Resource constraints on the battery energy storage potential for grid and transportation applications

Cyrus Wadia [a,b,1,2], Paul Albertus [c,*,1], Venkat Srinivasan [d,3]

[a] Lawrence Berkeley National Laboratory, Material Sciences Division, Berkeley, CA 94720, USA
[b] Energy Institute, Haas School of Business, University of California, Berkeley, CA 94720, USA
[c] Department of Chemical Engineering, 201 Gilman Hall, University of California, Berkeley, CA 94720, USA
[d] Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division, Berkeley, CA 94720, USA

ARTICLE INFO

ABSTRACT

Batteries have great promise for facilitating the grid integration of renewable energy and powering electric vehicles. One critical concern for the scale-up of battery production is the availability of the elements used in battery couples. We provide the first systematic comparison of supply limits and extraction costs of the elements in battery couples against short- and long-term scaling goals. Several couples can scale well beyond short- and long-term grid-storage goals, including: Na/S, Zn/Cl_2, and $FeCl_2/CrCl_3$. Li-based couples currently have the performance characteristics most suitable for electric vehicles, yet scaling beyond 10 MM vehicles per year will demand significant increases in Li production. We also provide a framework to evaluate new couples, such as those based on Mg, which may be an alternative to Li-based couples. While the extraction costs of the elements used in current battery couples are, in many cases, below 10 \$ kWh^{-1}, the cost of finished battery cells is in the range of 150–1000 \$ kWh^{-1}, well above cost targets of 100 \$ kWh^{-1} for both grid and transportation applications. Currently high costs remain a critical barrier to the widespread scale-up of battery energy storage.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

The rapid expansion of renewable energy has driven interest in energy storage to facilitate the widespread and large-scale deployment of intermittent, carbon-free energy sources [1–5]. Likewise, the future of electric vehicles (EVs) depends strongly on portable energy storage. Technologies that have been explored for various energy storage applications include pumped hydroelectric (PHE), compressed air (CAES), batteries, flywheels, and ultracapacitors [1,6–10]. Constraints on new system installations vary. For example, both PHE and CAES rely on favourable geography and geology to be cost effective, and the number of new sites is limited [8,11]. Batteries, in contrast to PHE and CAES, provide an important option for grid-scale storage because they can be sited close to demand load, reducing transmission installations and losses [12]. Furthermore,

batteries are the only suitable technology for near-term deployment in EVs [13,14]. Technology hurdles exist for batteries to meet performance targets, but of equal importance to their future use at large scales is the availability of the elements used to make the battery active materials that are combined to form battery couples (a battery couple contains anode and cathode active materials). Herein we present the first systematic analysis of limits on the availability of the elements for battery couples, providing a clear assessment of the potential to significantly scale-up battery production in the coming decades.

At present, lithium-ion, nickel metal hydride, and lead-acid batteries dominate the portable rechargeable storage markets, while sodium-sulfur and redox flow batteries have been deployed for stationary storage [15–17]. Our analysis includes these couples, as well as others that have been shown to operate reversibly (albeit at various degrees of performance and development), have current relevance in the battery markets, or are of interest to the research community. Some couples, such as Pb/PbO_2 (lead-acid) and $C_6/LiCoO_2$ (lithium-ion), are widely familiar while others, such as $C_6/LiMnPO_4$ and Li/O_2, are still in the research stage. With such a broad set of couples available, it is critical to identify which are suitable for grid vs. EV applications, as well as any resource limitations that set an upper bound on the energy storage potential (ESP) of each couple.

* Corresponding author. Present address: Robert Bosch Research and Technology Center, 4009 Miranda Ave, Palo Alto, CA 94304, USA. Tel.: +1 650 812 8019; fax: +1 650 812 8035.

E-mail addresses: cnwadia@lbl.gov (C. Wadia), albertus@berkeley.edu (P. Albertus), vsrinivasan@lbl.gov (V. Srinivasan).
[1] These authors contributed equally to this work.
[2] Tel.: +1 510 486 7376.
[3] Tel.: +1 510 495 2679.

2. Methods

We define the ESP as the maximum amount of energy (in TWh) that can be stored by the complete exhaustion of the limiting element of a battery couple. We evaluate the ESP by looking at the amount of the limiting element available under two constraints: annual production and total reserve base. Annual production and total reserve base data are taken from the United States Geological Service Mineral Commodity Surveys (see Supporting Information for Detailed Information) [18]. The annual production is reasonably well known, as it obtained by summing up the production data of the world's mines for each element. The reserve base is more uncertain; it reflects specific geologic information about the presence of a mineral, and is defined to include the demonstrated (measured and indicated) amount of a resource. It includes currently economic, marginally economic, and some sub-economic resources, encompassing "those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics." We stress that the current analysis considers only the elements present in the active materials of a battery couple.

To calculate the electricity storage potential (ESP) of an electrochemical couple, we first must consider separately the two active materials of the couple. Every couple under investigation has one limiting element that sets a finite limit on the amount of the couple theoretically available. The limiting element is defined as that which will be completely exhausted (from the annual production or reserve base) before the other elements of a couple. For example, in the case of $NiCl_2$, the more scarce material is nickel thus acting as the limiting element, but in $LaNi_5$ it is the not the nickel but rather the lanthanum that acts as the limiting element. The limiting element of each active material is first calculated, and then a limiting element is determined for the couple. We assume 100% of the limiting element is used to make batteries (in practice, batteries compete against other uses for the elements, so our results are a best-case scenario). In general, the ESP is calculated using the practical specific capacity (with units of $Ah\,g^{-1}$). The practical capacity is based on the realistic voltage range for the cell and the stability of the active materials. For example, the theoretical specific capacity of $LiCoO_2$ is $274\,mAh\,g^{-1}$ but only $140\,mAh\,g^{-1}$ is available below a potential of ca. 4.35 V vs. Li metal; above ca. 4.35 V, currently available electrolytes are oxidized [19]. In addition, we assume the capacity (in Ah) at each electrode is the same. In practice an unequal capacity balance is often used because of specific operating nuances of the electrode materials (e.g., in a lithium-ion cell with a graphite negative electrode the graphite typically has an excess capacity to prevent lithium deposition during charge). The following equation gives the total Coulombic capacity (J) in units of Ah:

$$J = \hat{C}A,$$

where A is the annual production or total reserve base of an active material in grams and $\hat{C}$ is the practical specific capacity of that active material ($Ah\,g^{-1}$). The value of A is based on the annual production or reserve base of the limiting element in the active material, corrected for the weight of the limiting element in the active material relative to the weight of the complete active material. J values are calculated for each active material of the couple and the minimum of the two is used in the following equation to calculate the ESP in TWh,

$$ESP_{p,n} = \frac{J(V_p - V_n)}{10^9}.$$

V_p is the potential of the positive-electrode material and V_n is the potential of the negative-electrode material. In this analysis, we use the mid-point potential of the equilibrium potential whenever possible.

Couple extraction costs (CEC) are expressed in $\$\,kWh^{-1}$ for each battery couple with x elements and calculated by the following equation:

$$CEC = \left(\frac{10^3}{(V_p - V_n)}\right)\left(\frac{1}{\hat{C}_p}\sum_{i=1}^{x}P_{p,i} \times \left[\frac{\frac{(x_i)(M_i)}{x}}{\sum_{j=1}^{x}(x_j)(M_j)}\right]\right. $$

$$\left. + \frac{1}{\hat{C}_n}\sum_{i=1}^{x}P_{n,i} \times \left[\frac{\frac{(x_i)(M_i)}{x}}{\sum_{j=1}^{x}(x_j)(M_j)}\right]\right)$$

where P_i is the mined price per element i given in $\$\,g^{-1}$; x_i/x_j is the ratio of molar quantities of an individual species in the active material; M_i/M_j is the ratio of the molar masses of an individual species in the active material; $\hat{C}_p$ is the practical specific capacity of the positive-electrode active material ($Ah\,g^{-1}$); and $\hat{C}_n$ is the practical specific capacity of the negative-electrode active material ($Ah\,g^{-1}$). The first term in brackets is the calculated potential of the couple with a factor of 10^3 to adjust the units. The second term in brackets is the derived $\$\,Ah^{-1}$ of the entire electrochemical couple and is calculated by summing the extraction costs multiplied by the individual mass fractions of each mined element. The left hand side of this term is for the positive-electrode active material and the right hand side is for the negative-electrode active material.

3. Results and discussion

3.1. Evaluation of the suitability of battery couples for grid and/or electric vehicle energy storage

Batteries for grid-scale and electric vehicle energy storage have significantly different performance requirements. While all 27 couples under investigation could be deployed for grid-storage applications, only a sub-set are appropriate for EVs. For the 27 couples under investigation, Fig. 1 shows the practical system-level specific energy and the theoretical specific energy based on the weight of the active materials alone (detailed references can be found in supporting Information). The system-level energy is one performance attribute to consider when choosing a battery; others include power capability, reversibility (the ability to cycle hundreds or thousands of times), operating temperature range, flexibility in size and shape, and round-trip energy efficiency. The couples in Fig. 1 are divided into five broad categories: aqueous, lithium-ion and lithium metal, high-temperature, flow, and metal air. These categories are not exclusive; for example, many flow-cell couples also use aqueous solutions [17]. Also, some couples may have multiple designs. For example, the Li/S couple was originally investigated in a high-temperature design, but recent work has focused on ambient-temperature designs [20,21]. In practice, a couple may achieve ca. 35% of the theoretical specific energy at the battery cell level (the extra weight comes from the electrolyte, current collectors, casing, etc). Fig. 1 includes the Department of Energy (DOE) EV pack (system-level) specific energy goal [22]. We assume the system-level practical specific energies of the couples is 70% of that at the cell level, to allow comparison with the EV pack goal on a common weight basis. Fig. 1 includes a vertical line
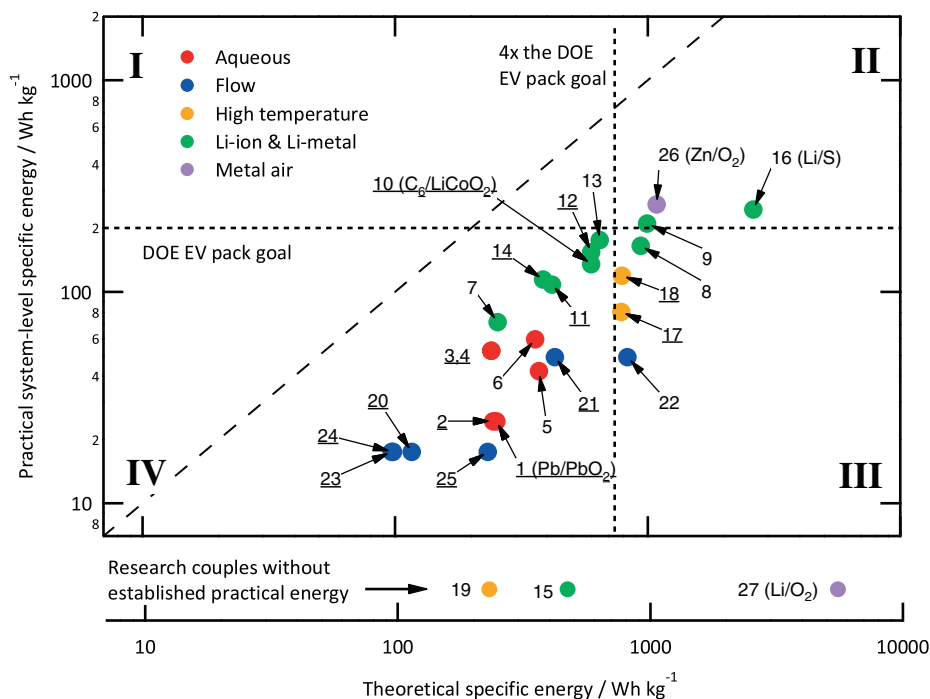
Fig. 1. The practical system-level specific energy of 27 couples and their theoretical specific energy based on the weight of active materials alone. The DOE pack goal for an EV with a 40 kWh battery pack is shown, as well as the approximate theoretical energy required for a couple to have a chance of meeting the pack goal. References for the practical specific energies are given in the supporting information. We have underlined the labels of those couples that have demonstrated very good reversibility (*i.e.*, a long cycle life). Couples still in the very early stages of development are shown below the main axes. All practical batteries fall short of the theoretical specific energy (the theoretical = practical diagonal line is indicated), as other components besides active materials are required. Following is a key to the couples and numbers: *Aqueous:* 1 Pb/PbO$_2$, 2 Cd/NiOOH, 3 REE-Ni$_5$H$_6$/NiOOH, 4 LaNi$_5$H$_6$/NiOOH, 5 Zn/NiOOH, 6 Zn/MnO$_2$, *Lithium-ion and Lithium metal:* 7 Li$_4$Ti$_5$O$_{12}$/LiCoO$_2$, 8 Si/LiCoO$_2$, 9 Li/LiCoO$_2$, 10 C$_6$/LiCoO$_2$, 11 C$_6$/LiMn$_2$O$_4$, 12 C$_6$/LiNi$_{0.8}$Co$_{0.15}$Al$_{0.05}$O$_2$, 13 C$_6$/0.3LiMn$_2$O$_3$·0.7LiMn$_{0.5}$Ni$_{0.5}$O$_2$, 14 C$_6$/LiFePO$_4$, 15 C$_6$/LiMnPO$_4$, 16 Li/S, *High-temperature:* 17 Na/NiCl$_2$, 18 Na/S, 19 Mg/Sb, *Flow:* 20 V(SO$_4$)/VO$_2$(HSO$_4$), 21 Zn/Br$_2$, 22 Zn/Cl$_2$, 23 Na$_2$S$_2$/NaBr$_3$, 24 CrCl$_2$/FeCl$_3$, 25 Zn/Ce(CO$_3$)$_2$, *Metal air:* 26 Zn/O$_2$, 27 Li/O$_2$.

showing the approximate theoretical specific energy required for a couple to have a chance, following more development work, to meet the DOE EV pack goal (the factor of 4 comes from multiplying 35% by 70%). Thus, Quadrants I and II show couples that have already achieved a practical specific energy meeting the DOE goal.

While Fig. 1 identifies couples that exceed the DOE EV pack goal, none of the couples have sufficient reversibility and other performance characteristics to be used in vehicles. Neither the Li/CoO$_2$ (#9) nor the Li/S (#16) couple can safely cycle the hundreds to thousands of cycles required by an EV application, and the Zn/O$_2$ (#26) couple has a limited reversibility, low power capability, and a low round-trip energy efficiency (*ca.* 60%, compared to *ca.* 90% for Li-ion couples). The DOE specific energy goals for plug-in hybrid (PHEV) and hybrid (HEV) electric vehicles are significantly lower, explaining the forthcoming use of couples such as C$_6$/LiFePO$_4$ (#14) and C$_6$/Li$_{0.8}$Co$_{0.15}$Al$_{0.05}$O$_2$ (#12), and the present use of the Rare Earth Element (REE) REE-Ni$_5$H$_5$/NiOOH couple (#3), in these applications [23,24]. In general, negative- and positive-electrode materials are interchangeable in lithium-ion systems ("lithium-ion" refers to a class of couples); this means many more combinations (such as Si/0.3LiMn$_2$O$_3$·0.7LiMn$_{0.5}$Ni$_{0.5}$O$_2$) are possible than we show in Fig. 1 [25,26]. The metal air cells, especially the Li/O$_2$ cell, may have very high specific energy, although the kinetics and reversibility of the O$_2$ electrode are poor and much development remains [27]. The performance of the Li/S system (#16) has improved significantly in recent years, and is an area of active research [20,21]. While the theoretical specific energy of Na/NiCl$_2$ (#17) and Na/S (#18) are high, they both operate at elevated temperatures (several hundred °C), and are therefore not suitable for EVs. The Zn/Cl$_2$ (#22) system also has a high specific energy but has not been built with a cell design suitable for EVs. From our discussion of Fig. 1 we

draw the conclusion that some couples will never meet the EV specific energy target, while those with the potential still need more development in terms of practical specific energy and other performance characteristics. Our discussion also shows that in the near term, the couples with the best potential to meet EV performance requirements are all based on Li. Thus, Li will be the most important element for the scale-up of EVs in the short and possibly long-term.

3.2. Availability and cost of the elements for scaling up battery energy storage

Fig. 2 shows each couple with its ESP for both annual production (Fig. 2A, representative of a "flow") and total reserve base (Fig. 2B, representative of a "stock"). We order the couples by annual production because of near-term relevance to the battery industry and the inherent uncertainty in reserve base projections. The limiting element in each couple is shown in brackets at the right of its label. Goals are used to provide appropriate order of magnitude comparisons. We include short-term (10–15-year) "flow" goals in Fig. 2A and long-term (40–50 years) "stock" goals in Fig. 2B. We also show long-term "flow" goals in Fig. 2A to allow direct comparison with current annual production data. The short-term grid-storage annual production goal is 1% of 2009 US daily electricity production, as many states have renewable portfolio standards targeting 20–25% of grid electricity supplies by the *ca.* 2025 time-frame [28,29]. An annual production of 1% of US daily electricity by *ca.* 2025 would facilitate the introduction of intermittent renewables to the grid. Previous studies of the U.S. electricity distribution system indicate a threshold of <8% for the penetration of intermittent sources like photovoltaics without cost effective storage [30]. For reference, currently about 2.5% of US electricity is cycled through a PHE storage unit and the fraction of US electricity in
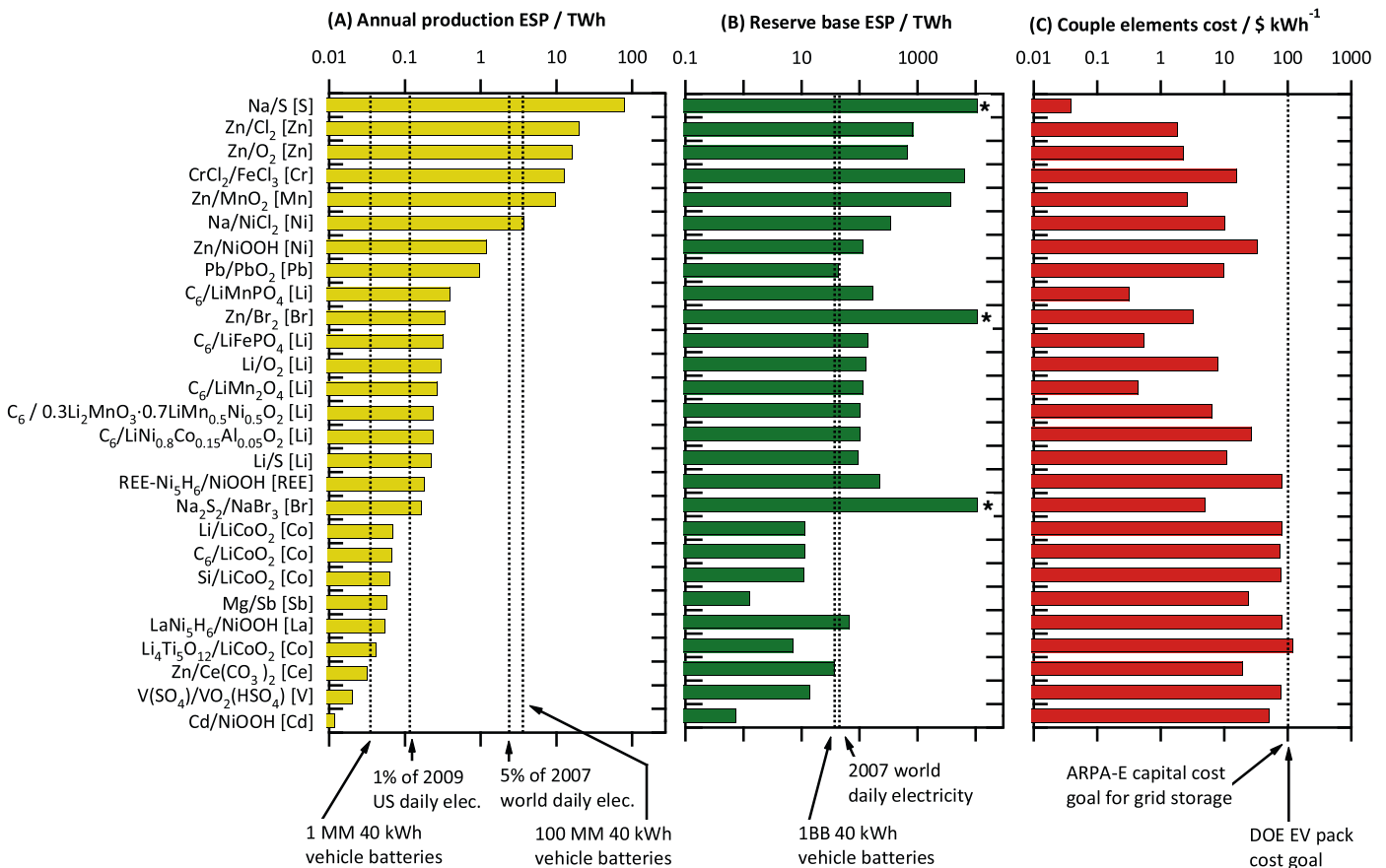
Fig. 2. (A) Energy storage potential (ESP) based on annual production of the elements. Short-term (10–15-year) and long-term (40–50-year) "flow" goals are provided for grid-storage and EV energy storage applications. The elements in brackets at the right side of the labels are the limiting elements in each couple. (B) ESP based on the reserve base of the elements. Long-term (40–50-year) "stock" goals are provided. *ESP well beyond the limit of the figure. (C) Extraction costs of the elements in the couples, calculated from the USGS prices of the elements.

2008 that came from intermittent solar and wind was about 2% [11,29]. The long-term grid-storage goal in Fig. 2A represents a 5% per year turnover (*i.e.*, a battery life of 20 years) of a battery stock able to store a day's worth of the world's electricity production in 2007, the most recent year for which international data is available [31]. For the short-term transportation goal we show the annual production of 1 MM 40 kWh vehicle batteries [32]. The DOE target size for an EV battery is 40 kWh, which allows a range of up to *ca.* 150 miles in a small car [22]. 1 MM EVs per year are significantly higher than current annual sales of hybrid-electric vehicles, but predictions about the coming EV market vary. The long-term EV "flow" goal in Fig. 2A is the required energy for 100 MM 40 kWh vehicle batteries. 100 MM vehicles is *ca.* 10% of the current world vehicle fleet, and the vehicle fleet turns over every 10–15 years [33]. The long-term "stock" goals in Fig. 2B represent, for grid-storage, 2007 world daily electricity consumption, and for the transportation sector, approximately the total current number of vehicles in the world [31,33]. With significant economic development in the coming decades, by the middle of the century these goals may represent significant fractions, though not all, of the world's electricity production and number of vehicles [34].

For grid-scale storage based on annual production, our results show that 18 of the couples could supply 1% of 2009 US daily electricity. It should be noted, however, that other industries compete for the same mined elements so using all the annual production of an element for making batteries is only possible with increased supply. Of those 18, five couples have an ESP nearly two orders of magnitude higher than the short-term grid "flow" goal, and three of these have already received development for grid-storage (Na/S,

Zn/Cl$_2$, and CrCl$_2$/FeCl$_3$). Therefore, several grid-storage couples could be scaled up in the short-term with minimal impact on the overall market of the elements in the couples. Interestingly, these five couples have a current annual production significantly above even a long-term "flow" goal of 5% of the 2007 world electricity production. Regarding the long-term goal of storing the 2007 world daily electricity production, eight of the couples have a total reserve base that could support battery storage an order of magnitude above that target. Thus, our analysis shows there are several battery couples that have already received significant development that contain elements with sufficient availability for meeting short- and long-term grid-scale storage goals. When one considers scaling up several of these couples simultaneously, the potential for battery grid-scale energy storage becomes even more favorable.

For EV deployment based on annual production, nearly all of the couples can meet the short-term goal of 1 MM 40 kWh vehicle batteries, although our discussion of Fig. 1 showed that not all have suitable performance attributes for transportation applications. The Li-based couples that are most likely to be used in EVs, as well as hybrid (HEV) and plug-in hybrid-electric vehicles (PHEVs) (*i.e.*, C$_6$/LiFePO$_4$, C$_6$/LiMn$_2$O$_4$, C$_6$/LiNi$_{0.80}$Co$_{0.15}$Al$_{0.05}$O$_2$, and C$_6$/LiCoO$_2$), have a sufficient ESP to meet the short-term target, although the availability of Co is an issue for couples with LiCoO$_2$. Of the Li-based systems in current production, the C$_6$/LiFePO$_4$ and C$_6$/LiMn$_2$O$_4$ couples have the highest ESP, although their practical specific energies are too low to meet the DOE EV goal. While modest expansion of Li production can support 1 MM 40 kWh vehicle batteries, to meet a long-term target of 100 MM 40 kWh Li-based EV batteries per year a dramatic expansion of annual production will be necessary (more

than one order of magnitude). Scale-up will require a long lead time, involve heavy capital investment in mining, and may require the extraction and processing of lower quality resources, which could drive extraction costs higher. With respect to the long-term "stock" goal of 1 billion 40 kWh vehicle batteries, the reserve base of several Li-based couples are sufficient, but near the limit of what is available. We also note that the Ni/MH batteries used in HEVs today have an ESP (for annual production and reserve base) similar to that of Li-based couples. Because HEV batteries are much smaller (e.g., 1 kWh) than EV batteries, more Ni/MH HEV batteries than Li-based EV batteries can be built, although if larger Ni/MH batteries were used, they would face similar supply constraints as Li-based couples. In short, for EV batteries, only some Li-based couples have the characteristics to satisfy EV performance targets, scale-up of production will be especially needed in the long-term, and if the entire estimated reserve base of Li were used for EV batteries, on the order of 1 BB 40 kWh batteries could be produced. If such a path is pursued, Li recycling will be necessary. Based on our analysis, we believe the transportation market to have significantly more material supply constraints than the grid-storage market.

In Fig. 2C we show the extraction cost for each couple. Extraction costs are obtained by crossing individual mined extraction costs of the elements with the mass fraction contribution to the complete battery couple. The extraction costs are estimated from the market price of the elements. Due to the variety of mineralogical forms, extraction costs should be viewed as an estimate and are best used for comparative purposes (see Supporting Information for More Information) [11,35,36]. Long-term capital cost goals for both grid-storage and EV systems are $100 \$ \, kWh^{-1}$ (for EVs, a 40 kWh system would cost \$4,000, considered a reasonable amount; for grid-scale storage, $100 \$ \, kWh^{-1}$ corresponds to 5000 cycles with energy at a cost of $0.025 \$ \, kWh^{-1} \, cycle^{-1}$, about 25% of the price paid by US consumers today) [22,37]. A better cost metric than capital cost alone for comparing battery couples is $\$ \, kWh^{-1} \, cycle^{-1}$ (or $\$ \, kWh^{-1} \, year^{-1}$), but there is currently insufficient information for such a comparison. For reference, battery cells today cost about 150 \$ to $1000 \$ \, kWh^{-1}$, while the most favourable PHE and CAES sites can store energy for as little as $10 \$ \, kWh^{-1}$ [8]. The most established and least expensive mass-market battery today is the Pb/PbO_2 couple, with a capital cost of about $150 \$ \, kWh^{-1}$ for a deep-discharge cell. As Fig. 2C shows, the extraction cost of the elements in the Pb/PbO_2 active materials are under $10 \$ \, kWh^{-1}$, illustrating the point that much of a battery's cost is in components besides the elements in the active materials. The $150 \$ \, kWh^{-1}$ is the cost of a Pb/PbO_2 battery cell alone, with system costs for grid-storage (e.g., power electronics, inverters) or an EV (e.g., power electronics, cooling system) adding to the cost. The $100 \$ \, kWh^{-1}$ system cost goals are significantly below the cost of a Pb/PbO_2 battery cell, implying costs must be lowered by at least a factor of two beneath that of Pb/PbO_2. For the Li-based systems, the price of Li metal was used for the couples Li/S and Li/O_2, while for the other Li-based couples the price of Li_2CO_3 was used (many synthetic processes start with Li_2CO_3, not Li metal). Fig. 2C shows the extraction costs of the elements in the active materials of several Li-based couples are below $10 \$ \, kWh^{-1}$ and comparable to Pb/PbO_2.

The couple extraction costs given in Fig. 2C are revealing because they represent the "theoretical" lower bound on system cost, and in particular show which couples will be unable to meet the cost goals of $100 \$ \, kWh^{-1}$ because the elements in the active materials are too expensive. In particular, Li-based systems containing Co have a high price for the elements in the active materials. Not surprisingly, the couples with high ESPs in Fig. 2A and B tend to also have low extraction costs. While the cost of the elements in the active materials in the battery couples in our analysis vary significantly, the cost of finished battery cells are in the range of $150–1000 \$ \, kWh^{-1}$, significantly above cost goals of $100 \$ \, kWh^{-1}$

for grid-storage and EV systems. More than overcoming performance limitations, achieving major cost reductions in batteries for both grid and transportation applications will be important for economic scale-up of energy storage.

4. Framework for evaluating electric vehicle couples not based on Li

Our analysis can also inform the search for EV battery couples based on non-Li couples. For example, among the couples in our present analysis, those containing Cl, Cr, Fe, Mn, Na, S, and Zn are found in couples with a particularly high ESP and have a low extraction cost; new couples utilizing these elements may be of particular interest. Mg-based couples have also been discussed as having the potential to achieve a high specific energy and eventually replace Li-based couples [38]. Fig. 1 provides benchmarks for the specific energy of a proposed couple, while Fig. 2 allows a comparison with the ESP of other couples and energy storage goals, as well as couple extraction costs. Mg, for example, has an annual production nearly two orders higher than Li (see Supporting Information), as well as a lower extraction cost, warranting further investigation providing active materials with only other abundant elements are used.

5. Limitations of the present analysis and suggestions for future work

This analysis provides a best-case scenario for the battery ESP based on the availability and cost of the elements for battery active materials alone, and can therefore be thought of as a "first order" analysis. Future work can address some of the limitations of the present analysis and the questions that it raises. We list some of the most important topics here.

(1) The ESP analysis based on the elements in the active materials alone neglect the balance-of-system components, which in general make up more than half (and sometimes closer to 85%) of the mass of an actual battery. The importance of these additional components when considering the ESP will differ from case to case. For example, the Na/S system requires special corrosion-resistant materials to hold liquid Na and S at high temperatures, and these materials may have a low abundance. Adding in these components would clarify whether materials other than the elements in the active materials are limiting for some battery couples, although it should be noted that cell designs and balance-of-system materials can change through time.

(2) The couple extraction costs we provide are based on the costs of the elements in the active materials, rather than the costs of the active materials actually used in batteries. Additional work could base the couple costs on the active materials directly rather than the elements within the active materials. Difficulty in obtaining such information prevented us from using the active material costs in this study. As one example, the price of the active materials in a $C_6/LiCoO_2$ cell (30 \$ \, kg^{-1}$ for the C_6, $40 \$ \, kg^{-1}$ for the $LiCoO_2$) is $108 \$ \, kWh^{-1}$, while the price of the elements alone is $77 \$ \, kWh^{-1}$ according to our calculations [39].

(3) Just as it is possible to add in the balance-of-system materials to the analysis of the limiting element and ESP, the balance-of-system components could also be added into the cost analysis, so that a more detailed comparison can be made between the costs of the different couples. However, this requires having access to detailed battery designs, and as grid-storage batteries in particular are at an early stage of deployment, such designs are presumably still changing rapidly.

(4) The reserve bases of the elements are uncertain because of the difficulty of collecting such information. Future work could use the economic reserves to compare the "stock" ESP of the couples, or the reserve base numbers can be updated if better information becomes available.

(5) A major scale-up of battery energy storage will require the establishment of new supply chains, which will have environmental, social, and potentially political implications. Reserves of Li, for example, are concentrated in Bolivia, while reserves of rare earths are concentrated in China. Further analysis of supply chains may help planners structure battery scale-up to help achieve environmental and social goals.

6. Conclusions

In the short-term (10–15 years) and long-term (40–50 years) there is sufficient availability of the elements for battery deployment in grid-scale applications. For the EV application, scale-up of Li production will be needed to meet short-term goals, but will be especially necessary to meet long-term goals. Eventually, on the order of 1 billion 40 kWh Li-based EV batteries can be built with the currently estimated reserve base of Li. Achieving aggressive cost reductions will continue to be a challenge for grid-scale and electric vehicle energy storage markets but the cost targets for battery storage should not be hampered by the costs of the elements in the active materials in most cases. Expansion of battery research into alternative materials may accelerate our ability to work through both the scaling and cost challenges inherent in long-term planning for battery energy storage.

Acknowledgements

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jpowsour.2010.08.056.

References

[1] N.S. Lewis, D.G. Nocera, Proceedings of the National Academy of Sciences of the United States of America 104 (2007) 20142–120142.
[2] Intergovernmental Panel on Climate Change (IPCC): Climate Change 2007—Impacts, Adaptation, and Vulnerability, Cambridge University Press, Cambridge, 2007.
[3] M.I. Hoffert, K. Caldeira, G. Benford, D.R. Criswell, C. Green, H. Herzog, A.K. Jain, H.S. Kheshgi, K.S. Lackner, J.S. Lewis, H.D. Lightfoot, W. Manheimer, J.C. Mankins, M.E. Mauel, L.J. Perkins, M.E. Schlesinger, T. Volk, T.M.L. Wigley, Science 298 (2002) 981–987.
[4] J.P. Holdren, Science 319 (2008) 424–434.
[5] C. Wadia, A.P. Alivisatos, D. Kammen, Environmental Science and Technology 43 (2009) 2072–2077.
[6] A.J. Nozik, Annual Review of Physical Chemistry 29 (1978) 189–222.
[7] L. Carrette, K.A. Friedrich, U. Stimming, ChemPhysChem 1 (2000) 162–193.
[8] H.S Chen, T.N. Cong, W. Yang, C.Q. Tan, Y.L. Li, Y.L. Ding, Progress in Natural Science 19 (2009) 291–312.
[9] M. Armand, J.M. Tarascon, Nature 451 (2008) 652–657.
[10] J.M. Tarascon, M. Armand, Nature 414 (2001) 359–367.
[11] EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, 2003, Palo Alto, CA. http://my.epri.com/portal/server.pt?Abstract_id=000000000001001834.
[12] P. Denholm, R.M. Margolis, Energy Policy 35 (2007) 4424–4433.
[13] R.M. Dell, D.A.J. Rand, Journal of Power Sources 100 (2001) 2–17.
[14] M. Wakihara, Materials Science & Engineering R-Reports 33 (2001) 109–134.
[15] R.J. Brodd, Journal of the Electrochemical Society 134 (1987) C108–C1108.
[16] R.J. Brodd, K.R. Bullock, R.A. Leising, R.L. Middaugh, J.R. Miller, E. Takeuchi, Journal of the Electrochemical Society 151 (2004) K1–K11.
[17] C.P. de Leon, A. Frias-Ferrer, J. Gonzalez-Garcia, D.A. Szanto, F.C. Walsh, Journal of Power Sources 160 (2006) 716–732.
[18] U.S. Geological Survey, Mineral Commodity Summaries, 2009, http://minerals.usgs.gov/minerals/pubs/mcs/.
[19] P. Arora, R.E. White, M. Doyle, Journal of the Electrochemical Society 145 (1998) 3647–3667.
[20] K. Kumaresan, Y. Mikhaylik, R.E. White, Journal of the Electrochemical Society 155 (2008) A576.
[21] J. Wang, J. Yang, C. Wan, K. Du, J. Xie, N. Xu, Advanced Functional Materials 13 (2003) 487–492.
[22] United States Advanced Battery Consortium, USABC Goals for Advanced Batteries for EVs, 2002, http://www.uscar.org/commands/files_download.php?files_id=27.
[23] United States Council for Automotive Research, RFPI—PHEV Batteries—April 2007—Final, 2007, http://www.uscar.org/commands/files_download.php?files_id=118.
[24] FreedomCAR Power Assist HEV Battery Goals, United States Council for Automotive Research, 2002, http://www.uscar.org/commands/files_download.php?files_id=26.
[25] M.M. Thackeray, C.S. Johnson, J.T. Vaughey, N. Li, S.A. Hackney, Journal of Materials Chemistry 15 (2005) 2257–2267.
[26] C.K. Chan, H. Peng, G. Liu, K. McIlwrath, X.F. Zhang, R.A. Huggins, Y. Cui, Nature Nanotechnology 3 (2007) 31–35.
[27] T. Ogasawara, A. Debart, M. Holzapfel, P. Novak, P.G. Bruce, Journal of the American Chemical Society 128 (2006) 1390–1393.
[28] U.S. Environmental Protection Agency, Renewable Portfolio Standards Fact Sheet, 2009, http://www.epa.gov/chp/state-policy/renewable_fs.html.
[29] E.I.A. U.S. Department of Energy, Electric Power Monthly: Net Generation by Energy Source, 2010, http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html.
[30] P. Denholm, R.M. Margolis, Energy Policy 35 (2007) 2852–2861.
[31] U.S. Energy Information Administration, International Energy Statistics, 2010, http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=12.
[32] N. Demirdoeven, J. Deutch, Science 305 (2004) 974–976.
[33] D Sperling, D. Gordon, Two Billion Cars, Driving Toward Sustainability, Oxford University Press, 2009.
[34] Intergovernmental Panel on Climate Change (IPCC), Climate Change 2007—Synthesis Report, Cambridge University Press, Cambridge, 2007.
[35] S.M. Schoenung, J. Eyer, Benefit/Cost Framework for Evaluating Modular Energy Storage, SAND2008-0978 (2008).
[36] D.T. Ton, C.J. Hanley, G.H. Peek, J.D. Boyes, Solar Energy Grid Integration Systems—Energy Storage (SEGIS-ES), SAND2008-4247 (2008).
[37] Department of Energy Advanced Research Projects Agency Energy, Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS) Funding Opportunity Announcement, 2010, https://arpa-e-foa.energy.gov/.
[38] D. Aurbach, Z. Lu, A. Schechter, Y. Gofer, H. Gizbar, R. Turgeman, Y. Cohen, M. Moshkovich, E. Levi, Nature 407 (2000) 724–727.
[39] W.F. Howard, R.M. Spotnitz, Journal of Power Sources 165 (2007) 887–891.