OCCASION

This publication has been made available to the public on the occasion of the 50th anniversary of the United Nations Industrial Development Organisation.

DISCLAIMER

FAIR USE POLICY

CONTACT

Please contact publications@unido.org for further information concerning UNIDO publications.

For more information about UNIDO, please visit us at www.unido.org

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

21616

SOLAR CELL MATERIALS, TECHNOLOGIES, APPLICATIONS AND THE IMPACT ON DEVELOPING COUNTRIES.

by
Dr. M.R.L.N.Murthy — Consultant

Backstop Off. Ms. Loeber S.

Special Article
Prepared for UNIDO Monitor "Advances in Materials Technology"
under contract No.CLT/96/067
July, 1996

SEMICON TECH CONSULTANTS
302, Sahara Apts., Deonar,
MUMBAI, INDIA.

R

CONTENTS

I. INTRODUCTION:

The concerns for ecological aspects are over weighing compared to materials as we march into 21 century. With widening gap between electricity demand and generation, specially in developing and newly industrialized countries, there is accelerated activity in power generation which would result in staggering amounts of air pollution if we continue depending on oil and fossil fuels. Developing clean energy sources thus has become an important task to arrest the gas emissions and to protect the ecological cycles of bio-systems on the earth (1).

It is fortuitous that Solar Energy Technology reached maturity at a time when mankind needed it most. What was once regarded good enough for promising power to satellites has come down for terrestrial application as well. Photovoltaics, the technology to directly convert sun light (solar radiation) into electric energy has significant advantages as an electric generator.

1. Clean and inexhaustible source: Solar Photo Voltaic Conversion systems tap the inexhaustible resource which is free of charge and available anywhere in the world, even in space. The amount of solar energy incident on earth (~1.5 x 10^{18} kwh / year) is about 10,000 times larger than the current annual energy consumption of the entire world.

2. Maintenance free operation: It has no mechanical moving parts and needs no lubrication and the simplicity of operation and low maintenance costs make life cycle cost of PV systems much lower than that of other traditional options. PV needs no transportable fuels and thus can be set up in any remote or normally inaccessible areas.

3. Modularity and Reliability: Suitable for stand alone systems from fraction of a watt to MW operations. System power could be increased modularily. PV is known for reliable operations over years. Solar cell consists of Semiconductor modules which can be mass produced like transistors and ICs. Modular increase in production scale with expanding market size results in cost reductions. Thus PV is poised for a phased growth into large market sectors.

4. Decentralized Operations: PV power generators can be deployed as sizable captive power sources or small stand alone systems dispensing the distribution net works and transmission losses.

5. Clean Energy: Solar Energy is environmentally benign. A gegawatt hour of electricity generated by PV instead of coal burning prevents as much as 1052 tons of CO_2 being spewed into the earth's atmosphere. PV is known not to produce any pollution in the form of ashes, wastes or even noise.

Despite several advantages in Photovoltaic generation as mentioned above, substantial R&D efforts were made only in seventies after oil crisis. It is only during eighties substantial growth in PV technologies based on crystal silicon and amorphous silicon was witnessed. The technology push could not attract the market pull resulting in limited application area as remote power sources such as powering light houses, telemetering power sources located in far-flung areas. The big barrier impeding the large scale production is high price of solar cells which was more than 60$/W during seventies dropping to 10$/W in eighties. However recent advances in technology over the last 10 years resulting in solar cells with higher efficiencies, scaled up production plants coupled with efforts at Government level in various countries the module cost has come down to 4 to $5/W in a firm bid for large scale purchase. The present scenario is good with PV reaching roof tops in urban area and getting connected to grid apart from a variety of applications in rural sector.

In the middle of nineties Solar PV power generation is receiving greater attention because of growing concern for ecological aspects, optimal energy utilization, life cycle costs and prompting large scale usage of solar energy. Realizing the importance and need of renewable energy international financial and institutions such as World Bank, GEF have initiated programs for wide spread utilization of solar energy in several developing countries.

This article reviews recent advances in Solar Photovoltaic Technologies, and expected technological innovations with the discovery of new materials and an in-depth analysis of techno economics of PV industry from the view point of large scale terrestrial applications. Key issues in achieving utility power applications in near future due to module cost reductions, the role of international organizations such as UN bodies, World Bank etc. in promoting solar energy in developing countries, the potential markets and funding mechanisms for PV market development and finally the impact of PV on developing countries.

II. SOLAR ENERGY MATERIALS:

The amount of solar irradiation in outer space is 1,353 W/m^{2}and on earth's surface it is reduced to 1,000 W/m^2 due to absorption and scattering effect of earth's atmosphere.

The ability of certain semiconductor materials to directly convert light (photons) into electrical energy is the basis of solar cell or photovoltaic cell. Solar cell, the primary component of the photovoltaic equipment has been the focal point for research and a variety of materials and a multiplicity of fabrication techniques were developed to achieve higher conversion efficiencies.

Solar Cell

A typical solar cell consists of a p-n (or p-i-n) junction formed in a semiconductor material. When light impinges on the solar cell the quantum energy contained in the photons is absorbed in the material resulting in liberation of 'electrons' and 'holes' which move freely in the material. In the presence of concentration gradients and an internal electric field that exist across the p-n junction the charge carriers diffuse and drift before they recombine and neutralize. The metal electrodes located on top and bottom surfaces of solar cell collect the charge carriers enabling an electric current to be driven through an external circuit. However, not all the light impinging on solar cell generate charge carriers nor all the charge carriers generated reach the electrodes to contribute towards current flow. Thus there is a conversion efficiency factor which is governed by the reflectivity of the surface, absorption by the material, rate of generation and recombination of electrons, the energy band structure of the semiconductor material used etc. The R&D efforts going on all over the world are mainly to increase this efficiency factor by employing advanced and innovative materials and techniques. Solar cell operation is illustrated in figure 1.

Solar Cell Technologies :

Although the interaction of light with matter has been known for a long time no practical devices were developed until fifties. The first devices could be traced back to fabrication of Solar Cell based on Crystal Silicon in 1954 and Gallium Arsenide in 1956 and found application in powering satellites. Efforts to increase the conversion efficiency and search for new cell materials and cell structures have been made, however, the impetus for accelerated R&D efforts and production oriented technologies came with oil crisis in 1973. Crystalline silicon PV Cells were recognized for use in remote stand alone applications (for small loads) and amorphous silicon cells in consumer electronic products such as watches and calculators made the beginning for PV Cells to be deployed in terrestrial applications. Industries have come up to commercialize the technologies and with scaled up productions demonstration plants upto a few hundred kilowatt rating were set up.

Parallel efforts for increasing cell efficiency led for the search of other semiconducting materials such as Cd Te, Cu In Se_2. Also several new materials such as multicrystalline silicon, ribbon and sheet and spheral silicon have been developed for cost reduction. Over the past 15 years several solar cell technologies have been developed in USA, Japan and European labs and they can be broadly classified as shown in figure 2.

Single Crystal Technology

With the advent of the Czochralski process of growing large silicon crystals (100 mm diameter and 1.0 ~ 1.5 m long crystal ingots) single crystal technology has been the mainstay for large-scale Solar Cell production by photovoltaic industries.

The fabrication of Solar Cell and module involves three stages: first the fabrication of single crystal silicon wafer; secondly, fabrication of single crystal silicon photovoltaic cell and finally fabrication of photovoltaic module.

Fabrication of single crystal silicon wafer

The first step is preparation of metallurgical grade silicon by mixing silica (SiO_2) with carbon (coal or charcoal) and deoxidized in arc furnace. The resulting silicon (97-98 per cent purity) is processed by the trichloro silane method to produce high purity poly silicon czochralski method (CZ) or float zone (FZ) method is employed to grow single crystals. The major percentage of crystal silicon for photovoltaic use is produced by CZ process. silicon crystal production is well established industry in many countries.

The specifications of the crystal ingots required for photovoltaics are less stringent than that of crystals required by the semiconductor industry producing integrated circuits. The heads and tails of the semiconductor grade silicon crystal are used for producing solar grade crystal ingots.

The crystal ingots are sliced by either ID saw to slice wafers in the range of 300 to 450 microns or wire saw to get thin wafers in the range of 120-200 microns.

Multi-crystalline Technology

Fabrication of Multi-crystalline Solar Cell is generally on the same lines as that of crystal silicon technology, but for some modifications introduced to counter the problems faced by grain boundaries, stresses, impurities etc., in cast silicon process technologies, which are reviewed elsewhere in this report.

Multi-crystalline Silicon

Multi-crystalline material at industrial level is being produced specially for photovoltaic applications for the last 10 years but in limited quantities. While Wacker Chemi and Solarex Companies are some of the companies which started producing Multi-crystalline material by the casting process, over the last eight years; other companies, such as Crystal Systems, IBM, Photowatt, OTC, Polyx, Crystalox, have come up with silicon cast ingots employing various techniques, namely, heat exchanger method, directional solidifaction cold crucible induction casting etc. Several ingots produced are in the range of 80-120 kg materials, generally with square cross sections of 44 x 44 cm or 55 x 55 cm and throughputs getting better and better.

Slicing

Both crystalline and Multi-crystalline ingots are sliced employing ID saw. However, during the last five years wire saws have been developed which reduces the Kerf loss to a great extent, to as much as 120 microns compared to the best values of 300 microns when sliced by ID saw. Another innovation in slicing technology is Fixed Abrasive Slicing Technique (FAST) which was recently developed by Crystal Systems. FAST utilizes a multi-wire blade pack with each wire held in a frame with equal spacing and tension, and slicing is achieved by reciprocating the blade pack in a slicer head.

The major process techniques developed as well as the slicing methods employed alongwith results on capacities of ingot growth time, size, life times, diffussion lengths and cell efficiencies have been detailed in Table 1. Shown in fig. 3 are silicon crystal growth machines, crystal ingots, cast silicon ingots, Round and Square wafers and Solar Cells.

Ribbon and Sheet technologies

Ribbon silicon crystal growth was envisaged mainly to reduce the wastage of precious silicon crystal which occurs during the slicing process (of the order of 30 - 40 per cent). A variety of techniques were developed to grow ribbons or sheets of crystal silicon.

Mobil Solar Energy Corporation employ graphite or ceramic die (Shaping the guide material) having a thin slit through the center lowered into molten silicon. The silicon is drawn up through capillary action. A seed crystal touching the melt at the top is slowly withdrawn upwards resulting in ribbon crystal growth. Mobil solar produces nanogon wafers where they get nine ribbon crystals in one run.

Westinghouse Corporation uses the dendritic web method. Unlike the die used in the EFG process this method employs two dendrites - elongated starter crystals are lowered into the silicon. As they are drawn up a sheet of crystal silicon is formed between them.

Hoxan Corporation from Japan has come out with a novel process called spin cast method to make 10x10 cm silicon wafers. A specified amount of molten silicon is allowed to fall from a quartz funnel onto a graphite mould with a 10x10 cm cross-sectional cavity. The mould is spun as the silicon melt is dropped to form a 10x10 cm silicon wafer. The silicon Solar Cell fabricated using the spin cast wafers have shown conversion efficiencies in excess of 10 per cent.

Fabrication of Solar Cell :

Solar Cell is the most important element of the photovoltaic device and the crucial part is diffusion to create the P-N Junction. After the initial etching and texturing process steps on the silicon wafer, a thin layer of phosphorous doped silicon is brought into contact with a layer of boron doped silicon in the diffusion process to create the P-N junction. Minute quantities of boron and phosphorous (one part in a million) are used as dopants. Electrode printing is done using Ag pastes and fixed for the electrode formation and solder coated.

After the cell is given its metallic contacts, the front surface is provided with an anti-reflective coating. Since Si is highly reflective, throwing back 35 per cent of light that strikes it, the cells are coated with a thin layer of silicon monoxide or titanium dioxide to counter the reflection.

Amorphous Silicon Cell

Amorphous silicon has a high optical absorption coefficient, which means most of the sunlight falling on it is absorbed after passing through a very short distance - less than a micrometer in hydrogenated amorphous silicon compared to 50 times that distance in crystalline silicon for the same amount of light to be absorbed. Another advantage is the ease with which it could be deposited over large areas as well as on curved substrate surfaces and the material and energy requirements are low.

Amorphous Silicon Solar Cell Fabrication Steps

The basic structure of the A-Si Solar Cell consists of thin layers of P-I-N materials sandwiched between a transparent top contact and metallized bottom contact deposited onto a glass superstrate. The basic fabrication steps are:

- Deposition of TCO layer on glass using APCVD process;
- Patterning of oxide layer by laser scribe;
- Deposition of P-I-N layer by PECVD process;
- Patterning of P-I-N layer by laser scribe;
- Metallization by vacuum evaporation or screen printing;
- Patterning of metallized layer by laser scribe or screen printing; and Encapsulation

Semiconductor Based Thin Film Technologies Other Than Silicon

CIS, Cds, CdTe are some of the compounds that are promising materials for conversion of sunlight into electricity in view of their high absorption coefficient for sunlight, relatively stable cells without the problem of degradation like A-Si cells and also because of the simpler technologies required.

A typical thin film Solar Cell is made of Glass/Mo/CIS/Cds/ZnO with the CIS layer of few microns thickness and a thin CdS layer of about 500A° to act as window. The Mo layer acts as the back contact material for CIS and ZnO layers on CdS services as the top contact.

Fabrication Steps For CIS Solar Cell

- Vacuum evaporation of Mo (0.5 - 2.0μ) and (0.45μ) as stacked layers using evaporation process;
- Selenised under H_2Se atmosphere around 400°C forming Cu In Se_2;
- Deposition CdS through vacuum deposition;
- Deposition of ZnO over CdS by R.F. sputtering or MOCVD; and
- Encapsulation with EVA.

Schematic diagrams of the various photovoltaic cell structures are shown in fig. 4a and the flow charts for manufacturing process steps of crystalline Si cells and Amorphous Si Cells are shown in fig. 4b.

Concentrator Techniques

By increasing the amount of sunlight impinging on the Solar Cell one can decrease the more expensive semiconductor material used in Solar Cell. Optical concentration systems of lenses and mirrors to focus sunlight are fabricated to achieve 100 to 1000 sun concentration.

- A parabolic trough reflector focusing sunlight on a string of cells and the reflector is rotated to follow the sun;
- Linear fresnel lens focusing sunlight on the row of cells and the whole device turns to track the sun; and
- Point focusing by fresnel lens to concentrate sunlight on single cell and using a two-axis tracking to follow the sun.

Other arrangements include multiple junction tandem cell wherein three or four cells of different materials are stacked one above the other; the top cell is activated by higher energy photons, the next cell down converting photons of lesser energy and the bottom-most cell activated by the further lower energy photons. This cell can achieve very high efficiencies and is economically viable with the use of thin films. Experts view that this could be the first photovoltaic technology to be cost effective for utility scale powerplant applications.

Concentrator cell represents approximately one-third of the cost of a typical concentrator collector and the cell efficiency is the dominant factor concerning collector performance (9). A review of concentrator cell technology is presented by King (10).

Solar Cells are made using a number of materials dominated by Silicon and they are designed as dictated by the parameters required for achieving high efficiency.

Criteria for high efficiency cells include low resistivity high life time, reduction of surface recombination velocity, band gap narrowing energy loss mechanisms such as photon losses, carrier losses and power losses contributing to degradation of cell efficiency. Some of the best results recorded on cell efficiencies on A-Si based technologies are presented in table - 2.

For a complete review of the various techniques employed for attaining high efficiency and R & D efforts by several labs and industries refer to "Solar Cell and their applications" UNIDO Monitor on Advances in Materials Technology (issue no. 31. March 1993).

Recent Achievements and Trends in Photovoltaic Developments:

The recent progress in Solar Cell research all over the world indicate the coming of the thin film age - not only tremendous progress in amorphous Silicon technology, but also in Cd Te and CIS thin film processing and even polycrystalline silicon films.

Silicon Film Technologies

1. Amorphous Silicon Solar Cell: Remarkable advances have been made in the technology of wide gap windows, heterojunction graded band profiling, doping, super lattice , BSF treatment and also the stacked alloys. Some of the recent developments are presented (11 to 19).

a) Band profiling triple junction stacked cell with 12.4 % efficiency (Sharp Corporation).

b) A - Si/ A - Si/ A - Si Ge stacked solar cell with 13.7 % efficiency (ECD - Sovonics)

c) Heterojunction with intrinsic thin layer (HIT) with an efficiency of 21 % (SANYO)

d) µc - Si C/Poly - Si heterojunction solar cell with 17.2 % efficiency with simple fabrication process (Osaka University)

2. Thin Film Polycrystalline Silicon Solar Cell

In view of the high cost of mono silicon material (400 µm per wafer) and the wastage associated with slicing the crystal (Kerf loss) there are R & D efforts to develop polycrystalline silicon material for solar cell satisfying the cell criteria such as light trapping, planar films with single crystal grains, a minority carrier diffusion length 2 times the thickness, benign grain boundaries, a substrate providing mechanical support.

Notable among others is Astro Power company which has developed Silicon - Film TM solar cell with 50 µ film (expected to increase to 14 % in near future) has a substrate providing mechanical support. The entire process is amenable for low cost production.

3. Compound Semiconductor Thin Films

Substantial progress has been made in the development of Cd Te Technology and Copper Indium Diselenide (CIS) technologies, specially during the last two years. Notable among them are

a) total area efficiency of 17.7 % has been achieved for a thin film Cu In Ga Se2 (CIGS) solar cell fabricated by NREL.
b) total area efficiency of 12.4 % for CIS fabricated by ISET.
c) aperture area efficiency of 13.0 % for CIGS mini module fabricated by Solarex, Siemens and showa companies
d) 9.1 % efficient, 6728 - cm^2 area Cd Technology module by Solar Cell Inc.

Since the world conference on Photovoltaic Energy Conversion in Dec 1994, several groups have focused their efforts on Cd Te, CIS and specially CIGS films producing excellent results shown in table 3.

PV Modules and Systems

Photovoltaic module is the basic building block of the stand alone Photovoltaic system and is the smallest complete, environmentally protected assembly of solar cells designed to generate D.C power (27). Single solar cell provides small amounts of power typically a 100 cm^2 cell gives about 3.0 A and 0.5 V in full sun light. Large number of cells generally 30 to 40 in number form a Photovoltaic module resulting in useful levels of power. The generic elements of a module encapsulation system are shown in fig. 5 alongwith layer designation and the function performed by meach layer. The 'superstrate' uses top surface such as toughened glass to provide strength for cells and light to shine on the cells and substrate to provide the mechanical support. The cells are encapsulated to protect the mechanical support. The cells are encapsulated to protect from environmental stresses such as wind, hail, differential expansion and humidity and to maintain at least 20 year lifetime. The various steps involved in a typical module assembly are given in table (4) the PV module assembly process steps are shown in fig. 6. After soldering and interconnecting the electrodes, the stringed cells are sandwiched between a tempered glass ad sheets of EVA for mechanical bonding and encapsulation. These are followed by cushioning sheets of glass fibers and are of mylar which provides the dielectric insulation. Finally the modules backing is applied in the form of a Tedler/Aluminum foil/Teldler laminate to seal the unit against moisture. The module is placed in a lamination chamber to evacuate all the air from the module and heat sealing the layers and integral unit. Shown in fig. 7 are the standard photovoltaic modules with single crystal silicon round and square cut cells, polycrystalline silicon module and thin film modules. Each Photovoltaic module has its own unique Current/Voltage relationship (I-V) curve determined by a I-V tracer. Majority of the Photovoltaic modules available in the market today are designed to charge 12 V batteries and deliver in the range of 15.5 to 17.0 VDC under standard operating conditions.

Photovoltaic Module System

Photovoltaic module is the chief constituent of the Photovoltaic system designed for any of the applications such as domestic lighting, irrigation and water pumps, small clinics, microwave relay stations, railway signals, road signs as well as large Photovoltaic systems connecting grid. The Photovoltaic module and array (made of several Photovoltaic modules) should be compatible with the balance of system (BOS).

BOS consists of batteries, inverter, charge controller, voltage stabilizer, safe guard controls and structural support.

Schematic diagrams for BOS for various configurations are shown in fig. 8. Schematic of basic DC stand alone system in which the Photovoltaic array is connected directly to load with storage (b) same as in (a) except array is connected to load via a voltage regulator which is an indispensable component if the Photovoltaic system is left unattended (c) an inverter is introduced to connect to A.C load (d) in this system power from the grid is substantial as an auxiliary source of electricity enabling supplementing the systems outpoint when needed and sold back to utility when Photovoltaic arrays' power is in excess. (please refer to the report on stand alone Photovoltaic systems, A hand book of recommended design practices by Photovoltaic design assistance Center, Sandia National Laboratories, Albuquerque, New Mexico, USA)

III. PHOTOVOLTAIC APPLICATIONS

Solar Cell technology provides a clean energy, without any moving parts, with minimal maintenance, with abundant and free fuel and also delivers power in a wide range from fractional watt to megawatts.

The first application for Solar Cell was in space during the 1960s followed by hand-held calculators with the advent of amorphous silicon technology and terrestrial applications with crystal silicon technology. During 1990s Photovoltaic powered cars have been demonstrated.

Although the initial applications of Photovoltaic have been limited to remote areas, deserts, mountainous areas due to high cost of commercial electricity in these areas, the applications for household use in villages and even urban homes are increasing as the Photovoltaic production costs are decreasing.

Listed here are some of the examples of Photovoltaic applications indicating typical power requirements:

System	Description	Required photovoltaic cell output (peak power)
Lighting	Indoor Lighting in villages, isolated areas, street lights, outdoor signs, tower lights, etc.	15W ~ 60W
Household equipment	Electrical home appliances, fluorescent lamps, refrigerators, drinking water pumps, radio, TV etc. can be powered even in areas where commercial electricity is not available.	40W ~ 2KW
Cathodic Protection	Protecting petroleum pipelines, gas pipes and telephone cables from corrosion.	500W
Land Transportation Control	Railway signals, unmanned railway crossings, road signs, barrier flashes and guide boards.	20 to 100W
Wireless and microwave relay stations	Microwave or UHF relay stations, TV broadcast stations serving remote areas.	60W to 3kw
Small clinics	Supplies lighting, refrigerator for storing medicines, powering other medical equipment especially in developing countries.	300W to 1 KW
Irrigation and Water Pumps	Irrigation pumps as well as drinking water pumps on a large scale in many developing countries.	1 KW - 4 KW

In view of the increasing pollution all over the world people are now aware of the need to reduce CO_2 and are planning to use Photovoltaic energy in urban areas as well.

In this USA, Japan and Europe several rooftops are powered by Photovoltaic for residential power requirements. Recently Sanyo Company announced developing A-Si technology suitable to use on curved tiles, traditionally used in Japan. Germany has started a thousand - roof project. These are pointers for widespread Photovoltaic applications even in urban locations in the near future.

Developing countries such as India, Brazil and China are increasing their Photovoltaic productions to cater for their rural power requirements.

In developed countries several Photovoltaic power plants in the range of 100KW to 5MW exist and there are proposals for utility grid connection. Semitransparent A-SiC solar cells and see-through type solar cells have new areas of application such as sun-roofs in motor cars and decorated windows in buildings.

The application of Solar Cell ranges from powering household equipment to connection of utility grid and photovoltaic also has the potential to contribute to global environmental issues in the near feature.

IV. TECHNO ECONOMIC ASPECTS OF PHOTOVOLTAIC INDUSTRY

Photovoltaic technology is a relatively mature technology. Photovoltaic costs have dropped ten fold in the last 20 years as shown in figure 9. Current prices of $ 4.0 to 5.0 still remain except for applications of low load and off grid applications.

Cost reductions, development of niche markets, efforts by Governments and international bodies for sustainable energy should bring in the necessary critical market volume. Then photovoltaic with its several plus points added to comparable costs to other energies would have exponential growth.

Cost reductions could be attained through improvements in technology, process and economics of scale.

Scaling up Manufacturing Process:

Solar Cell consists of semiconductor modules and it can easily be mass produced like transistors and ICs and photovoltaic technology specially thin films are highly amenable for mass production. For example, an amorphous silicon plant of 2 MW capacity costs about $ 12.5 million while an 80 MW capacity plants requires an investment of $ 81m and the production cost is expected to be $ 1.25/Wp. The scaling up production VS module cost is shown in fig. 10. At this price the market expansion would have an exponential growth which is indicated in fig 11.

Photovoltaic processing technologies and its effect on module cost

Crystal silicon technology is highest as of today 35% of total photovoltaic production despite high material cost. Employing process developments to reduce the wastage in crystal growth, slicing (kerfloss) and also reducing thickness of wafer from 400μ to 250μ the price is expected to be reduced to $2.5/Wp by the year 2000.

Multicrystalline silicon technology which holds about 28% of photovoltaic production also suffers from high material cost. High through puts, larger casting ingot production and also using cheaper silicon is expected cut down costs but because of lesser cell efficiency produced compared to single crystal the cost is expected be around the same value $ 2.5/Wp.

Amorphous Silicon Technology which is achieving higher stable conversion efficiencies (10% as of now) and also being suitable for mass productions is expected to reach a price level of $ 1.0/Wp by the year 2000.

Cost break up per peak watt of silicon (~ 400 μ) VS thin film based modules at a plant capacity of 3 MW per annum is shown in table 5 indicating thin film based modules would be less costly.

CIS and CdTe thin film technologies have grown remarkably well during the last two years and few MW size plants are being set. With higher efficiencies and being suitable for mass production and with lesser capital investment compared to amorphous silicon plants CdTe and CIS based module costs are expected to plummet to less than $1.0/wp by the year 2000.

The cost digression as a result of mass production of solar modules can also be estimated from an extrapolation of the real cost transitions in the past 20 years shown in fig. 12 are actual costs of photovoltaic modules (without BOS) size of module varying from < 1kwp to > 1MWp.

Energy Pay Back Period (EPP)

Electrical energy generated by a photovoltaic module depends upon the values of conversion efficiency and the average insolation level at the given site. The EPP is the quotient of the invested energy in fabricating photovoltaic module and the energy generated by the module in one year. Some numbers are available on Energy Payback period specially with the roof top photovoltaic modules of 2 to 3 KWp capacity. During 1994 joint cooperated program of house building industry and solar module manufacturers to develop photovoltaic roofing house was initiated under contract of New Sunshine Project in Japan. EPP for a 3 KWp roof top photovoltaic power house and the solar roofing house calculated on crystal silicon based and amorphous silicon based solar cells are given in table 6. EPP is much less for amorphous silicon based roof tops.

Comparing several factors such as material costs, suitability for mass productions and energy pay back period "Thin Film" technologies look to be having edge over crystal silicon technology for large scale production from viability and economic considerations.

This will be particularly true when worldwide photovoltaic module production per year cross 250 MW for want of feed stock silicon, unless solar grade silicon manufacturing plants are commissioned.

Scale of Merit

The present annual world photovoltaic production is around 90 MW market size and with the present sharp growth expected from 1997 (plans for commissioning photovoltaic plants to the tune of 270 MW are on the anvil, described elsewhere in the report) it is expected to cross 400 MW photovoltaic production per year by the year 2000. And one of thin film technologies with a share of 100 MW annual production could achieve substantial cost reductions due scale of merit.

An increase of mass production scale with expanding market size induces cost reductions by large scale merit. Fig. 13 shows cost reductions of the solar cell module in last 10 years for various Photovoltaic technologies. The scale merit refers to the percentage of unit cost after the mass production scale is increased by one order of magnitude. The results indicate a scale of merit of about 30% for crystal silicon Solar Cell and a 25% scale merit for the amorphous silicon Solar Cell because production steps of thin film are better matching to mass production.

Governmental and Institutional Promotionary role in photovoltaic industry

The development of photovoltaic technology in major photovoltaic producing countries depended on (1) Government Support (2) R&D efforts (3) Developing markets for sustainable energy growth and public awareness of the new technology for terrestrial applications.

USA: Department of Energy (DOE) plays the main promotional role by stressing the major end usage of photovoltaic for utilities in national program, coordinates various funding programs on R&D, standardization, advanced material technology development, demonstration of pilot projects, BOS systems through national institutions such as NREL and SNL.

Japan: Ministry of International Trade and Industry (MITI) promotes photovoltaic as a possible source of power supply by coordinating with agencies such as AIST, ETL, NEDO etc. The programs are oriented more to bring photovoltaic products to market and developing process techniques suitable to mass production.

Recently Japan has introduced new government regulations for promotion of photovoltaic systems by (a) tax reduction for private industry investment for photovoltaic including photovoltaic airconditioners (big loads) (b) 2/3 subsidy for photovoltaic system facility cost installation fee and data acquisition (c) 1/2 subsidy for residential photovoltaic system installation cost and a variety of incentives to achieve economic viability for photovoltaic systems.

Europe: Europe has multinational projects such as EUREKA and JOULE programs for promoting R&D as well as demonstration projects. Germany, Switzerland and Italy have strong photovoltaic programs. Germany started a 1000 roof top photovoltaic systems and has programs to increase terrestrial photovoltaic applications in a big way mainly from environmental considerations.

Switzerland has a program targeting 50 MW by year 2000 with strong commitment to integration in buildings. Italy has already established a 3.3 MW plant single largest plant in Europe shown in fig.14 and several photovoltaic industrial projects.

The photovoltaic promotional activities taken up by various governments help in overcoming some of the institutional and market barriers for photovoltaic propagation such as investment, subsidies, transaction costs, customer awareness etc. Based on the technical data on cell efficiencies, development of new technologies, system life time, production costs, production scale and the promotional measures taken by several governments for propagation of photovoltaics Prof. Hamakawa (28) proposed the scenario of the technical mile stones, achievements both in terms of conversion efficiency and costs of photovoltaic modules and BOS and finally the levelised electricity costs alongwith DOE estimated figures during 5th International PVSEC as presented in table 7. The predictions fell short by two years and the levelised electricity cost of $0.18/kwh and $0.07/kwh are expected to be achieved in 1997 and 2002 respectively.

Potential Markets For Photovoltaics:

Photovoltaics the zero-emission technology has enormous potential to reach various cross sections in the developing countries.

Rural and off-grid markets:

2 billion people in the developing countries still lack adequate energy for economic growth and basic needs. 400 to 500 million households in rural area have no access to grid connection or may not be available within the next two or three decades. Grid extension is very expensive varying between $5000 to 10,000 per a mile of extension depending on the location.

Solar House System (SHS)

An estimated 100W per house to provide 3 lights, a fan and a radio or a TV minimum domestic electrical needs known solar house system (SHS) shown in Fig.15 in rural areas mentioned above would require 40,000 MW a staggering power need which can not be met in near future by conventional grid. Thus it provides a very potential market for Photovoltaic specially because it is stand alone system and a low load application.

ASTAE World Bank and GTZ Germany have done have worked on these programs.

Drinking Water And Irrigation Pumps

Almost 1 billion people in the developing world lack access to safe drinking water supplies. Together with drinking water pumps the irrigation pumps for agriculture in the developing countries alone are using about 50 million diesel pumps each consuming 1 ton oil an year are being employed. This represents a huge market for photovoltaic as a least cost option if LCC is taken into account.

Health Clinics, Community Centres

Another very potential market in the rural area which are not electrified is a health clinic and community centre for education and entertainment. Health clinic as shown in fig. 16 having a refrigerator to keep life saving medicines, essential medical electronic gadgets, lights, fan, communication equipment and water pumps etc. is an indispensable minimum to cater the basic health needs of several hundreds of thousands of villages. Similarly community centre a gathering place in the village in the evening could be well utilized for education information and entertainment purposes. It could also be used for adult education programs such as what is practiced in developing countries like in India.

A community centre with a few lights, a fan, TV & VCR requires 1/2 KW coupled with the power requirement of about 1 kw or so for health clinic for about say 500,000 villages is 750 MW. These are the facilities for which photovoltaic is certainly the least cost option in the developing countries.

Photovoltaic Hybrid Systems

This forms a very important and potential market for photovoltaic for several medium range power applications. Because of high price of diesel fuel in developing countries photovoltaic powered systems are known to be cost effective in the long run. Shown in fig. 17 is a comparison of 60 KW systems run of photovoltaic and diesel indicating photovoltaic is cheaper over a period of 20 years. However, in view of the capital costs for photovoltaic system a photovoltaic diesel hybrid system proves economically and technically advantageous with loads between 50 to 250 KWh/day. Hybrid systems presently enable a trade off of capital and operating costs as shown in fig. 18 providing a more optimal solution.

Several units with 25 KW photovoltaic array alongwith 30 KVa diesel set delivering a load of 200 kwh a day in an island north of Australian main land and 4KWp photovoltaic and 12KVa powering emergency communication system in Florida. This indicates the great potential of photovoltaic in both developed and developing nations.

Application in small island countries

In several island countries in Pacific and Asian countries the needs such as water desalination plants, low power consuming industries cottage industries, fishing industry (requiring refrigeration for transport) and inter island communications are best served with photovoltaic and this forms another big potential market.

Hybrid systems including photovoltaic micro hydro systems which photovoltaic is used to pump water back for use and as storage media are some of the applications increasing the photovoltaic market potential.

Solar Roofs

In several developed countries such as Japan, USA, Germany etc. solar roof programs have been initiated. Typically the solar roofs are of the capacity 2 to 3 KW and for the last 2 years photovoltaic has made in roads in building and construction activities in view of the aesthetic considerations as well as suitability of geometric integration of photovoltaic modules into roofs like shingles and wall curtain and into larger buildings and facades fig. 19 shows at 13.14 KW photovoltaic modules incorporated in the architecture of the building, with massive supports coming from governments (Japan subsidizes 50% of the solar roof system cost). Shown in fig.20 a Japanese house with solar roof delivering 2 to 3 KW power. Fig. 21 to 24 show the penetration of Photovoltaic in building construction and highways.

This promises to be another potential market for photovoltaic in urban areas of developed countries. With cost reduction the potential market for solar roofs would be very huge.

Funding Mechanisms:

While it is cost effective on Life Cycle basis, photovoltaic still has a high front-end capital investment. Given the scenario of dispersed basis of individual photovoltaic customers located in rural and remote areas it has been difficult to mobilize high financing requirements from commercial or private sources.

Low customer density in a given service territory makes sales, installation, service and finally payment collection generally turns out to be expensive and unmanageable. This is the experience of GTZ which for 10 years has been involved in the dissemination of photovoltaic systems for rural households in developing countries.

Recognizing the need in developing countries for renewable energy technologies the World Bank through ESMAP (Energy Sector Management Assistance Programme) in cooperation with US DOE and other international organizations launched FINESSE (Financing Energy Services for the Small Scale Energy users). The objective of FINESSE is to identify and promote ways to provide economically viable and affordable alternative energy services in the developing world. It encourages NGO Organisation to assist in establishing and operate mini utilities to provide power to local communities and donor funding is channeled to NGO through commercial lending sources. Funding is provided directly to voluntary organizations with Government approval. In most instances it could operate as a revolving fund.

Solar House System

SHS is considered as a least cost economic option for rural lighting and power supply. However there are several financial barriers that limit the purchase of SHS rural households such as import duties, subsidiaries on kerosene, costs associated with establishing a retail and service network and high front end costs requiring financing.

SHS system needs to import BOS which attracts high tariff in several developing countries. In Srilanka duties add up to about $2.50/wp, India levies a 45% duty on photovoltaic equipment. Duty on imported batteries vary from 50 to 100% depending on the country.

In the early stage of market development the investment required for sales, training and service are very high for minimum quantum as can be seen from an example in Indonesia where SHS in west Java (Annual Sales are in thousands of systems per year) is 50% cheaper than in Lampung where SHS system sales are in hundreds per year.

It is expected that support from Government, by promotional campaign of SHS for rural households, tax credits at the retail or whole sale level, training and technical assistance to help establish retail and service networks, can bring in the necessary SHS financial viability.

The high initial purchase price represents the biggest barrier for rural populations, in developing countries where annual incomes are at lowest level. While 5% of the rural householders can afford cash payments for SHS system or even other gadgets 95% do need funding.

Financing Models

Broadly four funding models have emerged, Energy service companies (ESCO), Leasing, consumer financing and cash sales.

ESCO sells the energy service while retaining ownership of the hardware. Typically ESCO procures SHS in bulk from distributors or international market. ESCO personnel install the SHS and service the power generating components. The monthly cost charged to the customer can also be reduced by spreading the cost of photovoltaic system over the life time of the system.

In the leasing arrangement the intermediary retains ownership of some or all of the SHS and provides it to the customer under specified terms and conditions.

In consumer financing model the suppliers sell directly to consumers who can obtain financing from local banks or dealers. The summary of the various financing, scheme characteristics are shown in table 8. The financing terms vary substantially from country to country and depend on the cost of funds, degree of risk to the lender and loan processing and administration costs.

GEF Green Carrot Project (29): Green Carrot Program of GEF is mainly to accelerate the commercialization, market penetration and financial viability of photovoltaic technology in the developing countries. It has set $60 million fund providing $5 - 20 million rewards for a few companies for expanding commercial applications. GEF has identified among others Energy Service Companies or Leasing Companies operating either independently or with a country addressing markets in water pumping, develop photovoltaic / diesel hybrid systems in association with renewable energy vendors.

GEF also identified funding for increased technology transfer and developing country capabilities in photovoltaic market and manufacturing and for introduction of new financing mechanisms.

The awards could be used as base capital to attract further financing for significant manufacturing scale up. Several photovoltaic manufacturing companies in developing countries find it very difficult in view of limited market to scale up their product or establish cost effective technologies for want of funds as local interest rates are very high 20% or more. Now Ex-Im banks of several developed countries have initiated to give loans at LIBOR Level interest rates in their programs to encourage eco friendly technologies. This can bring economic viability for many photovoltaic industries in developing countries.

V. IMPACT OF PHOTOVOLTAICS ON DEVELOPING COUNTRIES

Despite enormous investments in rural electrification two billion people which is about half the population of the developing world, continue to live without adequate power supplies or no power at all. Even in those countries which implemented rural electrification only a few serve more than 20% of their rural population.

In rural areas the electrification program is problematic as line extensions are unreliable and are characterized by low loading ratios and high losses.

There is also a growing awareness of the pollution caused by use of fossil fuels and oil and the environmental degradation in the developing countries. The rapidly industrialization taking place in this world is known to worsen the situation.

These emerging realities are motivating leaders in developing countries that renewable energy in rural areas and energy efficiency in urban areas can play a vital role in satisfying developing countries energy needs while helping to mitigate environmental pressures.

It has been realized that photovoltaic energy is best suited for several low load applications such as solar house systems specially in rural sector.

Currently the photovoltaic power generation is 9 to 10MW in developing countries which is about 10% of the world photovoltaic production.

India, Brazil and China are some of the countries which have established photovoltaic industries with significant growth over the last eight years.

India: India is a fore runner in photovoltaic industrialization in developing countries with a cumulative photovoltaic module production of about 30MW over the last eight years. Ministry of power and non-conventional energy sources established 10 years back is responsible for setting up photovoltaic industries, supporting R&D efforts and establish IREDA Indian Renewable Energy Development Agency with the mandate to promote, develop and finance renewable energy technologies.

India with two companies in public sector and two in private sector has total capacity of 6 MW per annum based on crystal silicon technology with photovoltaic module shipments of the order of 3 to 4 MW. There is a poly silicon plant with 25 tons per annum capacity and silicon wafer facility producing more than 1 million wafers per annum. 1/2 MW amorphous silicon plant has been commissioned five years back and currently in progress is a production plant for manufacturing CdTe modules.

Currently there are about 15 companies with varying capacities to assemble photovoltaic modules.

Most of these companies manufacture photovoltaic modules as well as BOS required for various applications such as Street Lights, Water Pumping portable lanterns and solar house systems.

Photovoltaic production got a big boost in 1993 with Indian Government's decision to power rural telephone exchanges by photovoltaic (70w per unit) and started tendering on the average 3 to 4 MW per year reaching 7 MW this year.

So India is likely to have 9 to 10 MW market from 1997. However, this is insignificant compared to its potential for photovoltaic and the need for providing energy to the rural households.

India uses about 15 million diesel pump sets (each consuming 1 ton oil/year) used for irrigation. Phasing out the diesel pumps with photovoltaic powered pumps, setting up photovoltaic powered village clinics, community centres and SHS units for rural houses is the challenging potential for Solar energy utilization in India.

Brazil: Scenario in Brazil is not very different. The photovoltaic potential is comparable to India, Brazil too has established photovoltaic industries for Solar Cell, module and systems and exports more than million silicon wafers.

China: China has 7 photovoltaic plants with a production capacity of 4.5 MW and manufacture Solar Cells of 3.0 MW per year. Two plants manufacture crystal silicon and wafers. China has program to use photovoltaic for households in rural, nomadic districts and isolated islands. They have a target of providing photovoltaic electricity to six million of the present 120 million people who have no access to electricity.

Indonesia: In south east Asia Indonesia has made tremendous progress by embarking on a project to electrify 1 million houses with 50 W capacity SHS units amounting to 50 MW.

Zimbabwe with a $7 million grant from GEF is setting up domestic lighting systems.

Several pacific islands have installed photovoltaic powered gadgets including photovoltaic diesel hybrid systems. Photovoltaic powered refrigerators (to keep life saving medicines and vaccines) are being employed in several African countries. Figures 28 to 35 show some of the applications employed in various developing countries showing the impact of photovoltaics.

Recognizing the need for use of photovoltaic power in developing countries World Bank has taken solar initiative and providing funds for dissemination and propagation of photovoltaic energy applications (30,31).

GEF with its target of arresting gas emissions provides grants in developing photovoltaic industries and markets in developing countries.

UN bodies such as UNIDO (United Nations Industrial Development Organisation) plays an important role in forming Vital linkages between various nations for transfer of know how and technologies from developed countries to developing countries. It has programs such as COSERA for promoting and augmenting solar energy applications and market surveys by providing forums for countries in various locations for interaction, providing expert advice for technology promotion as well as feasibility studies for photovoltaic projects in developing countries.

Large scale photovoltaic power systems planned world wide: During 1996 large scale plans for photovoltaic plants totaling 280 MW have been proposed. 50 MW plant in India, 4MW in Hawaii, 10MW plant in California three plants 100MW, 70MW and 50MW in different locations of Nevada. Such big sized mass production plants would result in cost reduction and attract market pull.

VI. CONCLUSIONS:

The report has reviewed Solar Cell materials, technologies for production of various materials for Cell Fabrication, current techniques employed for fabricating crystal silicon, amorphous silicon and other semiconductor thin films and the recent achievements in developing high efficiency Solar Cells. While C-Si and A-Si efficiencies have improved substantially it is clear that thin films Cd Technology and CIS have become strong contenders for low cost manufacture of photovoltaic cells. With the development of efficient polycrystalline Si thin films and the initiation of mass production of CdTe and CIS thin films and $2/Wp goal looks to be realisable very soon. Detailed description of photovoltaic module assembly operations are presented in view of the increased activity for photovoltaic module and system operation in developing countries.

Techno economic aspects of the photovoltaic power generation are discussed taking into account the technology push and the desirable market pull gaining momentum. The potential and niche markets for photovoltaic, the funding mechanisms that are operating in developing countries as well as the photovoltaic industrial growth in several countries are presented.

Several country Governments realising the need of renewable energies specially photovoltaics in the rural areas have initiated projects such as solar house systems (SHS) and graduated from low load applications to medium load power applications such as water pumping. Having taken the solar initiative World Bank, GEF are actively participating in establishing photovoltaic power units in the rural areas of developing countries by introducing a variety of funding programs and financial schemes.

Solar roof top projects are becoming popular in several countries such as Japan, USA, Germany and Switzerland disproving the myth that solar energy is good only for rural sector.

1996 looks to be the beginning of rapid growth for photovoltaic industry worldwide with the announcement of plans for setting up photovoltaic plants of the order of 280 MW.

With the development of high efficiency solar cells also suitable for mass productions and scaled up manufacturing plants in the offing production costs would plummet to $2/Wp by 2000. This would have a remarkable impact on developing countries and accelerate the growth of photovoltaic industry.

Acknowledgements

The author is grateful to many a researchers from all over the world; from research institutes, industries, financial institutions and Government bodies, who took time to share their latest results and information about their activities for promotion of Photovoltaics. My thanks are also due to Mr.S.Varadarajan who assisted in bringing this article on to diskette.

Table 1 : Multicrystalline ingot grwoth techniques, ingot size throughputs, life times, diffussion lengths and cell efficiencies.

Name	SEMIX	–	–	–	EUROSIL	SILSO	BAYSIX	POLIX
Company	Solarex	Crystal Systems	Sumitomo Sitix	Kyocera	Eurosolare	Wacker	Bayer	Photowatt
Method	Casting	DS	DS	Casting	DS	Casting	Casting	DS
Crucible/Coating Mould/coating Re-use	Silica/prop. Silica/prop. no	prop./Si_3N_4 –	C/Si_3N_4 nx	silica C/prop. nx	silica/ Si_3N_4 – no	silica/- C/prop nx	silica/- silica/Si_3N_4 nx	C/liquid enc. – nx
Heater	C	C	RF	RF/C	C → RF	RF/C	RF	RF
Ingot Size [mm³] [kg]	240x240x200 30	550x550x150 100	330x330x200 50	330x330x250 62	550x550x210 150	440x440x280 125	220x330x250 40	410x410x130 60
Growth Rate [mm/min] [kg/h]	prop.	10			0.1 - 0.2 6	0.4 - 0.6 12		
Throughput [kg/h] [kwh/kg]	prop.	2-3 10			3 15	10 - 15		
Impurities Precipitates	C/O SiC	C/O/N	C/O/N		C/O/N	C/O/N SiC_2 Si_3N_4	C/O/N	
Lifetime[µSec] Diff.length[µm]	100	≤ 300			180	10 - 20	200	
Solar Cell eff[%]/ Size [cm³]	15.8.130 16.9/1	15.3/100 16.3/42 17/1	16.4/225 17.2/100 17.8/4	15/225	14/100 16.7/4	15.6/100 15.8/4	16.4/100	16.2/4

Table 2 : Summary of some top efficiency records in thin film Solar Cells and modules (As of Sept. 1994)

		Voc(V)	Jsc (mA/cm²)	F.F. (%)	η (%)	A(cm²)	Institute	Remarks
		0.967	17.7	70.3	12.0	0.033	Osaka Univ.	p µc-SiC (ECR)
a-Si		0.891	19.13	70.0	12.0	1.0	Solarex	
Single Junction		0.927	18.4	70.5	12.0	1.0	Fuji-Elect.	BF3 Pulse CVD
Small Area		0.90	18.9	72.0	12.3	0.09	TIT	δ-doped player
Cells		0.923	18.4	72.5	12.3	1.0	Fuji-Elect.	Pulse CVD; p-a SiC:H
More Than		0.899	18.8	74.0	12.5	1.0	Fuji-Elect.	p a-SiO:H/a-Si:H/n a-Si:H
12%		0.885	19.13	74.7	12.65	1.0	SEL	Reverse Bias Annealing
Efficiency		0.887	19.4	74.1	12.7	1.0	Sanyo	Superchamber
		0.909	19.8	73.3	13.2	1.0	Mitsui-Toatsu	a-C/a-Si ML/a-SiC/a-Si
a-Si Sub-		12.53/M	130.1/A	73.5	12.0	10x10	Sanyo	TCO improvement
Modules (M)		2.409/M	611.6/A	68.6	10.1	10x10	Mitsubishi	a-Si/a-Si/a-SiGe
More Than 10%		53.9/M	328/A	71.4	10.05	30x40	Fuji-Elect.	a-Si/a-Si, a-SiO player
		1.75	8.16	7.2	10.2	1.0	Solarex	a-SiC/a-Si
		1.80	9.03	74.1	12.0	1.0	Fuji	a-Si/a-Si
		2.29	7.90	68.5	12.4	1.0	Sharp	a-SiC/a-SiGe/a-SiGe
a-Si	2	2.32	7.30	73.0	12.4		Sumitomo	a-SiC/a-Si/a-SiGe
Basis	T	2.55	7.66	70.1	13.7	1.0	ECD/Sovonics	a-Si/a-Si/a-SiGe
Stacked		1.48	16.2	63.0	15.0	0.033	Osaka Univ.	a-Si/c-Si
Solar		2.4	6568/A	67.5	11.8	905.9	Canon/USSC	a-Si/a-SiGe/a-SiGe
Cells		0.871	16.4	72.0	10.3		ARCO	a-Si/CuInSe2
	4	0.432	17.4	68.0	+5.3 = 15.6			
	T	0.917	10.4	76.0	7.25	0.033	Osaka Univ.	a-Si/poly-Si

Table 3 : Module Performance of Semiconductor Thin Films CdTe and CIS.

Company	Material	Area (cm²)	ή (%)	Power (W)
SCI	CdTe	6728	9.1*	61*
SSI**	CIS	3830	11.2	43.1
SSI**	CIS	3859	10.3*	39.7*
BP Solar***	CdTe	4540	8.4	38.2
SSI	CIS	3261	10.1*	35.7*
Golden Photon	CdTe	3528	7.7*	27.2*
SSI	CIS	938	11.1*	10.4*
Matsushita	CdTe	1200	8.7	10
BP Solar	CdTe	706	10.1	7.1
Golden Photon	CdTe	832	8.1*	6.8*
ISET	CIS	845	6.9*	5.8*
EPV	CIS	791	7.2	5.7
EPV	CIS	722	6*	4.3*

*NREL-measured; **Unencapsulated; ***Not monolithic

Table 4 : Photovoltaic Module Assembly Process

Progress Flow Diagram		Description Of Process (Equipment Required)
1.	Cell Inspection	Measurement of Electrical Characteristics of each cell. (Solar Simulator: consisting of xenon lamp, an electron charge and a system which allows the characteristics of measured devices to be recorded).
2.	Interconnector Soldering	Manual soldering of interconnectors to the cell face. (Tables, soldering iron, teflon rubber, magnifying glass).
3.	Array Soldering	Cells are positioned and interconnectors are soldered at the back of each cell to form circuits. (Table, cell aligner jig, back side wiring tray)
4.	Reversing the Array	Array is inverted to the front face and after visual inspection EVA and Glass is placed on it. (Table, reversing equipment)
5.	Reverse to Backside	Array with glass and EVA reversed to back side again, onto a background lighted table. It is insepcted visually for any dust and miss-soldering. Backside EVA and film is placed and aligned. (Backside lighted table, magnifying glass)
6.	Laminate	The whole pile is placed in laminator for lamination. (Laminator)
7.	Shelving	Laminated array is placed in the shelf. (Racks)
8.	Curing	Laminated array is cured in the curing oven. (Oven, racks)
9.	Edge Cutting	Outward projected film and EVA is cut to the size of glass. (Cutting stand, heat cutter).
10.	Framing	Long and Short aluminum frame battens are lined with rubber and framed onto the encapsulated array, on frame assembler. It is (frame assembler, power screwdriver)
11.	Terminal Assembly	Terminals are soldered and terminal box is attached. (Soldering iron, table)
12.	Standardisation tests	Measurement of electrical characteristics, data for standardisation (simulator, I-V tracer, data printer)
13.	Final Inspection	Panel is compared with standard panels for performance test. Visually inspected and labeled. (Comparator tester, standard panels, simulator).

Table 5 : Cost breakup per peak watt of silicon (400 µ) vs thin films Photovoltaic modules at a plant capacity of 3 MW per annum. (All costs in US Dollars)

Sr. No.	Particulars	Silicon (Bulk)		Thin Films	
		Crystal Silicon	Multicrystalline Silicon	Amorphous Silicon	CdTe & CIS
1.	Cell Material	$ 2.0	$ 1.8	$ 0.5	$ 0.5
2.	Cell Process	$ 1.25	$ 1.35	$ 1.5	$ 1.25
3.	Module Cost	$ 1.00	$ 1.00	$ 1.5	$ 1.00
		$ 4.25	**$ 4.15**	**$ 3.5**	**$ 2.75**

Table 6 : Energy Payback Period (EPP) calculated for 3 KWp PV

Annual Production (MW/y)	roof top PV			Solar Cellar roofing house		
	10	30	100	10	30	100
1. c-Si						
output energy	9614	9240	7993	8327	7952	6706
EPP (years)	2.4	2.2	1.5	2.1	1.9	1.2
2. a-Si						
output energy	5675	5518	4355	4388	4230	3067
EPP (years)	2.1	1.6	1.1	1.6	1.2	0.7

Table 7 : Conversion Efficiency Data, Technical & Financial Milestones

Target Year		1992	1997	2002
Solar cell/module efficiency (%) 100cm^2 area level	Xstal-Si	18/15.5* (23.7)	20/18*	22/20
	Poly-Si [cast/sheet]	15.7/13.5 [15.7/12.3]	18/15.5 [18.14]	20/17.5
(Small area top data)	a-Si	10/8.7* (12.0)	12/10*	14/12
	stacked a-Si (4T/2T)	10.6/9.2 (16.8/15)	14/11	18/15
Production scale (MWP/year)		14.5	40	500
Module cost(¥/Wp)		650 ($4.5/Wp)	500* ($3.3/Wp)	100-200* ($1/Wp)
BOS cost (¥/Wp)		500 ($3.3/wp)	350 ($2.3/Wp)	250 ($1.7/Wp)
System life (year)		20	22	25
Levelized Electricity Cost ($/kwh)		42** ($0.29/kwh)	27** ($0.18/kwh)	11** ($0.07/kwh)

* Sunshine Project Milestones.

** Module efficiency 10%, annual shine period 1200 hrs/year are assumed.

Table 8 : Summary of Financing Scheme Characteristics:

Financing Characteristic	Financing Scheme: ESCO	Leasing	Consumer	Cash Sales
Affordability	Highest	Moderate	Low	Lowest
Interest rate	Low	Medium	High	Not applicable
Repayment Period	Long	Medium	Short	Not applicable
Down Payment	Low	Moderate	High	Full cost at purchase
Loan security	SHS	SHS	SHS and/or other collateral	None
Credit risk to lender	Low	Moderate	High	Not applicable
Administration costs	High	Moderate	Moderate	Low
SHS ownership	Generation components by ESCO rest by user.	Eventually by user	Eventually by user	User

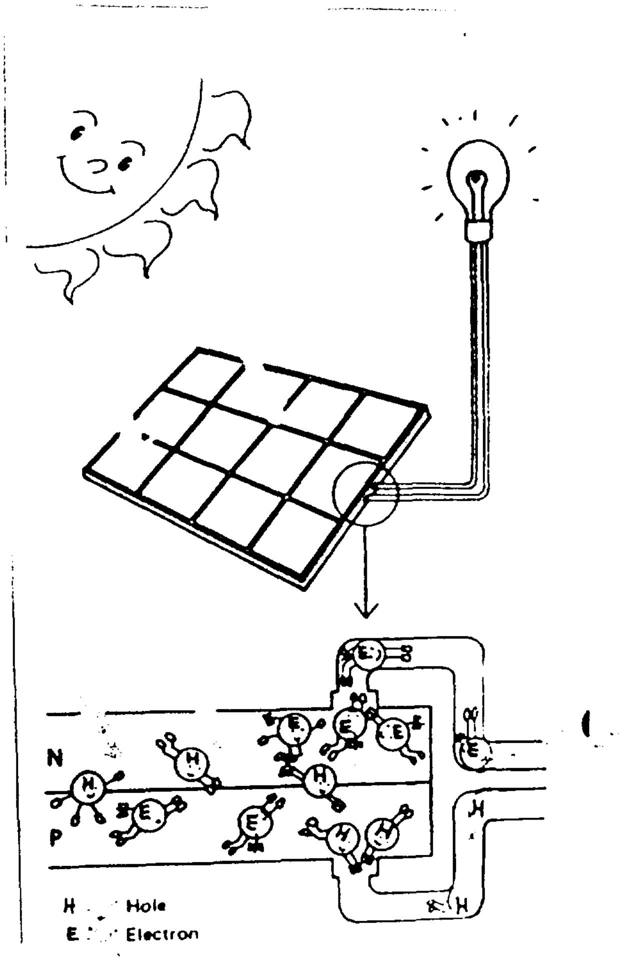


Fig. 1 Solar Cell: Incoming units of light energy (photons) are absorbed by electrons within the silicon wafer creating -ve charges (electrons) which are attracted to the n-type silicon and +ve charges (holes) are attracted to the p-type. A photo current flows voltage develops and electricity is produced.

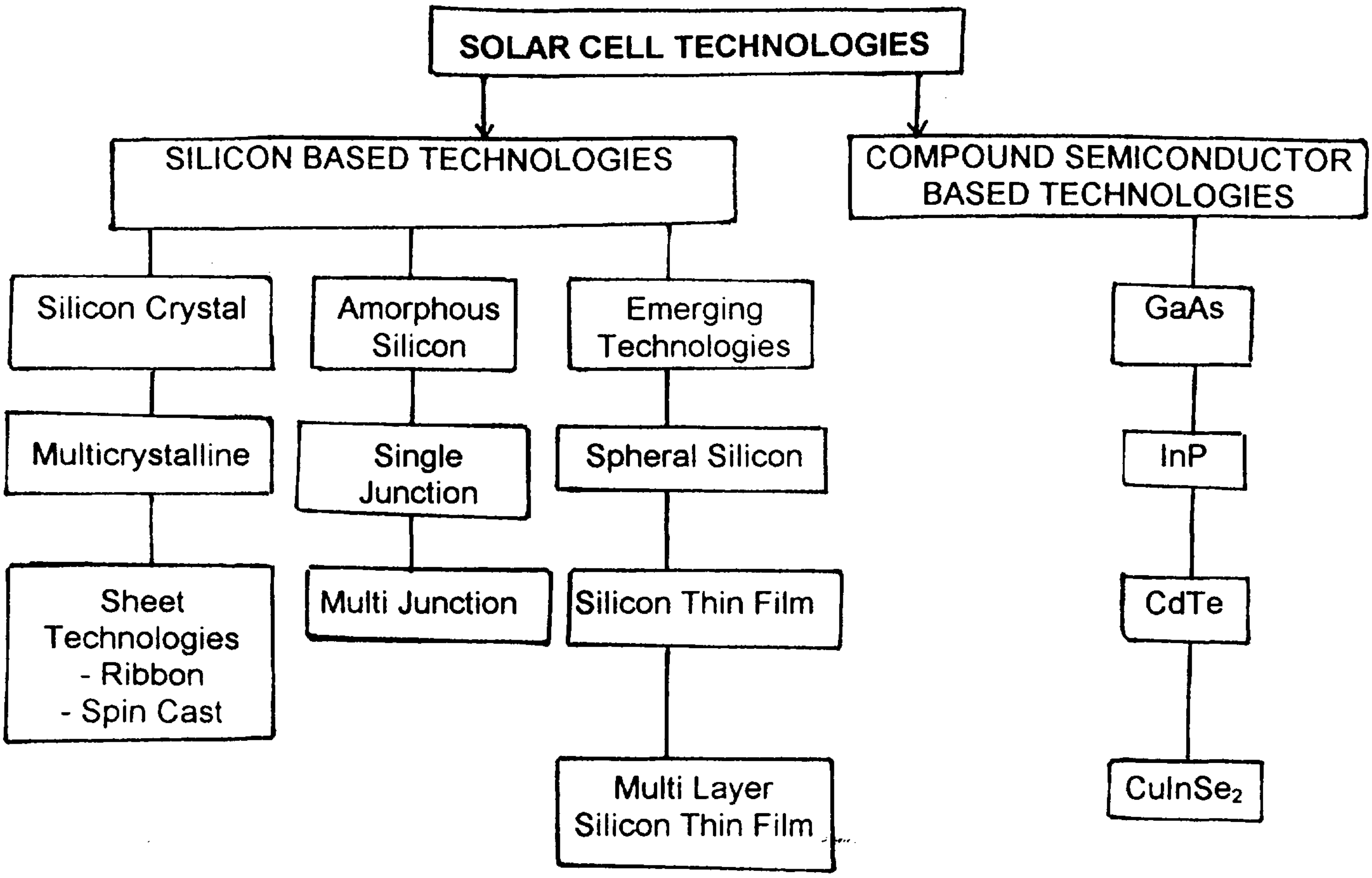


Fig. 2 Solar Cell Technologies:

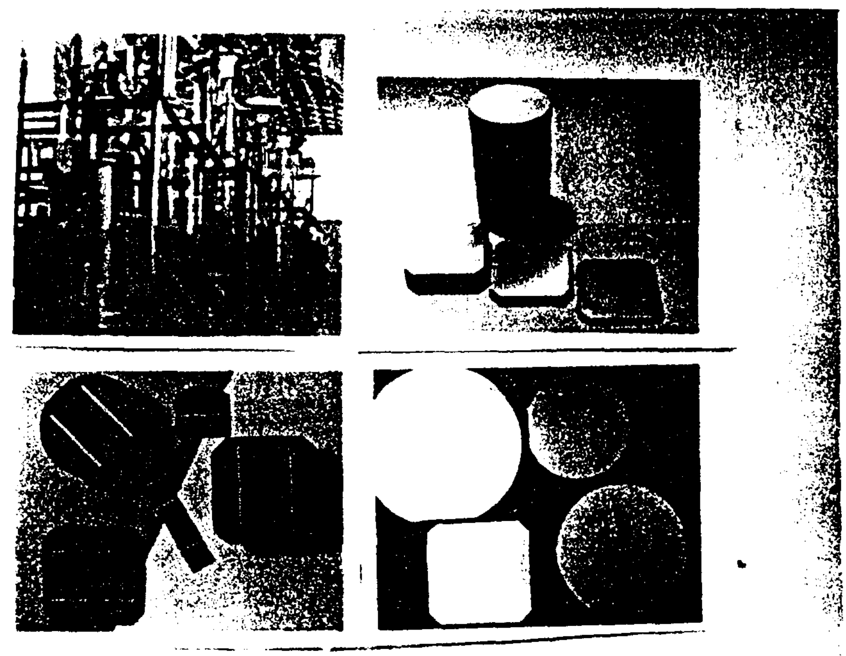
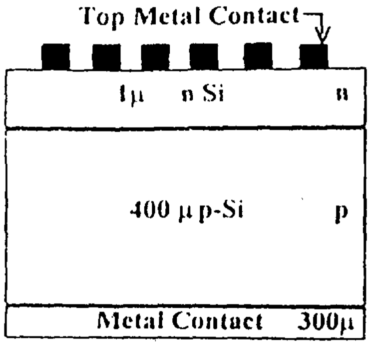
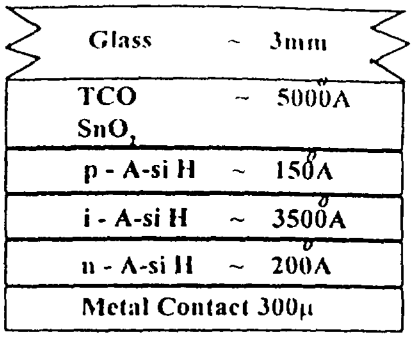


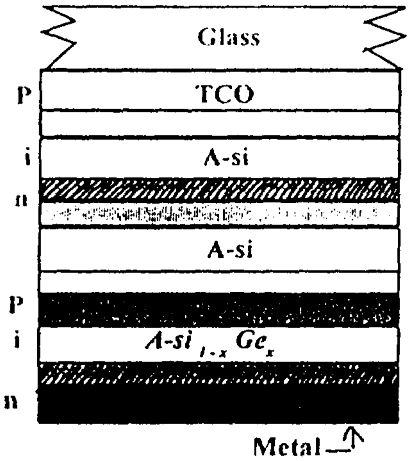
Fig. 3(a) CZ Crystal growing machines (b) Silicon Crystal ingots (c) Cast Silicon ingots (d) Round and Square wafers after slicing and (d) Solar Cells.



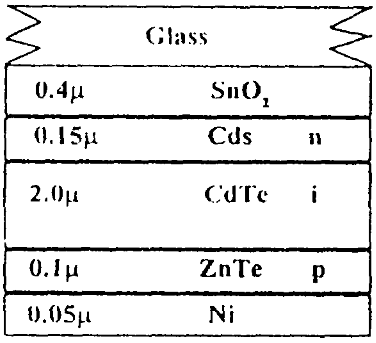
Crystalline Si Cell



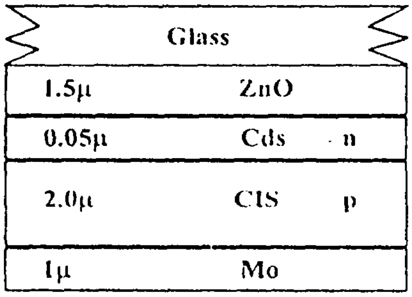
Single Junction A-Si Cell



Multi Junction A-Si Cell

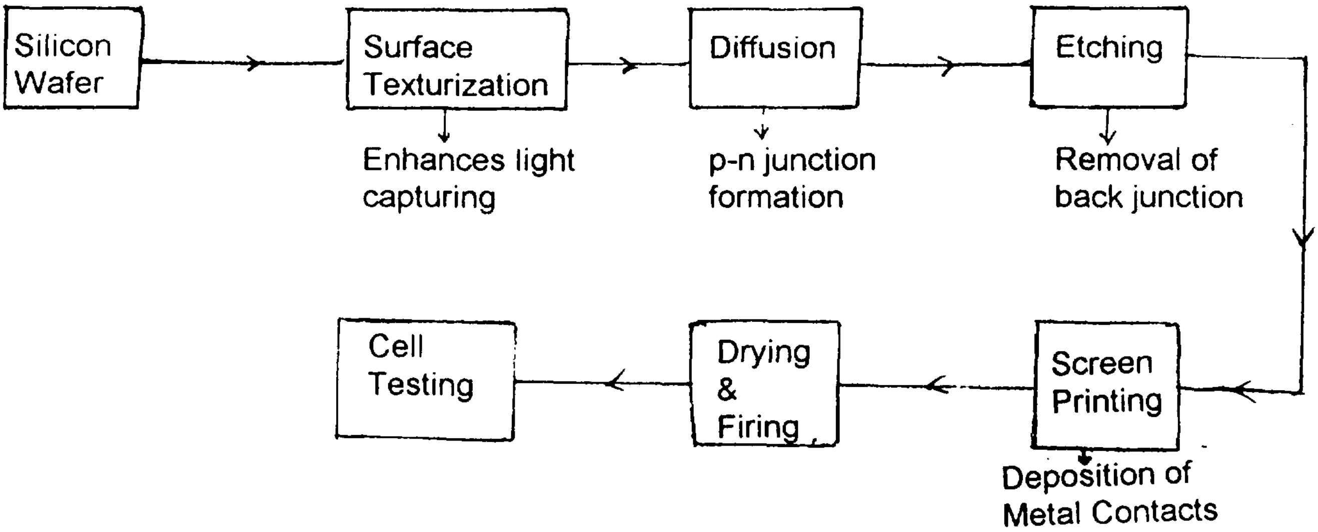


n-i-p CdTe Solar Cell

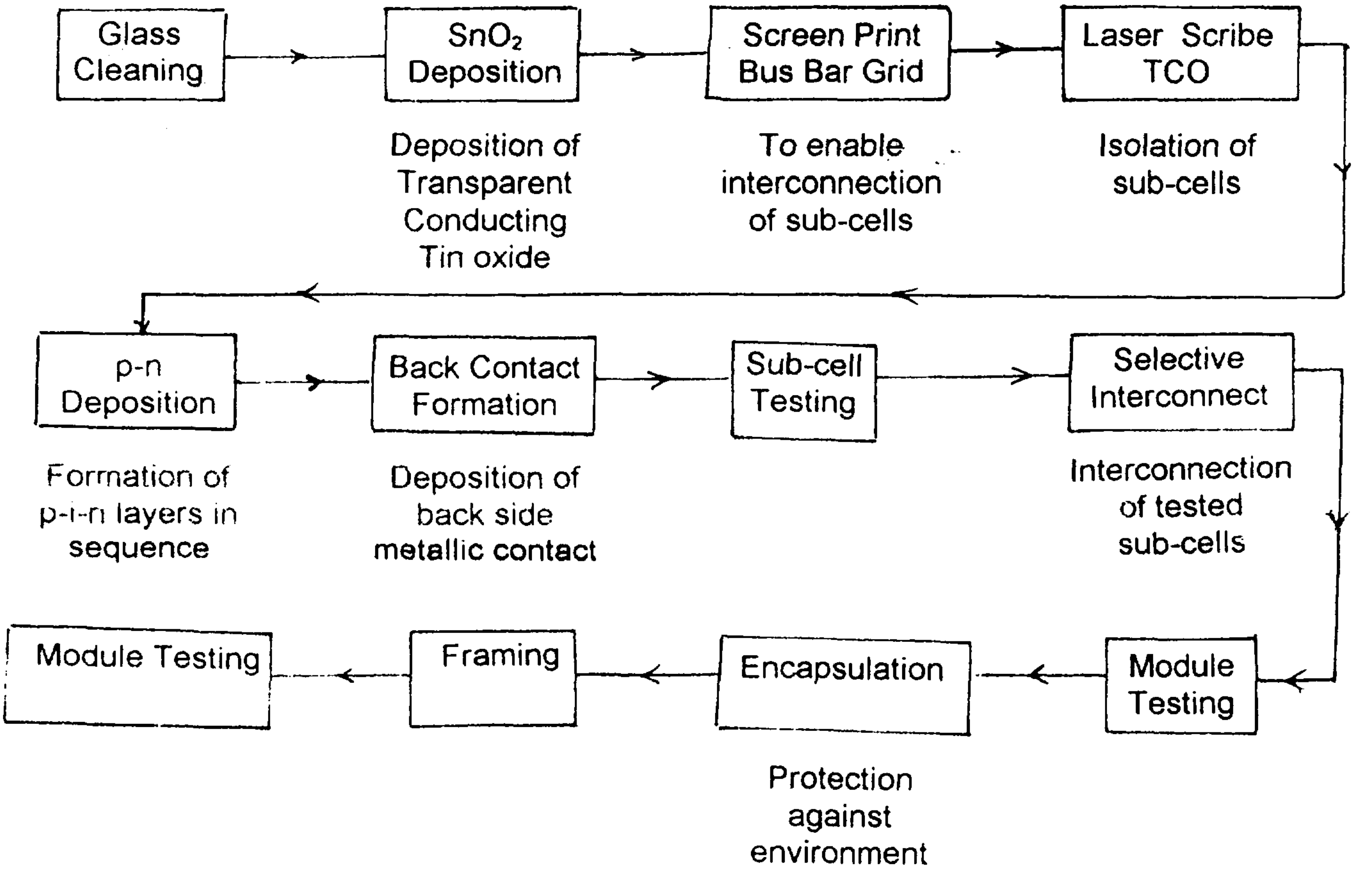


CIS Solar Cell

- Fig. 4 a Schematic diagrams of Solar Cell structures.



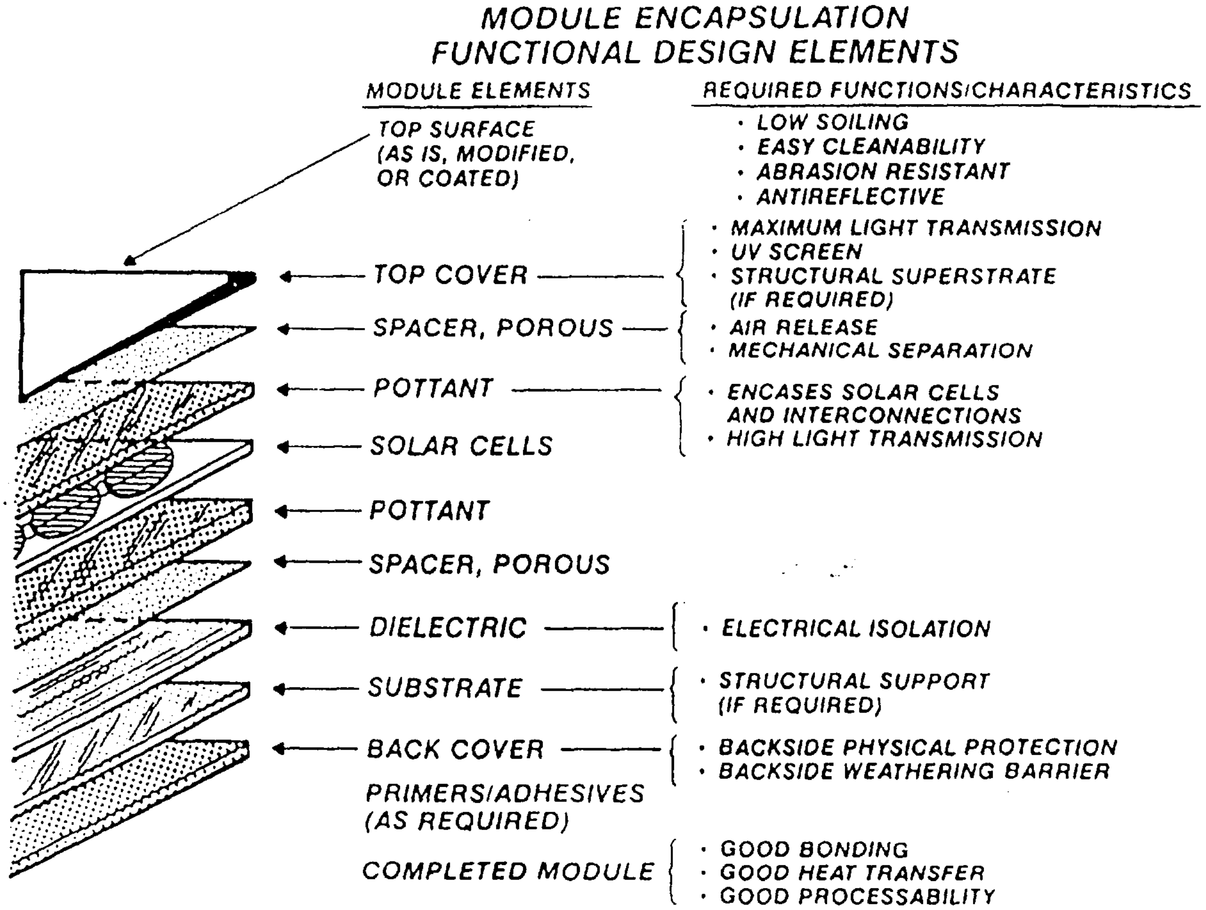
Typical flow chart for Fabrication of Crystalline Silicon Cell



Typical flow chart for Fabrication of Amorphous Silicon Solar Cell.

- Fig. 4 b Manufacturing process steps of Solar Cell

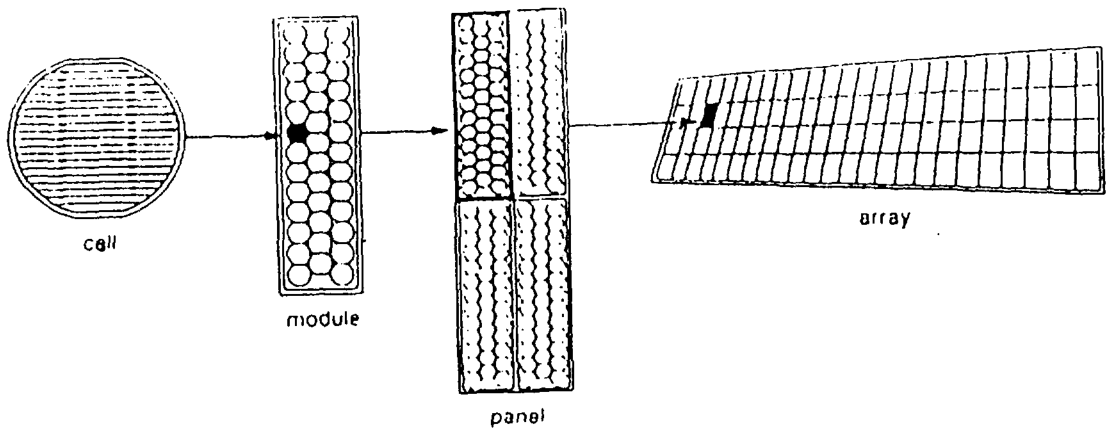
GENERIC ELEMENTS OF A MODULE ENCAPSULATION SYSTEM.



ENCAPSULANT SYSTEM OBJECTIVES

- Protect Cell from Environmental Stresses
  - Wind and Snow
  - Hail
  - Differential Expansion
  - Humidity
- Maximize Sunlight to Cell
  - Optical Transmission
  - Low Soiling
- Protect User from Safety Hazards
  - Electrical
  - Fire
- Maintain 20-Year Lifetime
- Maintain Low Area Cost

Fig. 5 Generic elements of photovoltaic Module encapsulation system.



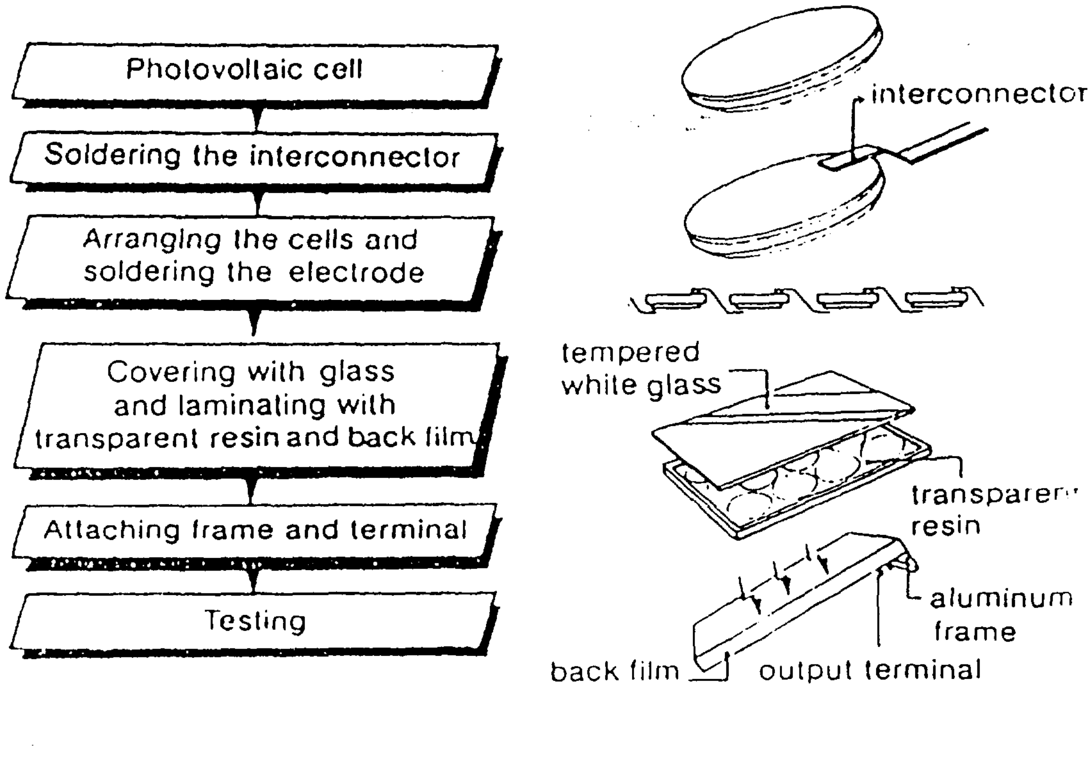


Fig. 6 Assembly Process steps of photovoltaic module.

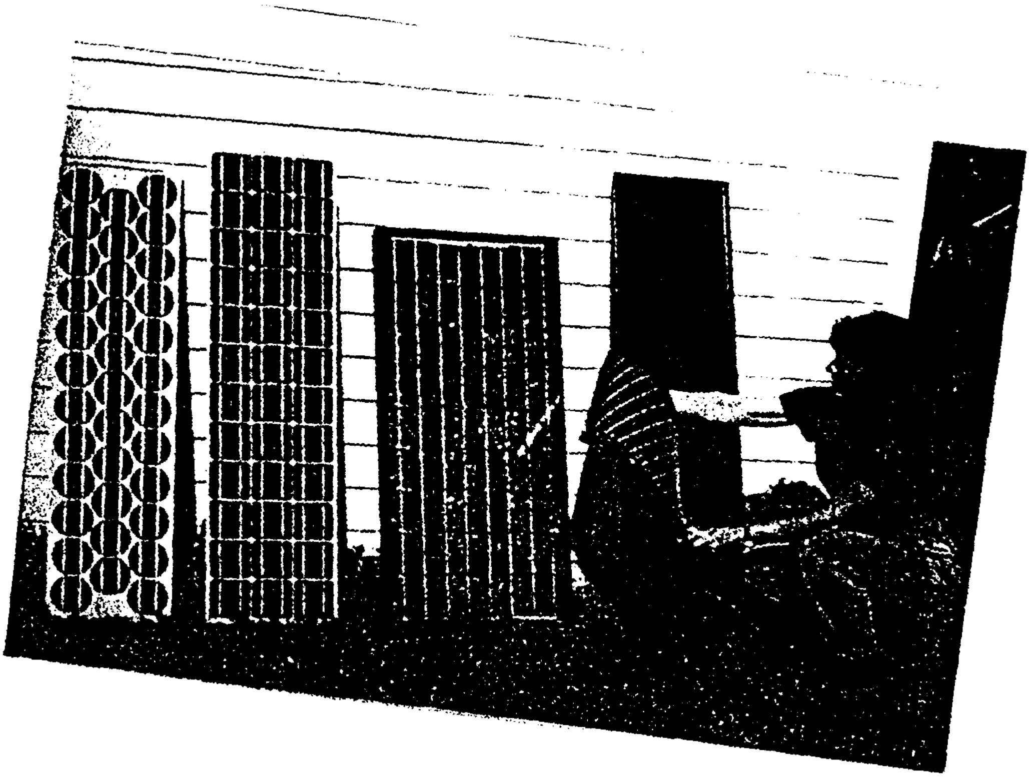


Fig. 7 PV modules. Left to right - Single Crystal Silicon modules with round cells and square-cut cells, polycrystalline silicon module, thin film modules (rigid and flexible)

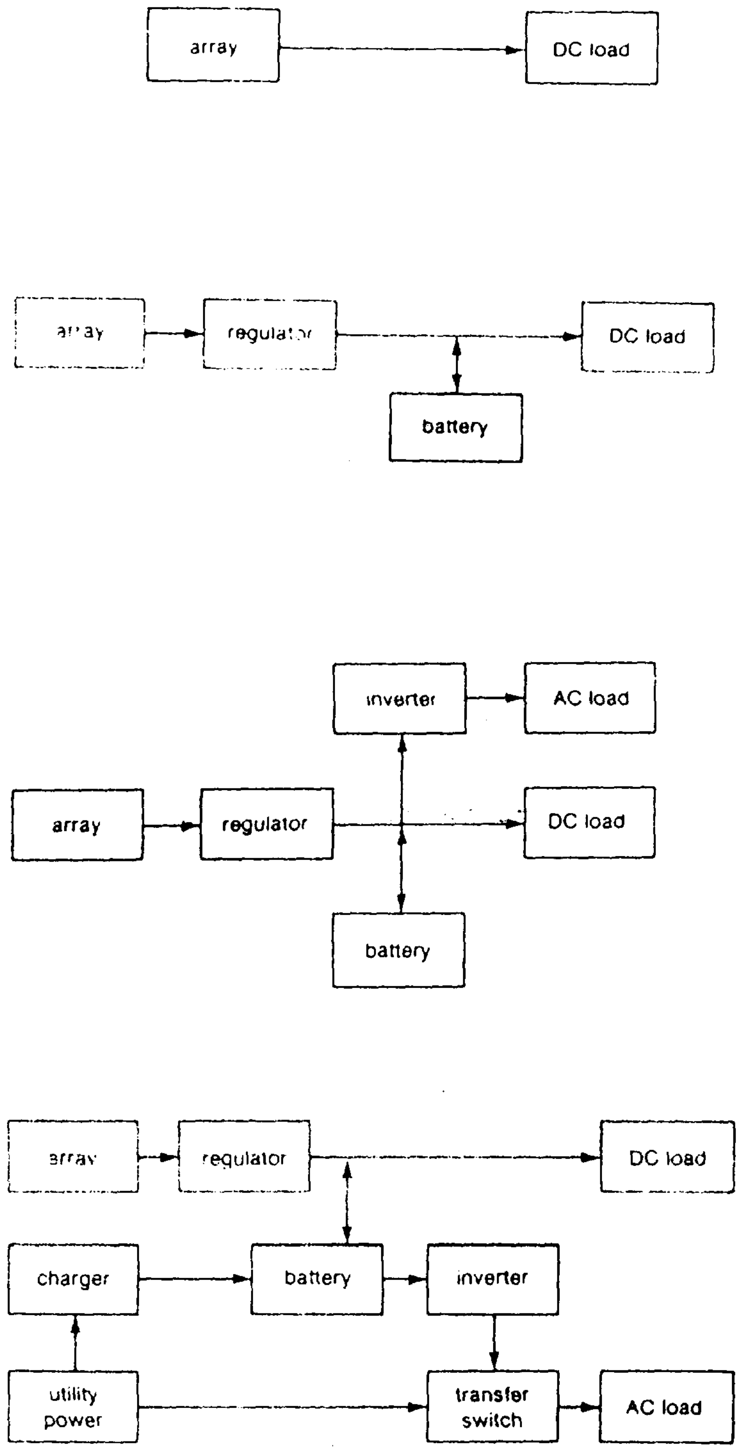


Fig. 8 Block diagrams of pv system (a) D.C. stand alone system - PV array connected directly to load (b) PV array connected to the load and battery via voltage regulator (c) system equipped with a voltage regulator, storage and inverter (d) system as in C and use of utility grid to supply backup power via a battery charger.

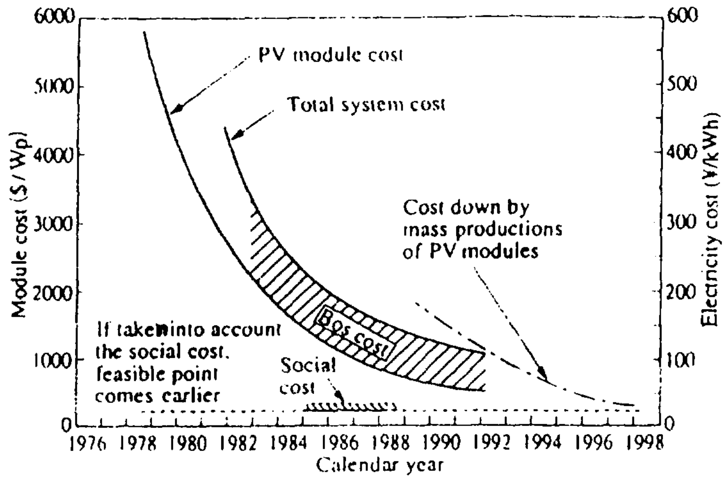


Fig. 9 PV costs have dropped ten fold in twenty years.

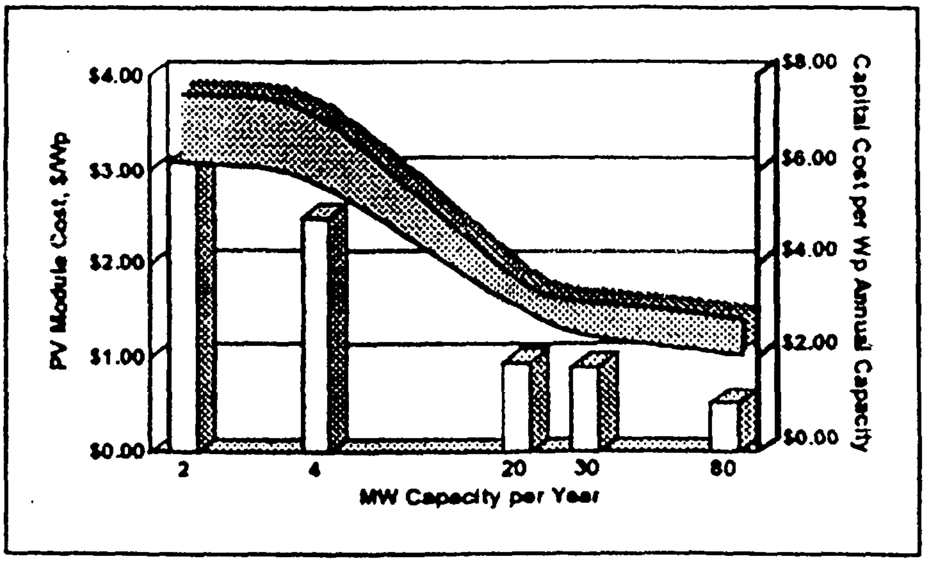


Fig. 10 Scale up productions VS module cost.

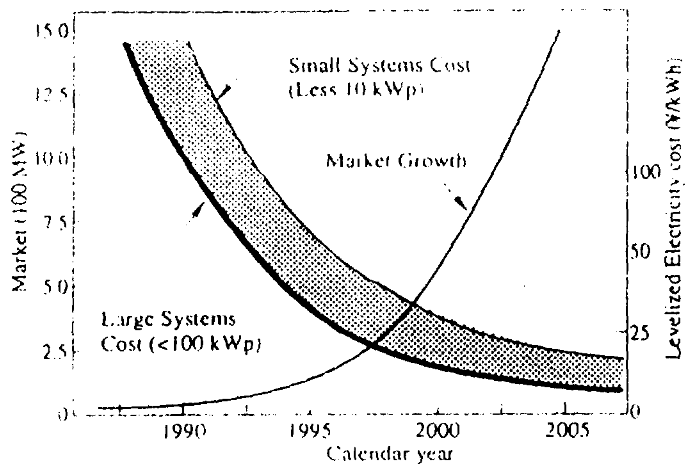


Fig.11 Module cost VS Market Growth:

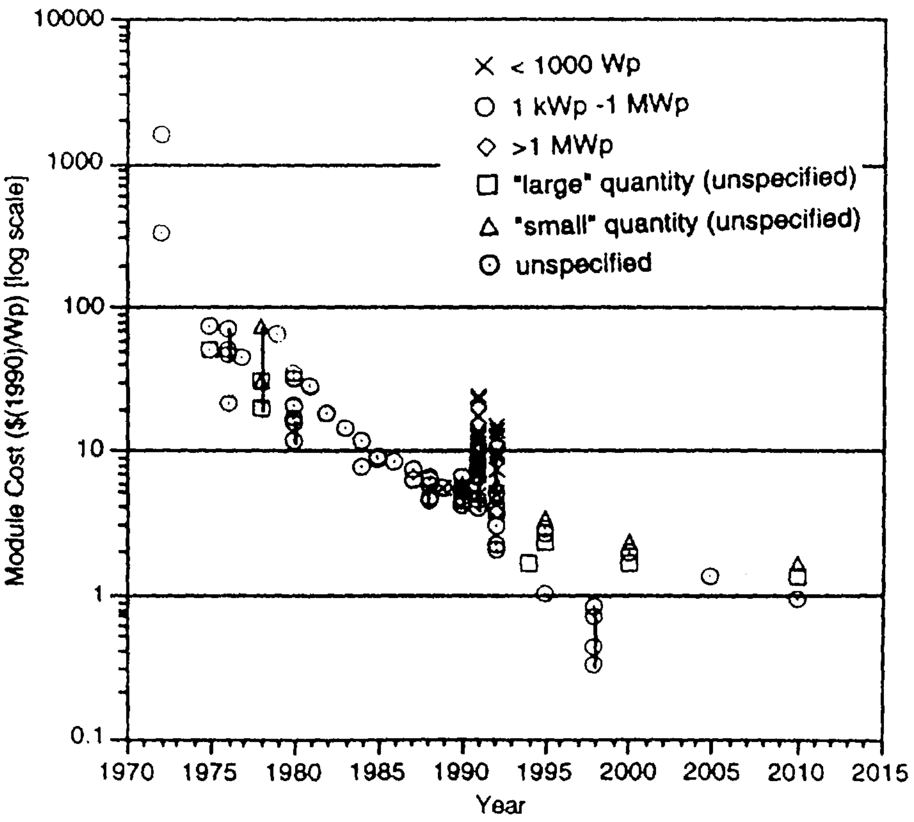


Fig.12 Actual costs of PV modules (without BOS) size of module varying from less than 1 KWp to more than 1 MWp.

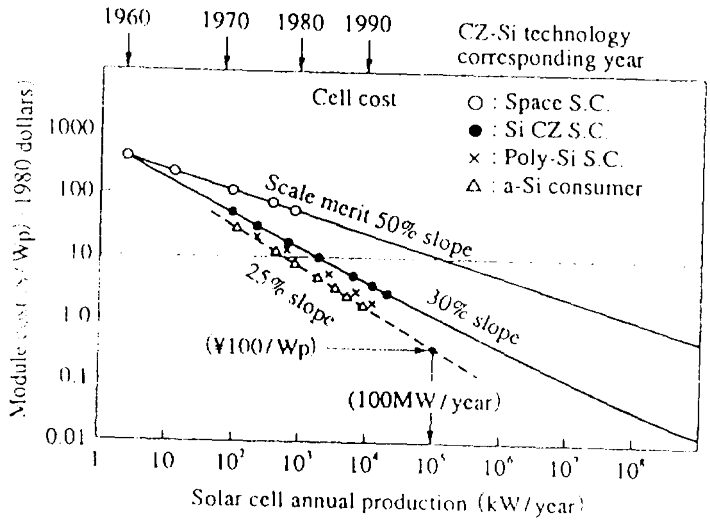


Fig 13 Cost reduction of PV modules based on various technologies indicating the scale of merit for a chosen technology

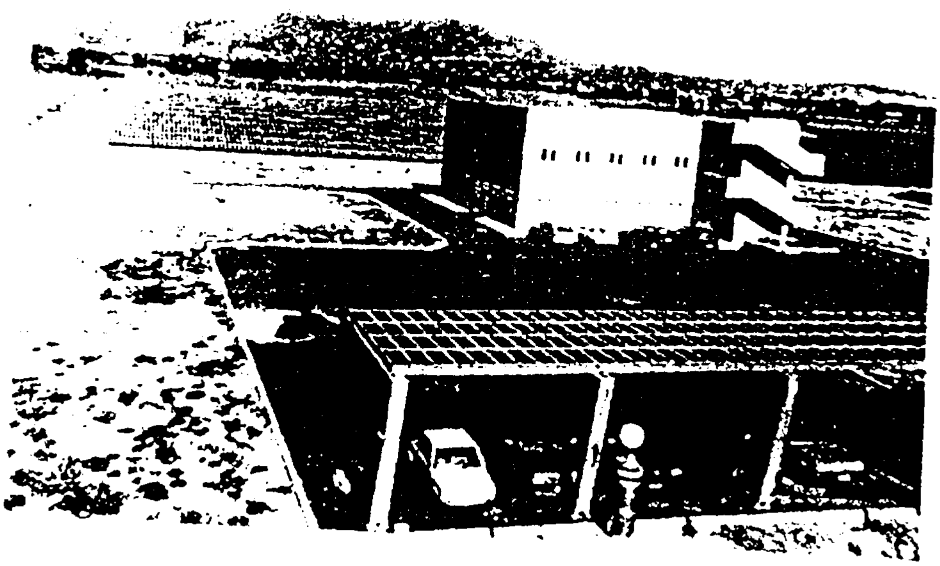


Fig 14 View of the 3.3 MW PV power station at Serre, Italy showing photovoltaic car parking in the foreground

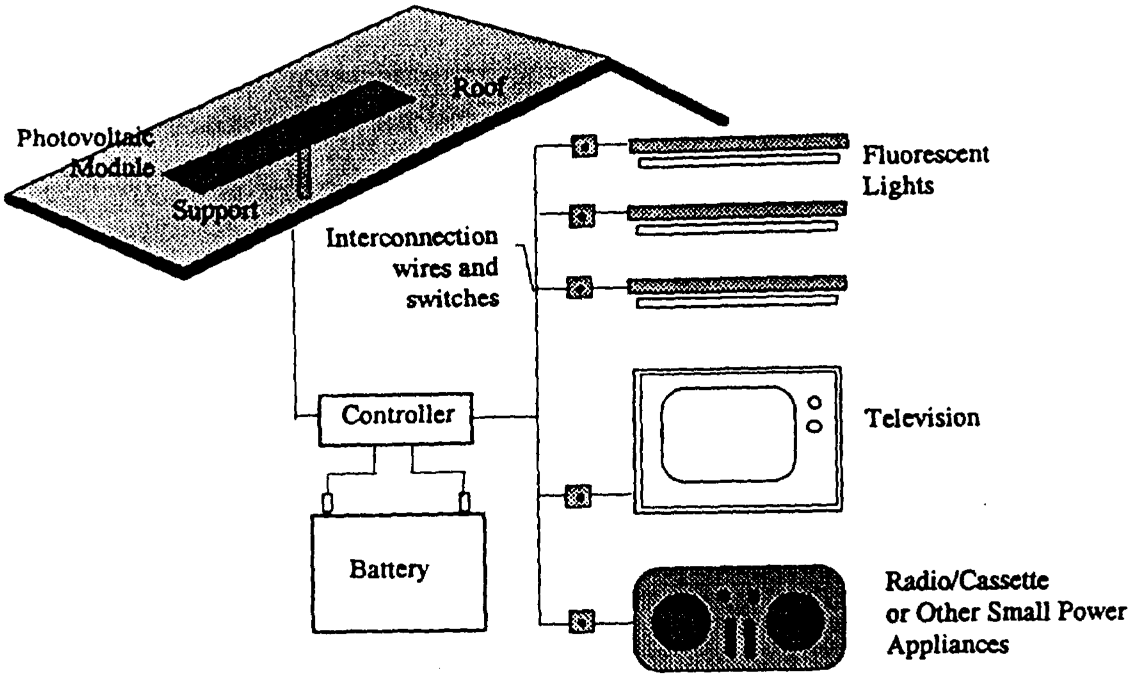


Fig 15 Schematic diagram showing the components of Solar House System (SHS):

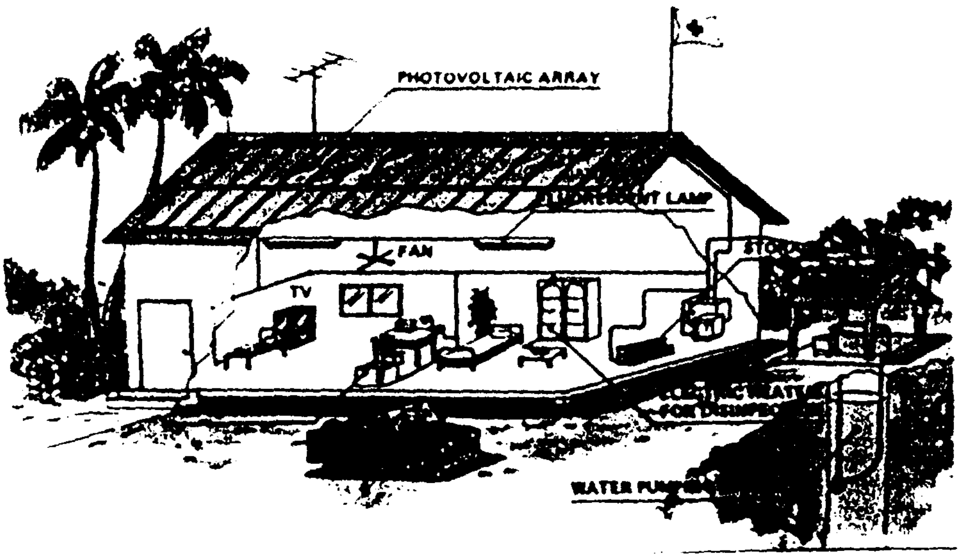
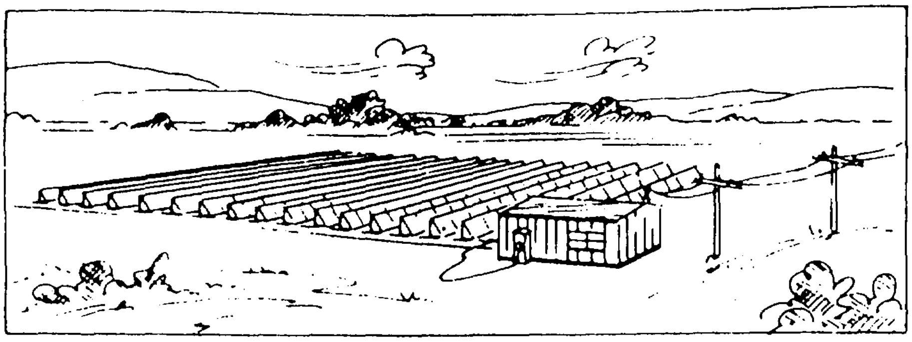
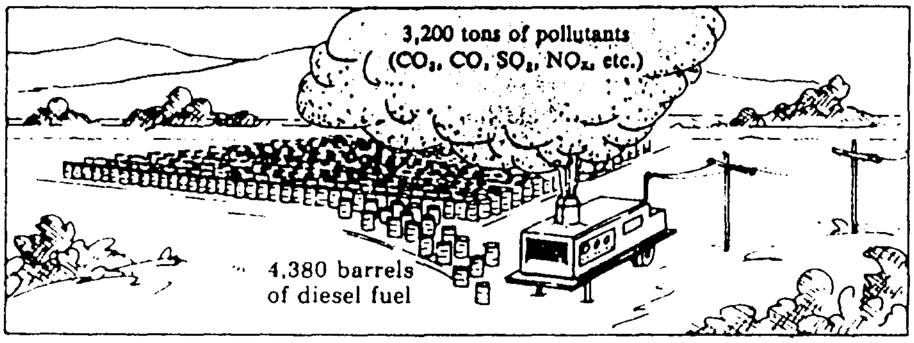


Fig.16 Picture of health clinic unit powered by PV with essential medical electronic gadgets, refrigerator to store life saving medicines and vaccines, lights, communication equipment water pumps etc



60-kilowatt photovoltaic system
Lifetime: 20 years— 131,400 kWh/yr
2,366 modules (97,000 cells)
½-acre array
20-year cost (1980 dollars):

Capital investment (land additional)	$600,000
Fuel	0
Total	$600,000



60-kilowatt diesel-electric generator
Lifetime: 20 years— 131,400 kWh/yr
Diesel replacements: 10 @ $16,000 each
Fuel: 9,000 bbl (1,039 tons)
20-year cost (1980 dollars):

Capital investment	$160,000
Fuel (@ $3/gal)	$1,134,000
Total	$1,294,000

(operation and maintenance extra)

Fig.17 Comparison of photovoltaics with diesel electric for power generation in remote areas. Because of high price of diesel in developing countries, PV systems are competitive in many areas unlike diesel unit spewing 3200 tons of CO_2 and other pollutants, PV is a clean energy.. Source: Paul Maycock.

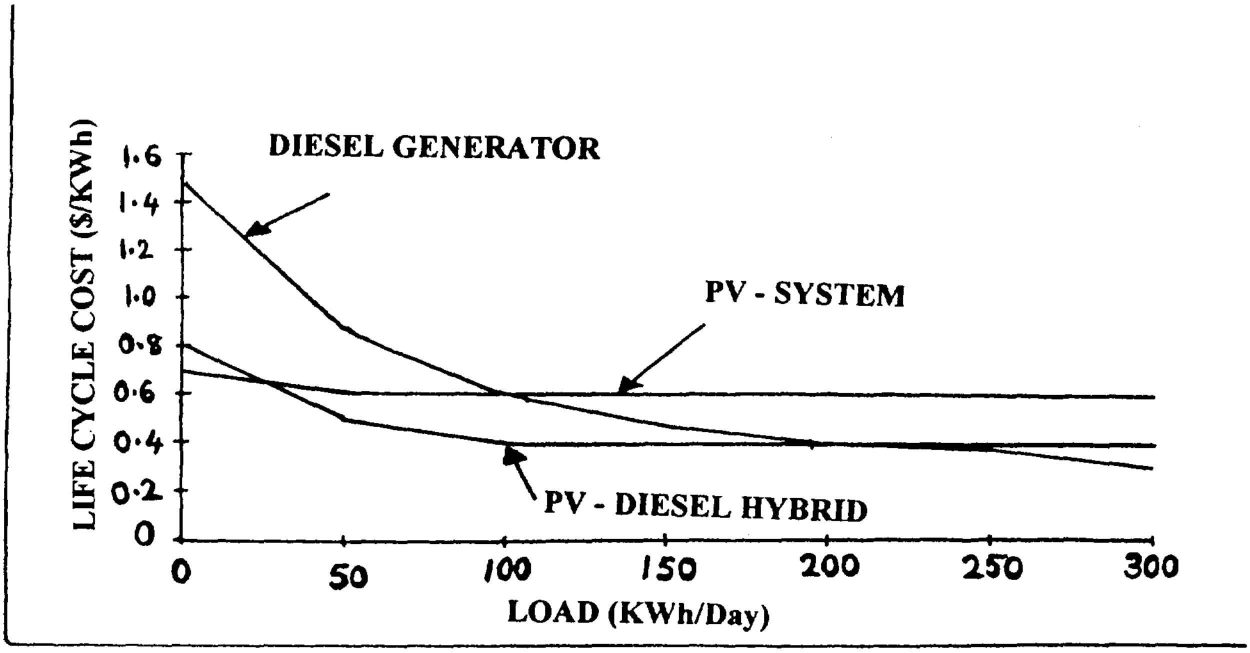


Fig.18 Photovoltaic - Diesel Hybrid System: Offers trade off of capital costs and operating costs for loads in the region 50 to 250 kwh / day.

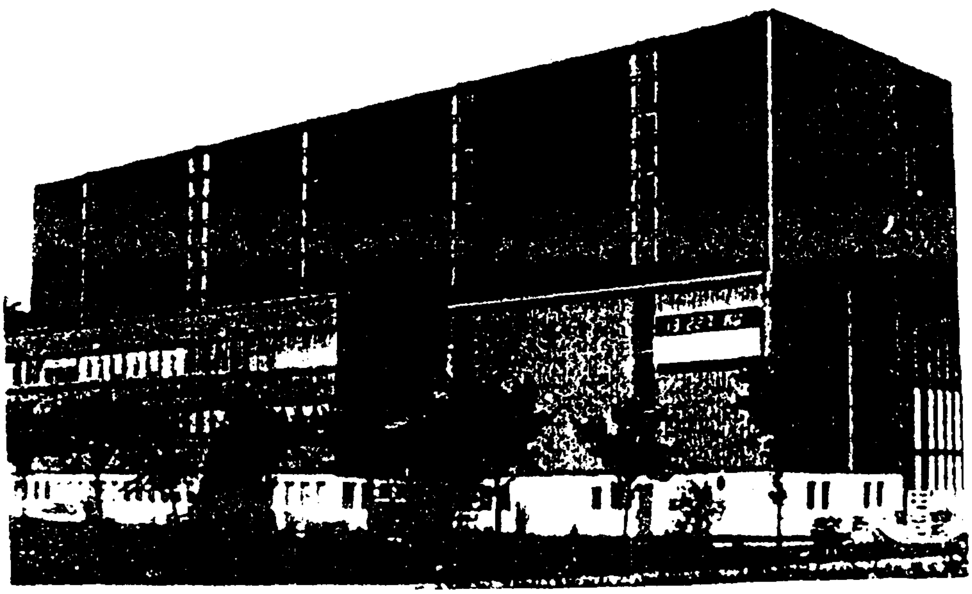


Fig.19 A Laboratory building at the ISPRA Research Institute in Germany with a 720 m^2 photovoltaic facade delivering a power of 13.166 kw.

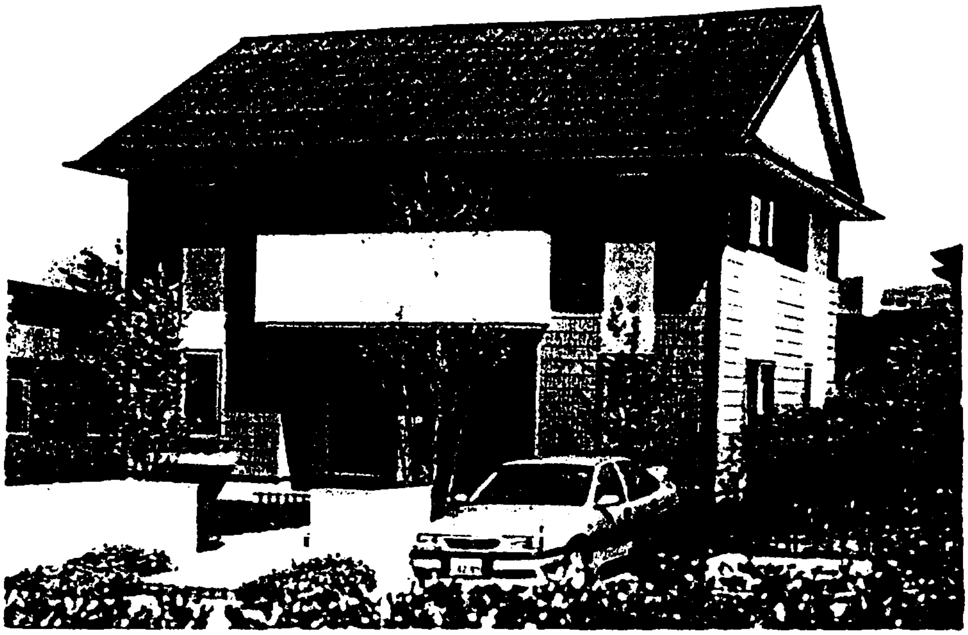


Fig.20 House with Solar Roof in Japan. Typically 2 to 3 kw photovoltaic powered roofs attracts 50% subsidy from Government.

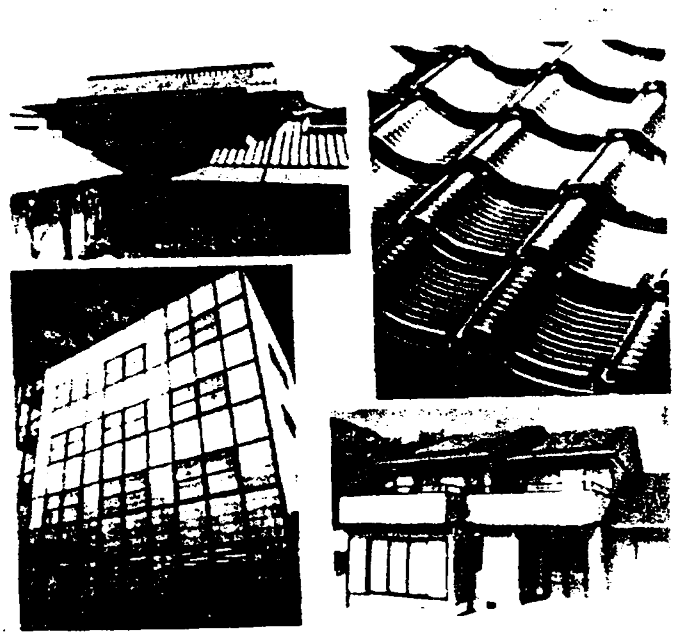


Fig. 21 PV in buildings - some examples of roofing tiles and building wall cells in Japan also showing amorphous silicon solar cell roofing on typical Japanese home.

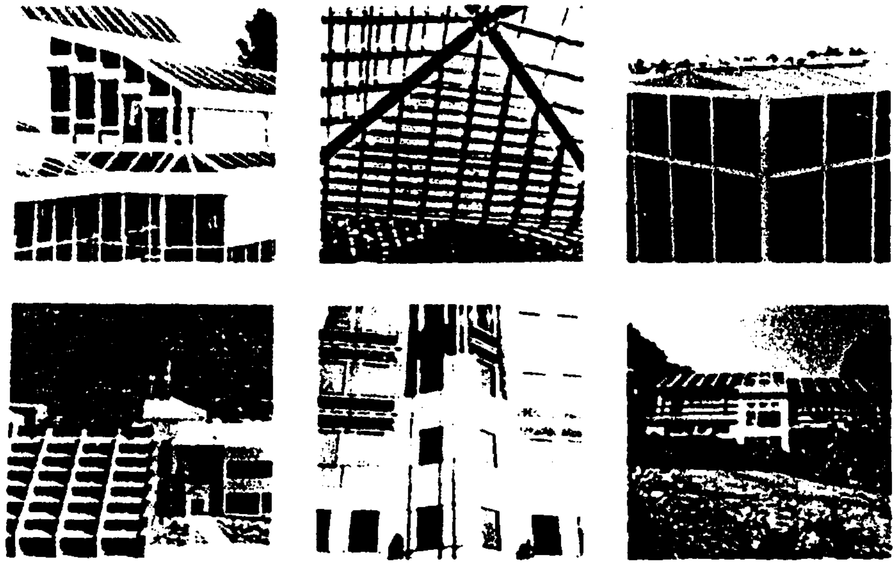


Fig. 22 Picture showing several homes and office buildings with PV built in architecture in Europe & USA

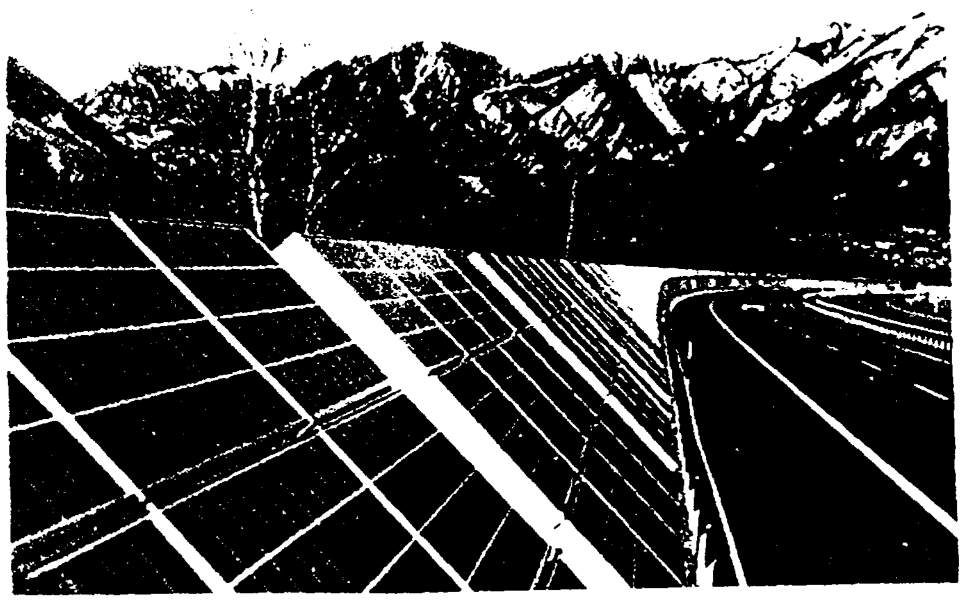


Fig 23 PV on highways. The first grid connected 100 KWp PV plant on sound barriers in Switzerland

Fig 24 Picture showing pre fabricated PV module systems for roof top and can be installed very quickly.

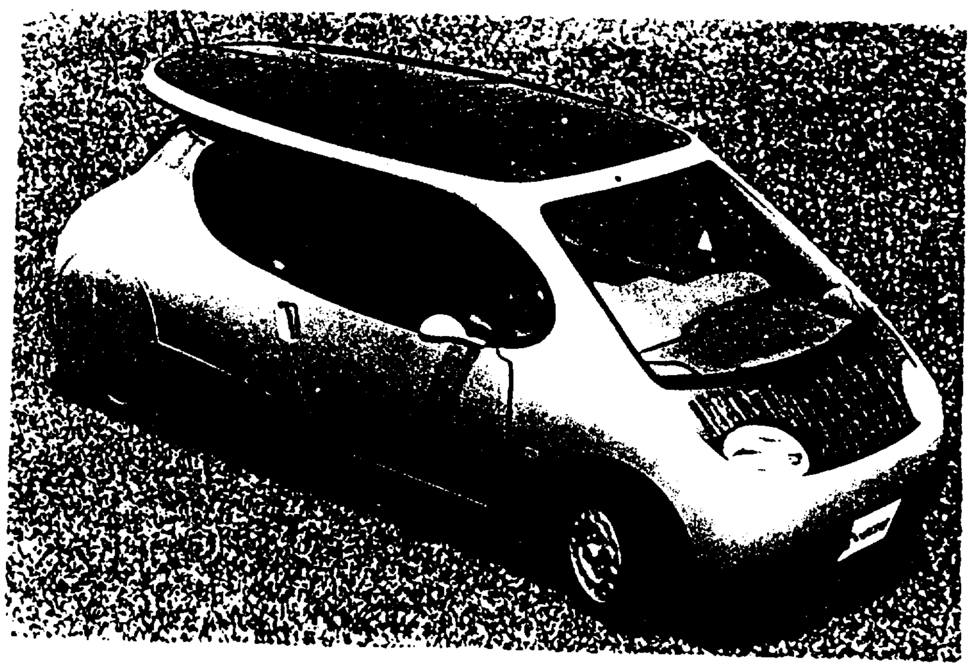


Fig 25 Plans are ahead in Japan and European countries to develop car for short distances

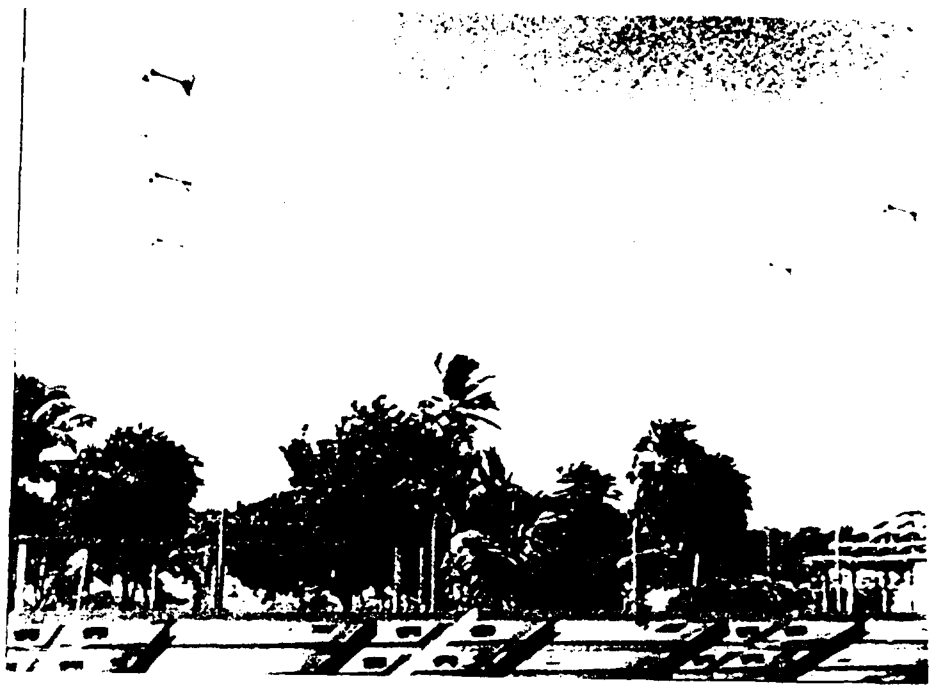


Fig. 26 PV is part of a large hybrid power generation system including 234 PV modules, a 40 kw inverter, a diesel generator and wind turbines. This PV hybrid system is located in a village Xcalak, Mexico.

Fig. 27 Interesting light effects produced inside a building by variation of distance between PV cells and amorphous silicon PV elements.

Fig. 28 This couple is standing in front of their village's water pumping system powered by PV in Penjemu, Gambia. This is done in a program of luring city dwellers back to their old agriculture ways.

Fig. 29 This picture demonstrates the versatility of PV systems in developing countries. Local mode of refrigerated transport used a PV powered refrigeration system mounted on a camel to keep the vaccines cool on the way to remote health clinic in Djibouti, Africa

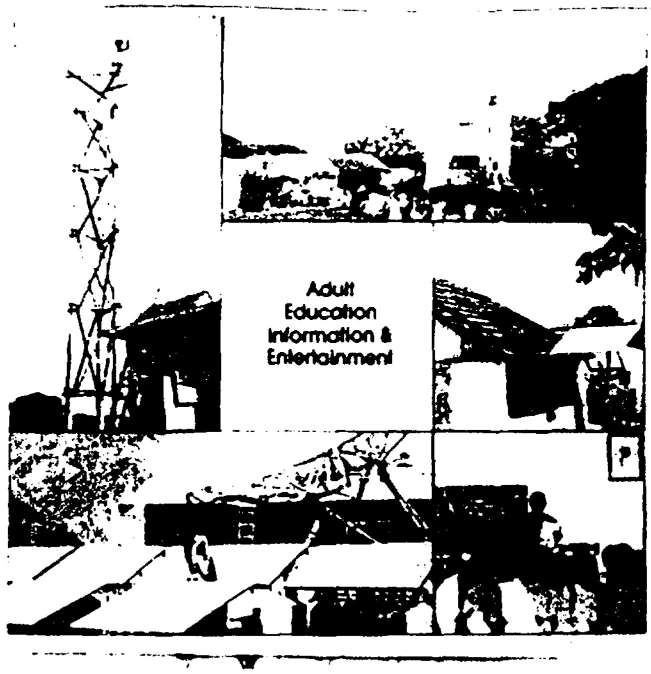


Fig 30 The country side community center: has a TV and VCR for entertainment, a direct reception TV system powered by PV and can receive the telecast directly from satellite and PV powered lights for organising training programmes and adult education. This kind of center are established in India.

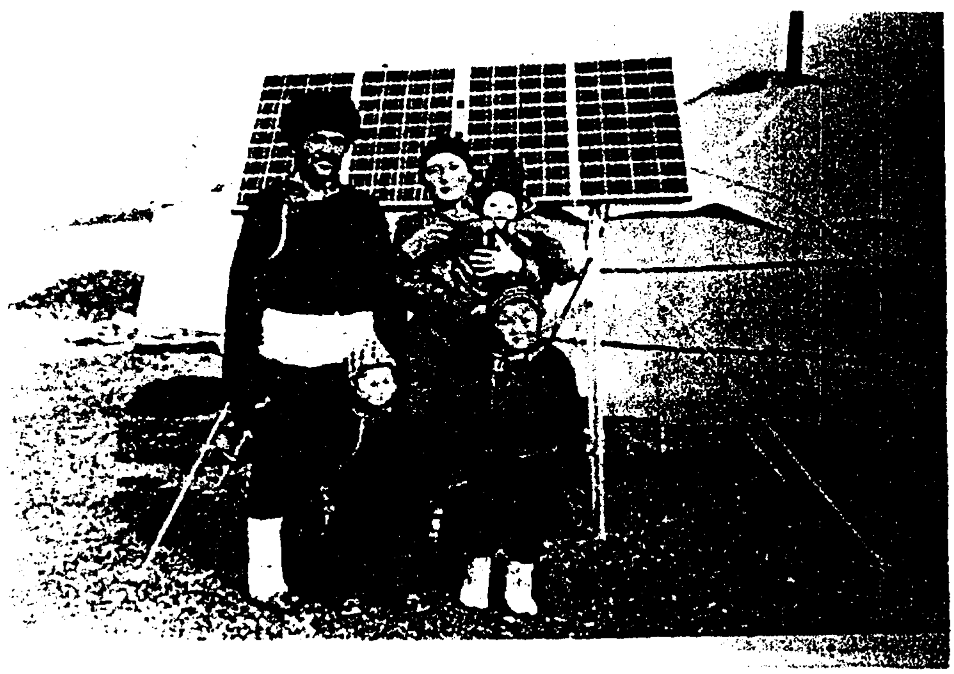


Fig 31 PV powered house of nomadic people in Mongolia.

Fig 32 Installation of PV module system in rural area is easy. A Siriono Indian erects a PV array to power lights and charge batteries in an encampment in north eastern Bolivia

Fig. 33 Shown in picture is a street light and a SHS unit to cater the electrical needs of the house in a remote village is southern India.

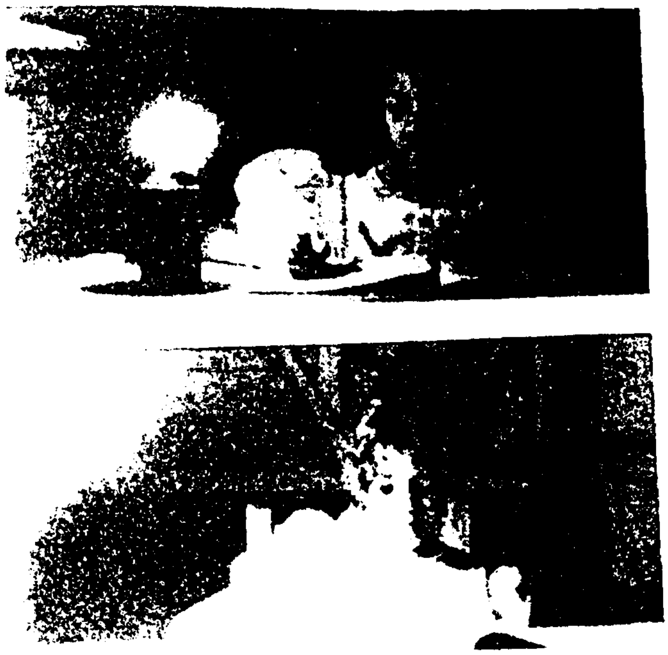


Fig 34 Picture illustrates that PV powered light placed in best location for reading and provides better quality of light compared to kerosene or candles - SHS unit in Dominican Republic

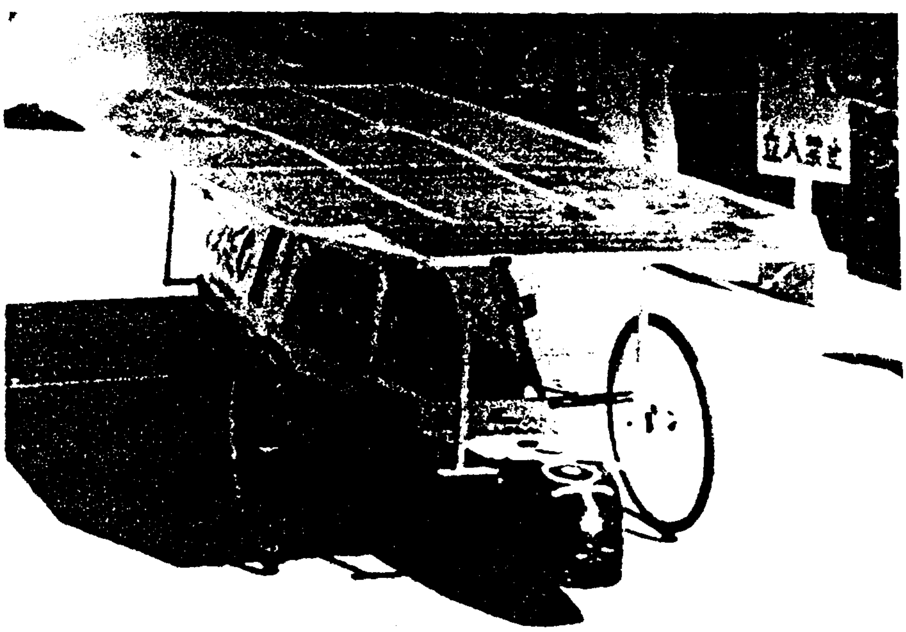


Fig. 35 This PV powered vehicle participated in a car rally in Japan With a few modifications A PV powered three wheeler could be an ideal common man vehicle for 2 of 3 passengers in developing countries.

References

1. M.R.L.N.. Murthy, Proceedings of UNCED - Global Forum, 1992, Rio Debentures Janeiro, Brazil.

2. B.A. Authier, 1975, German Patent (DOS) 2508803

3. D. Helmeich, R.M. Knobel and W. Ermen, Proc: 20th IEEE Photovoltaic Spel. conf. 1988.

4. T.F. Ciszek, Proc: 20th IEEE Photovoltaic Spel. cong., 1988.

5. C.P. Khattak and F. Schmid, Proc: IEEE Proc. conf., 1978.

6. J. Fally, E. Fabre and B.Chabot, Revue Phys. Vol 22, p 529, 1987.

7. K. Kameko etal, Proc: PVSEC - 3 Lisbon, 1991

8. D.A. Hukin, 10th EVPVSEC - 3, Lisbon, 1991.

9. E.C. Boes, 21st PVSC, 1990

10. D.L. King, 4th PVSEC, p 565, Sydney, 1989.

11. Ito, T. Tomita, Y. Tekeda and Y. Yamamoto, WCPEC, Hawaii, 1994

12. R.R. Arya, L.Yang, M. Benett and A. Wilkznski, Proc: 23rd IEEE PVSC, (1973) 790

13. L.L. Kasmarski. Proc: 3rd WREC Part 1 (1994) 252

14. W. Market, T. Horiuchi, M. Yoshimu, K. Hattori, H.Okomoto and Y. Hamakawa. Proc: PVSEC - 6, New Delhi (1992) 463.

15. A. Takami, S. Arimoto, H. Morikawa, S. Hamamoto, T. Ishihara, H. Kumabe and T. Murotami: Proc 12th EC - PVSEC Amsterdam (1994) 39

16. J. Yang, A. Banerjee, T. Glatfelter, K. Hoffman, X. Xer and S. Guha, WCPEC, p.380, 1994.

17. I.S. Chen, T. Jamali-beh, Y. Lee, C.Y. Li and C.R. Wronski. ibid (1994) p. 468.

18. F. Smole, M. Topoc amd J. Furlan. ibid (1994) p. 496.

19. Y. Hamakawa, phy stat Solar Cell (b) 194, 15 (1996)

20. A.M. Barnett, Proc: PVSEC - 6, New Delhi - 1992

21. R.W. Birkmire, H. Hichri, R. Klenk, M. Marudachalam, B.E. McCandless, J.E. Phillips, J.M. Schultz and W.N. Shafarman. American Institutional. Phys. Conf. Proc: 3583, (1995).

22. J.E.Granata, J.R.Sites, G.Contreras - Puente and A.D.Compaan, 25th IEEE Conf. 1996

23. L.S.Yip and I.Shih, ibid 1996

24. R.W.Birkmine and P.V.Meyers ibid 1996

25. D.Schmid, M.Ruckh and H.W.Shock ibid 1996

26. D.Kim, S.Pozder, Y.Zhu and J.V.Trefny, ibid, 1996.

27. M.R.L.N.Murthy, Proc. Seminar on Solar Devices, Cairo, 1993

28. Y.Hamakawa, Proc. PVSEC-5, Kyoto, 1990

29. GEF Report, Cultivating the green Carrot, 1995

30. World Bank Technical Paper No.240 Energy Services, 1994

31. Dennis Anderson and Kulsum Ahmed, World Bank Technical paper No.279, 1995

Figure Captions

- Fig. 1 Solar Cell: Incoming units of light energy (photons) are absorbed by electrons within the silicon wafer creating -ve charges (electrons) which are attracted to the n-type silicon and +ve charges (holes) are attracted to the p-type. A photo current flows voltage develops and electricity is produced.

Fig. 2 Photovoltaic Cell Technologies:

- Fig. 3(a) CZ Crystal growing machines (b) Silicon Crystal ingots & Cast Silicon ingots (c) Round and Square wafers after slicing and (d) Solar Cells.

- Fig. 4 a Schematic diagrams of Solar Cell structures.
- Fig. 4 b Manufacturing process steps of Solar Cell
- Fig. 5 Generic elements of photovoltaic Module encapsulation system.

- Fig. 6 Assembly Process steps of photovoltaic module.

- Fig. 7 PV modules. Left to right - Single Crystal Silicon modules with round cells and square-cut cells, polycrystalline silicon module, thin film modules (rigid and flexible)
- Fig. 8 Block diagrams of pv system (a) D.C. stand alone system - PV array connected directly to load (b) PV array connected to the load and battery via voltage regulator (c) system equipped with a voltage regulator, storage and inverter (d) system as in C and use of utility grid to supply backup power via a battery charger.

- Fig. 9 PV costs have dropped ten fold in twenty years.

- Fig. 10 Scale up productions VS module cost.

- Fig.11 Module cost VS Market Growth:

- Fig.12 Actual costs of PV modules (without BOS) size of module varying from less than 1 KWp to more than 1 MWp.
- Fig.13 Cost reduction of PV modules based on various technologies indicating the scale of merit for a chosen technology.
- Fig.14 View of the 3.3 MW PV power station at Serre, Italy showing photovoltaic car parking in the foreground.
- Fig.15 Schematic diagram showing the components of Solar House System (SHS):
- Fig.16 Picture of health clinic unit powered by PV with essential medical electronic gadgets, refrigerator to store life saving medicines and vaccines, lights, communication equipment, water pumps etc.
- Fig.17 Comparison of photovoltaics with diesel electric for power generation in remote areas. Because of high price of diesel in developing countries, PV systems are competitive in many areas unlike diesel unit spewing 3200 tons of CO_2 and other pollutants, PV is a clean energy.. Source: Paul Maycock.
- Fig.18 Photovoltaic - Diesel Hybrid System: Offers trade off of capital costs and operating costs for loads in the region 50 to 250 kwh / day.
- Fig.19 A Laboratory building at the ISPRA Research Institute in Germany with a 720 m^2 photovoltaic facade delivering a power of 13.166 kw.
- Fig.20 House with Solar Roof in Japan. Typically 2 to 3 kw photovoltaic powered roofs attracts 50% subsidy from Government.
- Fig. 21 PV in buildings - some examples of roofing tiles and building walls in Japan also showing amorphous silicon solar cell roofing on typical Japanese home.
- Fig. 22 Picture showing several homes and office buildings with PV built in architecture in Europe & USA.
- Fig. 23 PV on highways. The first grid connected 100 KWp PV plant on sound barriers in Switzerland.

- Fig. 24 Picture showing prefabricated PV module systems for roof top and can be installed very quickly.
- Fig. 25 Plans are ahead in Japan and European countries to develop cars for short distances.
- Fig. 26 PV is part of a large hybrid power generation system including 234 PV modules, a 40 kw inverter, a diesel generator and wind turbines. This PV hybrid system is located in a village Xcalak, Mexico.
- Fig. 27 Interesting light effects produced inside a building by variation of distance between PV cells and amorphous silicon PV elements.
- Fig. 28 This couple is standing in front of their village's water pumping system powered by PV in Penjemu, Gambia. This is done in a program of luring city dwellers back to their old agriculture ways.
- Fig. 29 This picture demonstrates the versatility of PV systems in developing countries. Local mode of refrigerated transport used a PV powered refrigeration system mounted on a camel to keep the vaccines cool on the way to remote health clinic in Djibouti, Africa.
- Fig. 30 The country side community center: has a TV and VCR for entertainment, a direct reception TV system powered by PV and can receive the telecast directly from satellite and PV powered lights for organising training programmes and adult education. These kind of centers are established in India.
- Fig. 31 PV powered house of nomadic people in Mongolia.
- Fig. 32 Installation of PV module system in rural area is easy. A Sirionо Indian erects a PV array to power lights and charge batteries in an encampment in north eastern Bolivia.
- Fig. 33 Shown in picture is a street light and a SHS unit to cater the electrical needs of the house in a remote village is southern India.
- Fig. 34 Picture illustrates that PV powered light placed in best location for reading and provides better quality of light compared to kerosene or candles - SHS unit in Dominican Republic.
- Fig. 35 This PV powered vehicle participated in a car rally in Japan. With a few modifications. A PV powered three wheeler could be an ideal common man vehicle for 2 or 3 passengers in developing countries.

Glossary

Ampere-hour (Amp-Hour or Ahr): A measure of electrical charge, equaling the quantity of electricity flowing in one hour past any point of a circuit. Battery Capacity is measured in amp-hours.

Array: A group of photovoltaic modules wired together to produce a specific amount of power. Array size can range from one to hundreds of modules, depending on how much power will be needed.

Balance of System (BOS): Parts of a photovoltaic system other than the photovoltaic array.

Cell (Photovoltaic): A semi-conductor device that converts light directly into De-electricity.

Charge Controller: A component of a photovoltaic system that controls the flow of current to and from the battery to protect the batteries from over-charge and over discharge. The charge controller may also indicate the system operational status.

Concentrator: A photovoltaic module which includes optical components, such as lenses, to direct and concentrate sunlight onto a solar cell of smaller area. Most concentrator arrays must directly face or track the sun.

Efficiency (of a solar cell or module): The ratio of electric energy produced to the amount of solar energy incident on the cell or module. Typical crystalline solar modules are about 10% efficient - they convert about 10% of the light energy they receive into electricity.

Grid-connected: A photovoltaic system that is connected to a centralized electrical power network.

Hybrid System: A power system consisting of two or more power generating subsystems (e.g. the combination of a wind turbine or diesel generator and a photovoltaic system).

Insolation: The amount of energy in sunlight reaching an area. Usually expressed in watts per square meter (W/m^2), but also expressed on a daily basis as watts per square meter per day ($W/m^2/day$).

Inverter: A device that converts direct current (dc) to alternating current (Acquisitions) electricity.

Irradiance: The solar power incident on a surface. Usually expressed in kilowatts per square meter. Irradiance multiplied by time equals insolation.

I-V Curve: The plot of the current versus voltage characteristics of a photovoltaic cell, module, or array. Three important points on the I-V curve are the open-circuit voltage, short-circuit current, and peak power operating point.

Kilowatt (kw): 1000 watts.

Kilowatt-hour (kwh): 1000 watt-hours. A typical residence in the United States consumes about 1000 kilowatt-hours each month at a price in the range of $0.6 to .15 per kilowatt-hour.

Life Cycle Cost (LCC) Analysis: A form of economic analysis to calculate the total expected costs of ownership over the life span of the system. LCC analysis allows a direct comparison of the costs of alternative energy systems, such as photovoltaics, fossil fuel generators, or extending utility power lines.

Load: In an electrical circuit, any device or appliance that uses power (such as a light bulb or water pump).

Module: A number of solar electric cells wired together to form a unit, usually in a sealed frame of convenient size for handling and assembling into arrays. Also called a "panel".

Peak Watts (WP): The maximum power (in watts) a solar array will produce on a clear, sunny day while the array is in full sunlight and operating at 25° C. Actual wattage at higher temperatures is usually somewhat lower.

Photovoltaic (PV) system: A complete set of interconnected components for converting sunlight into electricity by the photovoltaic process, including array, balance-of-system components, and the load.

Power: The rate at which energy is consumed or generated. Power is measured in watts or horsepower.

Silicon: A non-metallic element that, when specially treated, is sensitive to light and capable of transforming light into electricity. Silicon is the basic material of beach sand, and is the raw material used to manufacture most photovoltaic cells.

Stand-alone photovoltaic system: A Solar electric system, commonly used in remote locations, that is not connected to the main electric grid. Most stand-alone systems include some type of energy storage, such as batteries or pumped water.

Watt (W): A measure of electric power in a unit of time, equal to the rate of flow (amps) multiplied by the voltage of that flow (volts). One amp of current flowing at a potential of one volt produces one watt of power.

Watt-hour (Wh): A measure of electrical energy equal to the electrical power multiplied by the length of time (hours) the power is applied.

Bibliography

1. Jet Propulsion Laboratory: Block V Solar Cell Module Design and Test Specification for Residential Applications, California Institute of Technology, Pasadena, CA, 1981.
2. UNIDO Report on "Solar Cells and their Industrial Applications" by Dr.M.R.L.N.Murthy. Advances in Materials Technology Monitor, Issue No.31, March, 1993.
3. Stand-Alone Photovoltaic Systems: A Hand book of recommended Design Practices-SAND 87, 7023, Sandia National Laboratories Albuquerque, New Mexico, USA, November, 1991.
4. Development of Photovoltaic Array and Module Safety requirements Melville, N.Y.Underwriters Laboratories Inc. (Prepared for Jet Propulsion Laboratory, Psadena, California, under JPL contract No.955392 June 1982.
5. Photovoltaics Technical Information Guide, SERI/SP-271-2452 Debentures-85002924, Golden, Colorado. Solar Energy Research Institute, February 1985.
6. Cross, Bruce M., Ed. European Directory of Renewable Energy Suppliers and Services, 1993, London: James & James (Bookstore/library or Books Int'l, ph:703-435-7064 * Fax:703-689-0660).
7. Derrick, Anthony, Catherine Francis and Varis Bokalders. Solar Photovoltaic Products: A guide for Development Workers. Second Edition, London: IT Publications, 1991 (Bookstore/library/IT Power - see sources)
8. Maycock, Paul. PV Yellow Pages. PV News, P.O.Box 290, Casanova, VA, USA, 1993, updated annually, (author - see SOURCES).
9. Barlow, Roy, Bernard Mcnelis, And Anthony Derrick. Solar Pumping: and Introduction and Update on the Technology, Performance, Costs and Economics. World Bank Technical Paper No.168, 1993. (The World Bank or IT Power - see SOURCES).
10. Cook, Gary, Lynn Billman, and Rick Adcock. Photovoltaic Fundamentals. National Renewable Energy Laboratory (NREL), Golden, CO (see SOURCES).
11. Ventre, Gerard, J.W.Stevens, M.G.Thomas. Reliable Vaccine Refrigerators: A Comparison of Solar and Kerosene Refrigerators. SAND88-2434, Photovoltaics Systems Design Assistance Center, Sandia National Laboratories, Albuquerque, NM, 1988, English and Spanish (see SOURCES).
12. Fowler, Paul J. The Solar Electric Independent Home Book. Revised Edition, Worthington, Market: Fowler Solar Electric Inc., 1991. (Library/bookstore).
13. Bundesverband Solarenergie (German Solar Energy Industries Association). Selection of International Renewable Energy Installations. BSE Kruppstasse 5 * D-4300 Essen 1, Germany, 1991.
14. Coastal Area Resource Development: Energy in Small Islands. New York: U.N. Publications, 1988.
15. Goldemberg, Jose, Thomas B. Johansson, A.K..N.Reddy, and R.H.Williams. Energy for a sustainable world. Washington, D.C.: World Resources Institute, 1987.
16. Hankins, Mark. Solar Rural Electrification in the Developing World: Four case studies. Solar Electric Light Fund, 1739 Connecticut Ave., NW, Washington, D.C.20009, 1993.