New Energy Option for 21st Century

Recent Progress in Solar Photovoltaic Energy Conversion

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Abstract

A review is given on some important roles of the solar PV technology in sustainable development of 21st century civilization. Firstly, the motivations of the industrial developments attributable to the energy revolutions since James Watt's steam engine of the 18th century are discussed. The transitions of natural resources from solid (coal), liquid (oil) and gas (LNG, LPG) are closely related to not only the economy of mass production, storage and transportation but also environmental issues. Secondly, a brief discussion is given on **"the 3E Trilemma "** which is the most important issue facing in the 21st century's civilization life. Thirdly, a new strategy for the renewable energy promotion, the so called —Fundamental Principle to promote New Energy Development and Utilization—, and its action plan for PV technology development up to year of 2010 are introduced.

In the final part of the paper, the prospect of future industrialization of photovoltaics is discussed, then possible new roles to contribute to global environmental issues by the PV system developments are introduced.

Keywords: PV System, 3E-trilemma, environmental issue, clean energy revolution, new sunshine project, renewable energy

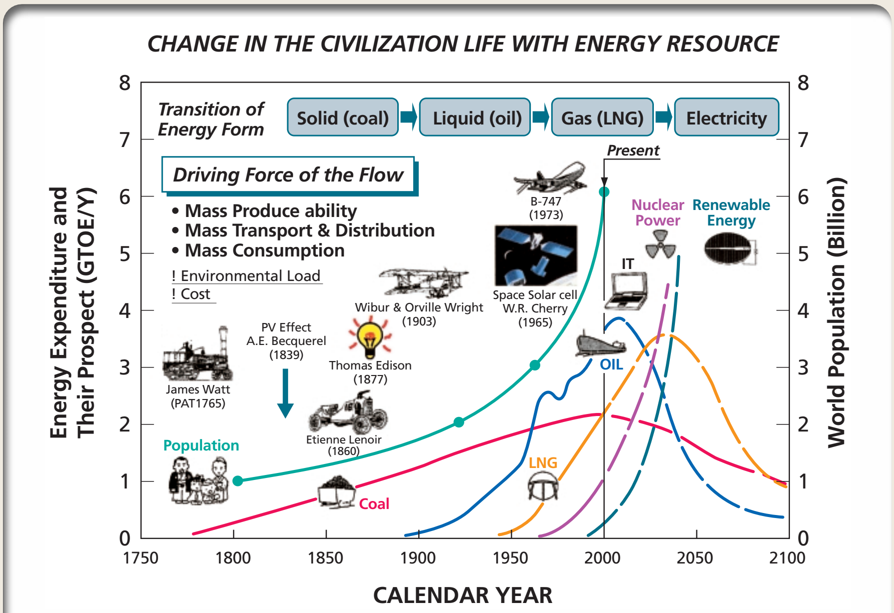

Fig. 1 Evolutions of industrial developments in civilization life with the form of energy resources

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1. Evolution of Civilization Life with Energy Revolutions

The industrial revolution started with the invention of steam engine by James Watt in 1765. However, technological maturity from R & D to market penetration, usually takes 15-30 years. The steam ship and the steam locomotive fueled by coal were developed in the 19th century. The same is true during the petroleum age, that is, Etienne Lenoir's invention of the internal combustion engine was in 1860 [1], but the petroleum age bloomed in 20th century with the development of gasoline engines for the automobile and the airplane. Figure 1 shows the changes in civilization with form of the energy resource since the start of the industrial revolution. Energy expenditures for the three main fossil fuels are plotted separately up to the year of 2000, and their future prospects are also predicted (the dashed lines in the figure) by following the renewable energy promotion scenario. From the observation of the relation between the industrial developments and their origins of energy resources, coal → oil → gases including LNG and recent LPG, the key issues are the convenience to respond to mass consumption of energy, that is, mass production technology, and ease of transport and storage. The driving force in the energy revolution is based upon the so called **"the Great Principle of Economy"**.

With this economy of usage reason, the form of primary energy resources have evolved from solid, liquid to gases. Another reasons originate from the environmental load. As can be seen from Table 1[2], the pollutant emission factor for electricity generation per kWh.on the unit of carbon equivalent gram is 322.8 for coal, 258.5 for oil and 178.0 for LNG, respectively. According to the recent energy analysis survey [3], the electricity generation factor in secondary energy is more than 40% in developed countries, and will increase to

Table 1 Pollutant Emission Factors for Electrical Generation (g/k Wh)

Pollutant Emission Factors For Electrical Generation (g/kWh): The Total Fuel Cycle

Energy Source	CO_2	NO_x	SO_x
Coal	322.8	1.8	3.400
Oil	258.5	0.88	1.700
Natural Gas	178.0	0.9	0.001
Nuclear	7.8	0.003	0.030
Photovoltaics	5.3	0.007	0.020
Biomass	0.0[1]	0.6	0.140
Geothermal	51.5	TR	TR
Wind	6.7	TR	TR
Solar Thermal	3.3	TR	TR
Hydropower	5.9	TR	TR

TR=trace

**Fossil fuel emission factors provided hy The American Gas Association; for nuclear and renewable energy sources from the Council for Renewable Energy Education.*

[1] with biomass fuel regrowth program

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50% in the 21st century. Electricity is the most convenient energy form, for the above-mentioned reasons, with respect to mass production, transport and distribution.

2. 3E-Trilemma and New Energy Strategy

In the discussions of the Grand Design for the 21st century's civilization, great attention is focused on the 3E-Trilemma. That is, for the activation of economic development (E:**Economy**) to occur, we need to increase energy expenditure (E:**Energy**). However, this raises the environmental issue (E:**Environment**) of more emissions of pollutant gases. On the other hand, the political option to restrain pollutant gas emission halts economic development. This problem is called the **3E-Trilenma**. Figure 2 shows an illustration of the cyclic correlation of economy, energy and environment [4]. Here, importance is placed on the change in the circuit from the infrastructure of fossil fuel's energy supply to that of renewable energy development and supply. According to the result of world energy trends analysis, the energy consumption per capita in a country is directly proportional to the country's annual income per capita or its GNP (Gross National Product) [4]. On the other hand, the world's population is steadily increasing as shown in Figure 3 (it reached about 6.1 billion in the year 2000), and it can be expected that worldwide energy demand will increase by multiples of the population increase and another factor due to promotion of modernization. This positive increment in energy demand seems unavoidable in the near future, even if energy saving technologies can be implemented to a moderate degree. For example, the rate of energy consumption per production unit in the heavy industries of developed countries might decrease, but this decrease will be completely compensated by the rapid increase in energy demand in moderate developed countries such as China, Malaysia and Thailand. As can be seen in Fig. 4, energy consumption in East and South Asia area is rapidly increasing with economic growth, and the percentage of imported fuels will reach almost 70% by the year 2010 [1].

Considering the two-sided nature of the energy policy, that is, continuous growth of mass consumption of the limited fossil fuels on one hand, and the severity of the global environmental issues on the other hand, the Agency of Industrial Science and Technology (AIST) of the Ministry of International Trade and Industry (MITI) of Japan decided to establish the "New Sunshine Program" for the development of clean energy technology and environmental technology in 1993. Figure 5 illustrates the comprehensive structure of the new program and its relation to the Sunshine Project, which was formulated in May 1973 prior to the first energy crisis and started in 1974. The Moonlight Project, which was initiated in 1978 and charged with the development of energy saving technologies, is another environmental technology project progressed from 1989 [5]. The past injected budgets are also shown in the figure. While the new pro-

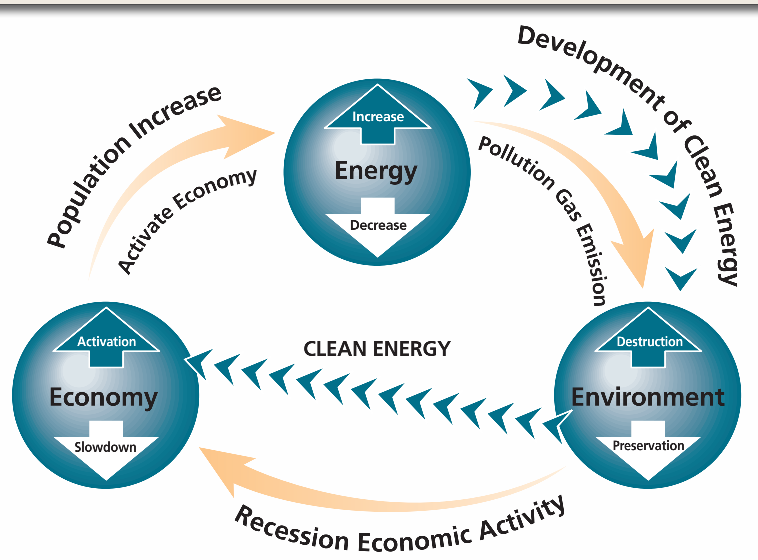

Fig. 2 3E-Trilemma, the most important task assigned to 21st century's civilization. Only way to solve it is to develop clean energy technology.

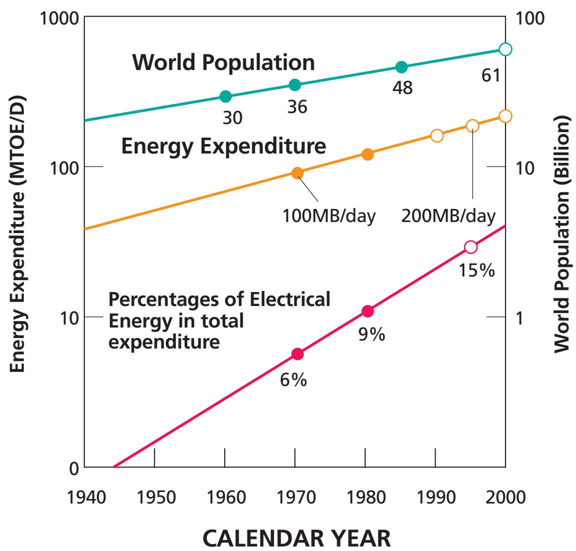

Fig. 3 Growth of world population, and energy demand total energy and electricity demand. Percentages are the ratios of electricity to total energy.

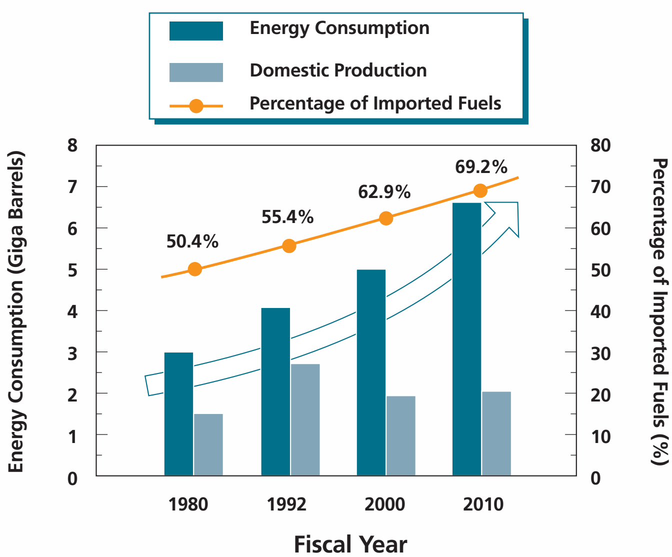

Fig. 4 Transitions of energy consumptions and domestic productions in East and South Asia, and the percentage of imported fossil fuels. (The area covers 11 countries)

gram consists of three parts; a) Renewable Energy Development Technology, b) High Efficiency Utilization of Fossil Fuels and Energy Storage, and c) International Energy Cooperation, the so-called WENET (World Energy Network) for utilizing hydrogen fuel produced by PV and a wide area energy distribution network system nicknamed “Eco-energy City”.

3. Key Issues for PV Industrialization

The direct conversion of solar radiation to electricity by photovoltaics has a number of significant advantages as an electricity generator. That is, solar photovoltaic conversion systems tap an inexhaustible resource which is free of charge and available anywhere in the world. The amount of energy supplied by the sun to the earth is more than five orders of magnitude larger than the world electric power consumption level that currently keeps modern civilization going. Roofing tile photovoltaic generation, for example, saves excess thermal heat and preserves the the local heat balance. This means that a considerable reduction of thermal pollution in densely populated city areas can be attained.

Figure 6 shows the trend in solar cell module annual production in Japan since 1993 as surveyed by the Optoelectronic Industry Technology and Development Association (OITDA) [6]. As can be seen from the figure, a remarkable increase of the annual production has been seen since the start of the New Sunshine Project in 1993. In spite of the various advantages of photovoltaic power generation as mentioned above, a big barrier impeding the expansion of large-scale power source application has been the high price of solar cell module, which was more than $30/Wp (peak watts) in 1974. That is, the cost of the electrical energy generated by solar cells was very high compared with that generated by fossil fuels and nuclear power generation. Therefore, the cost reduction of the solar cell is of prime importance. To achieve this objective, tremendous R&D progress efforts have been made in a wide variety of technical fields over the past 20 years, from solar cell materials, device structure, and mass production processes to complete photovoltaic systems. The result of the most recent fifteen years of R&D

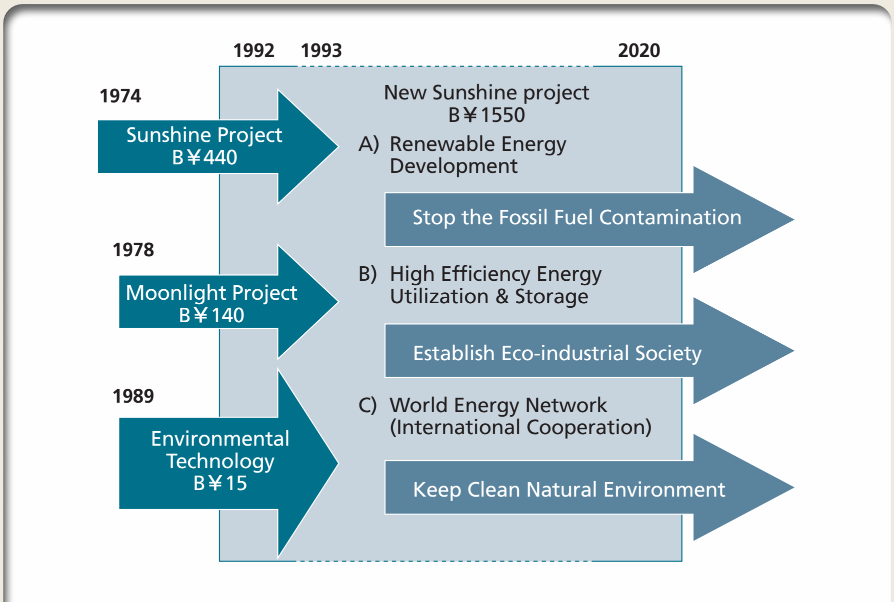

Fig. 5 Organization and objectives of the New Sunshine Project

efforts has been about a one order of magnitude price decrease, and currently, the module cost is less than $4/Wp in a firm bid for a large scale purchase.

In December 1994, a new initiative in the Japanese domestic renewable energy strategy, an initiatives of **"Fundamental Principles to Promote New Energy Developments and Utilization"** has been approved in a cabinet meeting. Related actions in the form of tax reductions, government subsidies, etc. were approved by the Congress on April 10, 1997 [5]. These strategies involve not only ministries and government offices but also local government authorities and private enterprises.

The new government policy targets development and promotion of PV technologies as being the most promised projects. Integrated installations of 400-MWp PV modules by FY2000 and 5.0 GWp by FY2010 for Japanese domestic use have been scheduled, as shown in Fig. 7. A special tax reduction for investment in renewable energy resources and government financial support in the form of a 50% subsidy on PV systems for public facilities, **PV Field Test Experiments**, and a 33.3% subsidy on private solar houses, **PV House Planning** of the field testing etc. are settled and in progress as the goverment regulations. Figure 8 shows number of government-subsidized PV houses over the period of the recent six years. As can been seen in the figure, the number of government subsidized PV house has been doubled each year. In the PV Field Test Experiment, a total of 259 sites generating 6.84 MW have been installed during the seven years since 1992. A noticeable trend of this project is its accelerated expansion. 73 sites generating 1.94 MW were installed in 1998 alone. As the result of the accelerated promotion strategy, the price for a 3-kW solar photovoltaic system for a private home, for example, has decreased sharply, down to 1/4 from 1993 to 2000 [4]. The figure also extrapolates the results to the expected cost of a mass-production scale program in the near future.

4.Future Prospects for Solar Photovoltaics

The targeted milestone volume of 5 GWp for PV installations by the year 2010 has been the topic of many discussions. For example, if 200 thousand solar PV homes were built annually, which corresponds to nearly 10% of the private homes built annually, the target can be met in only five years assuming a 5 kW PV/home. Figure 9 presents a scenario of cumulative PV system installations in Japan from the present day to 2030. The estimated installation volume of 65 GW in 2025 might cover more than 40% of the peak savings of electrical energy even taking into account the 12.5% PV system operation efficiency.

Figure 10 shows results of a simulation on the future trend of primary energy consumption (a) and the electricity generated by

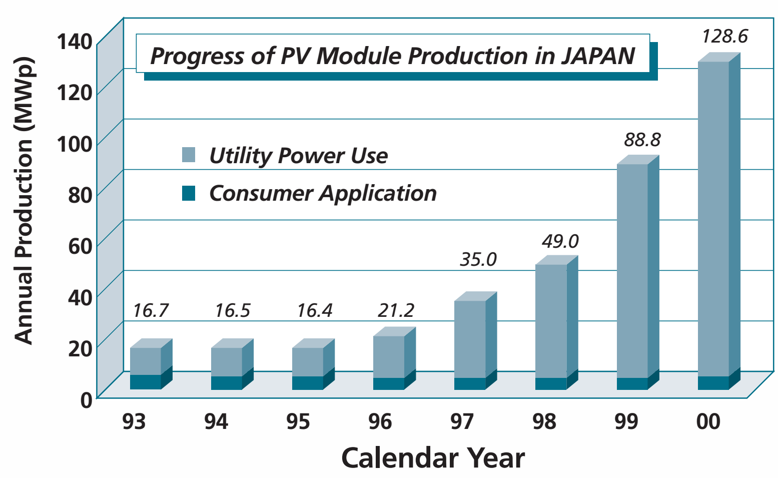

Fig. 6 Recent transition of the PV solar module shipment in Japan

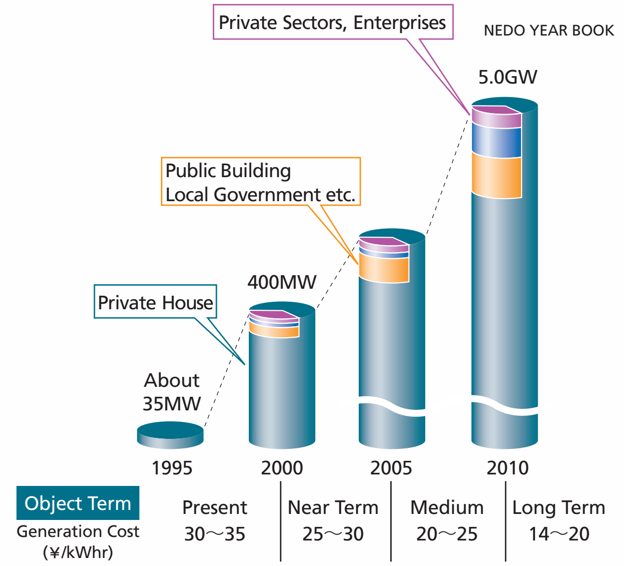

Fig. 7 NSS project milestone for PV system installation up to 2010

various energy resources (b) [7]. As can be seen in the figure (a), about 50% of the primary energy could be supplied by non fossil fuel which is nuclear plus renewable energy including PV by about 2050. As for electric power generation, 2040 will be the critical period in which renewable energy sources become the majority.

As described in the previous section, solar photovoltaic power generation is an almost maintenance-free clean-energy technology. Therefore, the penetration of PV technology into utility power generation might be of prime importance for market size expansion as a whole, using the scale merit of solar cells in the PV system development . With an increase in feasibility of semi-power applications and the exploitation of maintenance-free solar photovoltaics, many methods of anti-pollution processing can be performed with solar photovoltaic power. For example, ashing of pollutant gases by glow discharge decomposition and cleaning of water by electrochemical processing, as shown in Table 2 [8]. Mass production of hydrogen energy in the Sahara desert is planned using solar photovoltaics [9]. Photovoltaic water pumps and planting of trees may also help to halt desert expansion and to "green" the desert. The "Gobi project" has been organized for this purpose. In 1990, a preliminary study team began a survey of natural conditions in the Gobi Desert as part of a Japan-Mongolia program of cooperation [10].

These considerations indicate that an economically feasible age of photovoltaics will come earlier than expected in the near future, if efforts continue to be made to promote R & D work and through market stimulation. The most important emphasis should be placed on stopping the effects of contamination by fossil fuels with a worldwide energy policy and development of this novel, clean-energy technology for the future benefit of all mankind.

The energy revolution from coal age to the oil age was accomplished within only a quarter of a century from 1950 to 1975. The reason why the transition was so short is the large scale merit of oil in terms of mass production at the petrochemical plant. With respect to scale merit, the merit of mass-produced solar cells might be greater than that of oil at the stage of well-developed PV utilization systems. As has been reported elsewhere semiconductor devices have the highest scale merit, a fact that has been identified as having been responsible for the solid-state device revolution, from the age of the vacuum tube to today's electronics industry. For example, the DRAM (Dynamic Random Access Memory) has a scale merit of 25%. This means, if one increases production by one order of magnitude, the cost per unit becomes one fourth. Let us embark on a new energy revolution with clean-energy photovoltaics. Might it be possible to accomplish the clean-energy revolution within the next 25 years? It would be a worthy challenge, no longer simply a fanciful dream.

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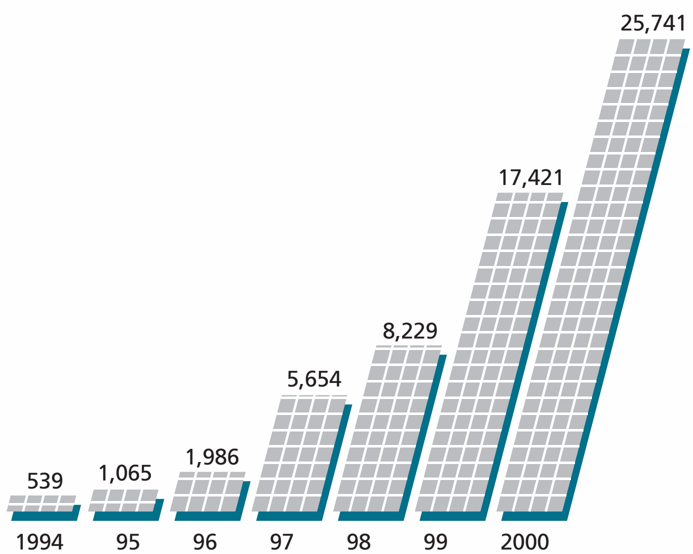

Fig. 8 Number of PV house approved for government subsidy

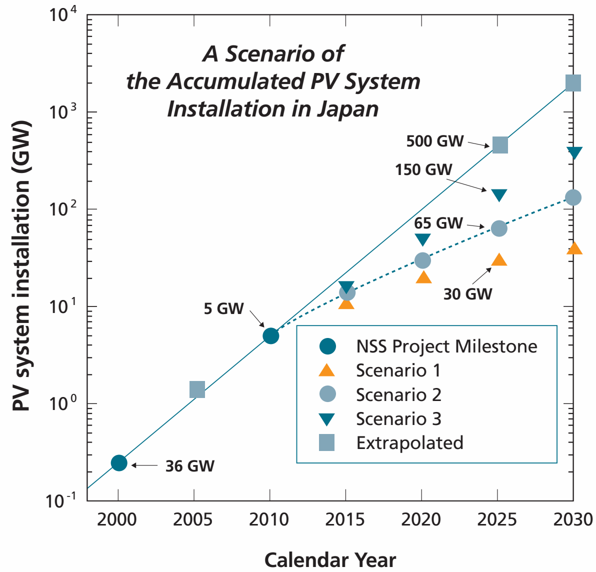

Fig. 9 Scenarios of cumulative PV system installation in Japan

Table 2 Contributions to the global environmental issues by PV

Local	(1) Solar PV power generation	Clean sustainable energy resource
	(2) Cleaning of polluted air	Ashing of pollutant bases by glow discharge decomposition by PV
Environment	(3) Cleaning of water	Electrochemical processing by PV
	(4) Generation of hydrogen energy	Electrolysis of water by PV
Global	(5) Stop of desertification Greening of deserts	PV water pumping at plantations

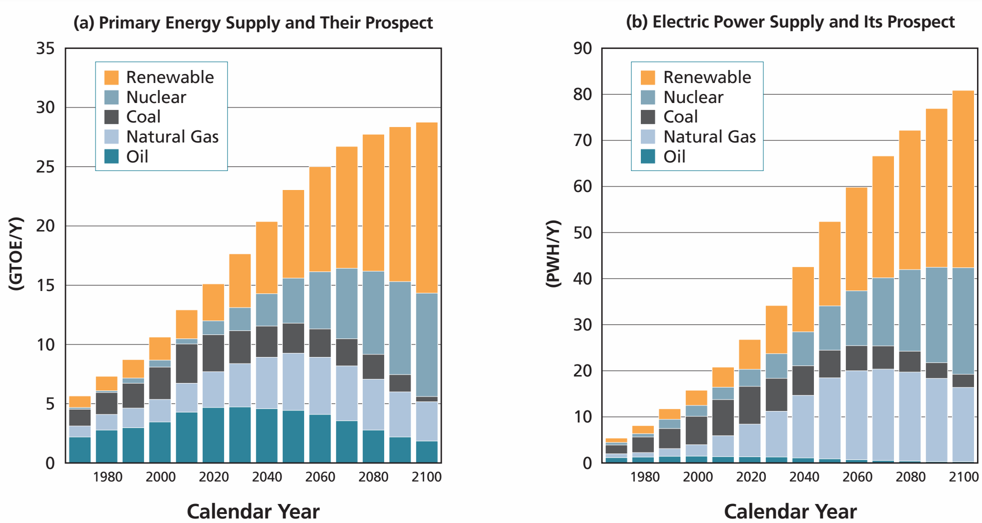

Fig. 10 Past expenses and prospects of the world primary energy demand (a) and that of electric power demand (b) for the 21st century calculated for the sustainable development scenario

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