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Impact of lithium abundance and cost on electric vehicle battery applications

Fritz G. Will

Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, CA 94 304, USA

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Abstract

This paper addresses the issues of realistic specific energy levels attainable with Li batteries, the maximum number of electric vehicles as limited by the identified Li world reserves and the anticipated battery price. The Li-ion battery, LiC_6/Li_xNiO_2, is taken as the basis for the analysis presented here. It is shown that economically recoverable Li world reserves are sufficient to meet the demands of current new passenger car world production and its anticipated growth in the next 50 years. Currently identified world reserves can power 2 billion cars with Li-ion batteries, that is four times the number of cars presently registered in the world. World annual Li production of 10 000 metric tons would have to be increased 13-fold to power current new car world production with Li batteries. Such increase of the production capacity is seen as principally feasible. The 'theoretical reactant cost' — the absolute minimum reactant cost — for the Li-ion battery with Ni oxide cathode is US$ 19.20/kWh, compared to US$ 15.40 for the Ni/Cd and US$ 29.40 for the Ni/metal-hydride (AB_5) battery. By comparison with the large-volume price for Ni/Cd vehicle batteries, a minimum price of US$ 330/kWh or US$ 8000 per 24 kWh battery is predicted for mass-produced Li-ion vehicle batteries, once the technology has matured. A battery life of 1000 cycles, already demonstrated in laboratory cells, results in a total vehicle mileage of approximately 126 000 miles when based on a 24 kWh battery. The cost of battery ownership and 'electric fuel' combined is 11 ¢/mile, that of car ownership and fuel combined 27 ¢/mile, if based on a vehicle price of US$ 23 000.

Keywords: Lithium; Rechargeable lithium batteries; Battery cost; Lithium reserves; Electric vehicles

1. Introduction

In the past few years, rechargeable Li-ion batteries [1–3] have been introduced into the consumer market, particularly the cellular phone and camcorder segments [2,3]. Li-ion batteries excel through their high cell voltage, low weight and volume for given stored energy, favorable power output, and long cycle life [3–5].

These outstanding characteristics have led to considering Li-ion batteries for electric vehicle (EV) applications. However, questions occur with respect to the abundance and the cost of Li for large-scale applications in EVs. These issues are addressed in the present paper.

Basis for the following analysis is the LiC_6/Li_xNiO_2 system as it presently appears to be the most feasible compared to Li batteries employing other oxide systems [5]. Furthermore, the choice of the oxide system has very little effect (within 8%) on the specific energy and, hence, on the Li demand for EV applications.

Among the other oxide systems are Co oxide and Mn oxide. The former has so far shown the best cycle life, but its large-scale application in EVs is less cost-effective than Ni oxide. Mn oxide, on the other hand, has a distinct cost advantage over both the Ni and Co systems, but has so far shown shorter cycle life.

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2. Results and discussion

2.1. *Specific energy*

In the present assessment, theoretical specific energy (TSE) values have been determined for three scenarios that demonstrate the significant effect of the type of Li anode used, and the reversibly achievable degrees of intercalation of Li into both the anode and cathode.

TSE is commonly based on 100% utilization of the cell reactants (no excess reactants beyond stoichiometric amounts are present) and reversible cell potentials. Further, the weight of electrode substrates and electrolyte (unless the latter enters into the cell reaction) is not counted when calculating the TSE.

2.1.1. *Scenario 1: Li metal anode/ideal NiO_2 cathode*

This scenario yields an upper limit for the TSE due to using Li metal rather than an Li intercalation anode and assuming 100% intercalation/de-intercalation of Li into NiO_2 ('ideal cathode'). In practice, Li metal anodes have failed to yield acceptable cycle life in spite of two decades of effort and 100% intercalation cannot be achieved because of phase changes. The cell reaction for scenario 1 is

$$\mathrm{Li} + \mathrm{NiO_2} = \mathrm{LiNiO_2} \qquad (1)$$

The reversible cell potential changes continuously during charge and discharge [3] as the activity of Li in the host oxide changes during intercalation and de-intercalation. The average reversible cell potential is 3.9 V. The reactant weight per Faraday is 97.65 g. With these values, we calculate 1070 Wh/kg for the TSE.

2.1.2. Scenario 2: ideal LiC_6 anode/ideal NiO_2 cathode

The Li metal anode is replaced by an LiC_6 intercalation anode, assuming 100% intercalation/de-intercalation. The cathode is the same as in scenario 1. The cell reaction for this case is

$$\mathrm{LiC_6} + \mathrm{NiO_2} = \mathrm{LiNiO_2} + 6\mathrm{C} \qquad (2)$$

The anode potential changes with the degree of intercalation and, in addition, depends on the type and pretreatment of the carbon or graphite host material [6–8]. For one of the better host materials, Lonza 15 graphite, the average reversible electrode potential during the assumed 100% intercalation/de-intercalation is 0.1 V versus the reversible Li/Li^+ electrode [6]. Hence, the average reversible cell potential for scenario 2 is 0.1 V lower than for scenario 1, that is 3.8 V. The reactant weight per Faraday is significantly larger than for scenario 1, namely, 169.7 g. These values result in a TSE of 600 Wh/kg, only 56% of the cell with Li anode.

2.1.3. Scenario 3: Li_yC_6 anode/Li_xNiO_2 cathode

Changes in the crystal structure of Li_xNiO_2 [5,9] do not allow reversible Li de-intercalation (charging) to $x<0.35$ and intercalation to $x>0.85$ [5]. In addition, Li intercalation into the carbon (graphite) anode leads to a steep increase of the electrode potential during charge for $y>0.85$ and decrease during discharge for $y<0.05$ [6–8]. This behavior limits the amount of energy that can be usefully delivered, and the reversible reactions are:

(i) anode

$$0.65\mathrm{Li_{0.85}C_6} = 0.5\mathrm{Li^+} + 0.5e^- + 0.65\mathrm{Li_{0.08}C_6} \qquad (3)$$

(ii) cathode

$$\mathrm{Li_{0.35}NiO_2} + 0.5\mathrm{Li^+} + 0.5e^- = \mathrm{Li_{0.85}NiO_2} \qquad (4)$$

(iii) cell

$$0.65\mathrm{Li_{0.85}C_6} + \mathrm{Li_{0.35}NiO_2} = \mathrm{Li_{0.85}NiO_2} + 0.65\mathrm{Li_{0.08}C_6} \qquad (5)$$

The average reversible cell potential is 3.6 V and the reactant weight per Faraday 283.8 g. These values yield a useful TSE of 340 Wh/kg or only 32% of the TSE of the Li metal/ideal NiO_2 cell and 56% of the ideal LiC_6/ideal NiO_2 cell.

Actual specific energy values of up to 115 Wh/kg have been achieved in D-size LiC_6/Li_xCoO_2 consumer cells, storing 14 Wh/cell [3,4] and 130 Wh/kg in D-size Li_xNiO_2 prototype cells [5].

A practical specific energy of 150 Wh/kg is a reasonable expectation for the much larger-sized EV batteries.

2.2. Lithium production and reserves

World production capacity for Li (in metal and compound form) in 1992 was approximately 10 000 metric tons of contained Li [10], compared to 9100 tons in 1983 [11]. The two most important uses were as an Li salt additive to the Hall cells in Al metal production as well as in glasses and ceramics [10].

The two major Li sources for Li products of all types are Li-containing minerals (spodumene, petalite and lepidolite) and subsurface brines. Over 80% of the total reserve base is in the form of brines [11].

Presently identified market-economic Li world reserves are approximately 7 million tons; the reserve base, including economic, marginal and subeconomic reserves, is approximately 14 million tons. These estimates may be low due to a likely underestimate of the not well-established reserves in P.R. China and the former USSR. Also, new market-economic reserves are periodically being discovered. As an example, a large salt flat was discovered in Bolivia a few years ago that added 5 million tons to the world Li reserves [10].

2.3. Number of EVs based upon Li production and reserves

The numbers of EVs corresponding to the Li world production, reserves and reserve base were determined for 24 kWh Li-ion batteries with Li_yC_6 anode ($y=0.05$ to 0.85) and Li_xNiO_2 cathode ($x=0.35$ to 0.85).

Employing the useful theoretical specific energy for this battery, 340 Wh/kg, the theoretical (minimum) reactant weight for this battery is readily calculated as 71 kg of which only 3.5 kg is Li and 29.2 kg is Ni; the balance is carbon and oxygen.

Based on the current Li world production of 10 million kg, if all of the production were applied to Li EV batteries, a maximum of 2.9 million EVs could be produced annually. This compares with a 1995 world production of 36 million cars [12].

New car world production has increased by an average of 2.6% per year in the past seven years [12]. Assuming this trend to continue in the indefinite future, annual new car world production would be 59 million in the year 2014.

If the entire 1995 world passenger car production would be powered by LiC_6/Li_xNiO_2 batteries and present Li demand for other uses would continue, current world Li production would have to be increased 13-fold. Such an increase in Li world production appears feasible if appropriately spaced, because world Li demand is currently lower than production capacity and major newly found reserves could be mined if the demand rose significantly. Likewise, a future growth rate of Li production of 2.6% per year appears feasible.

With regard to Li world reserves, a total of 2 billion EVs could be built with the identified economical reserves of 7 billion kg. This figure increases to 4 billion cars if the world reserve base of 14 billion kg is employed. By comparison, total world car population was 480 million in 1994 [12]. Other potential future large-scale uses of Li, such as in high-strength concrete, solid oxide fuel cells and fusion reactors, could, however, have a significant effect on the amount of Li available for batteries; it is not within the scope of this paper to project the timing or extent of such potential future applications.

The net increase of the world car population averaged 3% per year in the past seven years [12], comprised of 7.5% new cars produced minus 4.5% old cars removed. If this trend is assumed to continue, the entire world car population would be 870 million in the year 2014 and would consist entirely of 'new' cars produced since 1995.

Presently identified Li world reserves are sufficient to power the world's car population for 50 years at which time there would be 2.1 billion cars (assuming continued growth of 3% per year).

2.4. Impact of Li price on battery

The Li metal price has generally followed the rate of inflation in the past 30 years [10] and was US$ 74/kg in October 1995 for Li ingots, standard grade, in >450 kg quantities, f.o.b. [13]. Occasional fluctuations in Li price are linked to the price of Al metal since the Al industry is the largest consumer of Li. As would be expected, increasing demand for Al has generally resulted in higher Li prices and vice versa. Future large-scale uses in other technology sectors, such as EV batteries, concrete, etc., would likely result in higher Li prices. However, the current Li price was taken as the basis for the battery price considerations in this paper.

With US$ 74/kg, the minimum Li cost ('theoretical reactant cost' or TRC, based on the stoichiometric Li weight in Eq. (5)), is US$ 256.00/24 kWh battery or US$10.70/kWh. TRC is computed on the basis of the cost of the elements entering into the stoichiometric cell reaction and hence does not include the cost of electrode substrates, separators, etc. which do not scale with storage capacity. The cost of the electrolyte is included only if it enters into the cell reaction. With an Ni cost of US$ 7.00/kg, the TRC for Ni in the Li_xNiO_2 electrode is US$ 204.75 per 24 kWh battery or US$ 8.50/kWh. Therefore, the minimum reactant cost for Li and Ni combined is US$ 460.75 per 24 kWh battery or US$ 19.20/kWh. By comparison, the TRC for the Ni/Cd system is US$ 15.40/kWh.

2.5. Predicted Li-ion battery price

Small Li cells (1.3 Ah/3.6 V), made in Japan in large numbers for cellular phones and camcorders, are sold to original equipment manufacturers (OEM) for about US$ 8 each [14], equivalent to about US$ 1700/kWh. The OEM cost of slightly larger consumer cells (2Ah/3.6 V), when made in large numbers, has been projected as about US$ 5 each [14] or about US$ 700/kWh. EV-sized Li batteries have not been made in large numbers, and selling prices are thus not available. This paper will attempt to predict an approximate cost range for mass-produced Li EV batteries by comparison with a mass-produced, mature battery with similar TRC, the Ni/Cd EV battery.

Cost-effective Ni/Cd batteries as well as Li batteries employ pasted electrode technology. Cell manufacturing for both involves comparable complexity if, as is common, the anodes for the Li batteries are made in the fully discharged state, not containing Li. The active material for the cathodes in Li batteries, Li_xNiO_2, is prepared in a rather simple process from LiOH and NiO powders at about 700 °C in air [5].

Ni/Cd cells and batteries in small sizes, 1 to 100 Wh, and produced in large numbers, more than 100 000 per year of the same type, have traditionally sold for about US$ 1000/kWh. The battery price can decrease substantially for large batteries, if produced in modern plants in sufficiently large numbers. Recently, a price of US$ 330/kWh was given [15] for an annual production volume of 6500 Ni/Cd batteries of 12 kWh size. This corresponds to 130 000 modules of 600 Wh size and identical type.

Based on the comparison with Ni/Cd batteries, a selling price near US$ 330/kWh is predicted for mass-produced Li EV batteries, once the technology has matured. This results in a price of approximately US$ 8000 for a 24 kWh EV battery.

2.6. Cost of battery ownership and driving

The following considerations are based on the performance of the General Motors 'Impact' EV with a curb weight of 1350 kg and a range of ~90 miles on the highway or 70 miles in the city [16]. It employs a 16.8 kWh lead/acid battery with ~35 Wh/kg weighing ~480 kg. If the lead/acid battery were replaced by a 24 kWh Li battery with 150 Wh/kg (~160 kg), the car would achieve a range of ~150 miles on the highway and ~120 miles in city/suburban driving. A reasonably expected battery life of 1000 cycles [5] corresponds to a life time mileage of 126 000 miles for a 20% highway–80% city /suburban driving mix. For an average driving distance of 12 600 miles per year, battery life would be ten years.

Based upon these figures and the battery price of US$ 8000, the cost per mile due to battery first cost, is determined as 6.3 ¢/mile and the cost of money (at 7% interest) as 2.5 ¢/mile. With an energy cost of 10 ¢/kWh and a battery recharge efficiency of 80%, the 'electric fuel' cost is 2.5 ¢/mile. Thus, battery and fuel cost combined are 11.3 ¢/mile. Allowing US$ 15 000 for the car without battery results in a vehicle price of US$ 23 000 and a cost of car ownership and 'electric fuel' combined of 27.4 ¢/mile. This figure excludes maintenance, insurance and road taxes.

The current cost of ownership for gasoline-powered cars, averaged over different car sizes, is 31 ¢/mile. This figure includes maintenance, insurance and road taxes. While the initial investment in the battery, US$ 8000, is a large fraction of total vehicle cost, the cost of EV car ownership and driving over the life of the battery is competitive with gasoline-powered cars.

The US Advanced Battery Consortium (USABC) mid-term goals for EV batteries are 80–100 Wh/kg, 600 cycles and $\leq$ US$ 150/kWh, resulting in a cost per mile, due to battery first cost, of 5–5.5 ¢/mile (without cost of money). These figures compare with 150 Wh/kg, 1000 cycles and US$ 330/kWh as projected for the Li-ion battery, resulting in 6.3 ¢/mile. Therefore, on the basis of cost per mile over the life of the battery, the cost projection for the Li-ion battery is within 20% of the USABC mid-term goals.

3. Conclusions

The LiC_6/Li_xNiO_2 battery has the required technological features, namely high specific energy and power, as well as long cycle life, to make it a very attractive future EV battery.

The known economically recoverable world Li reserves are sufficient to produce EV batteries for the world's passenger car population in the next 50 years.

The projected US$ 8000 price of a 24 kWh Li EV battery, when amortized over its anticipated life of ten years or 126 000 miles, results in a cost of ownership, including 'electric fuel', of 11.3 ¢/mile. Allowing US$ 15 000 for the car without battery, yields a total cost of car and battery ownership, including fuel, of 27.4 ¢/mile. This figure is essentially competitive with gasoline-powered cars.

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