PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Present Status and Future Prospects of Silicon Solar Cell Arrays and Systems

H. Durand

*Phil. Trans. R. Soc. Lond. A* 1980 **295**, 435-443
doi: 10.1098/rsta.1980.0139

*Phil. Trans. R. Soc. Lond.* A **295**, 435–443 (1980)
*Printed in Great Britain*

# Present status and future prospects of silicon solar cell arrays and systems

By H. Durand
*President, Commissariat à l'Énergie Solaire, Paris, France*

The first part of this paper deals with the present state of the art of the single crystal silicon cell industry: production volume, cost breakdown and main technologies.

In the second section, improvements of the single crystal technologies, caused by mass production and automated physical processes, are described. These developments are compared, with regard to both cost and performance, with the future polycrystalline (or 'semicrystalline') materials, including amorphous silicon films. The various approaches, i.e. vapour or liquid film deposition, or oriented bulk ingot crystallization, are discussed.

The third part assumes that very low cost goals can be achieved, either through the development of sophisticated single crystal technology, or through a polysilicon breakthrough. Future markets for photovoltaic conversion, including medium-size power generating plants, are then considered.

## 1. Introduction

Silicon solar cells and arrays are currently the only photovoltaic devices commercially available, and they will most probably keep this dominant situation for many more years. They have been known for 25 years, are widely used for spacecraft, and in the past 5 years have shown a remarkable growth for terrestrial uses. However, although improved technology and automated production lines will undoubtedly bring a cost reduction by a factor of 5 or perhaps 10 with respect to present prices within the next 5–7 years, single-crystal cells are hampered by the high cost of the crystal pulling, and by kerf loss of this very valuable material during the wafer slicing operation. Therefore, great attention is paid to polycrystalline silicon research and development, with an emphasis on thin film deposition methods. Another cost reduction of a factor of 5 might be expected in the more remote future from these new technologies, then making solar electrictiy competitive with classical generators.

Another way of cutting prices lies in the use of optical concentration, which transfers the major part of the cost from the cell to the optical system. In spite of this potentiality, one cannot expect that rather complicated tracking mechanisms could eventually beat the low-cost polycrystalline technology of flat solar cell arrays.

Great attention is also paid to other materials: single crystals, such as gallium arsenide, which is suitable up to very high concentrations, or cheap thin films (amorphous silicon, cadmium sulphide and other Group II–IV compounds).

Thin films have not yet proved their reliability and currently have much lower efficiencies than silicon cells. However, very cheap technologies have been conceived for their production, and they remain alternatives to silicon.

## 2. Present status of the photovoltaic industry

The world production of silicon cell panels (encapsulated solar cells) is estimated in 1978 around 1 MW (peak). About three-quarters of this amount are manufactured by half a dozen of American companies. The non-U.S. production is dominated by a French manufacturer, with an annual production of 200 kW. The rest comes from Japan, with pilot-scale production in Germany and the U.K.

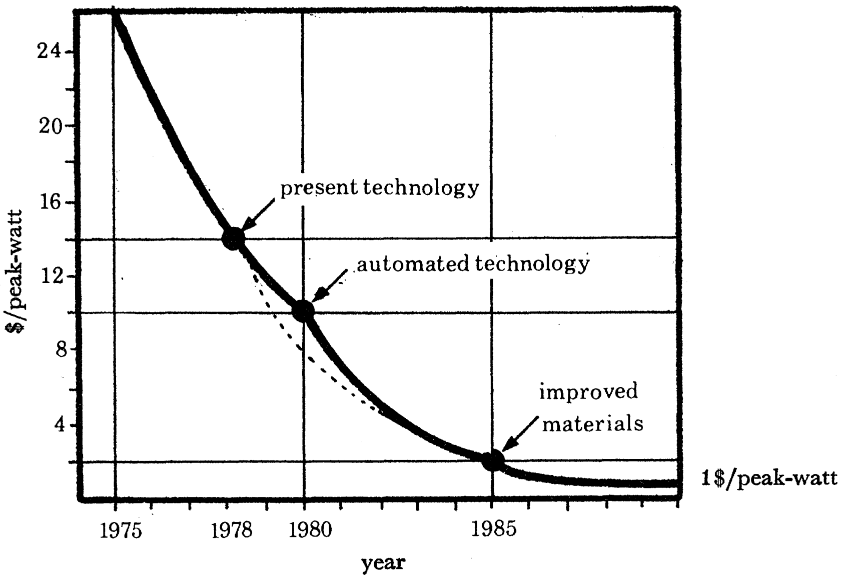

Figure 1. Expected price trend for photovoltaic panels.

The rate of growth of this industry is very high, doubling every year. At an estimated average price of £8–10 per peak-watt, this industry has a world-wide turnover of about £10 M, which roughly doubles with the associated system hardware. Prices have dropped steadily by 20% per year in the past four years. However, the market demand seems today to be larger than the production. But this phenomenon is rather temporary, as new and large production units are being built.

Figure 1 shows the long term trend of photovoltaic panel costs: this personal analysis is somewhat less optimistic than the predicted values by the U.S. Department of Energy, which forecasts prices as low as $1.00 /peak-watt around 1986 or 1987. In my opinion, two facts are overlooked:

(i) the cost of encapsulation, which is independent of the value of the active photovoltaic material, cannot decrease as fast and as much, especially because of the present tendency to use glass windows instead of plastic coatings, which are less reliable;

(ii) cheaper materials, such as 'polysilicon', are still in a research stage and might not become industrially available before 1985.

## 3. Cost reduction programmes

The strongest effort, by far, is made by the U.S. Department of Energy. The very recent (October 1978) 'Photovoltaic Act' passed by the Congress is a mobilization of gigantic efforts in order to cut photovoltaic devices prices: $1.5 \times 10^9$ dollars (£800 M) are to be spent within the

1978–88 period, with an immediate appropriation of 125 million dollars. 75% of this total is to be spent for R. & D., the rest for demonstrations (U.S. Congress 1978). The production is expected to double every year and reach 2 GW in 1988, while prices are said to be as low as U.S. $1 per peak-watt, thus bringing the cost of energy down to about 5 U.S. ¢ per kWh (assuming that, in a sunny country, a peak-kW installed produces 20000 kWh in its life-time).

The Government of the Federal Republic of Germany last year launched an eight year programme within the industry, which will receive during that period a total of 160 M D.M. (about £40 M). However, this programme differs from the American counterpart, because it is entirely devoted to a non-conventional polycrystalline silicon technology which will be described later on.

Table 1. Major photovoltaic programmes

| | | |
|---|---|---|
| U.S. | 1977–8 | 51 M$ (£28 M) |
| | 1978–9 | 125 M$ (£71 M) |
| France | 1978 | 20 M F.F. (£2.2 M) |
| F.R.G. | 1978 | 6 M D.M. (£1.5 M) |
| E.E.C. | 1978 | 5.5 M U.C. (£3.4 M) |

In France, the total annual Government subsidies to photovoltaic development runs presently around 20 M F.F. (£2.2 M). The great majority of these funds goes to silicon (single or polycrystal) projects.

Japan is known to be making a strong effort on polysilicon research, but few results have yet been published. The U.K. is not very active in terrestrial silicon cells. There is, however, a small-scale pilot production line in operation.

One should also mention the E.E.C. programme, which has, during the last three years, spent $17\times10^6$ Units of Account (about £10 M) on photovoltaics, with about 80% of the appropriation being engaged in silicon R. & D. or demonstration projects.

## 4. Cost reduction factors (single crystal technology)

One of the major factors will obviously lie in the large volume of production which is expected, together with the introduction of fully automated lines. However, the technology will have to adapt itself to mass production and cheap manufacturing processes. These are the main improvements that can be expected:

(i) Silicon starting material. The electronic grade ultra-pure silicon cost about £35/kg. Experimental results lead to the definition of a new 'solar-grade' silicon, with a much higher level of impurities (this is at least true for some of the impurities). Costs of the material are expected to drop by a factor of 5 or 6. However, many people believe that relatively impure silicon may lead to difficulties during the growth of large silicon single crystals, and therefore for this material is perhaps more suited for polycrystalline cells.

(ii) Size of the crystals. The major part of the world production is made with 5–8 cm diameter Czochalsky crystals. The present generation starts or uses 11 cm wafers, but 13, 16 or even 21 cm crystals are considered. The increase of the diameter is of great importance, since the handling of the wafers remains almost constant. Figure 2 illustrates this increase of cell size from 1970 to 1975 (French production).

(iii) Wafer slicing. Kerf and etching losses represent half of the single crystal used. The present technologies uses generally 300 μm thick wafer, a thickness which is quite redundant

(100 μm represent an optimum for the photovoltaic effect). It is hoped to bring the Kerf loss down to 100 μm and the thickness down to 200 μm, thus using half the quantity of crystal presently needed.

(iv) Cell technology. Many improvements are at the R. & D. stage. Schottky diodes have been definitively abandoned, despite their simplicity (the efficiency remains low, around 10–12 % at most). Diffusion is the preferred way to make the junction. However, new solid–solid diffusion methods are very promising, and may push out the traditional gaseous diffusion. Ion implantation, laser annealing, laser induced solid–solid diffusion are among the newcomers. The effective efficiency achieved on a production line, which was barely 10 % five years ago, currently reaches 13–15 % and is expected to be boosted to 18 %.

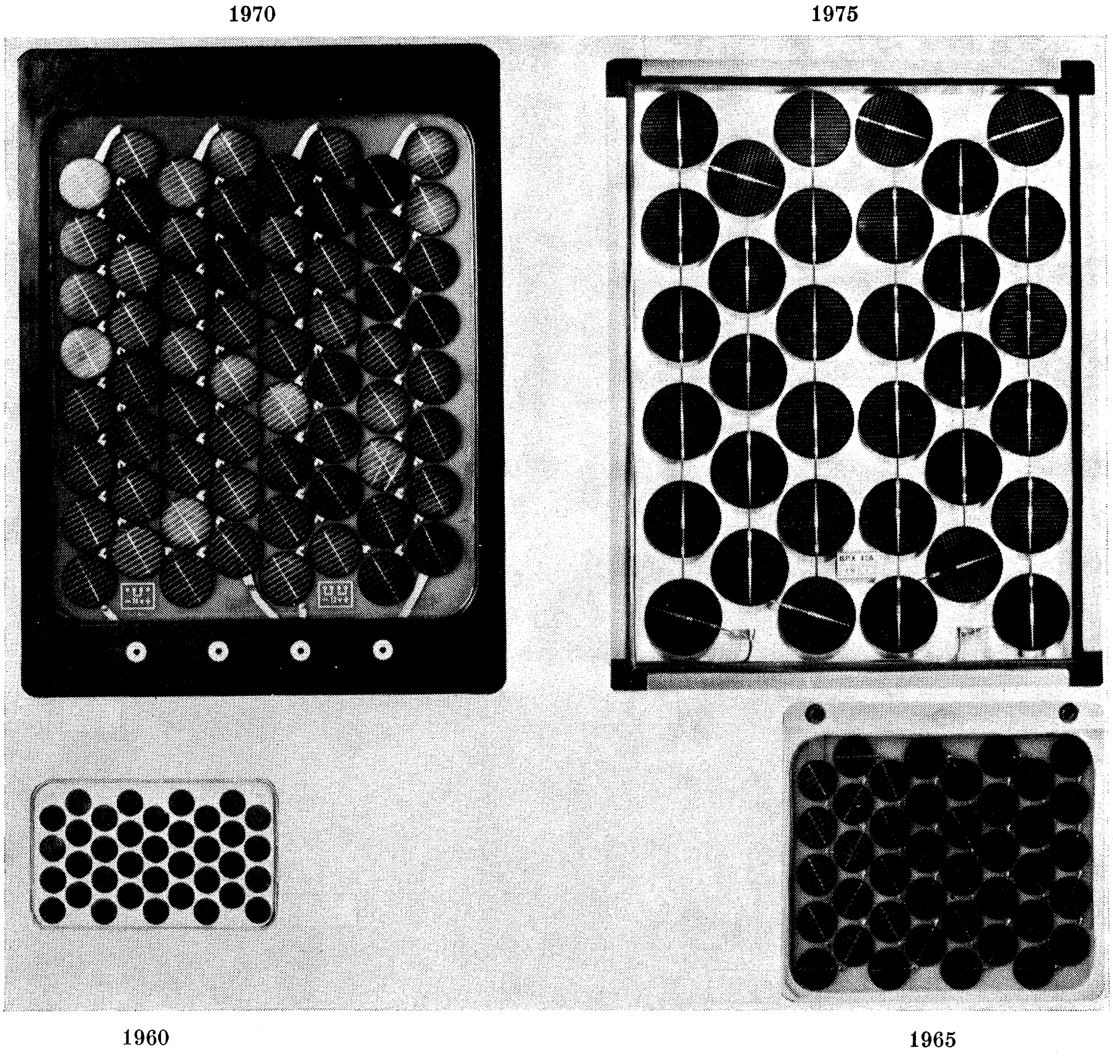

FIGURE 2. The area of cells has increased tenfold between 1960 and 1975.

(v) Contacts. Silk-screen contacts are widely studied in order to replace the expensive vacuum or photolithographic deposition. However, the durability of these new cheap contacts is not yet as good as the former ones, but becomes acceptable if a high quality hermetic encapsulation is used.

(vi) Encapsulation. Here, the price drop tendency is not yet as sharp as it is with the other items. More and more producers abandon the cheap plastic coating for a tempered glass window which is much more expensive but gives far superior reliability. Progress can be expected from larger panels (up to 1 $m^2$ for instance) requiring less handling. The packing factor of the cells within the panel is quite important in view of the expected high cost of the encapsulation per unit area: there is a tendency towards square cells, as used in space generators, instead of round ones, with packing factor increasing from 0.7 to 0.9.

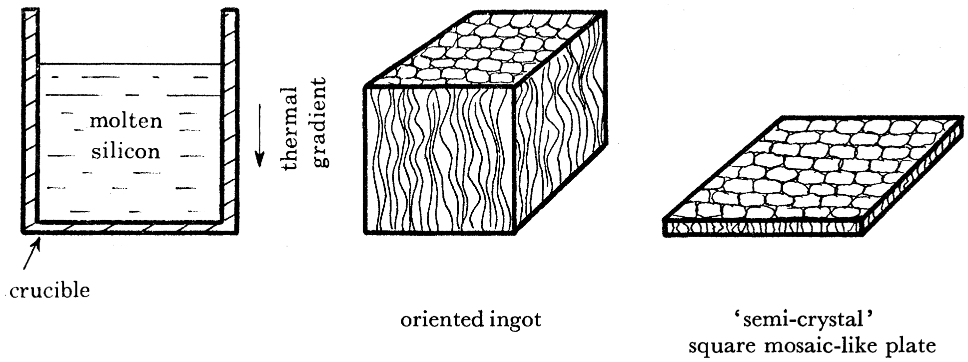

FIGURE 3. Crystallization under a thermal gradient gives rise to a 'columnar' structure.

## 5. THE NEW TECHNOLOGIES OF SILICON GROWTH

Great ingenuity exists in this field, and many dozens of methods have been investigated. Only the most promising ones are mentioned here.

(i) The so-called 'semi-crystal'. This method, contrary to all others, consists in a bulk but oriented crystallization of a silicon ingot. It therefore requires slicing perpendicular to the direction of preferred crystallization, with the unavoidable Kerf loss. Figure 3 shows the method schematically, which is actively studied in Germany (Wacker) and in the U.S. (Solarex). Efficiencies of 10% are easily achievable on large (10 cm × 10 cm) areas, and recently 14% (and even 16% on selected small samples) have been reported (Buhs 1978). The size of the grains is typically of the order of 1 $mm^2$, or more in the centre of the mosaic.

(ii) The 'epitaxial' films. Vapour phase decomposition of chlorosilane is applied on a large-grain metallurgical grade cheap silicon substrate. Efficiencies are nevertheless poor, because of contamination by the substrate (Chu 1978). Thick epitaxial layers (50 μm) are rather expensive. Attempts have been also made to use vapour phase deposition on other materials, such as stainless steel: grains are very small, and require recrystallization.

(iii) The 'ribbons'. The idea here is to grow directly a single crystal ribbon, directly usable for the cell production without any further slicing. The vertical ribbon pulling, so-called edge defined growth (e.f.g.) of Mobil–Tyco is the most advanced method and schematically shown in figure 4. However, if rather long (a few metres), relatively wide (7 cm), but unfortunately very thick ribbons have actually been obtained, the single crystal becomes very rapidly twinned, and dislocated and, after a few feet of pulling through the die, the structure resembles more an oriented (along the pulling direction) polycrystal than a true single crystal. Efficiencies, up to 12% have been reported with the best samples (Mackintosh *et al.* 1978). Other 'ribbon' pulling methods have been designed: horizontal pulling is studied mainly in Japan; the laser heated floating zone 'ribbon against ribbon' (i.e. poly-ribbon against single crystal ribbon) technology has been developed by Motorola in the U.S.

(iv) The 'silicon coating from the melt'. These technologies require a careful handling and control of molten silicon, which is deposited as an oriented thin film on a suitable substrate. Honeywell in the U.S. uses a dipping method, the substrate being a ceramic (mullite). In France, a more sophisticated technology is under development at Laboratoires d'Electronique et de Physique Appliquée, which may allow for a true continuous fabrication: figure 5 describes the process, where flexible graphite coated carbon ribbons come in contact with a 'drop' of molten silicon and are then pulled, thus allowing for the deposition of thin and controllable (from a few to 100 μm) film. Efficiencies of about 8 % are currently achieved, with grain sizes of about 1 mm$^2$ (Belouet *et al.* 1978).

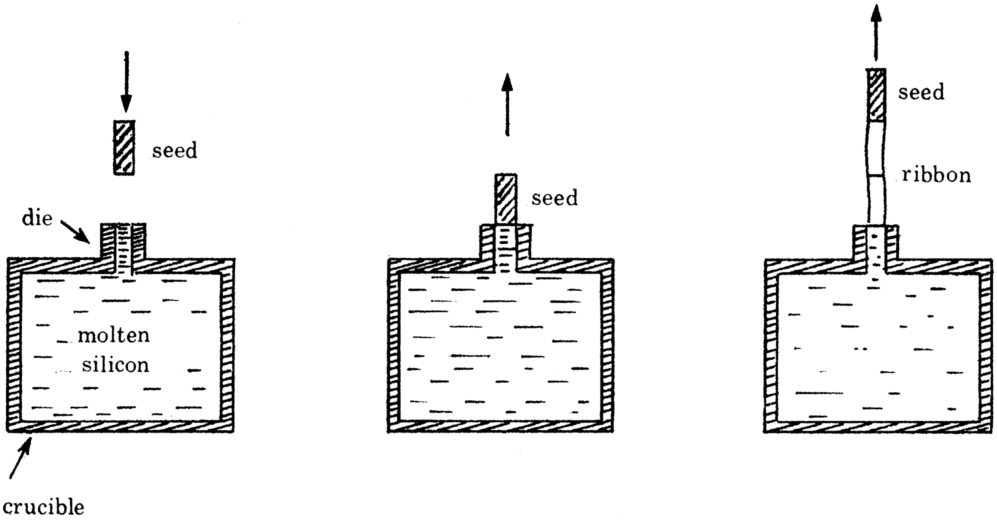

FIGURE 4. E.f.g. ribbon growth method. The molten silicon creeps by capillarity into the vertical die. The single crystal flat seed enters in contact with the molten silicon, and is then pulled.

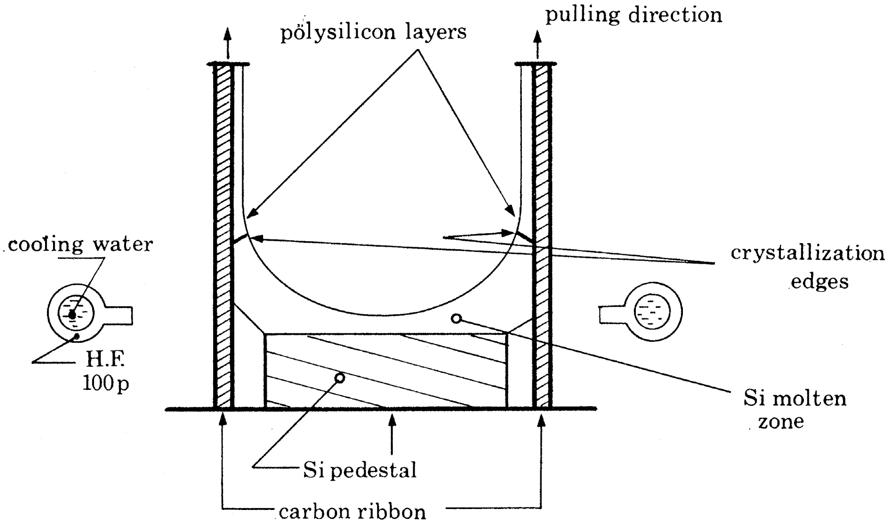

FIGURE 5. Silicon coating. Two or more flexible carbon ribbons are in contact with a silicon molten zone. By pulling the ribbons upwards, a controllable film of silicon is deposited on the carbon substrates.

(v) The 'dendritic' growth. This rather old method, which works rather well with germanium, has never been abandoned for silicon at Westinghouse Laboratories. Webs several feet long and 3 cm wide have been reported (Seidensticker *et al.* 1978). The efficiency of the cells is excellent (up to 16 %), but the reproducibility of this technique seems difficult to control, and the growth rate is slow.

Apart from this sampling of the polysilicon growing methods, many others are under tests, and many more will probably be imagined. Except for the first one, which is rather straight forward but potentially not as cheap as the others, the winner, if any, is still unknown.

From a scientific point of view, it is quite remarkable to think that the grain boundaries of polysilicon are not as harmful as expected. A few years ago, no expert would have guessed that 14 or even 16 % conversion efficiencies could have been achieved with such materials: one had imagined that grain boundaries would have trapped the carriers, or even worst, would have produced low resistivity short-circuits through the layer. All the interesting polysilicon technologies yield truly 'monograin' structures, where there is a single crystalline grain within the thickness of the sample, and grain boundaries are perpendicular to the layer: in practice, one gets hundreds or thousands of little cells in parallel, with a mosaic structure.

## 6. Amorphous silicon

This material has been 'rediscovered' recently in Great Britain, as being a potential thin film photovoltaic material. The novelty lies in a strong hydrogenation of the silicon free valences, thanks to a decomposition of silane or a cathodic sputtering in a hydrogen low pressure atmosphere. Very soon, efficiencies of 5 % were reported (Carlson & Wronski 1976), by using Schottky diode technology. However, little practical progress has been made since. But the understanding of the semiconductor mechanism of this 'alloy' has been extensively carried in many countries. It seems that several types of 'a-Si (H)' – amorphous silicon-hydrogen compound – exists, and among these at least one behaves like a true semiconductor. We are there facing a new category, the IV–I semiconductor. This material is potentially very cheap, because of its extremely low thickness (micrometre), and so fundamental research can perhaps bring it up to acceptable efficiency (10 % or, according to some authors, up to a theoretical value of about 15 %). The field is still wide open.

## 7. An alternative solution: optical concentration

Optical concentration is attractive: the amount of photovoltaic material is reduced by a factor which, depending on the system, can lie between a few units to 100 or even 1000 (with gallium arsenide). However, this is somewhat compensated by the cost of the tracking device, if any, and of the mirrors or lenses used. Furthermore, concentrating photovoltaic systems can only be used in clear-sky climates, and are unsuitable for Northern countries.

Refined technologies allow the use of special silicon cells up to concentration ratio of 20–30 with natural air cooling around radiators, and up to 100 with water cooling (the water, which can be maintained around 70 °C, can be used for heating purposes). Owing to this higher temperature, cell efficiencies lie, at most, around 12 %, and optical losses bring this figure closer to 9 or 10 %.

For very low (a factor of 3–5) concentration ratio, seasonally tilted systems are recommended: they consist generally of E–W oriented troughs, either with flat mirrors, or cylindro-parabolic mirrors. Linear Fresnel lenses are also in use.

For medium concentration (up to 30), one-axis tracking system and linear focusing are preferred. For higher values, a true sun-tracking two-axis mechanism is required with a point focusing. This last system currently seems the most promising one, in spite of a more complicated mechanical device. Plastic Fresnel lenses are generally used, and are fabricated today in rather large sizes (up to half a square metre).

One expects that, if such systems are industrially developed (and they are not today), a figure of $5 per watt-peak could be achieved, with a possible added value for hot water. However, if this technology is not exploited very soon, the progress expected in the flat arrays technology will beat the concentration method. Furthermore, the operating costs of concentrating systems are expected to be higher: for instance, nobody really knows how reliable the mechanical parts are, and whether such generators can be left unattended for a long period of time.

## 8. THE INFLUENCE OF THE ENERGY CONVERSION EFFICIENCY

Until a few years ago, there was a widely spread opinion according to which the efficiency of the conversion was relatively unimportant if very low cost materials were to be achieved: more refined value analysis shows that, for a complete photovoltaic generator, the fixed cost per unit area (i.e. costs that are independent of the nature of the active material) are far from negligible. These fixed costs comprise, on one hand, the price of the encapsulation, on the other hand, the cost of the land, the metallic supporting structure, and possibly the electrical wiring. For a given power, they become smaller when the intrinsic efficiency of the material and the packing factor within the panel increase.

On a medium term basis, the encapsulation materials may cost at least £20 per $m^2$; a simple structure, as mass-produced for greenhouses, costs about £10. Installation and wiring may bring the total up to £40 per $m^2$. Figure 6 shows the overall 'panel efficiency' (cell efficiency multiplied by the packing factor) plotted against the cost of the active photovoltaic material for different energy prices (assuming 20000 h equivalent peak-power lifetime and 10% capital depreciation per year). It shows how high-efficiency materials, even if they cost nothing, penalize the final price of energy.

## 9. THE PROSPECTS FOR PHOTOVOLTAIC GENERATORS

Photovoltaic electricity is currently unbeatable for small power stations, up to 1 kW, in remote areas: beacons, telecommunication links, television sets, even small pumping units, represent the major part of the commercial market. At such a small level, the storage problems with lead batteries can easily be solved.

As prices go down, the upper limit of the generator power will go up. Between $3 and $5 per peak-watt, Diesel engines of 100 kW or more will certainly be beaten by photovoltaics in remote villages and cities of developing countries, where electricity currently costs anything between 20 and 50 pence, reaching £1 per kWh in some places. The storage problem becomes serious at this level, and may represent an important part of the investment (about £50 per kWh stored).

If prices still continue to decrease, down to \$1 (or even \$0.5) per peak-watt, real power generating plant can be envisaged. Electrical storage becomes practically impossible (one can think of an indirect hydrogen storage). Electricity would then be produced at competitive price, if the electrical grids can cope with the random fluctuation of the solar production. Hydroelectricity complements very well the poor reliability of solar electricity: for instance, the southwest American electrical network is said to accept at least 15% of solar electricity without storage, the dams acting as buffers: solar electricity becomes then a kind of 'water conservation' system for hydroelectrical plants. Not all the countries have such favourable conditions; nor do they enjoy the sunny climate of Arizona. These factors can probably explain the exceptional enthusiasm of the U.S. Government for photovoltaics.

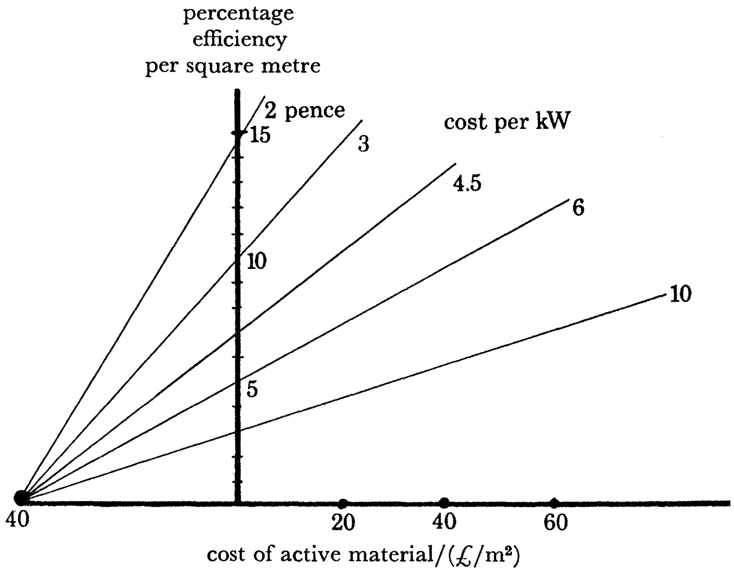

FIGURE 6. Influence of fixed costs on panel efficiency.

Nevertheless, even if such ambitious goals are not to be achieved, the more limited and more conventional markets for photovoltaic systems, especially in the developing countries, offers already a very large interest, which justifies the efforts and hopes of the scientific and industrial communities.

## REFERENCES (Durand)

Belouet, C., *et al.* 1978 *Proc.* 13*th IEEE Photovoltaic Specialists' Conference*, pp. 131–136. June 1978.
Buhs, R. 1978 *Proc.* 13*th IEEE Photovoltaic Specialists' Conference*, pp. 262–267. June 1978.
Carlson, D. E. & Wronski, C. R. 1976 *Appl. Phys. Lett.* **28**, 671–673.
Chu, H. Li 1978 *Proc.* 13*th IEEE Photovoltaic Specialists' Conference*, pp. 294–297. June 1978.
Mackintosh, B. H., *et al.* 1978 *Proc.* 13*th IEEE Photovoltaic Specialists' Conference*, pp. 350–357. June 1978.
Seidensticker, R. G., *et al.* 1978 *Proc.* 13*th IEEE Photovoltaic Specialists' Conference*, pp. 358–362. June 1978.
U.S. Congress 1978 *Solar photovoltaic energy research, development and demonstration Act of* 1978. U.S. Congress HR 12874.

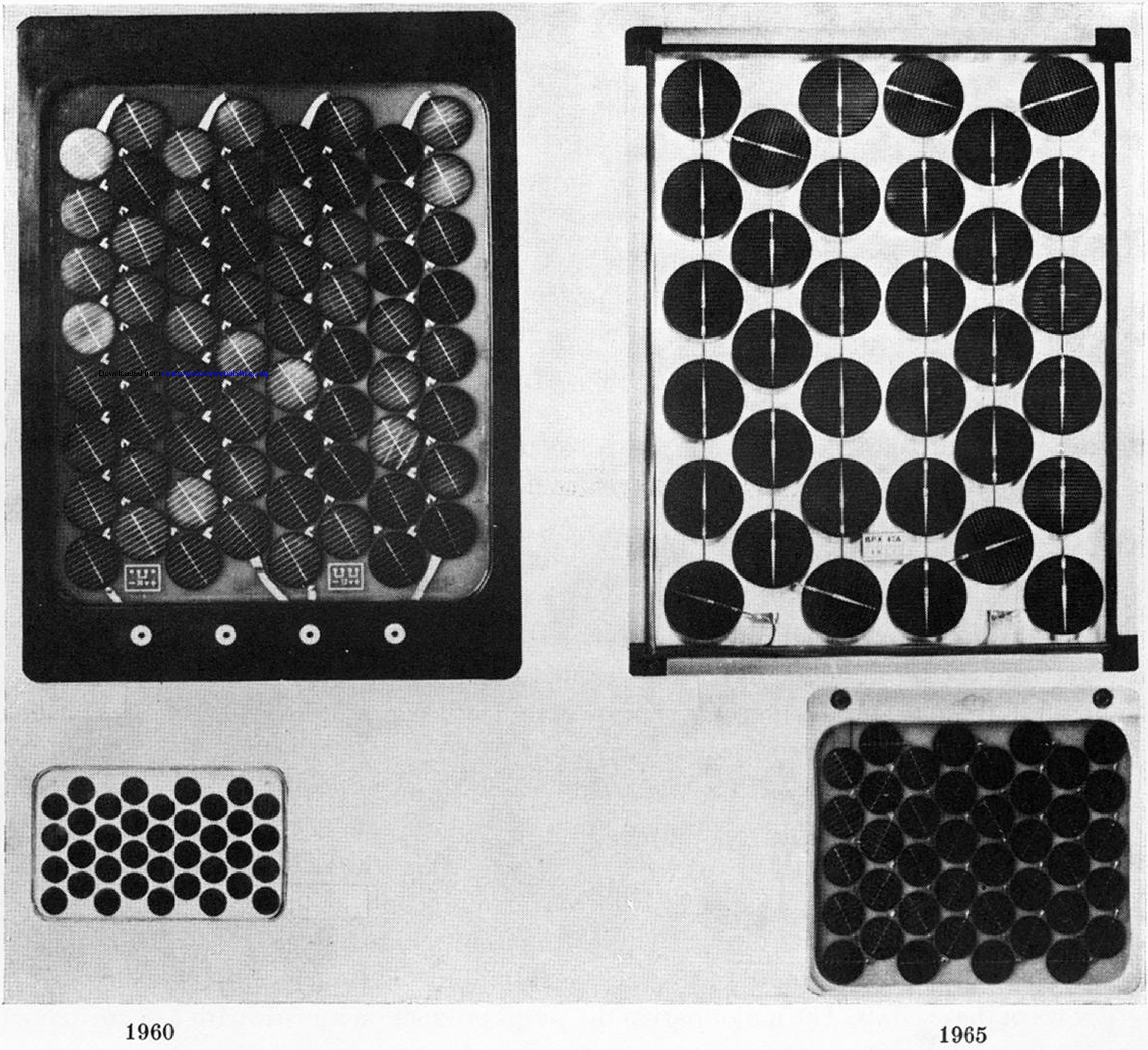

FIGURE 2. The area of cells has increased tenfold between 1960 and 1975.