



Graphene Oxide Sulfur Nanocomposite Cathode

- for High-Energy, Low-Weight Lithium Sulfur Batteries

Commercial Analysis

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LAWRENCE BERKELEY NATIONAL LABORATORY

Researchers: Dr. Y. Zhang, Prof. E. Cairns, Dr. L. Ji, & Dr. M. Rao

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Technology

Electric vehicles (EVs) use today's state-of-the-art lithium-ion battery cells, yet the batteries are still the weakest link in the vehicle's performance, durability, and cost. Even after decades of progress, lithium-ion batteries are too expensive and too heavy to propel EVs into the mainstream. To fulfill the promise of an EV revolution that decarbonizes transportation, a better battery is needed.

The lithium-sulfur chemistry is a potential breakthrough solution to this enduring battery performance problem. A lithium-sulfur battery (LSB) could achieve specific energy levels up to 800 Wh/kg, while lithium-ion cells today deliver only 250 Wh/kg, with potential improvement to 400 Wh/kg in the future. Lithium and sulfur are inexpensive raw materials, enabling lower cost batteries, and the cells can be produced in the same factories that are making lithium-ion cells today.

The breakthrough invention of the graphene oxide-sulfur nanocomposite cathode by Yuegang Zhang, Elton J. Cairns, et al. of Lawrence Berkeley National Laboratory may overcome the cycle life challenge that has previously prevented the commercialization of the lithium-sulfur cell.

A primary novelty of their design is based on using an *in situ* simultaneous reaction and deposition method to yield Graphene Oxide (GO) flakes, coated in a thin, complete layer of sulfur. The value of this design is that it is able to achieve a high degree of sulfur loading by using GO as a scaffold for sulfur deposition. The GO acts as a strong, thin, highly electronically conductive medium to disperse sulfur, and as such the GO-S material can be formed into cathodes with remarkably high sulfur content while retaining electronic connectivity needed to facilitate rapid electron flow in and out of the cathode. Tests show that this graphene oxide-sulfur composite cathode demonstrated extremely high reversible charge capacity.

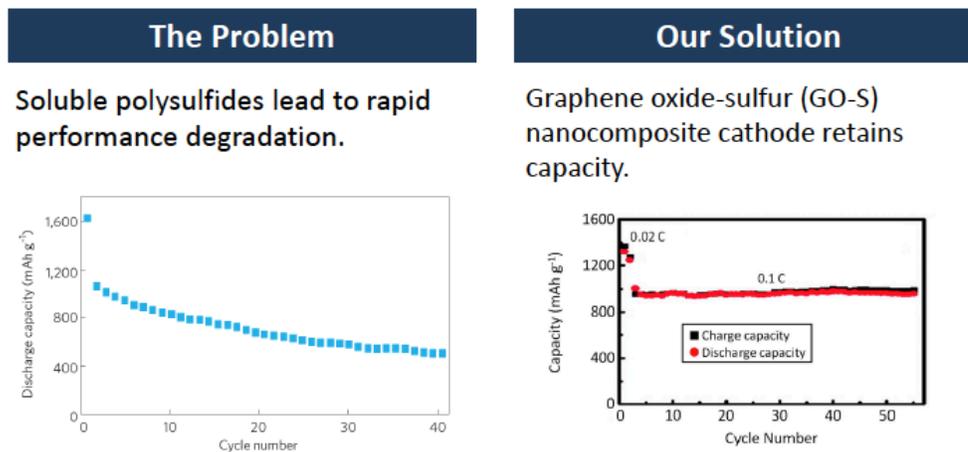


Figure 1 - GO-S Cathode Full Cell Performance

Applications

This technology can be applied to lithium batteries, electric car batteries and portable electronic devices in a wide variety of industries including consumer electronics, medical devices, automotive and defense. Target applications in these markets include Small Unmanned Aerial Vehicles (SUAVs), Soldier Power (i.e. the energy storage and delivery system that soldiers carry to power portable electronic devices),

communication and surveillance equipment, weapon systems, pacemakers, automatic external defibrillators (AEDs), cell phones, laptops and power tools. The table below shows several of these market segments and their respective criteria for adoption.

Table 1 –The different criteria performances for the 4 key application segments

1 Applications		2 Application Needs vs. LiS Performance					
		Weight	Volume	Cycles	Cost		
Defense	<ul style="list-style-type: none"> Storage Manpack power UAVs ... 	Manpack power	20 lbs		300	\$1-2/Wh	
	Cons. Elec	<ul style="list-style-type: none"> Tablet Cellphone Power tools 	Tablet	½ of device			
Vehicles		<ul style="list-style-type: none"> Battery EVs Range-extended EVs Hybrid EVs 	Power tool			400	
		<ul style="list-style-type: none"> Battery EVs Range-extended EVs Hybrid EVs 	Battery EVs			1000	\$0.5/Wh
	Medical	<ul style="list-style-type: none"> Pace Maker Defibrillator Pulse Oximeters 	Pacemaker	7 year life			

Market

Industry Overview

The global battery market is estimated at \$90 billion, with LIBs representing approximately \$10 billion or 11% of the total industry. World demand for batteries is forecasted to rise 8% annually through 2016, with secondary batteries being the largest driver of growth.¹ The market for small LIBs is predicted to grow 10% annually over the medium term, with demand for EV batteries forecasted to top small batteries by 2020.²

Given the rapid growth in mobile consumer electronics usage and a shift toward environmentally conscious purchasing, battery demand is shifting from primary (single-use) batteries to secondary (rechargeable) batteries. Primary batteries will continue to be used for convenience and in applications that require high reliability, such as emergency equipment. Primary batteries represent 43.3% of U.S. market. Primary lithium batteries have been gaining market share, reflecting the need for high energy density and low self-discharge in order to provide long service life. Lithium batteries compose 7.5% of the primary battery market and are expected to grow to 9.3% by 2017.

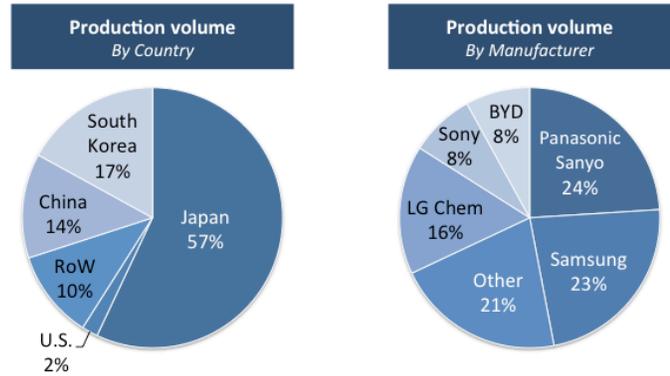
¹ Freedonia Group. [World Batteries to 2016](#). October 2012.

² Credit Suisse. *Battery and Battery Materials*. July 2012.

Secondary batteries are gaining market share in applications with high usage and access to charging, where frequently replacing primary batteries is inconvenient and expensive. Rechargeable batteries comprise the remaining 56.7% of the U.S. market. The largest market segment for secondary batteries is the automotive industry, where starter batteries account for almost 30% of the U.S. market.²

The LIB industry is highly concentrated amongst several large Asian manufacturers (see **Error! Reference source not found.**). This reflects the history of consumer electronics serving as the primary driver of advanced battery production. The manufacturers of these devices are largely Asia-based, and thus they have developed supply chains, including battery production, co-located in the same geographies. The region's dominance in LIB production is reflected in the following charts of the industry's concentration, segmented by country and manufacturer.

Figure 2. Li-ion battery production by country and company.



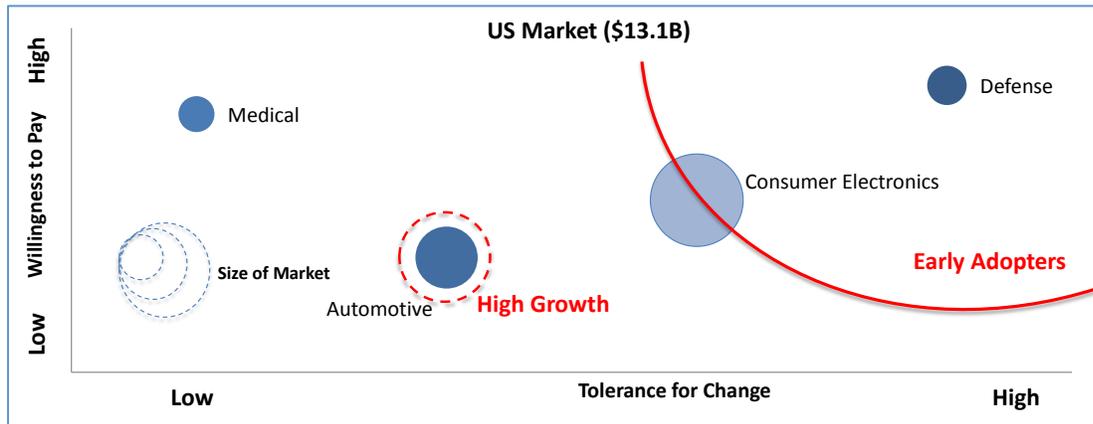
³ Error! Bookmark not defined., 3

88% of production is located in the top three countries: Japan, South Korea and China. The top five largest manufacturers (Panasonic/ Sanyo, Samsung, LG Chem, BYD, and Sony) are responsible for 80% of market share. Beyond its roots as a component of consumer electronics, the LIB industry's high degree of concentration also reflects the capital-intensive nature of mass production. Volume is critical in this industry, and building a large-scale LIB plant entails a capital expenditure of up to \$400 million.

Figure 3 below depicts the attractiveness of major battery markets for adoption of LSBs. Early adopter markets include defense and consumer electronics. In the future, automotive is attractive because it is expected to be the fastest-growing and largest market for batteries, and it should be a good performance fit for LSBs. The medical market may provide opportunities for LSBs in specific applications that have a relatively high tolerance for change compared to the overall medical market.

³ Center on Globalization, Governance, & Competitiveness, Duke University. *Li-ion Batteries for Electric Vehicles: The U.S. Value Chain*. October 2010. <http://cggc.duke.edu/pdfs/Lowe_Lithium-Ion_Batteries_CGGC_10-05-10_revised.pdf>.

Figure 3: Lithium-ion battery industry overview



Economics

The EV market presents a large and growing opportunity for lithium-sulfur, but supplying the industry is challenging. The fundamental metric driving battery selection is cost. Auto OEMs will not pay a premium for increased performance, so the price for lithium-sulfur must be on par with lithium-ion, whose forecasted price in 2020 is \$150/kWh. Minimum future LSB performance metrics for an advantage of LIBs include cycle life of 600 cycles, energy density of about 600 Wh/L, specific energy of 500 Wh/kg, and fast charging at greater than 1 C.

Analysts agree that prices will continue their downward trajectory for at least the next decade. While specific forecasted numbers vary across the industry, the general consensus is that LIBs will flatten out in the \$150-200 per kWh range. McKinsey forecasts that LIB packs for EVs will decline from today's \$500-600 per kWh to around \$200 per kWh by 2020 and to \$160 per kWh by 2025. The following chart, though less bullish in its predictions, provides a useful display of this price decline, as well as the forecasted growth in production. Should EV demand fail to significantly accelerate, however, it is reasonable to expect this price decline to occur at a slower pace.

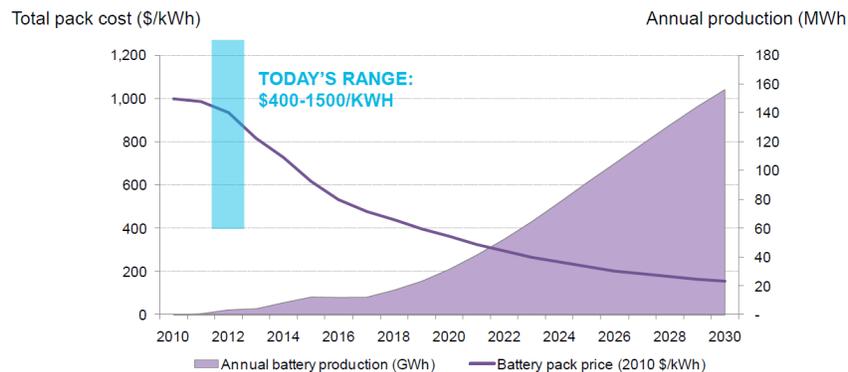


Figure 4 - Predicted decline in LIB costs reflects growing scale⁴

⁴ Bloomberg New Energy Finance, Battery Innovation: Incremental or Disruptive, March 2012.

These predicted price reductions reflect three key trends:

1. **Manufacturing at scale:** economies of scale and improved productivity are expected to drive 30-35% of price reductions.
2. **Improved technology:** advances in battery technology are forecasted to improve battery capacity by 80-110% by 2025, driving 40-45% of expected price reductions.
3. **Reduction in component prices:** margin compression and improved efficiency of component production are expected to drive 25% of price reductions.

Competitive Landscape

While academic research into LSBs has increased drastically over recent years, industrial efforts have been limited to relatively few players, and have shown to be fairly slow-moving.

Sion Power and PolyPlus, the most established competitors in the LSB field, have both operated for approximately two decades. Although each has indicated an accelerated pace of development in the last few years, neither has come close to introducing a commercial product. Both companies have suggested that most of their improvements to date have been in regards to new technology for protecting the lithium anode. PolyPlus, in particular, has built momentum for LSBs, as well as lithium-air and lithium-seawater batteries, by using a ceramic interlayer to separate the anode from the electrolyte.

As recently as several years ago, however, each company had reported specific energy in the 300-400 Wh/kg range, which would be considered a significant improvement from LIBs but still well short of the full potential of LSBs. More recently, a marked increase in funding for Sion and Polyplus suggests that their development has grown significantly closer to commercial viability.

Elsewhere, Oxis Energy has established itself as the sole marketer of fully solid-state LSBs with the use of polymer electrolytes. Oxis has announced plans to introduce batteries into small-scale electric transportation applications (electric scooters, bikes, boats) in the next two years. Dry polymer electrolytes have been considered to a lesser extent, due to their relatively low ionic conductivity and poor temperature performance, however, utilizing gel polymer electrolytes or low molecular weight polymer mixtures with solvent as envisioned by Dr. Cairns could improve the feasibility of this architecture.

A recent contributor to the commercial LSB field is Vorbeck Materials, which has asserted itself primarily as a materials supplier. To date, Vorbeck's work has focused on the large scale production of graphene and GO, but recently the company has begun work with Pacific Northwest National Lab (PNNL) and other institutions to investigate use of functionalized graphene sheets for LSB cathode applications.

Driving Forces

Manufacturers are competing for scale. Approximately 80% of the manufactured cost of a LIB is the bill of materials, primarily the anode, cathode, separator and electrolyte. As a result, production volume is the fundamental driver of cost reductions. Over the past five years, the incumbent Asian nations made significant investment in building production capacity, as did other countries who recognize the growing importance of this sector and are fearful of being left behind. For example, in the U.S. alone, since 2009

the federal government has invested \$1.26 billion in companies such as Johnson Controls, LG Chem, and Dow Kokam to build nine battery factories in four states.⁵

Electric vehicles are key growth driver. Bullish growth forecasts for EVs have resulted in billions of dollars of public and private investment in scaling battery production capacity over the past five years. The costs of liquid fuels are the single most important driver of EV adoption. In order for EVs to be cost-competitive with fuel-based vehicles, the industry must see a combination of declining battery prices and rising fuel prices. Currently, batteries represent 25% or more of the total manufactured cost of an EV. A useful benchmark often cited is that a complete pack price of \$250 per kWh would be competitive with \$3.50 per gallon gasoline.

Slow EV adoption will result in battery oversupply. Despite ambitious past growth forecasts, actual EV adoption has proven lackluster, resulting in a significant oversupply of production capacity. The following table depicts forecasted production capacity and resulting demand under three fuel price scenarios; all three situations are predicted to result in oversupply.

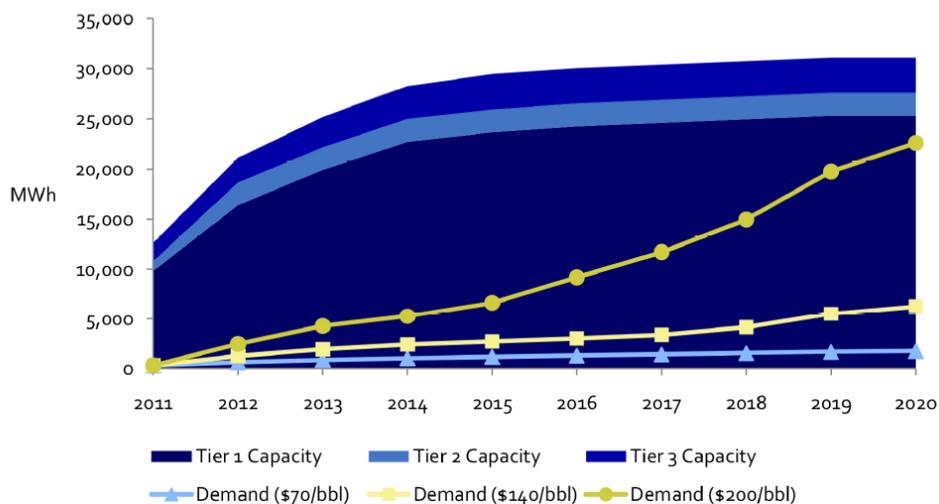


Figure 5 - Industry oversupply: LIB production capacity exceeds forecasted demand⁶

Despite challenges, LSBs are gaining momentum. While the concept of a sulfur cathode was demonstrated in the 1960s, LSBs have yet to be offered on a commercial scale. Over the past six months, however, the industry has seen a meaningful uptick in the interest surrounding LSB designs, as demonstrated by an increase in both government and private funding. ARPA-E's recent November 2012 allocation included funding for PolyPlus and Vorbeck Materials, two companies that are working to commercialize LSB designs for military and consumer applications, including EVs.⁷ Furthermore, as the following table of battery startups depicts, of the ten largest recipients of VC funding over the past two years, two are Li-S plays: Sion Power and Oxis Energy.

⁵ Wall Street Journal. China's New Target: Batteries. August 2012. <<http://online.wsj.com/article/SB10000872396390443991704577576881949308486.html>>.

⁶ Lux Research. Kevin See, Aaron Wirshba, and Michael Holman, *Using Partnerships to Stay Afloat in the Electric Vehicle Storm*. 2011.

⁷ U.S. Department of Energy, [ARPA-E Project Selections](#), November 2012.

Table 2 - VC-backed battery companies (Top 10 deals over the past 2 years)⁸

Company	Country	Status	Amount ↓
Boston-Power	United States	Private	\$125,000,000
Sion Power	United States	Private	\$50,000,000
Boston-Power	United States	Private	\$30,000,000
Microvast	United States	Private	\$30,000,000
Aquion Energy	United States	Private	\$30,000,000
Amprion	United States	Private	\$25,000,000
Oxis Energy	United Kingdom	Private	\$24,200,000
IntelliBatt	United States	Private	\$22,000,000
Leyden Energy	United States	Private	\$20,000,000
Contour Energy Systems	United States	Private	\$20,000,000

As a result of the previously discussed industry forces – high supplier concentration, slow demand growth and a resulting production overcapacity – the advanced battery industry will continue to grow increasingly competitive as prices are driven downwards. From April 2011 to April 2012, the average price of Li-ion EV battery packs fell 14%. Since 2009, they have dropped a total of 30%.⁹ Industry experts generally agree that advanced batteries are quickly becoming viewed as a commodity product, further emphasizing the importance of cost-competitiveness.

Intellectual Property

Published PCT application (PCT/US2012/058047) is available at www.wipo.int. The technology is available for licensing or collaborative research.

Licensing Strategy

Taking a technology from prototype to mass production requires tremendous capital investment and is filled with challenges that require a very different set of resources and competencies than those required to develop a new battery architecture. Challenges of scaling to mass production have resulted in the failure of many battery startups, including A123 and Imara. This is best left to the industry incumbents who bring deep technical expertise, substantial capital, and existing sales and distribution networks. As such, it is recommended that the technology is licensed to a strategic acquirer prior to embarking on manufacturing scale-up.

Next Steps

Companies interested in licensing this technology may contact ttd@lbl.gov or call 510-486-6457.

⁸ Cleantech Group. *i3 Platform: Batteries*. December 2012. <<http://research.cleantech.com/tags/batteries/900/activity>>.

⁹ Bloomberg, [Battery Prices for Electric Vehicles](#), April 2012.