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Global energy prospects in the 21st century: a battery-based society

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Abstract

Current energy needs are nearly totally dependent on fossil fuels. This is causing global warming and exhaustion of resources; it is important to switch to more efficient and effective energy use. These circumstances are expanding the role of secondary batteries. Non-fossil fuels such as photovoltaic cells and wind energy are unstable, but combining them with secondary batteries improves their stability as electric power sources. If electrical load leveling between day and night can be achieved by storing electric power, it will be possible to achieve a high capacity utilization rate for generating facilities that have high generating efficiency and produce little CO_2. Depending on the generating mix, the practicalization of electric vehicles will serve not only to alleviate air pollution, but also to limit CO_2 emissions. There are hopes for the development of large-capacity lithium secondary batteries with long cycle life, high energy density, high power density, and high energy efficiency. © 1997 Elsevier Science S.A.

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1. Introduction

The present age is often called the Age of Electricity because electricity is crucial to modern life. As such, battery technology is also essential. As almost all electricity is generated through the combustion of fossil fuels and there are fears that fossil fuels will be depleted, it is clear that the present Age of Electricity is based on a precarious foundation. This paper will examine a sustainable energy use for the 21st century and the role of the electric power industry. It will also address development in rechargeable lithium batteries as an electricity storage technology that will support a battery-based society in the Age of Electricity.

2. The human crisis: the trilemma

2.1. Population explosion and economic disparities

The population of the earth is currently estimated to be 5.7 billion. In the past two to three years, the world's population has increased at the rate of approximately 100 million annually. Most of this growth has occurred in the developing nations. By the middle of the 21st century, the world's population is predicted to reach 10 billion, of which 86% will be citizens of today's developing nations.

The developed nations comprise 20% of the population and account for 86% of world's GNP. In contrast, it is estimated that one billion people live barely above starvation level. Even if the per capita economic level remains the same, the world economy will have to expand tremendously to keep pace with population growth.

2.2. The rise in global energy consumption and its effects

Energy consumption, like population, is not distributed evenly. The OECD nations, which comprise 15% of the population, account for 54% of the global primary energy consumption. However, rapid economic growth and rising energy consumption in Asia, home to 54% of the world's population, have attracted much attention. The International Energy Agency estimates that up to 2010, growth in primary energy consumption in Asia, excluding Japan, will average 4.6% annually [1]. This far exceeds 1.2% growth projected for OECD nations and the world average of 2.1%. By the year 2010, Asia's primary energy consumption will be 2.2 times greater than in 1992 and will account for 26% of the world's total.

Developing countries will require enormous energy resources to raise their economies to levels of the developed

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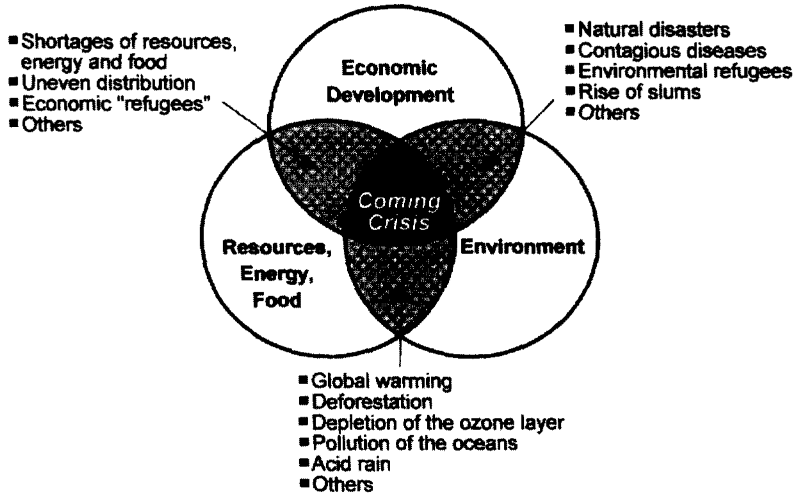

Fig. 1. Structure of the trilemma.

countries. Global energy consumption boosted by economic growth, particularly that of the developing nations is expected to double at least by the middle of the next century. Forty percent of the primary energy consumed in the world today comes from petroleum, 27% from coal, and 23% from natural gas [2]. Consequently, 90% of primary energy consumption is satisfied by fossil fuels. Excessive reliance on fossil fuels and future mass consumption are threatened for two main reasons.

The first threat is a limit to resources [3]. If humankind continues at the current pace, known recoverable reserves of petroleum may be completely exhausted in 40 and natural gas in 50 years. There are fears of a third oil crisis, heightened international tensions and a widening gap between the richer nations and the poorer ones in the next century.

The second threat concerns the negative impact of rising energy consumption on the global environment. The release of SO_x and NO_x into the atmosphere from the combustion of fossil fuels causes acid rain which knows no national boundaries. CO_2 emissions are accelerating global warming. The scarcity of petroleum resources will no doubt prompt a shift to coal. Burning more coal will only aggravate air pollution and seriously damage world agriculture and the global environment.

2.3. *Structure of the trilemma*

Under pressure from the population explosion, it is imperative to find a way of resolving three opposing factors that constitute a 'trilemma': economic development, ensuring a supply of food, resources and energy, and environmental conservation (see Fig. 1) [4]. Resolving this trilemma is critical to the future of humankind.

3. The importance of electrical energy

As energy consumption continues to growth worldwide, electricity is playing an increasingly significant role. It is clean, safe and convenient to use at any time of the day or year.

3.1. *The developing nations: a massive increase in electricity demand*

The per capita electricity consumption rises in proportion to per capita GDP. As the developing nations pursue economic growth, they must procure a stable supply of electricity to achieve industrialization and to attract manufacturers. Electricity demand in the private sector can be expected to rapidly increase in tandem with economic growth.

3.2. *The developed nations: a greater reliance on electricity due to the maturing of society*

The electrification rates in advanced countries are as follows: France, 46%; Germany and UK, 34%; USA, 37%; Japan, 40%. These rates are already high and are expected to rise further.

In the early 21st century, the Japanese population is expected to peak at 126 million inhabitants and gradually decline thereafter. The proportion of the population aged 65 years and older is predicted to increase by 14% between 1990 to 2020, rising from 12.5% to 26.6% [5]. As such, the demographic ageing of Japan will far surpass that experienced by European nations. The countries of Asia, with their rapidly growing populations will also eventually undergo the same phenomena as Japan and by the middle of the next century, their populations will stabilize and their societies will also mature.

The rise in the population of the elderly will entail computer-based assistance for the infirm and this will require more machines and home appliances. It will be necessary to have a clean, safe, easy-to-use power source which will increase reliance on electricity.

3.3. Era of Information Technology: the demand for a high-quality electricity supply

On a global level, manufacturing is becoming more technologically advanced and society is becoming increasingly dependent on the flow of information. More and more factories are now automated, and the supply of electricity must not only be stable, but also of high quality. The use of portable telephones is rapidly spreading in areas where construction of telephone lines has lagged behind. The mainstay of the telecommunications infrastructure, such as relays and exchanges, is electronic technology. Despite battery-powered backups, this infrastructure still requires a reliable power supply.

4. The role of the electric power industry and various issues

Society is becoming more reliant on electricity. Considering the limits to fossil resources and the environment, the role of the electric power industry and its responsibility are tremendous.

4.1. Efficient use of fossil fuels

Today's thermal power stations must raise their power generation efficiency above the present 30 to 40% level. There are three main ways to do this: (i) raise combustion temperatures to increase generation efficiency; (ii) utilize surplus heat and raise overall efficiency through cascade generation, and (iii) use waste heat from the final stage to raise overall energy use efficiency. Combined generation systems can be built and co-generation systems, which can supply both heat and electricity, may be able to use surpluses of both to raise energy efficiency.

4.2. Effective use of natural energy

The use of renewable natural energy sources is essential to end the present excessive dependence on fossil fuels. Electric energy, as a form of primary energy, now accounts for a mere 10% of all primary energy consumption, nearly all of which is either hydropower or nuclear power. Further development of geothermal and wind power resources in the future is desirable. Photovoltaic power generation, not only from facilities built by the electric power providers, but also from the rooftop solar panels of urban residences, will greatly contribute to a reduction in power demand peaks.

4.3. Operating power stations at high efficiency levels

The efficient operation of power stations is of great importance to reduce CO_2 emission. However, it is not possible for all power stations to operate at their rating, because power load often changes, depending on the season and time of day. This reduces the efficiency of operation and in turn, the power generation efficiency. Load leveling is a remaining problem that power suppliers are unable to overcome by themselves.

5. The role of the battery in an electricity-based society of the future

5.1. The need for electric energy storage: Japan as an example

Many parts of the world where the demand for electricity is soaring are located in subtropical regions. In the near future, when living standards improve, there will no doubt be a great demand for air conditioning both in homes and offices. As a result, midday load peaks will become more acute.

In Japan, the increase in demand for air conditioning created a load peak in the summer. The annual load factor is declining and is currently less than 60%. Load leveling has been attempted in Japan by pumped-storage hydroelectric plants. The capacity of these facilities is currently 20 000 MW, which accounts for 10% of total power generation capacity.

The Central Research Institute of Electric Power Industry (CRIEPI) has estimated the proper capacity of power storage facilities of the future and their percentage of total generation [6]. The results show that in 2030, the most suitable power storage facility capacity will be from 30 000 MW, in a low-growth scenario, to 55 000 MW, in a high-growth scenario, accounting for between 10 and 15% of total power generation capacity. The estimates suggest that new forms of energy storage, such as battery energy storage systems, will have to be developed to supplement the pumped-storage facilities.

5.2. Non-fossil-fueled dispersed power sources and their link with batteries

Natural renewable energy sources will be central to the future. In developing countries and other parts of the world where infrastructure construction has lagged behind, photovoltaic power generation and wind power generation are promising self-contained power sources. Nevertheless, battery storage facilities are needed to ensure a stable supply of good-quality power, day and night.

In Japan, electric power companies are now able to buy the electricity generated by solar cells. This should assist the spread of photovoltaic power generation. A lifecycle assessment on CO_2 emission reveals that it is better for solar panels to be placed on the roofs of houses than for power companies to set up solar farms as shown in Fig. 2 [7].

Although solar cells are effective in reducing midday load peaks, in the case of Japan, the period of peak demand in summer is not at noon, but at around 3 p.m. As a result, the peak reduction effect is halved. CRIEPI calculations suggest that if 2 h of power produced by the solar cells at their rated

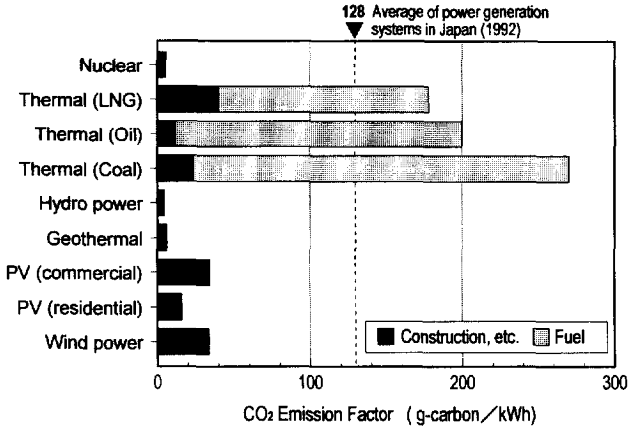

Fig. 2. Greenhouse gas-emission factor of power generation systems [7].

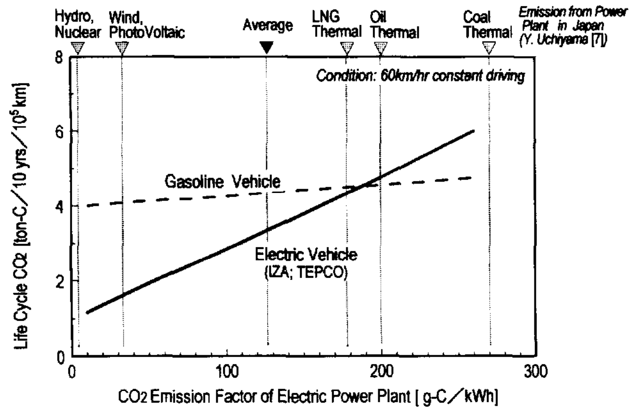

Fig. 3. Life cycle assesment on CO_2 emission of ordinary motor cars and electric vehicles [10].

output could be stored and then applied during the peak, there would be a peak cutting effect from this stored power [8].

If solar cells are connected to storage batteries, it would be possible to take also advantage of the cheaper electricity rates available at night. In Japan, the customer can choose a time-of-use rate, in which the price of electricity is lower at night and higher at daytime. This is intended to encourage a shift to using power at off-peak times. CRIEPI is developing small battery energy storage systems called 'load conditioners' to help reducing the load by drawing and storing power at night, and releasing it during the day. CRIEPI has completed development of a system which can be connected to solar cells and has carried out field tests using model houses [9]. When storage batteries are connected to solar cells, even if the supply of power from the power line is interrupted, the batteries will instantly compensate for the shortfall from the solar cells. Furthermore, excess power generated by the solar cells will be stored in the batteries. This system can also supply stable, high-quality power following natural disasters. CRIEPI concluded that the lifecycle for such a system using lead/acid batteries is too short, and would like to see the development of batteries with longer lifespans.

Load conditioners are equipped with microprocessors. If the load conditioners are linked in an information network, it should be possible to use them even under a real-time rate system by switching from one algorithm to another.

5.3. Electric vehicles — a major step to reduce air pollution

In California, the development of electric vehicles as zero-emission vehicles to meet the requirements of the State law to curb air pollution is attracting considerable interest from all over the world. The goal of these regulations is to reduce NO_x, CO and particle matter emissions from gasoline powered vehicles.

The CO_2 emission per unit of power generated at the power station will also contribute to lower CO_2 emissions. Fig. 3 shows CO_2 emission volume of two vehicles, an ordinary car and an electric sports car prototype developed by the Tokyo Electric Power Company, calculated through a lifecycle assessment under identical conditions [10]. If the electric car is recharged with electricity generated at a coal burning power station, the CO_2 emissions will not be reduced, and may actually increase. In contrast, if the source of the power is a renewable source, such as solar cells or hydroelectricity generation, CO_2 emissions can be reduced with certainty. In this example, the electric car uses nickel/cadmium batteries with a cycle lifespan of 2000 charging cycles and changing the batteries has not been accounted for. If a single change of batteries is included in these calculations, the entire curve for the electric car shifts upwards, qualitatively and the electric car loses much of its advantage over the gasoline-powered vehicle. However, if the energy density of the batteries can be increased and the charge/discharge efficiency raised, the economy will improve and the curve will again shift downwards. This will provide a useable means to reduce CO_2 emissions.

5.4. Effects of the introduction of electric vehicles and load conditioners

Both electric vehicles and load conditioners are examples of dispersed energy storage systems. CRIEPI has calculated the effects of their introduction in Japan [6]. If we assume that in 2030 electric cars comprise 10% of all vehicles and 10% of homes have load conditioners, the annual load factor will rise by 3 or 4%. It will be possible to reduce the power storage facilities that would otherwise have to be installed by 10 000 to 20 000 MW, and the unit cost of power generation will also fall.

5.5. A glimpse at the aging, information-based society of the future

In a mature society of the future, robots may undertake daily functions such as cooking and housework and may look after the elderly and the handicapped. New wireless telecommunications devices and electronic equipment will be used in homes and offices. Intelligent electronic devices in the future will include portable TV-telephones that have auto-

Table 1
Targets of lithium secondary battery R&D in the New Sunshine program

	Long-life type	High-energy-density type
Gravimetric energy density (Wh/kg)	120	180
Volumetric energy density (Wh/l)	240	360
Cycle life (no. cycles)	3500	500
Energy efficiency (%)	>90	>85
Cell capacity [a] (Wh)	Hundreds Wh class	Hundreds Wh class
Battery system capacity [a] (kWh)	20 kWh class	30 kWh class

[a] Targets in LIBES, Japan.

matic translation functions. A wide range of new products will allow global communication, unhindered by language or format. They will all need batteries. This will totally change the lifestyles of the elderly and the physically disabled.

6. The battery with the most promise for a battery-based society: the lithium battery

If an electricity-based society can transform energy efficiently, and through its efficient use, create a comfortable living environment, humankind will be able to overcome the trilemma. To create such a society, it will be necessary to develop new types of rechargeable batteries and use them effectively.

Rechargeable lithium batteries are the most promising. They have a high energy density which makes small size and lightweight possible. In addition, they have an energy storage efficiency and charge/discharge efficiency which is comparatively greater than those of other rechargeable batteries.

Energy density of a cell has greatly improved since 1990. The energy density of small, cylindrical lithium batteries at 300 Wh/l is triple that of lead/acid batteries. Unfortunately, today's commercially available rechargeable lithium batteries are primarily used in video cameras and other small devices. Table 1 shows the goals of lithium battery development in Japan [11]. In the future, commercial production of rechargeable lithium batteries for larger applications such as electric vehicles, load conditioners and domestic robots is likely.

The wider use of lithium batteries will depend on cost reduction and the development of a recycling system to protect the environment. The battery-powered systems of the battery-based society of the future will have to automatically recharge themselves during times of low power demand and offer high reliability and reasonable cost performance.

7. And finally: 'to know is nothing at all; to imagine is everything'

Anatole France (1844–1924) is France's most well-known author, philosopher and Nobel Prize recipient. In his novel 'The Crime of Sylvestre Bonnard', appears the line 'Savoir n'est rien; imaginer est tout', or 'To know is nothing at all; to imagine is everything'. This wise observation aptly describes efforts to develop rechargeable lithium batteries. Rechargeable lithium batteries will be essential to the electricity-based society of the future and the ultimate goal of achieving a battery-based society.

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