

## Profile of Akira Yoshino, Dr.Eng., and Overview of His Invention of the Lithium-ion Battery



### Personal information

Date of birth: January 30, 1948 (age 70)

Residence: Fujisawa, Kanagawa-ken, Japan

### Contact

Hitoshi Gotoh

Corporate Research & Development, Asahi Kasei Corp.

1-105 Kanda Jinbocho, Chiyoda-ku, Tokyo 101-8101 Japan

E-mail: gotoh.hc@om.asahi-kasei.co.jp

Phone: +81-(0)3-3296-5552, Fax: +81-(0)3-3296-3190

### Current positions

- Honorary Fellow, Asahi Kasei Corp.
- President, Lithium Ion Battery Technology and Evaluation Center (LIBTEC)
- Visiting Professor, Research and Education Center for Advanced Energy Materials, Devices, and Systems, Kyushu University
- Professor, Graduate School of Science and Technology, Meijo University

### Brief biography

Academic background:

- |            |  |
|------------|--|
| March 1970 | B.S., Department of Petrochemistry, Faculty of Engineering, Kyoto University         |
| March 1972 | M.S., Department of Petrochemistry, Graduate School of Engineering, Kyoto University |
| March 2005 | Dr.Eng., Graduate School of Engineering, Osaka University                            |

Work career:

- |              |   |
|--------------|---|
| April 1972   | Entered Asahi Kasei Corp.   |
| October 1982 | Kawasaki Laboratory, Asahi Kasei Corp.  |
| March 1992   | Manager, Product Development Group, Ion Battery Business Promotion Dept., Asahi Kasei Corp.   |
| August 1994  | Manager, Technical Development, A&T Battery Corp.   |
| April 1997   | Manager, Rechargeable Ion Battery Group, Asahi Kasei Corp.  |
| May 2001     | Manager, Battery Materials Business Development Dept., Asahi Kasei Corp.  |
| October 2003 | Group Fellow, Asahi Kasei Corp.   |
| August 2005  | General Manager, Yoshino Laboratory, Asahi Kasei Corp.  |
| April 2010   | President, Lithium Ion Battery Technology and Evaluation Center (LIBTEC)*   |
| October 2015 | Advisor, Asahi Kasei Corp.<br>Visiting Professor, Research and Education Center for Advanced Energy Materials, Devices, and Systems, Kyushu University* |
| July 2017    | Professor, Graduate School of Science and Technology, Meijo University*   |
| October 2017 | Honorary Fellow, Asahi Kasei Corp.*   |

\* Current position

### Major awards and recognitions received for development of the LIB

March 1999	Fiscal 1998 Chemical Technology Prize from the Chemical Society of Japan for achievements in the development of the lithium-ion battery
October 1999	Battery Division Technology Award from The Electrochemical Society for achievements in pioneering work on lithium-ion battery technology
April 2001	Ichimura Prizes in Industry—Meritorious Achievement Prize, from the New Technology Development Foundation (Ichimura Foundation) for achievements in the development and commercialization of the lithium-ion battery
October 2001	Kanto-block Commendation for Invention—Encouragement Prize of Invention of the Minister of Education, Culture, Sports, Science and Technology, from the Japan Institute of Invention and Innovation
June 2002	National Commendation for Invention—Invention Prize of the Minister of Education, Culture, Sports, Science and Technology, from the Japan Institute of Invention and Innovation
April 2003	Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology—Prize for Science and Technology, Development Category, from the Ministry of Education, Culture, Sports, Science and Technology
April 2004	Medal with Purple Ribbon, from the Government of Japan
November 2011	Yamazaki-Teiichi Prize from the Foundation for Promotion of Material Science and Technology of Japan, for the development and commercialization of the lithium-ion secondary battery
November 2011	C&C Prize from the NEC C&C Foundation, for pioneering contribution to the development and commercialization of the lithium-ion battery
March 2012	Designation as a Fellow of the Chemical Society of Japan
June 2012	IEEE Medal for Environmental and Safety Technologies from the Institute of Electrical and Electronics Engineers, for developing the lithium-ion battery, which enables significant fuel conservation and reduced emissions as power storage for electric vehicles and for smart grids incorporating renewables
June 2013	The Global Energy Prize
November 2013	The Kato Memorial Prize from the Kato Foundation for Promotion of Science, for development and commercialization of technology for the lithium-ion battery
February 2014	The Charles Stark Draper Prize for Engineering from The National Academy of Engineering
September 2016	The NIMS Award 2016 from the National Institute for Materials Science
April 2018	The Japan Prize

### Personal qualities

- Dr. Yoshino is a highly respected leader in many industry-wide efforts and initiatives.
- He has many international connections in industry and academia.
- He is an active leader in academic societies, and is widely trusted in scientific fields.

## Development and commercialization of the lithium-ion battery

### Introduction

Throughout the 1980s, the development of portable electronic products such as video cameras, notebook computers, and cellular phones led to a growing need for rechargeable batteries with greater capacity, or reduced size and weight for a given capacity. However, conventional rechargeable batteries such as lead-acid batteries and nickel-cadmium batteries, as well as nickel-metal hydride batteries which were under development at the time, posed limitations to reduction in size and weight. There thus remained an unmet need for a new, small and lightweight rechargeable battery to be put into practical use.

The two main battery classifications are disposable (primary) and rechargeable (secondary), and batteries may also be classified by the type of electrolyte employed, either aqueous or nonaqueous. Some common battery types are shown in Figure 1 in accordance with these classifications.

	Aqueous electrolyte battery	Nonaqueous electrolyte battery (high voltage/high capacity)
Primary battery (disposable)	Manganese dry cell, Alkaline dry cell	Metallic lithium battery
Secondary battery (rechargeable)	Lead-acid battery, Nickel-cadmium battery, Nickel-metal hydride battery	<b>Lithium-ion battery</b>

Figure 1. Types of battery

Aqueous electrolyte batteries have a disadvantage in that the available voltage per cell is in principle limited to around 1.5 V, the voltage at which water of the electrolyte begins to dissociate by electrolysis. Batteries that use aqueous electrolyte thus face a natural limit in terms of capacity, which therefore restricts the scope for reduction of size and weight. On the other hand, nonaqueous electrolyte batteries can obtain an electromotive force of 3 V or more per cell, offering much greater possibilities in terms of increasing capacity. An important example is the metallic lithium battery, a primary battery which was commercialized using nonaqueous electrolyte and metallic lithium as negative electrode material.

Although attempts had been made to convert the metallic lithium battery into a secondary battery, even the best efforts could not succeed for two main reasons: 1) under charging, lithium tends to precipitate on the negative electrode in the form of dendrites, which easily cause short-circuiting and 2) the high chemical reactivity of metallic lithium resulted in poor battery characteristics, including inadequate cycle durability due to side reactions, and moreover posed an insurmountable problem in terms of safety due to the inherent risk of a thermal runaway reaction.

### Subject of development

Dr. Yoshino focused on the creation of a practical new nonaqueous electrolyte secondary battery to meet the emerging need for a small and lightweight power source for portable electronics. He conceived the lithium-ion battery (LIB) in the early 1980s, and completed a practical prototype in 1986. (Priority patent application was filed in

1985 [1], and prototype cells were fabricated on consignment by a US company in 1986, with application to the United States Department of Transportation for a shipping permit also in 1986.) The resulting LIB is positioned as a nonaqueous electrolyte secondary battery in Figure 1.

The main technological achievements of Dr. Yoshino in the development of the LIB are as follows:

- 1) Proposition of fundamental technology for composition of the LIB, in which carbonaceous material is used as the negative electrode and  $\text{LiCoO}_2$  is used as the positive electrode. Of particular note, he discovered that only carbonaceous material with a certain crystalline structure was applicable to the negative electrode.
- 2) Invention of essential constituent technologies for the electrodes, electrolyte, and separator.
- 3) Development of peripheral technology such as safety device technology, protective circuit technology, and charging and discharging technology.

1. Proposition of fundamental technology

The invention and development of the LIB was made possible by Dr. Yoshino's proposition of a completely new combination of positive and negative electrode materials: carbonaceous material for the negative electrode and  $\text{LiCoO}_2$  for the positive electrode. [1] The cell reaction formula and operating principle are as shown in Figure 2.

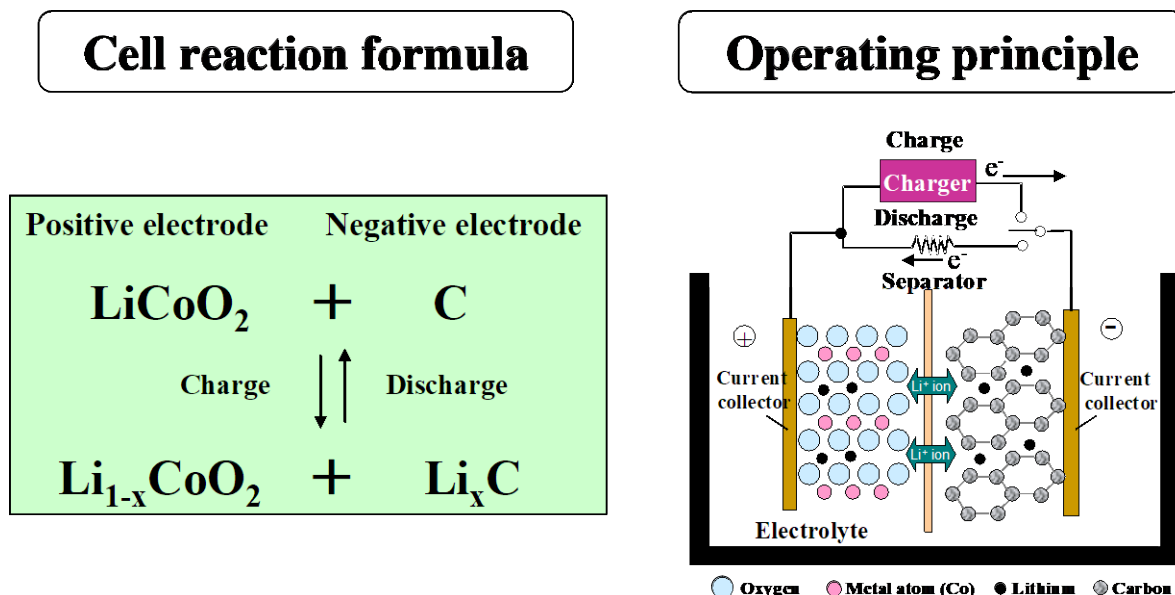


Figure 2. LIB cell reaction formula and operating principle

In the completely discharged state, lithium atoms are only contained as part of the  $\text{LiCoO}_2$  of the positive electrode. Under charging, lithium ions are released from the  $\text{LiCoO}_2$  and migrate into the carbonaceous material of the negative electrode. The reverse reaction occurs during discharging, and electric energy is stored or released by repeating these reactions reversibly. In this way, both the cobalt oxide compound of the positive electrode and the carbonaceous material of the negative electrode act only as a host of lithium ions, and no other chemical reaction occurs. This is the reaction principle of the LIB, which provides a completely new concept of operation as a secondary battery through the transfer of lithium ions between the positive and negative electrodes.

The use of  $\text{LiCoO}_2$  as a positive electrode material was first reported by Dr. J.B. Goodenough in 1979. [2, 3] In 1982, Dr. Rachid Yazami reported the world's first successful experiment demonstrating the electrochemical intercalation and release of lithium in graphite. [4, 5] Although Dr. Yazami used a solid electrolyte, this experiment provided the scientific basis for the use of graphite as negative electrode material—as is the mainstream in LIBs today.

In the early 1980s, Dr. Yoshino conceived the idea of a new secondary battery using  $\text{LiCoO}_2$  as positive electrode and polyacetylene as negative electrode. He confirmed the principle of this new secondary battery with an operational model in a sealed glass test tube. Shown in Figure 3, this test-tube cell functioned with the same cell reaction and operating principle as the LIB as it exists today.



Figure 3. The first test-tube cell (1983)

Although this cell was functional, the low real density of polyacetylene posed limitations on the available capacity, and the chemical stability of polyacetylene proved to be limited. Dr. Yoshino thus searched for a new carbonaceous material to use as negative electrode. Although graphite had been studied as a negative electrode material, it was known at that time that propylene carbonate, which was then the common organic electrolyte, would decompose during charging when graphite was used, and furthermore that the use of solid electrolyte resulted in electrical resistance which was too high to enable practical charging and discharging. Dr. Yoshino therefore studied the suitability of several carbonaceous materials as negative electrode. He found that carbonaceous material with a certain crystalline structure (Figure 4) provided greater capacity without causing decomposition of the propylene carbonate electrolyte solvent as graphite did. The secondary battery which he successfully fabricated based on this new combination of component materials enabled stable charging and discharging, over many cycles for a long period. [1]

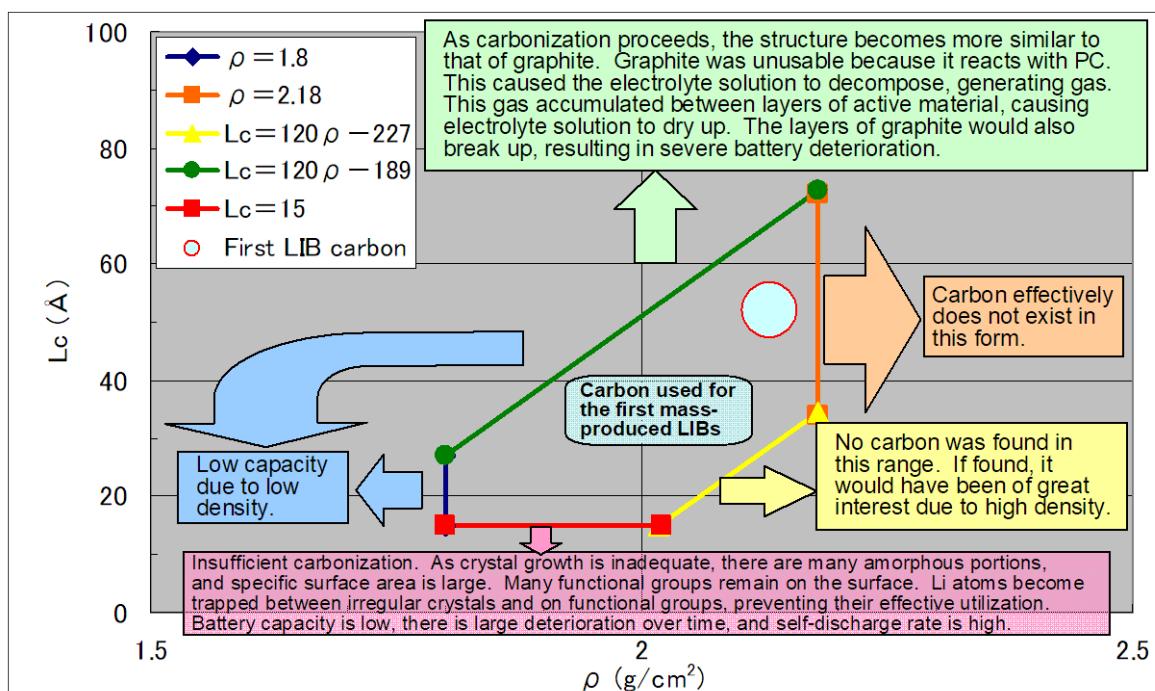


Figure 4. Carbonaceous material suitable for LIB discovered by Dr. Yoshino In 1985

This combination of electrode materials and this cell reaction principle impart the LIB with the following characteristics.

- Avoidance of problems stemming from the high chemical reactivity of metallic lithium, which had inhibited the practical development of a nonaqueous electrolyte secondary battery using metallic lithium for the negative electrode.
- Supply of lithium ions from the  $\text{LiCoO}_2$  of the positive electrode to the carbonaceous material of the negative electrode, which marks a new concept of a secondary battery based on the transfer of lithium ions.
- Achievement of an electromotive force of 4 V or more and a substantial improvement in energy density with the use of a nonaqueous electrolyte, which enables a significant reduction in size and weight as a secondary battery.
- Utilization of a cell reaction without chemical transformation, which provides stable battery characteristics over a long service life, including excellent cycle durability with little degradation by side reactions, and excellent storage characteristics.
- Achievement of a simple and efficient production process with no special atmosphere required for battery assembly, made possible because  $\text{LiCoO}_2$  is very stable in air, despite containing lithium ions, and the negative electrode is composed of carbonaceous material which is also stable.

## 2. Invention of essential constituent technologies

To enable the successful commercialization of the LIB, Dr. Yoshino also invented essential constituent technologies including technology for fabricating electrodes and technology for assembling batteries.

In the process of performing a large number of experiments with hand-made LIB prototypes, Dr. Yoshino devised various innovations to create a battery structure which would enable the LIB to be manufactured as a practical product. One of the most important concerns was to ensure safety, notably the prevention of ignition. In 1986, a US company was contracted to fabricate a certain number of semi-commercial prototype LIB cells (Figure 5), several of which were subjected to “abuse test” for evaluation. The test results verified that the basic LIB cell design provided the required level of safety, and this cleared the way to the commercialization of the LIB as we know it today.



Figure 5. Assembly of LIB prototypes on consignment (Jun 1986)

Figure 6 shows the basic cell structure and electrode structure of the LIB as originally devised by Dr. Yoshino and which continues to be commercially applied in present-day LIBs. A multilayer electrode assembly (electrode coil), prepared by winding sheets of positive and negative electrode with separator membrane in between, is inserted into a battery can. This is then infused with nonaqueous electrolyte comprising  $\text{LiPF}_6$  or  $\text{LiBF}_4$  dissolved in a mixture of carbonate compounds, and sealed. Both the positive and negative electrodes are structured with electrode material coated on both sides of a current collector. The current collectors conduct electricity from the active electrode materials to tabs connected to the electrode terminals. Aluminum foil is used for the



positive electrode current collector and copper foil is used for the negative electrode current collector, the thickness of each being around 10  $\mu\text{m}$ .

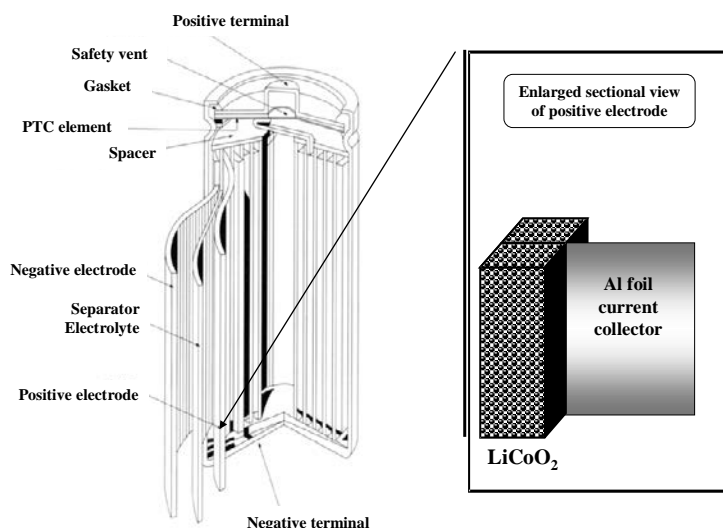


Figure 6. Battery structure and electrode structure of lithium-ion battery

In order to obtain discharge power comparable to that achieved with aqueous electrolyte secondary batteries, completely new technology for fabricating electrodes was required. Because the electroconductivity of nonaqueous electrolyte is lower than that of aqueous electrolyte, lower current density for a given area of electrode surface was required to prevent the excessive generation of Joule heat. This had been an impediment to the development of a practical rechargeable cell design enabling high current discharge using nonaqueous electrolyte. Dr. Yoshino resolved this problem by devising flat-sheet electrodes wound into a coil shape. Practical application was achieved with technology for fabricating thin-film electrodes (100 to 250  $\mu\text{m}$ ) in which a thin metal foil is used as a current collector and both surfaces of the foil are coated with electrode active material. Dr. Yoshino's selection of aluminum as positive electrode current collector material was one of the most important aspects of this development. Previously, only precious metals such as gold and platinum were considered able to withstand high voltage of 4 V or more. However, Dr. Yoshino found that aluminum foil was suitable for use as positive electrode current collector material because a passivation layer forms on the aluminum surface. [6]

Dr. Yoshino also devised the other constituent technologies essential for achieving a practical LIB. Notably, his invention of a highly functional membrane separator was a particularly important factor in achieving the safety required for successful LIB commercialization. The use of a microporous polyethylene membrane 20 to 30  $\mu\text{m}$  thick for use as separator provides a "fuse" function in which the material of the separator melts to close the micropores and shut off battery operation in the case of abnormal heat generation. [7]

Such thermal runaway could occur when the separator, which electrically separates the positive electrode from the negative electrode, is damaged, or when the



temperature inside the battery increases through exposure to external heat or due to internal heat generation caused by Joule heating from charging or discharging. The membrane separator having a “fuse” function effectively prevents such thermal runaway from occurring.

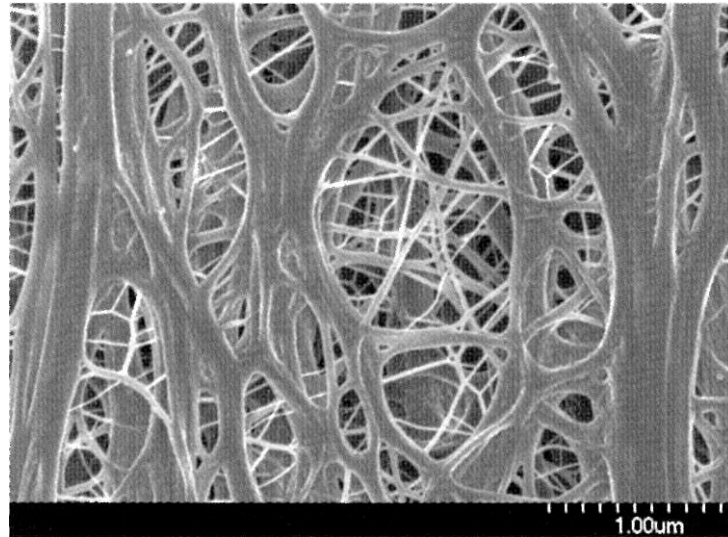


Figure 7. SEM photo of battery separator with “fuse” function

These essential constituent technologies impart the LIB with the following characteristics.

- a) High electromotive force of 4 V or more enabled through the use of  $\text{LiCoO}_2$  as positive electrode material and aluminum foil as positive electrode current collector.
- b) High current discharge enabled with large-area thin-film electrodes using metal foil as current collector with electrode material coated on both sides.
- c) Achievement of efficient, high-speed electrode production.
- d) High-density packaging with the coil-shaped, multilayer thin-film electrode assembly emplaced in a battery can.
- e) Significantly heightened battery safety with a polyethylene microporous membrane having a certain thermal characteristics used as separator.

### 3. *Development of peripheral technology*

Dr. Yoshino also devised peripheral technology which was instrumental to the development of a practical LIB, including safety device technology, protective circuit technology, and charging and discharging technology. One key example is a positive temperature coefficient (PTC) device which is sensitive to both electric current and temperature. Incorporation of this device in the LIB results in greatly improved safety, particularly in terms of protection against overcharging. [8]

## Summary of development

These achievements by Dr. Yoshino enabled the commercial development in the early 1990s of the LIB with features as shown in Figure 8, facilitating the widespread use of portable electronics and communications products such as notebook computers and cellular phones. Furthermore, utilization of the LIB for power storage in hybrid-electric and all-electric vehicles is now growing rapidly, and it is generally expected that the LIB will play a key role in breaking the world's dependence on fossil fuels to power transportation.

### 1. Small size and light weight

### 2. High cell voltage (4 V or more)

### 3. Low self-discharge rate

### 4. High current discharge



Figure 8. Features of the LIB

## Effect of commercialization

Commercialization of the LIB made available an energy density of around twice as high or more than could be obtained with nickel-cadmium or nickel-metal hydride batteries, in terms of both weight and volume, as shown in Figure 9, facilitating a major reduction in the size and weight of the power supply of portable devices. Moreover, by providing an electromotive force of 4 V or more, the LIB made it possible to drive a cellular phone with a single cell.

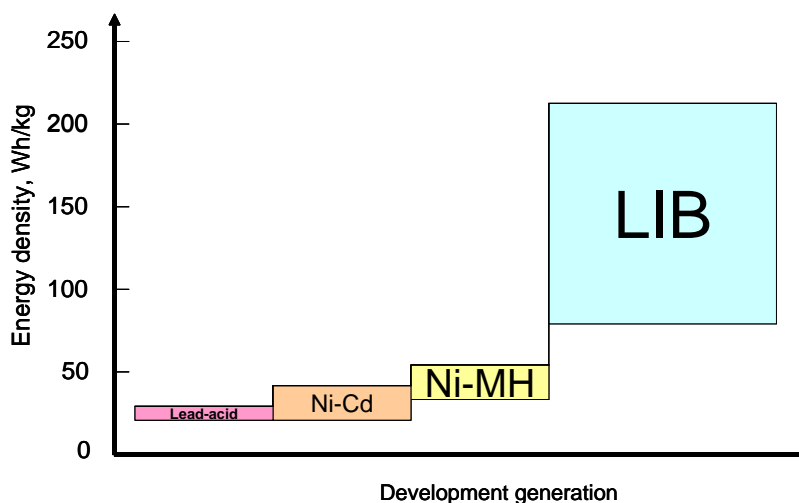


Figure 9. The evolution of rechargeable batteries

### Influence on society and industry

As shown in Figure 10, use of the LIB has expanded rapidly and is forecasted to continue to do so. Applications classified as “consumer use” include portable devices such as video cameras, mobile computers, cellular phones, and a variety of other electronic products with features and functions previously unavailable. With its high storage capacity, high current discharge, and excellent cycle durability, the LIB is increasingly being used in electric-powered vehicles, whose adoption as an environmental mode of transportation is forecasted to grow sharply.

High-volume production of the LIB and ongoing improvements to achieve greater performance have also driven many technological advances in the fields of carbonaceous materials, polymers, and ceramics, as well as progress in the related scientific disciplines of electrochemistry, surface chemistry, polymer chemistry, carbon chemistry, and ceramic chemistry.

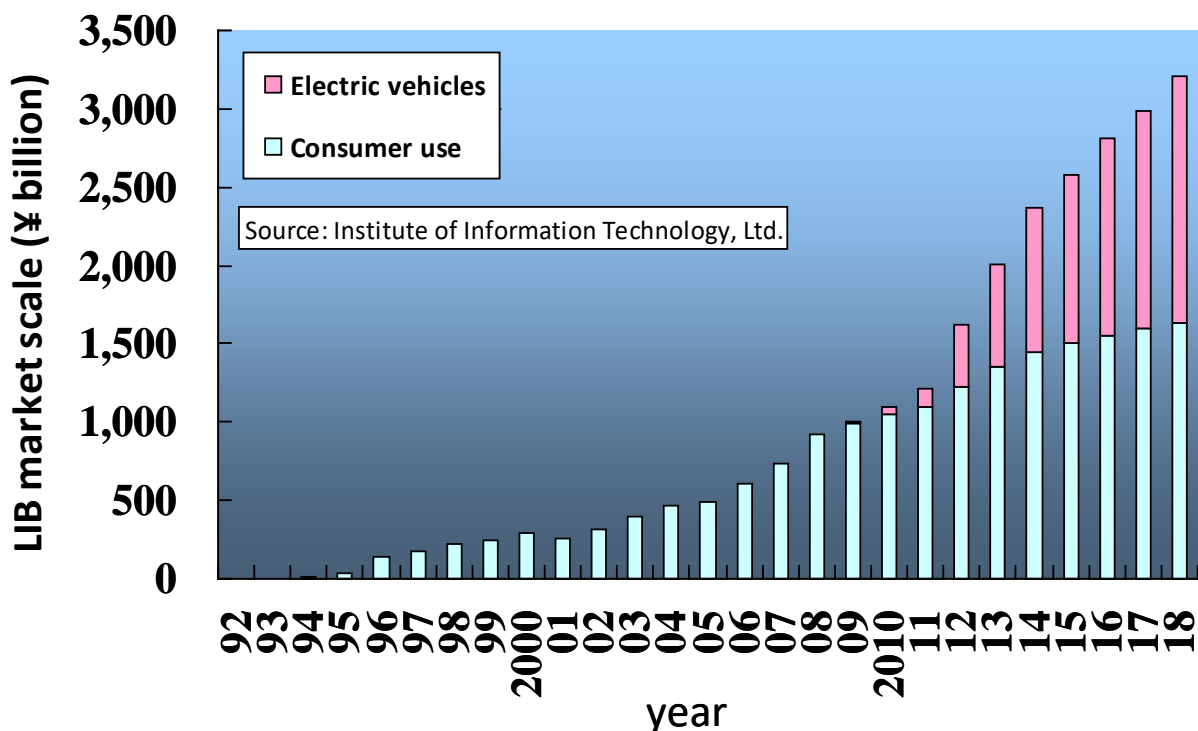


Figure 10. Forecasted expansion of LIB demand (reproduction prohibited)

### References

- [1] A. Yoshino et al., USP4,668,595 and JP1989293, filing date (priority) May 10, 1985 (Basic patent of the LIB. Certain crystalline carbon)
- [2] J.B. Goodenough et al., EP17400B1, filing date (priority) April 5, 1979
- [3] K. Mizushima, J.B. Goodenough et al., Materials Research Bulletin, 1980, 15, 783
- [4] R. Yazami et al., International Meeting on Lithium Batteries, Rome, April 27–29, 1982, C.L.U.P. Ed. Milan, Abstract #23
- [5] R. Yazami et al., Journal of Power Sources (April–May 1983), vol. 9, no. 3–4, pp. 365–371
- [6] A. Yoshino et al., JP2128922, filing date May 28, 1984 (Al current collector)
- [7] A. Yoshino et al., JP2642206, filing date December 28, 1989 (Separator)
- [8] A. Yoshino et al., JP3035677, filing date September 13, 1991 (PTC element)

### Major patents related to the LIB

Inventors	Title	Patent number	Filing date (Registration date)
Akira Yoshino Kenichi Sanechika Takayuki Nakajima	Secondary battery	JP1989293	May 10, 1985* (November 8, 1995)
Akira Yoshino Kenichi Sanechika Takayuki Nakajima	Secondary battery	USP4,668,595	May 10, 1985* (May 26, 1987)
Akira Yoshino Masahiko Shikata	Secondary battery	JP2668678	November 8, 1986 (July 4, 1997)
Akira Yoshino Kenichi Sanechika	Nonaqueous secondary battery	JP2128922	May 28, 1984 (May 2, 1997)
Akira Yoshino Kazuhiko Nakanishi Akira Ono	Explosion-proof secondary battery	JP2642206	December 28, 1989 (May 2, 1997)
Akira Yoshino Katsuhiko Inoue	Secondary battery with safety element	JP3035677	September 13, 1991 (February 25, 2000)

\* Priority date.

### Notable research reports

Authors	Title	Publication	Date
Akira Yoshino	Converting carbon material into a battery negative electrode (in Japanese)	TANSO (Journal of The Carbon Society of Japan), 1999, No. 186, 45–49	February 16, 1999
Akira Yoshino Kenji Otsuka Takayuki Nakajima Akira Koyama Satoshi Nakajo	Development of Lithium Ion Battery and Recent Technology Trends (in Japanese, published pursuant to receipt of prize from the Chemical Society of Japan)	Journal of The Chemical Society of Japan, 2000, No.8, 523–534	August 2000
Akira Yoshino	Development of Lithium Ion Battery	Mol. Cryst. and Liq. Cryst., 2000, Vol. 340, 425–429	September 2000
Akira Yoshino	Development process and the latest trend for lithium-ion battery technology in Japan (in Chinese)	Chinese Journal of Power Sources, 2001, Vol. 25, No. 6, 416–422	December 2001
Akira Yoshino	The birth of the lithium-ion battery	Angew. Chem. Int. Ed. 2012; 51(24): 5798-800	June 11, 2012

## Synopsis

*Demand for greater rechargeable battery performance could not be met with conventional technology.*

- Rechargeable batteries with reduced size and weight had been desired.
- Rechargeable batteries using aqueous electrolyte, such as lead-acid, nickel-cadmium, and nickel-metal hydride, could not provide high electromotive force and had low energy density. Scope for reduction in size and weight was thus limited.
- The use of nonaqueous electrolyte results in low current density per unit area of electrodes, making it difficult to develop rechargeable batteries with large current discharge.
- The use of nonaqueous electrolyte and metallic lithium negative electrode enabled high electromotive force and high energy density, but attempts to develop a rechargeable battery based on this configuration could not succeed.
- In a rechargeable battery, metallic lithium resulted in poor cycle durability due to its high chemical reactivity and the formation of dendrites, and furthermore posed an inherent safety problem due to the risk of thermal runaway.

*Several key developments enabled the successful commercialization of the lithium-ion battery (LIB) as a small, lightweight rechargeable battery.*

- The combination of carbonaceous material for the negative electrode and  $\text{LiCoO}_2$  for the positive electrode provided a completely new concept as the basic configuration of a rechargeable battery.
- By making it possible to use  $\text{LiCoO}_2$  as positive electrode material, cell voltage of 4 V or more was achieved.
- The use of carbonaceous material with a particular crystalline structure for the negative electrode eliminated the problems of cycle durability and safety, which had prevented the development of a practical rechargeable battery using metallic lithium as negative electrode material.
- Technology for fabricating electrodes, including an aluminum foil current collector that can withstand an electromotive force of 4 V or more, and technology for forming thin-film electrodes by coating enabled large current discharge to be obtained.
- The use of a separator membrane which melts to shut off operation at abnormal temperature provided excellent safety characteristics.

- Development of peripheral technologies such as safety device technology including a PTC device, protective circuit technology, and charging and discharging technology.

*Development of the LIB as a small, lightweight rechargeable battery has had a significant influence on society and industry.*

- With its small size, light weight, and high available power, the LIB facilitated the development and widespread adoption of many portable electronics and communications products with new features and functions.
- The LIB is increasingly becoming the power storage solution of choice for electric vehicles, whose widespread use has the potential to drastically reduce the consumption of hydrocarbon fuel for transportation in the near future.
- The commercialization and high-volume production of the LIB have stimulated many scientific and technological advances.