FEATURED ARTICLES

Electric Vehicle Batteries: Past, Present, and Future

To cite this article: Dennis A. Corrigan 2022 *Electrochem. Soc. Interface* **31** 63

Electric Vehicle Batteries: Past, Present, and Future

by Dennis A. Corrigan

Past Electric Vehicle Batteries

Electric vehicles (EVs) are not new; they date back to the 19th century, along with the invention of primary and secondary batteries and electric motors.[1] In fact, batteries and EVs predate the invention of the internal combustion engine (ICE). Electric cars like the early EV shown in Fig. 1 were commonplace around 1900. They had a limited range on the order of 25 miles due to the modest 25 Wh/kg specific energy of rechargeable batteries in that era. However, EVs initially competed well commercially with ICE vehicles, partly because hand-cranked engines were inconvenient and unpopular. Ironically, it was the invention of the electric-starter motor powered by lead-acid batteries that enabled ICE vehicles to take over and dominate the automobile industry for the rest of the 20th century. The lead-acid battery business thrived with the massive growth of the world auto industry. Today, the lead-acid battery market has reached about $40B in revenue and continues to grow.[2]

In the last decades of the 20th century, there was renewed interest in battery-powered EVs due to resource issues with petroleum and environmental concerns about toxic air pollution and greenhouse gas emissions. The OPEC oil embargo in the 1970s and the California Zero Emission Vehicle (ZEV) mandate of 1990 were key drivers that motivated the development of battery EVs by automakers. A variety of higher energy–density battery technologies that were developed for EV applications are included in Table I. Despite impressive theoretical energy densities, most of these new technologies had serious practical deficiencies. Among the most promising was the nickel-metal hydride (NiMH) battery.[3] It featured a specific energy of about 80 Wh/kg, more than twice the specific energy of modern lead-acid batteries with much improved specific power and cycle life. Utilizing the NiMH battery, General Motors (GM) developed the iconic EV1, a high-performance EV with a range over 100 miles that received considerable publicity and notoriety. However, EV1 production plans were scuttled with the cancellation of the ZEV mandate in 2002, which spawned various conspiracy theories, as highlighted in the film *Who Killed the Electric Car?*[4] This movie included a mock trial of who was to blame. Lots of villains were named, but curiously the battery was declared "not guilty." In fact, EVs were not commercialized at that time primarily because of deficiencies in batteries, especially their high cost.

Electric Vehicle Battery Requirements

The extensive development of EV prototypes in the 1990s resulted in a much more detailed understanding of the battery performance requirements for EVs.[5] For example, it was learned that for modern EVs, the battery volumetric energy density is more important than the specific energy. The United States Advanced Battery Consortium (USABC), established in 1991 as a partnership of the "Big Three" US automakers that eventually included the US Department of Energy, developed detailed performance targets to guide development of advanced batteries aimed at commercialization of EVs.[6] The 2020 update of the USABC requirements is summarized in Table II.

The USABC requirements envision a full battery pack system capable of providing power and energy for a commercially viable passenger car with a range of about 200 miles. With a vehicle energy consumption of about 225 Wh/mile, this would require a usable energy of 45 kWh. The battery also would need to provide about 100 kW of pulse discharge power to enable acceleration from 0 to 60 mph in 10 s or less. To utilize the efficiency advantage of regenerative braking, 50–100 kW of pulse charge power capability is also needed. As a practical matter, the battery pack must provide its power and energy at high voltage, within the voltage range of 220–420 V, for proper operation of practical electric motor drives. The power and energy are specified in the USABC requirements in terms of specific power (W/kg), power density (W/L), specific energy (Wh/kg), and volumetric energy density (Wh/L) derived from the EV power and energy requirements and the estimated mass and volume packaging constraints. To achieve the battery pack targets, the specific performance targeted for battery cells is higher. Taking into account an estimated 50% mass and volume packaging burden, battery cells at 350 Wh/kg and 750 Wh/L would be needed to achieve battery pack energy density targets of 235 Wh/kg and 500 Wh/L. EV commercialization also requires meeting life and cost targets. Consumers expect passenger vehicles to be capable of driving up to 150,000 miles over a 15-year lifespan. This requires the battery to be capable of providing 1000 full depth charge–discharge cycles that meet the rated energy and power requirements over a calendar life of 15 years. To ensure full performance capability over a 15-year lifetime, the initial battery performance must exceed the power and energy requirements to accommodate degradation over time. Additionally, to be competitive with ICE vehicles, the electric power

(continued on next page)

Fig. 1. *Early electric vehicle (left) typically with 20 mph top speed and 25 mile range and Tesla Model 3 EV (right) with 5-second acceleration to 60 mph and over 200-mile range. (Courtesy of National Museum of American History and Tesla Motors.)*

Table I: 20th Century Electric Vehicle Batteries

EV Battery	Cell Voltage (V)	Theoretical Specific Energy (Wh/kg)	Practical Specific Energy (Wh/kg)	Practical Energy Density (Wh/L)	Performance Issues
Lead-Acid	2.0	171	35	80	Low energy, short life
Nickel-Iron	1.2	314	45	55	Low energy, poor efficiency
Nickel-Cadmium	1.2	244	45	100	Low energy, toxic, high cost
Nickel-Zinc	1.6	372	60	110	Low energy, short life
Sodium-Sulfur	2.0	792	170	250	High temperature
Sodium-Nickel Chloride	2.6	787	125	190	High temperature
Zinc-Bromine	1.6	572	70	60	Toxic gases
Zinc-Chlorine	1.9	835	90	80	Toxic gases
Zinc-Air	1.3	1353	150	160	Low power, efficiency, life
Nickel-Metal Hydride	1.2	240	80	200	Low energy, cost

Table II: Electric Vehicle Battery Requirements

USABC Performance Criteria	Pack Target	Cell Target
Discharge Power Density (W/L)	1000	1500
Specific Power (W/kg)	470	700
Specific Regen Power (W/kg)	200	300
Usable Energy Density (Wh/L)	500	750
Usable Specific Energy (Wh/kg)	235	350
Maximum Voltage (V)	420	
Minimum Voltage (V)	220	
Calendar Life (years)	15	15
Cycle Life (cycles)	1000	1000
Selling Price ($/kWh)	125	100
USABC Safety Requirements		
Pass Electrical Abuse Tests (overcharge, overdischarge, external shorting)		
Pass Physical Abuse Tests (elevated temperature, water immersion, vibration, crush, drop, nail penetration)		

train must be comparable in cost to the ICE drive train. The USABC targets a battery pack cost of about US$5600 or $125/kWh. No single battery technology has yet met all the requirements of Table II. The most difficult targets are energy density and cost. EV battery packs have not achieved an energy density of 235 Wh/kg and 500 Wh/L at a cost of $125/kWh. In addition to the EV performance, life, and cost targets, the most important requirement for EV batteries is safety.[7] Safety is engineered at the vehicle, battery pack system, and battery cell level through detailed failure modes and effects analysis. The intrinsic safety of battery cells is confirmed through electrical and physical abuse testing included in Table II.

Present Electric Vehicle Batteries

The development of high energy–density EV batteries has proven to be a very difficult problem for electrochemists. Moore's Law exemplifies the dramatic exponential progress in semiconductor electronics, with a factor of two improvement every two years. Where is the Moore's Law of batteries? Progress in battery energy density has been slow by comparison, as shown in Fig. 2. It took over 100 years to achieve a single order of magnitude improvement in battery energy density. The breakthrough technology was the lithium-ion (Li-ion) battery for which the 2019 Nobel Prize was awarded to ECS members Stan Whittingham, John Goodenough, and Akira Yoshino.[8] The Li-ion battery was the enabling technology for many revolutionary portable electronic devices, such as cell phones and laptop computers.[9,10] It is now also the enabling technology for the high-volume commercialization of EVs.[10,11]

Intercalation batteries such as nickel-metal hydride batteries and Li-ion batteries are particularly advantageous for EV applications. Their charge storage reactions involve simple ion insertion processes while avoiding complex chemistry and profound structural changes. This characteristic enables high utilization of active materials, high power capability, and long cycle life. Of the intercalation batteries, Li-ion batteries are superior to NiMH batteries for EV applications largely because of their three-fold higher cell voltage and comparable advantage in energy density. Li-ion batteries are highly superior to all the 20th century EV batteries in Table I, not just because of their superior energy density, but also other favorable characteristics that

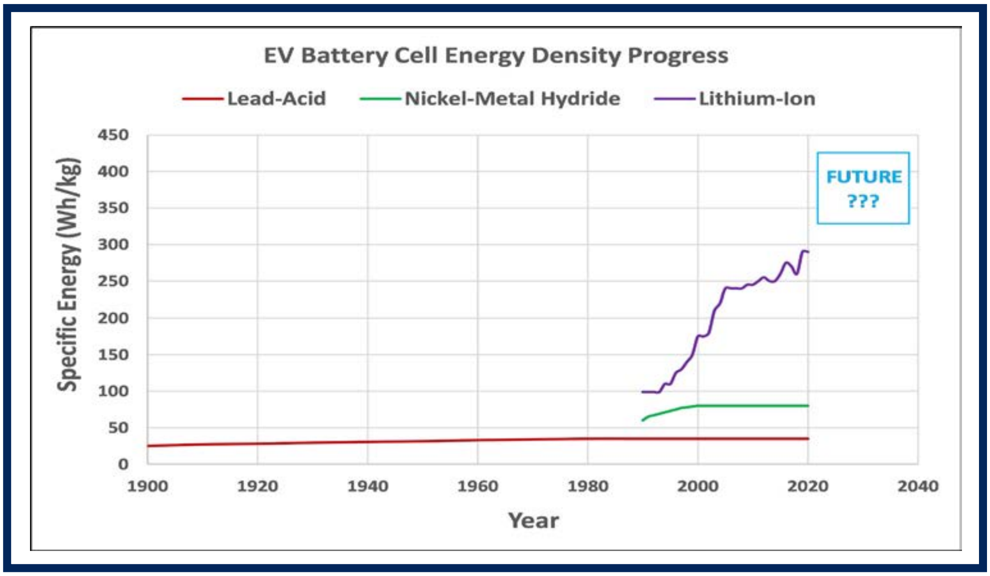

Fig. 2. *Specific energy progress in battery cells for electric vehicles. (Data from reference 5.)*

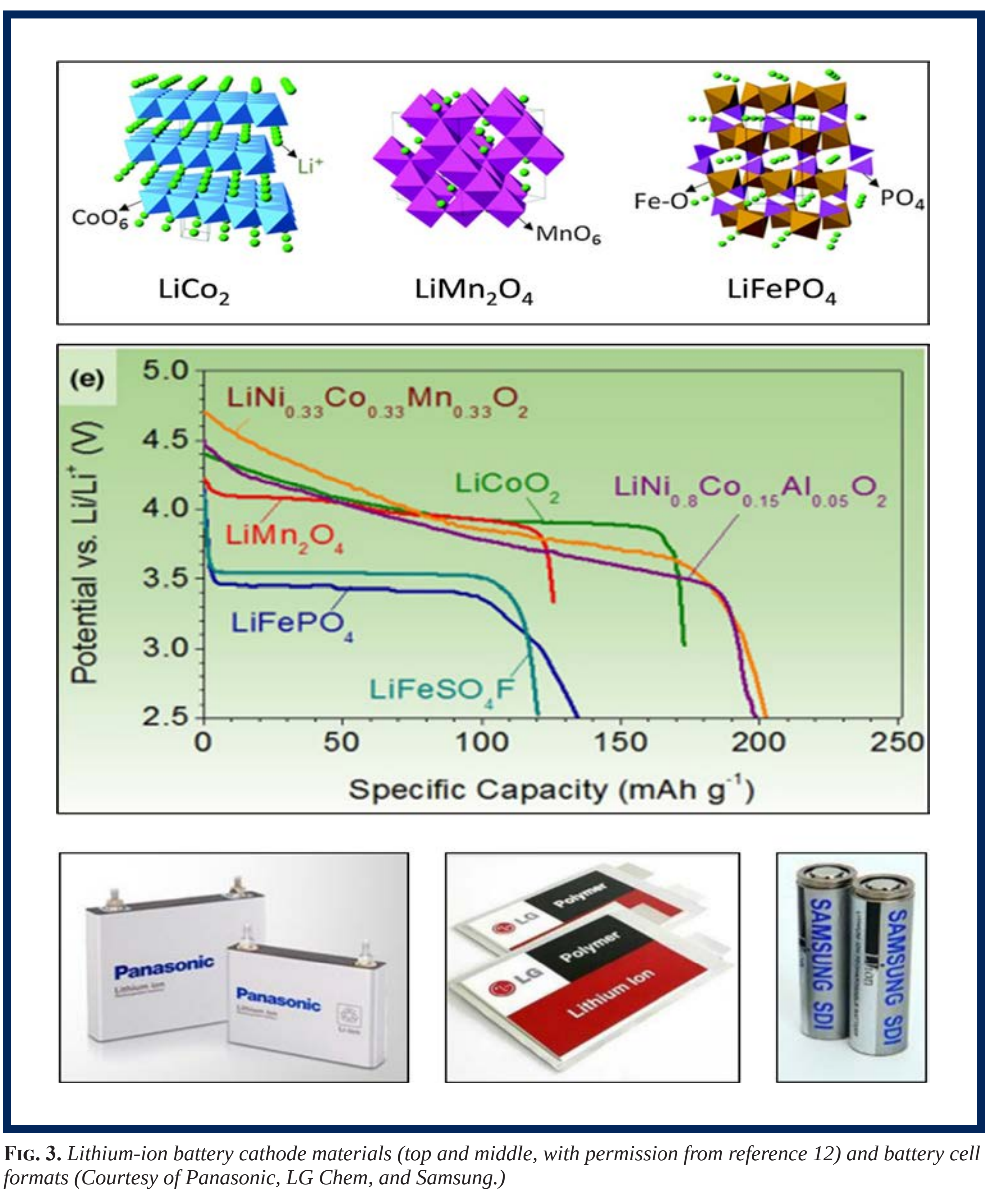

Fig. 3. *Lithium-ion battery cathode materials (top and middle, with permission from reference 12) and battery cell formats (Courtesy of Panasonic, LG Chem, and Samsung.)*

include high power, high efficiency, and long life. Their gravimetric and volumetric energy density are approaching 300 Wh/kg and 750 Wh/L, respectively, and are continuing to improve, as shown in Fig. 2.

The Li-ion battery was first commercialized in the 1990s for portable electronics. However, there were early concerns about safety, with various incidents involving battery fires both in laptop computers and in EV prototypes. In place of a high heat–capacity aqueous electrolyte, they contain low heat–capacity electrolytes composed of flammable organic solvents. This focused strong attention on battery safety. Improved manufacturing and quality control with cleanroom manufacturing environments evolved to avoid premature failures from particulate shorts through thin separators. Advanced multilayer separators with protective coatings were also developed to improve safety and cycle life. Electronics technology was developed to balance the state-of-charge in a battery pack to avoid the overcharge of individual cells. More thermally stable active materials were developed, including composite nickel-manganese-cobalt oxide and lithium iron phosphate cathode materials. Due to the development of alternative active materials, Li-ion batteries are not confined to one battery chemistry couple as are the other batteries in Table I. Li-ion battery technology is actually a family of battery chemistries with a variety of active materials.[8-12] Cathode materials have evolved from the cobalt oxide cathodes initially commercialized to a wide variety of alternatives, some of which are illustrated in Fig. 3. Alternative anode materials include natural and synthetic graphite materials, hard carbons, lithium titanate, and silicon. It is the utilization of alternative higher energy materials as well as improved cell design and packaging into prismatic, cylindrical, and pouch cells that has enabled the continuous improvement in Li-ion energy density.[9] Additionally, the development of improved cathode materials has also led to reduced costs through the reduction or elimination of cobalt, a highly expensive material with high cost volatility.

Li-ion battery technology can now meet most of the USABC targets for EV applications in Table II with the notable exceptions of specific energy, energy density, and cost. By 2020, there were Li-ion EV battery cells available with an energy density of

(continued on next page)

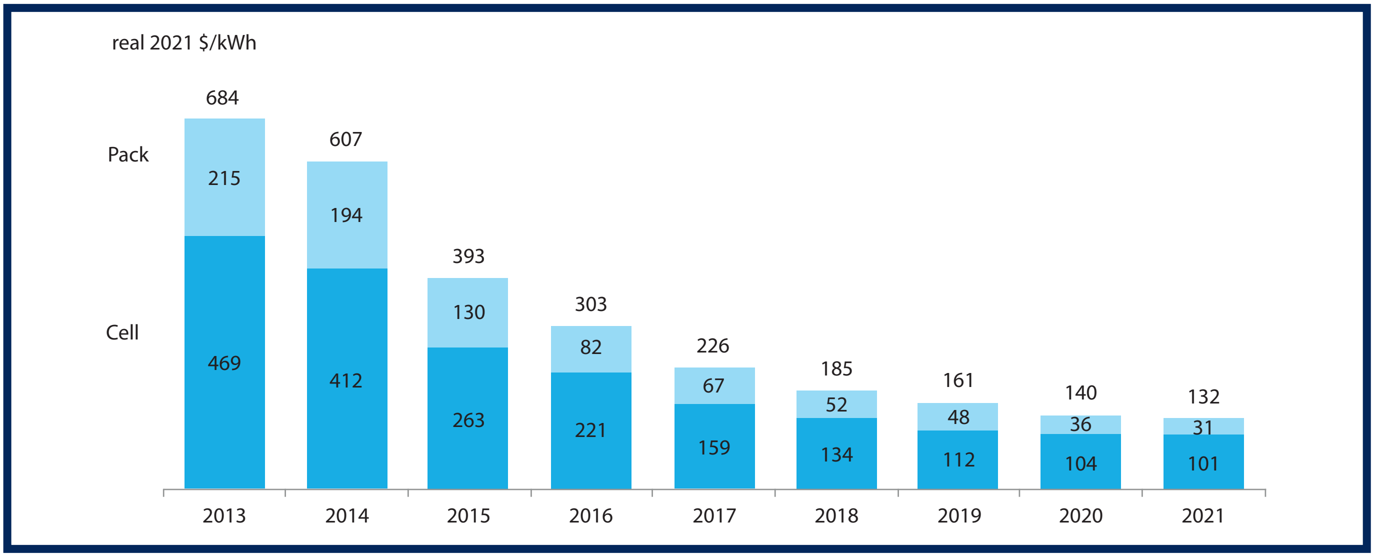

Fig. 4. *Lithium-ion battery cost reduction progress, volume-weighted average pack, and cell price split. (Courtesy of BloombergNEF, reference 13.)*

around 250 Wh/kg and 750 Wh/L, enabling production of EVs like the GM Chevy Bolt, Ford Mustang Mach-E, Fiat 500e, and the Tesla Model 3 (see Fig. 1) with excellent performance and a range of more than 200 miles. This range was achieved with 50 kWh battery packs that have a fully burdened specific energy of around 150 Wh/kg (40% less than the USABC target) by using clever engineering with trade-offs in cost and vehicle features. Even higher range EVs have been developed with current battery technology. A long-range version of the Tesla Model 3 has been offered that uses an 80 kWh battery pack for a range of over 350 miles, albeit with a substantial cost premium. Over the past decade, there has also been a dramatic reduction in the cost of Li-ion batteries (see Fig. 4).[2,13,14] Before 2025, battery cell and battery pack costs are projected to meet USABC targets of $100/kWh and $125/ kWh, respectively. EVs with a range of 200 miles were offered for a cost of under $40,000 in 2020. This was achieved with battery packs estimated to cost about $220/kWh, which translates to just over $10,000 for a 50 kWh battery pack using $150/kWh Li-ion cells.[14]

Future Electric Vehicle Batteries

Ideally, we would like to package 100 kWh of battery on an EV to provide a range of 400 miles. Can battery electrochemistry advances yield the 400 Wh/kg needed to make that happen? Is there a higher energy–density successor to Li-ion batteries? Lithium and fluorine, sitting at the upper corners of the periodic table, could be combined electrochemically with a cell voltage of 5.88 V, yielding a battery theoretical specific energy of over 6000 Wh/kg, an order of magnitude higher than that of Li-ion batteries. However, given the extreme reactivity and safety issues with fluorine, this does not seem like a practical approach for now. Lithium-air (Li-air) batteries utilizing oxygen reactants rather than fluorine have been a focus of extensive R&D studies over the last decade.[15] With a cell voltage of 3 V, these batteries have a very promising theoretical specific energy of about 2500 Wh/kg. However, Li-air batteries utilize fuel cell cathodes that burden them with additional cost, mass, volume, and complexity. They are also challenging to recharge and the energy efficiency on charge-discharge is low, on the order of 70% or less (Li-ion energy efficiency exceeds 90%). There are cycle life issues as well. Lithium-sulfur (Li-S) batteries have also received extensive R&D attention in the last decade.[16] In addition to a theoretical specific energy of 2500 Wh/kg, they avoid the complications of a fuel cell cathode. In addition, Li-S batteries also have promise to be a low-cost technology because sulfur is a very inexpensive reactant. Prototype Li-S battery cells have been developed with a gravimetric energy density of about 500 Wh/kg, about double that of Li-ion batteries. However, the volumetric energy density does not show significant improvement over Li-ion batteries. Furthermore, the complex sulfur reaction chemistry yields a multistep discharge curve around 2.2 V and poor charge-discharge energy efficiency as well as an inadequate cycle life. After a decade of intense R&D focus on these two promising battery couples, there is now skepticism about their practicality for EV applications in the short term.

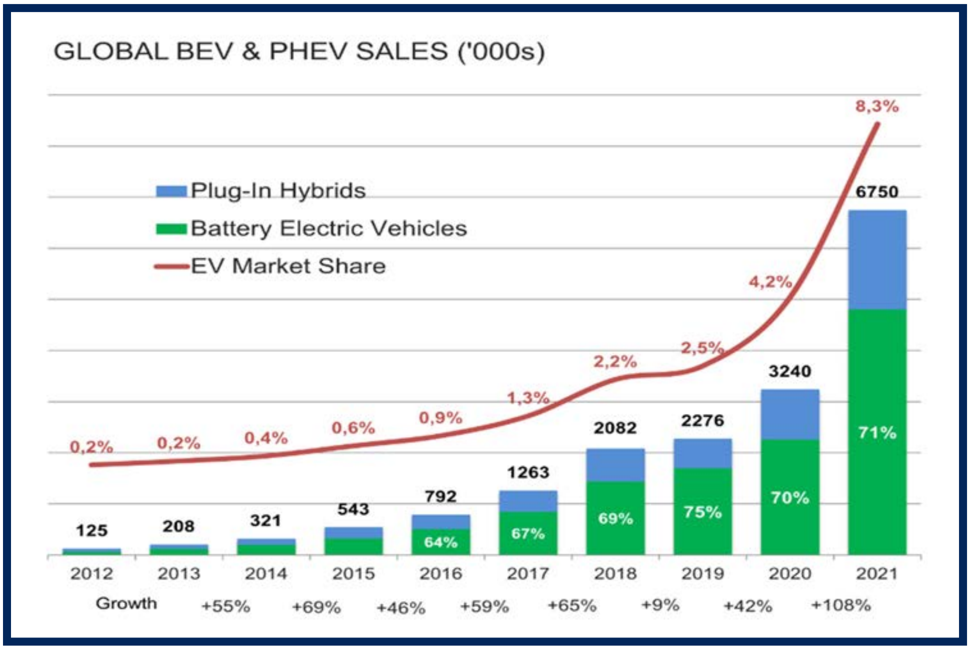

Fig. 5. *Global battery EV (BEV) and Plug-in hybrid EV (PHEV) sales and EV market share. (Courtesy of EV Volumes, reference 22.)*

Today, there is tremendous enthusiasm for solid state lithium batteries, as a most promising technology to succeed Li-ion batteries for EVs.[17-19] This technology is very popular with the investment community seeking to invest in EV technology futures.[17] Solid state batteries offer a pathway to replace graphite-based anodes with metallic lithium, with an order of magnitude higher specific capacity (mAh/g), leading to substantially higher gravimetric and volumetric energy densities. Theoretically, solid state batteries could reach 500 Wh/kg and 1000 Wh/L energy densities. Solid state batteries also have the potential to eliminate much of the fire safety issues of traditional Li-ion batteries based on flammable organic liquid electrolytes, which would be replaced with nonflammable solid ionic conductors. Additionally, higher temperature operation would be enabled, which could make battery pack thermal management systems smaller, simpler, and less expensive. While the potential benefits of solid state batteries are compelling, there are also R&D challenges that are somewhat daunting.[17-19] Solid state ionic conductors are generally inadequate in ionic conductivity compared to existing liquid electrolytes used in Li-ion batteries. There are serious materials compatibility issues with existing solid state ionic conductors. There are issues related to interfacial contacts and dendrite penetration through phase boundaries. Manufacturing processes for electrode assemblies need extensive development. However, there is intense competition among dozens of well-funded R&D organizations to find the solutions to these problems to provide the next generation of batteries beyond Li-ion.[17]

While we continue to look for the "magic bullet" solution to achieve 500 Wh/kg energy density, the energy density of Li-ion batteries continues to increase and the cost continues to fall. Maybe the next-generation battery after Li-ion will actually be advanced Li-ion batteries. There is now intensive work on the development of Li-ion batteries utilizing dimensionally stable metallic lithium anodes with conventional Li-ion cathodes and liquid electrolytes that have the potential to push the specific energy to 500 Wh/kg this decade.[20] This approach circumvents some of the key hurdles of solid state battery development, such as the low conductivity, materials incompatibility, and manufacturability issues associated with solid ionic conductors. There is a plethora of R&D approaches for higher energy density and reduced cost Li-ion batteries underway powered by massive industrial and government funding at battery companies, national labs, and universities. The Li-ion battery industry is a highly diverse international business with 2021 revenue exceeding $70B.[2] Mostly spurred by demand from the rapidly growing EV industry, that revenue is expected to at least triple in the next decade.[2]

Battery Electric Vehicles Today

Li-ion batteries have stimulated the dramatic transformation now underway in the world auto industry.[21,22] The EV market has grown by leaps and bounds over the last decade, as shown in Fig. 5. Plug-in EVs (including mostly battery EVs but also plug-in hybrid EVs) captured over 8% of the global light–duty vehicle market in 2021. This a truly international transformation. In 2021, the EV market share was 3% in the United States, over 10% in China, and over 60% in Norway. Auto companies in the United States and Europe now talk about converting all small passenger cars to battery EVs. They claim cost parity for EVs with ICE vehicles is coming in the next several years when the cost of Li-ion battery packs is projected fall below $100/kWh. This seems a little curious since a 400-mile range vehicle requires a 100 kWh battery pack in a typical car. That would price the battery pack at $10,000, approximately double the cost of a typical ICE drive train. However, current EV offerings targeting a 200-mile range using 50 kWh battery packs could be cost competitive with ICE cars, albeit not with a range of 400 miles. EVs also have the additional value proposition of substantially lower energy costs over ICE vehicles. In the United States in 2022, the energy cost per mile to drive an EV with an energy consumption of 250 Wh/mile is less than 20% that of a 25-mpg ICE vehicle (using baseline electricity costs of 15 cents/kWh vs. $5/gallon gasoline). The consequent energy cost savings for the EV would be more than $15,000 over 100,000 miles of driving.

An intrinsic disadvantage of EVs historically has been the slow recharge of batteries in comparison to ICE vehicle refueling at the gas pump. Gas cars can be refueled in 5 minutes (at an energy transfer rate of several megawatts). Normal battery recharge takes hours or at least many minutes due to the rate limitations of battery cells. Li-ion batteries can be recharged to 80% in 20 minutes. But that takes a lot of electrical power. For a 50-kWh battery pack, it would take about 150 kW. Building fast-charge infrastructure will take a lot of time, effort, and expense. Yet, it is underway. In the United States, Tesla has an installed network of more than 2000 fast-charge stations with a charge capability of up to 250 kW. This makes long-distance EV travel feasible, if not as convenient as for ICE-powered cars. Major R&D efforts are now focused by the US DOE and auto companies on improving the capability of batteries to be charged at faster rates, and the development of infrastructure to provide higher charge power.[23] Faster recharge will help reduce range anxiety for EV drivers and improve the commercial viability of 200-mile range vehicles.

Vehicle electrification, the transformation in the auto industry to electric and hybrid EVs, is now happening at a rapid pace. Li-ion batteries are enabling this dramatic transformation of the auto industry, and Li-ion batteries and their derivatives are likely to power the growing EV industry for decades to come.

 DOI: 10.1149/2.F09223IF

Acknowledgements

I thank Mark Verbrugge (GM), Ted Miller (Ford), Oliver Gross (Stellantis), Boryann Liaw (Idaho National Labs), and Mike Sanders (Avicenne) for helpful discussions.

About the Author

Dennis Corrigan, Director of Vehicle Electrification Programs, Oakland University

Education: BS in Chemistry (Purdue University); PhD in Electrochemistry (University of Wisconsin).

Research Interests: The development of electrochemical power devices for hybrid and electric vehicles, including lead-acid, nickel-zinc, nickel-metal hydride, and lithium-ion batteries as well as fuel cells and supercapacitors.

Work Experience: As Vice President of Ovonic Battery, he played a major role in the development of NiMH traction batteries for the EV1 electric vehicle. He was a founder of the electric drive vehicle education program at Wayne State University and developed core courses on electric and hybrid vehicles batteries. He has led research teams at GM R&D, ECD-Ovonics, Cobasys, US Army TARDEC, and XALT Energy.

Pubs + Patents: >170 presentations and publications and 19 US patents.

Work with ECS: Dennis has been a member of ECS since 1977 and has been very active in the Detroit local section of the ECS, serving three times as chair.

References

1. E. H. Wakefield, *The History of the Electric Automobile*, Society of Automotive Engineers, Warrendale PA (1994).
2. M. Sanders, "Market Report: Cell, Pack and Electrode Manufacturing in North America," NAATBatt 2022 Annual Conference (February 2022).
3. S. R. Ovshinsky, M. A. Fetcenko, and J. Ross, *Science*, **260**, 176–181 (1993).
4. *Who Killed the Electric Car?*, documentary film directed by Chris Paine, produced by Jessie Deeter, Sony Picture Classics (2006).

5. D. A. Corrigan and A. Masias, in *Linden's Handbook of Batteries*, 5th Ed., K. W. Beard, Editor, Chap. 26A, McGraw Hill, New York (2019).
6. *USABC Battery Test Manual for Electric Vehicles*, Vehicle Technologies Program, US Department of Energy, Idaho National Laboratory Report INL/EXT-15-34184, Rev 3.1 (October 2020).
7. V. Ruiz, A. Pfrang, A. Kriston, N. Omar, P. Van den Bossche, and L. Boon-Brett, *Renew Sust Energ Revs*, **81**, 1427–1452 (2018).
8. M. S. Whittingham, *Chem Rev*, **104**, 4271–4301 (2004).
9. J. Dahn and G. M. Ehrlich, *Linden's Handbook of Batteries*, 5th Ed., K. W. Beard, Editor, Chap. 17A, McGraw Hill, New York (2019).
10. G. E. Blomgren, *J Electrochem Soc.*, **164**, A5019–A5025 (2017).
11. M. Alamgir, *IEEE Electrification Magazine*, **5**, (1), 43–52 (2017).
12. N. Nitta, F. Wu, J. T. Lee, and G. Yushin, *Mater Today*, **18**, 252–264 (2015).
13. BloombergNEF 2022, https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/.
14. D. Howell, *Annual Merit Review*, DOE Vehicle Technologies Office, Washington, DC (2017).
15. L. Grande, et al., *Advanced Materials*, **27**, 784–800 (2015).
16. T. Li, et al., *Adv Funct Mater*, **29**, 1901730 (2019).
17. A. Scott, *Chemical & Engineering News*, **99**, (32), 20-22 (2021).
18. Y.-K. Sun, *ACS Energy Lett*, **5**, 3221–3223 (2020).
19. K. Kerman, A. Luntz, V. Viswanathan, Y.-M. Chiang, and Z. Chen, *J. Electrochem. Soc.*, **164**, A1731–1744 (2017).
20. J. Liu, et al., *Nature Energy*, **4**, 180 –186 (2019).
21. Argonne National Laboratory, Energy Systems Division, Light Duty Electric Drive Vehicles Monthly Sales Updates, https://www.anl.gov/es/light-duty-electric-drive-vehicles-monthly-sales-updates.
22. EV Volumes, https://www.ev-volumes.com/
23. E. J. Dufek, et al., *J Power Sources*, **526**, 23112 (2022).