THE STATE-OF-ART IN PHOTOVOLTAICS

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ABSTRACT

The paper reviews the principal characteristics of photovoltaic power generation (PV) systems firstly and briefly as a solar energy utilization apparatus as well as dispersed power system. The possible wide variation of system configuration and size enables many types of applications such as consumer goods, small stand-alone systems, solar home systems (SHS), rural village electrification, gird-connected roof-top residential systems, building integrated PV modules (BIPV), multi-megawatt centralized power station and very large scale PV systems (VLS-PV). Selectable types of PV arrays are: fixed flat-plate, one-axis flat-plate-tracker, non-imaging fixed concentrator, trough concentrator, 2-axis point-focus concentrator, etc.. The paper also briefly summarizes world and Japanese activities concerning photovoltaic systems including those for residential use, which is one of the major targets for a domestic alternative energy supply. Fiscal year 1999 marked the 25th anniversary of the Sunshine Project that was initiated in July 1974. The Sunshine Project was subsequently reorganized into the New Sunshine Program to include renewable energy, energy conservation and environmental technology. The major target of the Photovoltaic Technology Development Project in the Program, from an early stage of R&D, has been focused on utility-connected, residential applications mounted on roofs. Recently, it can be considered that technologies for the target have been fundamentally established and a series of new activities have been introduced to promote the commercialization and diffusion of PV systems. To review those activities, several condensed tables are presented, i.e., R&D history of residential applications, recent trends in regulation and code improvements, and new institutional activities to disseminate PV systems.

1. ADVANTAGES OF PHOTOVOLTAIC SYSTEMS

1.1 World Energy Tendency

In considering the future energy problems, basic conditions and tendencies may be summarized as follows:

(1) World energy demands will rapidly expand toward the middle of the 21st century, due to the world economic growth and population increase.

(2) The sustainable prosperity of human beings cannot be expected any longer if global environmental problems are ignored.

(3) Although the need for nuclear power generation will enlarge as a major option, difficulties in its siting are getting more and more notable at the same time.

(4) Alternatively, renewable energy is considered to possess large potential as well as providing energy conservation, carbon-lean fuels and CO2 disposal/recovery.

(5) The share of electric energy is rising more and more as secondary energy.

(6) Thinking about the long lead time for the development of energy technology, it is urgently

necessary to seek new energy seeds applicable for the next generation.

Accordingly, one major option is apparently to utilize renewable energy resources. Continuing efforts to develop renewable energy technologies over the next 15 years are considered to be even more necessary.

1.2 Solar Energy Resources and Potential

Solar energy is an origin of almost all of renewables as illustrated in **Fig.1**. Incoming radiant energy from the sun to the globe can be estimated as 172 500 TW (TW $=10^{12}$ W) by the multiplication of solar constant, 1.353 kW/m^2, by the cross section of the earth, 1.275×10^{14}m^2. Approximately 70 % of this energy, 120 000 TW, enters the terrestrial sphere and then becomes an energy origin to drive a variety of natural energy flow and phenomena. It reaches the atmosphere, hydrosphere, upper lithosphere and biosphere. From the lower lithosphere, geothermal energy also flows out, which is not of solar origin. Its percentage is not so large compared with the solar quantity. In addition, another smaller form of non-solar content is induced by the gravitation of the moon, i.e., tidal energy(1).

Since solar energy flow is distributed place to place, its density tends to become weak or uneven. This may be a main reason for difficulties in the efficient and economical utilization of renewables.

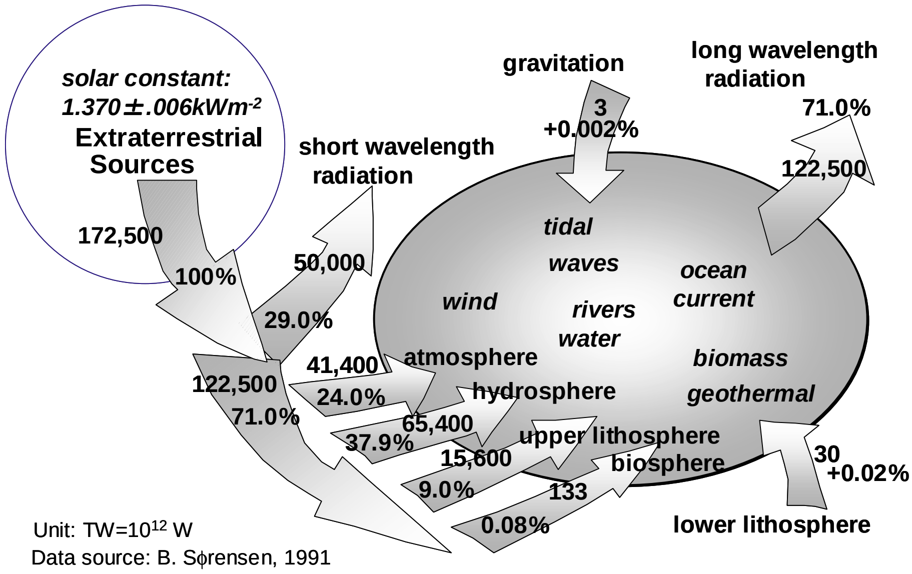

Fig.1 Renewable Energy Balance on the globe

As shown in **Fig.2**, the overall capability of solar energy is enormous on the earth. If the Gobi desert area between the western part of China and Mongolia is covered by ordinary PV modules nowadays with the space factor of 50%, it can generate electricity as much as the present world primary energy supply(2).

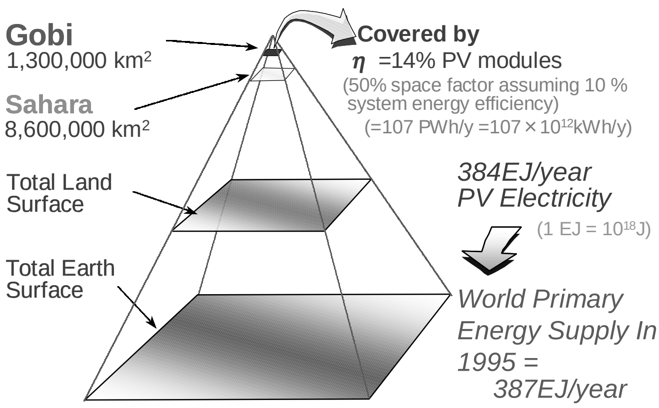

Fig.2 Solar pyramid showing the capability of solar energy

These are quite hypothetical values, ignoring the presence of loads near by the desert. However, at least it is indicating high potentials as primary resources for developing districts located in such a solar energy rich regions.

1.3 General Overview of Photovoltaics for the Future

It is believed that PV systems are very effective for eliminating the green house effect. In principle, features in PV system utilization are summarized as follows.

(1) PV systems as solar energy utilization

Since photovoltaics are one kind of solar energy utilization means, it has common features with other types of solar energy.

- Enormous total amount,
- Inexhaustible, renewable energy,
- The cleanest energy without emissions into environment,
- Usable everywhere on the earth without extremely uneven distribution,
- Deviating hour by hour and affected by the influence of weather.

(2) PV systems as solid state, static device

A photovoltaic system also has characteristics as a semiconductor device because photovoltaic cells are manufactured by semiconductor technology:

- Simple, direct energy conversion device,
- Light-weight enough for roof-top installation, aiming at efficient land utilization,
- Easy handling and maintenance-free system without rotating parts,
- Free selection of system scale by modular building-up configuration,
- No fuel transportation required for remote site,
- Flexible, economical investment plan attainable through short term construction.

(3) PV systems as decentralized energy systems

Normally, it is said that PV systems are appropriate for decentralized power generation rather than a central power station.

- On-site station free from transmission/distribution losses and costs,
- Flexible facility construction plan to meet local demands,
- Higher overall reliability obtainable because of small influence of individual system-down,
- Possible improvement of distribution grid characteristics by using high speed control of power conditioners,
- Useful for energy resource diversification of a certain region.

Since, by a simple calculation as described later, a large amount of PV installation is obtainable by using unused land throughout the world, studies about VLS-PV are to estimate whether it is feasible to ignore some of the advantages for decentralized systems.

2. PV SYSTEM TECHNOLOGIES

2.1 General configuration of System

Figure 3 shows the generalized configuration of PV systems. A minimum system can be composed of a PV module and a directly connected DC load. On the other hand, all the components indicated in the figure can be put together for complicated application. These components are selected to meet the purpose of a PV system to be designed.

In a stand-alone system, battery storage system is required to adjust a gap between solar radiation patter and load profile. If ordinary electric appliances designed for commercial AC system are to be driven by a PV system, an inverter is necessary. If the utility grid exists where a PV system installed, grid interconnection realizes quite convenient system for user.

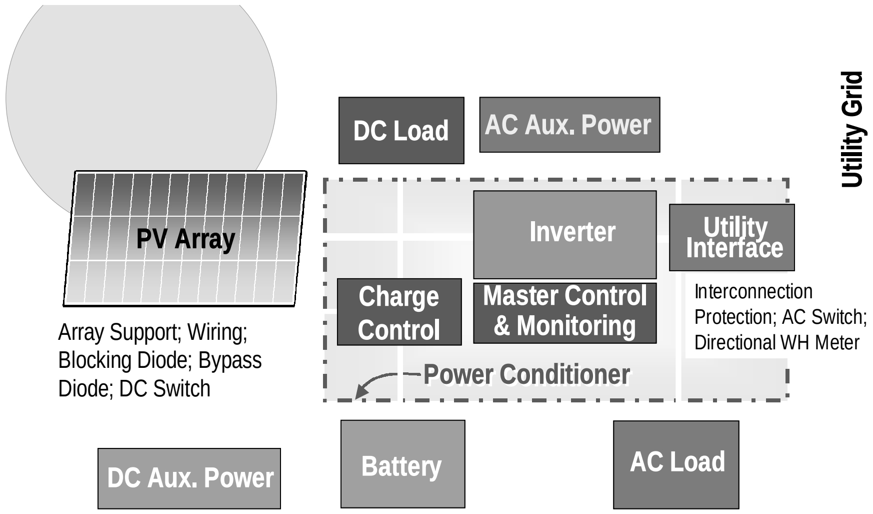

Fig.2 Generalized configuration of PV systems

2.2 Various Technologies and Issues

The author emphasizes the following keywords in different technological categories: module related technologies, inverter related technologies and system related issues. Some of them are described in detail in the following sections.

(1) Module related technologies:

- New PV cell technology innovation
- Building integrated PV module ... BIPV
- AC module.
- New module fabrication process without interconnectors between cells.
- Tracking, concentrators
- Long-term operation: EVA; degradation
- Decommissioning: 3 R’s … reduce, re-use, recycle.

(2) Inverter related technologies:

- Low-cost, compact, PWM power electronics
- Controls: grid-connection, MPPT, grid parameter control (voltage, harmonics, ...), ...
- Islanding prevention measures; multiple invertors.
- One central big inverter, multiple of PCU, string inverters, Micro inverters for AC modules.
- SHS controllers: battery charger, stand-alone inverters.
- Life Time.

(3) System related issues:

- System sizing rule for stand-alone systems with battery.
- Performance monitoring and extended system evaluation ... shading, mismatch, etc. can be identified by SV Method, which was developed by TUAT.
- Simulation: step-by-step annual operation, array I-V with different orientation and shading, battery operation, standard irradiation database.
- SHS for electrification.
- Grid-connected system without/with battery.

- Areal deployment ... community system.
- Very Large Scale PV System … VLS-PV concept.
- Battery, energy transport, ... new storage concept with advanced seeds.
- International collaboration.

2.3 Solar Home Systems - SHS

World 2 billion population has not yet been electrified. Stand-alone, Solar Home Systems having the individual capacity of less than 1kW are one majority of attractive applications. The basic configuration of SHS consists of several PV modules and 12V battery with a charge controller, domestic load such as a fluorescent light and color TV.

There are many international collaborations concerning this matter. IEC TC82 has been discussing this issue for settling international standardization. IEA PVPS/Task 9 has been dealing with to promote SHS in developing regions with the collaboration of international financial institutions and organizations. GAP(Global Approval Program) has also been establishing practical standards for developing countries.

A typical example is shown in **Fig.3**This mobile SHS was built for Mongolian nomadic family by NEDO's International Cooperation RD&D, the overview of which is also described afterwards. The advantage of this system is easily re-installable when a ger moves to other place. 200 sets of this type were delivered to nomadic family around mountains, grass lands and deserts in FY1992-1994. All the systems were planned to be monitored(3)..

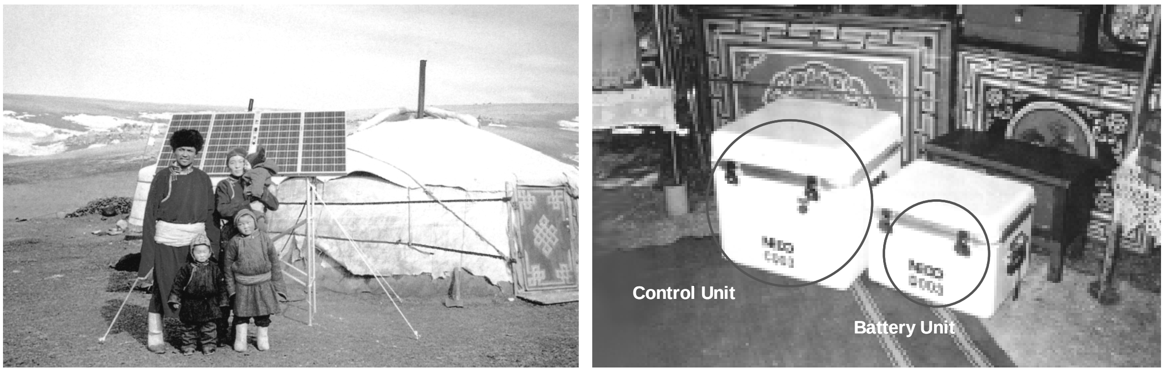

Fig.3 Typical SHS for Mongolian nomadic family with 200W PV modules

2.4 PV Community System

If a number of PV systems will be connected individually to the utility grid in an urban area, maximum total capacity of those PV systems is said to be restricted to a certain level due to technical problems for their interconnection. One solution to overcome this issue is a concept of PV community system. This advanced concept brings technical and economical merits from total optimization by centralized interconnection of an aggregation of areally distributed systems. PV integrated community energy system concept is to be considered quite feasible under the possible liberalization of electricity retail market by deregulation in near future. Some of earlier examples can be seen in Europe such as Amersfoort 1MW solar town(4), Herne 1MW shopping center(5), Munich 1MW New Messe, etc..100 residential systems in New Sloten zone near Amsterdam with total capacity of 250 kW employed the concept of "rent-a-roof" and centralized interconnection(6). The same concept was extended at the development of Amersfoort new town

2.5 Inverter Control and Grid Interconnection Issues

(1) Typical residential inverters

A large number of residential PV systems have been installed in Japan recently as described later. Typical grid connected inverters are characterized nowadays as follows.

- PWM inverters by FET or IGBT.
- grid interconnection with reversal power flow.
- Pmax tracking and islanding protection provided.

- Isolation of PV systems from the grid is attainable by standard frequency transformer, high frequency transformer and transformer-less, but the latter 2 options are majorities. In case of transformer-less inverter, DC leak current suppression function is also facilitated in the market.
- 100% power factor current-controlled voltage source inverter.
- current waveform controllable by instantaneous feed-back loop.
- stand-alone mode for grid service interruption.

(2) Value-added control

The power grid parameter improvement can be achieved by intelligent control function of PV inverters. This concept is called value-added control. It is explained as follows.

- Grid voltage control by the control with lead or lag PF to keep value within voltage window.
- To avoid interconnection restriction due to voltage excess.
- To suppress fluctuation caused by PV operation.
- Possibility extended to new grid control technology.
- Merits for utilities but no incentives for PV users.

(3) Grid interconnection issues

When PV systems are connected with the utility grid, the prevention of islanding phenomena is a critical measure. Islanding is defined as undesirable continuation of PV inverter operation when power grid is interrupted at the substation. During islanding, grid parameters are uncontrollable from power grid and controllable from PV systems. Total operational characteristics are determined by the sum of individual PV systems.

To detect islanding, various methods hade been proposed by Japanese R&D and now has been being discussed internationally by IEA PVPS/Task 5. At the moment no international standards are decided yet. The methods are classified to 2 categories, *i.e.*, passive methods and active methods(7). The former observes the variation of operational parameters such as voltage, frequency, phase angle, line impedance, etc.. For the latter, PV inverters controls operational parameters actively such as frequency shift control, power level modulation, etc.. Some other active controls at a substation were also proposed, but require additional facilities to the existing grids. In Japan the combination of one passive method and one active method is specified by the interconnection guideline.

After Kobe earthquake in Japan, stand-alone mode was allowed to fit in grid-connected inverters. When the grid is interrupted for long hours, PV systems are disconnected manually from the grid and then can be operated individually. Generally speaking, plural inverters cannot be operated in parallel in this stand-alone mode. It is a different level of technology and more sophisticated.

EMI issues by multiple inverters are also to be examined. Frequency spectrum varies compared with single operation. The most advanced concept of inverter technology is a value-added concept. In power distribution network, power electronics employed by PV inverters is most sophisticated technology and enables the active control of grid parameters such as grid voltage stabilization by phase angle adjustment.

2.6 AC Module and its Extension

Ac module is defined as a PV module having standard frequency and voltage AC output terminal(8). Normally, it consists of one or two DC module(s) and a module integrated inverter, the latter of which is abbreviated MIC. A PV system can be composed by AC modules as shown in **Fig.4**. AC module technology in the current market can be characterized as follows.

- Typical AC module capacity of around 100W.
- On-board inverter (MIC) on the back surface of PV module.
- Built-in functions such as interconnection protection.

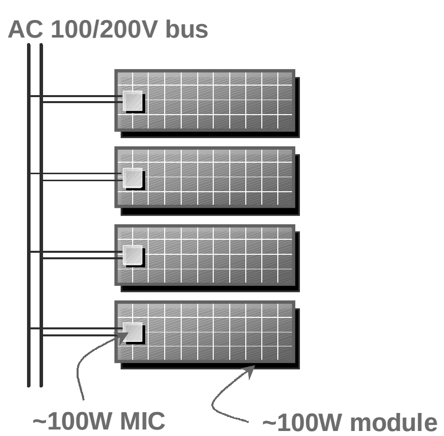

Fig.4 A PV system by using AC modules

- Full functions as a complete PV system even in case of one single AC module.
- Many commercial products in Europe and US.

Advantages of AC modules are summarized as follows.

- No necessity for DC wiring, the stability of which is not so reliable for longer term.
- Individual Pmax tracking for each AC module, which minimizes module mismatch in series connection.
- Any number of AC module can be freely allowed to form a parallel-wired array according to the shape of a given place although the number of series-connected DC module is only specified by string voltage given from inverter side.
- Seeking for mass production effects for inverter manufacturing as the same level of module.
- AC parallel wiring enables to compose larger systems.

2.6 Large scale Diffusion and Recycling

When a large scale diffusion achieved in the future, de-commissioning may cause environmental problem. Ordinary PV module is strong enough to withstand against very severe outdoor conditions. It means that it becomes very troublesome to destroy the module structure, which consists of glass, EVA and valuable Si wafers. There are several researches at earlier stages(9),(10). BP Solar developed a thermal process by fluidized bed furnace(10). This would be one of realistic solution at the moment.

This issue is reviewed as follows.

- The de-commissioning of a large amount of arrays has to be considered after their lives.
- A PV module is hard to be dissolved because of the necessity of long life for its outdoor operation.
- It is composed of laminated glass and transparent polymer film such as EVA. This structure is very tough mechanically and chemically.
- Although it seems to be impossible to recover silicon cells sandwiched by the lamination, there are some challenges.
- It is considered to be relatively easy to recover aluminum frame.
- It is necessary to develop a new structure for easy recycling.

2.7 Very Large Scale PV Systems - VLS-PV

(1) World Energy Requirements and Renewable Energy Needs

It is expected that renewable energy will be an important generation option for the 21st century as a response to global environmental problems. It is anticipated that with global population growth and economic growth the demand and supply of energy will be very tight, especially for developing countries. New energy sources and related technologies will have to be advanced with sufficient lead-time.

It is anticipated that photovoltaic technologies will provide one of the major energy sources in the future.

(2) Capability

Solar energy can provide all of the world’s energy needs in the next century. The purpose of the study is to prepare for the effective large-scale utilisation of this energy resource.

A great deal of potential exists in desert areas around the world for capturing and converting solar energy into electricity. If appropriate technologies can be found, they will assist in solving energy shortages in countries surrounding desert areas.

Photovoltaic technologies are on track of becoming technically and economically viable for application at the very large-scale level.

(3) Advantages and disadvantages of VLS-PV

The advantages of VLS-PV are summarised as follows:

- It is very easy to find lands around deserts appropriate for large energy production by PV systems.
- Deserts and semi-arids are, normally, high insolation areas.

- Estimated potentials of such areas can easily supply world energy needs in the middle of the 21st century.
- When large capacity PV installation is constructed, step-by-step development is capable by utilising the modularity of PV systems. According to regional energy needs, plant capacity can be increased gradually. It is an easier approach for developing areas.
- Even very large installation is attainable in a short period to meet existing energy needs.
- Remarkable contributions to the global environment can be expected.
- When VLS-PV is introduced to a certain region, other types of positive socio-economic impacts may be induced such as technology transfer to regional PV industries, new employment, economical growth, etc..
- The VLS-PV approach is expected to give a major, drastic influence on the chicken-and-egg cycle in the future PV market. If it does not happen, distance to VLS-PV may become a little far.

However, some disadvantages may also arise as describe below.

- Generally speaking, there are not large populations in deserts and semi-arids, to meet such a large potential in energy supply.
- If this ability is planned to be efficiently utilized in other districts, transmission will become one of the key issues because of the distance from the load centre. New seeds in energy transmission seem to be necessary such as long-distant HVDC transmission, super-conducting cables, hydrogen transport, etc..

(4) Review of Case Studies and Other Information

From a preliminary analysis[11], which has been studied as Task VIII of the IEA PVPS implementing agreement, it has been found that the cost of power generation by VLS-PV systems appears to be promising and attractive in regions where solar irradiation is abundant as shown in **Fig.5**.

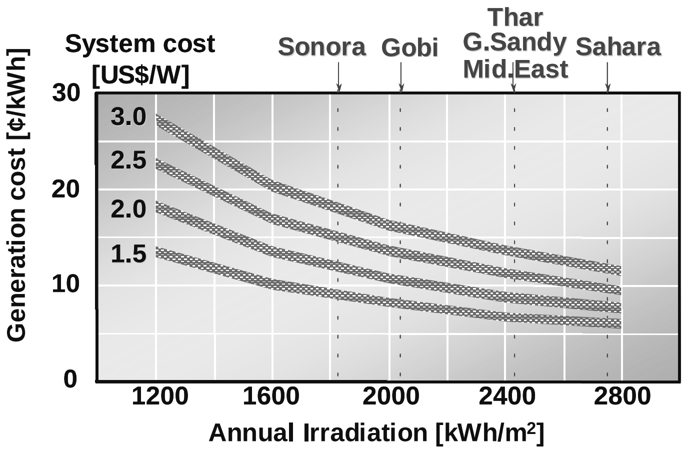

Fig.5 VLS-PV case study generalization

VLS-PV systems will affect the surrounding regions in terms of the economy, population and climate. A large-scale demand for PV systems can have positive regional impacts in terms of reducing greenhouse gas emissions and inducing employment through PV infrastructure development. Large-scale PV module production will reduce costs, making VLS-PV technology more realistic and competitive.

The value of energy from VLS-PV systems can be much enhanced if operated in conjunction with existing electricity supply infrastructure. Synergistic operation in combination with other types of power sources is also promising. A gradual evolution of multi-national networks can be expected in some regions. For forming such networks effectively, both high voltage DC transmission (HVDC) and relatively low voltage DC systems (HVDC light) seem to be feasible.

At present, the PV market is supplied mainly by crystalline silicon technologies but a number of current research and development activities are likely to see break-throughs in advanced materials and PV cell fabrication processes. The forecasted price of photovoltaics ranges widely with a low of around US$ 1 per watt for thin film technology being seen as feasible. In our stance for the VLS-PV, we have decided to consider things more positively for the future.

There is evidence that international institutions are now more interested in photovoltaics for use in developing countries. There will be a need for greater use of international institutions in facilitation VLS-PV systems in developing countries.

A preliminary assessment indicates that VLS-PV systems provide environmentally friendly energy systems for global use. Ongoing activities has been performed(12) and will be completed at the end of year 2002(13).

2.8 System Evaluation

(1) Estimation of electricity production from PV systems(14)

Although the conversion efficiency of a photovoltaic cell can be clearly measured according to standard test procedures, it does not mean operational ability under outdoor conditions. Meteorological conditions vary from place to place. At least, irradiation and ambient temperature have to be known when one wants to evaluate output energy to be generated by a PV system at a certain site. In addition, conversion efficiency may be reduced to a certain level because of various site conditions and system specifications. In fact this might create troublesome problems. Theoretical background is given to define system parameters, which may affect energy production capabilities.

Table 1 gives fundamental equations necessary for system sizing and evaluation. The first equation (1) shows energy balance between generated energy and consumed energy. The right-hand side is expressed by incident solar energy $\boldsymbol{H_A \cdot A}$, photovoltaic conversion efficiency $\boldsymbol{\eta_{PS}}$ at the standard test condition (STC) and other efficiency $\boldsymbol{K}$ found in an actual PV system (normally K<1). The left-hand side is evaluated by considering load energy consumption $\boldsymbol{E_L}$, dependence $\boldsymbol{D_P}$ of a PV system in the presence of other back-up energy and redundancies $\boldsymbol{R}$ for future load increase, safety margin, etc..

Conversion efficiency $\boldsymbol{\eta_{PS}}$ is simply defined by (2). Applying (2) to (1), PV array output power $\boldsymbol{P_{AS}}$ at STC is calculated by (3). This becomes quite helpful when PV array size is specified according to a given load consumption. Energy $\boldsymbol{E_p}$ generated by a PV system is evaluated by (4) for a specified array output capacity $\boldsymbol{P_{AS}}$. Sometimes, equivalent sunshine hours $\boldsymbol{Y_H}$ and system yield $\boldsymbol{Y_P}$, which are respectively defined by (7) and (8), are used to give $\boldsymbol{E_p}$ as shown in (5). When a PV system is monitored, system performance ratio is evaluated by (9), which is induced from (4).

Table 1 Fundamental Equations for System Sizing and Evaluation

Fundamental Equations	Parameter Definitions
<Energy balance> $H_A \cdot A \cdot \eta_{PS} \cdot K = E_L \cdot D_P \cdot R$ .....(1)	H_A: in-plane irradiation ($kWhm^{-2}$) A: array area (m^2) η_{PS}: PV efficiency at STC K: system performance ratio E_L: load energy consumption (kWh) D_P: solar energy dependence R: design redundancy P_{AS}: array output at STC (kW) G_S: reference irradiance (=$1kWm^{-2}$) E_P: system generated electricity (kWh) Y_H: equivalent sunshine hours (h) Y_P: system yield (h)
<PV efficiency definition> $\eta_{PS} = P_{AS} / (G_S \cdot A)$ .....(2)	
<Sizing> $P_{AS} = \dfrac{E_L \cdot D_P \cdot R}{(H_A / G_S) \cdot K}$ ..(3)	
<Generated electricity> $E_P = P_{AS} \cdot (H_A / G_S) \cdot K$ .....(4) $= P_{AS} \cdot Y_H \cdot K = P_{AS} \cdot Y_P$ .....(5)	
<Performance Evaluation> $Y_H = H_A / G_S$ .....(6) $Y_P = E_P / P_{AS}$ .....(7) $K = \dfrac{E_P}{P_{AS} \cdot (H_A / G_S)} = \dfrac{Y_P}{Y_H}$ .....(8)	

(2) System parameters

System performance ratio K is the most convenient value since it is normalized by site irradiation and system size. However, it is not a single parameter but consists of various parameters as shown in **Fig.6**, *i.e.*,

K_H : irradiation modification factor - caused by shadow, dust,
K_{PH} : incident angle dependent factor - due to module glass surface reflection,
K_{PT} : cell temperature factor - because of negative temperature coefficient of P_{max},
K_{PA} : array circuit factor - consisting of series-connected module mismatch and wiring resistive losses,
K_{PM} : load matching factor - caused by mismatch operation apart from P_{max} point,
K_B : battery circuit factor - including battery and its peripheral losses,
K_C : power conditioner circuit factor - including power conditioner and its peripheral losses.

The parameters listed above are not all the parameters which can be considered theoretically but the major parameters which apparently affect system performance ratio ***K*** in actual PV systems. When these parameters are evaluated, it is notified that they are calculated as energy ratio, not as power ratio.

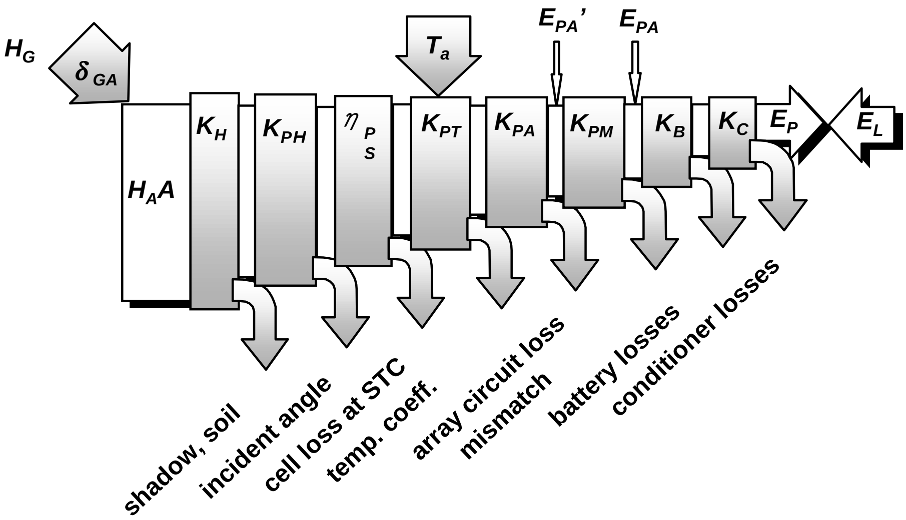

Fig.6 Various system parameters

(3) New system evaluation method[15]

By an ordinary monitoring method, performance ratio ***K*** and K_P can be calculated by following equations listed above for both system and array comparatively easily. However, other factors such as shading factor, mismatch losses cannot be easily evaluated. A new method called "SV Method"(Sophisticated Verification Method) has been developed by TUAT. By applying this procedure, a number of PV system were examined in NEDO's Field Test Program as shown in **Fig.7**.

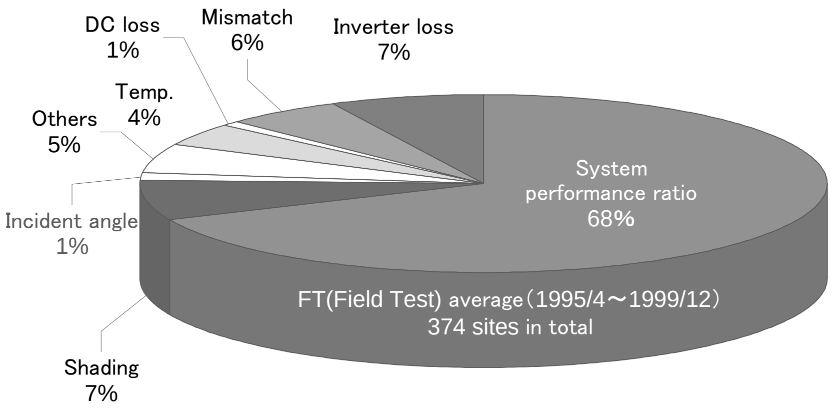

Fig.7 Precise evaluation of NEDO's Field Test Program by the SV method

(4) Energy Payback Time - EPT

When a PV system is evaluated, it is important to analyze all the benefits and costs for its whole life including production, construction and decommissioning as shown in **Fig.8**. In such a study, energy payback time - EPT is on of important measure for a power generation system(16). Fig.9 shows the EPT calculated for roof-top array and building integrated PV (BIPV) array respectively supposing the usage of both multi-Si and amorphous modules. It gives EPT of less than 2 years. In case of amorphous module, it is indicated less than 1 year for BIPV can be attainable.

Fig.8 Concept of life cycle analysis

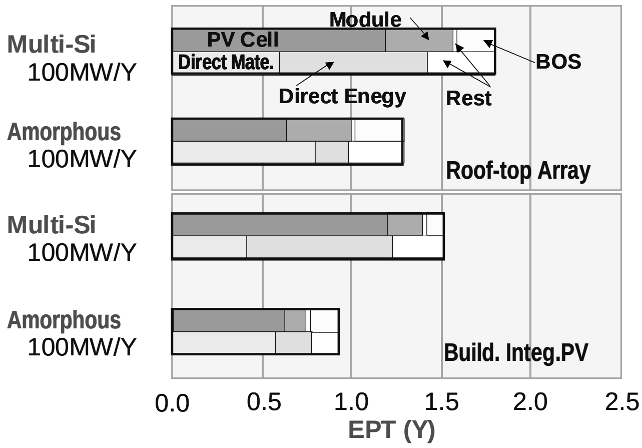

Fig.9 An example of energy payback time

3. WORLD PV MARKET AND POLICIES

3.1 World PV Module Production

(1) Present status

- The world market for photovoltaics has been growing at about 30% or more annually for the past several years.
- Japan has been currently market leaders. However, roughly speaking, the USA and the European market positions have also been similar level over much of the history.
- The total world market was estimated at 280 MW in 2000, a 37% increase from 1999. single-crystalline silicon had been the industry standard in PV markets. However, poly-crystal has taken over the top position in 1998 and has reached 47% share.
- Amorphous silicon also increased in production from 23.9MW to 26.5MW, but it actually lost market share to other technologies, remaining at 11.9% to 9.5%.

Figures 10 and **11** show the history of the world market from 1987 to 2000 by region and technology(17).

(2) Future market prospects

Extensive extrapolations of different market scenarios to the year 2010 have been developed using a computer-based model of the market(3). The business as usual scenario has been based on the same average 15% growth rate as experienced in the last decade. Accordingly, to remain on the safe side, the business as usual scenario has been calculated so that annual shipments are expected to reach 630MW in 2010 with the largest markets:

- solar home systems in developing countries.
- grid-connected, mainly building mounted systems in industrialized countries.

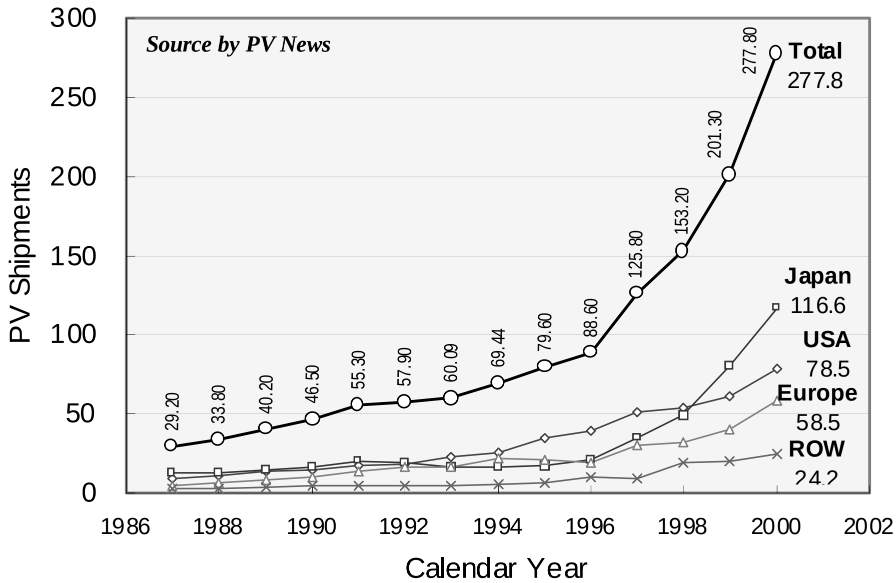

Fig.10　World PV module shipment by region

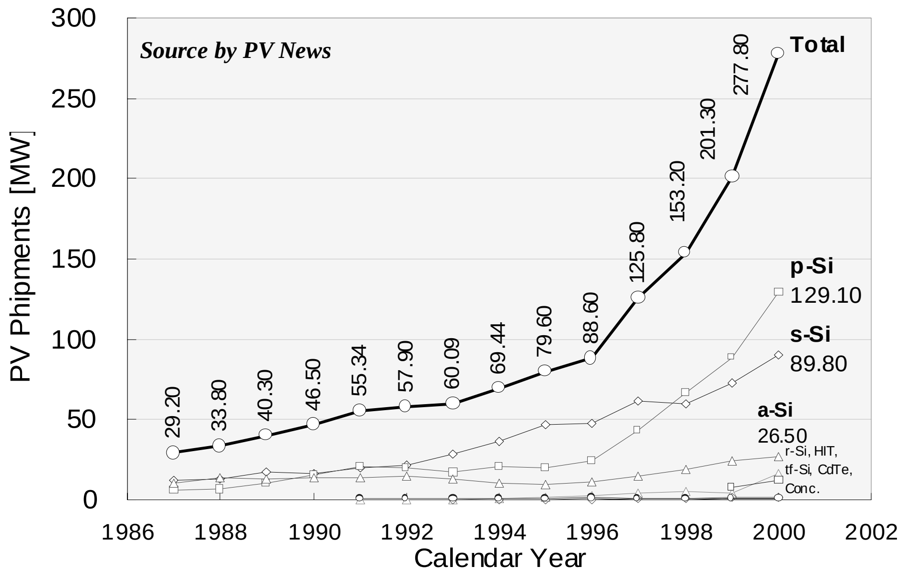

Fig.11　World PV module shipment by technology

Other accelerated scenarios by researchers at Australian National University forecast the international photovoltaic industry is to grow at a rate of around 20% per year over the next 15 years. This forecast growth rate, therefore, will give potential annual module shipments of some 1,600 MW/p by the year 2010. In addition, PV module manufacturer sales should be $3 billion per year by the year 2010. Considering Japanese target as much as 482MW by the year 2010, as described later, this outlook can be appropriate rather than the European scenario above.

Growth in the world market will depend on PV costs and technologies. Continuation of the present growth would lead to a substantial market by 2010 of the level of 2GW per year.

Thin film PV and deposition on a number of low-cost substrates continue to expand, and are well-represented in plans for new manufacturing capacity. Thin film research and development continue to show great promise in the USA, Europe and Japan. Improvements in performance and efficiency of solar cells are making it more competitive with single and polycrystalline.

Due to manufacturing capacity expansion especially in Japan, the cost reduction of modules and other components has been attained apparently.

3.2 Long term Budget Transition in 3 Regions

Figure 12 shows the rough transition of government budgets relating to PV programs for both the R&D and market stimulation. It is also compared with European countries and United States.
project goal and structure has also been maintained quite consistent.

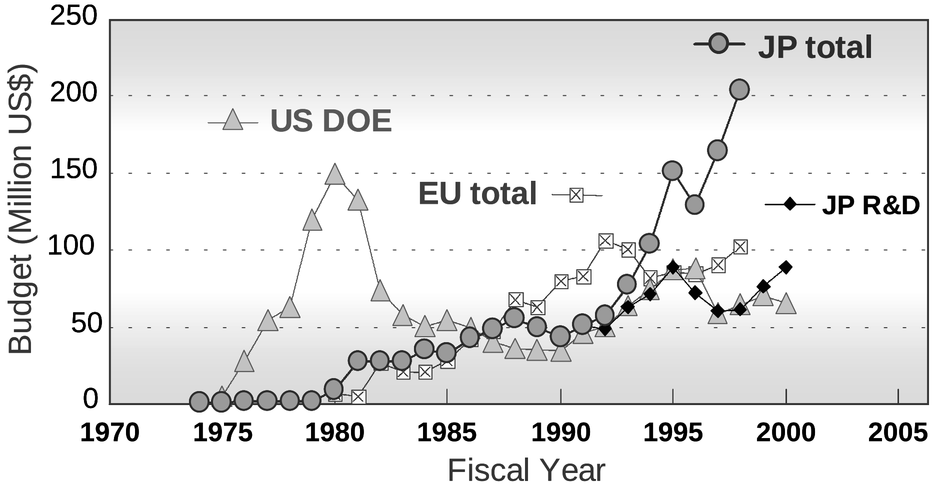

Fig.12 Government budget trends for PV R&D and market initiatives in different regions
EU countries include Germany, Italy, France, Netherlands and EU.
Budgets in current US$; data source from Resources Total System, Inc.

In spite that a drop in 1996 is seen in the graph, it was not an actual decrease on the basis of Japanese yen, because it became remarkably high, 84 ¥/$ in 1995. Recent decreases observed in R&D for 1995-1997 was caused naturally in conjunction with rapid takeoff of market introduction activities.

As shown in the same figure, European total budget, including EU, Germany, Italy, France, and the Netherlands, is considered to have been steadily growing. However, the budget level of each country varied from time to time and showed larger fluctuations. It is believed that future target toward 2010 has been also settled recently. It may be expected to grow into much higher level including market stimulation activities.

It seems that US R&D budget has been in a similar level compared with both EU and Japan although it was notably high during seventies and early eighties. Since US government settled “Million Roof” project 1999, it is also expected that US PV industries will grow rapidly although the present US government is reducing a budget size for many of R&D’s.

4. ACTIVITIES IN JAPAN

4.1 Long Term Basic Policy

When the former Sunshine Project was begun in 1974, photovoltaic cell fabrication research very fortunately happened to be adopted as part of the Solar Energy R&D Project, although it was not an extensive plan. The lion’s share of the budget was allocated to solar thermal applications and power generation at that time. In addition, the Sunshine Project was mainly concerned with coal gasification and liquefaction. Geothermal power and hydrogen energy were small entities.

In FY1977, the fundamental research of photovoltaic ‘system’ technology was proposed to the Ministry of Finance and successfully inaugurated in FY1978. The main objective of this research suggested the quite-new concept of dispersed-but-aggregated, utility-connected, residential rooftop systems. Since that time, this has become the mainstream of Japanese PV R&D because of the following reasons.

- Japan is a quite mountainous country and its usable land area is limited. The dispersed location of PV systems is a very natural course of consideration.
- The populated land area is almost entirely traversed by the utility grid. If a PV system requires to be backed up by an auxiliary power source, utility connection is only one realistic solution.

- The price of land is extremely high because of the limited amount of flat land, thereby making utilization for PV array fields economically unfeasible. As a result, the multi-utilization of space already used for other purposes becomes clearly advantageous. If roofs or other available space on residences are made available for PV arrays, the expense for the land can easily be eliminated and a large part of array support structure can also be neglected.
- At that time, however, it was inconceivable that a large number of such small-scale, utility-connected, residential PV systems could compete with conventional power sources. People imagined only concentrated systems for power supply in those days. However, the Sunshine Project began to seek another type of scale merits in large-scale, mass-production of such modular, tiny units other than conventional power generation technology with thermal-scale merits.

The following estimation was made during the early stages of the Project. The total number of private houses was 42 million in 1987. If 22% of all the houses were utilized for 3 kW roof arrays, total potential would be 27.6 GW. The size of 3-4 kW seems to be appropriate for the average Japanese house and produces roughly enough electricity for domestic consumption considering Japan's weather conditions. Additional roof spaces of 162.6 million m^2 could be obtained from 5.8 million multi-family residences providing another 8.13 GW PV installation potential for 50% of those houses assuming 10% efficiency.

Total potential was calculated as 35.73 GW from both results. If a 12% capacity factor is assumed, it corresponds to 37.6 TWh/Y. As Japanese gross energy consumption was 758.4 TWh at that time, it meant 5% of national electricity consumption could be supplied by the residential rooftop systems. This level was considered significant for future energy options in Japan.

4.2 Important Steps in PV System Promotion in Japan

As mentioned in Chapter 1, the original Sunshine Project commenced in 1974, just after the first oil crisis. In the 25 years since that time, the Agency of Industrial Science and Technology of MITI has been rather consistent in continuing a series of photovoltaic technologies R&D as follows.

Materials and Cells:

- silicon feedstock
- Si polycrystalline cells
- mass-production processing from Si refining to module assembly
- Si amorphous cells
- CdTe thin-film cells
- CIS or CIGS cells
- characterization of materials and cells

Systems and Components:

- utility-connected systems
- stand-alone systems
- power conditioners
- several types of advanced batteries
- utility-interconnection technology
- array designs
- building-integrated modules
- system evaluation
- international system demonstration

Table 2 summarizes important steps since 1974 including recent market introduction activities. A semi-governmental body, New Energy and Industrial Technology Development Organization (NEDO), was established in October 1980 and is responsible for both R&D and promotional activities for new energy technologies.

The first deregulation took place in 1990 through an amendment to the Electric Utility Industry Law. In 1992, electric power utility companies announced a buy-back plan for PV system-generated surplus power at the same level as the selling price. This is still in progress. In the next year, reversed power flow

Table 2 Important Steps in PV System Promotion until 2000

Year	PV System Promotion Activities	Remarks
1974	- Former Sunshine Project initiated for R&D of Solar Energy, Coal Gasification/Liquefaction, Geothermal Energy and Hydrogen Energy	Initiation of the consistent national programme.
1980	- NEDO founded for a series of New Energy R&D	Programme expounded by electricity tax.
1990	- Substantial simplification of installation procedures for PV systems under 500 kW through an amendment to the Electric Utility Industry Law	First recognition of PV systems by the Law.
1991	- Announcement by electric power companies of a plan to install 2,400 kW (actual result was 2,659 kW)	
1992	- Buy-up system for PV system-generated surplus power started at selling price by electric utilities (in progress) - Start of NEDO PV Field Test Project for public facilities	(Utility-interactive PV arrived!) Initiation of major subsidy!
1993	- Guideline to regulate grid-connection technology for systems with reverse power flow - New Sunshine Program commenced	Utility-interactive PV expanded!
1994	- Start of the PV System Monitoring Program for residential houses - Cabinet approval of the 'Basic Guidelines for New Energy Introduction' (PV system installation targets: 400 MW by 2000, 4,600 MW by 2010)	Subsidy expounded! Clear National Target!
1995	- Start of regional new energy vision policies at local governments (in progress)	
1997	- Enactment of the Law Concerning Promotion of the Use of New Energy - Monitoring Program for residential houses was modified to Residential PV System Dissemination Programme	
1998	- Original Field Test Project was redirected to Industrial Use - Revision of Long-term Energy Supply and Demand Outlook (PV system installation target: 5,000 MW by 2010)	
1999	- New Energy Subcommittee under Advisory Committee for Energy established for MITI - PV module approved as building material by Minister of Construction. - New Energy Technology Strategy. - Diet Member's Alliance organized for Natural Energy.	
2000	- Green Purchase Law by Government and Agencies established. - Supporting Project for Regional Activity on New Energy introduced. - "Green Power Fund" initiated by Electric Utilities.	

Table 3 Photovoltaic energy estimated from the supply side

Source: New Energy Subcommittee, Advisory Committee for Energy, METI

Potential Category	Physically Limited	Practically Defined		Govt. Target, 2010
		positive	realistic	
Oil equivalent	44,280 MLoe	21,000 MLoe	10,260 MLoe	1,220 MLoe
PV capacity	173 GW	86 GW	42 GW	5 GW
Assumptions	1) residential (72.7 GW): all sunny single-family residences with 4 kW PV 2) public institutions (5.5 GW): all schools, libraries, public halls, post offices, hospitals, etc., with 20-50 kW PV 3) industrial applications (57.2 GW): all office buildings; factory; etc. with 10-50 kW 4) infrastructures (37.50 GW): roads, railways, riverbeds, lakes, etc.	50% of physically limited potential considering siting restrictions and building codes	25% of physically limited potential considering siting restrictions and building codes	

from a small PV system to the grid was permitted by the modified 'Guideline to Regulate Utility-connection Technology'.

In December 1994, the Cabinet approved a quite aggressive government target called 'Basic Guideline for New Energy Introduction. According to this Guideline, PV system installation targets are described as 400 MW by 2000 and 4,600 MW by 2010. The latter target was subsequently increased to 5,000 MW by 2010 when the Long-term Energy Supply and Demand Outlook was revised in 1998 as described later in the center column of **Table 4**.

'The PV System Monitoring Program' was started in 1994 for subsidizing houses. This is operated through the New Energy Foundation (NEF) and was slightly modified and renamed the 'Residential PV System Dissemination Program' in 1997. Another subsidization plan, called 'Field Test Project', started as part of NEDO's activities in 1993. The plan is for public facilities with mid-sized PV arrays having capacities of 10 kW to more than 100 kW. Afterwards, in 1998, the Project was redirected to Industrial Use.

4.3 Government Target in Japan

Table 4 Outlook for New Energy Supply

Energy Sources	FY1999 Stock		FY2010 Target of New Energy Introduction Outlook		FY 2010 Target of New Energy Introduction Plan	
	TPES MLoe	Facilities MW	TPES MLoe	Facilities MW	TPES MLoe	Facilities MW
Photovoltaic (Solar Power)	53	209	1,220	5,000	1,180	4,820
Solar Thermal	980	–	4,500	–	4,390	–
Wind Power	35	83	120	300	1,340	3,000
Waste Power	1,150	900	6,620	5,000	5,520	4,170
Waste Thermal	44	–	140	–	140	–
Biomass Generation	54	80	–-	–	340	330
Biomass Thermal	–	–	–	–	670	–
Black Liquor, Waste Wood, etc.	4,570	–	5,920	–	4,940	–
Unused Energy Incld. Cooling by Snow & Ice	41	–	580	–	580	–
New Energy Total	6,930	–	19,100	–	19,100	–

Source: Long-Term Energy Supply and Demand Outlook, MITI & METI
[Note] MLoe: mega-litre oil equivalent

Fig.5 PV system introduction volume estimate newly settled for FY 2010

(Unit: MW)

		Actual introduction volume in FY 1999	Previous estimate		New estimate for FY 2010 target	
			FY 2010 business as usual	FY 2010 previous target		
PV system	Residential	115	2,170	4,200	3,200	- 800,000 x 4 kW/system
	Non-residential	94	370	800	750	- 13,000 x 30 kW/system for public facilities and office buildings - 360 MW for others
	(Subtotal)	*209*	*2,540*	*5,000*	*3,950*	
PV/ thermal hybrid system	Residential	-	-	-	700	- 200,000 x 3.5kW/system
	Non-residential	-	-	-	170	- 7,000 x 26 kW/system for public facilities and office buildings
	(Subtotal)	-	-	-	*870*	
Total		209	2,540	5,000	4,820	

Source: Ministry of Economy, Trade and Industry (METI)

Recently, the Ministry of International Trade and Industry (MITI) has been reviewing the New Energy Introduction Plan with discussions by the New Energy Subcommittee under the Advisory Committee for Energy. **Table 3** was provided for Committee discussions. Figures in the left column were originally examined in detail by a NEDO-contracted research party and include some applications other than residential rooftop systems. According to this estimation, a more precise target was being discussed by the Subcommittee very extensively and was decided in July of 2001. It is indicated in the right column of **Table 4** and **Table 5**. It is believed to be not only a final goal but also a milestone for further introduction of PV systems in the future.

4.4 Current Activities in Japan

Table 6 summarizes a series of current promotional activities in Japan.

Table 6   Current activities of PV system promotion in Japan

Items		Contents
Government Activities	Leading Govt. Agencies	- Agency of Industrial Science and Technology, MITI - Agency of Natural Resources and Energy, MITI
	R&D Project	- New Sunshine Programme
	Major Govt. actions on introduction and promotion	- Basic Govt. Guidelines for New Energy Introduction - Law Concerning Promotion of the Use of New Energy - PV Field Test Project for Public Facilities - Residential PV System Dissemination Project - PV Field Test Project for Industrial Use - Deregulation - Standardisation
	Support for developing countries	- International Demonstrative Research - Financial Support
Installed capacity up to1998		133.3 MW (estimated)
PV Introduction Target		4,820 MW by FY 2010
PV cell production (2000)		116.6 MW

From the beginning of 2001, the leading government agency is now the Agency of Natural Resources and Energy (ANRE) under METI, Ministry of Economy, Trade and Industry. It is responsible for both R&D and market introduction activities.

The major R&D project was called the 'New Sunshine Program'. In terms of Solar Energy, the following fields are included, *i.e.*, mass-production technology of low-cost PV cells, cost reduction of PV systems, BIPV modules, improvements in efficiency, etc.

These R&D projects are supervised by NEDO as a whole. Under NEDO, PVTEC (the Photovoltaic Power Generation Technology Research Association) is coordinating R&D contracts in terms of the mass-production technology of low-cost, high-efficiency PV cells, and the development of BIPV modules. Solar-grade silicon R&D has been dealt with by SOGA (Solar-Grade Silicon Technology Research Association). Some of contracts are handled directly by NEDO.

Fundamental researches have been carried out by AIST (National institute of Advanced Industrial Science and Technology), which was born at the beginning of 2001. A part of this new laboratory was called Electrotechnical Laboratory originally. Universities are also in charge of basic researches.

The introduction and promotion of PV systems are based upon guidelines and laws such as the Basic Government Guidelines for New Energy Introduction, and the Law Concerning Promotion of the Use of New Energy.

For medium-scale PV systems, the PV Field Test Project for Public Facilities subsidizes one-half of the installation cost for a public facility and two-thirds for disaster prevention-type applications through

NEDO channels. As mentioned above, the major part of this project has been redirected to industrial uses.

The Residential PV System Dissemination Project subsidizes at the maximum of 540,000 Yen/3kW at the time of FY2000 for instance. This subsidy can be applied for through the NEF channels.

Other related government actions are as follows.

- Deregulation of Electricity Utility Industry Law
- Standardization of PV systems
- Regional new energy introduction and promotion
- Support to new energy entrepreneurs
- Eco-School Pilot Model Project by the Ministry of Education/ MITI
- Next-Generation Urban Planning Project by the Ministry of Construction

International Co-operative Activities: International Demonstrative Research has offered 44 kW pumping systems for drinking water in Nepal, 200 sets or 40 kW in total of mobile PV systems for nomadic family in Mongolia, 44 kW battery charging stations in Thailand and 110 kW village electrification stations in Malaysia, each from Fy1992 to 1996. The Mongolian Project is presented by other presentation in this conference and evaluated precisely by Amarbayar Adiyabat. The second stage of Thailand project has been settled. New projects started in 1997 in Vietnam and in 1999 in Myanmer respectively.

Financial Support: Financial supports for developing countries were provided to the following countries.

- Pakistan: Village Electrification, 2 systems, 95.6 kW in total
- Thailand: Village Electrification, 3 systems, 150.0 kW in total
- Indonesia: Village Electrification, 2 systems, 123.0 kW in total
- Kiribati: Village Electrification, 2 systems, 6.6 kW in total

Table 7 shows the recent 4-year trend of government budget outlays for various activities for PV technologies and market. **Table 8** can also be applicable to PV systems, but is intended for other types of new energy in principle and not specific to PV systems.

Table 7 Itemized budget related to PV implications (1) in billion yen

Item		FY 1998	FY 1999	FY 2000	FY 2001
Development and promotion of PV system	Introduction and promotion of residential PV system	14.70	16.04	14.50	23.51
	PV Field Test Program for Industrial Use	2.40	2.41	4.00	1.99
	PV Field Test Program for Public Facilities	0.17	0.11	0.10	0.07
	Development of low energy consumption manufacturing process for SOG-Si	0.83	1.00	0.53	term.
	Development of technology for practical application of PV system	7.41	8.36	7.84	term.
	Research and development of PV power generation technology	-	-	-	5.05 term.
	Technological development for promotion of photovoltaic power generation	-	-	1.24	1.31
	International joint demonstrative development of PV system	0.28	0.26	0.28	0.28
	Enhancement of technical investigation for grid-connection of PV system	0.29	0.34	0.34	term.
	(Total)	26.08	28.52	28.84	32.21

Source: Ministry of Economy, Trade and Industry (METI), translated by Resources Total System

The total budget for photovoltaic systems has remained somewhat constant, *i.e.*, 26.08, 28.52, 28.84 and 32.21 billion Yen for these 4 years. The subsidy system for houses through NEF has maintained the highest share at 14.70, 16.04, 14.50 and 23.51 billion Yen. The Field Test Project through NEDO has also been considerable with 2.57, 2.52, 4.10 and 2.06 billion Yen for the 4 years.

Table 8 The FY 2001 budget bill related to PV implications (2) in billion yen

Item		FY 1998	FY 1999	FY 2000	FY 2001
Subsidy system for entrepreneurs who introduce new energy		5.39	10.34	11.49	14.04
Promotion of regional introduction of new energy, etc.	Regional new energy promotion policy	4.38	6.76	6.43	11.50
	Assistance to regional new energy and energy-saving vision development	0.80	1.24	1.23	1.23
	Support of community level introduction of new energy (by NGO)	-	-	1.06	0.15
	Support of regional activities introduction of new energy	-	-	-	0.91 (new)
	(Subtotal)	5.18	8.00	8.72	13.79

Source: Ministry of Economy, Trade and Industry (METI), translated by Resources Total System

A main player in R&D activities corresponds to 7.41, 8.36, 7.84 and 5.05 billion Yen in the table. International R&D and Demonstration, silicon feedstock process R&D, and grid-interconnection studies are also classified to the R&D sector.

4.5 Progress of Residential PV System Project in Japan

At the moment, Japan's residential project is providing a considerably large market for PV industries including foreign cell/module companies. **Fig. 13** shows the rapid market growth and market price reduction in recent years. Though not indicated in the figure, more than 10,000 residential systems may have been installed according to MITI's budget during the 3 years from 1998 to 2000. It is said that the total amount will reach the level of 200 MW by the end of FY2000, which is March 2001.

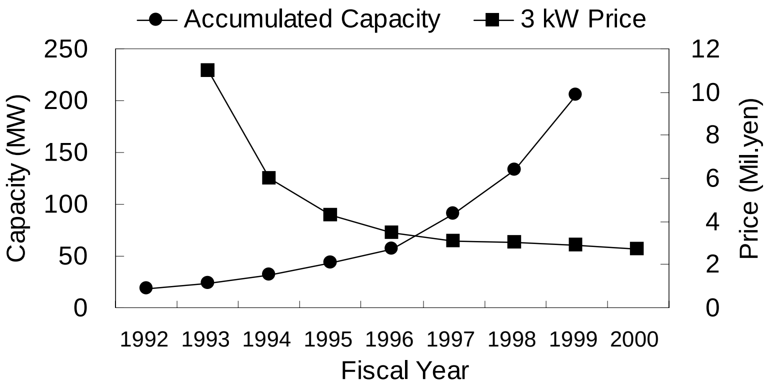

Fig. 13 Accumulated capacity and price trends in Japan

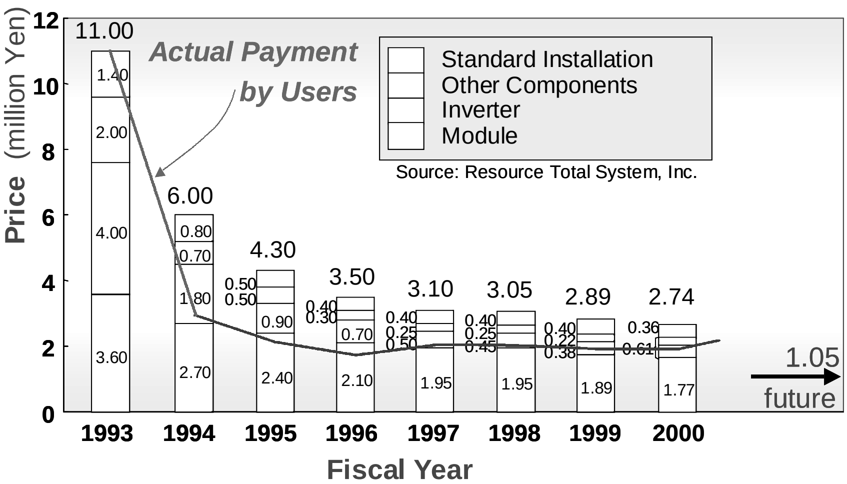

Fig.14 Price trends of a 3 kW residential system

Figure 14 describes the detailed cost structure of a typical 3 kW residential system in the Japanese market in recent years. Remarkable cost reductions in the BOS sectors can be seen first at 5 years after FY1993, *i.e.*, 1/5 of the original level. (It is noted that the Government Residential Project began in FY1994.) It is supposed that BOS cost reductions could be achieved by standardization due to the establishment of grid-interconnection guidelines and by mass production on account of subsidies. A 50% reduction in PV module price has also been observed. It can be said, at least, that the domestic market has been effectively activated through Government policies as well as due to extensive efforts by industries. It is also pointed out that, by measuring the effect of market activation, the subsidy rate has been carefully adjusted by MITI. At the outset, the rate was around 2/3. It was revised to 1/2 afterwards and now is 1/3 or less. It is also understood that other means to sustain the moderate growth of the PV market are being sought and are currently under discussion.

5. CONCLUSION - PROBLEMS AND FUTURE

The peculiarity of Japanese R&D of PV system technologies can be summarized as follows:

- R&D fund has been quite stable and effective for the development of photovoltaic technology.
- The residential roof-top application was proposed at the early stage of the development and has been focused as a major target
- In conjunction with the second point, grid interconnection technology, especially islanding issue has been studied with great efforts. This is considered as one of major achievement in the world.
- It is believed that the government fund for R&D and market stimulation have been well functioned up to now.

These circumstances in Japan could maintain excellent human resources in academic organizations and industries fortunately. On the other hand, it is also true that such long-term development requires makes it difficult to regenerate the resources and may cause the hollowing-out. It seems to be still necessary and important to prepare attractive future images to get people.

From this viewpoint, finally, the author would like to raise the following suggestions.

- It is necessary and important to consider long-term outlook of the world energy structure at least in the middle of 21 century, 2030 to 2050. Energy technology requires quite long lead-time to commercialize. Future targets for the introduction of renewables have to be extended further. 2010 targets are only a milestone and must be cleared at least.
- Japan has to play an important role to provide a renewable energy option for the future of the world, thinking of both the global warming and future energy structures. IEA PVPS/Task V and Task VIII may be indicated as a first, good example.
- Although further deregulation and liberalization in power industry may be essential, additional social or financial measures are desired with emphasis to be taken for avoiding returning back to oil.
- To maintain human resources, it is necessary to form a Center-of-Excellence. It is also suggested to accumulate knowledge and to disseminate it by establishing national and international institutions.

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