OCCASION

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

DISCLAIMER

This document has been produced without formal United Nations editing. The designations employed and the presentation of the material in this document do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations Industrial Development Organization (UNIDO) concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries, or its economic system or degree of development. Designations such as "developed", "industrialized" and "developing" are intended for statistical convenience and do not necessarily express a judgment about the stage reached by a particular country or area in the development process. Mention of firm names or commercial products does not constitute an endorsement by UNIDO.

FAIR USE POLICY

Any part of this publication may be quoted and referenced for educational and research purposes without additional permission from UNIDO. However, those who make use of quoting and referencing this publication are requested to follow the Fair Use Policy of giving due credit to UNIDO.

CONTACT

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

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

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

16366

Distr.
LIMITED

IPCT.38
15 July 1987

ENGLISH

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

TECHNOLOGY TRENDS SERIES: No. 5

Technological and Commercial Trends in Photovoltaics*

Prepared by

Calestous Juma **
UNIDO Consultant

728

* The views expressed in this document are those of the author and do not necessarily reflect the views of the secretariat of UNIDO. This document has been reproduced without formal editing.

** Science Policy Research Unit, University of Sussex, Brighton, United Kingdom. This study was prepared under the guidance of Dr. Kurt Hoffman, University of Sussex.

V.87-87705 0214D

Summary

The world photovoltaic industry has recently undergone major structural changes associated with technical innovations. Trends in photovoltaic technology have gone through three stages associated with single-crystal, polycrystalline and amorphous conversion materials. These material-based shifts have been largely supported by the public sector. The patterns of public sector support, have, however, been slightly different in Japan, the USA and Europe. These differences are related to variations in the industrial policies of these countries. The rapid changes occuring in the technology and demand for major public sector support makes it difficult for most developing countries to enter the photovoltaic market as producers. However, a few countries may in the short term acquire technological capabilities related to peripheral (balance of system) parts of the photovoltaic systems. The state-of-the-art cell technology will for a long time to come be inaccessible to most developing countries.

Contents

INTRODUCTION

The world photovoltaic industry emerged in the post-1973 era with much enthusiasm for the prospects of a rapid and widespread market penetration. Since then, the industry has been undergoing major structural changes. This paper reviews the developments which have shaped the industry in the last decade and shows that the role of technical change has been a major factor in industrial re-organization while underscoring the role of the public sector as an institutional maker of these changes. The main theme of this paper is that trends in photovoltaic technology have evolved through three stages associated with single-crystal, polycrystalline and amorphous conversion materials. The material-based shifts have been largely supported by the public sector. The patterns of public sector support have, however, been slightly different in Japan, the USA and Europe.

The paper is divided into five chapters. The first reviews the latest developments in photovoltaics. It highlights the main changes in innovation and their implications for industrial competitivenes. The second examines the institutional arrangements which have helped promote the industry. Comparisons and contrasts are drawn from the recent experiences of the USA, Japan and Europe with emphasis on the links between industry, government agencies, public sector institutions and universities. The third deals with recent patterns of photovoltaic commercialization. This chapter reviews commercial trends in the USA, Japan, Europe and the rest of the world and identifies the leading suppliers of photovoltaic systems as well as their corporate strategies. The fourth chapter deals with the international flow of photovoltaic technology and assesses the factors which influence the current state of technology transfer. The final chapter outlines policy implications of these changes for developing countries and identifies possible areas of commercial involvement.

I. TECHNICAL CHANGE IN PHOTOVOLTAICS

Rapid technical changes are taking place in photovoltaic products and processes. Efforts are directed at improving existing technologies, investigating new materials and designing new industrial processes. These activities are aimed at reducing production costs, improving product quality and finally producing technologies that can compete with, and eventually displace, some conventional sources of electricity. Photovoltaic systems have been reliably used to power satellites since the 1960s. Since then costs have fallen from US$ 1,000 per peak watt (pW) to less than US$ 10 per pW in the 1980s. The reductions in cost have been a result of innovation. The high production costs of photovoltaics result largely from expensive materials, energy-intensive processes, high labour costs (including hand assembly of cells) and support equipment such as the array structure, electric wiring, battery storage, meters, power conditioning devices and voltage regulation equipment. The production costs of photovoltaics can be subsumed into the broad categories of capital and labour. Much of the innovation, especially in the USA, has been directed at rationalizing these factors of production with the help of the Solar Array Manufacturing Industry Costing Standards (SAMICS) computer programme developed by the Jet Propulsion Laboratories (JPL) at Pasadena, California. The programme has been operative since 1977 and firms simply sell on the telephone with preliminary cost estimates and obtain a comprehensive analysis of the price of the finished array. SAMICS has also been used to model factories. Photovoltaic systems consitute two main parts: the conversion material and the rest of the photovoltaic system.

A major R&D effort over the last decade has been to raise conversion efficiency. This process has had several techno-economic advantages. Firstly, it has led to a reduction in the cell material used for a unit of power output and secondly, it has helped save space in both production and use. It has also contributed to reducing production costs. Silicon cells, which are widely used in photovoltaic systems, have a theoretical efficiency of 25 per cent, although laboratory cells have recorded 19 per cent efficiency and current operating systems yield only 10-13 per cent. Raising the efficiency has therefore significant cost-reducing effects. However, the high costs of producing silicon cells and the limits to raising their efficiency has led to the search for alternative conversion materials. Some of the candidate materials are given below with their theoretical maximum conversion efficiencies.

Table 1. Candidate conversion materials

Material	Efficiency (%)
Germanium	13
Cadimium sulphide	18
Cadimium telluride	25
Indium phosphide	26
Gallium arsenide	27
Aluminum-antimonide	27

Source: Maycock et al. (1981).

Of these materials, cadmium sulphide and gallium arsenide are the most prospective. The latter converts a wide section of the solar spectrum and is therefore inherently more efficient than other materials. Moreover, this material does not lose efficiency when exposed to heat as much as other materials, a property that makes it an ideal option for use in concentrators. The turn to concentrators is partly due to the techno-economic imbalances between the high cost of conversion material and the imperative to reduce unit electricity costs. In concentrators, plastic, glass and metal replace conversion materials. For example, a concentration of 50 suns would require only 2 per cent of the material that would otherwise be needed.

Table 2. Highest proven cell efficiency (cm2)

Type	Efficiency	Structure	Area (cm^2)	Developer
Crystalline silicon	19.10	Single-crystal float zone	4.00	University of New South Wales
Crystalline silicon	18.00	Single-crystal	4.00	Spire Corporation
Polycrystalline	11.00	$(CdZn)s/CuInSe_2$	1.00	Boeing Aerospace
Polycrystalline	10.90	CdS/CdTe	1.00	Eastman Kodak
Amorphous silicon	10.10	Glass/TCO/p-i-n	1.09	RCA Corporation
Amorphous silicon	08.50	Glass/TCO/p-i-n	1.00	Fuji Electric
Gallium arsenide	20.34	CVD heteroface	1.00	Spire Corporation
Gallium arsenide	19.00	CVD heteroface	4.00	Hughes Research Laboratories

Source: Fischetti (1984).

Other novel methods of increasing conversion efficiency include tandem cells under which different materials are used together to capture the different sections of the solar spectrum, however these approaches involve the re-arrangement of the various materials. Alternative techniques are being applied which involve the re-arrangement of the solar spectrum itself. An example is the luminescent solar collector (LSC) which comprises a flat box with a reflective mirror base and a top cover doped with luminescent dyes. The dyes absorb light and re-radiate it at wavelengths that can be converted by a specific material at one of the inner edges of the collector. The system has a maximum theoretical efficiency of 70 per cent. Many of the technologies are still in the early stages of development and are still far from market entry. However, the dominance of single-crystal cells is being challenged by polycrystalline and amorphous cells.

Single-crystal silicon is still the main source of photovoltaic electricity. These cells are produced from sawing round silicon ingots grown by the Czochralski process, originally developed for the semiconductor industry. This process however is slow, expensive and results in material loss during sawing. It is costly and has a purity of 99.999999 per cent, two orders of magnitude higher than the 99.9999 per cent required for photovoltaics. Moreover, industrial projections show that single-crystal wafers may not achieve the less than US$ 1-per-peak-watt needed to make photovoltaics competitive with other sources of electricity. An alternative technique being developed is to produce ribbons from molten silicon. A typical ingot-wafer throughput is about 0.15 square metres (m^2) per hour while that of a ribbon machine is 0.5 m^2 per hour. Mobil Solar (USA) has made ribbons with 12-14 per cent efficiency and Westinghouse Electric (USA) has produced ribbons with 16 per cent efficiency. The firms, as well as Energy Materials (USA) have pilot plants for ribbon production.

Single-crystal cell production requires a high degree of process control and firms such as Solarex Corporation (USA) and AEG-Telefunken (FRG) have turned to polycrystalline cells instead. Polycrystalline cells are made from silicon, but alternative materials with higher efficiency are now being developed. These include cadmium tellaride (CdTe) and Indium dise. nide ($CuInSe_2$). A pilot plant has been built by Sovoloco Company, a joint venture of Boeing Aerospace and Reading & Bates to develop indium diselenide polycrystalline cells. Boeing has demonstrated a $CuInSe_2$ with more than 11 per cent efficiency. The cells are produced through the thin film technique, using the industrial methods of high-speed coating perfected by the paper industry (Fischetti, 1984).

While polycrystalline cells are trying to compete with single-crystal cells, there is a rising generation of amorphous conversion material that has become the main focus of global photovoltaic R&D. Amorphous cells were first manufactured in 1974. The cells recorded low efficiencies of about 1 per cent and have since been considerably improved. By 1982, RCA Corporation produced a cell with 10.01 per cent efficiency. This process was subsequently acquired by Solarex for attempted mass production. By 1983 amorphous cells accounted for 25 per cent of world photovoltaic electricity. These cells are easy to manufacture and handle. Japanese firms have been dominant in this field, largely because producing such cells lend themselves more easily to automated mass production. Most of the world's US$ 150 million devoted to photovoltaics R&D is now directed towards amorphous cells.

Efforts to reduce the cost of conversion cells have tended to shift the share of total unit energy cost to the non-cell parts of the photovoltaic system, collectively known as the balance-of-system (BOS). This accounts for about 50 per cent of the total system costs. About 33 per cent of BOS costs are directed towards electrical components (wiring, interconnects, control circuits, load management and voltage regulating devices), about 20 per cent to power storage, about 20 per cent to installation and checkout and the rest to array, structure and site preparation. Unlike the cell, BOS components are usually made of stable technologies which are not likely to undergo any radical changes. As a result, the effects of BOS innovation on total costs has tended to be slower than those accruing from conversion material improvement. BOS cost reductions can also be effected through innovation at the cell level. For example, the use of larger cells reduces the need for interconnections and therefore cuts down on BOS costs. However, BOS-psecific innovations are required to reduce overall system costs. Apart from reducing BOS costs, there is pressure to match the reliability of the components with that of the cells. Some of these problems cannot be solved until the system is in operation and the feedback incorporated into subsequent R&D. This is largely why the initial stages of photovoltaic penetration were devoted to testing.

Table 3. Advanced battery development

Type	Major Developer	Efficiency (dc-to-dc)	Volumetric Energy Density (Wh/l)
Zinc-chlorine	Energy Development Associates (US); Furakawa Electric (Japan)	70	70
Zinc-bromine	Exxon Research and Engineering; Energy Research Corp. (USA); GEL Inc. (USA); Meidensha Electric Manufacturing (Japan); Studiengesellschaft für Energiespeicher und Antriebssysteme (Austria)	70	75
Sodium-sulphur	Ford Aerospace (USA); Dow Chemical (USA); Chloride Silent Power (UK); Compagnie Générale d'Eléctricité (France); Brown Boveri & Cie (FRG); Yuasa Battery (Japan); Hitachi; Shanghai Insitute of Ceramics (China)	80	250 (Based on cell performance)
Iron-chromium redox	Sohio (USA); Mitsui Engineering and Shipbuilding (Japan)	70	10

Source: Zorpette (1984).

One of the most significant BOS components is power storage. The conventional lead-acid and nickel cadmium batteries are expensive, inefficient, prone to rapid discharges, relatively short-lived and require substantial maintenance. Alternative advanced batteries being developed are more powerful, long-lasting, reliable and easier to handle. The options being developed include zinc-chlorine, zinc-bromine, sodium-sulphur, hydrogen-halogen and iron-chromium redox batteries. Unlike the conventional batch batteries, the advanced alternatives operate on continuous flows; the reactants and products flow through the battery in a continuous process.[1/] All solid-state storage systems such as the flywheel are being developed as an alternative. The flywheel being developed at the Massachusetts Institute of Technology's Lincoln Laboratory is expected to spin in a vacuum at a high speed (7,500-15,000 revolutions per minute) during the day and release enough energy for household use during deceleration at night.

So far there are three generations of technologies competing for market penetration: single-crystal, polycrystalline and amorphous cells. It appears that single-crystal cells are reaching their conversion limits. The avenues

1/ Jorné, 1983.

for raising conversion efficiency while at the same time reducing unit energy costs lead necessarily to amorphous materials. This shows that the technology will still remain in radical flux until a dominant material emerges. Much of the R&D in new photovoltaic systems has hitherto been devoted to product innovation while process technologies are still at pilot stages. This situation is likely to continue until systems that favourably compete with conventional sources of energy enter the market and command partial market stability. This entry is largely a function of technical change and institutional support for the emerging technological systems.

II. INSTITUTIONAL LINKAGES

The development of photovoltaic technology in the major producing countries has relied heavily on public sector support at three main levels: support for R&D, provision of markets and raising public awareness to the technology. It was largely through the support of the public sector that photovoltaic technology was developed to become potentially viable for terrestrial applications. The support for R&D has been conducted as national programmes, the expansion of the market has involved international agencies and led to application of photovoltaic technology in the developing countries. While the R&D programmes set price goals and levels of efficiency to be achieved over specific time scales, the expanding markets provided financial and operating experiences that were subsequently used in R&D. Most of the R&D in the USA, western Europe and Japan has been carried out through complex government-industry, industry-university and government-university linkages which are important in the early development of science-based innovations such as photovoltaics.

The USA had a major photovoltaic programme, the Federal Photovoltaics Utilization Programme (FPUP) under which the government authorized some US$ 98 million for the 1979-1982 period. The funds were spent on encouraging government agencies to incorporate photovoltaic systems into their activities and providing market support for the sale of modules. This was largely a procurement programme aimed at setting up small remote-type systems. This programme guaranteed a market for those technologies that were then ready for application and could not compete favourably with the conventional sources of electricity. Moreover, such a programme ensured that the state would meet the installation and monitoring costs.

Table 4. Intermediate-size USA Government programmes

Application	Location	Size (kWp)	Completed
Agriculture	Mead, NE	25	July 1977
Radar Tracking Station	Mt. Laguna, CA	60	Aug. 1979
AM Radio Station	Byan, OH	15	Aug. 1979
Housing/Visitor Centre National Park	Natural Bridges Nat'l Monument, UT	100	Jun. 1980
UPS for Newman Substation (Utility)	El Paso, TX	20	Dec. 1980
High School	Beverly, MA	100	Feb. 1981
Shopping Centre	Lovington, MN	100	Mar. 1981
Community College	Blythevill, AR	240	May 1981
Light Mfg. Facility	San Bernadino, CA	35	Sept. 1981
Hospital	Kauai, HA	35	Sept. 1981
Public Science and Arts Building	Oklahoma City, OK	135	Feb. 1982
Sky Habour Airport	Phoenix, AZ	225	Apr. 1982
Airport Utility Plant	Dallas-Ft. Worth, TX	27	Jun. 1982
Office Building	Albuquerque, NM	47	Jun. 1982
Junior College	Senatobia, MS	101	Stopped
Intercultural Activities Building, Georgetown Uni.	Washington, DC	300	1984
Central Utility	Sacramento Municipal Utility District, CA	1000	1984

Source: Macomber (1984).

The initial funding was focused towards R&D with supporting experiments and involved universities, research institutes and the private sector. However the government actively supported the design, construction and operation of intermediate-type photovoltaic power systems ranging from 15 kW to 1,000 kW. By 1985 some 17 systems had been completed and were operating as planned. Similar plants are now being installed by the private sector under a subsidy tax benefits scheme. In addition, federal laws require electric utilities to interconnect small (renewable energy) generators (less than 80 MW) to their systems and pay a fair price for any energy produced by the renewable energy system and fed into the grid. The incentives have led to increased private sector involvement in plant installation.

The photovoltaics programme suffered from budget cutbacks, but despite the reductions, photovoltaic R&D expenditure was only second to solar, thermal and much higher than any other renewable energy system. The reduction in the federal funding for photovoltaics has had three main effects. First, the Department of Energy (DoE) through the Solar Energy Research Institute (SERI) has had to concentrate on funding advanced R&D. Second, large corporations, especially oil firms have moved into R&D to fill the gap created by reductions in federal funding. Finally, private manufacturers have had to sell their current systems to immediate markets without having to wait for cost-reducing innovations. One of the effects of this latter development has been the construction of intermediate-sized photovoltaic systems, some of which feed into the national grid.

The DoE has continued to support more specialized photovoltaics R&D since federal funding was reduced. Moreover, SERI has set up strong industrial and university links to ensure that viable technologies are commercialized. SERI's target is to help in the production of modules that will produce electricity at US$ 0.20 per kWh by 1988. This is a short-term target that will eventually see costs reduced to US$ 0.15 per kWh, a figure that will have to be reached if photovoltaics is to favourably compete with electricity derived from oil. The DoE's strategy is to solve some of the key obstacles to the industrial production of the most advanced photovoltaic technologies. The tasks have been distributed to several leading federal agencies which maintain close collaboration with industry and universities.

Table 5. Privately-built photovoltaic systems

Builder/Supplier	Application	Location	Size (kWp)	Completed
Solarex Corporation	PV Factory	Frederick, MA	200	Oct. 1982
Copley Energy Inc./ Solarex	Central Utility Demonstration, Del Marva Power	Denton, MA	15.7	Dec. 1982
Exxon/Solar Power	Epcot Centre (Pavilion/utility)	Walt Disney World, Florida	70	1982
ARCO Solar/BDM	Central Utility, Southern California, Edison Co.	Hesperia, CA	1,000	Dec. 1982
ARCO Solar/Fluor	Central Utility, Pacific Gas & Electric	Carrisa Plain, CA	16,000	1984

Source: Macomber (1984).

SERI is charged with the responsibility of conducting research in photovoltaic (amorphous thin films, polycrystalline thin films, crystalline silicon, high-efficiency concepts and photo-electrochemical cells) materials while the Sandia National Laboratories deal with R&D in concentrators and power conditioning. The JPL focusses on single-crystal silicon cells and the processing of large-area amorphous silicon thin films. The work at the three centres is conducted in close collaboration with industry and university research institutes. SERI also manages subcontracted R&D, develops state-of-the-art measurement and device capabilities and transfer of technology to industry. During the 1984-85 fiscal year, SERI subcontracted cost-shared research on amorphous cells to Chronar, Solarex, 3M and Spire. SERI has also subcontracted Xerox to continue research on the light-induced degradation of amorphous cells and Chevron to continue work on materials purification.

Apart from R&D, SERI also conducts the innovative concepts programme and the university participation programme. The innovative concepts programme is aimed at identifying new materials and device configurations. Promising innovative concepts are carried through a stage of preliminary research before they are selected for further R&D. The university participation programme is aimed at establishing and maintaining the infrastructure needed for conducting photovoltaic-related research at universities. This programme ensures that university research is conducted in an atmosphere of academic freedom unhampered by restrictions, bureaucracy and excessive reporting. This programme enables SERI to maintain contacts with universities and link them with industry. New concepts from universities can therefore be transformed rapidly into R&D projects depending on their relevance to the overall goals of photovoltaic development.

SERI has its own internal research capability in every priority area. The internal research capability complements the subcontracted work and relies on methodologies and techniques developed by the institutes.[2/] SERI employs a large number of photovoltaic experts. Techniques that have potential market value are quickly subcontracted to commercial firms for further development and market introduction and SERI therefore plays a crucial role in the institutional links between the government, industry and universities.

SERI, in conjunction with other government agencies, has participated in aid programmes aimed at setting up photovoltaic plants in developing countries. This has been done in collaboration with the US Agency for International Development and the National Aeronautical and Space Administration (NASA). This public sector collaboration has led to the establishment of photovoltaic pilot projects in countries such as Bangladesh, Burkina Faso, Egypt, Guyana, Mali, Morocco, Nepal, Niger, Panama, Philippines, Rwanda, Saudi Arabia, Tanzania, Thailand and Tunisia. The participation of SERI in international programmes has also been extended to projects funded by the European Economic Community. For example, SERI is involved in two pilot projects set up by the Community in Greece and French Guyana and maintains links with other projects such as the activities of NASA and the US Centres for Disease Control (CDC) on testing photovoltaic refrigeration. This project was conducted in conjunction with the World Health Organization's Expanded Programme on Immunization (EPI). This programme offered ideal conditions for establishing the role of photovoltaics in refrigeration, especially for medical purposes. Areas that could not be hitherto supplied with vaccines and other drugs could now take advantage of photovoltaic cells as a source of coolant energy. Western Eueopean countries under the auspices of the European Economic Community (EEC) launched a major programme in the late 1970s

---

2/ SERI, 1984.

involving state agencies, universities, industry and public utilities. Photovoltaics R&D accounted for US$ 15.5 million over the 1975-79 period and was increased by some 190 per cent to reach US$ 59 million ofer the 1979-83 period. The programme has focussed on the construction of 15 pilot photovoltaic plants ranging from 30 kWh to 100 kWh. The construction of pilot plants was aimed at building operating experience.

Table 6. European photovoltaic pilot projects

Site	Output (kWp)	Application	Main Contractor	Co-sponsor
Aghia Roumeli Greece	50	Village grid	SERI-Renault	French Gov't; Greek Public Power Corp.
Chevetogne Belgium	63	Swimming pool; lighting	Association Momentanée IDE-ACEC	Belgian Gov't
Fota Island Ireland	50	Dairy farm	Cork Uni.; AEG-Telefunken	Irish and German Gov't; Irish Public Utility
Giglio Island Italy	45	Water disinfection; cold storage unit	PRAGMA	Italian Gov't; ENEA
Hoboken, Belgium	30	Electrolysis	ENI	Belgian Gov't
French Guyana	35	Village grid	SERI-Renault	French Gov't
Kythnos Island Greece	100	Island grid	Siemens	German Gov't; Greek Public Power Corp.
Marchwood, UK	30	Local power supply	BP-Solar	UK Government
Mont Bouquet France	50	Power for radio and TV emitters	PHOTOWATT	French Gov't; Télédiffusion de France
Nice, France	50	Nice Airport's electronic devices	PHOTOWATT	French Gov't; Nice Chamber of Commerce
Pellworm Island FRG	300	Recreation centre	AEG-Telefunken	FRG Gov't
Rondulinu, France	44	Village grid	Leroy-Somer	French Gov't; French Pub. Utility
Terschelling Is. Netherlands	50	Power to naval school	HOLEC	Dutch Gov't; FRG Gov't
Tremiti Is., Italy	65	Desalination unit	Italenergie	Italian Gov't
Vulcano Island, Italy	80	Island grid	ENEL	

Source: CEC (1985).

Like the USA, the EEC programme undertook R&D specifically to reduce cell costs by improved processing and alternative materials. The work was subcontracted to universities, research institutes and industry in the various European countries. For example, Leuven University (Belgium) has a subcontract to look into alternative techniques of cell fabrication while work on silicon thin film is underway at Democritus University at Thrace (Greece). Other work in cell processing has been subcontracted to Photowatt International (France). Much of the work on amorphous materials is conducted in universities. Research on morphous silicon is conducted at the Max-Planck Institute (FRG), the University of Dundee (UK), the University of Sheffield (UK), the University of Rome (Italy) and the Centre d'Etudes Nucléaires (France). Following the completion of the first set of pilot projects, the EEC decided to establish more photovoltaic plants but with smaller capacities on a more decentralized basis. This will provide more operating experience and promote public awareness of the technology.

European countries have not reached the level of US photovoltaic R&D but the considerable support being offered by their governments through the EEC would strengthen their position in both R&D and commercialization. It is notable that the EEC programme is supported by a project on radiation data collection for solar energy application. Radiation climatology data would enhance policy-making in the application of photovoltaics. Already, the programme has released volumes of the European Solar Radiation Atlas on both horizontal and inclined surfaces. The work on radiation climatology is also being extended to the use of satellite data for predicting surface solar radiation. Such information is not only useful in the design of photovoltaic modules, but it is also useful in their application. The various European countries also support photovoltaic R&D through national programmes. France, for example, has set aside US$ 154 million for photovoltaic development over the 1982-84 period, of which the government's contribution amounts to US$ 52 million. The FRG has spent over US$ 40 million on photovoltaics over the 1980-84 period. These countries are likely to increase their R&D spending as competition with the USA and Japan intensifies. New institutional links will have to be established to promote the transfer of technology from universities and research institutes to industry.

Another country that has relied on government support for photovoltaic development is Japan. Photovoltaic R&D in Japan is conducted under the "Sunshine Project" launched in 1974. The funding for photovoltaics has been increasing rapidly. For example, the funding was raised by over 140 per cent during the 1980-82 period alone, bringing the total allocation to US$ 30 million. By 1984, Japan was spending some US$ 60 million on photovoltaic R&D, equally shared by industry and the government. While the US concentrated its early photovoltaic R&D on crystalline material, Japan concentrated on amorphous cells. These materials were selected because they lend themselves more easily to mass production. Under the project, the government funds a dozen large companies and 10 research institutes. Unlike the USA, which has dedicated photovoltaics firms, the work in Japan is done by large electrical, electronics and materials companies. These include Toshiba, Hitachi, Mitsubishi, Sanyo, Fuji Electric, Sharp, Matsushita Electric, Osaka Titanium and others. Japan concentrates on bringing viable technologies to the market as soon as possible. Much of the marketing links are built in collaboration with the Ministry of International Trade and Industry (MITI).

MITI's involvement in photovoltaics was strengthened in 1983 with the formation of the New Energy Development Organization (NEDO). Among other tasks, NEDO aims at driving down the peak watt costs of electricity derived from amorphous cells to below US$ 2.24 and apply the technology to heavy electrical uses. The three-year project has a budget of US$ 13.45 million which is being spent on high-performance devices, large-area devices and high manufacturing efficiency. Moreover, the project also aims at reducing the performance degradation of modules to less than 15 per cent in a 10-year period. The work was distributed to three major Japanese firms. Sanyo is working on the development of high-speed manufacturing processes while Fuji is working on large-area cells measuring at least 120,000 square milimetres. Mitsubishi is developing a method to manufacture high-performance, tandem cells from amorphous material measuring 100 square milimetres and exhibiting at least 12 per cent efficiency. This shift to industrial application is another innovative approach since photovoltaic systems have hitherto been used in non-industrial applications.

NEDO is also involved in setting up long-term links with foreign countries. Market surveys have been conducted in the ASEAN countries and demonstration projects, especially solar villages, are part of NEDO's activities. Already NEDO is building a solar park at Malaysia's Kebangsaan University at a cost of US$ 2.1 million. The park will use solar battery equipment, photovoltaic arrays and solar drying systems. This project was set up in conjunction with the Japanese New Energy Fund, a body of private concerns and will be implemented over the 1986-87 period. This arrangement represents an example of the institutional links between the Japanese government, private industry and research institutes to establish overseas markets for photovoltaic products.

The participation of government agencies has not been limited to financial and institutional support alone. State intervention has also been directed at the structure of the photovoltaic industry itself, mainly to consolidate the existing financial and market resources and strengthen national competitiveness. In France, for example, the State was instrumental in the creation of Photowatt, which is the consolidation of a photovoltaic-related capability previously held by Elf Aquitaine, Compagnie Générale d'Electricité (CGE) and Radiotechnique Compelec. This merger was master-minded by the State solar energy agency, Commissariat de l'Energie Solaire (COMES). This merger was in response to the competitive threat posed by the USA, Japan and other European countries in photovoltaics.3/ The mergers however only promoted the efficient use of available photovoltaic-related resources and were therefore an ideal development. The real challenge was to support this development with major R&D programmes.

It is important to recognize the role of international agencies in the promotion of photovoltaic technology. The United Nations Development Programme (UNDP), for example, funded a World Bank-executed project on photovoltaics. This was mainly a testing project to establish the economic viability of photovoltaic systems, the findings of which have been used to influence the direction of R&D in photovoltaics, especially through requesting manufacturers to design components to meet particular performance criteria. The role of the World Bank was influenced largely by the need to ensure that photovoltaic systems compete fairly with conventional systems, especially in water pumping. The industrialized countries have also used arrangements such as the Lomé Convention to promote the export of photovoltaic modules.

3/ Hoffman, 1985.

Under the auspices of the EEC, Belgium has installed 750 photovoltaic systems in Zaïrean schools and hospitals for lighting, radio links and vaccine refrigeration. A teachers' college which uses photovoltaics has also been set up in Zaïre. Similar projects have been set up in various developing countries under multilaterial or bilateral agreements. The United Nations has also promoted photovoltaic application through various training and education schemes and the provision of infrastructure for photovoltaic-related research. Although some of these institutional activities do not have immediate effects on the market, they create an awareness which in the long-term may influence the penetration of photovoltaic systems in developing countries.

Another public sector application which has not received much attention in the literature is the military application of photovoltaics. Although this end-use is still low (estimated at 0.1 MW of the world module output in 1984), it is likely to expand. Troops usually rely on batteries for the supply of electricity to power communication systems and other equipment. Photovoltaic systems are well suited for small-scale mobile uses and the ultra-modern rechargeable batteries are going to be increasingly used in conjunction with photovoltaic systems.4/

III. WORLD PHOTOVOLTAIC MARKET TRENDS

The commercialization of photovoltaic modules has been largely influenced by the state of the technology and the level of public sector participation. This is closely associated with the fact that the technology is not competitive in large-scale uses and its penetration has been restricted to selected markets. A large number of modules has also been sold to the public sector for demonstration and testing purposes. The commercialization process has been dominated by firms now controlled by oil majors and the export of photovoltaic modules to the developing countries has been slower than predicted. However, current sales patterns are influenced by technical changes in photovoltaics and has also changed the market share of suppliers.

4/ Warwick, 1985.

Table 7. World photovoltaic module production

	1980	1981	1982	1983	1984
Shipments (MWpk)					
United States	--	--	5.7	13.1	11.7
Japan	--	--	1.8	5.0	8.0
Europe	--	--	1.6	3.3	3.6
Other	--	--	0.2	0.3	0.8
TOTAL	3.4	5.5	9.7	21.7	25.0
Module price (US$/Wpk)	15.0	11.0	10.0	8.0*	6.0*
Module sales (US$ million)	40.0	60.0	80.0	150.0*	160.0*
System sales (US$ million)	85.0	130.0	180.0	400.0*	600.0*

*Estimate
Source: Maycock (1985).

The USA is still the dominant supplier of photovoltaic modules although its share has been dropping. In 1982 the USA accounted for 61.2 per cent of world module shipment. This share dropped to 60.1 per cent in 1983 and 46.8 per cent in 1984. In the meantime, Japan's share has been rising steadily; it rose to 23.1 per cent in 1983 and 35.6 per cent in 1984. European shipments have dropped from 18.2 per cent in 1982 to 15.3 per cent in 1983 and 14.4 per cent in 1984. These changes are accounted for by the patterns of technical change and public sector participation. Japan has increased its share of the world market largely because of its use of amorphous cells in consumer electronic products such as calculators, watches and toys. This is a field where Japan has a dominant position.[5/] Sharp, for example, controls about 40 per cent of the world's calculator market. The high levels of shipment recorded by the European countries can be accounted for by the establishment of EEC-sponsored pilot projects as well as aid-linked exports to African countries.

5/ Juma, 1983.

Table 8. Photovoltaic application trends (kWp)

	1979	1980	1981	1982	1983
PUBLIC SECTOR					
Demonstration					
US	100	250	400	350	350
EEC	150	150	300	250	250
Other	15	50	50	100	1020
Real World Uses					
Communication	100	150	200	250	350
Navigation/signals	50	60	65	85	100
PRIVATE SECTOR					
Demonstration	15	25	75	1250	25
Commercial Uses					
Cathodic protection	10	25	50	55	55
Pumping	30	75	100	100	75
Remote housing	--	260	340	425	475
Other	15	25	30	35	40
CONSUMER PRODUCTS	15	30	150	400	600

Source: *World Solar Markets* (1983).

Early market studies assumed that photovoltaics would be applied to areas such as water pumping and rural electrification in the immediate term. This view led to the assumption that the developing countries would become a dominant market in photovoltaic applications. The situation has however proved different. These end-uses have seen much slower growth than consumer electronics, central generators and telecommunications. There are several reasons why this has happened. The entry of amorphous cells opened new markets in consumer electronics. The cells still have a high rate of degradation and are therefore more suitable for consumer goods. About 28 per cent of the world photovoltaic power output in 1984 was used in consumer electronics, which was largely amorphous silicon (some 7.0 MWp).

The reduction of federal support for photovoltaics forced producers to seek immediate markets and as a result, a large share of US module shipments is applied in central generators. About 24 per cent of the world photovoltaic application in 1984 was in central generators (about 6.3 MWp). This application is expected to expand in the USA. The other major use of photovoltaic cells has been telecommunications, which accounted for some 25 per cent (5.0 MWp) of the world module shipment. The use of photovoltaics in telecommunications has been expanding in the developing countries, largely because the smallest diesel generators used to power equipment usually produce 3 kW, which is too high for normal requirements. Photovoltaic modules can therefore be designed to match the power needs of telecommunication equipment. Other areas that have seen high photovoltaic penetration rates are cathodic protection and off-grip housing (mainly in the USA). By 1984, water pumps accounted for about 1.6 per cent of the world photovoltaic power output (about 0.4 MWp); the envisaged large market has yet to be tapped although recent estimates show that photovoltaics is becoming increasingly competitive with diesel engines in isolated areas.

These changes in consumption patterns also reflect corporate marketing as well as innovation strategies. ARCO Solar, a subsidiary of the oil major Atlantic Richfield (the largest US module producer) has embarked on central generator projects jointly with public utilities as a means of becoming firmly established in the local electricity sector. One of the recent additions to this output is the 16 MW plant at Carissa, California. The USA is concentrating on tapping local markets while at the same time expanding its exports through federal programmes. The total US module exports amounted to 2.0 MW in 1983 and rose to 2.9 MW in 1984. This is an increase of about 45 per cent but still represents only 24 per cent of the total output. The exports were dominated by Solarex and ARCO Solar.

Table 9. US Photovoltaic shipments

	1982	1983	1984
Arco Solar	2.40	6.00	5.50
United Energy	0.45	4.50	3.00
Solarex	1.30	1.30	2.10
Solar Power	0.40	0.40	--
Solec	0.20	0.30	0.40
Photowatt	0.21	0.30	—
Mobil Solar	0.04	0.07	0.08
Motorola	--	0.10	0.30
Others	0.61	0.10	0.30
TOTAL	5.61	13.07	11.68

Sources: *PV Investment Newsletter*, April 1984; Maycock (1985).

The Japanese have focussed their commercial targets on consumer goods and have been slow in terrestrial applications. This is reflected by the fact that despite their 80 per cent increase in module shipments (from 5.02 MW to 8.9 MW) over the 1983-84 period, terrestrial applications remained unchanged at 1.6 MW. The 300 kW that was added to the Japanese terrestrial applications was mainly part of government and industrial experiments, but as indicated elsewhere, the Japanese government has invested in R&D for large-scale photovoltaic systems for industrial use. In the meantime, over 100 million photovoltaic-powered calculators were produced by Japanese industry. Amorphous cells account for about 70 per cent of Japan's photovoltaic production, a factor which limits the range of terrestrial application, given their high degradability. It is expected that photovoltaics will be increasingly incorporated into consumer products and other devices, such as cash and vending machines. It is notable that the US firm, Energy Conversion Devices (ECD) which has been operating a joint venture in Japan with Sharp, is setting up plants jointly with Sohio (Standard Oil of Ohio) to produce amorphous modules in the USA. The ECD and Sohio venture is organized under Sovonics Solar Systems. Sohio spends some US$ 30 million on photovoltaic development annually.

The Sovonics venture represents a major shift in USA firms towards the commercialization of amorphous cells. The world share of amorphous modules was 14.3 per cent in 1983 and rose to 27.8 per cent in 1984. In the meantime, the share of single crystal modules dropped from 50.2 per cent to 43.2 per cent. The growth in polycrystalline modules was marginal, rising from 14.3 per cent in 1983 to 15.8 per cent in 1984. The possibilities for polycrystalline application are being pre-empted by amorphous cells. Nearly all the global photovoltaic R&D expenditure of US$ 150 million is directed towards amorphous cells. Some of the funding is being directed at alloy materials which have hiterto not been used in commercial applications. Corporations such as ARCO Solar which have been dominant suppliers of single crystal cells are now turning to the production of amorphous cells. Solarex, which was acquired in 1983 by Standard Oil (Indiana), started shipping amorphous-silicon modules in 1984 using technology licensed from RCA, which has ceased to participate in this field (Iversen, 1984). New production facilities are also being established to produce amorphous cells. For example, Chronar has finished a 1 MW amorphous module plant at Port Jervis, USA, and another in Wales, UK. It is expected that firms such as Chronar will seek to extend their markets in Europe.

Table 10. Japanese photovoltaic shipments

	1982	1983	1984
Sanyo	0.50	2.00	3.50
Sharp	0.60	0.80	0.50
Fuji	0.20	0.80	2.50
Kyocera	N/A	0.40	0.65
ECD/Sharp	N/A	0.30	0.40
Komatsu	N/A	0.20	0.10
Kaneka	—	—	0.30
Hoxan	N/A	0.10	0.30
Nippon Electric	N/A	0.15	0.20
Hitachi	N/A	0.07	0.15
Japan Solar Energy	N/A	0.05	N/A
Mitshubishi	—	—	0.10
Others	0.30	0.20	0.20
TOTAL	1.68	5.02	8.90

Sources: *PV Investment Newsletter*, April 1984; Maycock (1985).

The commercialization of photovoltaics in European countries has remained unstable and uncertain. The increases of the early 1980s were related to EEC pilot projects and aid-related exports. The completion of the EEC pilot projects has led to a reduction in the growth rate of photovoltaic shipments from Europe, leading to a further market squeeze by Japanese and European firms. This squeeze is likely to continue, especially when given the choice of material in European photovoltaic production. Nearly all the existing plants in the EEC countries are based on crystalline silicon. The only shift has been towards polycrystalline silicon among firms such as Pragma (Italy). Others such as Telefunken, Photowatt, France Photon and Energy Nouvelle have been dependent on polycrystalline silicon. This technology, as pointed out earlier, is being pre-empted by amorphous cells and it is not certain how soon European countries are likely to shift to amorphous production as a competitive strategy, but the transition period has started. Pragma, now controlled by Agip Oil, has invested US$ 30 million in developing amorphous cell capability. It also receives government and public sector support for its R&D. European firms are likely to be left behind in the race for alternative conversion materials as the USA embarks on even more advanced conversion R&D concepts.

With the relatively weak industry-university links in photovoltaics, it is not likely that the research now being subcontracted to universities by the EEC will be quickly transferred to the private sector for commercialization. The slow response to technological transition is reflected by the rate at which the European countries have been able to enter the amorphous silicon business. Moreover, the USA has quickly responded to the Japanese challenge and embarked on major amorphous silicon projects. Ironically, the Japanese entry into amorphous silicon technology was based on research that was initially done in the UK and the USA.

Table 11. European photovoltaic shipments

	1982	1983	1984
Telefunken (FRG)	0.60	0.95	0.75
France Photowatt	0.40	0.60	0.50
France Photon	0.25	0.40	0.30
Helios (Italy)	N/A	0.35	0.30
Pragma (Italy)	N/A	0.25	0.40
Ansaldo (Italy)	0.10	0.25	0.40
Zontec	—	—	0.25
Siemens	0.10	0.15	0.15
Isophoton (Spain)	N/A	0.10	0.15
BP Solar (UK)	N/A	0.10	0.20
IDE Belgosolar	0.05	0.05	0.05
Energy Nouvelle (Belg.)	N/A	0.05	0.05
Others	0.18	0.04	0.10
TOTAL	1.68	3.29	3.60

Sources: *PV Investment Newsletter*, April 1984; Maycock (1985).

The developing countries have not been significant in the commercialization of photovoltaic systems. So far, their output has only changed from a minuscule 0.28 MW in 1983 to 0.70 MW in 1984. The largest growth rate has been recorded in India which has expanded its output from 0.11 MW in 1983 to 0.30 MW in 1984. The rest of the shipment is accounted for by Brazil, and Singapore, which has an assembly facility. All the output from the developing countries is single-crystal. India is likely to increase its output and Saudi Arabia has set up a single-crystal module plant aimed at supplying local and regional markets. The world photovoltaic market has also seen the entry of the Australian Tideland Signal which shipped 0.05 MW in 1983 and 0.10 in 1984.

The developing countries have remained targets for photovoltaic commericalization despite the disappointing sales in the last five years. The EEC is a major supplier of modules to these countries as part of their aid programmes. Individual countries such as Italy and France ship over half their photovoltaic output to developing countries, mainly to Africa. One of the major emerging markets for photovoltaics is India, which has hitherto been partially protected against external competition. The government has liberalized the photovoltaic market and local Indian firms are seeking joint ventures with US, Japanese and European firms. The Indian firms insist on the state-of-the-art technology.

Table 12. Developing country shipments

	1982	1983	1984
Bharat HE (India)	N/A	0.01	0.10
Heliodynamica (Brazil)	N/A	0.07	0.20
CEL (India)	N/A	0.10	0.20
Solar Generator (Singa.)	N/A	0.08	0.08
Continental Dev. (India)	N/A	0.02	0.02
Others	0.20	N/A	N/A
TOTAL	0.20	0.26	0.70

Sources: *PV Investment Newsletter*, April 1984; Maycock (1985).

The commercialization of photovoltaics has been dominated by large oil, electronics and electrical companies which have long-standing experience in the management of new technologies. The shift towards amorphous cells permits these corporations to complete the vertical integration of their photovoltaic activities. With single-crystal technology, photovoltaic producers were dependent on the supply of ingots from three main sources in the world; Volker (FRG), SEMIX (USA) and Pragma (Italy). This control was broken with the shift to polycrystalline material which saw the entry of new material producers in the industry. This diversification now provides the firms with the opportunity to look into new materials and remain self-sufficient in their supply. The 1983-84 period saw the entry of at least seven firms into the amorphous silicon business. These were Solarex, ARCO Solar, Chronar, Kyocero, Taiyo Yuden, Sharp/ECD and Kaneka. Already the industry has experienced take-overs which were specificially aimed at acquiring capability in amorphous technology. So far it is still not certain whether the current amorphous materials will dominate the market in the medium term.

It is likely that other firms that have photovoltaic-related technology will enter the market. Firms such as Pilkington could take advantage of the amorphous technology to sell their glass as part of the encasement. Judging from SERI's research programme, it appears that the screening of new materials for photovoltaic properties will continue to be a significant R&D area and it is going to take considerable R&D before a dominant material emerges. The rise of amorphous cells, which had an efficiency rate of merely 1.0 per cent in 1974, indicates how dependent the photovoltaic market is to technical change. This adds to the uncertainties concerning the traditional sources of electricity that the systems seek to compete with.

IV. PHOTOVOLTAIC TECHNOLOGY FLOWS

The international flow of photovoltaic technology has been largely influenced by the dominant conversion technology and the expected market penetration. Photovoltaic technology has gone through three partially overlapping generations: single-crystal, poly-crystal and amorphous cells. These three generations have not only shaped the structure of the industry,but have also influenced the patterns of technology transfer. In the first place, the fact that the technology has been in a state of constant flux has reduced the widespread diffusion of process know-how. Secondly, the high process control that is associated with ingot growing made it difficult for new firms to enter the market or for the technology to be quickly diffused. Thirdly, the uncertainties surrounding the competitiveness of photovoltaics, coupled with the rapid rate of technical change, reduced its rate of diffusion and the flow of process technology.

As a result of these factors, the flow of photovoltaics technology has been largely between the USA, Europe and Japan. The transfer of photovoltaic technology to the developing countries has been restricted either to assembly facilities such as the Solarex plant in Singapore or to near-obsolete single-crystal cells such as the Spire 1 MW plant for Saudi Arabia. In nearly all the known cases of technology transfer, the flow has been mainly turn-key plants with very little transfer of know-how. This has resulted from the fact that the technology itself is in constant flux and much of the R&D is conducted at the point of origin or in university and government centres. The shipment of plants has therefore been largely to enter a specific market and reduce module assembly costs.

The case of Japan has been quite different. The ECD/Sharp joint venture has meant the transfer of US amorphous technology to Japan, but in return, the USA, through Sovonics, has acquired the engineering and production know-how that enables the Japanese to get a product onto the market faster than other countries. This cross-flow of technology is based on the realization that the two parties have complementary capability. It is notable that the Japanese aimed for amorphous cells when the rest of the world was banking on single-crystal cells and when polycrystalline cells were unveiled by Solares, new firms sought to enter the market with this innovation. As a result, firms such as Holec (Holland) acquired the technology from Solarex hoping that it would have a better performance than the single-crystal cells. This hope was not realized and Holec had to cease production.

The most important part of a photovoltaic system is the conversion material. The fabrication of the cell is linked to the rest of the BOS components and therefore the process technology will not be settled until the cell is stabilized. However, firms such as Spire have started producing 1-MW plants producing single-crystal modules for export. Saudi Arabia has acquired one such plant and other plants are destined for Canada and China. It is not certain how convertible this plant is to new conversion materials. Spire's strategy is to form a standardized collection of BOS components onto the market and not wait until the dominant cell has emerged. The logic behind this reasoning is that any new cell will be readily incorporated into the plant. It is also notable that Spire does not include cell fabrication in the technological package but only BOS component production and assembly.

While such plants are being set up, using the near-obsolete single-crystal technology, other firms are extending their international operations with amorphous technology in the belief that these cells are likely to dominate the market in the future. Chronar has set up a 1-MW plant in Wales (UK) and is negotiating for similar facilities in France and Morocco. ECD has already signed a Memorandum of Understanding with China to work towards establishing process facilities there. It appears that China is not only opening up its market for Japanese photovoltaic products but is also searching the international market for the technology. The Spire agreement would provide China with the required knowledge for the production of BOS components while the ECD joint venture would enable them to have access to the state-of-the-art amorphous technology. China is in a strong bargaining position given its large, dispersed population which provides an ideal market for stand-alone or decentralized grid modules.

The use of US photovoltaic technology in Japan is not restricted to ECD. With the use of ion implant machines from Spire, the Japanese firm Hoxan has been able to build a 9 MW single-crystal plant at Sapporo. The sheer size of this plant indicates that the Japanese did plan to take advantage of economies of scale in a technology that is likely to be displaced in the long run by amorphous materials. At this production capacity prices are below US$ 5 per pW. Hoxan is a new firm in the business and it appears that their strategy was to go for scale economies while the technology was still viable. This corporate strategy is built on the realization that the mass production of amorphous cells is just starting and there is room for the co-existence of different cell types on the market. Moreover, amorphous cells themselves are going to undergo efficiency- and process-related changes.

It is notable that the shift to amorphous cells outside Japan has been pioneered by emerging small and medium-sized firms. The decision by firms such as Chronar to enter the market with plants based on new conversion materials illustrates the uncertainties concerning the sources of innovation and position of firms in the market structure. The late 1970s and early 1980s saw the rapid emergence of subsidiaries of oil majors. It was felt then that this control would make it difficult for developing countries to enter the photovoltaics market, but the problem seems to be the nature of the technology rather than the structure of the market. This argument, however, does not preclude the negative effects of monopolistic control.

The location of production facilities in the developing countries to take advantage of cheap labour has been part of the strategies of firms such as Solarex. So far only the Singapore case has materialized. There are numerous proposals which have so far not been implemented. In the meantime, firms are emerging which tend to specialize in the export of productive facilities to the developing countries. The US firm, Sunpower, for example, has plans for a US$ 1.2 million contract with the Philippine Sunpower Industries and Development for photovoltaic manufacturing. This arrangement involves the setting up of facilities to produce thin film modules for export. Sunpower intends to give technical, marketing and training facilities under a five-year project that was scheduled to begin in 1984. Cell production was set to start in two to three years and similar projects were being considered in six other countries.

The initial optimism over assembly plants in developing countries was based on the view that since 50 per cent of module production costs went to BOS components, it would be possible to have them assembled in the developing countries using cheap labour. Moreover, reductions in cell costs would increase the share of BOS components that have been partially standardized and are not likely to undergo any major cost-reducing changes. This view was also supported by the assumption that the developing countries would be a major market for photovoltaic systems, especially in water pumping and rural electrification. Such assembly plants have so far not been set up on scales previously envisaged. One of the reasons for the slow transfer of production facilities to the developing countries is the rapid rate of innovation in conversion materials which is making photovoltaic process technologies near-obsolete at any one moment. The possibilities for selected assembly sites in the developing countries still exist but will have to await the emergence of dominant conversion materials.

It appears that some firms are interested in automated production and will most likely consider setting up production facilities in the industrialized countries to take advantage of advances in automation and local photovoltaic markets. Firms such as ECD are already adopting Japanese-type automated production thereby pre-empting the need for cheap labour. This development is linked to the fact that photovoltaic sales are growing faster in industrialized countries than in developing countries. It appears therefore that the rate of technology flow to the developing countries is likely to be slower than originally projected. This, however, may change as access to automated production technology is uneven even among industrialized country firms, some of which may use the cheap labour as a basis for competition. Moreover, the need to have access to specific developing country markets may lead to the establishment of labour-based production facilities in those economies.

Much of the technology flow in the 1980s has been between European and US firms. This flow was associated with trans-Atlantic corporate links which were made in the late 1970s to enable US firms to have access to developing country markets through traditional European links with former colonies. For example, Solarex established corporate links with European firms such as Holec, France Photon, Moteurs Leroy-Somer and Solaris. The Solarex link with Moteurs Leroy-Somer was significant because the latter controlled a pump manufacture company, Pompes Guinard. This enabled Solarex to couple its photovoltaic systems with the pumps exported to developing countries by Pompes Guinard. On the whole, the flow of photovoltaic technology to other countries is likely to be limited to a few countries, while widespread offshore activities associated with the semiconductor industry are not likely to occur in the near future.

V. IMPLICATIONS FOR DEVELOPING COUNTRIES

The development of photovoltaics has a number of features which raise several policy questions for developing countries. In the first place, the decision of a developing country to enter the market as a producer will be influenced by the size of the local or envisaged market. In this respect, countries such as India and Brazil have a higher chance of entering the market as producers, but the situation is not as simple as that, since photovoltaic production is not only science-intensive but requires specific microfabrication techniques. The rapid rate of scientific advancement, especially in material sciences has been the basis of technological know-how in this field. The level of public sector involvement and the activities of universities as exemplified by SERI's institutional network illustrates the need for scientific advance as a necessary requirement for technological development.

Not only does entry into the market require a strong scientific and technological base, but it also needs complementary industrial know-how. Many of the techniques now used in the photovoltaic industry have been adopted from other sectors of the economy. This fact is reflected in the patterns of market entry and corporate restructuring. While some of the developing countries may have access to traditional single-crystal know-how, the shift to thin film and ribbons based on amorphous materials requires new initiatives in technology acquisition or local development.

Despite these problems, some developing countries can build photovoltaic-related capabilities in BOS components and loads. The need for local BOS manufacture has been a major conclusion of a recent World Bank testing and demonstration programme. Building BOS capability requires the ability to unpackage photovoltaic systems. Indeed, the current trends in innovation show continued system-packaging as a means of raising system efficiency while at the same time integrating the production process. However, while this is going on opportunities to acquire BOS technology are also emerging. The sale of BOS manufacturing plants by Spire provides an opportunity for some developing countries to acquire design concepts relevant for module assembly. The acquisition of such plants alone will not guarantee the transfer of technology. The process needs to be associated with carefully worked out policy guidelines which enable the importing countries to assimilate the know-how.

It is difficult to judge whether in the long run the industrialized countries will be willing to transfer cell-related technology to developing countries. This paper has argued that this will be restricted to a few countries in the short and medium term. Countries with potentially large markets, such as Brazil, China, India and Mexico have a stronger bargaining position and could have limited access to cell-related know-how. These countries have on-going R&D projects and some of them (specifically China and India) are actively seeking joint ventures with photovoltaic manufacturers.

On the whole, no general policy guidelines can be given on the potential entry of developing countries into the photovoltaic market. What, however, seems an ideal strategy for most countries is to constantly monitor the changes occuring in the technology (among other technologies of course) and base their policy decisions of technological expectations and their possible contribution to the local energy budgets. Countries such as Brazil, China and India which are already searching the international market for technologies, will require different policy guidlines based on their current level of technological advancement in this field. Other countries such as those in Africa may seek access to the technology from a collective forum given the low bargaining power of individual nations.

CONCLUSION

This paper has reviewed recent developments in photovoltaic technology and shows that the industry has been undergoing major structural changes. These changes have been associated with technical innovations in conversion materials and the related public sector support. It was pointed out that the technical transition has gone through three different types of conversion materials (single-crystal, polycrystalline and amorphous). These changes were linked to industrial re-organization and different patterns of public sector support. The rapid changes occuring in the technology and the demand for major public sector support makes it difficult for most developing countries to enter the photovoltaic market as producers. However, a few countries may in the short term acquire technological capabilities related to peripheral parts of the photovoltaic systems.

Bibliography

CEC (1985), Solar Energy R&D Programme: Results and Conclusions, Commission of the European Communities, Brussels, Belgium.

Fischetti, M. (1984), "Photovoltaic-cell Technologies Joust for Position", IEEE Spectrum, March, pp. 40-47.

Hoffman, K. (1985), "The Commercialization of Photovoltaics in the Third World: Unfulfilled Expectations and Limited Markets", Development and Change, Vol.16, No.1, pp. 5-37.

Iversen, W. (1984), "Amorphous Silicon Wins Place in the Sun", Electronics, April 5, pp. 95-96.

Jorné, J. (1983), "Flow Batteries", American Scientist, Vol.17, pp. 507-512.

Juma, C. (1983), Photovoltaics in Developing Countries: Techno-Economic Expectations and Strategic Responses, Unpublished M.Sc. Thesis, University of Sussex, Brighton, UK.

Macomber, H. (1984), "Status of Large US PV Systems Applications", Palz, W. ed., Photovoltaic Power Generation, Proceedings of the EC Contractors' Meeting, Hamburg/Pellworm, 12-13 July 1983, D. Reidel Publishing Company, Dordrecht, Holland.

Maycock, P. (1985), "The Current PV Science Worldwide", Palz, W. et al., Sixth E.C. Photovoltaic Solar Energy Conference, D. Reidel Publishing Company, Dordrecht, Holland.

Maycock, P. et al. (1981), Photovoltaics: Sunlight to Electricity in One Step, Brick House Publishing, Andover, Mass., USA.

SERI (1984), SERI Photovoltaic Advanced Research & Development: An Overview, Solar Energy Research Institute, Golden, Colorado, USA.

World Solar Markets (1983), "Worldwide Installed PV Capacity--Plotting an Accurate Picture", December, p. 3.

Zorpette, G. (1984), "High-tech Batteries for Power Utilities", IEEE Spectrum, October, pp. 40-47.