Lithium Economy: Will It Get the Electric Traction?

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Guest Commentary

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Lithium Economy: Will It Get the Electric Traction?

The dramatic explosion of the portable electronics market owes much to the ubiquitous batteries that power them. However, the days of the conventional battery systems seem numbered. The performance levels of conventional batteries are often found wanting for projected applications, be it in the burgeoning electronics industry or in the transportation sector. A shift in gears from the internal combustion engine vehicles (ICEVs) to electrically operated vehicles is in the cards. A common sight on the roads at the turn of the century, battery-operated cars, which were pushed out of the race by superior ICEVs, made a transient resurgence in the 1970s as a result of the first oil-shock. However, today, a rebirth of the electric vehicle is both necessary and imminent. Today, we are addicted to oil and seem settled in the cozy comfort of the gas-guzzling ICEVs but are confronted by a number of issues, geo-politics and the consequential price wars and disruptions in the supply of petroleum products, the longevity of petroleum resources, and stricter policies on climate change and vehicular emissions. In the battle for alternative fuels for a decarbonized transportation sector, electricity has a definite edge. Much of the groundwork for this transformation in the way that we move about came through the U.S. government's Hybrid and Electric Vehicle Act of 1976. However, there is a lingering fear that battery technology has not lived up to the demands of the electric vehicle. An immediate choice, therefore, seems to be the plug-in hybrid electric vehicle (PHEV).

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As compared to the ICEVs or other electric-driven vehicles, the one advantage that stands out in favor of the PHEVs is its fuel flexibility. A PHEV could be powered with batteries that can be charged conveniently by using electricity from the grid or a fuel such as gasoline, ethanol, and hydrogen, or both. (See Figure 1.) They also comply with set goals on air quality, climate change, and energy security. However, that is only the beginning of the story; the ultimate goal is an all-electric vehicle. This goal is a major driver in the search for better electrochemical storage technologies. Major impediments cited today for the penetration of PHEVs in the market are the inadequate performance of available batteries and their high cost. However, as Axsen et al.[1] argue, on the basis of a range of performance goals by experts and potential buyers, the impediments are both technical and perceptual. They note that on the technical side, battery development is constrained by inherent trade-offs among five battery attributes, power, energy, longevity, cost, and safety. On the perceptual side are previously untested assumptions of what is expected of a PHEV. Therefore, the "true" requirements of PHEV technology will depend on consumers' valuation of different PHEV designs and capabilities.[1] According to Anderman,[2] PHEV development may be a misguided "detour" given the large gap between present battery performance and PHEV requirements.

Figure 1. Graphic courtesy of KR. Karuppiah.

The above arguments should not be construed to imply that scientists are absolved of their responsibility to develop batteries that not only are radically different from existing ones but also outperform them, for the stakes are too many.

Table 1 summarizes the requirements of batteries for electric vehicle applications.[3] The reader is directed to http://www.uscar.org/guest/view_team.php?teams_id=11 for additional details.

Barriers, Concerns, and Challenges. There is so much anticipation in the air about electric vehicles and plug-in hybrids. The first all-electric Nissan Leaf and the plug-in Chevy Volt that have hit the streets hold promise of more to come. Several questions still haunt the potential buyer despite the right noises being made at the appropriate fora. For the layman, such questions include cost, battery safety (especially after the several instances and product recalls involving lithium ion batteries), longevity (despite the 8 year, 100 000 mile warranty on Nissan Leaf and Chevy Volt batteries), and refueling concerns. With the current costs of lithium batteries hovering around \$800−1000/kW-h, the customer needs to shell out three times the cost of conventional systems on a kilowatt-hour basis. The customer tends to ask if the extra money is worth the advantages in terms of extended life, lower weight, and reduced volume. Although the track record of lithium batteries in hybrids such as Toyota Prius lasting more than 200 000 miles could jolt any ICEV manufacturer, the news has hardly percolated down to the lay customer. Technically inclined customers, however, will distinguish between the chemical processes in batteries as well as the fact that the Prius battery is called into action in short bursts to assist the gasoline engine; they also will note that while regenerative braking helps rejuvenate the hybrid battery, those in the all-electric and the plug-in are deeply discharged of their capacities, significantly diminishing their useful life.

The challenges facing the manufacturer and the scientist are more daunting: cost, life cycle, energy density and specific energy, deep cyclability, low-temperature performance, availability of metals and other raw materials, and abuse tolerance. What can

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Table 1. Minimum and Long-Term Goals for Electric Vehicle Batteries[3]

parameter of fully burdened system	units	minimum goals	long-term goals
power density	W/L	460	600
specific discharge power (80% DOD, 30 s)	W/kg	300	400
specific regen power (20% DOD, 10 s)	W/kg	150	200
energy density (C/3 discharge)	W-h/L	230	300
specific energy (C/3 discharge)	W-h/kg	150	200
Sspecific power/specific energy		2:01	2:01
total pack size	kW-h	40	40
life	years	10	10
cycle life (80% DOD)	cycles	1000	1000
power, capacity degradation	% of rated	20	20
selling price (25k 40 kW-h units)	$/kW-h	<150	100
operating temperature	°C	−40 to +50	−40 to +85
recharge time	hours	6	3−6
high rate charge	minutes	20−70% SOC in <30 min @150W/kg	40−80% SOC in 15 min

be forbidding for the buyer and hard to sell for the manufacturer relates to battery cost, which is an overriding factor in battery commerce. Consumers do not seem to accept the argument that fuel savings can offset the high initial costs. Large-scale manufacturing is a way to reduce cost, but that must be matched with a parallel penetration of the market, which again will depend on the price that the customer has to pay! That leads us to a catch-22 situation. The high cost of present-day lithium batteries is derived from raw materials, a large part of which is accounted for by the metal and the electrolyte, materials processing (including nanotechnology), packaging, specialized manufacturing protocols, and the large cooling systems in the case of large batteries. However, it must be noted that the lithium content is only around 0.5−1% by weight of a typical lithium ion battery, which translates to around 80 g of the metal per kW-h or just 1−2 kg per battery-operated electric vehicle.[4] To illustrate this more clearly, the Chevy Volt battery costs more than $10 000 but contains only about $180 of lithium. A report by an expert UN group on Sustainable Development of Lithium Resources in Latin America noted that as compared to the cost of lithium ion batteries, the cost of lithium carbonate raw material and that of lithium in the batteries was less than 5%.[5] However, given that the global vehicle population is expected to touch 2 billion by 2020,[6] the prospects are all the more daunting, and any disinclination to wean away from the ICEVs should spell cataclysmic to the environment. However, switching to a lithium-based traction mode would entail a humongous growth of the automotive lithium battery sector, which according to Sperling and Gordon would reach $50 billion by 2020.[7] Such mass production of lithium batteries should bring down the cost of the battery considerably. Another determinant in vehicle cost is the economics of rare earth metals used in permanent magnets in the motors, whose supply profile may hit at the underbelly of the electric traction initiative.[8] Therefore, breakthroughs in cost reduction can be achieved only by use of low-cost materials, processing and packaging, and governmental sops such as reduced levies.

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Battery technology is heavily dependent on metal resources such as lead, cobalt, nickel, lithium, and lanthanum. Due to its high equivalent weight, lead is no longer a serious contender for electric vehicle applications. Contrary to common belief, lithium is more abundant on the earth's crust than lead. Thus, any looming concern on the reserves of lithium is misplaced, although as much as 70−80% of the known reserves are believed to be located in the *salars* (salt pans) of the Lithium Triangle, perched atop the Andes on the borders of Argentina, Bolivia, and Chile, sometimes referred to as the Lithium ABCs. The identified resources in Argentina, Bolivia, Brazil, and Chile are 2.6, 9.0, 1.0, and 7.4 million metric tonnes, respectively.[9] Less but substantial reserves have also been identified in China (5.4 million metric tonnes) and the U.S. (4.0 million metric tonnes).[9] Mineral deposits, including lithium minerals, worth a trillion U.S. dollars were recently discovered in war-bedraggled Afghanistan.[10] The deposits in Afghanistan are projected to match those in Bolivia, which is known to hold about half of the world's known reserves of the metal. However, the claims are questionable. Moreover, mere identification of a lithium source does not make it viable for exploitation. Optimistic predictions on the production cost of lithium metal are about $13/kg, but these do not factor in the 9-figure development outlay. Again, because much of the easily accessible sources, especially the hard rock sources such as spodumene, hectorite, lepidolite, pegmatite, and petalite, have already been tapped into, harvesting the metal from diluted resources such as the oceans would prove to be cost-intensive.[11] Seawater is an abundant source of lithium with as much as 230 billion tonnes of lithium in it. However, the lithium concentration in seawater is only 0.17 ppm, compared to 1000−3000 ppm in the Salar de Atacama of Chile. Moreover, the magnesium/lithium ratio in seawater is 7000:1, compared to 6.4:1 in the Salar de Atacama. Such large concentrations of magnesium render the evaporation of feedwater slower; the extraction of lithium is further complicated by the similar chemistries of the two metals. On the contrary, brine processing, as from the Latin American salt pans, should be relatively inexpensive, with reduced lead times.

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The shift in addiction from oil to lithium naturally carries a cost premium. The shift may be described as an eco-energy revolution given that ICEVs represent a major contributor of carbon emissions. It is thus necessary to optimally and efficiently use raw materials in anticipation of supply crises in an increasingly demanding market. Current technologies suggest that the extraction of lithium as lithium carbonate from the *salars* is more economical and environmentally benign than that from sources such as pegmatite. However, at the large scales of extraction required for transforming the automobile scene, the production facilities could pose severe challenges to the environment in terms of water table and fresh water supplies as well as the fallout of the extraction on the flora and fauna in the neighborhood. Although the environmental impacts of evaporative extraction from the salt pans are little understood, we cannot be cavalier about its possible environmental consequences. The penalty of such an exercise on the local people, biodiversity, and ecosystem services must be carefully assessed.[12] For example, contamination of water with softeners from the PVC barriers in the evaporation basins could affect the reproductive and functional health of the people in the region.[13] Any negative effect on native biodiversity can lead to far-reaching consequences.

Technologies for recycling lithium and other metals from spent batteries are excessively costly and energy-intensive, but recourse to recycling could become standard practice if the lithium supply market turns volatile. Today, spent lithium ion batteries from cell phones and laptops are simply tossed into the trash. These batteries contain too little lithium to be extracted. Current recycling efforts focus only on recovering cobalt and nickel[14] because the virgin lithium from the mines is a lot cheaper than recycled lithium. However, the scene could change with extensive use of large traction batteries.

The weight and volume targets for electric vehicles require materials with higher energy densities. The targets call for a 2–3 times reduction in both weight and volume. Several lithium ion anode materials are on the anvil that can deliver capacities at least twice as high as those of graphite (such as alloy anodes and silicon); similar strides are yet to be recorded on the cathode side. Simple calculations show that simultaneous improvements in the energy densities of the anode and cathode only can lead to an advantage at the cell scale. Additionally, the supporting hardware including the battery management system should be re-evaluated with an eye on cost, weight, and volume. Reduction in the weight of the vehicle chassis and the permanent magnet should also be addressed. While light metal–carbon composites are increasingly being assimilated into vehicle design, weight reduction measures relating to the copper windings and the cores in the motor are hard to come by.

Any compromise on tolerance to abuse can set the clock back by years on battery-operated vehicles by way of reduced customer confidence. However, reliability and ruggedness under routine and extreme drive conditions must be established. This must especially be factored in while commissioning lithium-based batteries as they are intrinsically unsafe with high-energy materials in contact with organic electrolytes. Although they may pass standard laboratory safety tests, lithium batteries, especially in large formats, could be subjected to unusual environs, often inadvertently, reminiscent of those that favor their propensity to explode. This calls for additional safety measures, especially for quick dissipation of heat, which can undo actions aimed at reducing cost, weight, and volume. The incorporation of safety electronic circuitry at the cell and pack levels has enabled hazard-proof battery configurations.

Extended cycle life is another major concern for the development team. Repeated use and aging can lead to a natural decline in the performance of batteries. Particularly taxing are the debilitating discharge regimes where the battery is the sole power provider (as in the all-electric) or a high-power source (as in a PHEV). Batteries in these vehicles are subjected to deep depletion of capacities and yet expected to deliver power. The heavy strain naturally cuts into their lifespan. Much ground needs to be covered before quality performance is possible with 5000 deep-discharge cycles required of such batteries, although several laboratory-level test cells have passed this benchmark. Some folks brag about 300 000 cycles, but it is good to remember that these numbers apply only under shallow discharge conditions as in HEVs. It is easy to see that batteries drift to a state of senescence, reflected more by a reduction in the vehicle's drive range, as the battery ages or is subjected to unfriendly discharge modes.

Another issue that is of concern to the customer is recharging batteries. The primary source, of course, has to be grid power. Among charging options being studied are stand-alone chargers and charging systems that use modified inverter units. The second class of chargers has added benefits such as vehicle-to-battery (V2B) and vehicle-to-grid (V2G) capability. Communication interfaces between the vehicle and the grid are being researched. Of particular importance to vehicles that use hybrid power sources such as batteries with fuel cells/ICEVs is the need for active control of power sharing between the two drive-train components. This is currently done best using algorithms that help to efficiently distribute the electrical power demand between the components. In so doing, the capabilities of the individual components are maximized without being detrimental to any. The adaptive control strategy also helps achieve fuel savings under varied driving conditions.

Batteries for Electric Vehicles. Despite the tremendous improvements brought about over the past 150 years, the ICEVs still remain inefficient. The typical efficiency of a gasoline engine is 25–30%, which means that, in practice, one should be able to derive about 1/4 of the approximately 13 kW-h/kg energy density from the fuel. However, the actual energy available at the wheels after accounting for losses is only 1.7 kW-h/kg. This is still much more than the 0.15 kW-h/kg that the best of lithium ion batteries can provide. The nearest that any battery can get to this is the lithium–air system, which boasts of a theoretical energy density of 12 kW-h/kg excluding oxygen mass. According to Girishkumar et al.,[15] the lithium–air system should be capable of delivering 1.7 kW-h/kg at the wheels after accounting for overpotentials, battery components,

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Table 2. Technical, Economic, and Performance Aspects of Selected Batteries[a]

system	voltage (V)	specific energy (W-h/kg)	energy density (W-h/L)	specific power (W/kg)	energy cost (W-h/$)	advantages	disadvantages
sealed Pb acid	2.1	30–40	60–75	180	5–8	cheap	heavy
Ni–Cd	1.2	40–60	50–150	150	2–4	reliable, inexpensive, high discharge rate, good low-temperature behavior	heavy, toxic, memory effect
Ni–MH	1.2	30–80	140–300	250–1000	1.4–2.8	high energy density, environment-friendly	high internal resistance, high self-discharge, gas formation
Li ion ($LiCoO_2$)	3.6	160	270	1800	3–5	high specific energy, low self-discharge	expensive, requires safety electronics
Li-ion ($LiFePO_4$)	3.25	80–120	170	1400	0.7–1.6	safe and promising	technology under development
Li polymer	3.7	130–200	300	3000	3–5	high specific energy, low self-discharge	expensive, requires safety electronics

[a]Adapted from: *Encyclopaedia of Electrochemical Power Sources*; Garche, J.; Dyer, C. K.; Moseley, P. T.; Ogumi, Z.; Rand, D. A. J.; Scrosati, B., Eds.; Elsevier: Amsterdam, The Netherlands, 2009; Vol. *1*, pp. 271, 401, 459.

casing, and so forth. However, this laboratory curiosity could take time to mature into a practical technology as further materials research is needed to develop anode and cathode protection as well as nonflammable electrolytes with electrochemical stability over a large potential range.[16]

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Currently, available battery technologies that may be considered for traction applications are given in Table 2. Among the several battery chemistries, only two, the nickel–metal hydride (Ni–MH) and the lithium ion systems, qualify as serious contenders for traction purposes. The Ni–MH is already used in HEV mode in the Toyota Prius, while the lithium ion is used as the sole power source in Nissan's Leaf and Mitsubishi's iMiev. A major advantage of using the Ni–MH system is its superior safety characteristics as compared to the lithium ion batteries, which have recently been dubbed "infernal batteries".[17] However, with safety levels of lithium ion batteries being raised, they command an unassailable position especially with a cell voltage of ∼4 V and a specific energy of 100–180 W-h/kg.

The best bet among existing battery technologies is that of lithium ion batteries, the canonical power systems for modern and continually unfolding gadgets. The initial and replacement costs of lithium ion batteries are, however, exorbitant. Mass production might reduce the cost by a fraction, but it is also necessary to ensure that they have long service lifes and reduced failure rates, which will bring down the operational costs over the lifespan of the battery. It is also necessary to pack more energy per unit weight and volume.

Recently, Sumitomo Electric Industries unveiled a porous form of aluminum (aluminum Celmet), which when used as a current collector leads to a capacity enhancement of as much as three times.[18] Rapid recharge of batteries is another area that begs attention. Nanostructured architectures for battery-active material are another way forward.[19] In one study, such an architecture was demonstrated to support charging of a lithium ion electrode at a 400C rate (that is, in less than 10 s!)[20] By a different approach, Gerbrand Cedar[21] at MIT accomplished fast charging of lithium ion batteries by "closing the gap" between batteries and ultracapacitors. Researchers at Rensselaer Polytechnic Institute claim to have developed a lightweight, ultrathin, and flexible carbon-nanotube-based device that can be used as both a battery and a supercapacitor. The device also can be printed like paper.[22] The device is said to provide a steady output like a battery as well as quick bursts of energy like a supercapacitor, making it a potential choice for traction applications.

Ramifications of peak oil and the urgency to save the environment are driving a new course for transportation. The course being charted will give rise to a new energy order and is to be based on the economics and technologies of lithium, the gray gold. Although the metal is not scarce, deposits of its minerals are concentrated in politically turbulent regions such as Afghanistan and Bolivia. While countries such as Bolivia are trying to cash in on this bounty without interference from the developed world, they lack the technical expertise to exploit the resources. However, all of the heated projections on electric/hybrid electric vehicle production have cooled due to economic recession and high vehicle prices. While switching our addiction from the soon-to-be-drained out oil to lithium is projected to make way for technologies with low carbon footprints and, therefore, a cleaner environment, large-scale mining and exploitation of lithium is not without environmental fallouts. The grass always looks greener on the other side, but alternative technologies should be carefully examined for their long-term sustainability. The oil-to-lithium switch reminds us of Woody Allen's words: "More than any other time in history, mankind faces a crossroad. One path leads to despair and utter hopelessness. The other, to total extinction. Let us pray we have the wisdom to choose correctly."[23]

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Views expressed in this Guest Commentary are those of the authors and not necessarily the views of the ACS.

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