an issue.
- Could in fact work with Li-ion system as well, but this would just be a Li-ion battery with a new electrolyte system.

The Lithium Protective Layer: Status and Challenges

- **Why a protective layer?**
  - ✓ To separate the chemical and mechanical interphase stability requirements against the anode from those against the cathode
  - ✓ If the protective layer is made into thin films, lower ionic conductivity could be acceptable
- **Since lithium is dissolved on discharge, maintaining adherence during cycling is challenging**
- **Attractive data on small-lab cells at 0.5-2 mA/cm^2; however, for commercially-viable BEV cells, 8-15 mA/cm^2 will be required (electrode-loading of 4-5 mAh/cm^2 and rate capability of 2-3C)**
  - **Will the concept work at commercially-viable thicknesses and current densities and with an affordable design?**
- **Most viable short-term approaches, at least for inorganic SE:**
  - Use thin solid electrolyte layer only against the negative electrode and maintain liquid electrolyte at the positive electrode
  - **But this is a hybrid, not a true solid-state battery, metallic lithium and liquid electrolyte are a risky combination**

Li-NMC: Can we achieve cost parity with Gr-NMC?

For cost parity at the cell level, the needs are:

- $13/kg electrolyte for sulfide-based, $6/kg for oxide-based
- $100/kg Lithium 'foil' (assuming 1.5X -/+ ratio)
- Same cell-manufacturing cost as 2025 mature Li-ion cells

Gr-Si /LE/NMC, versus Li-SE-NMC ; 2025		4mAh/cm2	10 micron (2 mAh/cm2) Li 'foil' + Li from Cathode			10 micron (2 mAh/cm2) Li 'foil' + Li from Cathode		
		Gr-Si/LE/NMC	Li/LiPxSy/NMC	Li/LiPxSy/NMC	Li/LiPxSy/NMC	Li/LLZO/NMC	Li/LLZO/NMC	Li/LLZO/NMC
		Base	Base	Very optimistic	Parity w' G/LE	Base	Very optimistic	Parity w' G/LE
Anode cost	$/kg	9	500	300	100	500	300	100
Electrolyte cost	$/kg	7.5	100	40	13	100	30	6
Anode Weight	kg/kwh	0.71	0.035	0.035	0.035	0.035	0.035	0.035
Electrolyte weight	kg/kWh	0.69	0.98	0.98	0.98	1.96	1.96	1.96
Anode cost	$/kwh	6.4	17.5	10.5	3.5	17.5	10.5	3.5
Electrolyte cost	$/kwh	5.2	98	39	12.8	196	59	12
Separator cost	$/kwh	5.0	0	0	0	0	0	0
Combined cost	$/kwh	17	116	50	16	214	69	15

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Li-NMC: the Most Promising of the 'Future Technologies'

Inside the next 10-15 years, a metallic lithium-based anode against a solid lithiated metal-oxide cathode could offer the opportunity for a Li-metal-based cell.

- ✓ Improvement in volumetric and gravimetric energy density on the order of 30-40%
- Source of Li metal to be evaluated, foil-, powder-, or vapor-based
- Needs to be protected against dendrites with a solid-glass polymer or ceramic material
- The least expensive source of lithium for the cell is a (Co-poor) cathode
  - Will probably still need a 'startup' lithium surface for plating
- Uses liquid or blend electrolyte in the cathode, or operates above room temperature
- Safety and cycle life still TBD
- **Cost, cycle life, manufacturability, and charge rates** are the biggest challenges, all impacted by the anode
- Best-case time to market in mass EVs: > 10 years

CONCLUSIONS: Beyond Li Ion for Mass-Market EVs?

- Li ion with silicon at the anode and 90% nickel NMC (or higher) at the cathode is likely to match/exceed 750 Wh/liter while providing nearly all other automotive battery requirements.
- Cell cost lower than $100/kWh is achievable but to obtain a cost lower than $80/kWh will require a significant reversal in metal pricing or new cathode chemistry.
- Any 'post-Li-ion' mass-market battery EV technology will have to provide at least a 25% improvement in energy density and/or a 20% reduction in cost against the numbers above, while maintaining parity with all other key cell parameters. **A formidable challenge!**
- Li-metal oxide chemistry (NMC or related) can meet the first criterion but adequate cycle life and cost parity are a longer shot.
- **The 2025 mass-market EV battery technology will be Gr-Si/NMC Li ion with liquid electrolyte (M – Mn, Al, Mg or other metal)**
  - **Probably also in 2030…**

IV. xEV Battery Market Forecast to 2025

1. **xEV Battery Market Overview**
2. Mild & Strong Hybrids
3. EVs & PHEVs
4. Demand for Materials
5. Directions of Individual Cell Makers

xEV Battery Market Overview

- Li ion is the only solution for EVs and PHEVs. The cell market value for 2018 is estimated at $13.7 billion and the forecast for 2020 is about $22 billion. The corresponding values associated with the pack business are $18.4 billion and $29.7 billion respectively.
- EV cell pricing for the highest volume is below $140/kWh with quotations in the $110-130/kWh for the early 2020ies.
- The NiMH market peaked at about 1.5 million HEV packs and an estimated value of about $1.6 billion. The market is slowly dropping. PEVE is now the only major supplier.
- The Li-ion HEV market is growing predominantly in mild-hybrid configurations. It has 5-6 major suppliers. The 2018 pack business is evaluated at about $1.3 billion despite the large number of vehicles that utilize the technology.
- Outside China, LG Chem and Panasonic are the market leaders; Samsung (aggressive), SK innovation, GS Yuasa Group, and AESC are other significant players.
- There are many suppliers in China. CATL is market leader and is in prime position with international automakers. BYD is another important player, primarily for BYD's own EVs and e-buses.
- PEVE, Blue Energy Japan, and Hitachi focus on HEV applications.

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2018 Automotive Li-Ion Battery Market

2018 Automotive Li-Ion Battery Market		China Household EVs		ROW Household EVs		EV Commercial China		PHEVs all	HEVs Strong	HEVs Mild	Total
Parameters	Unit	OEM	Replacement	OEM	Replacement	OEM	Replacement				
Unit sales volume	000	792	30	562	15	192	10	610	2,120	850	5,181
Average battery capacity	kWh	33	28	58	40	105	90	11	0.7	0.35	N/A
Average cell pricing	$ / kWh	145	145	140	140	140	140	200	475	475	N/A
Available with Report purchase											
Battery market	$ million	**4,986**	**162**	**6,005**	**112**	**3,380**	**148**	**2,113**	**1,215**	**257**	**18,379**
Battery capacity	MWh	26,136	840	32,596	600	20,160	900	6,710	1,484	298	89,724
Percent $ market	%	**27%**	**0.9%**	**33%**	**0.6%**	**18%**	**0.8%**	**11%**	**7%**	**1.4%**	**100%**
Parameters		EV-OEM	EV-Replace	EV-OEM	EV-Replace	Bus-OEM	Bus-Repl	PHEV	HEV Strong	HEV Mild	Total

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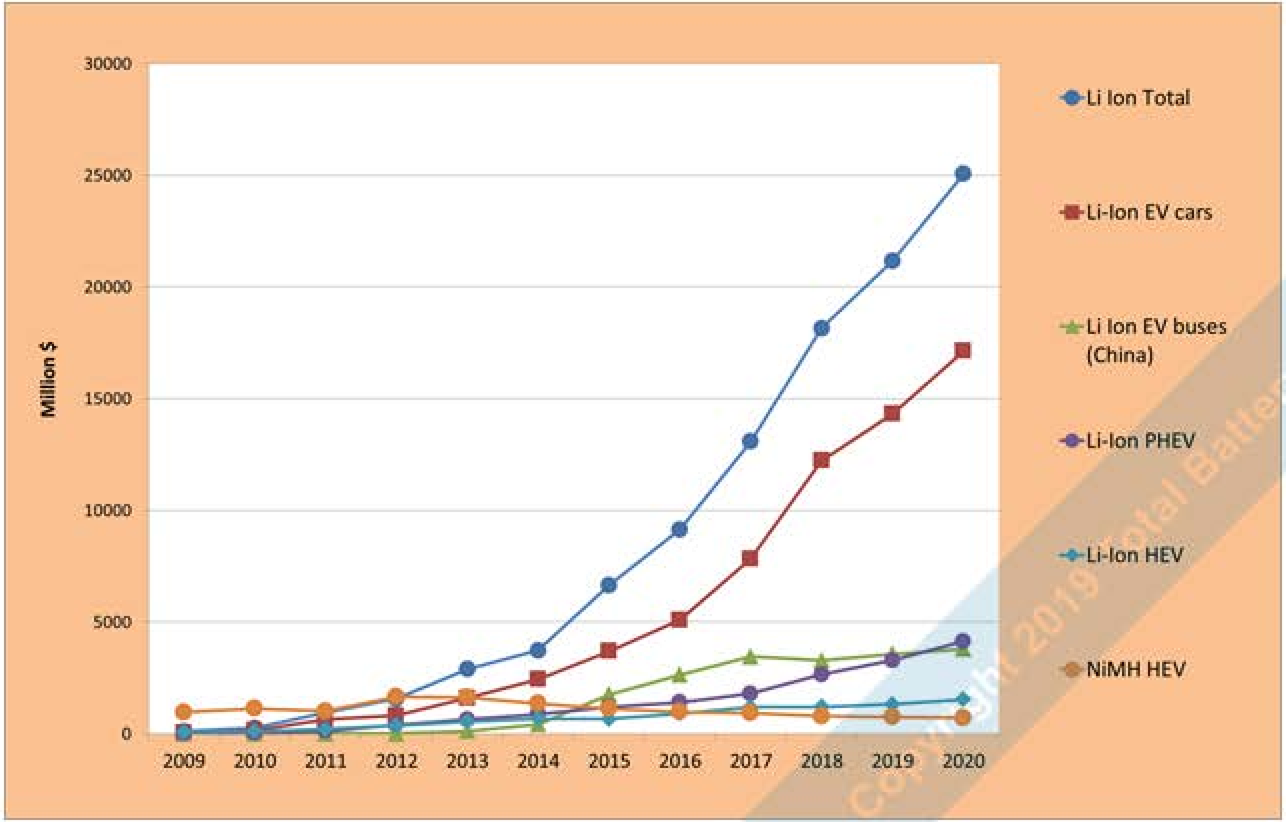
xEV Battery Pack Business



2020 Automotive Li-Ion Battery Market

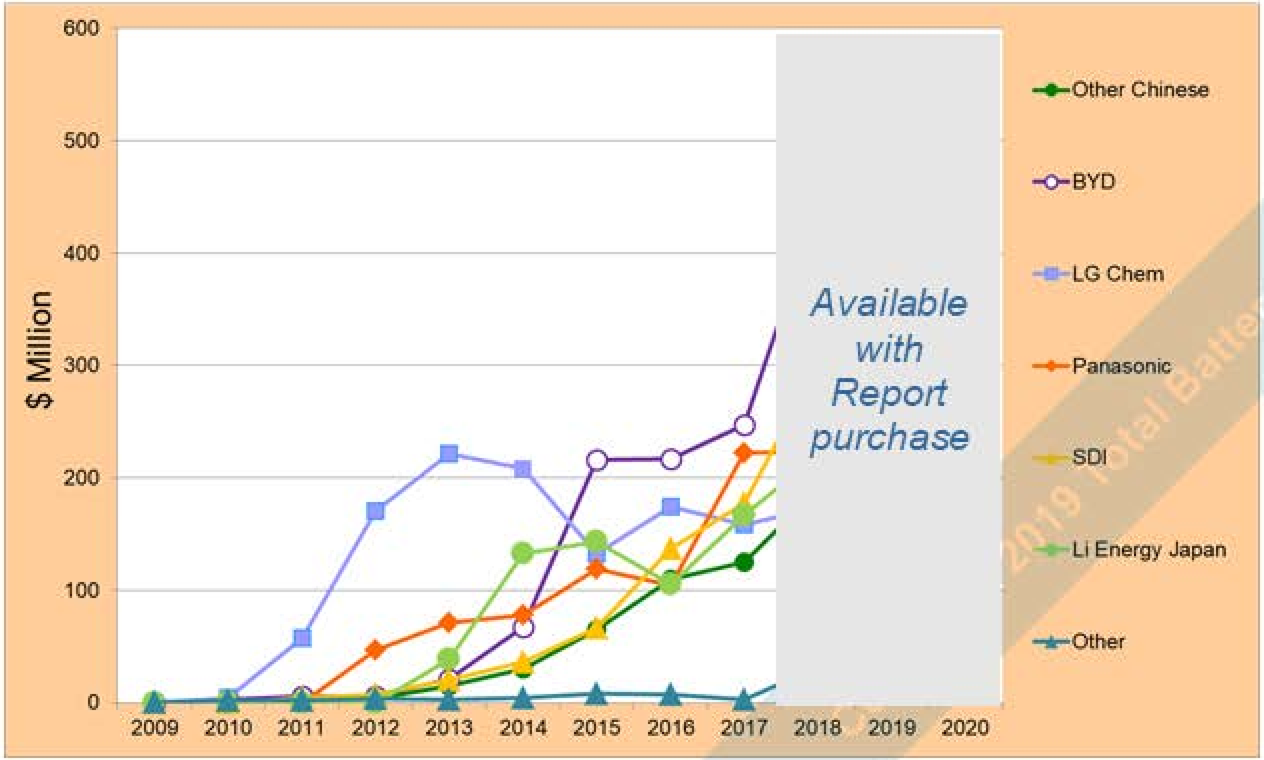
2020 Automotive Li-Ion Battery Market		China Household EVs		ROW Household EVs		EV Commercial China		PHEVs	HEVs Strong	HEVs Mild	Total
Parameters	Unit	OEM	Replacement	OEM	Replacement	OEM	Replacement				
Unit sales volume	000	1,363	70	902	30	232	80	890	2,000	1,100	6,667
Average battery capacity	kWh	40	32	63	50	125	115	13	1.1	0.44	N/A
Average cell pricing	$ / kWh	125	125	125	125	130	130	165	450	450	N/A
Available with Report purchase											
Battery capacity	MWh	54,520	2,240	56,826	1,500	29,040	9,200	11,570	2,200	484	167,580
Percent $ market	%	30.2%	1.3%	31.5%	0.8%	12.7%	5.5%	10.1%	6.3%	1.6%	100%
Parameters		EV-OEM	EV-Replace	EV-OEM	EV-Replace	Bus-OEM	Bus-Repl	PHEV	HEV Strong	HEV Mild	Total

Strong HEV OEM/Supplier Relationships

Strong HEV (Li Ion)	2012	2014	2016	2018	2020
Toyota	PEVE	PEVE (Panasonic)	PEVE (Panasonic)	PEVE (Panasonic)	PEVE (Panasonic)
Honda	Blue Energy	Blue Energy	Blue Energy (Panasonic)	Blue Energy (Panasonic)	Blue Energy (Panasonic)
Ford	Panasonic	Panasonic	Panasonic	Panasonic	Panasonic
Hyundai	LG	LG	LG	LG	LG
GM	Hitachi	Hitachi	Hitachi	Hitachi	Hitachi
Nissan	AESC	AESC / Hitachi	AESC / Hitachi	Panasonic / Hitachi	Panasonic / Hitachi
VW / Audi	Panasonic	Panasonic	LG	LG	LG
Daimler	JCS	JCI	NA	SKI	SKI
BMW	A123	A123	NA	NA	NA

PHEV Battery Cell Market by Producer

(including PHEV Buses)



EV OEM/Supplier Relationships

EV	2012	2014	2016	2018	2020
Nissan	AESC	AESC	AESC	AESC	AESC / LG
Tesla	Panasonic 18650	Panasonic 18650	Panasonic 18650	Panasonic 18650-21700	Panasonic 18650-21700
Renault	AESC	LG	LG	LG	LG
Mitsubishi Motors	LEJ	LEJ	LEJ	LEJ	LEJ / LG
BMW	SDI	SDI	SDI	SDI	SDI
VW / Audi	Panasonic	Panasonic	Panasonic / SDI	LG / SDI	LG / SDI
BJEV	------	------	CATL / Gotion	CATL / Farasys	CATL / Farasys
Geely	------	------	CATL	CATL	CATL
Chery	------	------	A123 / CATL	A123 / CATL	A123 / CATL
FCA	SDI	SDI	SDI	SDI	?

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EV Battery Cell Market by Producer

PHEV-EV Cell Materials Demand 2020

PHEV & EV	Specific Capacity	Material Consumption	Cost Per kg	Production Volume	Material Consumption	Market
Materials	mAh/g	Tons/MWh	$/kg	MWh	Tons	$ Million
NMC / NCA	170	1.86	28	137896	256977	7195
LFP	155	2.25	12	*Available with Report purchase*		
LMO	110	2.83	8			
Graphite/Carbon	330	0.96	8			
Electrolyte	NA	0.81	9			
Separator, per m^2	NA	9	0.8	164896	1,484,064	1187
Total Key Materials						**11569**

V. Appendix

1. Levels of Vehicle Hybridization

2. Lead-Acid and NiMH HEV Batteries and Ultracapacitors

Key Hybrid Functions

	IC Engine Stop/Start	Brake Energy Recovery	Rolling Stop Start	Low-speed Electric Torque Assist	High-speed Electric Motor Assist	Low-speed Electric Drive	High-speed Electric Drive
Micro-1 Hybrid	Moderate	Limited	No	No	No	No	No
Micro-2 Hybrid	✓	Moderate	Limited	No	No	No	No
48V Mild Hybrid	✓	✓	Moderate	Moderate	Limited	Limited	No
Strong Hybrid	✓	✓	✓	✓	✓	✓	No
Plug-in Hybrid	✓	✓	✓	✓	✓	✓	✓
Electric Vehicle	n/a	✓	n/a	n/a	n/a	✓	✓