Lithium-Air Batteries

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Abstract

Batteries with high specific energy densities increasingly attract attention as potential energy sources for electric vehicles (EV). Lithium-air batteries are the most promising system because of their theoretical specific energy density much higher than conventional batteries. However, there is (still) no technical basis to support high energy density estimated from the calculation. The article discusses the current state of lithium-air (or lithium-oxygen), and their future prospects, with emphasis on materials.

Keywords: battery, electric vehicle, specific energy density, materials

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1. Introduction

Lithium-ion batteries, marketed for the first time in 1991, have gone a long way. The world market is expected to reach 30 billion euros by 2019, with applications in almost every industry — from intermittent renewable energy storage devices for smartphones to electric cars.

As cars have an increasing power, engineers around the world have begun to look for alternatives with greater storage capacity. One of these alternatives resides in lithium-air technology, batteries consisting of metal anode, and air, as cathode, which constantly extract oxygen from ambient air.

Of particular interest in the transport context: with the specific energy and energy density of the Li-ion cells of today's automobiles, the range of distances travelled is limited to about 70 miles for a 200 kg battery (Figure 1), assuming energy specific of 150 Wh/kg at cell level and 105 Wh/kg at battery level (70 % of the weight of a battery are the cells).

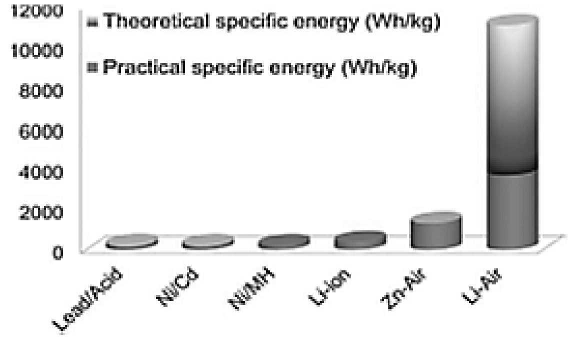

Figure 1. The theoretical, specific and practical energy densities of different types of rechargeable batteries (after [26])

This means that in order to allow electric vehicles with a similar range of distances travelled, for today's vehicles fuelled with liquid fuels, there is a need for a battery system with specific energy and energy density much higher than at present.

Lithium-air batteries are considered promising technologies for electric cars and portable electronic devices, due to their potential to deliver high power, proportionate to their weight.

However, such batteries have some important drawbacks: they lose much of the injected energy in the form of heat and degrade relatively quickly. They also require extra expensive components to pump oxygen out, in an open cell configuration that is very different from conventional sealed batteries. A new chemical battery variant, which can be used in a conventional, fully sealed battery, theoretically promises similar performance to lithium-air batteries, once all these shortcomings have been overcome.

Metal-air batteries that use ambient oxygen reduction have the highest energy density because most of the cellular volume is occupied by the anode, while the cathodic active material is not stored in the battery. Metallic lithium is a tempting anodic material for any battery, due to its particular specific capacity [3842 mAh g^{-1} for lithium, compared to 815 mAh g^{-1} for Zn].

Combining high lithium energy with ambient oxygen appears to be a promising option. More precisely, in all electrolyte classes, transformation from Li-O_2 to Li-air is still a major challenge, as the presence of humidity and CO_2 significantly reduces cell performance due to their strong metal lithium reaction. The search for electrolyte systems capable of providing a solution to the challenges posed by the use of metal lithium, exposure to the environment, and manipulation of the formation of the discharged reactive product are particularly recent. [1]

Li-Air batteries are potentially viable, high-energy chemical energy sources (Figure 2), which could provide potential specific potentials up to ~3000 kg^{-1} Wh, being rechargeable.

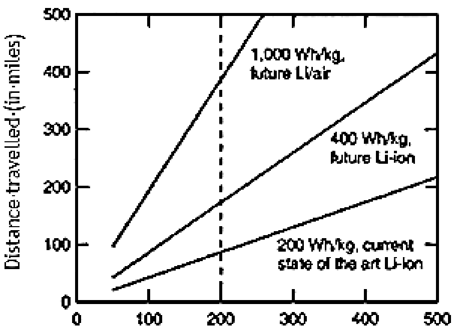

Figure 2. Weight of the accumulator (kg)

Although their implementation is the biggest promise in a number of applications, from portable electronic devices to electric vehicles, there are also impressive challenges in the development of cathode materials and electrolyte systems of these batteries. [2]

Indeed, while some observers predict that Li-ion cells may reach 400 Wh/kg by using high-capacity cathodic materials (275 mAh/g) and anode alloys (2000 mAh/g) significantly higher values can be obtained even with higher capacity Li metal cathodes and improved packaging of active materials. A Li-Air battery has the potential to truly exceed the battery technology used today as well as the battery technology currently being developed for medium-term implementation (for example, which can reach 400 Wh/kg).

In non-aqueous lithium-air batteries two reactions to the main electrodes occur:

$$2Li + ½O_2 \leftrightarrow Li_2O \qquad (1)$$

and

$$2Li + O_2 \leftrightarrow Li_2O_2 \qquad (2)$$

In the absence of practical considerations, the complete reduction of O_2 in Li_2O is desirable because of its specific energy and higher energy density, but Li_2O_2 appears to be a product that is easier to form than Li_2O. [4-6] In addition, when Li_2O_2 is formed, complete cleavage of the O-O bond may not be necessary, which is kinetically important. [7, 8]

Reactions involving Li and O_2 in an aqueous medium depend on pH. In a basic aqueous medium, the reduction of O_2 includes H_2O as the reactant and results in the formation of LiOH:

$$2Li + ½O_2 + H_2O \leftrightarrow 2LiOH \qquad (3)$$

The distance (in miles) according to the weight of the battery, for different specific energy values of the cell. It is assumed that the battery cells weigh 70 % of the weight of the battery, the Li-Air cell has an energy efficiency of 83 % and the energy efficiency of Li-ion cells is 93 %, and 300 Wh/mile are required from the battery. The distance is given at the beginning of a battery life and it is assumed that 100 % of the capacity can be used; in practice, not all energies can be used, and the available energy decreases as the age of the battery increases. The US Department of Energy is considering 200 kg for electric vehicle (EV) batteries. [3]

The product of this reaction is aqueous LiOH, having a solubility limit of about 5.25 M at standard temperature and pressure. [9] If LiOH exceeds the solubility limit, LiOH will precipitate from the solution as the monohydrate. H_2O, rather than LiOH. [9]

Table 1 summarizes the physical properties of the Li-Air active materials in the unloaded state as well as a current generation and a "next generation" of Li-ion interstellar material for comparison. [10, 11-28]

Table 1. Physical properties of active lithium-ion and lithium-air active material, selected positive active electrode, as well as Li metal [11].

Active material	Specific capacity (mAh/g)	Density (g/cm³)	Capacity density (mAh/cm³)	U° *vs* Li metal (V)	Theoretical specific energy (*vs* Li metal) (kWh/kg)	Theoretical density (kWh/L)
LiO	1794	2.01	3606	2.91	5.22	10.49
Li_2O_2	1168	2.31	2698	2.96	3.46	7.99
$LiOH{\cdot}H_2O$	639	1.51	965	3.45	2.20	3.33
LiOH	1119	1.46	1634	3.45	3.86	5.60
Li metal	3861	0.534	2062	0.0		

One of the shortcomings of the lithium-air batteries is the mismatch between the tensions involved in charging and discharging the batteries. The battery output voltage is less than 1.2 V than the voltage used to charge, which is a significant loss of power in each load cycle. Thirty percent of the electricity is squandered in the form of heat at the load.

The main advantage of a lithium-air battery is its high energy density, which (theoretically) is 10 times higher than that of lithium-ion batteries. The biggest challenge, however, is to improve their life cycle, which was only 50 cycles maximum. This figure fades in comparison to that of lithium-ion batteries, which can reach 400 to 1200 life cycle cycles.

The initial objective was simple: to increase this capacity from 50 to 100-150 cycles and demonstrate the progress in functional cells for three years. In this respect, the STABLE project [16] is a complete success, with a lifetime of 151 cycles. To reach this result, researchers have focused on battery anode, cathode, electrolyte materials and technologies, and battery assembly techniques that play a central role in performance, cost and environmental impact. The lithium-air battery life cycle has improved through various means. The first bi-functional catalysts were found to be very active, able to effectively regenerate the battery. The lithium anode was then protected against dendrite formation using suitable membranes, and the stability of the electrolyte was ultimately increased to enhance the solubility of Li_2O_2 and to avoid clogging the cathode.

A lithium-ion battery has three main parts: two electrodes (an anode made of graphite and a cathode made of cobalt lithium oxide or a metal similar to oxide) and a very thin, but porous polyethylene separator. All these materials are stored inside the battery. The electric current flows between the anode and the cathode through an external circuit through a liquid called the electrolyte.

A lithium-air battery also has an anode and a cathode. Here, the anode is made of metal with lithium, and the cathode is oxygen, taken from the atmosphere. Like the lithium-ion battery, the electric current flows between the anode and the cathode by liquid electrolyte. However, since the cathode is not stored inside the battery, and because oxygen weighs far less than a metal oxide cathode, a lithium-air battery is extremely light (Figure 3).

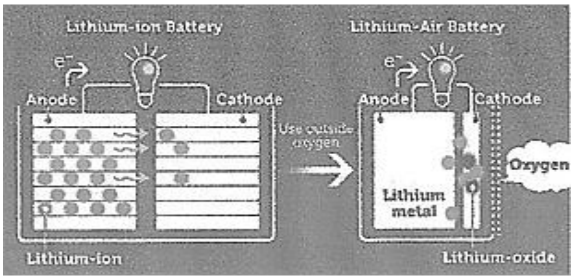

Figure 3. The lithium-air battery reduces the volume/weight by obtaining O-electrons from the air (after [25])

At present, lithium-air batteries are partly in the early stages of development. If a lithium-air battery would become practically usable, three to four times the energy of a lithium-ion battery would be offered. In the best case scenario, a lithium ion battery stores approximately 240 watts per kilogram of battery weight. The lithium-air battery, on the other hand, would provide more than 1,000 watt hours per kilogram of battery weight.

Oxygen is environmentally friendly; it is not toxic and much easier than other materials, thus reducing VE resistance to advancing. Any vehicle that uses it could therefore run more electricity than with a lithium-ion battery. For example, an electric car powered by a lithium-ion battery can travel about 200 to 250 miles with a single charge, while one powered by a lithium-ion battery could easily run between 400 and 500 miles, with a single charge.

The army is interested in lithium-air batteries for strategic reasons. In addition, being long-lasting, they are easy to carry, so for example an infantry soldier in a remote area could simply open a packet and expose the batteries to the air. Commercial applications include the storage of electricity generated by wind turbines and solar panels.

The major advantage of a lithium super-oxide battery is that it allows, at least theoretically, the creation of a lithium-air battery, which is made up of what chemists call a "closed system". (Open systems require a consistent supply of oxygen from the environment, while closed systems do not - making them safer and more efficient). Stabilization of the super oxide phase could lead to the development of a new "closed" battery system, based on lithium super oxide, which has the potential to truly provide an energy density five times the density offered by the lithium-ion battery.

2. Solid state batteries

Conventional lithium-air batteries draw oxygen from outside air to lead to a chemical reaction with the battery lithium during the discharge cycle, and the oxygen is then released back into the atmosphere during the inversion of the charge cycle. In the new variant, the same type of electrochemical reactions takes place between lithium and oxygen during charging and discharging, but these occur without ever allowing the oxygen to return to a gaseous form. Instead, the oxygen remains inside the solid and converts directly between its three redox states in the form of three different chemical solids (LiO_2, Li_2O_2, and Li_2O), which are mixed together. This reduces the voltage drop by a factor of five, from 1.2 volts to 0.24 volts, so only eight percent of the electricity is activated in heat; this means a faster charging time for cars because removing heat from the battery is less a safety issue, but energy efficiency benefits.

This approach allows solving another problem of lithium-air batteries; because the chemical reaction involved in loading and unloading converts oxygen into gaseous and solid forms, the material passes through immense volume changes that can disrupt the electrical conduction pathways in the structure, drastically limiting its lifespan (Figure 4).

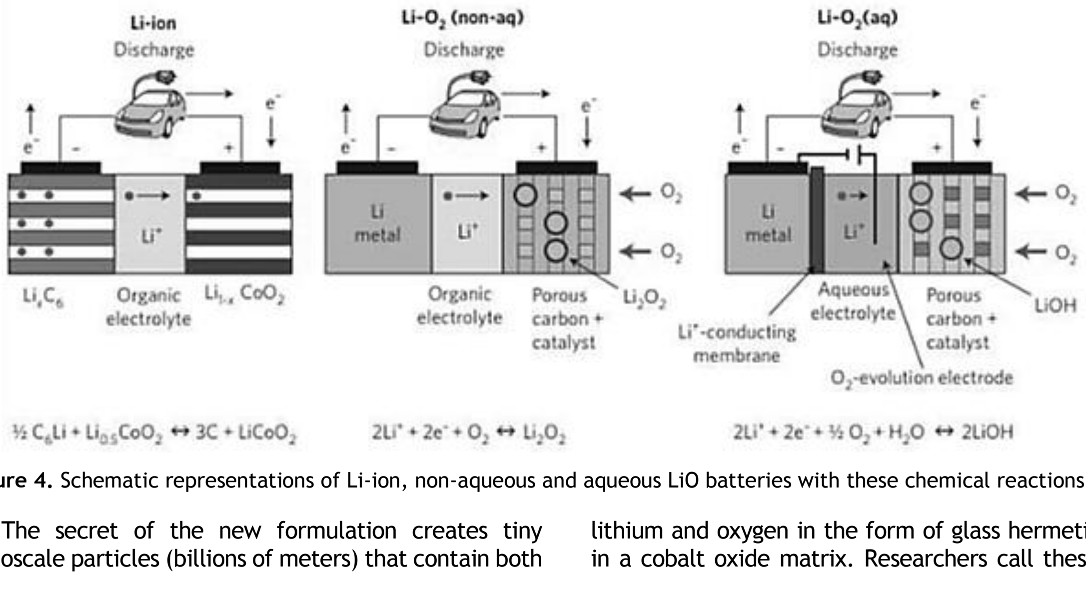

Figure 4. Schematic representations of Li-ion, non-aqueous and aqueous LiO batteries with these chemical reactions [17]

The secret of the new formulation creates tiny nanoscale particles (billions of meters) that contain both lithium and oxygen in the form of glass hermetically sealed in a cobalt oxide matrix. Researchers call these nanolithia particles. Under this form, the transition between LiO_2, Li_2O_2, and Li_2O can take place entirely within the solid material. In addition, because such batteries can be installed and run just like conventional lithium-ion solid batteries without having any of the auxiliary components needed for a lithium-air battery, they could be easily adapted to existing installations or models packaging of conventional automobile batteries, electronic devices, or even energy storage in the grid-scale power storage system.

Figure 5 schematically shows how to increase Li_2O_2 on the carbon surface.

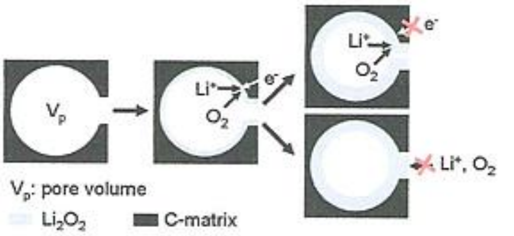

Figure 5. Schematic illustration of the pore filling during unloading

Li_2O_2 layers — increasing — lead to passivation of the cathode by electrical isolation (right, up) and pore blocking (right, down).[1] In a restricted access electrode, pores could either passivate or block pores. Both phenomena result in a volume of unused pores and therefore limit the discharge capacity.

Although lately, lithium-air batteries were making less and less interest, a fundamental breakthrough could convince industries to reconsider this type of battery.

Shape change can occur due to uneven current densities. Assuming that lithium dendrites and other forms of development of microscopic morphology can be suppressed, macroscopic changes in anode shape may occur due to uneven distribution of current density across the cell. When there is a high resistance to the current flowing from the tab (Figure 6) to the outer edges of the current collector (for example, if the collector thickness is too small relative to its surface), the current density may be very uneven, with a higher current density near the tabs.

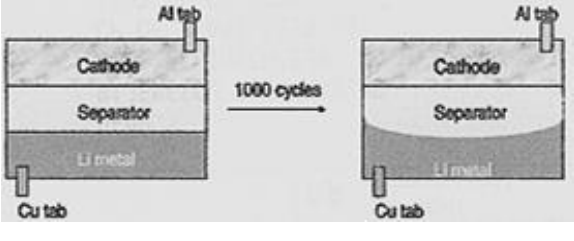

Figure 6 represents the macroscopic redistribution of Li-metal in a Li-air cycled cell at the end of the load (after [1])

Therefore, storage and dissolution are preferably performed near tabs, as shown in Figure 6. Applying a pressure can alleviate this problem.

Zhang et al. [14] demonstrated that a selective O_2 membrane operates in ambient air with a relative humidity of 20-30 % (Figure 7).

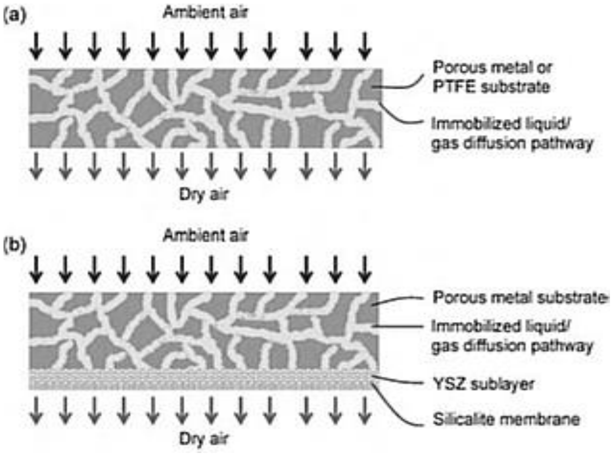

Figure 7. Scheme of two types of O_2 membrane structures: *(a)* liquid immobilized in a homogeneous porous substrate, and *(b)* immobilized liquid in a silicate membrane covered with a porous (asymmetric) metal substrate [12]

The thickness of the polymer membrane was 25 nm, representing ~1 % of the cell volume (see Figure 8).

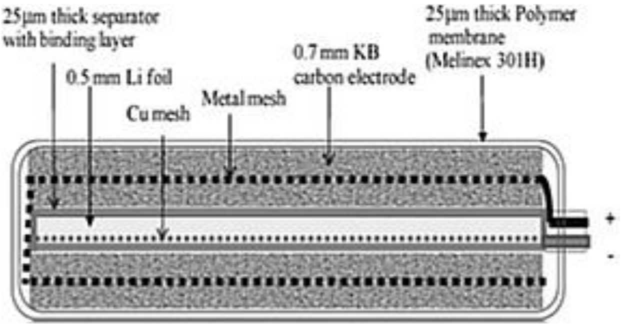

Figure 8. Scheme of a sealed test cell used by Zhang et al. for the ambient operation of the lithium-air battery [13]

Current densities between 0.05 and 0.1 mA /cm^2 have been demonstrated, but at higher current densities, oxygen penetration through the membrane has been insufficient.

Up to now, no membrane has been completely effective in preventing the introduction of contaminants into the cell when ambient air is used as an oxygen source. Selective O_2 membranes are preferred for non-aqueous cells, while good OH-selective anion exchange membranes are an attractive option for aqueous cells. In addition to achieving good selectivity and preventing solvent evaporation, the candidate membranes should allow for high rates of O_2 or OH^- transport.

3. Intervention of nanotechnology

Nanowires (or nanospheres) are a thousand times thinner than a human hair and present new possibilities for future batteries. Other types of batteries can be destroyed after a number of recharges. The new batteries will be recharged repeatedly, but they will not "die" anymore. This discovery uses gold nanowires in an electrolyte-gel to prevent the batteries from being recharged. In fact, batteries were tested at recharging over 200,000 times in three months, without any degradation. This could be ideal for future electric cars, spacecraft and telephones, as they will no longer need new batteries.

Scientists from the US and South Korea have discovered new catalytic materials that will allow the creation of lithium-air batteries that can store up to five times more energy than today's lithium-ion batteries. Lithium-air batteries work by taking oxygen from the air and using it in chemical reactions that produce electrical energy rather than internal storage and oxidation, as with Li-ion batteries.

To remove aluminium oxide and replace it with a new outer titanium oxide layer, Dr. Wang Changan (Tsinghua University) and Dr. Li Ju (MIT) allowed the battery to absorb aluminium nanoparticles in a mixture of sulphuric acid and titanium oxysulphate. By chance, they have forgotten the nanoparticles in a particular lot, which allowed them to "soften" so much that they were soaked in the blend of aluminium nanoparticles. Initially, aluminium nanoparticles had a diameter of 50 nm, but after "soaking", the nanoparticle had an internal "yolk" of only 30 nm of aluminium, while the titanium hydroxide coating was 4 nm. All this is done without adding expensive components or materials. Carbonate used as liquid electrolyte in this battery is the cheapest type of electrolyte. Moreover, the cobalt oxide component is less 50 % less than the nanolithium component. Generally, the new battery system is scalable, inexpensive, and much safer than lithium-air batteries. And the cobalt oxide component is less 50% less than the nanolithium component. Generally, the new battery system is scalable, inexpensive, and much safer than lithium-air batteries.

The team of researchers is expected to pass from this lab scale (proof of concept to a practical prototype) within about a year.

This is a fundamental breakthrough that could change the oxygen-based battery paradigm. In this system, the carbonate based electrolyte works very well with dissolved super oxide crates, which is quite impressive and may have to do with the absence of any O_2 gas in this watertight system. All active cathode masses throughout the cycle are solid, which not only has high energy density but also compatibility with the current battery manufacturing infrastructure.

4. Giga-factory Tesla

Batteries are known to be hard to improve. Nowhere was this more obvious than the opening on 29 July 2016 of the Tesla Giga-factory, a massive battery installation in Nevada. Elon Musk, the founder of Tesla, built the plant, as increasing battery efficiency is more difficult than optimizing the manufacturing process.

It is an ironic coincidence to publish, in the journal Nature Energy, a document that shows how a prototype of a new battery can store twice as much "juice" as the lithium-ion cells produced by Giga-factory. The new battery, set up by Li Ju at MIT, is also a way of marketing, but the design is such that marketing should not be too difficult.

The fundamental idea behind Dr. Li's device is not new. It is a version of what is known as a lithium-air battery with a research goal on energy storage since the 1970s. Theoretically, such batteries could hold more than four times the energy on kilogram of lithium-ion batteries.

Their construction, however, proved difficult. As their name suggests, they draw air. The part they need is oxygen, but also other atmospheric components — water vapours and carbon dioxide in particular - that often lead to battery damage.

Even versions that work with pure oxygen have been affected by problems. The use and recharge of existing lithium-air batteries waste a great deal of energy because the process involves changing the oxygen from a gaseous state to a substantially solid, and then back to the gaseous state again. Such phase shifts require a large amount of energy and thus lead to more than 30% of the input electrical energy. In addition, the volume changes accompanying the passage from gas to solid and back to the gas exert pressure on the battery electrodes. This means that the battery quickly degenerates to the point where the battery can no longer be recharged.

The reason the battery operates (Figure 9): The distance between the iodine-based nanoparticles of low graphene oxide (rGO) favours the cathode to produce lithium superoxide (LiO_2) and inhibits the generation of peroxide (Li_2O_2).

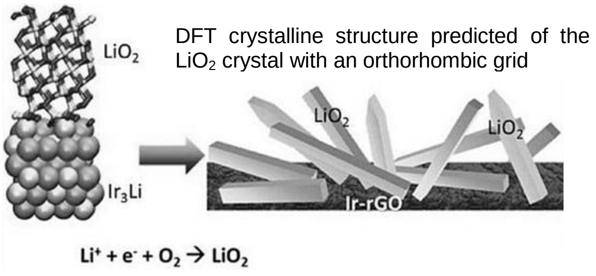

Figure 9. The lattice cage between LiO_2 and Ir_3Li may be responsible for the LiO_2 discharge product found for the Ir-rGO cathode material (Credit: Argonne /Larry Curtiss)

The essential difference between the design proposed by Dr. Li and previous attempts is that the air is not actually involved. Instead, the cell is hermetically sealed and uses the oxygen stored inside the battery itself in a chemical called lithium super-oxide (LiO_2). This compound is unstable, and is easy to make it part of the oxygen, which leads to high efficiency and a good life cycle.

To stop the super-oxide from spontaneously disintegrating, Dr. Li incorporated into the voids of a cobalt oxide matrix (yellow, as imagined by the artist in figure 10), in which the white spheres are lithium ions. The oxygen ions are in red and blue stripes - the "lightning" of electricity.

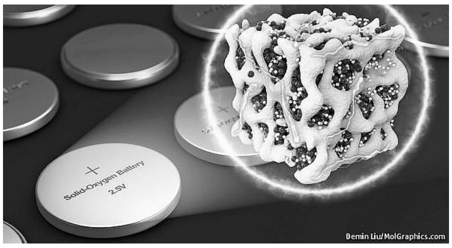

Figure 10. Battery ion cage

In a new concept of battery cathodes, nanometric nanoparticle particles made of lithium and oxygen compounds (represented by red and white) are incorporated into a sponge-like (yellow) cobalt oxide network that keeps them stable. [24] This gives stability to super-oxide structure.

When the new battery discharges the power, the lithium ions of a liquid electrolyte that fills the matrix introduce the solid and react with the oxygen in the super-oxide to form either lithium (Li_2O_2) or lithium (Li_2O) both being also solid. Those chemical reactions lead the electrons to an external circuit, where they can be used by a mobile phone or the electric motor of a vehicle.

They push the electrons back into the circuit, though, by connecting the battery to a power supply. The chemical reactions will go in the opposite direction, charging it again. The fact that oxygen remains in a solid state along these processes is essential for the success of the new battery. Instead of 30 %, energy losses are only 8 %. Similarly, life expectancy is prolonged. In the studies, the battery was discharged and recharged 130 times and lost less than 2 % of its capacity.

Previous practical lithium-air batteries have been received with scepticism, but in this case, other researchers in the field, not involved in the study, seem convinced that the solution proposed by Dr. Li might indeed be something. Dr. Li hopes that in a year he can turn the prototype into something that could be produced in series (figure 11).

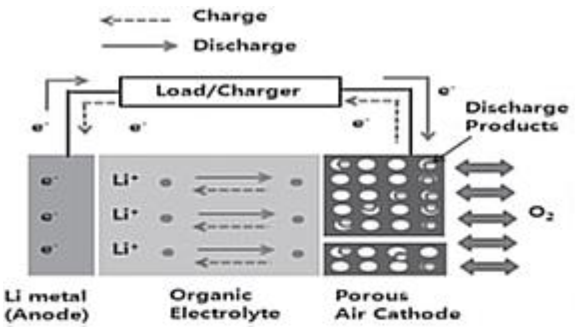

Figure 11. Operating principle of Li-air cell with organic electrolyte [22]

This is an ambitious goal, but from an engineering perspective, the challenges are similar to conventional lithium-ion batteries, so rapid development is possible. And it is also an attractive objective. For Tesla and its rivals, these batteries could feed a virtuous cycle of lighter machines with longer charging intervals. Dr. Li sees this potential as well; and his team filed a patent and began to talk to potential future manufacturers.

The question is now: who will get the license for the first industrial technology?

All previous works on lithium-air batteries have shown the same phenomenon: the formation of lithium peroxide (Li_2O_2), a solid precipitate that clogs the pores of the electrode.

In a recent experiment, however, Argonne, Jun Lu, Larry Curtiss and Khalil Amine scientists, together with US and South Korean collaborators [15], were able to produce stable crystalline lithium super-oxide (LiO_2), instead of lithium peroxide, while discharging the battery. Unlike lithium peroxide, lithium super-oxide can easily dissociate into lithium and oxygen, which leads to high efficiency and a good life cycle.

5. Summary and perspectives

Lithium-air is a fascinating energy storage system. Efficient operation of the air as a battery electrode has long been a dream. Air is, in principle, a cost-free material characterized by a very high specific capacity. In the particular case of the lithium-air system, energy levels close to petrol were postulated. It is not surprising that during the last decade great attention has been paid to this battery of various academic and industrial laboratories at the world's top level. In spite of this intense investigation, a series of problems have emerged that hinder the rapid development of the electrochemical lithium-air system. Although more progress has been made recently, the question of whether this battery will have an effective economic and social impact remains open. There is a review, a critical assessment of the progress made so far, along with an attempt to propose future R & D trends. A prognosis if lithium-air can play a role in battery technology over the next few years is also postulated.

Recent investigations of both the aqueous and non-aqueous lithium-air systems have resulted in a better understanding of the main challenges for this technology. Despite several research groups that have demonstrated limited cycling of non-aqueous cells using carbonate solvents, it is now clear that these solvents participate in lithium and oxygen-consuming reactions in the limited cycling of non-aqueous cells using carbonate solvents; it is now clear that these solvents participate in reactions that consume lithium and oxygen during discharge and are not reversibly generated during loading. Therefore, the lifespan of carbon-based lithium-carbon cells is limited by the amount of solvent available for the reaction and the accumulation of side-reaction products. Appropriate research on non-carbonated solvents is ongoing, but adequate reversibility remains so far elusive.

Electrode and sandwich massive volume changes may require special cell design features, including electrolyte or solvent reservoirs, flexible gaskets, pressure application, and the use of components with outstanding mechanical properties. Recirculation of the cathode stream into aqueous cells can attenuate the change in volume in the positive electrode. Some components, such as flexible seals for metal lithium-protected cells, have already been developed for primary cells, but reversible cycling has to be demonstrated.

Since these "solid oxygen" cathodes are much lighter than the conventional cathodes of lithium-ion batteries, the new design could store twice the amount of energy for a given cathode weight, and refining the design, the new batteries could — in the end — double that capacity again.

The lithium-air battery uses oxygen as an oxidant, rather than another type of material. The result is one fifth of the price and one fifth of the weight of the lithium-ion battery, and could make phones and cars have a five-time life expectancy. Of course, as with any other research, it may take five to ten years to become an industrial reality.

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Biography

Titu I. BĂJENESCU was born in Câmpina (Romania) on April 2, 1933.
He received his engineering training at the Polytechnic Institute Bucharest.
He served for the first five years in the *Romanian Army Research Institute*, including R&D tours on radio and telecom maintenance, and in the reliability, safety and maintainability office of the Ministry of Defence (main base ground facilities).
Experience: design and manufacture of experimental equipment for Romanian Army Research Institute and for air defence system.
He joined *Brown Boveri* (today: *Asea Brown Boveri*) Baden (Switzerland) in 1969, as research and development R&D engineer.
Experience: design and manufacture of new industrial equipment for telecommunications.
In 1974, he joined *Hasler Ltd.* (today: *Ascom*) Berne as Reliability Manager (recruitment by competitive examination).
Experience: Set up QRA and R&M teams. Developed policies, procedures and training. Managed QRA and R&M programmes. As QRA Manager monitoring and reporting on production quality and in-service reliability.
As Switzerland official, contributed to development of new ITU and IEC standards.
In 1981, he joined *Messtechnik und Optoelektronik* (Neuchâtel, Switzerland, and Haar, West Germany), a subsidiary of Messerschmitt-Bölkow-Blohm (MBB) Munich, as Quality and Reliability Manager (recruitment by competitive examination).
Experience: Product Assurance Manager of “intelligent cables”. Managed applied research on reliability (electronic components, system analysis methods, test methods, etc.).
Since 1985, he has worked as an independent consultant and international expert on engineering management, telecommunications, reliability, quality and safety.
Mr. Băjenescu is the author of many technical books, published in English, French, German and Romanian.
He is a university professor and has written many papers and articles on modern telecommunications, and on quality and reliability engineering and management. He lectures as invited professor, visiting lecturer or speaker at European universities and other venues on these subjects.
Since 1991, he won many Awards and Distinctions, presented by the Romanian Academy, Romanian Society for Quality, Romanian Engineers Association, etc. for his contribution to reliability science and technology.
Recently, he received the honorific titles of *Doctor Honoris Causa* from the *Romanian Military Academy* and from *Technical University of the Republic of Moldavia*.
In 2013, he obtained, together with prof. Marius Bâzu (head of reliability laboratory of Romanian Research Institute for Micro and Nano-technologies – IMT) the *Romanian Academy "Tudor Tănăsescu" prize* for the book *Failure Analysis*, published by John Wiley & Sons.