Lithium Ion Batteries: Answer to Communications-Energy Crunch

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Abstract – **Cellular base station towers consume significant amount of diesel, leading to pollution besides necessitating costly imports. Aspirations of youngsters to own cars is putting unbearable strain on foreign exchange reserves to pay for crude.**

India is looking at having an all-electric car fleet by 2030 with an express objective of lowering the fuel import bill and running cost of vehicles. For this, India is required to set up large lithium-ion batteries (LiBs) manufacturing plants.

Manufacturers are constantly improving lithium-ion batteries.

Indian market for Lithium batteries is poised to grow at CAGR of 32% till 2021 on account of expansion of telecommunication network and increasing penetration of consumer electronic products such as smartphones, Tablet PCs, laptops etc and growing demand for electric and hybrid vehicles. Large scale deployment of solar power projects is expected to boost the demand for lithium-ion batteries, as they are considered the most suitable option for storage.

Keywords: Energy crunch, Lithium ion batteries, Lithium ion polymer battery, Telecom towers

I. INTRODUCTION

ENERGY costs account for a third of network operating expenses. Cellular base station towers consume substantial diesel, leading to pollution besides necessitating imports. Batteries are used when grid power fails. Operators are installing lithium-ion batteries (LiB), due to advantages like low maintenance, high energy-density, high charge/discharge efficiency, negligible self-discharge, tiny memory effect and environment-friendly.

Nickel Cadmium batteries were used earlier in cell phones. Cadmium is toxic heavy metal causing soil-pollution. Today, lithium-ion is one of the most successful and safe battery chemistries. Worldwide >2 billion LiB cells are produced annually. These rechargeable batteries are used for portable electronics, *e.g.* Mobile phones, Laptops, iPods, PDAs and digital cameras. Cobalt-oxide based LiBs are used in cell phones whereas Manganese type, called NMCs are used in electric cars. LiBs are finding usage in aircrafts, defence and aerospace. NASA Space station crew replaced aging nickel-hydrogen battery packs with new Lithium ion units.

China has 60% share of global LiB production. Here, Maruti is collaborating with Denso and Toshiba to manufacture LiBs. Reliance is investing $3.5 billion to create 25 GWh LiBs capacity. JSW, Adani and Mahindra are also in the fray.

For many years, nickel-cadmium had been the only suitable battery for portable equipment from wireless communications to mobile computing. Nickel-metal-hydride and lithium-ion emerged in the early 1990s. Today, lithium-ion is the fastest growing and most promising battery chemistry.

The government is contemplating incentivising manufacturers to set up facilities for making lithium-ion batteries in India to lower the cost of electric vehicles, a move likely to discourage Chinese car makers seeking to enter the market. Efforts are being made to remodel the battery made by Indian Space Research Organisation so that it can be used in electric vehicles. Manufacturing facility is proposed by Bharat Heavy Electricals Limited entailing an investment of Rs 100 crore. Maruti also wants to invest Rs 2 lakh crore for manufacturing lithium batteries.

Attempts to develop rechargeable lithium batteries failed due to safety problems. Pioneer work with the lithium battery began in 1912 under G.N. Lewis [1] but it was not until the early 1970s when the first non-rechargeable lithium batteries became commercially available. Lithium is the lightest of all metals, has the greatest electrochemical potential and provides the largest energy density for weight.

Because of the inherent instability of lithium metal, especially during charging, research shifted to a non-metallic lithium battery using lithium ions. Although slightly lower in energy density than lithium metal, lithium-ion is safe, provided certain precautions are met when charging and discharging. In 1991, the Sony Corporation commercialized the first lithium-ion battery.

Figure 1. The 100MW Lithium-battery farm set up on 10,000 square meters of land has enough storage capacity to power more than 30,000 homes in South Australia.

Figure 2. Lithium-ion batteries are considered the most suitable option for use in Telecom towers.

World's largest lithium-ion battery farm was made operational last year in South Australia. India is looking to give a major push to use of electric vehicles, and the main challenge would be in reducing the cost of lithium-ion battery used in such vehicles. There is a need to set up large lithium-ion batteries manufacturing plants in India.

Currently, lithium-ion batteries are not manufactured in India and therefore the country has to depend on imports from Japan or China. Country would also need to set up infrastructure for charging EVs. To develop low-cost lithium-ion batteries in India, efforts are being made to remodel the battery made by Indian Space Research Organisation (ISRO) so that it can be used in e-vehicles. State-run Energy Efficiency Services Ltd (EESL) recently said that it would procure 10,000 electric cars. By 2025, the cost of traditional combustion engine cars and electric vehicles would be almost the same.

Chile, China, Australia and Argentina are home to the world's highest lithium reserves (Table 1). Afghanistan too has rich Lithium deposits. Since India has none, the country plans to acquire Lithium mines abroad.

TABLE 1 – TOP LITHIUM RESERVES

SN	Country	Reserves in MT
1	Chile	7,500,000
2	China	3,200,000
3	Australia	2,700,000
4	Argentina	2,000,000
5	Portugal	60,000
6	Brazil	48,000
7	USA	35,000
8	Zimbabwe	23,000

Figure 3. Mahindra's electric car "e2o Plus" plugged in for charging at a showroom in New Delhi.

Electronic devices, such as a laptop or cell phone are also powered by a lithium-ion battery. These rechargeable batteries are extremely popular and versatile and can be found in many different types of electronic devices from computers to cars and of course, power tools. Even NASA makes use of the lithium ion battery in space!

The raw material is available from about 7 countries which include Australia and Brazil; the equipment is available from Germany, Korea and others.

II. BRIEF HISTORICAL DEVELOPMENTS

- *1991* Sony released the first commercial lithium-ion battery.
- *2001* Patent filed for the lithium Nickel Manganese Cobalt oxide (NMC) class of positive electrode materials, which offer safety and energy density improvements over the widely used lithium cobalt oxide.

- *2002* Chiang and his group at MIT showed a substantial improvement in the performance of lithium batteries by boosting the material's conductivity by doping it with Al, Nb and Zr.
- *2011* Lithium-ion batteries accounted for 66% of all portable battery sales in Japan.

As of 2016, global lithium-ion battery production capacity was 28 gigawatt-hours, with 16.4 GWh in China.

III. WORKING FUNDAMENTALS

Different classes of Li-ion batteries use varying cathodes made of other lithium molecules. The anodes are generally made of carbon. Like any other batteries, chemical reactions between the anode, cathode, and electrolyte produce electric current. The materials used for the anodes and cathodes determine the performance, capacity, cost and safety of a particular class of Li-ion battery.

Lithium ions move from the negative electrode to the positive electrode during discharge and back when charging (Fig. 4). Li-ion batteries use an intercalated lithium compound as one electrode material, compared to the metallic lithium used in a non-rechargeable lithium battery. The electrolyte, which allows for ionic movement, and the two electrodes are the constituent components of a lithium-ion battery cell [2].

Positively charged lithium ions are attracted to and move towards the cathode. Once it is bombarded with these ions, the cathode becomes more positively charged than the anode, and this attracts negatively charged electrons.

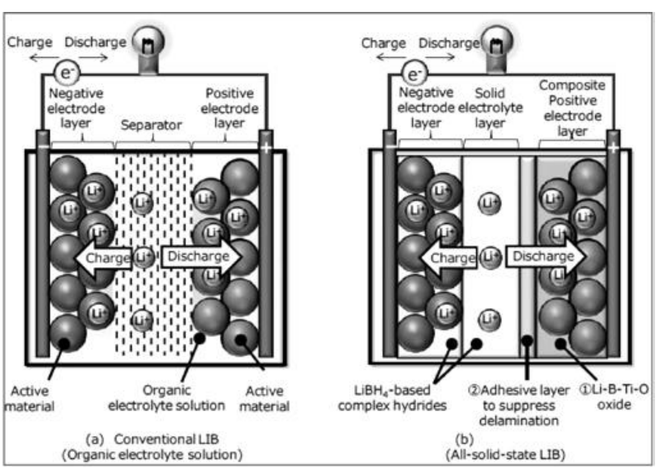

Figure 4. Lithium-ion battery powering a lamp.

As the electrons start moving toward the cathode, they go through external component and use the energy of the electrons "flowing" toward the cathode to generate power.

Electrolyte plays a key role in transporting the positive lithium ions between the cathode and anode. High purity electrolytes are a core component of Li-ion batteries. The most commonly used electrolyte is comprised of lithium salt, such as $LiPF_6$ in an organic solution.

The conventional Li-ion battery consists of a separator, a positive electrode layer, and a negative electrode layer (Fig.4a). The battery is filled with organic electrolyte solution in which lithium ion conducts between the two electrode layers during the charge and discharge process. An issue of the conventional Li-ion battery with the organic electrolyte solution is thermal durability. The upper operating temperature was limited to around 60℃ owing to volatility of the organic electrolyte solution. Consequently, it is difficult to use the conventional Li-ion battery in a high temperature environment without a cooling system. Therefore, the solid electrolyte with no volatility has been developed for the utilization of Li-ion battery in a high temperature environment. The lithium ion conductivity of solid electrolyte, however, is lower than that of the organic electrolyte solution, and the internal resistance of all-solid-state Li-ion battery should be reduced for its commercialization [3].

Prof. Shin-ich Orimo's lab in Advanced Institute for Material Research (AIMR) have been conducting research on LiBH4-based complex hydrides as novel solid electrolytes. They have confirmed the fast lithium ion conductivity in the wide temperature range from room temperature to 150℃. This research, part of a collaborative project between Hitachi and AIMR developed the new technology to reduce the internal resistance that is a factor of deterioration of charge-discharge performance. This new technology was validated to yield the battery operation at a temperature as high as 150℃ with a discharge capacity of 90% of theoretical value. This technology is significant as it allows the thermally durable Li-ion battery to be used in a wider variety of applications, such as large-scale industrial machines with motors, and medical machines which need to be heated for autoclave sterilization. Since this technology does not require the cooling system, it is expected to lead to further developments of compact battery systems and reduce the overall costs [4].

IV. LITHIUM-ION BATTERY PROPERTIES

The energy density of lithium-ion is typically twice that of the standard nickel-cadmium. There is potential for higher energy densities. The load characteristics are reasonably good and behave similarly to nickel-cadmium in terms of discharge. The high cell voltage of 3.6 volts allows battery pack designs with only one cell. Most of today's mobile phones run on a single cell. A nickel-based pack would require three 1.2-volt cells connected in series [5].

Lithium-ion is a low maintenance battery, an advantage that most other chemistries cannot claim. There is no memory and no scheduled cycling is required to prolong the battery's life. In addition, the self-discharge is less than half compared to nickel-cadmium, making lithium-ion well suited for modern fuel gauge applications. Lithium-ion cells cause little harm when disposed.

Energy Density: 250–693 W·h/L (Amount of energy stored in a region of space per unit volume). Charge/ discharge efficiency: 80–90%. Manufacturers are constantly improving lithium-ion. New and enhanced chemical combinations are introduced every six months or so.

• Low self-discharge.
(Self-discharge is a phenomenon in batteries in which internal chemical reactions reduce the stored charge of the battery without any connection between the electrodes) A Lead acid battery has 5% self-discharge per month; NiCd: 15% .

Specific power: 250 - 340 W/kg. A lead-acid battery can store only 25 watt-hours per kilogram.

Despite its overall advantages, lithium-ion has its drawbacks. It is fragile and requires a protection circuit to maintain safe operation. Built into each pack, the protection circuit limits the peak voltage of each cell during charge and prevents the cell voltage from dropping too low on discharge. In addition, the cell temperature is monitored to prevent temperature extremes. The maximum charge and discharge current on most packs are limited to between 1C and 2C. With these precautions in place, the possibility of metallic lithium plating occurring due to overcharge is virtually eliminated.

Aging is a concern with most lithium-ion batteries and many manufacturers remain silent about this issue. Some capacity deterioration is noticeable after one year, whether the battery is in use or not. The battery frequently fails after two or three years. It should be noted that other chemistries also have age-related degenerative effects. This is especially true for nickel-metal-hydride if exposed to high ambient temperatures. At the same time, lithium-ion packs are known to have served for five years in some applications.

With such rapid progress, it is difficult to assess how well the revised battery will age. Storage in a cool place slows the aging process of lithium-ion (and other chemistries). Manufacturers recommend storage temperatures of 15°C (59°F). In addition, the battery should be partially charged during storage. The manufacturer recommends a 40% charge.

The most economical lithium-ion battery in terms of cost-to-energy ratio is the cylindrical 18650 (size 18mm x 65.2mm). This cell is used for mobile computing and other applications that do not demand ultra-thin geometry. If a slim pack is required, the prismatic lithium-ion cell is the best choice. These cells come at a higher cost in terms of stored energy.

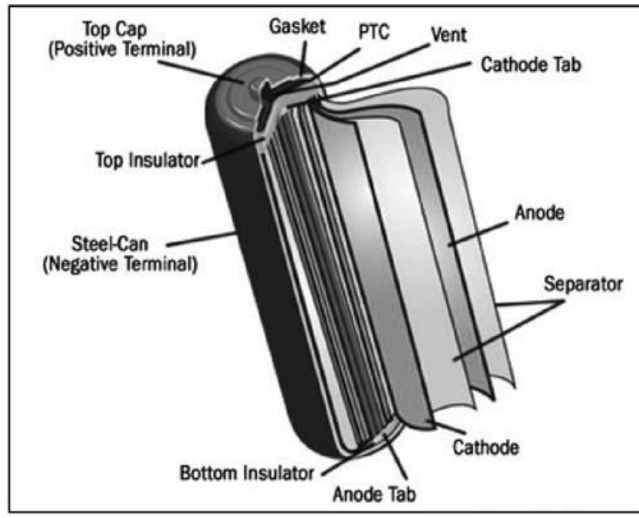

Figure 5. Inside structure of clindrical Lithium-ion battery.

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Advantages

- *High open-circuit voltage:* Li-ion battery has a chemistry that results in higher open-circuit voltage than other aqueous batteries such as lead acid, nickel-metal hydride, and nickel-cadmium.
- *Smaller and lighter:* Li-ion battery is lighter than other rechargeable batteries in consideration of battery capacity. This makes it more practical in portable consumer electronic devices in which physical specifications such as weight and form factor are important.
- *High energy density:* Li-ion battery has higher energy density than other rechargeable batteries. This means having high power capacity without being too bulky. This is suitable for use in power-hungry devices such as laptops and smartphones. Advancements in technology open potential for higher capacities.
- *Low self-discharge:* Li-ion battery also has a low self-discharge rate of about 1.5 percent per month. This means that the battery has a longer shelf life when not in used because it discharges slowly than other rechargeable batteries. (nickel-metal hydride battery has a self-discharge of 20 percent per month).
- *Zero to low memory effect:* Li-ion battery has zero to minimal memory effect. (Memory effect is a phenomenon observed in rechargeable batteries in which they lose their maximum energy capacity when repeated recharged after being only partially discharged). This memory effect is common in nickel-metal hydride rechargeable batteries such as NiCd and NiMH.
- *Quick charging:* Li-ion battery is quicker to charge than other rechargeable batteries. It actually takes a fraction of a time to charge when compared to counterparts.

- *Longer lifespan:* Li-ion battery can typically handle hundreds of charge-discharge cycles. Some lithium ion batteries lose 30 percent of their capacity after 1000 cycles while more advanced lithium ion batteries still have better capacity only after 5000 cycles [6].

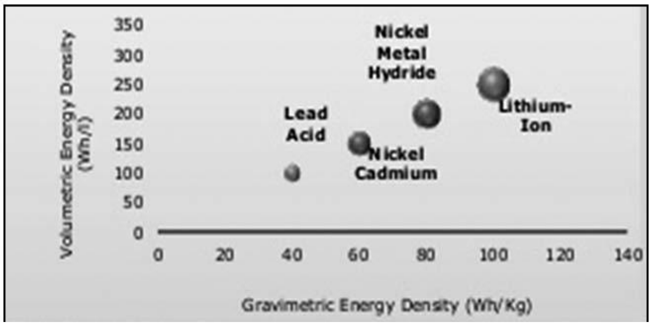

Figure 6. Comparison of various forms of batteries by energy density.

Limitations

- *Expensive:* Li-ion battery is expensive to manufacture. In fact, the total product cost of this battery is around 40 percent higher than nickel-metal hydride battery. (This battery needs an on-board computer circuitry to manage and ensure that voltage and current are well within the safe limits. This circuitry makes it more expensive).
- *Sensitivity to high temperature:* Li-ion battery is susceptible to the downside of too much heat caused by overheating of the device or overcharging. Heat causes the cells or packs of this battery to degrade faster than they normally would.
- *Aging effect:* Li-ion battery will naturally degrade as soon as they leave the factory. This means that it is not completely durable despite longer charge-discharge lifecycle because of this normal degradation that transpires whether consumers use them or not. Storage in a cool place at 40 percent charge reduces the aging effect.
- *Deep discharge:* Li-ion battery has low self-discharge. The general integrity of this battery remains intact even if partially discharged. However, deep discharge or when the voltage of a lithium ion cell drops below a certain level, it becomes unusable.
- *Environment impact:* According to a report by Friends of the Earth, lithium extraction inevitably harms the soil and causes air contamination. Researchers are working on new battery chemistries that replace cobalt and lithium with more common and less toxic materials. University of Birmingham research is trying to find new ways of recycling lithium-ion.
- *Safety concerns*: Li-ion battery may explode when overheated or overcharged. This is because gases formed by electrolyte decomposition increases the internal pressure of the cell. Overheating or internal short circuit can also ignite the electrolyte and cause fire. This risk might also subject Li-ion batteries to transportation restrictions, especially when shipped in larger quantities.

In September 2016, Samsung recalled approximately 2.5 million Galaxy Note 7 phones after 35 confirmed fires. The recall was due to a manufacturing design fault in Samsung's batteries which caused internal positive and negative poles to touch [7].

LiBs for Smart phones: A Li-ion pouch cell is a sealed bag containing carefully layered anode and cathode sheets, separators between them, and -- permeating all of these layers -- a liquid electrolyte. Though tablet batteries comprise several cells (three in the new iPad), smartphones are generally powered by single cells. Either way, at one end of the battery, a printed circuit board (PCB) is connected to the positive and negative terminals of each cell and provides active protection against short circuits, overcharge, and forced discharge. Li-ion pouch cells tend to be fragile and rely on the smartphone case for protection, and so officially are not user-replaceable.

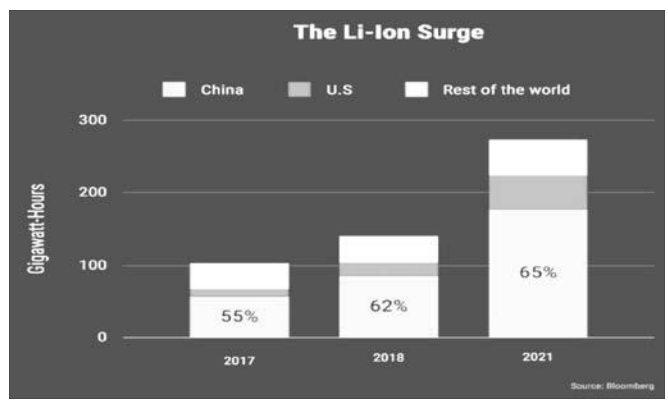

Figure 7. China dominates Li-ion surge (For each vertical bar, lowest rectangle shows China's share, middle one depicts the US share and topmost rectangle is from Rest of the world).

VI. THE LITHIUM POLYMER BATTERY

The lithium-polymer differentiates itself from conventional battery systems in the type of electrolyte used. The original design, dating back to the 1970s, uses a dry solid polymer electrolyte. This electrolyte resembles a plastic-like film that does not conduct electricity but allows ions exchange (electrically charged atoms or groups of atoms). The polymer electrolyte replaces the traditional porous separator, which is soaked with electrolyte.

The dry polymer design offers simplifications with respect to fabrication, ruggedness, safety and thin-profile geometry. With a cell thickness measuring as little as one millimeter, equipment designers are left to their own imagination in terms of form, shape and size. Unfortunately, the dry lithium-polymer suffers from poor conductivity. The internal resistance is too high and cannot deliver the current bursts needed to power modern communication devices and spin up the hard drives of mobile computing equipment. Heating the cell to 60°C and higher increases the conductivity, a requirement that is unsuitable for portable applications.

To compromise, some gelled electrolyte has been added. The commercial cells use a separator/ electrolyte membrane prepared from the same traditional porous polyethylene or polypropylene separator filled with a polymer, which gels upon filling with the liquid electrolyte. Thus the commercial lithium-ion polymer cells are very similar in chemistry and materials to their liquid electrolyte counter parts.

Lithium-ion-polymer has not caught on as quickly as some analysts had expected. Its superiority to other systems and low manufacturing costs has not been realized. No improvements in capacity gains are achieved - in fact, the capacity is slightly less than that of the standard lithium-ion battery. Lithium-ion-polymer finds its market niche in wafer-thin geometries, such as batteries for credit cards and other such applications.

Advantages

- Very low profile - batteries resembling the profile of a credit card are feasible.
- Flexible form factor - manufacturers are not bound by standard cell formats. With high volume, any reasonable size can be produced economically.
- Lightweight - gelled electrolytes enable simplified packaging by eliminating the metal shell.
- Improved safety - more resistant to overcharge; less chance for electrolyte leakage.

Limitations

- Lower energy density and decreased cycle count compared to lithium-ion.
- Expensive to manufacture.
- No standard sizes. Most cells are produced for high volume consumer markets.
- Higher cost-to-energy ratio than lithium-ion.

VII. RESTRICTIONS ON LITHIUM CONTENT FOR AIR TRAVEL

Air travelers ask the question, "How much lithium in a battery am I allowed to bring on board?" One can differentiate between two battery types: Lithium metal and lithium-ion.

Most lithium metal batteries are non-rechargeable and are used in film cameras. Lithium-ion packs are rechargeable and power laptops, cellular phones and camcorders. Both battery types, including spare packs, are allowed as carry-on but cannot exceed the following lithium content:

- 2 grams for lithium metal or lithium alloy batteries
- 8 grams for lithium-ion batteries.

Lithium-ion batteries exceeding 8 grams but no more than 25 grams may be carried in carry-on baggage if individually protected to prevent short circuits and are limited to two spare batteries per person [8].

From a theoretical perspective, there is no metallic lithium in a typical lithium-ion battery. There is, however, equivalent lithium content that must be considered. For a lithium-ion cell, this is calculated at 0.3 times the rated capacity (in ampere-hours).

Example: A 2Ah 18650 Li-ion cell has 0.6 grams of lithium content. On a typical 60 Wh laptop battery with 8 cells (4 in series and 2 in parallel), this adds up to 4.8g. To stay under the 8-gram UN limit, the largest battery you can bring is 96 Wh. This pack could include 2.2Ah cells in a 12 cells arrangement (4s3p). If the 2.4Ah cell were used instead, the pack would need to be limited to 9 cells (3s3p).

VIII. RESTRICTIONS ON SHIPMENT OF LITHIUM-ION BATTERIES

Anyone shipping lithium-ion batteries in bulk is responsible to meet transportation regulations. This applies to domestic and international shipments by land, sea and air.

Lithium-ion cells whose equivalent lithium content exceeds 1.5 grams or 8 grams per battery pack must be shipped as "Class 9 miscellaneous hazardous material." Cell capacity and the number of cells in a pack determine the lithium content.

Exception is given to packs that contain less than 8 grams of lithium content. If, however, a shipment contains more than 24 lithium cells or 12 lithium-ion battery packs, special markings and shipping documents will be required. Each package must be marked that it contains lithium batteries.

All lithium-ion batteries must be tested in accordance with specifications detailed in UN 3090 regardless of lithium content (UN manual of Tests and Criteria, Part III, subsection 38.3). This precaution safeguards against the shipment of flawed batteries.

Cells and batteries must be separated to prevent short-circuiting and packaged in strong boxes.

IX. CONCLUSION

Lithium-ion batteries score over alternatives like Nickel-cadmium and Lead-acid configurations. They are poised to reduce consumption of diesel in Telecom towers operations besides substituting fossil-fuel vehicles with electric vehicles. Their superior properties, like high energy density made them suitable for use in smartphones and other consumer electronic items. Intense research is going on to minimise environment impact of Lithium mining as well as disposal.

REFERENCES

[1] A. Mauger and C.M. Julien, "Critical review on lithium-ion batteries: are they safe? Sustainable?", *Ionics,*.vol. 23, no. 8, pp. 1933–1947, June 2017.

[2] Ali Eftekhari,"Lithium-ion batteries with high rate capabilities", *ACS Sustainable Chemistry & Engineering,* vol 5, no. 3, pp. 2799–2816, 2017.

[3] Gholamabbas Nazri and Gianfranco Pistoia, *Lithium batteries: science and technology,* Springer, ISBN 1402076282, 2004.

[4] Davide Andrea, *Battery Management Systems for Large Lithium-Ion Battery Packs,* Artech House. p. 234, ISBN 1608071049, 2010.

[5] https://phys.org/news/2015-12-high-thermally-durable-all-solid-state-lithium.html#jCp

[6] T. Yamabe, "Lithium ion rechargeable batteries: tracing the origins of research and development: focus on the history of negative-electrode material development", *The journal Kagaku,* vol. 70, no. 12, pp. 40–46, 2015.

[7] Susanne Fowler and Paul Mozur, "Samsung's Recall – The Problem with Lithium Ion Batteries". *New York Times,* 2 September 2016.

[8] S. V. Sazhin, E. J Dufek and K.L.Gering, "Enhancing Li-Ion battery safety by early detection of nascent internal shorts", *Journal of the Electrochemical Society,* vol. 164, A6281, 2016.

[9] Report: India Lithium-ion Battery market by Type, by Application, competition forecast and Opportunities: https://www.researchandmarkets.com/reports/3923190/india-lithium-ion-battery-market-by-type-lithium.

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