The Photovoltaic power generation era is coming
(Global energy network equipped with solar cells and international superconductor grids: GENESIS)

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Abstract. Solar cells are considered a critical technology for overcoming global environmental problems and energy problems. This paper reviews the development history, current status, and application technologies of solar cells. The paper concludes with a discussion on the prospects of a future global-scale energy supply system based on solar cells.

1. Introduction
Solar energy is an ideal form of energy because it is clean, inexhaustible, and available everywhere in the world. The Earth receives 170 billion MW of solar energy from the Sun. Among the methods available for utilizing the Sun's energy, the most prominent method is solar cells, which use the photovoltaic (PV) effect of semiconductors to convert solar light energy to electrical energy. In this paper, the author will review the steps and status of solar cell development before going into solar cell applications. Then the author will cover future prospects by talking about a global energy supply system comprised of solar cells.

2. Need for clean energy
2.1. Dwindling energy resources
The consumption of fossil fuels has reached a turning point from the standpoint of confirmed global energy reserves, as shown in Figure 1.

Figure 1. Reserve of various energy sources.
If we continue to consume energy at current levels, we will exhaust all fossil fuel resources on the Earth within 200 years. Not only is there a limit to the ultimate amount of reserves, but predictions hold that the future population will increase, as shown in Figure 2. Therefore, we can expect an explosive increase in the amount of energy consumed, shown in Figure 3, as the population of the world and energy consumption per capita increase. In 2020–2030, the gap between the energy required for humankind and the production volume of fossil fuels (called “energy gap”) will grow. As a result, we need new energy sources.

![Figure 2. Predicted future world population.](image1)

![Figure 3. History of energy consumption by human.](image2)

2.2. Solar energy as a new source of clean energy

In view of global environmental problems and dwindling energy resources, we must develop new energy sources that are both abundant and safe as a substitute for fossil fuels. In this respect, solar energy is an ideal form of energy because it is clean, inexhaustible and available everywhere in the world. The Earth receives 170 billion MW of solar energy, as shown in Figure 4. This quantity is enormous that one hour's worth of solar energy could provide the annual energy needed for the entire world.
Among the methods available for utilizing solar energy, the most prominent method is solar cells, which use the photovoltaic effect (PV effect) of semiconductors to convert solar light energy to electrical energy, as shown in Figure 4. When sunlight enters a semiconductor which has a p-n junction, a hole with a positive charge and an electron with a negative charge are produced. These are separated along the p-n junction, and the positive and negative charges collect at both electrodes. When these two electrodes are connected, electric current flows and work is performed. Since sunlight is used as an energy source, the result is a power generating element that does not require fossil fuels, does not produce exhaust gas, and does not have moving parts. In addition to providing the many features of solar energy, solar cells also offer the following.

1. They provide electrical energy directly.
2. The conversion efficiency is the same irrelevant of the scale of power generation, that is, whether it is 1 W or 1 MW.
3. The service life is basically semipermanent because there are no movable parts.

Finally, silicon—the main material comprising solar cells—is the second most abundant element on the Earth, so there is absolutely no problem in resource availability.

2.3. The recent massive earthquake and PV
Recently, a massive earthquake occurred in the sea off East Japan. The earthquake and ensuing tsunami damaged nuclear power plants, resulting in serious accidents. We must propose to mankind a new energy source that will replace nuclear power. Solar cells can surely be considered a critical technology for overcoming global environmental problems and energy problems.

3. Progress in solar cells
3.1. History of solar cells
The history of solar cells began with Pearson in the United States in 1954. In 1958, solar cells were sent up in a satellite. Since then, they have been used in lighthouses and other locations, but their high price prohibits them from achieving widespread use. Following the so-called “oil shocks” of 1973, however, the superior characteristics of solar cells received attention as a substitute source of energy. Technical development was pursued in the United States and in each country of the EU under the supervision of the National Renewable Energy Laboratory in Japan as part of the Sunshine Project. The history of solar cells is shown in Figure 5. The first step is called "the dawn of solar power generation." The second step is called "advances to supply electric power." The third step is called "world-scale spread of solar power generation." We are currently in the world-scale PV era.
3.2. Status of solar cells

3.2.1. Types of solar cells
There are many different types of solar cells depending on the material used (silicon, compound semiconductors, organic semiconductors, etc.) and the shape of the crystals of the material (single crystal, polycrystalline, amorphous, etc., or a combination). Silicon is the typical material use for solar cells. Some representative methods for manufacturing Si solar cells are shown in Figure 6.

![Figure 5. History of the solar cell.](image)

![Figure 6. Comparison of fabrication methods of various solar cells.](image)

3.2.2. Improvements in conversion efficiency
The most important factor determining the performance of solar cells is the efficiency of energy conversion. In the beginning, the efficiency of solar cells was low, but conversion efficiency was improved by the efforts of many people, as shown in Figure 7. This data is based on the data of the National Renewable Energy Laboratory. The practical module used as electricity was improved to 13%–20% in the crystalline Si module, 6%–11% in the film Si module, 8%–12% in the compound (copper indium gallium selenide: CIGS) module.

3.2.3. Production volume and cost
The world production volume of solar cells increased to approximately 24 GW in 2010 (Figure 8). The world PV cumulative capacity was approximately 35 GW in 2010.

The sharp decrease in cost is a consequence of the increased production volume and manufacturing technology developments (Figure 9).
4. Applications and systems using solar cells

4.1. Use of solar cells in consumer electronics

First, solar cells were used as a remote power supply, such as power supplies for satellites and lighthouses. Then, solar cells were applied as a power supply for various kinds of electric products, such as electronic calculators, wristwatches and radios by Japanese electric companies. Figure 10 shows various types of electronic products powered by a-Si solar cells. These solar powered pocket calculators were put on the market in 1980. They were the world's first practical use of the amorphous silicon solar cells.
4.2. Application to power generation systems

In 1992, the regulations for grid connections of solar power generation systems were changed in Japan. PV system owners could sell the electricity produced by the PV system back to the electric power company through the utility grid. Figure 11 shows the first practical use of a reverse-flow PV system in an actual house (the author’s house). Reverse flow means that surplus power is fed back to the power system. Figure 12 shows the operation data for the PV system from 1992 to last year (2011), a period of more than 19 years. The peak electricity is stable, and the system still operates well.

Environmental problems have prompted governments around the world to expand plans to promote the PV. A new system called a Feed-in Tariff was established in Germany. It buys electricity generated by
PV systems at a high price (3 times the normal price). Similar systems are also spreading to other countries. Large-scale PV generation systems have been installed all over the world. Figure 13 shows a large-scale PV plant in Germany.

4.3. Effects of PV

4.3.1. Energy Payback Time (EPT) One of the most important concepts when evaluating solar cells as a new energy source is energy payback time (EPT). EPT is the number of years required for solar cell modules to generate the same amount of electric power as was consumed in their fabrication. ETP depends on the conversion efficiency and the production volume of solar cells.

\[ EPT = \frac{E_0}{E_g} \]  

where \( E_0 \) is the energy needed to produce PV, \( E_g \) is the annual energy generated by PV.

The EPT is estimated to be approximately 1 year for a-Si solar cells, and 1.5-2 years for poly-Si and single crystal Si solar cells\(^2\). In any case, the EPTs of these solar cells are much shorter than their lifetime, which is estimated to be longer than 20 years, that is, the solar cells can possibly self-multiply, as shown in Figure 14. Thus, solar cells are quite suitable as a new energy source.

![Figure 14. Self-multiplication of solar cells with solar energy.](image)

4.3.2. Reduction of CO\(_2\) emission The PV of 1 KW reduces CO\(_2\) emission to approximately 0.57 ton in one year. Table 1 shows the quantity of reduction of the CO\(_2\) emission according to the scale of the PV system\(^2\).

| Scale of the PV System | Quantity of Reduction of CO\(_2\) Emission (Unit ton) |
|------------------------|--------------------------------------------------------|
| 1KW                    | 0.56                                                   |
| 1MW                    | 5.6x10\(^2\)                                           |
| 1GW                    | 5.6x10\(^5\)                                           |

5. What are the challenges for PV systems?

Approximately 60 years have passed since the development of Si solar cells. During this time, their efficiency has increased 4 to 10 times. Their cost has decreased to approximately 1/100. This proves that PV systems can act as an alternative energy source.

However, PV is not yet sufficient to become a basic energy source for people.
Future problems include the following:
(1) The generation cost of the PV system needs to be equivalent to the conventional electricity cost, which is called "grid parity." It is necessary to cut the cost of the PV system by a half or a quarter.
(2) The life of the PV system must be much longer. It should be extended from 20 to 40 years.

6. Future prospects for the GENESIS Project
The author proposed a global energy system for the future of PV was proposed at the 4th PVSEC (held in Sydney, Australia) in 1989\(^3\). The project was named the GENESIS Project. GENESIS stands for a Global Energy Network Equipped with Solar cells and International Superconductor Grids. The project proposes PV systems to be built all around the world, especially in desert areas, and connected to one another by superconductive cables without transmission loss, as shown in Figure 15.

The shortcoming of the PV system is that it does not generate power at night. However, because the sun is always shining somewhere in the world, the electric power can be transported from the day-time areas to the night-time areas by an international network. Table 2 shows the world’s energy consumption and the required PV system area. It was estimated that in 2010, the world’s energy consumption will require approximately 14 billion kl of oil per year. Assuming 10% PV system efficiency, an area approximately 800 km\(^2\) would be required. This area is not very large and equals to only 4% of the world’s total desert area.

![GENESIS Project](image)

**Figure 15.** The GENESIS Project.

| Year | Energy consumption (billion kl/y.) | System efficiency (%) | System area (km\(^2\)) |
|------|----------------------------------|-----------------------|------------------------|
| 2000 | 11                               | 10                    | 729                    |
| 2010 | 14                               | 10                    | 802                    |
| 2050 | 35                               | 15                    | 1,030                  |
| 2100 | 111                              | 15                    | 1,850                  |
Implementing this project is not unrealistic. The three steps shown in Figure 16 reflect our view for realizing this project.

Step 1: PV systems are installed in homes and factories, and these are connected to an electric power grid. 35 GW of the global PV systems are connected to the utility grid. Note that the first step of the GENESIS Project has already started.

Step 2: Each country’s transmission lines are subsequently connected to create an international network. In Europe and other continental regions, electric power supply grids have already been connected to those in other countries.

Step 3: Many large-scale PV plants are built in the desert to expand the international country network, and thus creating a global network.

Not only the solar cells, but also superconductive cables are important for the GENESIS project. A breakthrough occurred 5 years ago in this field when Bi-based high-temperature superconducting wires were developed by Sumitomo Electric Industries, Limited\(^4\).

These wires have been drastically improved since then. The critical current exceeds 250 A, and the cable length exceeds 1 km. In fact, in 2006, a superconductive cable was connected to a practical operating power grid in the United States.

7. Conclusions
The serious nuclear power plant accident has prompted people to reaffirm the need for safe, clean energy. PV systems are the leading candidate as a new, clean energy source. In order to resolve our energy problems, we must build a global PV system.

References
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