HISTORICAL DEVELOPMENT OF SOLAR CELLS

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Introduction

One hundred and thirty-three years have passed since it was first observed that the mere incidence of light can generate a voltage in a suitable structure, ninety-six years, since the first solid state photovoltaic device was made, and a mere sixteen years since production lines have been opened to produce such devices for the utilization of solar energy. None of these anniversaries is a nice round number which would give reason for commemoration, such as the twenty-fifth recurrence of the Power Source Symposium. However, the importance of the solar cells as the prime power source for man's-endeavors in space, and the expectation that they may, some day, also form a key power source on earth, as the resource and environmental problems associated with the present fossil and nuclear energy sources continue to increase, warrant a review of the history at this occasion.

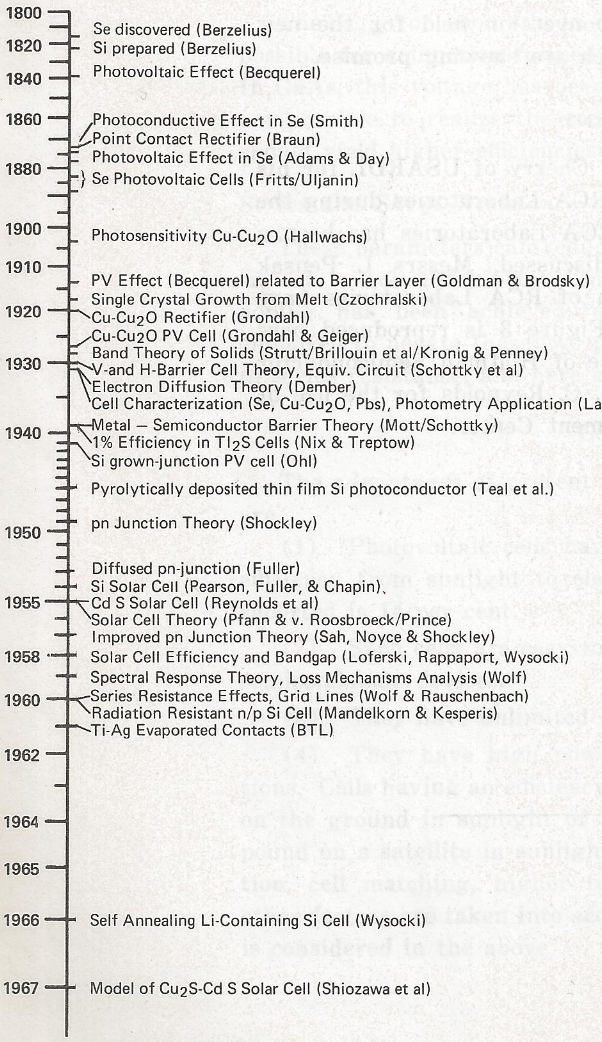

Table 1. Key events in the development of solar cells.

In the time available only a few of the key historical events can be mentioned. The emphasis will be placed on recent developments and on data which are not generally available.

Basic History

The key events in the development of photovoltaic solar energy conversion devices have been collected into a table which is logarithmic in time (Table 1). It becomes immediately apparent from the rather uniform density of milestones that the frequency of contributions has increased in an approximately exponential manner until the recent past. This corresponds to the general trend of science and technology development during this period. Also evident is a relative starvation of events during the last ten years, which is attributable to an — at least temporary — level of maturity reached in this field.

The discovery of the basic effects behind the operation of solar cells has taken a span of approximately 100 years, starting with the discovery of selenium in 1817 by Berzelius, who was also the first to prepare elemental silicon. This was followed by the discovery of the photovoltaic effect in electrolytic cells by Becquerel in 1839, and the discovery of photoconductivity in selenium in 1873 by Willoughby Smith. This latter event spawned a flurry of activity which included the discovery of the spectral sensitivity of selenium photoconductors, the proposal of a light meter, and the observation of the photovoltaic effect in a solid-state selenium structure by Adams and Day in 1876. Seven years later, the first selenium photovoltaic cell was described by Fritts, who two years later also attempted the first simulation of the human eye response by a combination of selenium cells and color filters. Then, in 1904, the photosensitivity of copper cuprous-oxide structures was observed by Hallwachs, and in 1914, the photovoltaic effect was for the first time connected with the existence of a barrier layer.

With these discoveries the foundation was laid for the further development of a photovoltaic device technology. However, more than a decade elapsed before a new period of concerted activity started. The development of the copper/copper-oxide rectifier has led to new interest in this structure for photovoltaic devices. Consequently, their characteristics were carefully explored, frontwall and backwall cells developed, and first theories for their operation developed. In the course of this work, the equivalent circuit was established

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which is still in common use. Applications for the new device were developed, primarily in photometry and light control systems, and production lines started. On the heels of the development of the copper/copper-oxide photovoltaic device followed the perfection of the corresponding selenium device which quickly exceeded the performance of the former device by about an order of magnitude and consequently, replaced the copper/copper-oxide photovoltaic devices. Solar conversion efficiencies of approximately 1% were ultimately achieved with the selenium frontwall devices, a value which was also reached with the thallium-sulfide photovoltaic device developed around 1941.

With the progressing development of the silicon technology, the "grown pn-junction" technique led to the preparation of a single crystal silicon photovoltaic device in 1941. However, it was not until the impurity diffusion method of pn-junction formation had been developed twelve years later, that the silicon solar cell became a practical device. A conversion efficiency of 6% was achieved in the first year, and within another two years, private industry started producing the devices with the hope for significant markets. Fabrication process improvements, improved understanding of the theory of device operation and, accordingly, improved design of the device led to gradually increasing efficiencies which reached approximately 14% in terrestrial sunlight by 1958. From that point on, the prime engineering effort has shifted towards adapting the cells better to their use for space power systems, toward improving their reliability and, in particular, their resistance to nuclear particle radiation, and, by no means least, reducing their fabrication cost.

At this time, effort towards solar cell development is being spent significantly only on silicon solar cells. What happened to solar cells from other materials?

As was seen, the development of cells made from materials other than silicon was started with the Cu-Cu_2O photovoltaic devices which were in due time supplanted by the selenium cells. Significant runs of these cells were manufactured at various producers.

Considerable development effort, in magnitude not much less than that spent on silicon solar cells, has been expended towards the development of cadmium sulfide, cadmium telluride, and gallium arsenide solar cells. The gallium arsenide solar cell held promise first as a higher efficiency device, and later as a device which is more favorable in high temperature operation. The cadmium sulfide and cadmium telluride devices held promise for their potential for fabrication in thin film form at low cost.

The gallium arsenide solar cell was never able to pass the silicon device in efficiency at room temperature. Its development was hindered by the high absorption coefficient connected with the direct bandgap of gallium arsenide, which resulted in junction formation and contact difficulties, and by the high price of the raw material. The cadmium sulfide device showed promising initial efficiences as a single crystal device. As a thin film device, its efficiences are lower, but not so much as to be completely discouraging. This marginal efficiency, combined with reliability problems, have prevented the acceptance of this device for space applications, despite its proven high radiation resistance. It is questionable, whether realization of the promised low cost would have changed this situation. The cadmium telluride device, finally, has lacked in all three of the attributes: efficiency, reliability, and cost. Effort has also been spent on other materials and on variations of device structure, both on silicon cells and on compound semi-conductor devices.

When the silicon solar cells appeared on the scene, they were thought to find a large market in terrestrial applications, first replacing the selenium cells which exhibited lower performance, fatique phenomina, and limited operating lifetime. It turned out however, that the spectral response of the selenium cells made them ideally suited for applications in photographic light meters and in general photometry. The higher output of the silicon cells was largely based on their broader spectral response. In order to reduce this to the "standard observer curve," optical filters are necessary, the addition of which made the silicon cell quite uncompetitive. Even in other applications, the positive attributes of the silicon cells did, in most instances, not outweigh their price disadvantage. And how about their use as solar energy converters? The workers at Bell Telephone Laboratories originally foresaw a splendid future for the device as a terrestrial solar energy converter, and they intended to prove this capability of the device by installing a solar cell array on a telephone pole in Georgia to power a repeater amplifier. This array fulfilled its function satisfactorily for over a year, with bird droppings the only problem encountered. However, based on the original installation costs, the cost of the energy generated was not competitive with conventional power.

Looking at this situation with the eyes of a modern research manager, but with the information potentially available in the mid-nineteen-fifties, it would appear that research money has been wasted in developing the silicon solar cell. A small market research study would have shown that the application of the device for terrestrial solar energy conversion could not have been competitive in most applications, including the one tested by the Bell Telephone researchers. Telephone communication lines will mostly be placed in reasonably populated areas, where power lines also are relatively available. Furthermore, since the telephone amplifier was used in a wire communications system, it might have been more economical than using solar cells, to supply the necessary power by "duplexing" methods over the same wires which carry the communications. And the two semiconductor device companies which opened production lines for the silicon solar cell in 1956 also did not do any market research before entering into the new venture, and they addressed the wrong market.

But now comes the irony: nobody at that time foresaw the impending budding of the space age, and nobody realized that the solar cell is the unique device to provide significant amounts of power in space for long time periods at minimal weight and cost. In the early planning for the space program, the decision makers apparently considered the solar cells as an insignificant and unreliable curiosity, and decided to equip the United States' spacecraft with chemical batteries which were able to provide power only for a few weeks. Thus, there was no reason to spend development effort on solar cells for purposes of the space program. A few engineers at the United States Army Signal Corps, Fort Monmouth, N.J., however, were sufficiently innovative and were also given enough engineering freedom to incorporate six small groups of the then commercially available silicon solar cells on the 6″ diameter Vanguard I satellite to power its 5mW back-up transmitter. They did not realize the implications of the long life of the silicon solar cells, since they did not provide a shut-off device for the transmitter, so that the satellite cluttered up a radio band for over six years.

Now, the Russians launched, in May 1958, a much bigger spacecraft powered by solar cells, only two months after the launching of Vanguard I. This satellite operated for over two years. In the meantime, we continued for another year and a half to launch 22 satellites equipped with electrochemical batteries. Then the turnaround occured rapidly, so that from that moment on, essentially all spacecraft with a mission duration of more than a couple of weeks derived their prime power from silicon solar cells. The solar cell power system of that time had an installed capacity of up to 150 Watts. However, since the solar panels were non-oriented, the actual output was only a small fraction of the installed capacity.

It was assumed at that time, that solar cell power supplies could be only of small size — up to approximately 200 Watts — and that other power sources would have to be developed for spacecraft requiring larger power supplies. This number has gradually been pushed upward, to approximately 500 Watts by 1963, which was attained on the Nimbus Spacecraft, launched in August 1964, to be followed soon by close to 1000 Watts installed power on the Orbiting Astronomical Observatory (1966), and 1-½kW installed on some Air Force satellites. At present, the Orbiting Laboratory is under construction, which, including the Appollo Telescope Mount, will have an installed solar photovoltaic capacity of 20kW, and under consideration for the manned Space Station are solar power arrays with a capacity of 100kW. Thus, an upper limit to the size of photovoltaic solar converter arrays in space does no longer appear to exist, and further increases in size seem to be merely mechanical and electrical engineering problems.

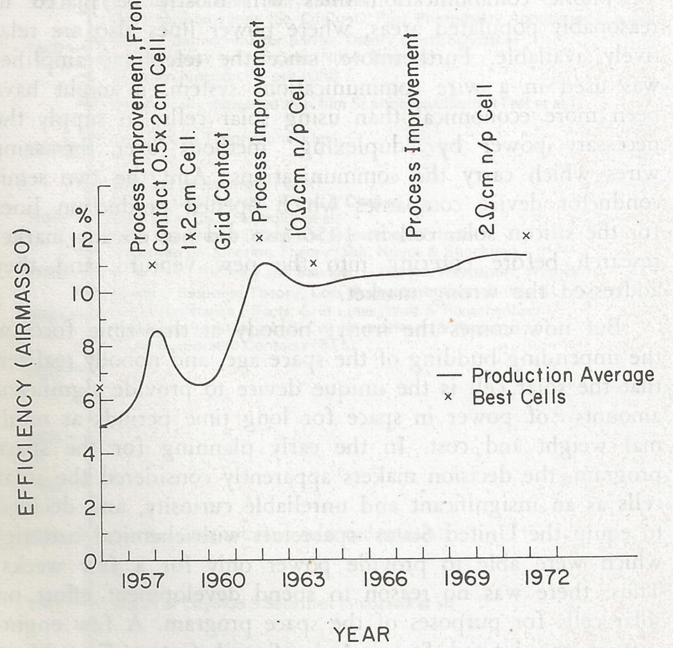

Figure 1. Historical development of silicon solar cell efficiency, with indication of the main influences which caused efficiency changes.

Thus, a new unforeseen market has developed, which has, up to this time been the only significant one for solar cells. Figures 1 to 5 provide a few data about the development of the device in this market, from the efficiency, quantity, and cost viewpoints. Such data are, for competitive reasons, not collected in any statistically meaningful way. The data of figures 1 to 5 represent therefore educated estimates, which do not include any of the short term fluctuations which are so bothersome to the manufacturers.

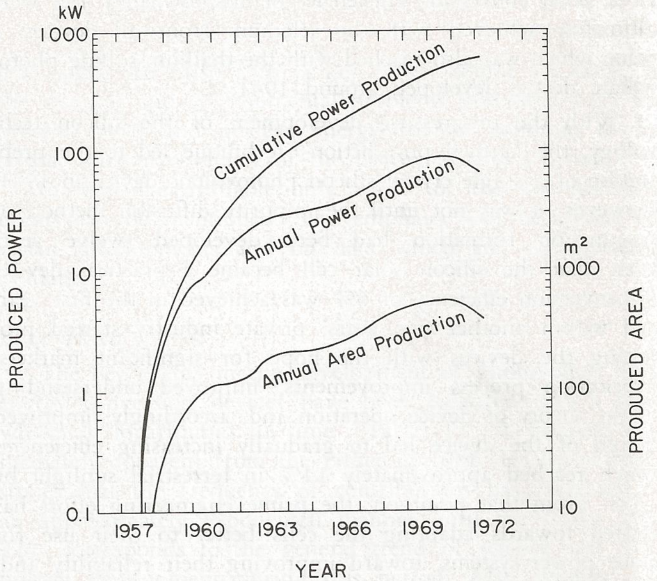

Figure 2. Historical development of the annual production of silicon solar cells in terms of area produced and of potential power output. Also shown is the cumulative production in terms of potential power output.

Figure 1 presents the development of the efficiency of silicon solar cells, both for the production average and the best cells. The rapid improvement in efficiency during the first two years was primarily based on abandoning the circular cells with large wrap-around areas, which exhibited high series resistance, and on concentrating on narrow rectangular cells (0.5 x 2 cm) of low series resistance. Also, considerable progress was made in general control of the fabrication process, so that at the end of this period, individual cells were made which were nearly as good as the best obtainable now. Since it was too cumbersome to assemble the large numbers of the 0.5cm wide cells, the users perferred the 1x2cm configuration which however, exhibited lower efficiency due to increased series resistance. This caused a dip in the average efficiency by 1959. The subsequent introduction of the contact grid remedied this situation, and, together with further process improvement, the production averages reached 11% efficiency at air mass 0 by 1961, while the best cells improved only slightly over those obtained four years earlier. Then came the realization of the considerably greater resistance to nuclear particle radiation in space of the high resistivity "n on p" silicon cells, compared to the prior "p on n" cells. Their general acceptance led to the drop in production efficiency seen around 1963. Further process improvement over the next six years brought a gradual efficiency increase, which was followed by a step increase due to a larger scale return to a lower resistivity.

Figure 2 presents plots of the development in total annual production of silicon solar cell area and power output, as well as of the cumulative power output of the silicon solar cell produced. Understood under the word "production" are here the cells sold, not including the cells of low output or other defects. It is evident that the production has increased rapidly until 1962, and since 1968 leveled off at approximately 70kW per year. The cumulative production of silicon solar cells amounts to approximately 600kW at the present time.

Figure 3 shows the distribution of production over the various manufacturers, based on the area produced annually. It is seen that originally there were two manufacturers, one following the first with a delay of about ½ to 1 year. But then, in a span of three years, three additional manufacturers entered the field. With an essentially saturated market, this led to great overcapacity. As a result, within five years, three manufacturers had left the field which now again is served by two producers.

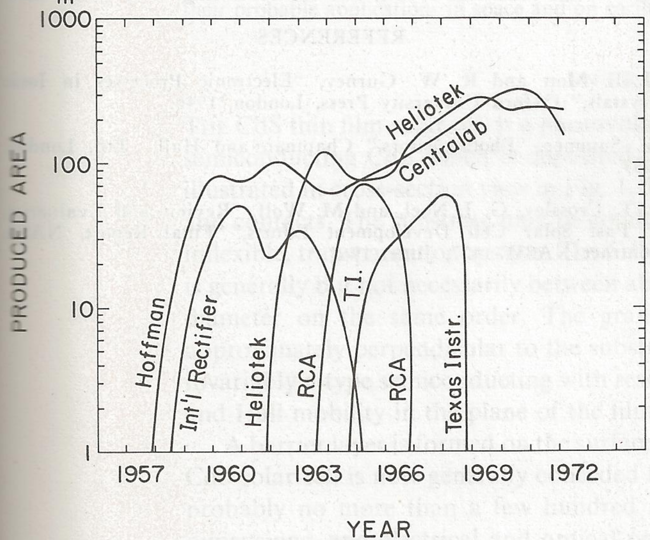

Figure 3. Estimates of the annual production of silicon solar cells by the various manufacturers in the United States of America, given in terms of area produced.

Figure 4 shows the cost development of the cells, both on the unit area and the unit output power basis. In 1956, large circular cells were fabricated to address the terrestrial market. Their price was relatively low, partially based on the large area of each cell (~7cm²), but probably also partially caused by insufficient knowledge of the true costs. With the shift to the 0.5 x 2 cm cells, costs increased drastically. However, based on their higher efficiency, the cost per unit output power did not change as greatly. Then, with larger quantity production, process rationalization, and fabrication of the 1 x 2 cm cell, the price decreased considerably until about 1960. Subsequently, with greater customer emphasis on higher efficiency and on cell quality in general, the prices stabilized temporarily. Then, overcapacity exerted further price pressures. Continued production rationalization, shift of production to larger area cells (2 x 2 cm and 2 x 6 cm) have permitted further price reduction to the present level of approximately $0.90 per cm² or $60.-per Watt. Figure 5 finally presents the cost data in form of the "learning curve."

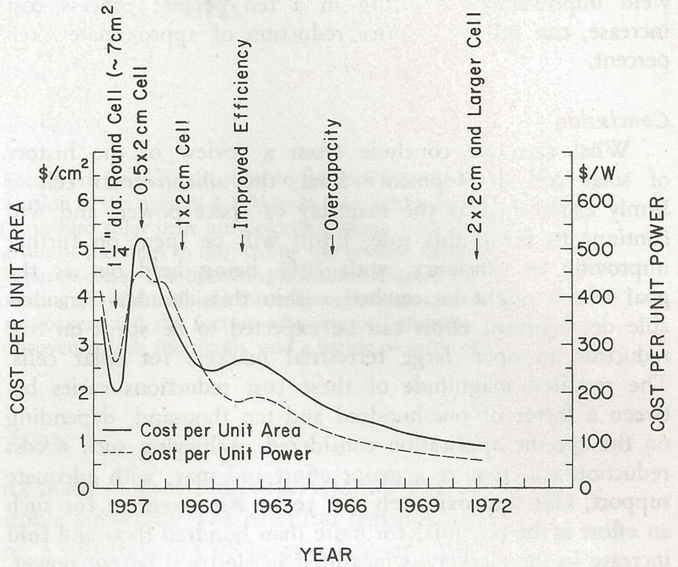

Figure 4. Historical development of silicon solar cell price per unit area and per unit potential power output, showing the identifiable events which caused price changes.

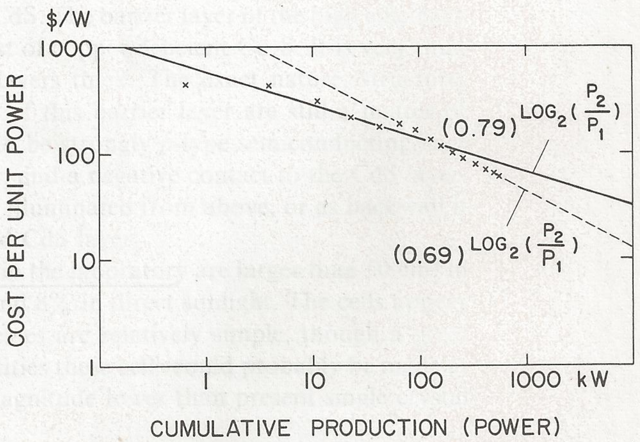

Figure 5. Cost of silicon solar cells plotted as function of cumulative production in term of potential power output (learning curve).

One area of great importance can only be sketched here. This area is the development of the production processes, which are responsible both for the performance achievable on the production cells and for their prices. Key accomplishments in this area include the continuous refinement of control of the diffusion processes to both obtain improved device performance and to process larger numbers of wafers simultaneously, the introduction of the large capacity slurry sawing technique, which causes less crystal damage and permits economical fabrication of large wafers, and the improvement of the crystal growing techniques to yield ingots up to several kilograms in weight. Most closely connected with all these production methods is the improvement of yield, the prime objective in the fabrication of any semiconductor device. A cost reduction in any process step can be useless if it results in lower yields. Conversely, a twenty percent yield improvement resulting in a ten percent process cost increase, can provide a price reduction of approximately ten percent.

Conclusion

What can one conclude from a review of the history of solar cell development? First, the silicon solar cell is firmly established as the mainstay of space power, and will continue to fulfill this role. Effort will be spent on further improving its efficiency, with 20% being held out as the goal which might be reached within this decade. Considerable development effort can be expected to be spent on cost reduction to open large terrestrial markets for solar cells. The required magnitude of these cost reductions varies between a factor of one-hundred and ten thousand, depending on the specific application considered. Achieving such a cost reduction will require a major effort and may, with adequate support, take approximately ten years. An incentive for such an effort is the potential for more than hundred thousand fold increase in the market, as measured in electrical output power.

What will happen with other solar cell materials? The cadmium sulfide thin film cell is a strong contender for the terrestrial solar cell market. It has the potential of reaching the cost goals more easily than the silicon cell. However, it will first have to be fully established that the reliability and operating life of the cadmium sulfide thin film cell are adequate. Further improvements in the efficiency of the device will ease its acceptance. Barring unsurmountable problems, it can be expected that these three goals will also be achieved within the next ten years, provided adequate support is given.

As the history of the solar cell has shown so clearly, the development of events can easily differ from forecasts made on the basis of insufficient information. Therefore, a reasonable amount of research and development on other solar cell approaches and other materials should be continued, until sufficient information has been acquired to permit decisions to accelerate or decelerate further efforts in specific areas.

ACKNOWLEDGEMENT

The author wants to express his thanks to Messrs. W. Cherry, K. Ling, and E. L. Ralph for helping to refresh his memory on some of the historical events, and for reviewing some of the data.

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