Automaker Energy Storage Needs for Electric Vehicles

Alvaro Masias, Kent Snyder and Ted Miller

Abstract The success of electric vehicles (EVs) is strongly tied to their performance and ability to meet customer expectations. A comparison of EV battery performance against the requisite targets created by the international community is presented. The performance attributes of greatest interest are energy, power and life. It is shown that only power has achieved the level of performance required by the automotive community for mass commercialization.

Keywords Electric vehicle · EV · BEV · Lithium ion battery · LIB

1 Research Objective

The success of global long term vehicle electrification efforts will depend heavily on the performance of their requisite batteries. The current revival of Electric Vehicles (EVs) is being enabled by recent improvements in Lithium Ion Batteries (LIB). Recently, a large number of automakers have made electrified vehicle product announcements and the US Government has targeted 1 million such vehicles to be on the road by 2015 [1]. Despite these recent announcements and targets, all current EVs require customers to make sacrifices when compared to similar gasoline powered vehicles. Our research objective is to quantify the gap between conventional gasoline powered vehicles and the battery technology of EVs in terms of energy, power and life. The current performance gap between EVs

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and gasoline powered vehicles is large and is attributable to the performance limits of LIBs. These limits stem from material and design constraints of the current technology and will require extensive R&D to resolve over the long term. It is projected that over the next 10 years, significant reductions in the performance gap are likely, although the two systems will still not achieve parity.

2 Methodology

Our methodology is to quantify the current performance gap between internal combustion engine (ICE) and battery driven vehicles, with a focus on the performance features of energy, power and life. Due to its inherent performance advantages and nascent technical maturity, we will focus exclusively on lithium ion based battery chemistries. Performance specifications and targets for batteries are commonly described at various hardware levels (cell, module or pack) and for ease of comparison we will express all figures of merit in terms of actual or estimated pack level performance. EV research has been pursued in the recent past by various global organizations and as such our research will consider the performance and targets from a variety of international sources over the past 15 years. These performance specifications and targets will be considered for automotive relevant applications, rather than for consumer electronics applications which have historically been the technology driving industry for batteries. In the case of energy and power, these figures of merit will be examined as beginning of life (BOL) values. The study of life is most relevantly considered in terms of end of life conditions (EOL), and as such, given its greater complexity we will look at a variety of influencing factors.

The modern gasoline powered ICE vehicle has been in mass production since Henry Ford released the Model T in 1908 [2]. Since that time ICE vehicles have been tailored to meet ever evolving consumer expectations. Due to this optimization of features and capabilities, modern ICE vehicles also serve as the most useful benchmark for determining the features that EVs require to achieve mass market acceptance. Much as an engine determines many of the performance characteristics of an ICE vehicle, so too does the battery drive the capabilities of an EV. The most prominent technical performance features of an EV are its energy, power and life, and therefore these features will be the focus of our analysis.

Lithium is a very attractive material to base batteries on owing to its very low electrochemical potential which gives it the promise of a high cell voltage. As a result, lithium based batteries have been in development for over 40 years since the first intercalation/deintercalation was demonstrated in the 1970s [3]. Twenty plus years of research culminated in the first commercial production of a lithium ion battery by Sony Energy Device Corporation in 1991 [4]. Sony was able to create a product suitable for the consumer electronics market whose form factor (18,650 cylindrical cell or 18 mm ∅ and 65 mm height) has since become an industry mainstay and is today produced in the billions annually. Due to its ubiquity and

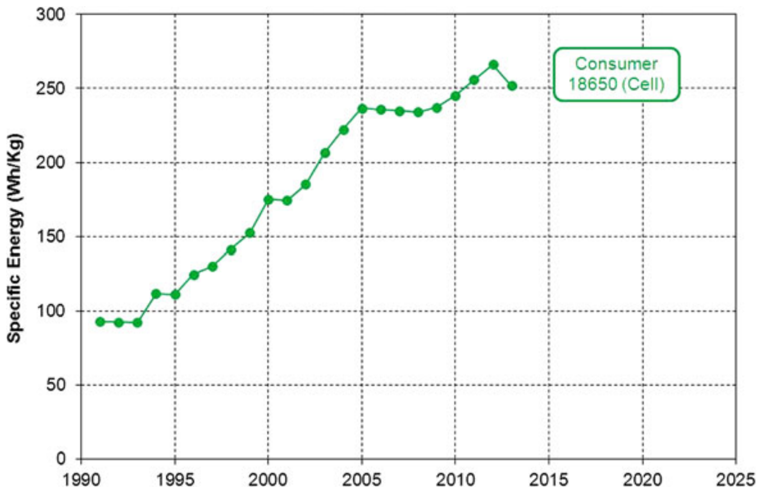

Fig. 1 Consumer 18,650 cell specific energy (Wh/kg) over time [5]

massive production volumes, the 18,650 cell is a useful benchmark for the development of lithium ion battery technology as a whole. The significant rate of progress of one figure of merit, specific energy (Wh/kg), is shown below in Fig. 1.

Despite the continuous improvements in commercial lithium ion technology over the last 20 years, it has been only in the last couple of years that the technology has been suitable for some automotive applications. In automotive applications we need to consider not only cell level figures of merit, but also at the module (a mechanical assembly of cells, often containing electrical/thermal sensing and interfaces) and battery pack level (a mechanical assembly of modules, often containing electrical and thermal control hardware and software). The assembly of cells into modules and subsequently packs is what makes the hardware relevant to an automotive designer and user. Although module and pack designs can vary substantially, they all add additional weight and volume which effectively de-rates the cell level performance values. In the case of weight, estimates of a 20 loss at the module level and a further 10 % loss at the pack level are often made by industry groups [6]. These estimates would yield a battery pack weight efficiency of 72, which falls at the high end of practical designs which yield values ranging from 50 to 75 %. The impact of these de-rated engineering estimates is shown in Fig. 2 below.

Vehicle electrification is a global phenomenon and the research of its development must be cast with a similarly wide viewpoint. Each of the three most mature automotive manufacturing regions (United States, Europe and Japan) has published EV battery targets. In the US, the United States Advanced Battery Consortium (USABC) is composed of Chrysler, Ford and General Motors in partnership with the US Department of Energy [7]. The European Council for Automotive Research and Development (EUCAR) is an analogous organization in

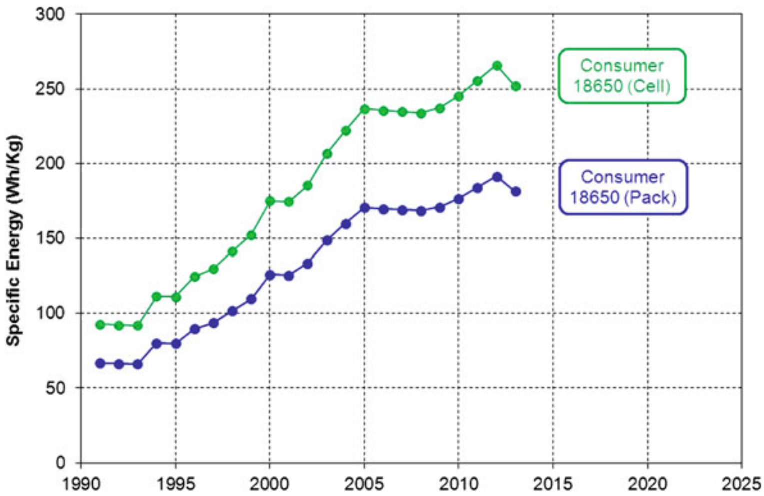

Fig. 2 Consumer 18,650 pack specific energy (Wh/kg) over time

Europe [8]. In Japan, the Ministry of Economy, Trade and Industry (METI) established an agency to promote the development of new energy technologies in the form of the New Energy and Industrial Technology Development Organization (NEDO) [9]. Each of these respective organizations, USCAR, EUCAR and NEDO has created EV battery targets to guide industry's technology development in 1996, 2009 and 2008, respectively. Our research approach is strengthened by considering EV battery targets from a variety of regions in the world, published over a span of many years.

One of the principle differences between consumer electronics and automotive applications is the duration of use in terms of both calendar and cycle life. Typically, consumer electronics require 500 cycles and 1–2 years of useful life. In automotive applications, the battery is part of a traction system which is expected to last the life of the vehicle, requiring thousands (and in the case of hybrid electric vehicles, millions) of cycles over 10–15 years [10]. Due to this long duty cycle requirement for automotive applications, designers must specify BOL and EOL performance requirements, as the battery will inevitably degrade during use.

For our study we have identified power, energy and life to be of primary interest. Given that the majority of public battery performance specifications provided by battery makers and targets published by industry groups are BOL values, we will focus on this timing when considering energy and power. Due to the inherent requirement to consider life as an EOL condition and the large variety of calendar ageing and cycle life conditions, its study is more complicated. As such our approach is to look at a variety of factors which influence life performance including energy use, temperature and testing requirements.

Table 1 BOL EV targets [6, 11–12]

	USABC (1996)		EUCAR (2009)			NEDO (2008)			
Hardware level	Pack			Pack			Module		
Target timing	Minimum	Long Term	2010	2015	2020	2008	2015	2020	2030
Energy (Wh/kg)	230	300	90–100	130–150	180–200	100	150	250	500
Power (W/kg)	150	200	400–750	500–950	600–1,250	1,000	1,200	1,500	1,000
Calendar life (Y)	10	10	8–10	10	15	5–8	8–10	10–15	10–15
Cost (/Wh)	$0.15	$0.10	$0.40–0.50	$0.30	$0.15	100–200ø	30ø	20ø	10ø

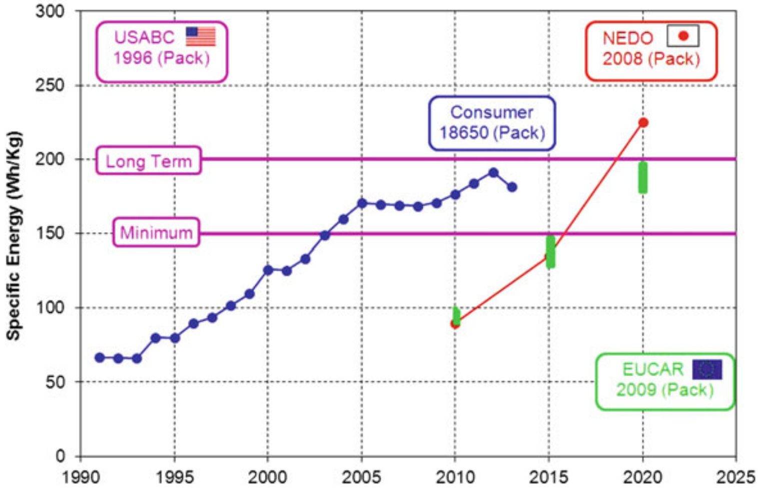

Fig. 3 Pack specific energy (Wh/kg) targets & 18,650 estimates

3 Results

Our research compared the performance of existing batteries to those of an international community of EV battery targets. These targets were developed in the United States, Europe and Japan over a period of many years. The most relevant targets for a variety of time periods are shown below in Table 1. The USABC goals have no timing attached, but rather represent a minimum level of performance and one required for true long term commercialization. The EUCAR and NEDO targets span 5 year intervals up to 2,030.

A comparison of Table 1 across organizations and time reveals a few consistent trends. A combined appraisal of specific energy implies that a value of ~200 Wh/kg is required for a competitive EV and is predicted in the early 2020s. The EUCAR and NEDO targets for power are noticeably more aggressive than the USCAR values. This is likely due to the pace of development of battery technology between 1996 and 2009/2008, which is the timing of the USCAR and EUCAR/NEDO goals respectively. The energy of a battery is an intrinsic property determined by the choice of materials and their electrochemical properties of voltage and capacity. Power on the other hand is an extrinsic property, influenced by the material behaviour, but also substantially controlled by improved designs achieved through engineering refinements. Given the large industry which has evolved around lithium ion batteries in the last 20 years, it is not surprising that the fast pace of engineering improvements has exceeded that of new material discoveries. An appraisal of the life targets shows alignment on a life of the vehicle expectation of 10–15 years, as outlined above.

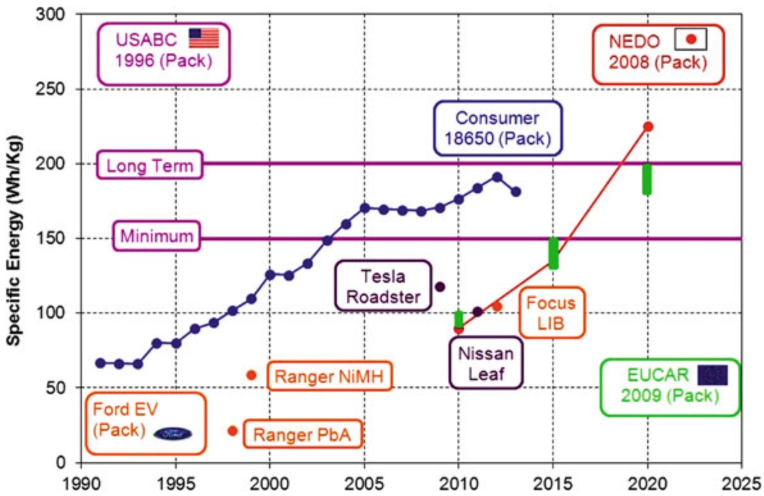

Fig. 4 Pack specific energy (Wh/kg) targets & performance

3.1 Energy

As outlined in our methodology, 18,650 cylindrical cells are the lithium ion battery format produced in the highest volume commercially to serve the consumer electronics industry. While posing many challenges for automotive applications, the usage of those cells in automotive applications was first proposed and demonstrated by AC Propulsion. The suitability of 18,650 s for automotive aside, this cell format and size is at the forefront of specific energy developments and so considering its rate of improvement can prove instructive relative to the broader class of lithium ion technology. In Fig. 3 below, it is shown that even when considering highly engineered and mass produced 18650 cells, the specific energy of current 18,650 technology is below the goals outlined by USABC for long term automotive production.

Although considering the capabilities of 18,650's in abstract designs is a useful calibrating investigation, it is also beneficial to examine existing vehicle designs. In Fig. 4, a variety of EV battery specific energies are plotted. Three EVs from Ford are shown, the 1998 Lead Acid Battery Ranger EV, the 1999 Nickel-Metal Hydride Ranger EV and the 2012 Lithium Ion Battery Focus EV. For comparison, the Nissan Leaf EV is also shown and overlays almost exactly over the Focus EV. Additionally, the Tesla Roadster using 18650 cells is shown and it should be noted that the specific energy achieved is far below the value estimated for the 18,650 cell-based pack specific energy capability available in that year. The specific energy achieved in an actual automotive application (Tesla Roadster) is approximately that

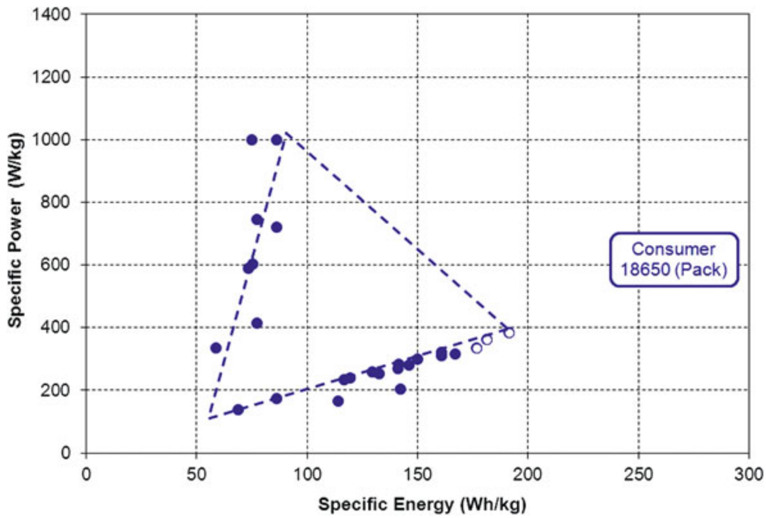

Fig. 5 Specific power (W/kg) of various 18,650 [13–15]

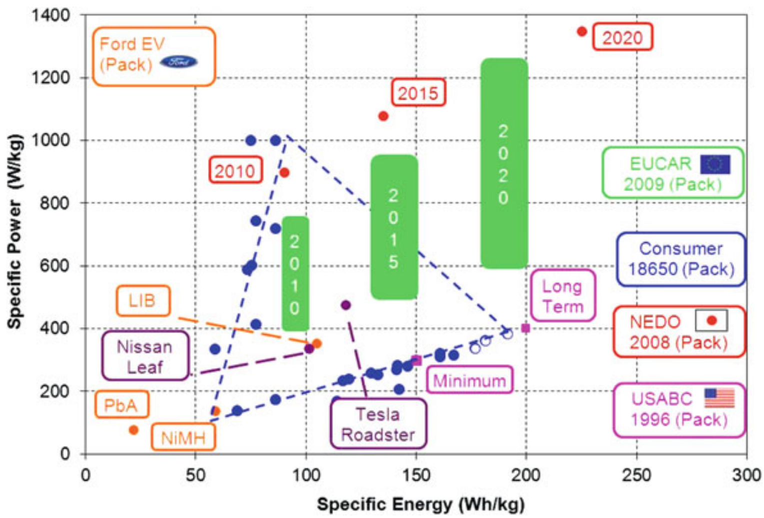

Fig. 6 Specific power (W/kg) targets & performance

which was predicted to be possible with an 18,650-cell-based pack about 8–9 years earlier. This can be attributed to several factors specific to battery designs for automotive applications, but in general communicates the challenges in using cells designed for consumer electronics in an automotive application.

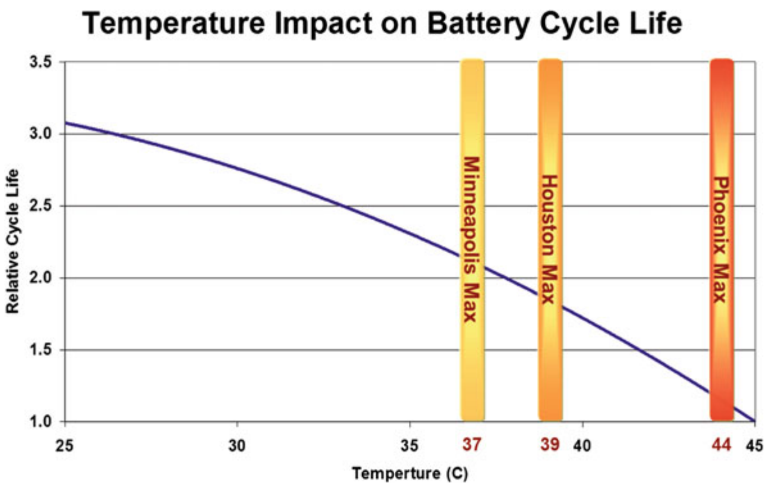

Fig. 7 Temperature impact on battery cycle life [16]

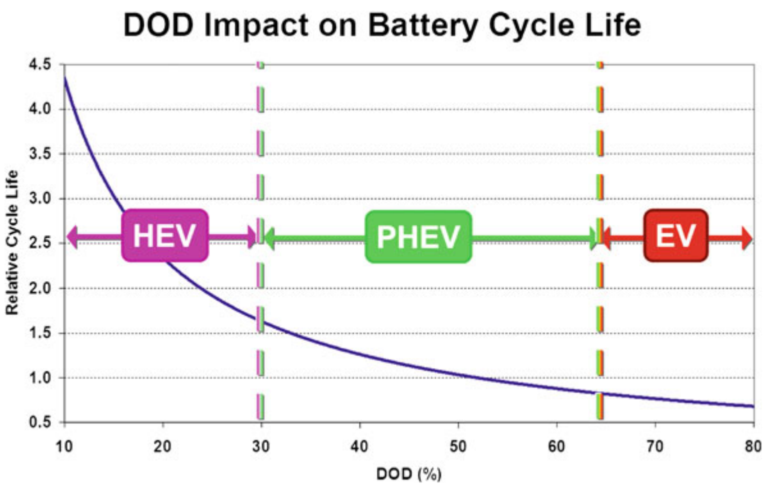

Fig. 8 DOD impact on battery cycle life [17]

3.2 Power

Our analysis of the power capability of existing lithium ion battery technology also begins by considering that achieved in the 18650 format. A general principle of battery design is that power and energy can be optimized, but rarely at the same

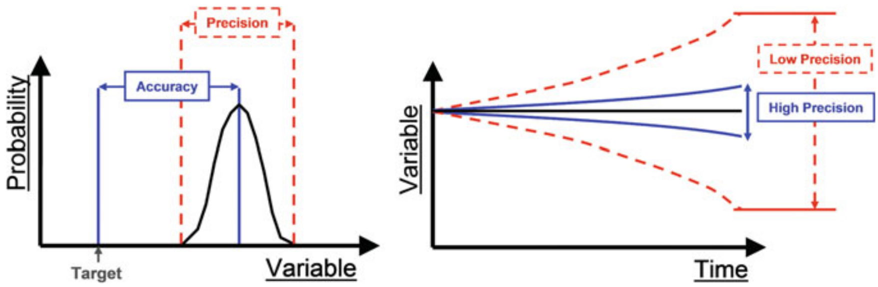

Fig. 9 Precision versus accuracy

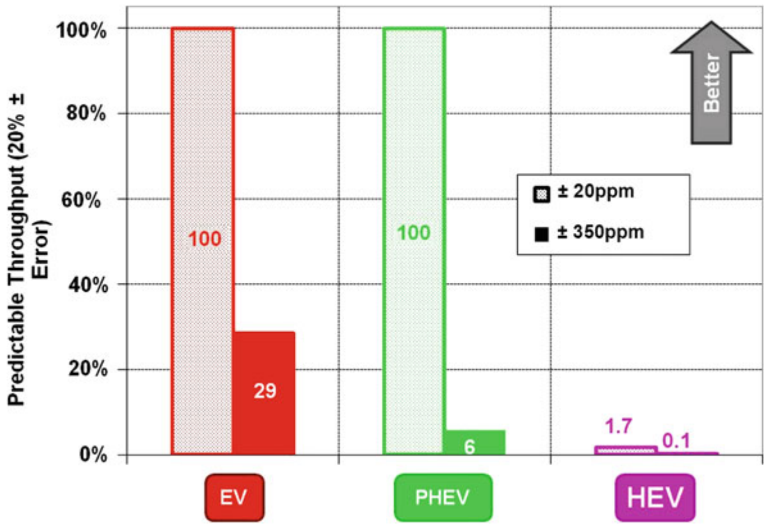

Fig. 10 Impact of precision on USABC test patterns (±350→ ±20 ppm)

time, and this is shown below in Fig. 5 summary of existing state of the art 18,650-cell-based pack specific power versus energy. These cells are designed for either high energy or high power applications and the estimated performance envelope of the technology takes the shape of a triangle.

As in the case of energy, it is useful to consider the EV battery targets of the USABC, EUCAR and NEDO, as well as the performance of existing vehicles, and those results are plotted in Fig. 6. It is apparent that the performance of the Ford Focus, Nissan Leaf and Tesla Roadster all fit comfortably inside the 18,650 performance triangle. Additionally, the higher power performance targets of EUCAR and NEDO introduced in the methodology are highlighted here when compared to USABC targets.

3.3 Life

As outlined in the methodology, the research of life factors in this study is more complicated than that of energy and power, owing to the necessity to consider EOL versus BOL conditions, respectively. To address this EV battery need, we will examine three important factors affecting life requirements: temperature, energy usage and testing.

The relationship of the impact of temperature on battery cycle life is shown in Fig. 7. The relative cycle life decreases noticeably as the temperature increases, reflecting the impact on lithium ion battery materials and the related electrochemistry. For reference, the maximum annual temperatures of three US cities are shown, Minneapolis, Houston and Phoenix.

The depth of discharge (DOD) is the percentage of a battery's energy which has been used during a cycle. 100 % DOD cycle swings are not possible in automotive applications for a number of reasons; including their impact on life, as shown in Fig. 8. The DOD swing of various applications (Hybrids (HEV), Plug-In Hybrids and EVs) can vary from vehicle to vehicle, but the US Department of Energy-estimated DOD ranges are shown in Fig. 8 [17].

An often overlooked complexity of the life requirement is the need for high precision that the large cycle number and long calendar requirements introduce in terms of battery life data collection, life estimation and validation. In Fig. 9, we describe the distinction between precision and accuracy (L), as well as highlight the impact of a low precision system (R). Due to the high testing burden, the validation of automotive batteries benefits strongly from the ability to predict end of test performance based on an initial data set. Figure 9(R) shows the dangers of using data from a low precision system to perform such calculations. The compounding nature of precision and predictions can lead to a dramatic magnification of the impact as shown in Fig. 9(R).

The current state of the art in battery testers is estimated to achieve a precision of 350 ppm [18]. Based on extensive discussion with an industry expert and manufacturer, Arbin Instruments, a precision of 20 ppm may be achievable using existing technology concepts. During use, many performance variables will degrade and approximately 20 % degradation is often considered end of life. In Fig. 10, we calculate the impact of 350 and ±20 ppm precision on the accumulated error involved in energy throughput (MWh) prediction using the USABC test patterns. It is shown that with a ±20 ppm tester, it would be possible to predict 100 of an EV and PHEV battery's life with <20 % error at the test's onset. Such a prediction would not be possible with a ±350 ppm tester due to its high error.

4 Conclusions

In the three key battery performance categories (energy, power and life), only power has been achieved at levels sufficient to promote widespread electrification. Energy improvements have proven more elusive as they are based on fundamental material principles, whereas power is more generally a product of engineering effort. The quantification of life is more difficult and requires an understanding of the specific vehicle design and use conditions, as well as the impact of temperature, energy use, and testing as highlighted.

While the wholesale replacement of gasoline powertrains by EV powertrains will continue to be limited by LIB costs for the foreseeable future, continued incremental LIB cost reductions are expected. Although EVs will not reach performance and cost parity with gasoline systems over the timeline of this study ($\sim$10 years), it is projected that the scale of the gap will continue to decrease.

References

1. "One Million Electric Vehicles by 2015: February 2011 Status Report." US DOE. http://energy.gov/sites/prod/files/edg/news/documents/1_Million_Electric_Vehicle_Report_Final.pdf. Accessed 10 July 2012
2. Ford H (1988) "Today and tomorrow". Productivity Press, Cambridge
3. Whittingham MS (1976) Electrical energy storage and intercalation chemistry. Science 192(4244):1126–1127
4. Reddy T (ed.) (2011) "Linden's handbook of batteries, 4th edn." McGraw-Hill, New York
5. "Battery Association of Japan Website" (2012) http://www.baj.or.jp/, Accessed 12 July 2012
6. "NEDO Technology Development Roadmap Secondary Battery (Battery RM 2010)." (2012) New energy and industrial technology development organization (NEDO). http://www.nedo.go.jp/content/100153876.pdf. Accessed 10 July 2012
7. "USABC Website"(2012) http://www.uscar.org/guest/teams/12/U-S-Advanced-Battery-Consortium. Accessed 12 July 2012
8. "EUCAR Website" (2012) http://www.eucar.be/. Accessed 12 July 2012
9. "NEDO Website" (2012) http://www.nedo.go.jp/. Accessed 12 July 2012
10. "USABC Manuals" http://www.uscar.org/guest/article_view.php?articles_id=86, Accessed 13 July 2012
11. Teyssot A (2009) "HELIOS European project and EUCAR/VDA research roadmaps". EVS24, Stavanger, Norway, 13–16 May 2009
12. "USABC Goals for Advanced Batteries for EVs" (2012) United States advanced battery consortium (USABC). http://www.uscar.org/commands/files_download.php?files_id=27. Accessed 10 July 2012
13. "Panasonic 18650" (2012) Panasonic. http://industrial.panasonic.com/www-cgi/jvcr21pz.cgi?E+BA+3+ACA4001+4++WW. Accessed 14 July 2012
14. "LG Chem 18650" (2012) LG chemical. http://www.lgchem.com. Accessed 14 July 2012
15. "Samsung 18650" (2012) Samsung SDI. http://www.samsungsdi.com/battery/cylindrical-rechargeable-battery.jsp. Accessed 14 July 2012
16. Pesaran A, Smith K, Markel T (2009) "Impact of the 3Cs of batteries on PHEV value proposition: cost, calendar life, and cycle life." advanced automotive battery and EC capacitor conference, Long Beach, 8–12 June 2009

17. Duong T (2010) "Direction for energy storage R&D in the vehicle technologies program." Scalable energy storage beyond Li-Ion, Oak Ridge, 7 Oct 2010
18. Smith AJ, Burns JC, Trussler S, Dahn J (2010) "Precision measurements of the coulombic efficiency of lithium-ion batteries and of electrode materials for lithium-ion batteries." J Electr Soc 157(2):A196–A202

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