

Lithium-Sulfur Battery: Chemistry, Challenges, Cost, and Future

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Lithium sulfur (Li-S) battery has higher theoretical and experimental specific energy. Therefore, Li-S battery is the most capable energy storage option for electrical vehicles and power grid. However, it has life cycle issue to prevent its usage in electrical vehicles. Li-S battery need to improve life cycle issue in order to work with current battery applications. Li-S battery has complex chemistry and process to discharge and charge Li-S cell. The cost and manufacturing process of Li-S batteries will be one of the biggest challenge for commercial transformation from research and development stage. The Oxis Energy is developing Li-S battery for past 10 years and they have goal price US\$250/kWh by 2020 with high volumes and more cheaper compare to lithium-ion battery.

Introduction

Since 1991, Sony Inc. had started using Lithium-ion (Li-ion) batteries commercially. It has been more than 25 years Li-ion batteries are in commercial market. Li-ion batteries have expanded their roots to all cutting edge technologies such as cell phones, computers, and other devices. Now, Li-ion technologies are moving towards energy storage. The Tesla has introduced commercially functional electric car which is based on Li-ion batteries. Electrical power storage for renewable energies (solar, wind, and other resources) is the next challenge for Li-ion. Currently, Li-ion technologies have stretched their capacities of energy storage and density. Therefore, scientists and engineers are working on Lithium-Sulfur (Li-S) and Sodium-Sulfur (Na-S) batteries. Here, I am going to discuss emerging new technologies in batteries with chemistry and background of Li-S batteries, comparison between Li-S and Li-ion, and future of sulfur base batteries.^{1,2}

Chemistry and Background of Lithium-Sulfur batteries

Chemistry of Lithium-Sulfur

An electric battery is energy storage devices. An electric battery can store chemical energy, which can produce chemical energy into electrical energy. As we know that an electric battery is made up of electrochemical cell. Electrochemical cell has two terminals. One is positive terminal which is also known as cathode and other is negative terminal which is also known as anode. During chemical reaction between cathode and anode, electrochemical cell produces electrical energy. We have been using this electrical energy in daily applications such as cell phone, laptop, and other devices. Here I have explain chemistry of the Lithium-sulfur (Li-S) batteries. The Li-S batteries are made up of basic elements of lithium and sulfur. The Li-S batteries use carbon-sulfur as cathode and Lithium metal as anode. In Li-S battery, the Carbon-sulfur is obtained as the waste products of petroleum process, which make Li-S batteries economi-

cally cheaper in price. Carbon-sulfur gets separated by electrolytic process. The electrolytic process requires an electrolyte, an ionized solution and molten metallic salt, to form complete electric circuit between two electrodes.³ Pure sulfur is manufacture from electrolytic process for Li-S battery.^{4,5}

Process of Lithium-Sulfur Cell

During discharge, lithium metal is dissolved at negative electrode to produce lithium ions and electrons to travel towards positive electrode and start reaction with sulfur at cathode. The process will produce Lithium-polysulfide and energy gets released during this reaction. This happens during the Li-S battery discharge and reverse process happens during battery charge. Sulfur has the high theoretical capacity of $1672 \frac{mAh}{g}$, which is 10 times higher than that of conventional cathode materials (such as $LiCoO_2$ and $LiFePO_4$) for lithium ion batteries, therefore, much higher energy density can be achieved using sulfur as cathode. Lithium metal has the theoretical capacity of 3862 mA h g^{-1} . Li-S cell can produce 2.15 voltages during chemical reaction between lithium and sulfur.^{6,7}

When you have complete circuit, the Li-S battery is discharging as you can see that in Figure 1a). During Li-S cell discharge, Lithium metal is oxidized to lithium ions and electrons at negative terminal. The lithium ions and electron get separated from lithium metal and move toward positive terminal to start reaction with sulfur. Lithium ions and sulfur produce Lithium-polysulfide in

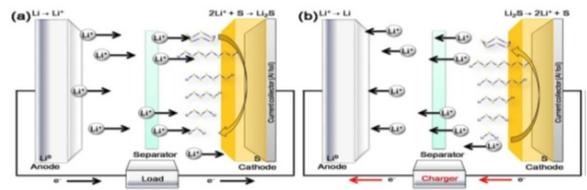


FIG. 1: Ideal Lithium-Sulfur battery during (a) discharge and (b) charge⁸

complete circuit. The lithium-polysulfide half way transforms to lithium sulfide (Li_2S) as end product of lithium-sulfur discharge. When you are charging lithium-sulfur battery, you have reverse reaction from lithium sulfide product. The lithium ions separate from lithium sulfide and attract to negative terminal on the lithium metal. Once lithium ions are on the lithium metal, we have sulfur on the positive terminal as you can see in Figure 1b).⁸

The lithium-sulfur cell has open circuit voltage in beginning of discharge. As you can see in Figure 2, the lithium-sulfur cell has three different stages during charge and discharge processes: the upper plateau region, the sloping region and the lower plateau region. The lithium ions and the allotropes of sulfur react with each other. The reaction reduces high-order polysulfide in the upper plateau region at approximately 2.3 V.^{7,9}

When the reduce polysulfide dissolves into the liquid electrolyte, it increases electrolyte viscosity. Also, it slows down lithium ions conveyance rate. This process results voltage drop between 2.3 V (Li_2S_8) and 2.1 V (Li_2S_6) as you can see that in Figure 2. The high-order polysulfide transforms into Li_2S_4 about approximately 2.1 V in the sloping region. Li_2S_4 transforms from solid-liquid phase to slow solid-state in the lower plateau states. Also, the end discharge product Li_2S achieved is in slow solid state as we can see that in Figure 2. This is how lithium sulfur cell works to discharge cell from S_8 to Li_2S_4 and Li_2S_4 to Li_2S . The reverse process of Li_2S to S_8 shows flat curve in lower and upper plateau during charging process.^{2,10,11}

Lithium-Sulfur battery vs. Lithium-Ion battery

Differences between Li-Ion and Li-S

Materials and Properties of Batteries

The Lithium ion batteries has the blend of lithium metal compound with other metals and carbon (graphite) element as the cathode and anode respectively. There

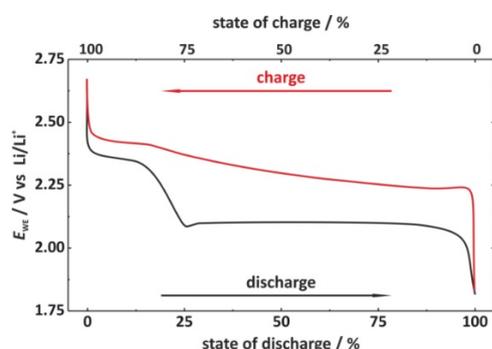


FIG. 2: Lithium-Sulfur cell stages for battery discharging and charging⁷

are several possibilities of lithium metal compound with other metals. Here are some ideal choices: lithium iron phosphate ($LiFePO_4$), lithium nickel oxide, lithium aluminum oxide, lithium cobalt oxide (LCO) and lithium manganese oxide. A fully charged Li-ion cell yields approximately 0.5 V. Operating temperature can range from -30°C to 60°C .^{10,11}

However, Lithium-sulfur batteries uses carbon-sulfur as cathode and Lithium metal as anode. Carbon-sulfur is waste product of petroleum process. The Li-S batteries can be produced with more density compared to the Li-ion batteries because sulfur has low atomic weight. Therefore, the Li-S batteries have more storage capacity compared to the Li-ion batteries. The electrical energy output of a single Li-S cell is approximately 1.8 V if it is fully charged as you can see that in Figure 3.⁸

Challenges and Cost

The Li-S battery has lot to improve before becoming reliable commercialize product. As we know that the battery has low cost materials and simple processing techniques. However, the Li-S battery has still issue with life cycle use. It depends on lithium-sulfur cell on developing better electrochemical stability and reversibility. The electrochemical consumption of lithium-sulfur cell get reduced because of protective materials in cell. The polysulfide diffusion and shuttle behavior are results of the soluble polysulfide which were dissolved during the process into liquid electrolyte. The diffusing polysulfides undergo unstable electrochemical reaction with sulfur and transforms into nonconductive conductors. The lithium-sulfur cell electrodes are shown in Figure 4 with shuttle system and reaction between lithium and sulfur material. The lithium-sulfur technology need to overcome many materials and system obstacles. The cost of one ton sulfur is approximately \$110, which is cheaper material to construct Li-S batteries.^{7,9,11}

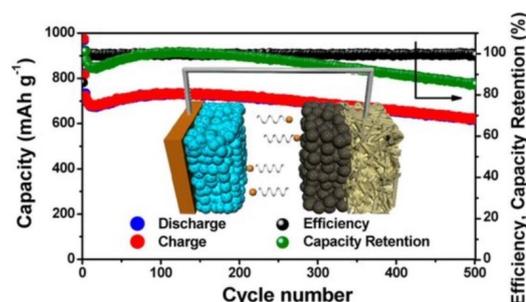


FIG. 3: of Li-S Efficiency, Cycle and Capacity Graph¹²

Usage in current and future application of energy

Li-Ion batteries are currently dominating in this technology world surrounding us. We are seeing them in laptops, cell phones, telecommunication devices, power tools, electric vehicles, and other devices. There are ideas, articles, and research papers on Lithium ion batteries which use them as energy storage device for electric grid. Oxis Energy and Prions, UK base energy companies, launched project Heliso. They are integrating solar photovoltaic power generation with Li-S batteries for energy storage of solar energy. This will be available for European and Asian markets for residential applications. Oxis energy is aiming for \$250/kWh of Li-S battery price in 2020 for mass production in terms of cost. This is based on cheaper material price required for the Li-S battery compared to the Li-ion battery. The Tesla motor has created world class electric passenger car on Li-ion batteries. Tesla model S has range of 240 miles with 70 kWh and 265 miles with 85 kWh Li-ion batteries.^{10,13}

However, Li-S batteries are in process of becoming commercially available to consumer. Oxis Energy Ltd and Hyperdrive innovation Ltd are UK base companies. They are collaborating to develop a low temperature battery, which can perform at about -80 ° C temperature. It will be useful application for extremely low weather condition such as Antarctic. The Oxis Energy Ltd has been developing Li-S battery for more than 10 years. The company has developed prototype of airport style passengers carrier at University of Oxford. The company has already built Li-S cell with 375 Wh/kg, where Li-ion cell is producing 200-265 Wh/kg. As we know sulfur has light atomic weight, it can store more energy compared to same size of lithium-ion battery pack. There is a better possibility of Li-S batteries to succeed Li-ion batteries. However, Li-S battery must overcome life cycle and discharge challenge. If that happens in near future, than that will be beginning of new era of Li-S batteries. If

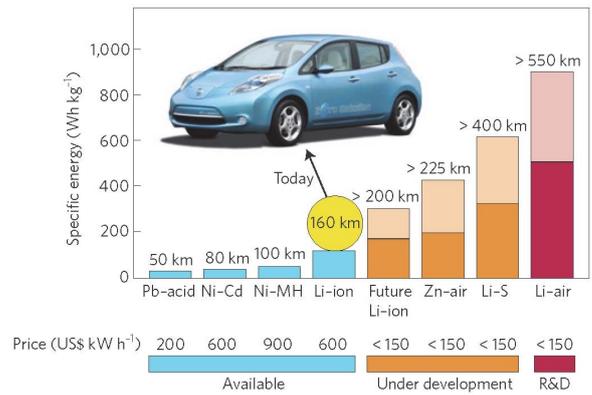


FIG. 5: Portable batteries comparison chart⁸

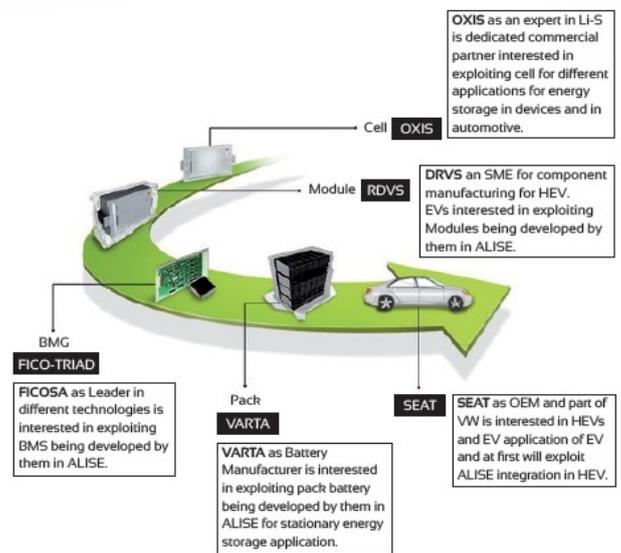


FIG. 6: ALISE to develop Li-S batteries for Electrical Vehicles¹⁰

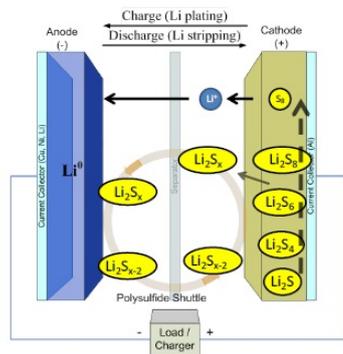


FIG. 4: Lithium-Sulfur battery with polysulfide shuttle system⁹

you replaced Li-ion batteries in Tesla Model S with Li-S batteries, the range of car will be approximately 360 to 400 miles with single battery discharge. Li-S will be with better energy discharge from same size of battery packs.^{10,14}

ALISE Advanced Lithium Sulfur Battery for xEV is collaboration to achieve longer life cycle and stability for Li-S battery by the European Union. Where different companies are coming together for transition of Li-S Batteries, they are going take Li-S from research and development to market commercially for different consumer products. As you can see in Figure 6.^{2,10,15}

Conclusion

As I have explained with my capacity and ability in batteries with chemistry and background of Li-S batteries, comparison between Li-S and Li-ion, and future of sulfur base batteries. There are many better ideas to develop batteries. Oxie Energy and Prions will introduce Li-S batteries to commercial market in March 2016, where they are integrating solar energy and Li-S batteries. It will be interesting to see battle between Li-S and Li-ion for energy storage. Lithium-sulfur batteries need to improve long life cycle and higher discharge rate to surpass the Lithium-ion batteries. Also, tesla motor is in process of developing Gigafactory for lithium-ion batter-

ies and car production. It will bring down cost of Li-ion batteries. Therefore, Li-S batteries need to improve their higher energy discharge to compete with L-ion batteries. Also, Li-S batteries need to improve better life cycle. There are so many different type of sulfur base batteries in research such as Sodium sulfur by Faradion. Na-S batteries but have energy density challenge. NASA, Oxis and Faradion are working together in order to find solution to these challenges. Lets not forget Fuel cell technology, which has potential of developing better electric vehicle technology. Fuel cells and rechargeable batteries will be one of the key element in shaping future and horizon of new technology in batteries.^{1,3}

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