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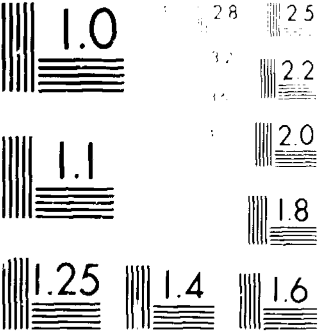
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EMERGING PHOTOVOLTAICS TECHNOLOGIES:

IMPLICATIONS FOR DEVELOPING COUNTRIES*

Note by

UNIDO Secretariat

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INTRODUCTION

1. This paper presents a very brief review of technological advances relating to solar photovoltaic systems and proceeds to consider the implications of those advances for developing countries.

2. It should be borne in mind at the outset that at present energy through photovoltaic systems can only provide a very small portion of the energy requirements of any country, developed or developing. In the longer time horizon, however, solar energy could be an important renewable source of energy, particularly to developing countries. The longer lead time should enable developing countries to formulate well-considered strategies for the application of solar energy. In the short term, solar energy lends itself to selective decentralized applications, particularly in areas which do not have other alternatives. The emphasis on photovoltaic systems is not intended to minimize conventional thermal and hydro-energy.

I. STATUS OF SOLAR PHOTOVOLTAIC TECHNOLOGIES

3. There are four basic areas of activity in the development of the engineering and technology of solar photovoltaic systems:

- i) basic raw material, particularly silicon;
- ii) solar cells and modules;
- iii) balance of system (BOS) components; and
- iv) complete system engineering.

These areas need equal attention in order to effect the large-scale utilization of solar photovoltaic systems.

4. Technology development of photovoltaic conversion systems is primarily addressed through: (a) fundamental research on solar cells; (b) research and development on solar cells, particularly to reduce their cost and the number of steps involved in fabricating them; (c) mass

production technology of solar cells based on large-scale continuous process methods; and (d) reduction of component costs (though it is felt that sufficient attention is not being paid to this respect).

5. Fundamental research is primarily directed to material research, high conversion efficiencies and studies of the physical phenomena of amorphous and crystalline silicon.

6. As regards the cells, single crystal silicon solar cell technology is fairly well established and understood and a number of countries have fabrication facilities. The cells have been found to be reliable and technically feasible, but the main problem in their large scale use is their high cost. Several approaches are being followed to reduce the cost of solar cells. Technology development is in a highly dynamic state, resembling the situation in the semi-conductor industry some years ago. Not less than nine technological routes [1/] for solar photovoltaic cells have been reported based on silicon, gallium arsenide and cadmium sulphide. These routes relate to: single crystal silicon that is sliced; silicon ribbon that is pulled through a shaping guide directly out of the melt; ribbon technology based on the dendritic growth process; use of ceramic substrate; heat exchanger method; semi-crystalline method; cadmium sulfide; amorphous silicon; and concentrating.

7. A technical panel on solar energy thought that concentration systems would have relatively little future since the cost of concentrators is more or less constant. [2/] In the not too distant future, concentration would not be cost-effective. Polycrystalline solar cells and the single-crystal ribbons have great promise, although the production techniques of single-crystal ribbons are far more complicated. Cadmium sulphide thin-film solar cells have a promising future, provided the degradation problems

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1/ Paul Maycock in Alternative Sources of Energy Conference in Sept. 1980;

2/ P. 9, Report of Technical Panel on Solar Energy on its first session, A/CONF.100/PC/11.

are solved. Some commercial concerns are already producing cadmium sulphide solar cells. Amorphous silicon cells have promise if efficiencies and reliability could be improved.

8. Improvements in efficiencies of amorphous silicon have been reported,[3/] with RCA reporting on its 10.1 per cent cell and at least nine companies reporting efficiencies above 7 per cent. It is anticipated that amorphous silicon photovoltaic panels will be introduced by the Japanese in the spring of 1984, probably first in consumer electronics such as watches, calculators and cassette players. Manufacturing costs of less than US$ 1 per peak Watt are projected for photovoltaic panels made with amorphous silicon or other thin films such as cadmium-teluride or copper-indium-diselenide. How soon these panels could be commercialized is, however, a matter of considerable debate.

9. Assessments keep changing, given the dynamic state of technological development. A recent forecast for 1990 concluded that non-silicon cells will have only a five per cent share of the photovoltaic market, with single crystal silicon cells holding 40 per cent.[4/] It appears that though shares will be obtained by different technological routes, the shares would be largely determined by the conversion efficiencies.

3/ Solar Energy Intelligence Report, October 11, 1982, p. 330.

4/ Paul Maycock reported in Solar Energy Intelligence Report, June 14, 1982, page 195, "Maycock concluded that: (1) Concentrators using single-crystal silicon cells will gain 20 per cent of the world market by 1990, comprising half the 40 per cent share mentioned; (2) Polysilicon slices will gain another 25 per cent of the market in the world as low-cost silicon is used and 14 per cent cells are made for US$2.50 per Wp in 1990 module prices, but lower efficiency than single-crystal modules will limit market penetration; (3) Sheet silicon will gain 15 per cent of the market as the output level of edge-defined film-fed growth and dendrites is broken by a new high-speed process resulting in polycrystal cells, market penetration of slice options is equalled by 1988, and sheet modules have a 12 per cent efficiency and are priced at $2-2.50/Wp in 1990; (4) Amorphous and thin-film silicon can gain a market share of 15 per cent by 1990 when they will be available for $2/Wp at 10 per cent efficiency; and (5) Non-silicon option will obtain a 5 per cent, with the best bets today being cadmium-telluride and copper-indium-diselenide, but the electrochemical, luminescent and other "new" approaches are "not likely to gain product status by 1990 as fundamental failure mechanisms in very thin films adversely affect market acceptance." Maycock also thought that the cost reduction goals of the Department of Energy of the United States will not be met by 1986.

10. In this connection, it should be recognized that higher efficiencies not only produce economies in themselves but also more then proportionate savings in the balance-of-system cost. It has been reported that balance-of-system costs will likely account for half of the system cost in future economical applications.[5/] However, research on balance of systems is not as much reported as that on cells.

11. The range of technological effort required is illustrated by the 'Sunshine' project in Japan which includes besides fundamental research and R and D on solar cells, R and D in cell fabrication technology, testing standards and procedures and photovoltaics power systems technology.[6/]

12. A brief review of the international technology market on solar photovoltaic systems would be in order.[7/] There is an estimated 300 to 400 firms world-wide involved in various parts of the industry. Most of these are concentrated in OECD countries, particularly in the United States, France, Federal Republic of Germany, Japan and Italy. Less than 10 per cent of these are reported to be actually producing cells on a commercial basis. However, up to twice that many firms, are either currently poised to move into raw material production or cell fabrication or else are primarily involved in R and D efforts which may lead them to commercialization at some time in the future. The largest group of firms world-wide are multi-product firms, supplying the balance of system components. While at this end of the spectrum entry of small firms is possible, in regard to photovoltaic cells production, the trend appears to be towards much slower rates of entry and increasing concentration of market shares, particularly because of increasing investment intensity for both R and D and production. The small independent firms, specialized in production of photovoltaics are the losers. They have either succumbed to substantial losses or more commonly to take over bids by large international companies. Such large companies included oil majors, electronic firms working in similar areas in the semiconductor production line and other big companies. There is no perceptible trend towards off-shore production in the developing countries as was the case in the electronics industry in the 1970s.

5/ Solar Energy Intelligence Report, October 11, 1982, p. 331;

6/ Miyoshi Takahashi, "Present Status of Photovoltaic Research and Development in Japan" in Solar Cells, Vol.6, No.4, September 1982;

7/ Information provided by Kurt Hoffman. The nature of the international solar energy technology market can also be seen illustratively from the Directory of solar equipment manufacturers, UNIDO/IS.340.

II. IMPLICATIONS FOR DEVELOPING COUNTRIES

13. Solar photovoltaic energy sources produce direct current electricity, directly from solar energy; their maintenance requirements are minimal and the demise of a single unit does not shut down the whole system. Unlike all other sources of generated electricity, the cost per unit of electrical energy generated does not depend drastically on the capacity of the photovoltaic energy unit installed. Therefore, small stand-alone units are just as viable economically as large and centralized units, at least at the present level of technology. The possibility that the user himself is responsible for the supply of his own electrical energy requirements, with little dependence on external agencies for fuel or maintenance, is very high. All these advantages make solar photovoltaic energy sources eminently suitable for use in areas which are not connected to the electric grid and which are not likely to be connected to it in the near future.[8/] Viewed from this perspective, solar photovoltaic energy sources would be highly relevant to developing countries.

14. Solar photovoltaic energy sources can be developed either as centralized or as distributed systems. In table 1 the possible development schemes of solar photovoltaic energy sources are listed. At present, the centralized schemes have little importance. Of the three schemes of distributed sources, the community-based and the user-owned stand-alone systems are of importance. The concept of user-owned stand-alone systems connected to a utility grid is of less relevance, primarily because distribution grids are unavailable in most places.

8/ T.K. Bhattacharya, "Solar Photovoltaics, an Indian Perspective" in Solar Cells, Vol.6, No.3, August 1982, p. 253.

TABLE 1

Possible deployment schemes for solar photovoltaic energy sources

Nature	*Scheme*	*Power level (MW)*	*Status*
Centralized	Solar power satellites	5000	Fantasy
	Land-based central power stations	100	Future
Distributed	Community integrated and owned[a] (Usage: residential loads, potable water, cottage industries, community services, perhaps also irrigation)	$(10 - 100) \times 10^{-3}$	Technically feasible; few attempts so far
	Utility (grid) connected stand-alone user owned (Usage: residential loads)	5×10^{-3}	On the horizon
	User-owned stand-alone (Usage: irrigation, lighting, industrial applications such as communications, remote area electronics etc.)	1×10^{-3}	Technically a reality; economically uncertain

(Source: T.K. Bhattacharya, "Solar photovoltaics: An Indian Perspective" in Solar Cells, Vol.6, No.3, August 1982, p. 254)

Possible photovoltaic applications in rural areas of developing countries are shown in table 2.

TABLE 2
Photovoltaic applications in rural areas of developing countries.

Application category	*Typical uses*	*PV system power requirements*
Water pumping	Potable water	0.08 Wp l^{-1} d^{-1} [a]
	Irrigation	85 Wp (ha mm)$^{-1}$ d^{-1} [b]
Refrigeration	Food preservation	100 Wp per 5 ft^2 refrigerator
	Drug and vaccine preservation	
Lighting	Homes	16 Wp per 20 W fluorescent lamp [c]
	Work areas	
Communications	Educational TV	40 Wp per TV set [d]
Food preparation	Milling	3.5 Wp per kilogram of flour per day
	Decortication	
Cottage industry	Metal or wood forming	2.0 kWp per 1 hp motor [e]

[a] 30 m total dynamic head.
[b] For 5 m head; 60% field efficiency.
[c] Average use 2 h per night.
[d] 32 W TV set, 4 h operation per day.
[e] 8 h operation per day.

(Source: Louis Rosenblum, William J. Bifano, Gerald F. Hein and Anthony F. Ratajczak, "Photovoltaic power systems for rural areas of developing countries", Solar Cells, Vol.1, Number 1, November 1979, pp. 65-79)

15. A photovoltaic power system typically consists of a solar cell array, energy storage and regulation and control devices. The solar cell array structure serves as a means of integrating the relatively small, low-power, low-voltage modules into a useable assembly (the module is the basic building block and contains a number of solar cells, electrically connected and encapsuled in a supporting frame). It mechanically supports the modules and provides routing and attachment points for the wire harness which connects modules and collects power from the array. Energy storage typically consists of a number of lead acid cells connected in series and/or parallel to provide the desired voltage. Sufficient storage capacity and voltage regulation are needed for effective functioning. For multiple applications, additional control features are required to manage the multiple loads.

16. Table 3, which is presented on page 8, shows some application projects attempted in rural areas.

17. The foregoing indicates that the potential for developing countries is great and that selective applications are feasible. However, a number of questions have to be addressed. Firstly, the question arises as to at what stage of the declining cost curve should the developing countries enter. The price at which the applications will be cost-effective will depend on the opportunity cost which will vary from country to country (in relation to the fuel and electricity prices) and according to the type of application. Developing countries have to closely watch the development of the technology and particularly the reduction in costs. In general, the question arises whether, considering the declining costs, the developing countries should refrain from making major long-term commitments for the acquisition of technology. Assessments from a developing country point of view of alternative technologies for manufacture of cells and of alternative systems are needed.

TABLE 3

Photovoltaic application

	Use	User	Date operational	Location	Power level (Wp)
Single applications					
Communications	Educational TV	Government of India	July 1976	(1) Ahmedabad, India (2) Sambalpur, India	55 55
[a] Refrigeration	Food preservation	National Park Service	June 1976	Isle Royale, Michigan	220
[a] Refrigeration	Medical	Village residents, Papago tribe	July 1976	Sil Nakya, Arizona	330
[a] Instrument	Weather data	National Weather Service	April–September 1977	(1) New Mexico; (2) New York; (3) Hawaii; (4) Alaska; (5) Maine; (6) Florida	75 - 150
[a] Highway	Dust storm warning sign	Department of Transport, Arizona	April 1977	Casa Grande, Arizona	116
[a] Instrument	Insect survey traps	Department of Agriculture	May 1977	College Station, Texas	23 and 163
[a] Refrigeration	Water cooler	Interagency Visitor Center	October 1977	Lone Pine, California	446
Cluster applications					
[a] Fire lookout	Two-way radio, refrigerator, lighting, potable water	Forest service	October 1976	(1) Pilot Peak, California (2) Antelope Peak, California	294 294
[a] Village power	Potable water, lighting, refrigeration, washing machine, sewing machine	Village residents, Papago tribe	December 1978	Schuchuli, Arizona	3500
[b] Village power	Potable water, grain milling	Village residents	February 1979	Tangaye, Upper Volta, Africa	1800

[a] Part of the DOE Tests and Applications Project, managed by LeRC. [b] *Sponsored by the AID.*

Source: Louis Rosenblum, William J. Bifano, Gerald F. Hein and Anthony F. Ratajczak, "Photovoltaic power systems for rural areas of developing countries", Solar Cells, Vol.1, Number 1, November 1979, pp. 65-79)

18. A related question is whether and when developing countries should enter into manufacture or whether they should confine themselves to applications. Surely, developing countries with the requisite capital and skills would be interested in their own manufacturing capability. Pilot facilities already exist in a few developing countries. Besides, a distinction has to be made between manufacture of solar cells and that of the systems. It should be noted that apart from the fact that the systems should be suitable to developing country conditions, considerable value is added in building up the systems. These capabilities should be developed in the developing countries.

19. The development of applications is needed whether or not a country will take up manufacture of cells and systems. Here is a need to assess the experience gained so far through pilot applications. Besides the technical, economic and social problems in the introduction of applications should not be minimized. 10/ It may be necessary to stimulate the interest of both producers of solar energy equipment and their users. The encouragement of innovative firms may also be necessary in this process. The public sector in the public services area could be large users for selective applications and these possibilities should be fully utilized.

20. There is a somewhat paradoxical situation that though solar energy is abundant in the developing countries and hence it is those countries which will be the main consumers of the technology, the production and R and D efforts are concentrated in the developed countries which look to the developing countries as potential markets which would permit large-scale production and reduction in costs. This fact combined with the competition that exists in this technology provides the developing countries with a certain bargaining strength which needs to be effectively used. In this connection, a proposal

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10/ According to Markus, a combination of technical, social and financial obstacles makes it likely that most developing countries will choose the conventional energy systems; among other reasons, "it is very difficult for renewable energy applications focussed at village level to make sizeable reductions in oil imports". World Solar Markets, August 1932, p. 4.

made recently needs to be mentioned, viz. that regional and international organizations could guarantee large-scale purchase of photovoltaics in a way that can reduce the cost and make it acceptable to developing countries. 11/ Carefully used, large-scale purchases might provide a bargaining power. Ineffectively used they might accentuate technological dependence. Some collective negotiating strategies on the part of developing countries may be useful in regard to this question.

21. It is useful to refer here to the experience of developing countries in the importation of photovoltaic systems. For example, in most Arab countries "their solar energy plan becomes completely integrated in the overall development plan of the industrial power rather than with neighbouring countries which might have similar conditions vis-à-vis solar energy"12/. In Mexico, the anarchy in the international price structure (owing to variations in quality, political aspects and dumping) is reflected in the local market, resulting in the overexploitation of a weak market. 13/ Commercial activities, though introduced since 1972-73, have not contributed to the development of indigenous photovoltaic know-how even when they have given some knowledge of system design, installation and operation.

22. The strengthening of technological capabilities of developing countries is obviously essential. That capability should extend beyond research and development to selection, negotiation and acquisition, on the one hand, and systems design, applications, marketing and servicing on the other. At least 18 research institutions in 13 countries have been reported to be working in photovoltaic conversion. 14/

11/ E.g., Recommendation of a Pan-American Congress on Energy hosted by Pan-American Confederation of Engineering Associates (UPADI), reported in Solar Energy Intelligence Report, September 27,1982, page 313;

12/ M.A. Kettani, "Photovoltaics in the Arab World" in Solar Cells, Vol.6, No.3, August 1982, pp. 239-249;

13/ E.J. Perez and J.L. Del Valle in "Prospects for photovoltaics in Latin America: The Mexican Case" in ibid, pp. 281-293;

14/ See Directory of Solar Research Institutes in Developing Countries, UNIDO/IS.341. The countries are Algeria, China, India, Ivory Coast, Jordan, Kuwait, Mali, Mexico, Nigeria, Pakistan, Saudi Arabia, Singapore and Yugoslavia.

The question is how their capabilities could be upgraded and an exchange of experience promoted among them. 15/ Such exchange of experience should extend to testing of prototypes, running of pilot projects, etc. In view of the long-term importance of solar energy to developing countries, it is for consideration whether a consultative group on solar energy, research and application (CGSERA) may be established. That group could draw upon the experience of top-level specialists in this field as also development specialists and stimulate co-operation among research institutions, particularly in developing countries, assess the experience of projects in developing countries and identify sources of funding for research and development including the building up of appropriate systems.

23. Since large-scale application of photovoltaic technologies would appear to be still a decade away, it is important that developing countries utilize this period effectively in building up their capabilities, carefully assessing alternative technologies and pilot projects and achieving technological self-reliance in this area. Thus the 1980s and particularly the next five years will be a crucial one for developing countries and for the nature and direction of the development of the industry as a whole.

15/ Pakistan is implementing a UNIDO executed project (funded by UNFSSTD) on silicon technology. On projects of photovoltaic applications in developing countries see Solar Cells, Vol.6, No.3, August 1982.