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NEW MATERIALS FOR ELECTRONIC AND SOLAR DEVICES*

Paper prepared by the Industrial Operations
Technology Division as a basis for
promoting the establishment of projects

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* This document has not been edited.

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CONTENTS

Part I. NEW MATERIALS FOR ELECTRONIC AND SOLAR DEVICES

1. INTRODUCTION

New materials are of major importance in the latter half of the 20th century and will remain so into the first decade of the 21st century. They are both scientifically and technically important to mankind through their daily impact on the quality of life. Developing countries and especially those with valuable energy and mineral resources will increasingly look to materials technologies to improve the quality of life of their people[1].

There is an urgent need for co-operation and co-ordination of activities in this field. This was stressed in discussions related to follow-up activities of the World Materials Congress held in Chicago in September 1988.

Governments of developed countries have chosen to promote new materials technologies because of the resultant benefits for the entire economy. For example, the Japanese Ministry of International Trade and Industry (MITI) is currently working closely with industry to establish co-operative research programmes in semiconductors, carbon fibres, advanced polymers, biomaterials and high-technology ceramics.

Major developments in materials in recent years include the following: fibre optics, synthetic polymers, silicon nitride and silicon carbide ceramics, metal-matrix composites, semiconductor detectors and sensors, powder metallurgy consolidation techniques, very large scale integrated-circuit silicon, solar materials for photovoltaics and solar thermal conversion[2-4]. These technologies are now being used commercially and will have a significant impact on society throughout the latter half of the 20th century.

The last two decades have seen many advances in preparation methods for new materials. The optical attenuation of silicon fibres has been reduced by over five orders of magnitude at selected wavelengths. Developments in optical materials and advances in semiconductors have brought new developments in advanced sensors, control systems, inspection systems, medical diagnostics and communications.

Advances in turbine and compressor disc materials have been achieved due primarily to improvements in powder metallurgy technology and alloy design advances that permit higher additions of hardening elements, such as aluminium, titanium, molybdenum, tungsten to achieve higher tensile, creep and fatigue properties.

In the near future advanced structural ceramics that can provide both a broader spectral band pass and improved aerothermodynamic protection will see a wide applications in industry.

Materials development for new and renewable sources of energy[5,6] will be intensified in the next 20 years to improve efficiency of solar conversion. Efforts will continue towards finding methods for producing low cost highly efficient solar cells for converting sunlight directly to electricity using photovoltaics (PVs). Continued processing improvements and cost reductions in producing thin film, polycrystalline, silicon cells on low-cost substrates with efficiencies of more than 10% can be expected. Further progress is also expected in improving the efficiency, purity and defect-state passivation of amorphous silicon cells.

Solid state semiconductor power devices, based on silicon and gallium arsenide (at the highest frequencies), will continue to replace older electro-mechanical equipment because they give better performance at lower cost. Elevated temperature sensors and electronic circuits based on gallium arsenide and silicon carbide will be developed and widely used in processing control and sensing. Fibre optics materials (quartz, quartz with dopants) will be widely used for optical transmission of information.

A project concept on new materials for electronic and solar devices is given in Annex I-1.

2. UNIDO ACTIVITIES ON NEW MATERIALS FOR ELECTRONIC AND SOLAR DEVICES

Industrial development is increasingly linked with technological advances in new materials. UNIDO estimated in 1986 that 65% of the industrial production of the developing countries may be affected to a certain extent by technological advances in new materials.

For developing countries the following approach has been adopted: whatever the level of development, every country needs a minimum level of competence to deal with emerging technologies within a realistic time frame and must establish effective national groups for this purpose.

The International Forum on Technological Advances and Development in Tbilisi (USSR) in 1983 suggested a rough scale of three different levels of technological competence for developing countries:

i. Minimum level indicates an awareness of the technological advances possible identification of appropriate technology and its relevance on the country and the ability to assess, select, negotiate and utilize processing technology; autonomous decision-making;

ii. Medium level includes the above factors and in addition, the ability to adapt or generate processing technology, iii <u>High level</u> includes all the above factors as well as capacity for commercialization, design, manufacture of equipment, and participation in competitive international markets.

UNIDO activities in new materials cover a wide range of materials issues. Within this area UNIDO functions in two ways, namely through:

a) technical assistance activities which require requests from Governments, and

b) promotion of industrial development.

Currently the Department of Industrial Operations (DIO) is implementing new materials projects in the following areas:

- ceramics, glass and composites in Ethiopia, India, China, Rumania and Turkey
- fibre optics technology, carbon fibres in India, Republic of Korea, Egypt
- powder metallurgy, blazing alloys in China, India
- solar materials for PVs-amorphous silicon in India, Pakistan
- plastics technology in Pakistan, Turkey and Yugoslavia
- rare earths in Mexico
- rare metals in India, Democratic People's Republic of Korea, Yugoslavia and Zambia.

Within UNIDO the nomenclature of new materials is extended to include sensors, detectors for different wavelengths; multicomponent compounds for PVs, selective coatings; and electric and superconductive advanced ceramics.

The UNIDO programme on technological advances includes[1]:

a) information analysis and the monitoring of technology trends in selected materials and development of information network for new materials;

b) support of national policy and programmes in the field of new materials, including assistance in setting up material characterization and testing laboratories in developing countries;

c) programmes for international co-operation including the establishment of networks of centres of excellence in selected new materials.

Training in the processing of new materials, manufacture and design of electronic and solar devices based on these materials is arranged in the worlds leading Centres (Annex I-2). Names of world-renowned technologists and scientists are available on the UNIDC roster for projects on new materials (Annex I-3). Some examples of advanced technology and new materials for electronic and solar devices are given in Annex I-4.

2.1 New Materials for Electronic Devices

<u>The field of new materials processing and applications</u> offers a unique opportunity for improving international co-operation and competition in materials science and engineering.

In the new materials area there is great interest in thin layers of ternary and quaternary alloys including quantum wells and superlattices for lasers prepared by MOVPE growth. For example, there are projects in this area at the Indian Institute of Technology, Kharagpur, India, and in optoelectronics applications in China. These projects aim to raise the level of scientific research in electronic and solar materials technologies and to speed up the application of advanced technologies in commercial manufacturing of electronic and solar devices. Application of the new materials devices will increase their effectiveness and reliability and will lead to their highly productive commercial manufacture. On the basis of already existing research institutes in developing countries it is being proposed to organize Advanced Materials Centres.

The field of new materials processing and applications is entering a period of unprecedented intellectual challenge and productivity.

Governments have taken an active role in deciding which areas of materials processing and applications should be emphasized taking into account their contribution to enhancing industrial competitiveness.

Materials processing and applications are crucial to the success of industries. Industries such as electronic and electrical engineering are important in strengthening the national economy.

Despite the growing opportunities in materials science and engineering, a shortage of the educated personnel is foreseen. National policies need to focus on the appropriate education and to co-ordinate efforts in order to meet the challenge of international competition.

2.2 New Materials for Solar Energy Devices

It is foreseen that in the near future there will be a significant increase in the development and application of solar energy. It is an almost unique non-polluting source of energy. Effective utilization of solar energy requires highly productive converters such as PV cells, flat-plate collectors for solar radiation conversion utilized in water and space heating. Solar energy can be widely used in countries where sunlight radiation is high (e.g. many Asian, Latin American and African countries). In recent years there were major achievements in the production of these materials and in the fabrication of solar energy converters based on them.

The constraints encountered by developing countries in exploiting their energy resources and in improving the efficiency of their industrial energy consumption can be grouped under five main headings[6]:

- lack of finance
- lack of know-how
- lack of skilled human resources
- lack of equipment
- lack of plans and specific proposals.

These constraints are interconnected.

UNIDO has already accumulated some valuable experience in the introduction of new concepts for the application of PV systems in developing countries including India, Pakistan, Brazil and the Republic of Korea, and negotiations have been entered into with a number of R & D institutes and firms in industrialized countries for promising solar energy prospects and related technologies.

2.3 Other Areas

At present UNIDO is broadening its scope of activities in new materials with high performance characteristics - electrical, optical, electrophysical (for photovoltaics, sensors, integrated circuits, detectors and others) which are applied in electronic and electrical engineering industries.

Developments in optical materials and concurrent advances in semiconductors and electronically active polymers will bring new developments in advanced sensors, control systems medical diagnostics, microsurgery techniques and communications. Some examples are given as follows:

- glass and polymer optical waveguide materials
- rare-earth transition metal and ceramic-ferrite materials for higher efficiency microwave transmitters, guidance controls and power management systems
- multinary compound semiconductors for millimetre-wave radar amplifiers
- multinary compound ceramics for heat engine applications
- nickel-titanium memory alloys
- cubic-boron-nitride cutting materials
- high-strength coated waveguides
- selective antireflective optical coatings
- and others.

3. OBJECTIVES

The UNIDO Programme on Technological Advances[1] was initiated to increase awareness through early identification and assessment and, where relevant, to initiate the necessary action in the following areas:

- transfer and application of technology
- strengthening institutional infrastructure appropriate for the further development of new and renewable sources of energy and of new materials processing and application
- identification of financial resources
- continuous training of technical and managerial personnel
- elaboration of relevant legislative and regulatory framework.

These objectives will be achieved through:

- expert group meetings, studies and current awareness bulletins;
- mobilizing the co-operation of selected individuals and institutions;
- promoting national action through policies and programmes in developing countries;

- providing technical co-operation and advisory services as and when required.

4. CONCLUSIONS

UNIDO should be in the forefront of technical assistance activities in new materials by being capable of tackling the emerging needs of developing countries. This will lead to building up the confidence of the governments in requesting technical assistance from UNIDO in this important field.

Implementation of UNIDO projects on processing and application of new materials (electronic, solar, fibres, ceramics, composites) will foster co-operation and co-ordination between governments of developed and developing countries.

Future international development programmes on new materials for developing countries should focus on setting up the technological infrastructure of these countries, improving their capabilities of acquiring and using those technologies transferred under international co-operation with technical assistance of UNIDO.

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6. New and renewable sources of energy and the activities of UNIDO in this field (UNIDO, Department of Industrial Operations, April 1988, v.88 - 23785 4639T)

PROJECT CONCEPT*

1. Project Title: New materials for electronic and solar devices, Phase I: Introduction and Awareness Development Programme.

2. Duration: 18 months.

3. Recommended UNDP Contribution: US$175,000.

4. Counterpart Organization: Ministry of Science and Technology in co-operation with the Ministry of Industry and University.

5. Purpose of the Project: Through an existing institution to introduce and to make aware of the international trends (applied R&D, applications, industrial liaison, extension, training and information dissemination, etc.) in new materials and advanced technology. In addition, to develop a national programme of action to strengthen an existing institution so as to become a national 'focal point' for all aspects of new materials and advanced technology and act as a 'bridge' between applied R&D and industrial applications.

6. Scope of the Project: New materials technology for electronic and solar devices covers a wide spectrum - special alloys, steel, ceramics, fibre, optics, optical processing materials, powder metallurgy, composites, plastics, super-conductors, space - related materials, solar cells, packaging, cutting tool tips, industrial sensors, micro-electronics related materials, metal metrics composites, rare metal materials, corrosion, precision engineering, quality control, material testing, NDT, instrumentation, etc. A national institutional facility will be a step towards the orientation of various dispersed but critical activities towards a national goal/programme on a selective basis.

7. Immediate Objectives:

   - to analyse the country's potential and need;
   - to organize a national seminar and also give specialized lectures;
   - to make aware of international trends through study tours and fellowships; and
   - to develop a national line of action.

8. Outputs:

   - an issue paper on the country's need and potential in new material and advanced technologies;
   - institution/government/applied R&D/university/industry interlink;
   - a programme of action including a guideline on measures to strengthen a national technical/scientific institution in the area of new materials and advanced technology.

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* Until approval has been obtained this document should not be considered as a formal submission of a full project proposal.

9. UNDP inputs (Phase I, 1991/92, 18 months):

Expert for Analyses	3 m/m	US$	30,000
5 consultants for giving lecture in specialized areas, 2 weeks each	2.5 m/m	US$	30,000
Study tour for 4 persons (1 month)	4 m/m	US$	35,000
5 fellowships in specialized areas, 2 m/m	10 m/m	US$	50,000
Staff mission (2 nos.)		US$	10,000
National Seminar		US$	10,000
Miscellaneous		US$	10,000
Total		US$	175,000

10. Impact of Phase I Activities:

Phase I is an awareness and training programme in the area of new materials and advanced technologies. In addition, it will also elaborate the following techno-economic aspects:

- how appropriate are projects on new materials to the needs of the country;
- if the production of such materials will be developed, would it be competitive with imported products;
- size and type of market in the country for new materials;
- at what stage is the national production of such materials;
- what materials are of the most interest for the country;
- where are the capabilities of national institutes for materials research and would they be a basis for advanced materials centres; and
- what are the main tendencies of materials production in the country, the main areas of manufacturing interest and products.

11. Eventual need for a national programme and institutional capability in new material and advanced technology area:

(i) Purpose of such a programme to promote applied R&D and industrial applications of new material technology within the framework of a national institutional facility to act as a catalyst for technological innovation, technological capacity building, absorption, adaptation and extension of technology, co-ordination, establishment of R&D institutional interlink with institutions, universities and industry, reduction of time between applied R&D and industrial application and commercialization and technical human power development in advanced technologies

(ii) The development objectives will be to raise the level of technological capability and techniques to speed up the application of advanced materials in commercial applications.

(iii) The immediate objectives will be to expand the capabilities of materials science/technology research institute as centre for development and application of advanced materials technology for the country.

(iv) The results of such a programme will be as follows:

(a) a centre for advanced materials established (to include the equipment and personnel trained for preparation of these materials);
(b) existing research groups on various aspects of new materials strengthened at the Centre of Advanced Materials;
(c) new technology of advanced materials introduced;
(d) skilled specialists of the Centre of Advanced Materials trained in the preparation and diagnostic of new materials; they will be able to provide competent consultancy on the problems and on introduction of these techniques into practice; and
(e) industrial liaison, extension, documentation, information dissemination and operational data base.

12. Justification and scope for the start of a national Centre on New Materials and Advanced Technology:

(i) Developing new materials and organizing their production is of vital importance to scientific and technical progress. Specialists are unanimous in the view that over the next few decades new materials will to a significant extent determine a country's international competitiveness, since they represent as much as 30 to 50% of the value of finished goods, and innovations in the technology of their manufacture are likely to have a substantial influence on the economics of production as a whole. Moreover, new materials offer radically new possibilities and may form the basis of hitherto non-existent products.

(ii) As the new material technology has become an integral part of the process of advanced industrialization and globalization of industrial technology, some 'advanced' developing countries have established a national institutional focal point.

(iii) Therefore selected developing countries could establish such an integrated national institutional facility which could be created through either strengthening and expanding of an existing department or establishing of a new one. The overall tasks of such an integrated institutional set-up may be as follows:

- Based on global trends in new material technology and identification of the need/potential, to identify areas of national level importance with special reference to the year 2000 and beyond.

- Acting as a national co-ordinator for a national network of activities involving specific national institutions, universities, private and public sector with reference to a 'National Programme of Action' which will include targeting end-user, application, specialization, time schedule, technical human power, training, finances, facilities and results to be accomplished.

- Establishment of a national level data base and data bank with a view to monitor and co-ordinate national activities in technology of new materials.

- Undertaking of specific applied R&D in critical areas, and the follow-up with respect to industrial liaison and industrial and commercial applications.

- Acting as a central coordinator and awarding research financial grants, as appropriate, to other institutions, universities and manufacturers to undertake specific applied R&D and monitoring results - industrial/commercial application.

- Dissemination of information, training, publication, etc., at a national level and establishment of international contacts in an integrated way.

(iv) These aspects assume that a national technological policy on new material exists and the work programme is within such a framework. Otherwise the proposed national institutional facility will have to take up this task.

(v) It is recommended that the overall programme for new materials and advanced technology includes the following aspects:

(a) Technological/scientific principles for controlling properties of materials made from dispersive powder and fibres.

(b) Theory and practice of production of powder materials and fibres:
  - high-melting powder compounds;
  - metal powders;
  - amorphous materials; and
  - organizational aspects of production of new materials in the
  - chemical and electronic industries.

(c) Theory and practice of processes for manufacturing products from powder materials:
  - pressing;
  - injection moulding;
  - sintering;
  - cold and hot forming;
  - isothermic pressing;
  - extrusion moulding; and
  - rolling.

(d) Materials with special properties:
  - structural materials;
  - semiconductor materials;
  - heat-proof and heat-resisting materials;
  - electrotechnical materials;
  - magnetic materials;
  - superconducting materials;
  - radiation resisting materials; and
  - solar materials.

(e) Economic aspects of production of powder materials, including marketing and problems in organizing joint ventures

(f) Specialized technological and research equipment for new materials.

Centres for Study Tours on New Materials and Possibilities for Training

1. North Carolina State University, Triangle Park Microelectronic Centre, NC, USA.
2. North Carolina State University, Raleigh, USA.
3. University of California, Berkeley, Advanced Materials Centre, USA.
4. Livermore Lab., CA, USA.
5. Institute of Metal Physics, Aachen Technical University, Germany.
6. Institute of Applied Physics, Hamburg, Germany.
7. Institute of Semiconductors of Aachen Technical University, Germany.
8. Institute of Solid State Physics, Zurich Technical University.
9. Institute of Inorganic Chemistry, Zurich University, Switzerland.
10. Paris University, Laboratory of Applied Chemistry, Orsay, France.
11. Rome University, Italy.
12. Institute of Solid State Electronics, C.N.R. Rome, Italy.
13. Chalmers University of Technology, Goteborg, Sweden.
14. Vienna Technical University, Institute of Electrotechnics and Electronics, Austria.
15. OKA - Austrian Alpen Photovoltaic Company, Austria.
16. Institute of Radio Engineering and Electronics Academy of Sciences of the USSR, Moscow.
17. Institute of Crystallography, Academy of Sciences, Moscow, USSR.
18. Institute of Chemical Engineering Moscow, USSR.

19. Institute of Power Engineering, Moscow, USSR.

20. Institute of Steel and Alloys, Moscow, USSR.

21. Mendeleev Institute of Chemical Technology, Moscow, USSR.

22. Leningrad Physical-Technical Institute, USSR.

23. Lomonosov Institute of Fine Chemical Technology, Moscow, USSR.

24. Institute of Rare Metals, Moscow, USSR.

25. Institute of materials Problems, Ukrainian Academy of Sciences, USSR.

UNIDO Roster for Projects on New Materials
Names of Technologists/scientists

(the list is neither exhaustive nor final)

1. Dr. W. Seikhauz, Livermore Lab., CA, USA (Electronic Materials).
2. Prof. G. Rozgonyi, North Carolina Micro-electronic Centre, State University, USA (Electronic Materials).
3. Prof. F. Levy, Lausanne Technical University, Switzerland (Electronic Materials, Superconductors).
4. Prof. P. Paroli, Rome University, Italy (Electronic Materials, Advanced Ceramics, Magnetic Materials, Superconductors).
5. Prof. A. Revcolevschi, Paris University, France (Electronic Materials, Superconductors).
6. Prof. M. Albella, Madrid University, Spain (Electronic Materials).
7. Prof. L. Luque, Solar Energy Centre, Madrid, Spain (Solar Materials).
8. Prof. W. Fallmann, Vienna Technical University, Institute of Electrotechnics and Electronics, Austria (Microelectronic Materials).
9. Prof. C-G. Granqvist, Chalmers University of Technology, Goteborg, Sweden (Solar Materials).
10. Prof. M. Koltun, Institute of Power Engineering, Moscow, USSR (Solar Materials).
11. Prof. A. Popov, Institute of Power Engineering Moscow, USSR (Optoelectronic Materials).
12. Prof. B. Djubua, Electronics Industry, Moscow, USSR (Electronic Materials).
13. Prof. V. Kravchenko, Institute of Radio Engineering and Electronics Academy of Sciences Moscow, USSR (Electronic, Optoelectronic Materials).
14. Prof. E. Givargizov, Institute of Crystallography Academy of Sciences, Moscow, USSR (Electronic Materials).

SOME EXAMPLES OF ADVANCED TECHNOLOGY AND NEW MATERIALS FOR ELECTRONIC AND SOLAR DEVICES

1) Corrosion prevention technology:

The experience and knowledge of adequate corrosion engineering in the relevant economic sectors as well as of adequate means of corrosion prevention or protection, such as heavy-duty corrosion inhibitors, efficient cathodic protection, installations, are important factors. Corrosion-resistive coatings technology is available, and being comparatively simple may by introduced in developing countries. Establishment of activities in the area of corrosion prevention and protection would solve corrosion problems and make it possible to apply state-of-the-art corrosion prevention technology. In this context, determination of exact topics of study and applications of corrosion prevention technology and preparation of specifications for equipment (corrosion prevention, testing and chemicals) are important.

2) Inorganic materials for application in the electronics industry:

Application of new materials in electronic devices will increase their effectiveness and reliability and will lead to their highly productive commercial manufacture. To develop a method for the preparation of electronic materials, such as semiconductors, metals and insulators with reproducible properties necessary for manufacturing electronic devices, it is necessary to study growth mechanisms, the material's physical and chemical properties and correlation of these properties with growth parameters.

In developing a technique of electronic materials preparation it is necessary to employ effective methods, such as chemical vapour deposition (CVD). To prepare these materials with the desired properties one needs to study the correlation of growth parameters with physical and chemical properties which requires a complete diagnostics of the materials. The CVD apparatus, instrumentation for measurement of conductivity, Hall mobility spectrometers, spectrophotometers, etc., will be needed.

3) Special and rare materials:

A number of rare metals such as titanium, zirconium, hafnium, molybdenum, tungsten, tantalum, copper in the form of powders, foils, wires are widely used in electronics (high power vacuum devices of super high frequency, space satellite cables for space satellite communication), in the chemical industry (for purification of gases, in high temperature technological processes etc.) and in everyday life (microwave ovens). Developing the production of such materials would lead to creation of highly effective above-mentioned electronic devices, to elaboration of high quality technological processes in chemical and electronic industries. For production of such materials of high quality it is necessary to work out a technology of their preparation and purification. Application of these materials in techniques will increase effectiveness and reliability of devices based on these materials and will lead to their highly productive commercial manufacture.

4) Materials for solar energy devices:

Effective utilization of solar energy requires highly productive converters such as photovoltaic (PV) cells, flat plate collectors for solar radiation conversion utilized in water and space heating. Solar energy can be widely used in countries where sunlight radiation is high. To develop solar devices of high efficiency it is necessary to first develop advanced materials technology. In recent years, research on such materials has been considerably intensified. There have been major achievements in the production of these materials and in fabrication of solar energy converters based on them in industrialized countries. Research in the development of these materials as well as their application to fabrication of solar energy converters will lead to increased efficiency of such devices and to an increase of the productivity of their commercial fabrication in developing countries.

For local development of solar energy devices, it is necessary to know the technology of solar materials, study of optical characteristics of these materials, techniques of fabrication PVs and flat plate collectors and techno-economic study of production of solar converters. This will also require equipment, such as CVD apparatus or magnetron sputtering, for preparation of solar materials, for study of optical characteristics of materials, (reflectivity and transmission), for design and fabrication of PVs and flat plate collectors, etc.

5) Optical processing materials:

The level of society development in some ways is determined by the solution of the problem of operative processing, storage and multiplying of information. Tremendous flow of new information creates a need to develop new means of its processing, storage and dissemination. Along with traditional silver haloid photo technique of optical processing the alternative techniques are intensively developing; electrophotography (xerox-process), photothermoplastic process of optical recording and holographic storage on the base of photostructural transformations and photoinduced phase transitions (optical discs).

In these techniques the non-crystalline conductors are used as photo sensitive media (hydrogenized amorphous silicon -Si:H and its alloys, amorphous selen Se and its alloys, halcogenide glass-like semiconductors). They have a serious advantage in comparison with traditional silver-haloid photo materials, as follows: i) possibility of multiple use of photosensitive layer, recording in the real time scale, absence of wet processes during the procedure of obtaining the image and high resolution. But photo sensitivity of these materials is not very good. ii) Implementation of such materials into practice for manufacture of new devices for optical recording of information will solve a problem of operative processing, storage and multiplying of information.

The development of such a national programme will require the following steps:

- to determine exact topics of study and applications of optical processing materials, investigation of materials and optical processing procedure, and application of elaborated materials of optical processing into practice; this will need equipment and instrumentation, such as optical processing materials production, diagnostics of these materials, design of optical processing devices.

6) Powder metallurgy technology:

a) The past decade has witnessed the emergence or firm establishment of innovative powder-metallurgy technologies in materials processing: coatings of wear-resistant and corrosion-resistant composite materials (vast range of applications - ranging from 6,000 to 7,000°C plasma to ferro-concrete and artificial bones and teeth); amorphous materials (unique magnetic and corrosion-resistant properties, as well as nearly absolute radiation resistance); metals and alloys characterized by memory of shape; ceramic materials (materials of so-called second-generation heat-proof metals, including chromium and beryllium, these are very brittle materials and obtaining them in the plastic state required further development of the theory of brittle rupture and in the physics of metals. Such metals being used in making photo-masks, high-resolution photo-cathodes, computer storage devices, corrosion-resistant coatings and motors capable of operating at high working temperatures, beryllium being used in making special composites and cryoresistors, and chromium, in making materials for the active zone of fast-neutron reactors); energy-storing materials (hydrides); so-called vaccum-containing materials, etc.

b) The properties and possible applications of the materials are very impressive:

- melting temperature of up to 4,000°C (carbides of group IV). They attain diamond hardness and have extremely high corrosion resistance. Feedstock for their production would be unlimited.

- tool materials ranging from cutters to abrasives and presses: cheap and widely available SI_3N_4 for engineering tools, shock-resistant cutting tools and so-called non-tungsten shock-resistant tools. Diamonds based on C and BN.

- components of a new generation of internal-combustion engines and gas turbines. Since, by using ceramics, operating temperatures are raised by 300-600°C, fuel savings of up to 30-35% can be achieved. This means a revolution in power engineering and transport. The main problem - that of developing shock-resistant ceramics - has in principle been solved.

- use of the optical, electrical and magnetic properties of ceramics for laser diodes, light-emitting diodes, optical communication lines, integrated-circuit boards, electric heating elements, energy converters and high-temperature superconductors, solid electrolytes (sensors to measure gases in smoke or the atmosphere), thermistors, piezoelectroic transformers and filters, piezoelectric motors, information storage devices, thick-and thin-film non-precious metal resistors, accumulators, condensors, ferrites, magnetic fluids.

- bioceramics (artificial teeth and bones), catalysts, catalyzers, chemical reagents.

- refractory materials (industrial-furnace linings), heat exchangers, recuperators, liquid metal casting-moulds; heat-extracting supports for electronic devices.

c) In conclusion the above analysis shows the influence of the latest advances in materials science on possible scenarios for the development of power engineering over the next decade, particularly in connection with the search for energy-producing methods, alternatives, that would be sufficiently clean from the environmental standpoint.

7). Fibre optics materials:

- project elaborated.

PART II. PHOTOVOLTAICS DIRECT SOLAR-TO-ELECTRICAL ENERGY CONVERSION

1. INTRODUCTION

Photovoltaic (PV) cells (often called solar cells) are semiconductor devices which are capable of converting sunlight directly into electricity. All photovoltaic installations consist of small, individual generating units - the PV cell. Individual cells range in size from a few millimetres to a metre in linear dimension. Devices are available with a large range of efficiencies and voltages. Some cells are designed to withstand high solar intensities and high operating temperatures while others are designed to minimize manufacturing costs.

Photovoltaic systems have been developed and refined over the past 15 years. The capital needed and the delivered electricity costs generated by them are high, compared with conventional large-scale electricity production. However, given the increasing demand for electricity and the declining cost of the systems, due to improved technology and increased output, photovoltaic systems can be expected to play an increasingly important role in electricity generation in the future. This is particularly the case in the developing countries, where a small amount of electricity in rural areas can have a major impact on living conditions.

Photovoltaics have the following advantages:

a) Since they convert sunlight to electricity entirely with solid-state electronic components, they are not dependent on fuels such as diesel and kerosene, which are often in short supply and expensive in rural areas. Moreover, they reduce reliance on imported fuels such as coal and oil:

b) They produce no pollution and appear to have very limited environmental impact:

c) They are modular in design and can be built up on a site in a flexible way, thus minimizing front-end financial risk and investment costs. Each system can be sited to meet the particular demand:

d) They are durable and easy to maintain. Operation and routine maintenance are simple, and there is little degradation in performance over 15 years or more.

The principal types of photovoltaic cells are reviewed in Table 1.

Photovoltaic cells can be interconnected in series and in parallel to achieve the desired operating voltage and current. The basic building block of a flat-plate solar array is the module in which the interconnected cells are encapsulated behind a transparent window to protect the cells from the weather and mechanical damage. One or more modules are then attached to a supporting structure to form a panel. A number of panels makes up an array field, which, along with the balance-of-system components, makes up the complete system. They array field may be sub-divided electrically into a number of sub-arrays working in parallel. Flat-plate arrays are normally fixed, with the modules supported by a structure that orientates them due south (in the northern hemisphere), inclined at or about the angle of latitude that maximizes the amount of solar radiation received on an annual basis. A steeper angle of inclination will enhance the output in winter, at the expense of some reduced output in summer.

A preparatory assistance project concept for "PVs: direct solar-to-electrical energy conversion" is given in Annex II-1.

A list of current solar energy terminologies is given in Annex II-2.

Table 1. Properties of photovoltaic cells

Type of cell	Efficiency Laboratory record (percentage)	Production record	Advantages	Disadvantages
Single-cell (monocrystalline) silicon	23.1	10-13	Well established, tested technology Stable Relatively efficient	Uses much expensive material Much waste in slicing wafers Costly to manufacture Round cells cannot be spaced in modules efficiently
Polycrystalline silicon	18	10-12	Well established, tested technology Stable Relatively efficient Less expensive than single crystal Si Square cells for more efficient spacing	Uses much expensive material Much waste in slicing wafers Fairly costly to manufacture Slightly less efficient than single crystal
Gallium arsenide	29.2		Highest theoretical efficiency Can operate at high temperature (therefore useful for concentrations)	Very expensive Materials not abundant
Thin-film amorphous silicon	13.8	4.8	Very low material use Potential for highly automated and very rapid production Potential for very low cost	Sunlight induced degradation (Staebler-Wronski effect)
Thin-film cadmium telluride	12.3		Same as for amorphous silicon Does not degrade	Only in small-scale production for indoor applications
Thin-film copper indium diselenide	14.1		Same as for amorphous silicon Does not degrade	Not yet in production

2. APPLICATIONS OF PHOTOVOLTAIC SYSTEMS

Since photovoltaic modules provide an independent, reliable electrical power source at the point of use, they are particularly suited to remote or inaccessible locations. (See Figs. 1(a), 1(b) and 2). Suitable applications are outlined below.

a) Rural electrification: lighting and power supplies for remote buildings and villages, street lighting, individual house systems, battery charging, minigrids.

b) Water pumping and treatment systems: pumping for drinking water and irrigation, de-watering and drainage, ice production, saltwater desalinization systems, water purification.

c) Health care systems: lighting in rural clinics, UHF transreceivers between health centres, vaccine refrigerating, ice-pack freezing for vaccine carriers, sterilizers, blood storage refrigerators.

d) Communications: radio repeaters, remote television and radio receivers, remote weather measuring, mobile radios, rural telephone kiosks, data acquisition and transmission (river levels, seismographs).

e) Transport aids: road sign lighting, railway crossing and signals, hazard and warning lights, navigation buoys, fog horns, runway lights, terrain avoidance lights, road markers.

f) Security systems: security lighting, remote alarm systems, electric fences.

g) Corrosion prevention systems: cathodic protection for steel structures, well-head protection, lock gate protection.

h) Miscellaneous: ventilation systems, caper and recreational vehicles power, calculators, pumping and automated feeding systems on fish farms, solar water-heater circulation pumps, path lights, yacht/boat power, vehicle battery trickle chargers, earthquake monitoring systems, battery charging, fountains, emergency power for disaster relief.

At the annual consumption less than 20,000 kWh the utilization of solar stations with battery storage systems is already more profitable than the use of conventional power sources, namely diesel-generator, or extension of the grid. The following small-scale applications were tested already. (See Table 2).

The pattern of the consumption is changing very quickly as the new more powerful stations are becoming operational.

Detailed description of PV system applications is given section 2.

3. TECHNOLOGICAL STEPS IN THE SOLAR CELL PRODUCTION

There is not yet established technological pattern of the cells production. However, there are several steps which are obviously in each technological process of the cell production:

- production of the pure silicon feedstock (or alternate feedstock).
- preparation of the thin sheet of silicon.
- fabrication of cells.
- encapsulation of cells and module assembly and encapsulating.

The module itself must be also established at some structure, with necessary collectors, and electrical interconnectors.

3.1. Materials for solar Cells

Silicon-based PV is the reference technology for both flat plate and concentrator systems. It is clear that cells with good electrical characteristics can be produced. Field experience indicates that useful cell life under operating conditions can be adequate. This technology, therefore, provides a vehicle for evaluating systems, with known bounds on performance and maufacturing costs.

The basic PV cells efficiency is given in the following Table 3.

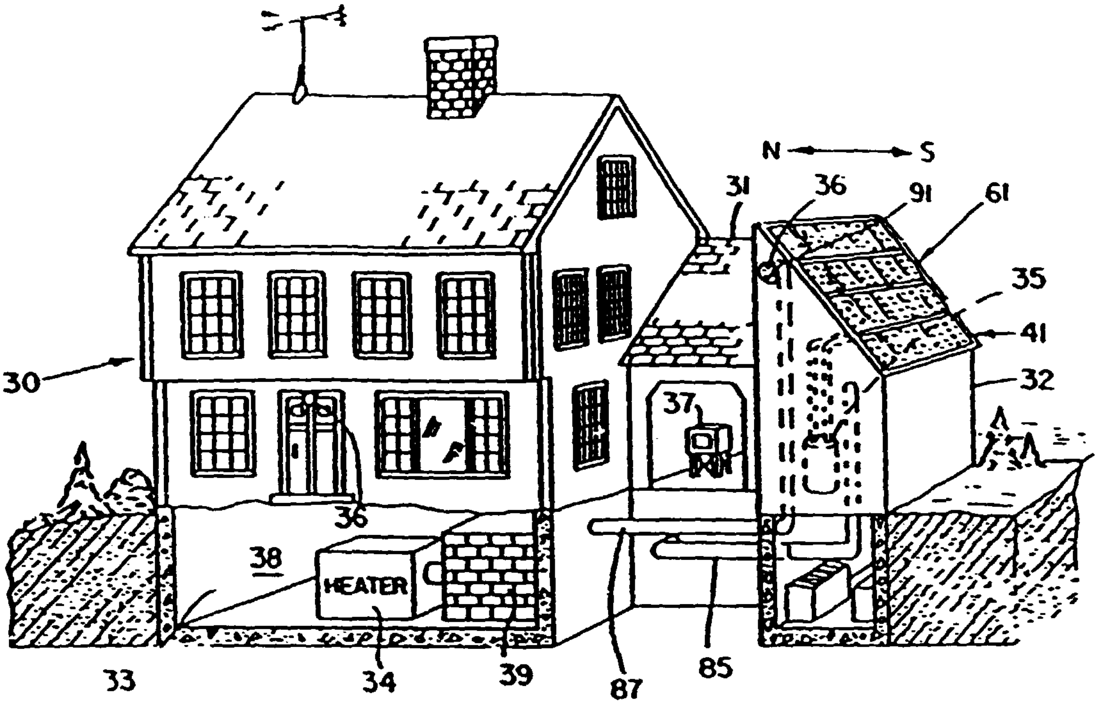


Fig. 1.(a) Solar Heated House

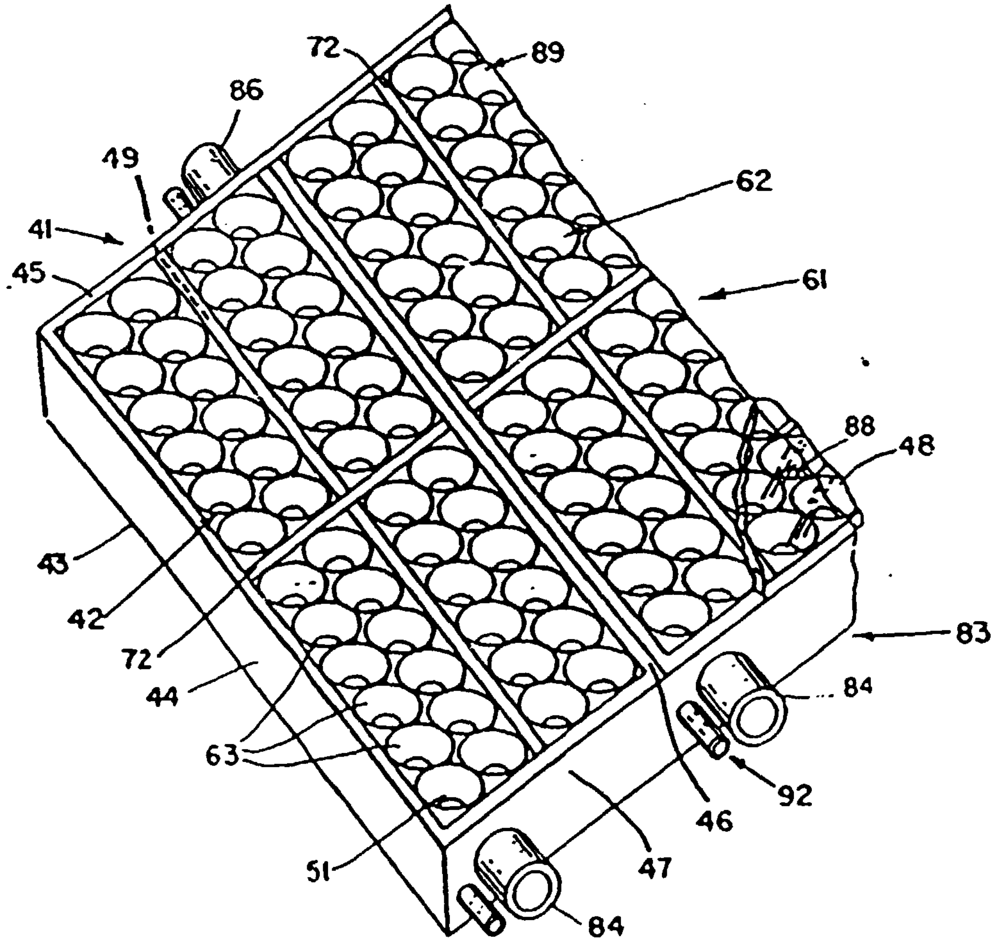
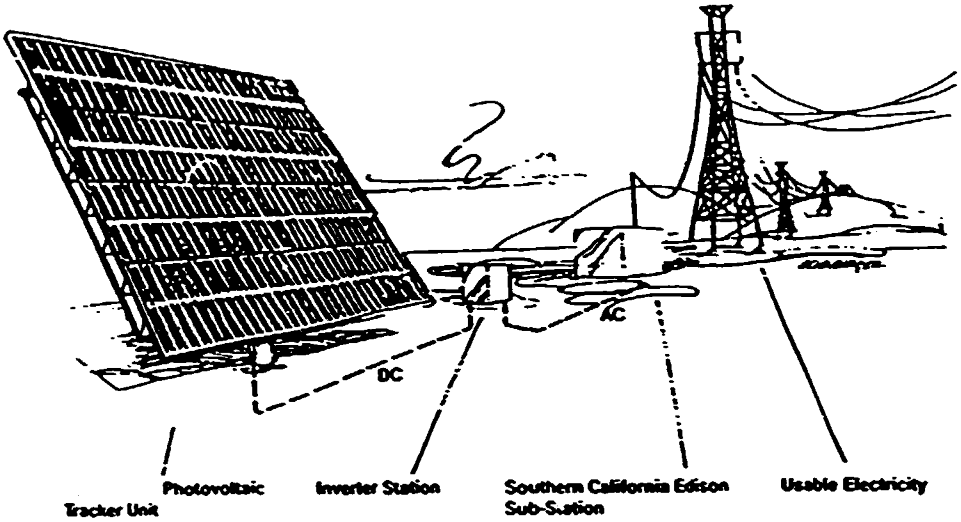


Fig. 1.(b) Detail of PV Panel

Fig. 1.(a), (b). Sholar Heated House and Detail of PV Panel.



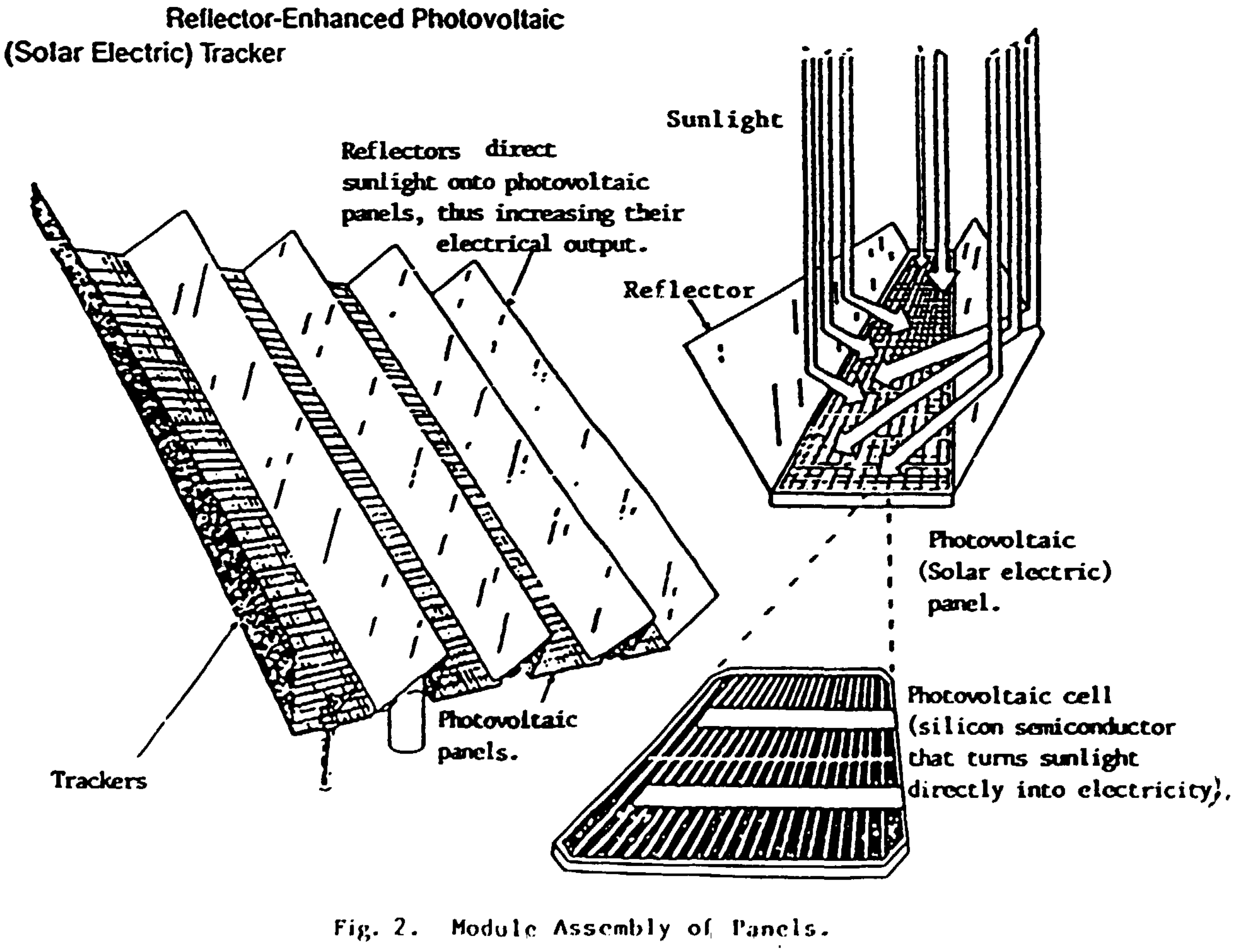


Fig. 2. Module Assembly of Panels.

Table 2. Small Scale Applications.

Application	Demand	Installation
Scolar TV	20-100 W 50h/week	3-5 modules of 11 W/peak, interconnection boxes, batteries 80Ah with necessary electronic devices.
Hertz relis	150-250 W	Solar panel, control system, batteries, transformer (optional).
TV retransmission station	50-100 W	Solar panel, control system, batteries.
House lighting heating, cooling (fig. 1)	300-500 W	Solar panels, control system batteries.
Wrist watches, calculators	0.05 W	Solar cell, rechargeable battery.
Solar power stations	> 1 MW	Complex systems.

The solar power stations are constructed as a pilot installations to elaborate on the application logistics. Several examples are given mainly from USA.

Place Cost	Capacity Company	Components
Lugo (CA)	1 MW	108 heliostats
	ARCO SOLAR	
		a 10kW
Carisa Plain	6.5 MW/peak	789 heliostats
	ARCO SOLAR with FLOUR	
Rancho Seco	1 MW/peak	
US$12	ACUREX,ARCO SOLAR	
(CA)		
millio..		
Sacramento	5 MW electric	
	United Energy	
Daget (CA)	70MW thermic	
	Corporation	
Borrego	15MW electric	
	UEC, TURBOFLASH	
Springs	215MW thermic	
	cell	

Table 3. Photovoltaic Cell Efficiencies*

Device	Probable maximum achievable efficiency	Maximum measured efficiency	Performance of commercial cells
	Silicon Devices		
Single crystal homojunction	20-22	19	10-15
Polycrystalline homojunction	?	7-14(?)	-
Amorphous Schottky with platinum	15	5.6	-
	Thin films		
CdS/Cu_2S (chemical vapour deposit process) (heterojunction)	15	8.6	2-3
CdS/Cu_2S(spray process) (heterojunction)	8-10	5.6	-
$(Cd/Zn)S/Cu_2S$(heterojunction)	15	6.3	-
$CdS/CuInSe_2$(single crystal) (heterojunction)	24	12	-
$CdS/CuInSe_2$(thin film) (heterojunction)	15	6.9	-
GaAs(Schottky AMOS)	25-28	14	-
Single crystal Schottky with indiumtin oxide	20	12	-
	Cells for use in concentrated sunlight		
Optimized silicon cell (single-crystal homojunction), 200 times concentration	22	18	12.5
Interdigitated back-contact silicon, single-crystal homojunction, 100 times concentration	26-27	15(20?)	-
Thermophotovolatic	30-35	13	-
$Ga_xAl_{1-x}As/GaAs$(180 times)	25-26	24.5	-
$Ga_xAl_{1-x}As/GaAs$(1,700 times)		19	-
Multicolor cell(GaAs/Si/Ge)	40	-	-
Vertical multijunction(silicon)	30	9.6	-

*Techniques for reporting efficiencies differ. Wherever possible, efficiencies were chosen which assume air mass 1 and include losses due to reflection and contact shading.

3.2. Cell Fabrication

The process of converting silicon wafers into an operating photovoltaic cell involves a number of unit processes as follows:

- creation of the photovoltaic junction;
- addition of electrical contacts;
- antireflecting coating of cell.

Actually many steps of the cell fabrication are laborious and expensive, therefore, the operation of the cell producing installation must reach economic capacity, which is considered not being less than 10MW per year and economic optimum capacity may be around 50MW per year.

3.3. Module Assembly and Encapsulation

The following processes are related to the technical design of the PV installation, establishing the physical form of the panel and allowing for its installation. As the form of the panels are not unified the processes of assembly are very much diversified. (Fig. 3)

However, following processes are always included into the technological line:

- assembly panel structure;
- installation of cells;
- installation of additional devices (concentrators etc.);
- establishment of electrical joints;
- encapsulation of cells and panels against weather influence; etc.

for mass production of certain type of panels the continuous processes are developed and tested.

4. EXAMPLES OF THE PROCESSING TECHNOLOGY

Technological processes are numerous especially in the case of the production of the PV materials. More than 20 processes are operational and selection of the process requires detailed analysis. This cannot be done unless all details are known, but these are given only under license agreement. Therefore, for the beginning only high-level experts can assist in the selection of the purposeful processes. General principle of the production line composition is given on the Fig. 4 which is self explanatory.

Some efforts have been made to adapt existing technological lines to produce PV panels. Two examples are given below:

1) adaptation of the float glass production; (Fig. 5)
2) pilot plant producing from prefabricated window glass. (Fig. 6)

5. ECONOMIC ASPECTS OF THE PV PANELS PRODUCTION

As mentioned above not only one kind of technology exists for PV materials production or for cells and assembly of panels. Therefore it is obviously difficult to predict any investment and operation cost before the design of the factory. However, it is possible to indicate range of shares of different unit processes in the cost of the operation. The data may not be up-to-date, however they are informative in showing the split of costs:

Unit Process	Ingot Technology	Non-ingot Technology
	% of operating	costs
Polysilicon	15	20
Crystal growth and cutting	25	35
Cell fabrication	36	25
Encapsulation of cell	4	3
Module assembly and encapsulating	20	17

Actually price for the non-ingot technology of the cell may be considered around US$5 peak watt. The capacity peak watt has to be divided at least by 10 to obtain net watt capacity.

However the cell application in the complex installation requires certain infrastructural costs, as was mentioned above in section 2. The division or these costs in the case of the low watt system which operates continuously is as follows:

Components	% of the investment costs
Cells/modules	42
Supports	7
Electrical wiring	6
Batteries	20
Civil works	25
total	100

The composition of investment cost does not consider the production of the pure material. The cost of the silicon production plant of the commercial capacity may vary from US$20 million to US$40 million.

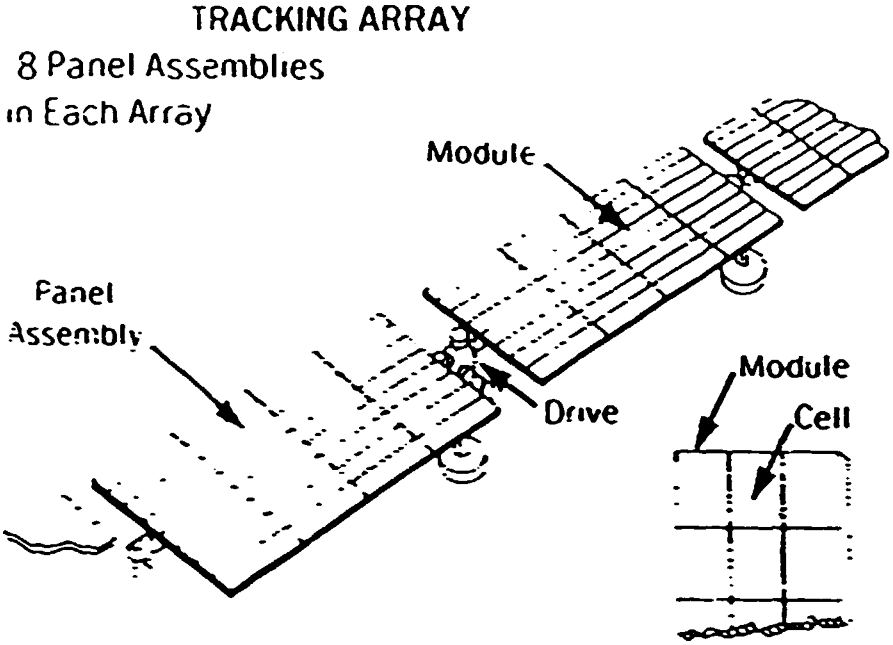
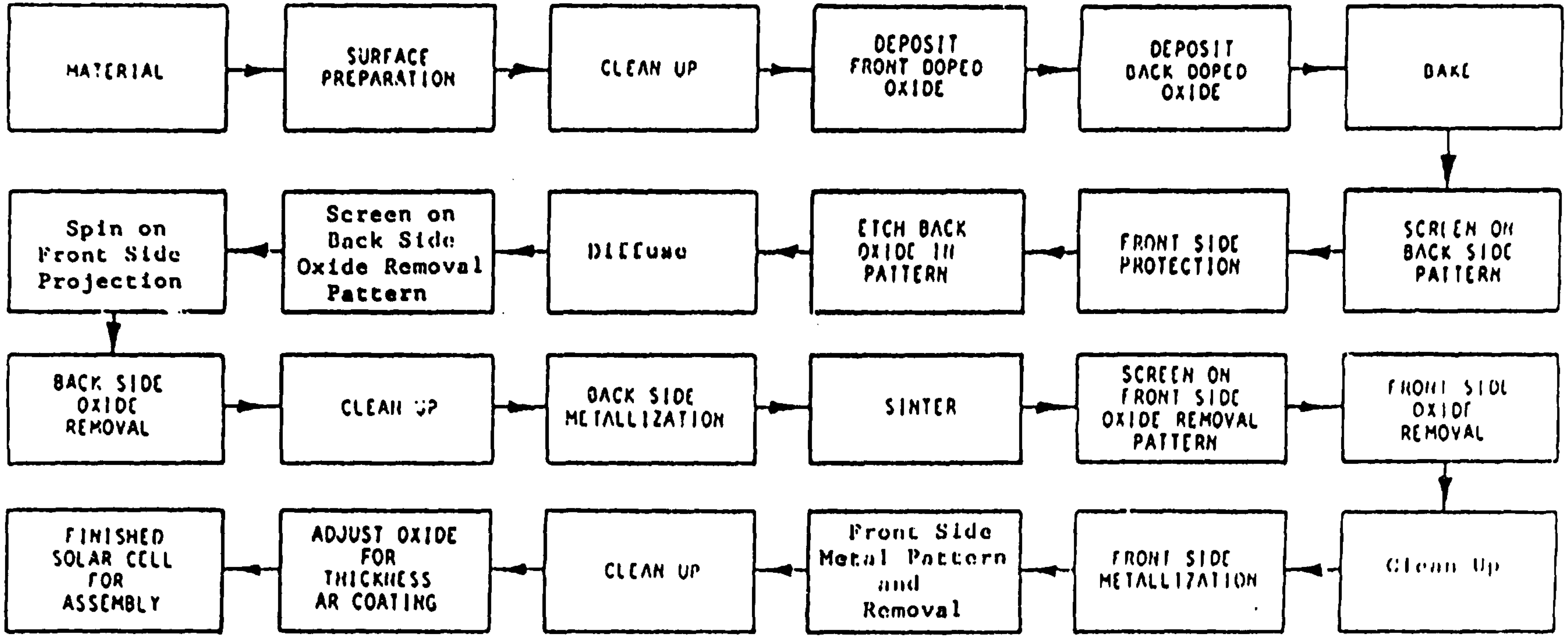
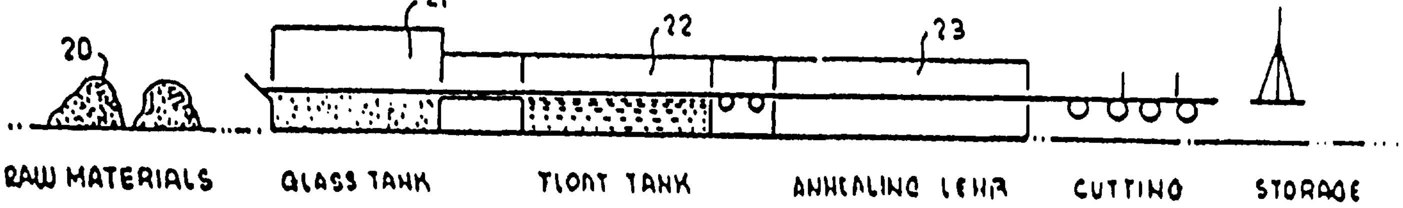


Fig. 3. Encapsulation of Cells and Panels.



Note: AR = antireflection

Fig. 4. Process for Fabricating Inexpensive High Performance Solar Cells Using Doped Oxide Junction and In Situ Antireflection Coatings.



Adaptation of Float-Glass Plant to Continuous Solar Cell Manufacture

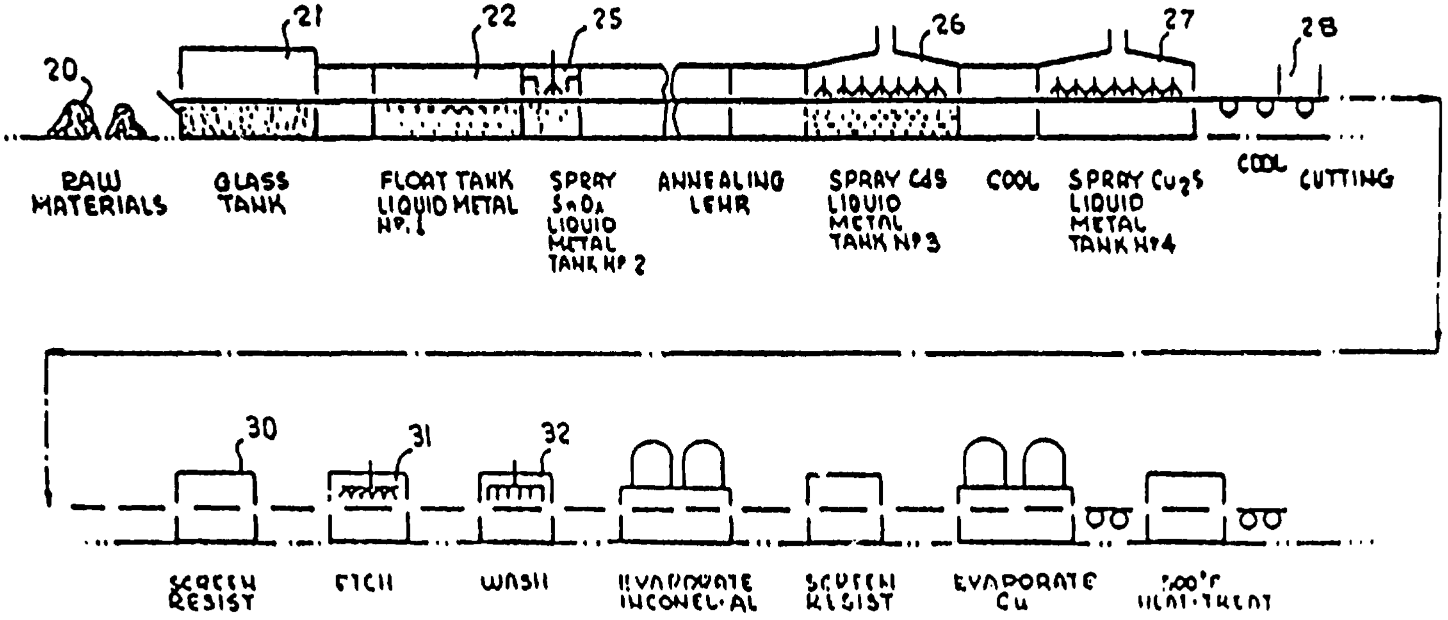


Fig. 5. Float Glass Plant.

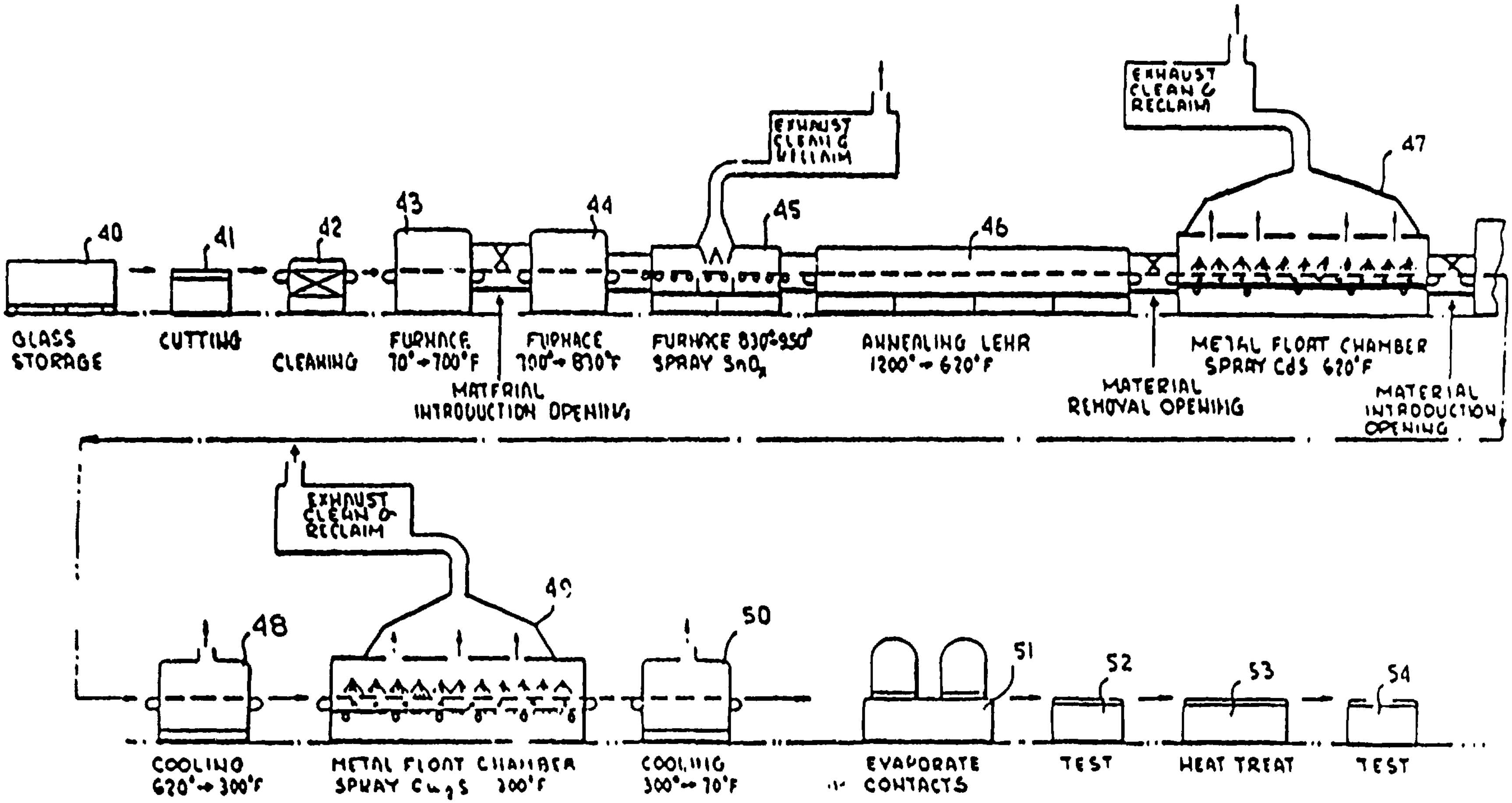


Fig. 6. Pilot Plant for Continuous Solar Cell Manufacture from Prefabricated Panels of Window Glass.

5.1. Costs

It is widely accepted that the major factor inhibiting the widespread use of photovoltaics is their high cost. However, over the past 15 years, the price of the modules and systems has been steadily falling in real terms.

Module prices for both forms of crystalline silicon are currently about $4/Wp (exclusive of delivery or taxes) for large orders Bearing in mind that the cells account for about 60 per cent of the module price, some further price reductions, possibly down to about $2-$3/Wp, are foreseen through the introduction of cheaper silicon and larger, fully automated manufacturing plants. Even with efforts being made world-wide to develop different thin-film technologies it is probable that large-area thin film cells will become available by 1990, with much improved efficiency and stability, compared with current products art prices below $3/Wp.

Obviously it is impossible to be certain that cost and price reductions can be achieved. This dependent on development of the market demand as well as the technology. Two very recent proposals for significantly reduced costs (and prices) are worth further study.

The Chronar Corporation in the United States has built its "Eureka" plant which produces thin-film amorphous silicon modules. When in full production of 10MWp per annum, it should yield modules at a cost of $1/Wp. This will require a scale-up of the thin-film deposition equipment to deposit the films over an area of at least 1 m^2 and to develop a processing line for them.

Suryovonics of India, which is a partner of Energy Conversion Devices of the United States, has proposed its "global concept for low-cost photovoltaics". A 3MWp per annum plant is currently under construction in Hyderabad. The proposes programme is to expand the capacity to 200MWp per annum. But this proposes a novel approach of large-scale production of cells followed by decentralized finishing of modules.

The process involves two stages. The cell type is a multijunction, multilayer of morphous silicon. In the first stage of the process, the amorphous silicon layers are coated onto thin stainless steel in the form of a long roll. This "front-end process" produces what is called "coated web" - which is a roll of photovoltaic cells up to 0.5m wide and up to 600m long. The second stage of production, called the "back-end process", is to cut the coated web to appropriate size and shape and encapsulate it into photovoltaic modules. The "global concept" is to produce the coated web in a large plant (200MWp per annum) and ship it to a number of finishing plants whose capacity would be required to meet local market demand, which could be from 200kW to several MW per year. The main capital investment is in the front-end plant.

The claimed production costs for the coated web process are summarized in Table 4. Investors for the venture are currently being sought. (Possible cost reductions and future scenarios are discussed further in section 6 of this report)

Table 4. Production Costs Claimed for Suryovonics Photovoltaic Modules

Cost	Capacity (MWp per year) 2	25	75-150
Capital (millions of dollars)	10	40	90
Coated web ($/Watt)	1.88	1.02	0.56
Module finishing ($/Watt)	2.0	1.50	0.94
Finished module ($/Watt)	3.88	2.52	1.50

The economic characteristics of photovoltaic systems are different from those of most small systems in that the initial outlay on purchasing the equipment (the capital cost) is high; there are no fuel costs; maintenance costs are generally low; reliability is high, so that replacement costs are low; and the output of a system depends on its location, so its economic viability has to be assessed for each case.

In undertaking an economic evaluation, the following parameters should be considered:

a) The life-cycle costs, which are the sum of the costs and benefits of the system accrued over its lifetime, expressed in present day value;

b) The payback period, which is the length of time it takes for the total cost to be "paid for" by the value of benefits gained from the system;

c) The rate of return, which is the value of the benefits gained from the system compared to the initial investment made.

5.2. Future Trends

5.2.1. Major Programmes and Projects

Significant research, development and demonstration programmes have been undertaken internationally on photovoltaic technologies since the mid-1970s, by Governments, private organizations and intergovernmental organizations such as the European Economic Community (EEC). Although expenditure by the International Energy Agency (IEA) member countries has decreased since a peak of some $300 million per year in 1981/82, since 1982 photovoltaics have been the biggest programmes among the renewable technologies within IEA as a whole. The decline in expenditure since 1982 largely reflects the withdrawal of United States Government funding from the very large-scale demonstration plant programme of the late 1970s through the early 1980s. However, this has, to some degree, been compensated for by Germany. The national programmes of the United States, Japan and Germany, between them account for some 85% of IEA governmental expenditure.

There is also a substantial research, development and demonstration efforts by private industry, on which published information is not readily available. It may be assumed, for example, that photovoltaic manufacturing companies in the United States, in particular, have filled some of the gaps in research, development and demonstration expenditure created by the Government's withdrawal. In addition, there will inevitably be spin-off benefits for photovoltaic technology from research, development and demonstration in related areas (notably the semi-conductor and micro-electronics industries).

It is possible to identify three main themes underlying both national and industrial research, development and demonstration programmes: enhancing cell efficiencies; reducing costs; and, for amorphous silicon cells, inhibiting the degradation process.

The United States programme on photovoltaics for utility-scale applications is the best documented. It has the clearly defined goal of achieving a performance level such that grid electricity can be generated economically.

The world's largest project in the developing countries is worth noting. It is being funded by EEC as a component of a regional programme to combat desertification in the Sahel and West Africa. Approximately $35 million has been allocated to the regional agency: "Comité inter-états pour la lutte contre la Sécheresse dans le Sahel" for the procurement of photovoltaic pumping systems and related equipment for water and electricity supply in Burkina Faso, Cape Verde, Chad, Gambia, Guinea-Bissau Mali, Mauritania, Niger and Senegal. The project will install approximately 1,350 photovoltaic pumping systems along with about 500 other photovoltaic systems (for lighting, battery-charging and refrigeration). The total installed capacity will be about 1.3MWp. Tenders for the first systems are currently being evaluated, and installations should commence in 1990.

5.2.2. Technology and the World Market

The photovoltaic market is best considered by application, as follows:

a) Consumer products - watches, calculators, shavers, vents, portable radios, cassette players and garden, sport and leisure products powered by photovoltaic cells;

b) Remote power applications (i.e., remote from a national electricity grid) - water-pumping, refrigeration, telecommunications, navigational aids, cathodic protection, area lighting, building power, village power etc.;

c) Grid connected - photovoltaic systems interfaced with a national utility grid, which may be considered as either central power stations feeding the grid or distributed residential, commercial and institutional building systems reducing the grid demand and/or feeding the grid.

The breakdown of the 1988 photovoltaic market by application is shown in Tables 5 and 6 by module origin and region of application, respectively. to date, the grid-connected market has yet to become significant. Photovoltaics for consumer products accounted for approximately one third of the 36MWp of photovoltaics sold in 1988. The remote power market used approximately 60% of photovoltaics produced in 1988, of which it is estimated that only one-third was for the developing country market.

Table 5. Photovoltaic Market, by Module Origin, 1988
(MWp)

Module origin	Consumer products	Grid connected	Remote application	Total
Europe	1.6	0.6	4.1	6.3
United States	0.8	1.5	9.0	11.3
Japan	9.2	0.6	3.2	13.0
Rest of the world	0.1	0.2	4.3	4.6
Total	11.7	2.9	20.6	35.2

Table 6. Photovoltaic Market, by Region of Application, 1988
(MWp)

Region of application	Consumer products	Grid connected	Remote application	Toal
Europe	3.0	0.8	3.7	7.5
United States	4.0	1.0	5.9	10.9
Asia	3.6	1.0	6.8	11.4
Africa	<0.1	-	1.1	1.2
Rest of the world	1.0	1.0	3.1	5.1
Total	11.7	3.8	20.6	36.1

It has been noted above that there has been a steadily growing market for photovoltaic modules, coupled with decreasing costs. There is obviously a link between cost/price and market size, but it is incorrect to expect that a reduction in price will lead directly to a larger market.

There have been many projections of future photovoltaic costs and markets. The United States National Photovoltaic Programme 1987-1991 aims to support the photovoltaic industry to achieve its ultimate objective - that, in the early 1990s, utility-sized photovoltaic systems will be economically justified and will be built in some parts of the United States. Beyond the 1990s, research and development would further reduce prices such that after the year 2000 photovoltaics would make a significant contribution to the electricity supply. The United States view of the evolution of photovoltaic technology is set out in Table 7.

Figure 7 gives photovoltaic module price forecasts to the year 2025. The baseline case is considered to be very realistic, with the low case being optimistic.

Figure 7. Forecast for the global photovoltaic market: accelerated case

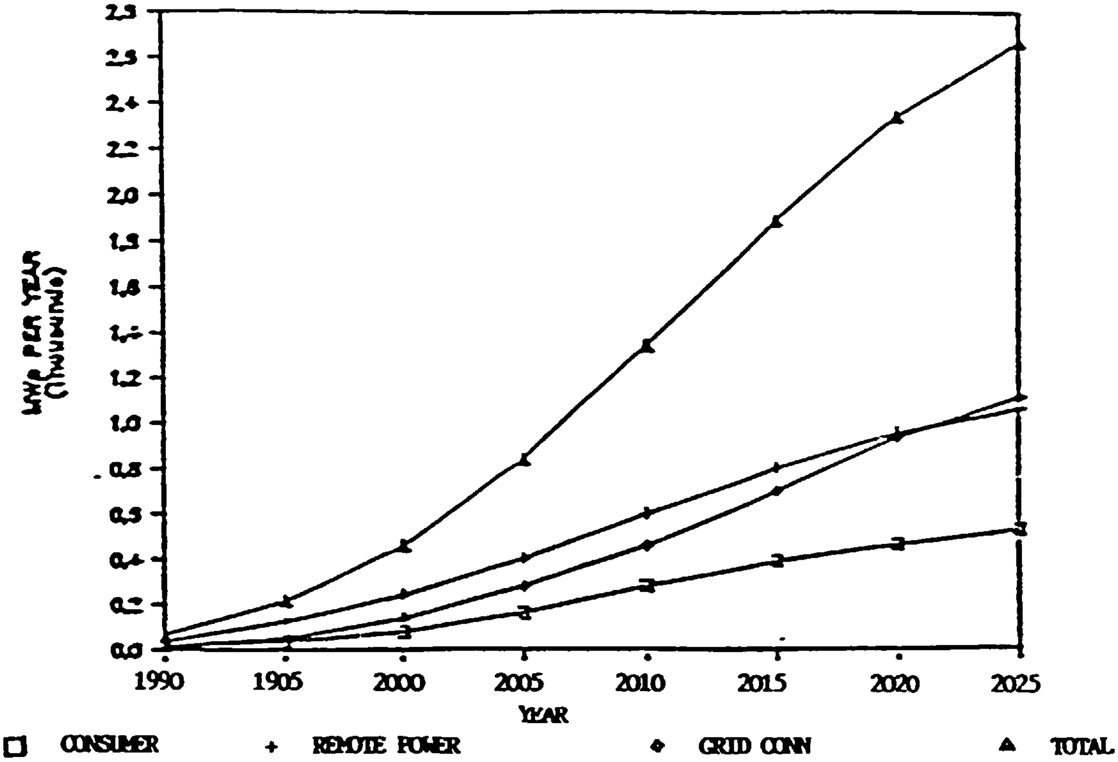


Table 7. Evolution of Photovoltaic Technology and Applications a/

Decade	Technological advances	Application
1950	Bell Lab discovery	
1960	Crystalline silicon	Space programme
1970	New thin-film materials	Terrestrial research and development begun
1980	Mix of crystalline silicon and amorphous silicon	Remote applications become viable
1990	Multijunction thin-film cells	Utility market penetration begins
2000	High-performance low-cost cells	Significant photovoltaic contribution by national utilities

a/ Predictions by the United States Department of Energy.

Manufacturers

Over the past 15 years a photovoltaic industry has emerged in practically every industrialized country and in many developing countries. As may be expected in a new area of technology, there have been a number of failures and disappointments as well as some notable successes. Many of the main photovoltaic manufacturers are subsidiaries of, or are majority-owned by, major oil companies, which see photovoltaics as a natural extension of their energy interest and as a field that may become very large in the future. In the United States, there are now some 10-15 companies well established in the manufacture and marketing of photovoltaic modules and systems.

In Europe, there are 8-10 photovoltaic manufacturers (Siemens AG, Germany, Helios-Italy, OKA-Austria, etc.) with annual production of at least 100 kWp. There are also smaller organizations more concerned with marketing systems using bought-in components. In Japan, at least six companies are active in photovoltaics, including several of the main manufacturers of electrical and electronic goods.

A number of developing countries are setting-up their own photovoltaic industries. Locally manufactured photovoltaic modules are not significantly cheaper than similar products made in industrialized countries, but because foreign products are usually subject to import taxes, local manufacturers are protected and are thus able to secure the local market, supplying photovoltaic systems for demonstration projects and professional applications such as telecommunications.

In India there are two well established manufacturers, and production capacity exceeds 3MWp per annum, with output around 2MWp. Approximately 3,000 villages have photovoltaic systems installed (or due to be installed) mainly through government-financed demonstration projects. A very large new production facility is being built, and an experimental production line for amorphous silicon is also under construction.

China has 12 photovoltaic manufacturing plants, with a production capacity of 4.5MWp per annum, but output was only about 550kWp in 1989.

Market development is the most important requirement if the use of photovoltaics is to expand. Output of PV modules in 1989 is expected to be 44 MWp. (See Table 8)

Table 8. Approximate Output of Photovoltaic Modules, 1976-1989

Year	Output (MWp)	Year	Output (MWp)
1976	1	1983	20.1
1977	1.5	1984	24.7
1978	2	1985	24.1
1979	2.3	1986	27.4
1980	3	1987	28.1
1981	5	1988	31.5
1982	5.2	1989	44

6. APPLICATIONS OF PV SYSTEMS

More than 6,000 photovoltaic pumps are known to be operating throughout the world, and they are doing a good job of providing rural water and irrigation supplies. They are used to pump from boreholes, open wells, rivers and canals. Less common applications include de-watering, drainage pumping and water circulation for fish farms.

With technical problems now largely resolved, experience suggests that reports of poor performance are largely caused by incorrectly specified data on solar irradiation, water resources and water demand. Proper consideration must be given to those parameters and also to the characteristics (yield and draw-down) if a system is to be operated correctly.

A comprehensive UNDP global project on photovoltaics in water pumping, executed by the World Bank, was completed in 1983. It included the testing of pumping systems in Egypt, Mali, the Philippines and Sudan. The following accomplishments were reported:

a) Mali provides a good example of solar pumping experience. Over the past 11 years more than 100 photovoltaic pumping systems have been installed, mainly under the auspices of Mali aqua Viva, a charitable organization. A high degree of local involvement has been insisted upon, especially with construction work on water tanks, foundations, access etc. This has provided up to 25% of the initial cost of any one project and generated a high level of enthusiasm within the locality. Borehole centrifugal pumps have been the type most widely used in Mali, originally coupled to surface mounted direct current motors. More recent installations have changed to using pumps with submerged alternating current motor/pump sets because of their lower maintenance costs. Reliability of the equipment in the harsh Sahelian environment has been good, with the solar pumping systems operating for more than 95% of the time. Most recent installations have operated faultlessly and effectively since being commissioned;

b) India has the largest number of solar pumps of any one country. More than 500 systems have been installed for village water supplies. Good responses have been reported, along with wide user acceptance. The modules and systems have been indigenously designed and manufactured by Central Electronics Limited. The potential for the application of photovoltaic systems in India is so great that several other companies have started photovoltaic production.

In villages, there is a constant demand for water throughout the year, and there is need to store water for periods of low insolation. In Sahelian Africa the typical amount stored would be from three to five days of demand. In environments with rainy seasons, the reduced output of the solar pump during the rainy period can be offset by rain-water harvesting. The majority of solar pumping systems installed, to date, are for village water supply or livestock watering.

A solar irrigation system needs to take account of the fact that demand for irrigation water will vary throughout the year. Peak demand during the irrigation seasons is often more than twice the average demand. This means that solar pumps for irrigation are under-utilized most of the year. Attention should be paid to the system of water distribution and application to the crops. The system should minimize water losses, without imposing significant additional energy-loss in the pumping system, and be of low cost. solar pumps are available to pump from anywhere in the range of 1.5m to 200m head and with outputs of up to 250m^3/day.

Solar pumping technology continues to improve. (See Table 9). In the early 1980s the typical efficiency of solar energy compared to hydraulic (pumped water) energy was about 2%, with the photovoltaic array being 6-8% efficiency the solar pump has an average daily solar energy to hydraulic efficiency of more than 4%. Photovoltaic modules of the monocrystalline type now have efficiencies of over 12%, and more efficient motor and pumpsets are available. A good sub-system (that is, the motor, pump and any power conditioning) should have an average daily energy throughout efficient of 30-40%. A photovoltaic system for pumping 25m^3/day through a 20m head requires a solar array of approximately 800Wp in the Sahelian regions. Such a pump would cost approximately $6,000 FOB. Other costs are shown in Table 10.

A range of prices is to be expected, since the total system comprises the cost of modules, pump, motor, pipework, wiring, control system, array support structure and packaging. Systems with larger array sizes generally have a lower cost/Wp. The cost of the motor pumpsets varies according to application and duties: a low-lift suction pump may cost less than $800, whereas a submersible borehole pumpset costs $1,500 or more.

Table 9. Specifications for photovoltaic pumping systems

Motor pump/configuration	Output (m^3/day) at 5kWhm/m^3/day insolation	Head (m)	Solar array (Wp)	System price (US$ FOB)
Submerged borehole	40	20	1,200	7,000-8,000
Motor pump	25	20	800	6,000-7,000
Surface motor/submerged pump	60	7	840	5,000-6,000
Reciprocating positive displacement pump	6	100	1,200	7,500-9,000
Floating motor/pumpset	100	3	530	4,000
	10	3	85	2,000
Surface suction pump	40	4	350	3,000

6.1. Vaccine Refrigeration

All vaccines must be kept within a limited temperature range throughout transportation and storage. The provision of vaccine refrigeration - known as the vaccine "cold chain" - is a major logistical undertaking in areas where electricity supplies are non-existent or erratic. The performance of refrigerators fuelled by kerosene and bottled gas is often inadequate, and diesel-powered systems frequently suffer fuel supply problems. Solar power can provide a more sustainable cold chain.

The World Health Organization (WHO) began looking at solar power for refrigerators in 1980 and has since made major contributions through the publication of technician and user handbooks and by running training courses. An infrastructure guide is currently in preparation. The World Bank has recently commissioned a status report and will hold a briefing in early 1990. Major programmes to utilize solar refrigerators are under way in the following countries:

a) Zaire. The Department of Public Health and Social Affairs, with the technical and financial assistance of the European Economic Community, is installing 100 photovoltaic refrigerators (and 750 lighting systems) in rural hospitals and health centres. The operation will equip roughly 400 health establishments spread out over more than 20% of Zaire's territory. A Zairian firm designed and now produces the refrigerators, utilizing importer compressor and batteries. User reaction has been good, and the systems have been more reliable than kerosene refrigerators. In 1986, the WHO undertook an evaluation of the installations. Their conclusions were very supportive;

b) Mali. Over six years of trials have taken place in mali leading to the conclusion by the Laboratoire de l'energie solar that, with periodic maintenance checks, the rate of equipment failure is negligible;

c) Sudan. Under co-operation programmes with agencies in the United States and Germany, solar refrigerators are being installed in many rural health centres;

d) Indonesia. A programme to install 300 photovoltaic refrigerators, together with 2,000 conventional refrigerators, is currently under way, with World Bank funding.

Projects involving significant numbers of solar refrigerators are also now under way in Chad, Ghana, Kenya, Mozambique and Sudan.

Compared with kerosene or bottled gas, refrigerators fuelled by photovoltaic systems have the following advantages;

a) Improved vaccine storage facilities as a result of the elimination of fuel supply and fuel quality problems, greater mechanical reliability, and better refrigerator performance (and temperature control);

b) Reduced running costs as a result of the elimination of kerosene fuel costs, including transportation costs; reduced vaccine losses; lower refrigerator maintenance costs; and reduced need for back-up refrigerators when there are fuel supply or repair problems;

c) Cold chain management benefits due to longer equipment life (photovoltaic array, 15 years; battery, 5 years; refrigerator, 10 years); reduced logistical problems arising from non-availability of working refrigerators; and reduced logistical problems arising from low vaccine losses.

The disadvantages of solar refrigerators are as follows:

a) The repair or replacement of a main component, such as the compressor control unit, requires skilled technicians;

b) Since solar systems are site-specific, more time is needed for planning and setting them up;

c) User training demands are high since overloading a solar refrigerator can cause it to become too warm.

A true comparison of solar refrigerators and comparable kerosene and gas-fuelled refrigerators can only be made through a life-cycle cost analysis. A solar photovoltaic refrigerator is likely to cost \$3,000-\$4,000 and will cost more to install than a kerosene unit. A kerosene refrigerator will cost only \$600-\$800 but will use 0.5-1.0 litres of fuel per day, require frequent maintenance and have a shorter life. In general, life-cycle costs are approximately the same for solar and kerosene refrigerators, but because of their greater reliability and the refrigeration or freezing. Storage capacity ranges between 10 and 200 litres of vaccine, with ice production rates of up to 5 kg per 24 hours.

Lead acid batteries are most commonly used, but long-life, deep-cycle batteries are preferred. A capacity to run the refrigerator for five days without sun is recommended. The charge regulator maintains the power supply within the current and voltage range tolerated by the refrigerator and prevents overcharge of the battery. Some models include an audible alarm or warning light to signal when the battery voltage becomes low. Lightning surge protection must be provided for tropical areas.

Vaccine refrigerators are required to maintain vaccine between +0°C and +8°C at all times. In addition, there is normally a requirement for a separate freezer compartment to freeze ice packs used for transporting vaccines in cold boxes. The performance of a refrigerator or freezer is dependent on the ambient temperature; therefore, specifications are usually defined at 32°C and/or 43°C. The following criteria are used to assess performance:

a) Internal temperature distribution and variation within the permissible range of from +0°C +8°C;

b) The rate of ice pack freezing in kilograms per 24 hours;

c) Holdover time during loss of power - i.e., the length of time that the internal temperature of the refrigerator remains below 8°C when the power supply has been disconnected.

For system sizing, the energy consumption of a photovoltaic refrigerator in kilowatt hours over a 24-hour period must be known. For a 100-litre refrigerator without an ice-pack freezing capacity and operating at an ambient temperature of +32°C, the energy consumption is typically 300-500Whr. At an ambient temperature of +43°C, with a freezing capacity of 2kg of ice packs per 24 hours, the energy consumption of the same refrigerator would rise to about 600-1,200 Whr over 24 hours. Overloading a solar refrigerator increases energy consumption considerably.

A good vaccine refrigerator should be able to maintain correct internal temperatures for at least 10 hours in the event of being disconnected from the battery and solar array. WHO publishes data on approved photovoltaic refrigerators.

6.2. Lighting

Photovoltaic systems for lighting should be considered wherever kerosene fuel supplies are erratic or expensive; good quality lighting is required (e.g.. in schools and home industries such as needlework); and solar irradiation levels are moderate to high (>3 kWh/m/^{2}/day). They are suitable for lighting domestic or community buildings (homes, schools, community centres, mosques, churches); streets, area or security lighting (car-parts, industrial areas, warehouses); portable light units; and specialized commercial lighting, such as terrain avoidance lighting for aircraft and other navigational aids.

Solar refrigerators are the preferred option as savings are made where vaccines are not spoiled owing to unreliable refrigeration conditions. Table 10 shows the relative costs of utilizing the two types of refrigerator in a health centre in Pakistan, serving a population of 12,000 with a crude birth rate of 4.5%. It can be seen that a photovoltaic refrigerator is more economic.

Table 10. Costs a/ of photovoltaic vs. kerosene refrigerators for vaccine storage in a Pakistani health centre b/

	Kerosene	Photovoltaic
Array (125 Wp - 15 yr. life)	-	13,047
Battery (2,400 Wh - 5 yr. life)	-	5,107
Refrigerator	10,400	22,490
Installation	2,880	7,219
Total, cost of installed refrigerator	13,280	47,864
Annual maintenance costs	1,400	479
Annual fuel costs (3.08 Rs/litre)	675	-
Annualized refrigerator life-cycle cost	5,579	8,894
Refrigerator reliability/availability	60%	97%
Doses of potent vaccine available	3,600	5,820
Programme cost per outlet	21,300	21,300
Annualized refrigerator life-cycle cost per dose of potent vaccine	1.55	1.53
Programme cost per dose of potent vaccine	5.92	3.66
Total cost per effective dose	7.47	5.19

a/ Measured in rupees.
b/ 6,000 doses/year required.

Photovoltaic refrigerators operate on the same principle as normal compression refrigerators, but the compressors and motors use low voltage (12 or 24) direct current rather than main voltage alternating current. A photovoltaic refrigerator will have higher levels of insulation around the storage compartments to maximize energy efficiency, a battery bank for electricity storage, a battery charge controller and a compressor, which converts the power from the battery to a form required by the compressor motor. Most refrigerators include a freezer compartment for ice pack freezing.

Where main electricity does not exist or is impractical, lighting is provided by kerosene lamps; kerosene hurricane lamps; diesel generators that power electric lamps, or automotive batteries that power electric lamps (periodically taken to towns for recharging). The relative merits of providing electric light by diesel generators, batteries and photovoltaics are given in Table 11.

Kerosene lamps and candles have the obvious drawback of producing only a low light output and being a fire hazard. Although they have the lowest purchase price, they are expensive to run and inefficient. Even though individual photovoltaic lamps, compared to kerosene lamps, may be more expensive to buy initially, in general they are cost-effective on a life-cycle cost basis and provide light of better quality. The relative economics of photovoltaic versus kerosene lighting are shown in Table 12.

The major difference between photovoltaic and other electric lighting systems is that direct current is produced; thus, the use of direct current lights is preferred. It is possible to use light with alternating current, however, by incorporating an inverter into the system, but the procedure will result in significant electrical losses. Hence, a larger array will be needed.

Table 11. Comparison of Power Sources for Electric Lighting

System	Advantages	Disadvantages
Diesel generators	Operating and maintenance experience is widespread	Creates noise and air pollution. Requires a reliable fuel supply.
	Moderate capital cost Easy to install Can be a combined power supply for additonal uses	High runnig costs High maintenance costs Low operating efficiency
Automotive battery recharging	Low capital cost Easy to install Batteries locally available	Relies on transportaion to charging stations High charging fees Short battery lifetimes
Photovoltaics	High reliability Low maintenance requirements Low running costs Suited to most locations Long life-expectancey for main components	Involves the introduction of a new and often poorly understood technology High capital costs Not physically robust; vulnerable to damage Specialized batteries not widely available.

Table 12. Life-cycle cost comparison: Kerosene and Photovoltaic Lighting Systems

Kerosene		Photovoltaic	
Weekly fuel requirement		Weekly energy requirement	
Kerosene pressure lamp	2.8 litres	Fluorescent lamps 2x8W	64 Wh
Hurricane lamp	1.2 litres	Battery charging efficiency is only 80 per cent; hence, requirement	80 Wh
Weekly energy costs			
Kerosene at $0.3/litre	$ 1.20	Average daily insolation	5 kWh/m^2
Annual total	$ 62.40	Required array size	18 Wh
Capital costs		Capital costs	
Pressure lamp	$ 20.00	PV array	$150.00
Hurricane lamp	$ 55.00	Battery (100Ahx12v)	$140.00
		Fluorescent lights (2)	$ 34.00
		Voltage regulator	$ 50.00
Total	$ 75.00	Total	$374.00
Recurrent costs		Recurrent costs	
Present worth of fuel		Battery b/	$141.00
discounted at		Tubes c/	$ 28.00
10 per cent over 15 yrs -		Voltage regulator d/	$ 24.00
$62.40 x 7.61	$475.00		
		Total	$193.00
Present worth of replacements a/	$ 95.00		
Total life-cycle costs (15 yrs)- $25 + $475 + $95	$595.00	Total life-cycle costs (15 yrs) - $374 + $193	$567.00
Annualized cost	$ 78.00	Annualized cost	$ 74.00

a/ Lamps are replaced every two years.
b/ Replace every five years.
c/ Replace every two years.
d/ Replace every eight years.

In terms of the number of installations, lighting makes the greatest use of photovoltaics, with tens of thousands of units installed world-wide. User experiences have been excellent, with increasing demand for more systems in localities where a photovoltaic light has been installed. Specific examples of lighting experience include:

a) Dominican Republic. Approximately 70% of the rural population have no access to the utility grid. In 1984 a photovoltaic rural electrification project was set up, using seed money from the United States Agency for International Development to install lighting systems. The fees charged for the systems have financed the purchase of further equipment, so that the project is now self-financing, with more than 50 systems installed.

b) Thailand. In many villages, lighting is obtained by charging automotive batteries in towns and then using them to run 12-volt lamps. With Japanese seed-funding, the Ministry of Rural Electrification has installed 500Wp photovoltaic battery-charging stations. Due to savings on replacement batteries and transportation cost, a photovoltaic system will pay for itself in three years or less.

Many direct-current lights are now commercially produced, but the most efficient in terms of light output (lumens) per watt of power consumed are low-voltage fluorescent tubes. If they are not available, conversion of alternating-current tubes is possible by changing the alternating current starter and ballast components to produce a direct current version.

6.3. Grid-Connected Systems

There has been much discussion of the possibility that photovoltaics will eventually become cheap enough to be economical for grid-connected applications. At present, with oil and coal prices low, that prospect seems remote, but in the long term it could change, particularly for countries rich in solar energy but low in conventional fuels and unwilling (or unable) to introduce nuclear technology. Many countries have made a strong political commitment to the use of renewable energy resources, and some have gone further by deciding not to build any new nuclear power plants.

Grid-connected systems are simpler and less expensive than stand-alone systems, since they require little or no battery storage. The grid itself can serve as "storage", with the photovoltaic plant supplying power to or drawing power from the grid, depending on the load and solar irradiance. there are a number of grid-connected photovoltaic systems in the United States, and the generation of economical solar electricity for grid distribution remains the goal of the United States Department of Energy. It could be of great importance in the future.

7. CONCLUSIONS

Except for photovoltaic cell costs, which continue to fall steadily, there are few remaining technical obstacles to the eventual widespread utilization of the direct conversion of solar energy into electricity.

There are many applications (section 2) in which photovoltaic power is an economically competitive choice (Fig. 8). Even though photovoltaic power has advantages over other technologies and is economically viable, major efforts are still required before it will be accepted and make an impact on the market.

A strategic approach to development should be adopted to use the limited resources of finance and technical skills to achieve a significant use of photovoltaics in developing countries. The ultimate objective would be to introduce suitable systems into the community on a commercial basis, with or without governmental subsidies.

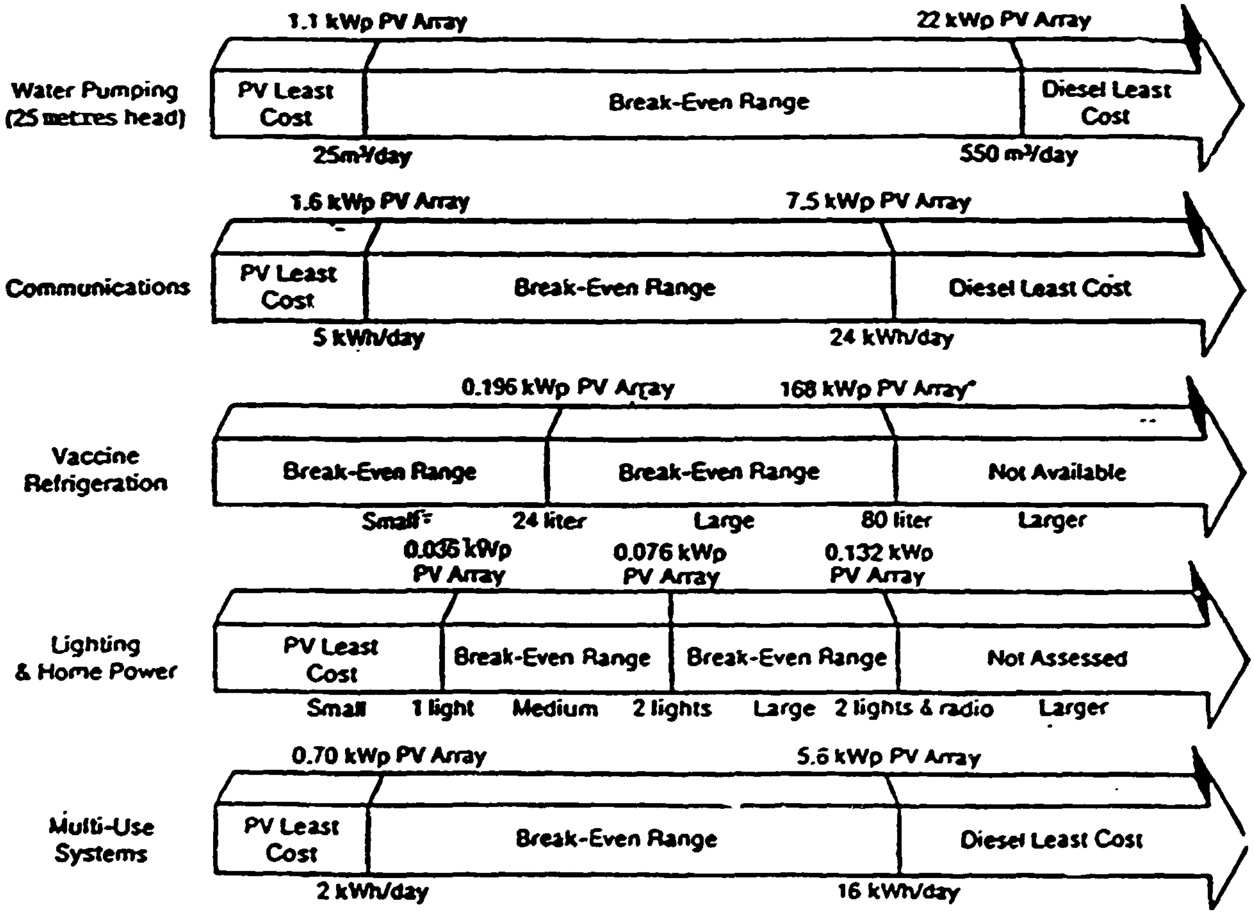


Fig. 8. Economic Ranges for Photovoltaic Systems

The full process would involve:

a) Research to identify the basic physical principles, materials and designs;

b) Laboratory-based development work to adapt system designs to suit local materials and needs, to characterize performance under local conditions and to identify how performance can be improved;

c) Field work on pilot plants to demonstrate and test representative systems under realistic field conditions, preferably when used by local people such as villagers or farmers;

d) Full-scale demonstration plants, with prototype commercial units installed at a number of representative sites throughout the country, with the full involvement of the industrial interests and continued technical support from the research institution responsible for the original development;

e) Commercialization, with local manufacture/assembly of systems and associated marketing and follow-up activities.

Photovoltaic projects must be considered along with other development projects and ranked in order of the net benefits likely to accrue to the country as a whole, taking into account both economic and social benefits. The effects a project would have on matters such as employment, food production, balance of payments and possibilities for local manufacture and assembly of as much of the photovoltaic system as practicable need to be considered.

These matters are not easy and straightforward to evaluate. It is, nevertheless, important to appreciate that the viability of photovoltaic projects should not be assessed simply in terms of economics or major energy substitution. For example, the energy requirements for telecommunications are relatively small, but the benefits that can result from installing reliable photovoltaic generators can be of very great significance.

Each developing country needs to assess its own needs and institute a staged development for each photovoltaic application of interest, taking into account the status of development reached in similar situations elsewhere. An essential requirement is to build up the necessary institutional support with the skills and finance needed to implement the programme.

The market for photovoltaic systems is still very small compared to its potential. The most pressing need is market-building. In order for the industry to survive, grow and thrive, real commercial markets should be opened and developed.

Self-sustaining commercial markets for renewable energy systems can be developed by identifying and quantifying the principal barriers that must be overcome. Manufacturers, development assistance agencies and Governments must invest in market development activities if real markets are to emerge. The highest priority should be to educate critical institutional decision-makers in market countries, particularly in development financial institutions, electric utilities and rural electrification programmes, and in ministries that make procurement decisions about photovoltaic-powered systems such as water pumps and health systems.

The United Nations Development Programme (UNDP), in an effort to meet the challenge, held three workshops in 1985. Since then, although photovoltaic technology has continued to mature, the developing country markets have not. Currently there are several international agencies supporting and funding photovoltaic projects of various types. Very little attention has been paid to market-building.

UNDP action has been welcome but is insufficiently funded. The United Nations International Trade Centre has launched a programme to help photovoltaic manufacturers (initially in Brazil and India) increase their exports. This important development also suffers from limited funding.

8. LEADING PV RESEARCH CENTRES AND COMPANIES

1. Lewis Research Centre (NASA), solar cell branch, Ohio 4135, USA. Prof. Henry Brandhorst.
2. Lawrence Livermore Laboratory, CA. Dr. W. Seikhauz (rostered in UNIDO).
3. Krzhishanovsky Institute of Power Engineering, Moscow, USSR. Prof. M. Koltun (rostered in UNIDO).
4. Fraunhofer Institute for solar energy systems, Oldmamrstrasse 22, D-7800 Freiburg, Germany.
5. Paul Sherrer Institute Zurich (Switzerland).

<u>Companies</u>

1. Siemens AG, Germany.
2. OKA, Austria.
3. Helios, Italy.
4. Solarex, Newton PA 18940, USA.
5. ARCO SOLAR licenses, Chatsworth, CA 91313, USA.

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PROJECT CONCEPT* PREPARATORY ASSISTANCE

PHOTOVOLTAICS: DIRECT SOLAR-TO-ELECTRICAL ENERGY CONVERSION

I. Background and Justification

In the near future there will be a tremendous rise in the development and application of solar energy. It is an almost unique non-polluting source of energy. Effective utilization of solar energy requires highly productive convertors such as photovoltaic (PV) cells, flat plate collectors for solar radiation conversion utilized in water and space heating. Solar energy can be widely used in countries where sunlight radiation is high (many Asian, Latin American and African countries). To develop solar devices of high efficiency it is necessary to first develop and implement advanced semicounductor materials technology. In recent years research on such materials has been considerably intensified (USA, USSR, Japan, Germany, Spain, Sweden and Austria). There have been also major achievements in the production of these materials and in fabrication of solar energy converters based on them. The transfer of this technology to the developing countries is possible if the relevant level of industrial infrastructure, scientific support and qualified manpower could be ensured. The local markets have to be investigated, potential application options selected and production programmes defined. Also potential licensors have to be identified and their intentions to co-operate with developing country industrialists clarified. At this first stage of identification UNIDO can play an instrumental role in selecting the experts and ensuring the possibility of the contacts with producers and licensors.

II. Development Objective

To increase solar energy consumption in developing countries through the application and development of the production of PV cells as well as the solar energy convertors.

III. Immediate Objective

To identify markets and technological options of production of the PV materials and solar energy convertors.

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* Until approval has been obtained this document should not be considered as a formal submission of a full project proposal.

IV. Outputs

1. Report on the potential applications of the solar convertors and availability of the raw materials and industrial infrasturcture to start the production of PV materials and solar energy convertors.

2. Report on the preliminary assessment of the investment project structure and its cost.

3. Report from the study tour identifying potential licensors and their co-operation intentions.

V. Inputs

a) Government inputs

National counterpart staff
Information on the PV industry status in the country
Offices and secretarial support
Local transportation means

b) UNIDO inputs

International experts (2) 3 m/m
Technologist in PV materials and solar energy convertors
Economist to assess costs/prices

Study tour for 4 people 3 m/m
to visit institutes and firms in

USSR	-	Institute of Power Engineering by Krzhizhanovsky, Moscow.
	-	Solar Power Stations (Crimea, Caucacis).
Austria	-	Verbundgesellschaft (Wien). Oberosterrische Kraftwerke AG, Upper Alps. Vienna Technical University.
Spain	-	Madrid Politechnical University.
Germany	-	Siemens AG, Munchen.

Skeleton Budget

International consultants	3 m/m	US$30,000
UNIDO staff travel		US$10,000
Study tour	3 m/m	US$20,000
Miscellaneous		US$ 5,000
	Total:	**US$65,000**

LIST OF CURRENT SOLAR ENERGY TERMINOLOGIES

Photovoltaics (PV)	The science and technology based on the utilization of the photovoltaic effect.
Photovoltaic cell	Photovoltaic cells convert light energy directly into electrical energy. A photovoltaic cell consists of a thin film of a semi-conductor in contact with another appropriate material, usually a metal.
Solar cell	The basic photovoltaic device which generates electricity when exposed to sunlight. (JRC specif. 101)
Module	The smallest complete environmentally protected assembly of inter-connected solar cells.
(Solar cell) panel	A group of modules fastened together, pre-assembled and inter-connected, designed to serve as an installable unit in an array.
(Photovoltaic) array: Solar (cell) array: Photovoltaic generator	A mechanically integrated assembly of modules or panels together with support structure but exclusive of foundation, tracking, thermal control and other components, as required, to form a dc power producing unit.
(Cell) conversion efficiency photovoltaic efficiency( )	The ratio of the maximum power to the product of area and irradiance, expressed as a percentage: $N = \frac{\text{Maximum Power}}{\text{Area x Irradiance}} \text{ x } 100\%$
Fill factor (FF)	The ratio of maximum power to the product of open-circuit voltage and short-circuit current: $FF = \frac{\text{Maximum Power}}{\text{V x I}}$
Current voltage characteristic	The output current of a photovoltaic generator at a particular temperature and irradiance, plotted as a function of output voltage.

Maximum power point	(The power at) the point on the current-voltage characteristic where the product of current and voltage is a maximum (W).
Short circuit (photo) current I_{sc}	The output current of a photovoltaic generator in the short-circuit condition at a particular temperature and irradiance. (JRC, Specification No. 101)
Energy band diagramme	Diagramme in which electron energies are plotted vertically as functions of the distance through a crystal shown horizontally; useful where electron-energy changes occur only in one direction through the crystal.
Energy state density	Number of energy states per unit energy range per unit volume of material (i.e. per electron volt per cubic metre, eV^{-1} m^{-3}). Symbol N (E).
Spectral response	The short-circuit current density generated by unit irradiance at a particular wavelength (AW^{-1}), plotted as a function of wavelength.
Global insolation.	The total solar radiant energy incident upon unit area of a horizontal surface during a specified time period (units as for direct insolation.). Global insolation = Direct insolation (horizontal) + Diffuse insolation (horizontal) for the same time period.
Direct irradiance	The radiant power from the sun (and a small area of sky surrounding it, defined by the acceptance angle of the pyrheliometer) incident upon unit surface area. ($W\ m^{-2}$).
Band gap	Range of unallowed electron energies between two adjacent energy bands; energy gap between Valence and conduction bands in a semiconductor. Unit: electron volt (eV)

Boundary layer	Space charge layer acting as a potential barrier. The double electrical layer which is formed at the surfaces of contact between two substances, which have two different values of the work function, by the diffusion of electrons from the substance having the lower work function towards the other. The loss of the electrons causes equivalent positive charges to appear in the former substance.
Polycrystalline silicon	A polycrystalline material is a semiconductor material, deposited by vacuum evaporation or another suitable method, consisting of a multitude of tiny crystals with random orientation, used as the active region of thin-film transistors.
Wafer	Piece of semiconductor separated from a large crystal by a slicing operation, such as cutting with high speed abrasive wheels; polished and prepared, it serves as the unit for solid-state diffusion processes (many hundreds of devices being fabricated in its surface region at one time).
Cascade arrangement	An array of solar cells employed to utilize a larger part of the solar spectrum than a single cell is able to do.