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The advent of battery-based societies and the global environment in the 21st century

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Abstract

In paving the way for a new electricity-based civilization in the 21st century, we hope to find the key to solving the trilemma of securing energy and resources, maintaining economic growth, and preserving the environment. In these circumstances, secondary batteries are expected to be used on a large scale in a new field—for energy purposes and to positively affect preservation of the global environment, resulting in the advent of a new battery-based society in the 21st century. It is important to develop secondary batteries not only with high specific energy for convenience, but also with large capacity, high energy efficiency and long life cycle for effective use of primary energy resources including natural energy. Lithium secondary batteries are a promising option.

Keywords: Electric energy; Battery energy storage; Secondary battery; Electric vehicle; Lithium battery

1. Introduction

In the 20th century, the rapid advancement of science and technology became the engine for great industrial and economic growth. Through this growth the peoples of developed countries came to enjoy a comfortable and convenient way of life. Electricity was and is the key energy that supports that life of ease and the world's socioeconomic system. As symbolized by the recent rapid growth in the use of compact portable telephones, computers and other electronic devices, it is also evident that batteries, particularly rechargeable batteries, have become an essential part of our electricity-dependent day and age. There can be no doubt that in the 21st century consumption of electricity and dependence upon it will increase. As batteries provide a high added-value energy source which makes life in a networked society even more convenient, there also can be no doubt the use of batteries will likewise increase (Fig. 1).

However, we need to be more conscious of our environment in the 21st century. The responsibility of developed countries was clearly laid out at the Third Conference of the Parties of the U.N. Framework Convention on Climate Change (COP3) held in Kyoto in 1997. Amid fears of global warming and environmental degradation as a result of massive consumption of fossil fuels, target figures for greenhouse gas reductions were established.

From now on, instead of pursuing greater convenience, it will be crucial for mankind to pursue technological development that uses limited energy resources more efficiently and therefore reduces the burden on the environment. Battery technology will be no exception. More than this, in the electricity and energy fields batteries will play a critical role in helping the 21st century become the *Century of the Environment*.

2. Electricity-based civilization and batteries

2.1. Development of electricity-based civilization and spread of battery use

Electrification rate defined as the percentage of electric power generation out of total primary energy is one indicator of the dependence on electric energy. Among developed countries electrification rates are already around 40%, while the world average is about 30% [1]. These rates are expected to continue to rise on into the 21st century. There

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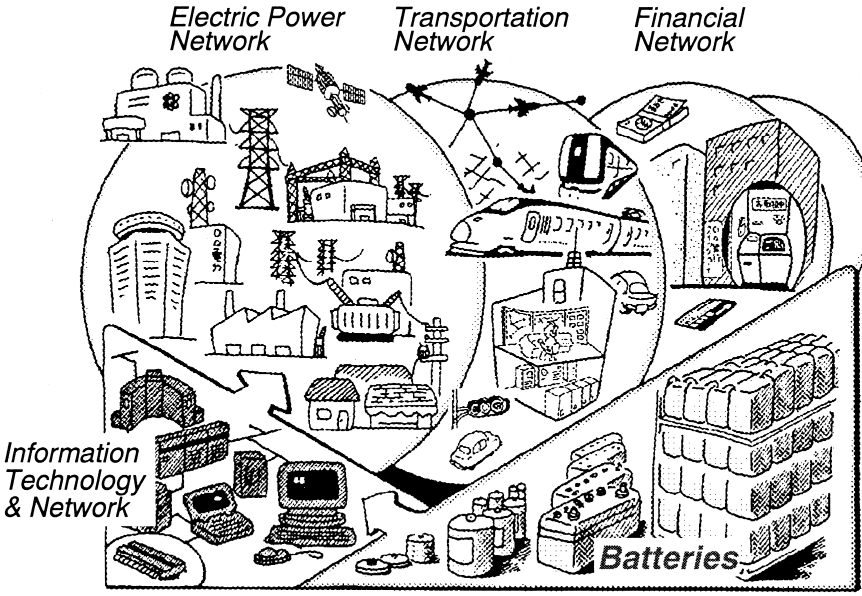

Fig. 1. Information-networked societies supported by battery technologies.

are several reasons for this continued rise. Compared with thermal energy, chemical energy, kinetic energy, potential energy and other forms of energy, electric energy is much superior in quality. It can be used more easily and cleanly and be converted more efficiently than other forms of energy.

One reason why batteries are to be found in all facets of modern life is that electronic devices have become much more portable and convenient to use. Another but essential reason is that today's handy electronic gadgets run on electricity, and considering limited spaces available for power sources and other constraints, batteries are the only feasible means of supplying electric energy. The batteries used to run these electronic devices are energy sources with high added value. For example, to supply electric energy to the electronic devices, we pay 2000 times more for the cheap manganese dry cell and 50 times more for the rechargeable cells than the cost of conventional commercial electric power.

2.2. Overcoming the trilemma

Mankind is now faced by a 'trilemma' with three aspects: securing resources and energy, maintaining economic growth, and preserving the natural environment [2]. At COP3 in Kyoto, the reduction of levels of greenhouse gas emissions by developed countries was discussed; however, NO_x and SO_x emissions are also a serious problem, causing local air pollution and acid rain on a global scale. The source of all these harmful gases is the mass consumption of fossil fuels. At present, 39% of the world's primary energy sources come from petroleum, 25% from coal and 21% from natural gas—meaning that about 85% of all the world's energy comes from fossil fuels [3]. The issue of how to wean our planet off dependence on fossil fuels is the key to avoiding the resources problem, protecting the global environment and solving the trilemma.

Fossil fuels are not only energy resources, but also raw materials with a high utility value. For this reason, the available energy of fossil fuels must not be wasted. The efficiency of converting the chemical energy in fossil fuels into electric energy is only about 40% in Japan and other developed countries. In developing countries it is as low as 30%. Consequently, improving generating efficiency is an important issue.

If the rapid surge in energy consumption driven by both worldwide population growth and economic expansion continues at its present pace, mankind will surely use up all the petroleum and natural gas resources. It will then have no choice but to switch to coal, a fossil fuel with a high unit output of greenhouse gases. It must develop technology for more efficient and cleaner coal-fired thermal power generation. In addition, the world must thus develop renewable energy sources, such as hydropower, geothermal power, solar energy and wind power, capable of meeting energy demands over the long term.

The sole purpose of civilian use of uranium is the generation of electricity. Since the way to renewable energy development is still uncertain, it is important to engage in nuclear fuel recycling, including the use of fast-breeder reactors. Only this will provide an escape from the confines of limited uranium reserves and help the world cope with a future of scarce fossil fuels.

Whether the source is renewable energy or nuclear energy, the energy supplied will be in the form of electricity in most cases.

3. Roles and issues for batteries in the 21st century

3.1. Requirements for the batteries

Limitations on fossil resources and the environment that become apparent in the 21st century will force society to utilize energy resources efficiently and effectively and to adopt widespread recycling. As a result of these changes, fossil fuel resources expended in the manufacture, operation and disposal of batteries must be reduced. To achieve this goal, the following issues must be required:

(a) reduction of the amount of energy required for manufacture and disposal

(b) shift from the use of disposable batteries to rechargeable batteries

(c) improvement of the charging/discharging efficiency of batteries

(d) development of recycling technologies

In parallel, large rechargeable batteries for energy storage and energy management should be developed, directly or indirectly linked to the electric power systems. These batteries will reduce the need for fossil fuels for power generation, and will promote the diversification of electricity sources.

The batteries we need to develop are the following:

(a) batteries for decentralized energy storage systems to enable load leveling, peak cutting and to stabilize the supply of electricity from decentralized natural energy sources such as wind power generators and solar cells;

(b) batteries for electric vehicles that will help us to use fossil fuels more economically while coping with power burdens;

(c) batteries for hybrid electric vehicles which have both batteries and a gasoline engine to use fossil fuels more efficiently.

3.2. From disposable (primary) to rechargeable (secondary) batteries

3.2.1. Battery usage

The estimates of primary manganese and alkaline–manganese cell consumption in 1990 are approximately 10 per person in developed countries and the world average was about 3.4 batteries per person. The use of primary batteries is likely to increase, particularly in developing countries.

In Japan, the use of disposable batteries has peaked and the use of rechargeable batteries is growing year by year. As shown in Fig. 2, some 1.3 billion rechargeable batteries were produced [4] and the total storage energy capacity of these rechargeable batteries has been calculated at about 16 GWh in 1996. At present, lead–acid batteries for internal combustion vehicles account for 70% of this storage capacity. Entering the 21st century, the use of large capacity rechargeable batteries will grow within the electric power and automobile industries, resulting in a likely dramatic increase in the production capacity of rechargeable batteries. In the 21st century, rechargeable battery-based societies will probably emerge all over the world.

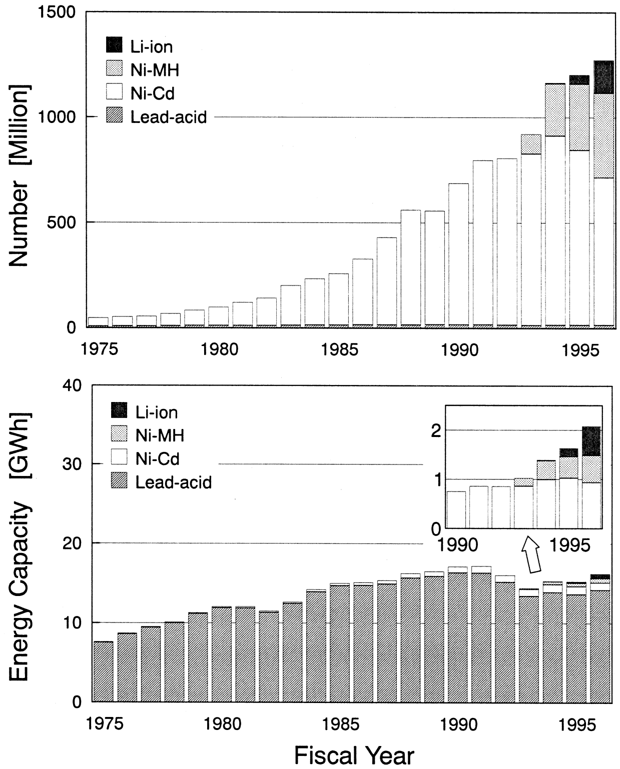

Fig. 2. Number and estimated energy capacities of secondary batteries annually produced in Japan.

3.2.2. Battery energy recovery rate

From the point of view of energy efficiency, it is important to compare the amount of energy that goes into the manufacture of a primary battery with the amount of energy that can be taken out. Taking primary lithium–manganese oxide batteries as an example, the amount of energy received is about 19% of the energy that goes into the electrochemical synthesis of their active materials. In fact, no more than a few percent of the energy put into the manufacture of batteries can ever be received back.

For rechargeable batteries, by increasing the number of charging cycles, the amount of energy expended during manufacture becomes comparably smaller and the energy recovery rate becomes close to the energy efficiency of the battery per charge as shown in Fig. 3. If the rate of recovery of the energy invested in the manufacture of rechargeable batteries is to be improved, then it is crucial to increase the lifespan and charging/discharging efficiencies of those batteries.

It is desirable that where there is sufficient infrastructure of electric power supply, the use of rechargeable rather than disposable batteries be increased.

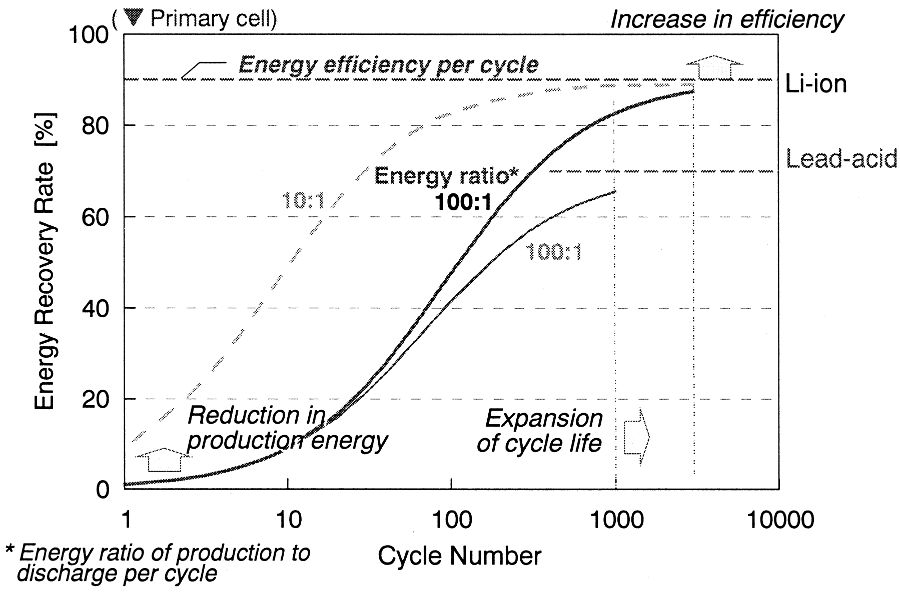

Fig. 3. Energy recovery rates of secondary batteries through cycling.

3.3. Batteries as a power source for electric vehicles

Energy consumption in the transport sector is increasing globally. There are an estimated 600 million or so cars in the world today. If vehicular energy efficiency can be improved and a shift can be made from fossil fuels to alternative energy sources, consumption of fossil fuels will be greatly reduced. The use of electric vehicles and the introduction of environmentally low emission vehicles, beginning with cities in developed countries, will help lessen the problems of environmental pollution caused by vehicle exhaust gases.

Since electric cars are zero emission vehicles, they are seen as a solution to localized environmental pollution problems. Looking forward to the 21st century, it is easy to imagine a world using less petroleum, natural gas and other fossil fuels, owing to their scarcity. Power generation will increasingly be through nuclear power and renewable sources like wind power and solar power, which have low unit emissions of greenhouse gases and other pollutants. Most energy used will be supplied in the form of electricity, so electric vehicles and batteries that have the performance to match gasoline-powered vehicles must be developed.

The hybrid electric vehicle, with its combination of rechargeable battery and internal combustion engine, is seen by many as a more efficient way to use fossil fuels. The role of the battery in a hybrid vehicle is to level out

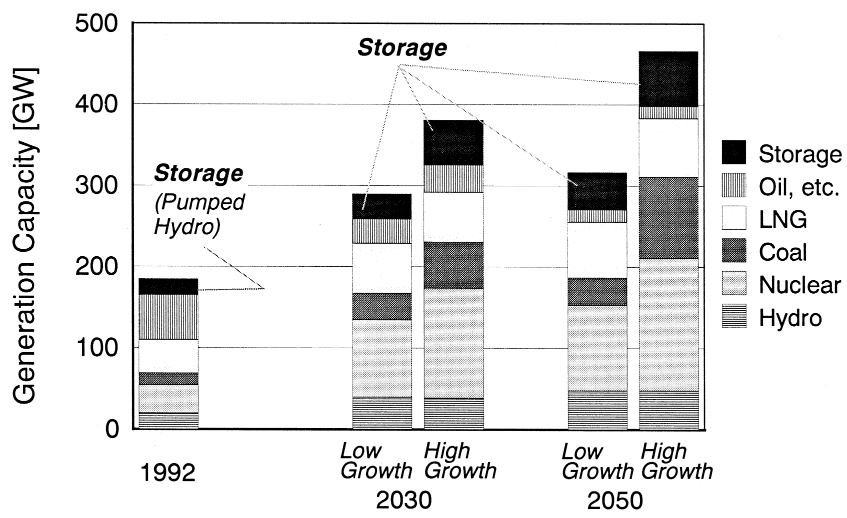

Fig. 4. Estimated future optimum generation mix in Japan [5].

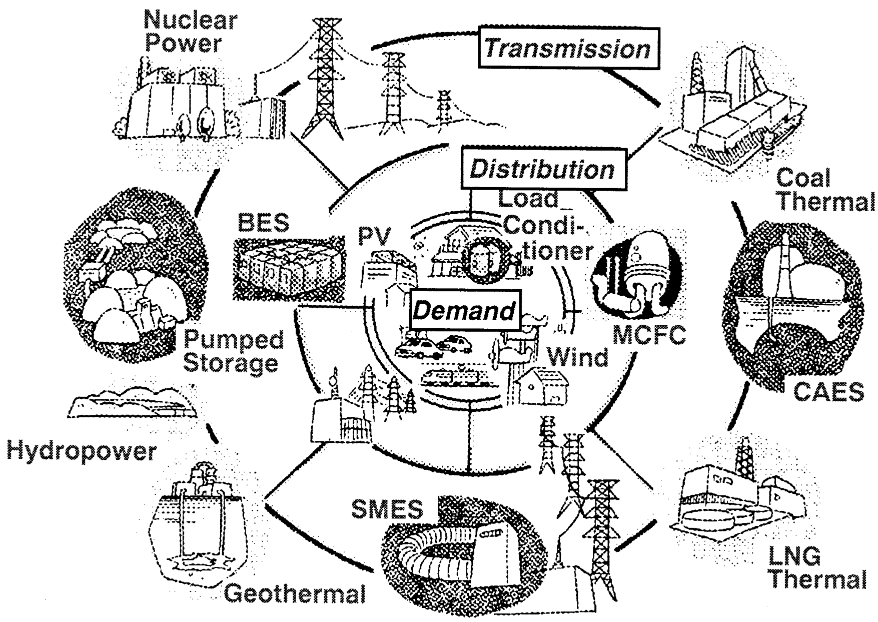

Fig. 5. Electric power network with battery energy storage systems in the 21st century.

the load on the engine and to enable effective use of the regenerated energy at braking. Overall energy efficiency is raised when the hybrid vehicle is driven in the city and has to start and stop often.

3.4. Battery energy storage systems

3.4.1. Efficient operation of large power plants

It is important to level the load of electric power systems for efficient operation of large scaled electric power plans. However, the load factor of electric power systems is now reducing. There will be greater needs for energy storage facilities.

At present, pumped-storage hydroelectric plants have been used for load leveling and as standby power sources. In Japan, these account for 20 GW of power generation, about 10% of the total as shown in Fig. 4. The number of locations where large pumped-storage hydroelectric plants can be built is limited, and these are far away from the demand sites, so the overall energy storage efficiency is low. The issue of electricity storage facilities is likely to become increasingly important [5].

3.4.2. Decentralized battery energy storage: supply side system

In addition to large-scale/distant storage facilities like pumped-storage hydroelectric plants, the need is growing for small- and medium-sized decentralized electricity storage facilities built in areas of power demand or near decentralized power sources such as wind power. There is

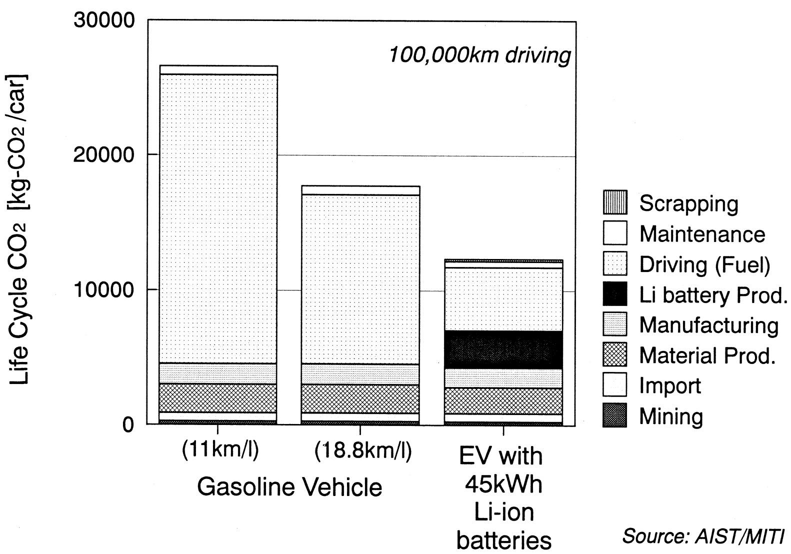

Fig. 6. CO_2 life cycle analysis of gasoline-powered vehicle and electric vehicle [8].

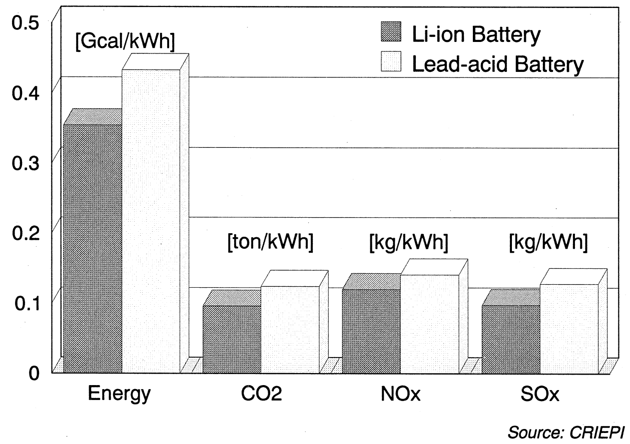

Fig. 7. Environmental impact analysis of electric vehicle batteries production. (This work has been supported by NEDO in the New Sunshine Program.)

also increasing importance in the development of battery energy storage facilities (see Fig. 5).

The construction of battery energy storage systems at each substation in areas of power demand would not only assist with load leveling, but add value by using power electronics technology to stabilize the system and improve the quality of the supplied power [6]. In a power distribution system containing intermittent power generation such as solar power and wind power, decentralized battery energy storage plants would be able to stabilize and level out the power supply.

3.4.3. Dispersed battery energy storage: demand side system

We are now studying dispersed type energy storage devices for electricity users and have proposed the concept of a load conditioner [7] for use in the home, and for commercial applications such as in restaurants and shops. Such devices would enable consumers to take advantage of the difference in electricity charges between nighttime and daytime.

For domestic use, there is interest in a system combining a load conditioner and solar cells, and also interest in a value-added system with a backup power supply for office buildings as an emergency power supply.

4. Expectations for development of rechargeable lithium batteries

Rechargeable lithium batteries have a high energy density; not only are they light and compact, but there are hopes they can both be highly efficient in the storage of electric energy and that their charging/discharging lifespan can be lengthened. With regard to reducing the environmental burden and utilizing primary energy resources effectively, it is hoped that high-capacity batteries will be developed, perfected and widely used for both dispersed battery energy storage and for electric vehicles.

4.1. Life cycle assessment of rechargeable lithium batteries

Life cycle assessment (LCA) was applied to assess the output of CO_2 in electric vehicles with lithium batteries and in gasoline-fueled cars over the lifetime of the vehicle —from manufacture to disposal [8]. LCA has shown that the lifetime CO_2 emissions of lithium battery electric vehicles are less than that of an ordinary car, as shown in Fig. 6.

CRIEPI has also analyzed the amount of energy, and CO_2, NO_x and SO_x emissions involved in the manufacture of EV batteries. Comparing unit energy storage capacities, results of the analysis have shown that lithium batteries require less energy and generate lower CO_2, NO_x and SO_x emissions in their manufacture as shown in Fig. 7. Com-

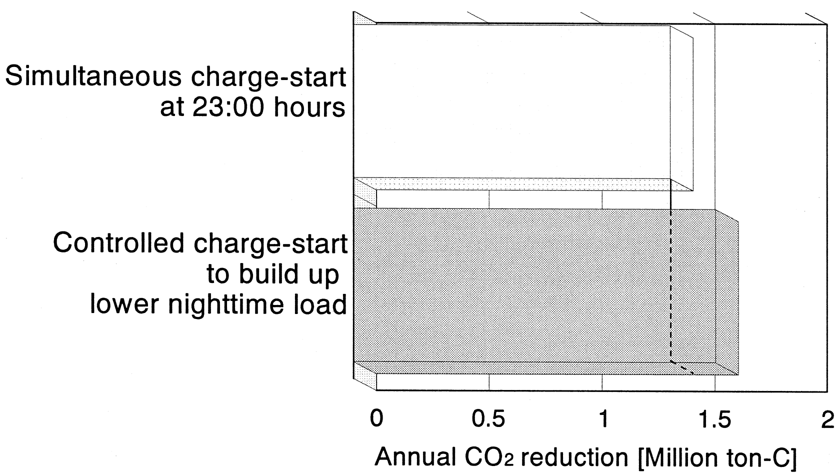

Fig. 8. Effect of controlled nighttime charging of 5 million electric vehicles on CO_2 emission for the year 2010 in Japan [9].

pared with lead–acid batteries, rechargeable lithium batteries have a higher energy efficiency and a longer life cycle. They are hence expected to prove far superior to use.

4.2. Reducing charging loss

Nickel–hydrogen or lead–acid batteries must be deliberately overcharged to prevent differences between the charging of individual cells. From analysis of the average energy consumption efficiency of an electric vehicle powered by nickel–hydrogen batteries, we have found that if the overcharging step is omitted, the average energy consumption efficiency can be enhanced by about 30% [9].

Rechargeable lithium batteries have a very high charging/discharging energy efficiency; therefore, average energy consumption efficiency can also be expected to be high. In the future, as rechargeable lithium batteries become larger and connected together in packs, it will be essential to develop charging control methods that ensure the life cycle of batteries is not reduced, and that the high efficiency of the batteries is maintained.

4.3. Effectiveness of nighttime charging control

It is desirable that the recharging of dispersed battery energy storage devices and electric vehicles will eventually be performed with control or induction that will enable more effective utilization of fossil fuels.

In a simulation of the widespread use of electric vehicles in Japan, it was found that, if the charging power peak was induced to coincide with the time of lightest load at dawn, the CO_2 and NO_x reduction effect was heightened because of the efficient operation of thermal power stations (see Fig. 8) [9]. This simulation shows the effectiveness of nighttime charging control.

To control nighttime recharging of dispersed battery energy storage systems and electric vehicles, we need to know the remaining capacity of the batteries. Rechargeable lithium batteries possess a voltage slope which makes it comparably easier to accurately estimate their remaining capacity than to estimate those of other aqueous electrolyte batteries.

4.4. New Sunshine Program and LIBES's activities

In FY 1992 in Japan, as part of the government's New Sunshine Program, LIBES began contracted research and development of rechargeable lithium batteries for use in dispersed battery energy storage systems and electric vehicles.

In 1997, the basic plan was revised and clearly stated it would develop a 'modular battery' possessing the highest performance levels as shown in Table 1. LIBES will make maximum efforts to ensure a constant standard of stability, reliability and economy. Currently, LIBES is working to achieve its developmental objectives and overcome various issues.

Table 1
Goals of lithium battery module R&D in the New Sunshine Program

	Stationary type	EV application type
Module capacity	2 kWh class	3 kWh class
Gravimetric energy density (Wh/kg)	120	150
Volumetric energy density (Wh/l)	240	300
Power density (W/kg)	–	400
Cycle life (cycle)	3500	1000
Energy efficiency (%)	> 90	> 85

5. Conclusion

The 21st century is at hand. Batteries have a steadily growing role in reducing the environmental burden created by the consumption of fossil fuels, and in enabling the effective utilization of renewable energy and other natural energy sources. There is now a great opportunity for the development of large batteries. The new battery-based society will be one in which batteries can make a contribution to conserve and effectively use limited resources. If the high-efficiency, long-life, large-capacity and reasonable-cost rechargeable lithium batteries currently under development can be made to work practically, and these batteries are used in the battery-based society of the 21st century, then they will in all likelihood make a great contribution to overcoming the world's environmental and energy problems.

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