Journal of Power Sources 384 (2018) 312–317

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

On the optimal sizing of batteries for electric vehicles and the influence of fast charge

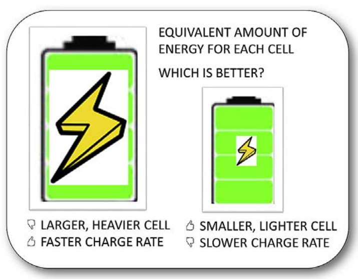
Mark W. Verbrugge*, Charles W. Wampler

Chemical and Materials Systems Lab, General Motors Research and Development, Warren, MI 48092-2031, USA

HIGHLIGHTS

- We propose a customer adaption cost that decreases with battery energy capacity.
- Including the adaption cost yields an optimization problem for battery sizing.
- Newer, higher energy density cells cannot be fast charged at present.
- Established lithium ion cells with lower energy density can be fast charged.
- We evaluate the trade-off between fast charge and higher cell energy density.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Lithium battery
Cubic spline
Electric vehicle
Cost
Fast charge
Energy density

ABSTRACT

We provide a brief summary of advanced battery technologies and a framework (i.e., a simple model) for assessing electric-vehicle (EV) architectures and associated costs to the customer. The end result is a qualitative model that can be used to calculate the optimal EV range (which maps back to the battery size and performance), including the influence of fast charge. We are seeing two technological pathways emerging: fast-charge-capable batteries versus batteries with much higher energy densities (and specific energies) but without the capability to fast charge. How do we compare and contrast the two alternatives? This work seeks to shed light on the question. We consider costs associated with the cells, added mass due to the use of larger batteries, and charging, three factors common in such analyses. In addition, we consider a new cost input, namely, the cost of adaption, corresponding to the days a customer would need an alternative form of transportation, as the EV would not have sufficient range on those days.

1. Introduction

We are at a crossroads in terms of balancing two promising technologies: (1) higher energy density (Wh/L) and specific energy (Wh/kg) batteries, relative to today's conventional graphite/metal-oxide lithium ion systems, and (2) fast-charge capability, defined here as greater than Level 2 charging, or greater than about 20 kW. Currently in the United States, conventional Level 2 charging of 6.6 kW is available in homes and various community locations. In the ideal case, high energy batteries would be able to accommodate fast charge, but two of the most promising high-energy cell technologies, i.e., cells employing Si-enhanced or Li-metal negative electrodes, are problematic insofar as they cannot at present accept fast charging without significant degradation in cell life.

Performance characteristics for Li-Si batteries have been studied in Refs. [1–7]. The 1976 publication by Sharma and Seefurth [1] provides electrochemical data at higher temperatures for the Li-Si system that clearly identify the relevant equilibrium phases (which give rise

* Corresponding author.
E-mail address: mark.w.verbrugge@gm.com (M.W. Verbrugge).

https://doi.org/10.1016/j.jpowsour.2018.02.064
Received 18 December 2017; Received in revised form 13 February 2018; Accepted 21 February 2018
0378-7753/

to clear potential plateaus). Graetz et al. [2] employed thin films of Si to assess that behavior of Li-Si at room temperature without the complications associated with making porous electrodes from particulate Si. Li et al. [3] employed a similar thin-film configuration to perform PITT (potentiostatic intermittent titration technique) measurement; it was found that the Li diffusion coefficient in Si is about two orders of magnitude lower than in graphite, which is problematic for fast charging. References [4–7] provide reviews of recent Li-Si publications.

The other leading candidate for high-energy batteries uses Li-metal negative electrodes. Early work on Li metal electrodes, prior to 1970, is reviewed in Refs. [8–10]; stability of the Li-electrolyte interface is exacerbated by the growth of nodules and dendrites that lead to high electrode surface areas, an open problem that is exacerbated by high charging rates [11–13]. Recent work associated with stabilizing the Li-electrolyte interface, with emphasis on the solid-electrolyte interphase, can be found in the publication by Peled and Menkin [14].

The tradeoff between high-energy, as provided by cells with Li-Si and Li metal negative electrodes, and fast-charge capability, which can be obtained from conventional lithium ion cells employing lithiated graphite or titanate negative electrodes, for examples, poses a dilemma in the design of electric vehicles (EVs).

Herein we derive and implement a simple model to assist in evaluating such matters as cell performance, cost, life, and fast-charge capability. The approach is useful in terms of comparing and contrasting battery systems and shedding light on technological tradeoffs.

2. A framework for approaching EV design and architecture

Because EVs are usually range-constrained relative to conventional ICEVs (a vehicle with an internal combustion engine), we need to estimate the cost for the customer to adapt to a new mode of transportation when the EV fails to provide the needed driving distance. Pearre et al. [15] have studied this problem and found it expedient to assume that the days of adaptation per year N_A is a function of the vehicle range x, and no other variables. We employ the 75 percentile driver[1] data of [15]. To facilitate computations, we fit $N_A(x)$ with a cubic spline function, as detailed in the Appendix and plotted in Fig. 1.

For our cost function S, we consider four components, S_{cell}, S_{chg}, S_A, and S_M, corresponding to cell, charging, adaptation, and added-mass costs, respectively:

$$S = S_{cell} + S_{chg} + S_A + S_M \tag{1}$$

The variables and parameters used in this work, and base values, where appropriate, are provided in Table 1. Given an EV range x based on a single (full) charge of a battery pack with useable capacity Q, we can immediately calculate cell and added-mass costs: $S_{cell} = Qs_{cell} = Cxs_{cell}$ and $S_M = ((Cx/q_{SE}) - M_0)s_M$, respectively, where C is the energy consumption per unit distance for the vehicle and M_0 is the reference mass as described in Table 1. No account has been taken to incorporate additional costs that might be associated with fast-charge capability for some fraction of the pack that can be fast charged. This aspect of cell pricing remains an open issue relative to the analysis.

We shall consider two forms of EVs in terms of charging capability: those that use a conventional, Level 2, 220 V charger of 6.6 kWh and those for which a fraction f of the pack capacity Q can be fast charged in time τ. The cost for charging the vehicle over its lifetime t, in the absence of fast-charge capability, is given by $S_{chg} = (365 - N_A)m_{avg}tCs_{chg}$, where $365 - N_A$ corresponds to the days per year the EV is charged. For fast-charge EVs, the range of the fully charged battery, x, plus that of one fast charge is thus $(1 + f)x$. We do not consider more than one fast-

[1] The 75 percentile driver requires adaption $N_A(x)$ days per year; on all other days of the year, the driver's needs are satisfied by the EV range x.

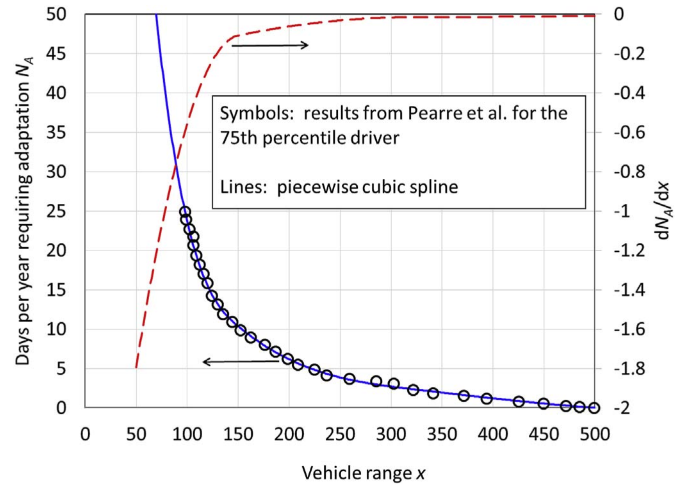


Fig. 1. Solid line corresponds to piecewise cubic spline of the Appendix, and the data are from Ref. [15].

charge event, as it is less likely that the customer will want to use the EV to drive distances longer than $(1 + f)x$ by successively fast charging; that is, we assume that the customer would adapt to an alternative form of transportation if her/his trip were projected to exceed the range $(1 + f)x$, and the days of adaptation/year with fast charge is N_A evaluated at $(1 + f)x$, or . In addition, because we assume that the number of fast-charge events would be small and can be neglected in the charging cost, we estimate the lifetime charging cost based on the average daily mileage m_{avg} as:

$$S_{chg} = [365 - N_A((1 + f)x)]m_{avg}tCs_{chg} \tag{2}$$

Because fast charge capability increases the number of days the EV is driven, i.e., because $N_A((1 + f)x) < N_A(x)$, the charging cost increases with fast charging, but for the same reason, the adaption cost with fast charging, $S_A = N_A((1 + f)x)ts_A$, decreases from that of conventional Level 2 charging, corresponding to $f = 0$. Last, it is important to understand the power P_{FC} needed for fast charge:

$$P_{FC} = \frac{fQ}{\tau} = \frac{fC}{\tau}x \tag{3}$$

Equation (3) is not part of the optimization, but one should be aware of the power P_{FC} needed for fast charge to ensure the power need is not unreasonable. Equation (3) is used to calculate the power needs reported in Fig. 3 (to be discussed).

In summary, the total cost function with fast charging is given by

$$S(x) = \underbrace{Cxs_{cell}}_{S_{cell}(x)} + \underbrace{[365 - N_A(x(1 + f))]m_{avg}tCs_{chg}}_{S_{chg}(x)} + \underbrace{N_A(x(1 + f))ts_A}_{S_A(x)} + \underbrace{\left(\frac{Cx}{q_{SE}} - M_0\right)s_M}_{S_M(x)} \tag{4}$$

We can identify the optimal range with respect to our total cost function by solving for x when $dS/dx = 0$:

$$\frac{dS}{dx} = Cs_{cell} + \frac{d}{dx}[N_A((1 + f)x)](-m_{avg}Cs_{chg} + s_A)t + \frac{C}{q_{SE}}s_M = 0 \tag{5}$$

This equation can be solved for the optimum range x for which the cost function is minimized. (As discussed in the Appendix, when N_A is a cubic spline, dS/dx is piecewise quadratic, so the optimality condition 5 can be solved analytically.)

3. Results and discussion

Plotted in Fig. 2 are three cases. As noted in Table 1, we examine a conventional cell technology (e.g., similar to that of the Chevrolet Bolt