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Czochralski-Silicon Solar Cell Arrays: Present Costs And Future Prospects

Robert M. Moore

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A Division of Midwest Research Institute

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PREFACE

A multipath learning curve model is proposed to characterize the price dynamics for terrestrial Czochralski-silicon solar cell arrays. This is successfully tested against the actual price evolution over the period 1974-1979.

Based on the successful modeling of this historical period, the multipath learning curve model is then used to forecast the 1985 array price. This forecast utilizes the (DOE/JPL) LSA Project production growth goals.

Finally, the impact of the resulting price and annual sales on the semiconductor and solar cell array industries is extrapolated, and the implications for industry structure and industrial R&D focus are developed.

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Approved for:

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SUMMARY

OBJECTIVE

To develop a multipath learning curve model of the transition of Czochralski-silicon solar cell arrays from a satellite-application-product to a terrestrial-application-product.

To test the validity of this model, by applying the historical data for the initial period of this transition (viz., 1974-1979).

DISCUSSION

Following the success of the multipath learning curve model in predicting the price dynamics for 1974-79, forecasts are made for 1980-1985. The results are a set of forecast prices for each year corresponding to estimated confidence levels of 10%, 50%, and 90%. The forecasts for 1985 (in 1979 $'s) are:

- $2.2 per peak watt .... at 10% estimated confidence level.
- $3.1-$3.2 per peak watt .... at 50% estimated confidence level.
- $4.8 per peak watt .... at 90% estimated confidence level.

CONCLUSIONS AND RECOMMENDATIONS

Based on the solar cell array price forecasts, and the associated market value forecasts, the near-term (1985) outlook for industrial investment can be summarized as follows:

- The 1985 Czochralski-silicon solar cell array business does not represent an attractive investment for the major companies involved in silicon materials or device/integrated circuit manufacture. Significant resource commitment cannot be reasonably expected from this sector until the late-1980s, if at all.
- The 1985 solar cell array business represents a very attractive market for small companies presently in this market. The intrinsic resource base of such companies is too small, however, to support the required investment level over the 1980-85 period. To participate in this growth industry, they must acquire financial backing from venture capital or major energy corporations.

Recent developments indicate that several of the international energy corporations have decided to make the major investments that are required to develop the Czochralski-silicon solar array technology base.

If an alternative route of development, based on 100-micrometer thick Si ribbon/sheet/web technology is taken, then there is expectation of about 5-to-1 reduction in cost per square meter for the Si material. However, a strong commitment to this technology is realistic only if the solar cells produced from this material have an efficiency competitive with Czochralski wafer-based cells, or if the cell-processing and/or array-assembly costs can be substantially reduced relative to the Czochralski technology.

A primary conclusion is that the form (e.g., wafer vs. ribbon) of Si-crystal material chosen for emphasis is less important than the R&D emphasis that must be placed on reducing the "core" cost element—the high-purity polysilicon feedstock.

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SECTION 1.0

INTRODUCTION

The present technology for "terrestrial" Czochralski-Si solar cells is an adaptation of the processing developed and standardized for space/satellite power supply applications. This technology is in turn dominated by the processing techniques created by the general semiconductor industry. The reason for this technology dominance is the relative size of the current markets for these products. The relative importance of 1979 factory sales of terrestrial solar cells, space/satellite solar cells, semiconductor devices/integrated circuits, and Czochralski-Si wafers can be summarized as follows:

- Low-cost solar cell arrays produced specifically for the "terrestrial" marketplace are estimated to have a 60% share of the total solar cell array market value.
- Solar cell sales represent 0.2% of the total semiconductor industry annual market value.
- Solar cell usage of Czochralski-Si wafers represents a 3% share of the total Si wafer annual market value.

Under these circumstances, there has been little incentive for the major semiconductor device or materials companies to commit resources to the development of solar cell and array technology, and the field has been left to smaller companies that target specialized market areas.

There is a slightly different perspective from the standpoint of national energy needs. Exhibit 1 illustrates this point for the year 2000 [1,2,3,17]. The market value has increased by a factor of 400; the market is dominated by terrestrial applications; the energy production is a significant fraction of national electrical energy consumption; and the energy cost to the user has dropped by a factor of 20-50.[a] At this point, the sales of solar arrays would still be a small fraction of the total semiconductor market—perhaps 2.5%. However attractive this potential total market of $10 billions may appear in absolute terms, the uncertainty and delayed payback associated with a market this far into the future limits the possible commitment of industrial resources by those companies that plan to participate in the total semiconductor market of $600 billions in the year 2000.

The near-term outlook is far more important for industrial planning. One view of the prospects for 1985 is presented in Exhibit 2 [3]. At this point, much of the evolution cited for the year 2000 is already well under way—the factory sales are about 1% of the total semiconductor market, the terrestrial share of the total solar array market is about 95%, and the end-user energy cost has dropped by a factor of 5-10. The basis for this transition is a growth in annual unit demand for terrestrial solar cell arrays that exceeds a factor of 100, and an associated reduction in manufacturing costs through technology improvements and automated processing.

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[a] All costs, annual sales values, etc., in this paper are quoted in constant "1979 dollars."

Present Market
1979

- Sales: $27 millions.
- Predominately terrestrial applications (ca. 64% share).
- Negligible % of annual national energy supply.
- Energy cost: 0.9-$1.3/kWh.

Long-Range Prospects
2000

- Sales: $10 billions.
- Dominated by terrestrial power applications (>99%).
- 20% of annual electrical energy consumption.
- Energy cost: 3¢-7¢/kWh.

Exhibit 1.

Near-Term Outlook
1985

- Potential factory sales: $500 millions.
- Predominately terrestrial power applications (ca. 95%).
- Less than 0.1% of annual US electric power consumption.
- Energy cost to user: 15¢-40¢/kWH.
- Basis for estimates:

  Annual demand - 240 x 10^6 peak watts/year

  Factory selling price - $2.2/peak watt

  End user cost - $4.4/peak watt

  Cost of capital - 10%, amortized over 7-year period

Exhibit 2.

An overview of one possible trend in solar array costs through 1985 is presented in Figure 1. Because of the inherent uncertainty of such predictions, the costs are presented with estimated confidence levels. The basis for these cost estimates is presented in detail in a later section.

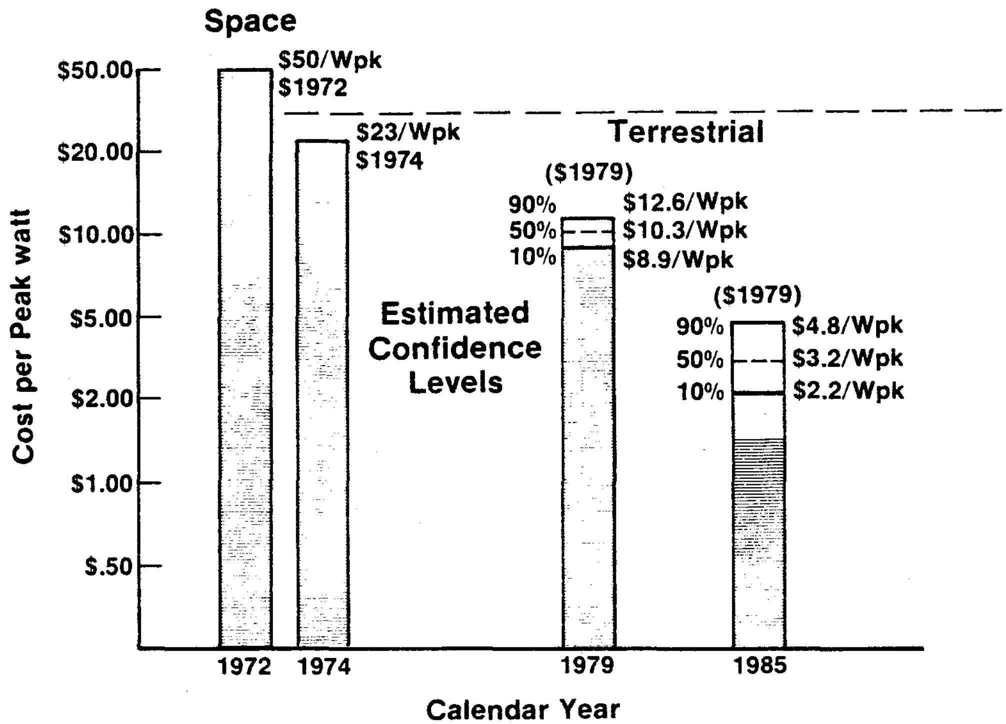

Figure 1. Overview of Solar Array Costs

The predicted effect of the increased production volume, technology improvement, and process automation on the cost structure for terrestrial solar arrays is illustrated in Figure 2. A clear transition is shown from a cost structure dominated by labor-intensive processes (i.e., array-assembly and cell-processing) to a cost structure dominated by the direct materials cost—as represented by the Czochralski-Si wafer plus direct materials for cell processing and array assembly.

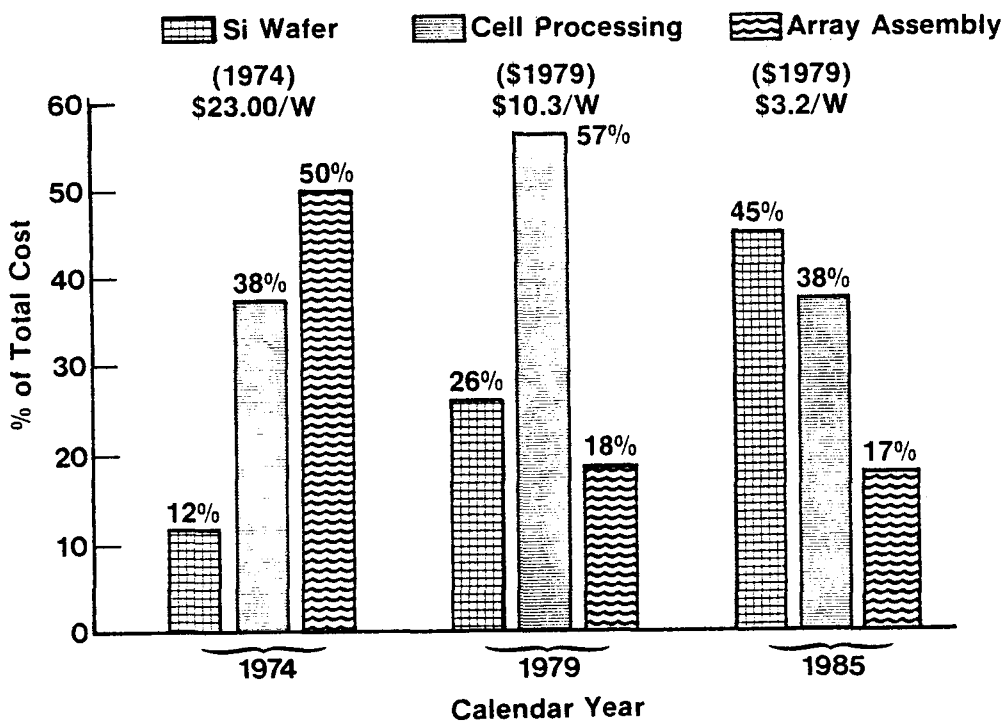

Figure 2. Terrestrial Array Cost Structure (1979 and 1985 @ 50% Confidence Level)

In the following five sections, the background and development of these Czochralski-Si Wafer-cell-array cost estimates are presented in some detail. The last two sections examine the potential industrial impact of these projected developments.

SECTION 2.0

BACKGROUND

Between 1972 and 1974 the quoted cost for Si-wafer solar cell arrays, in large quantities, underwent a reduction of approximately 55%. As shown in Table 1 [2,5-7], the cost reduction can be viewed concisely by a breakdown into the costs associated with the Si-wafer, the cell-processing, and the array-assembly-and-encapsulation operation.

Table 1. 1972 and 1974 Cost Structures

	1972 Costs ($/m²)	1974 Costs ($/m²)	Decrease (%)
Single-Crystal Si Wafer	2000	290	-85
Cell Processing	2700	870	-70
Array Assembly & Encapsulation	2000	1160	-40
Total	$6700/m²	$2320/m²	-65%
Peak Output	140W/m²	100W/m²	...
Factory Price	$50/peak watt (1972 $'s)	$23/peak watt (1974 $'s)	-55% (Relative to current $'s)

The largest percentage decrease occurred for the Si-wafer cost. This was primarily the result of relaxing the satellite-oriented specifications and requirements in three respects: (1) use of full wafer area rather than 2 x 4 cm slab; (2) use of "chemical polish" rather than specular "optical finish"; and (3) relaxation of resistivity limits to permit fuller use of crystal boule volume. The cost reductions in the cell-processing and array-assembly-and-encapsulation tasks were obtained through similar relaxation of space-oriented specifications that were not cost effective for terrestrial applications.

The effect of this "terrestrial evolution" on the cost structure of Si solar cell arrays is illustrated in Figure 3. A transition has been made from the relatively evenly distributed cost structure of 1972, which essentially represents space design, to the distribution of 1974, which is dominated by labor-intensive processes, with the Si-wafer cost limited to approximately 12% of the total.

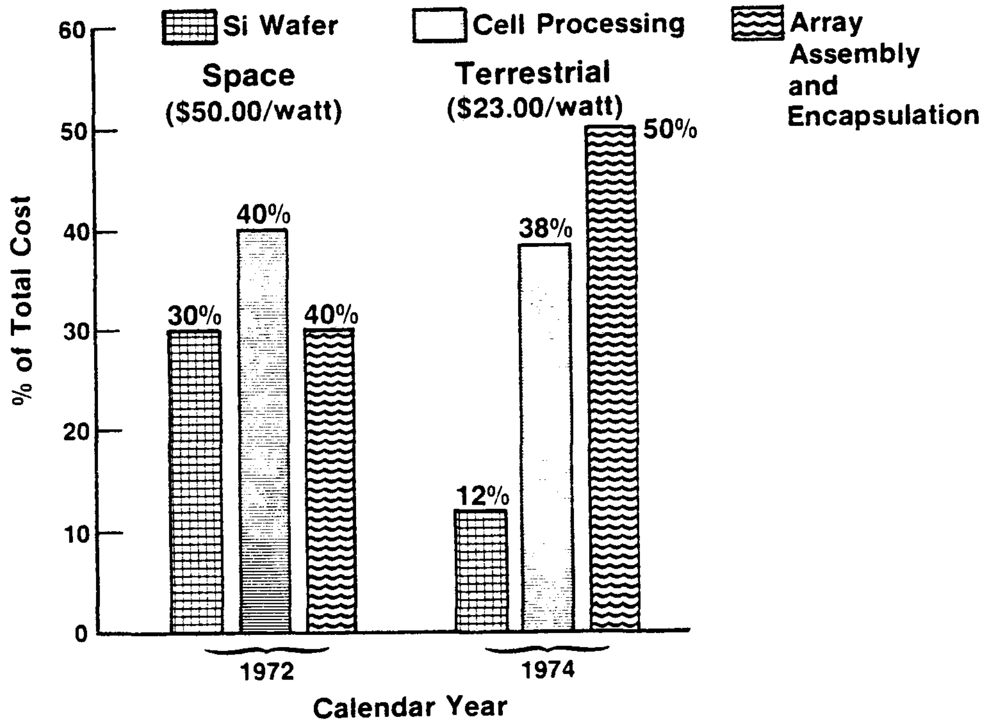

Figure 3. 1972 and 1974 Cost Structures

Expectations of further decreases in Si-wafer solar-cell-array costs is based primarily on the reductions normally associated with rapid increases in annual production rates, and the resulting cumulative-production-related "learning" phenomenon. Table 2 provides some perspective on the magnitude of production rate that would be associated with achievement of the objectives of the DOE/JPL "Low-Cost Solar Array" Project (LSA Project) [4,8,9,16]. The unit peak kW production rate for low-cost terrestrial arrays must essentially double each year during the 1980-85 period to meet these goals for solar cell array production "experience" (i.e., cumulative production). This is optimistic by historical standards (e.g., the 1974-79 period).

Even assuming an optimistic 10% annual unit volume increase for satellite arrays, the annual and cumulative terrestrial-array-production has assumed dominance in 1979 [1]. This evolution is illustrated in Figure 4, in bar graph form. In 1979, the cumulative space/satellite unit production is less than 50% of the total solar array "experience"; in 1985, it is less than 1%.

Table 2. Solar Cell Production "Experience"

	Terrestrial		Space-Satellite		Total	
	Rate (MW/Year)	Cumulative (MW)	Rate (MW/Year)	Cumulative (MW)	Rate (MW/Year)	Cumulative (MW)
1974	0.015	0.025	0.15	0.9	0.165	0.925
1979	1.0	2.0	0.25	1.8	1.25	3.8
1985	240.8	475.	0.44	3.9	241.2	480.
Relevant Cost Factors	"Array Assembly & Encapsulation"				Cell Processing	

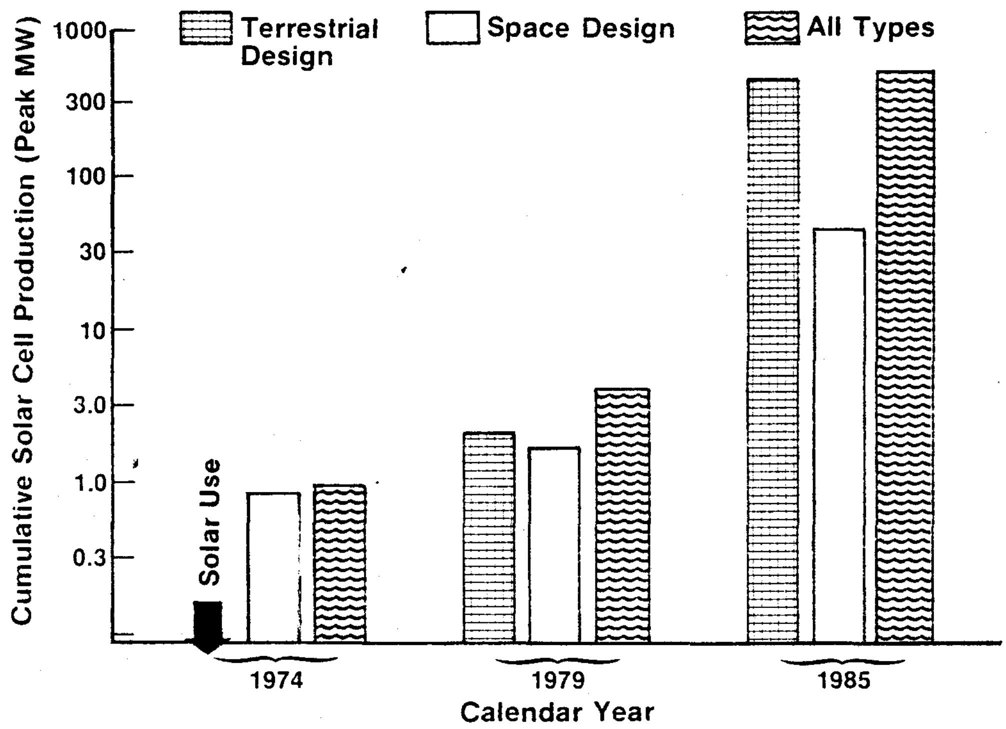

Figure 4. Solar Cell Experience

As indicated in Table 2, the learning benefit associated with terrestrial production can be considered as directly applicable to the terrestrial-specific "array-assembly-and-encapsulation" process for low-cost terrestrial solar arrays. In contrast, the more general "cell-processing" technology is most realistically governed by the learning effect based on total cell production.

The third essential component of the cost structure for single-crystal Si-wafer solar cell arrays is the Si-wafer cost. The evolution of this cost element is governed by the cumulative experience for Si-wafer production.

The impact of the greatly increased solar array production on the total Czochralski wafer production is presented in Table 3, using the array production growth of Table 2 and extrapolating the historical growth of the general semiconductor demand [6,16]. It can be seen that the annual demand due solely to "solar" use is a dominant factor in 1985, based on the historically optimistic LSA goals. This is illustrated in graphical form in Figure 5. However, the Czochralski wafer "experience" (i.e., cumulative production) is still dominated by the general semiconductor market usage, even for this very rapid growth in "solar" use.

Table 3. Si Wafer Production

	"Solar Cells" Annual Demand (km^2)	"Semiconductor" Annual Demand (km^2)	Total Annual Demand (km^2)	Total Cumulative (km^2)	Learning Ratio (re 1974)
1974	—	0.21	0.21	1.3	—
1979	0.014	0.44	0.457	2.7	2.1
1985	1.54	0.80	2.34	9.7	7.5
Annual Growth Rates	~100%	~13%	~25%		

The significance of this conclusion is that the learning-curve cost reduction for Czochralski-Si wafers will be determined both by the continued growth and cumulative experience of the general semiconductor market, as well as by the forecasted rapid growth of the solar market (required to achieve the DOE/LSA market goals). As has already been indicated in Table 2, the other two essential cost elements, cell-processing and array-assembly, are governed by the learning associated with the cumulative experience for total Si-solar-array production and terrestrial-array production, respectively.

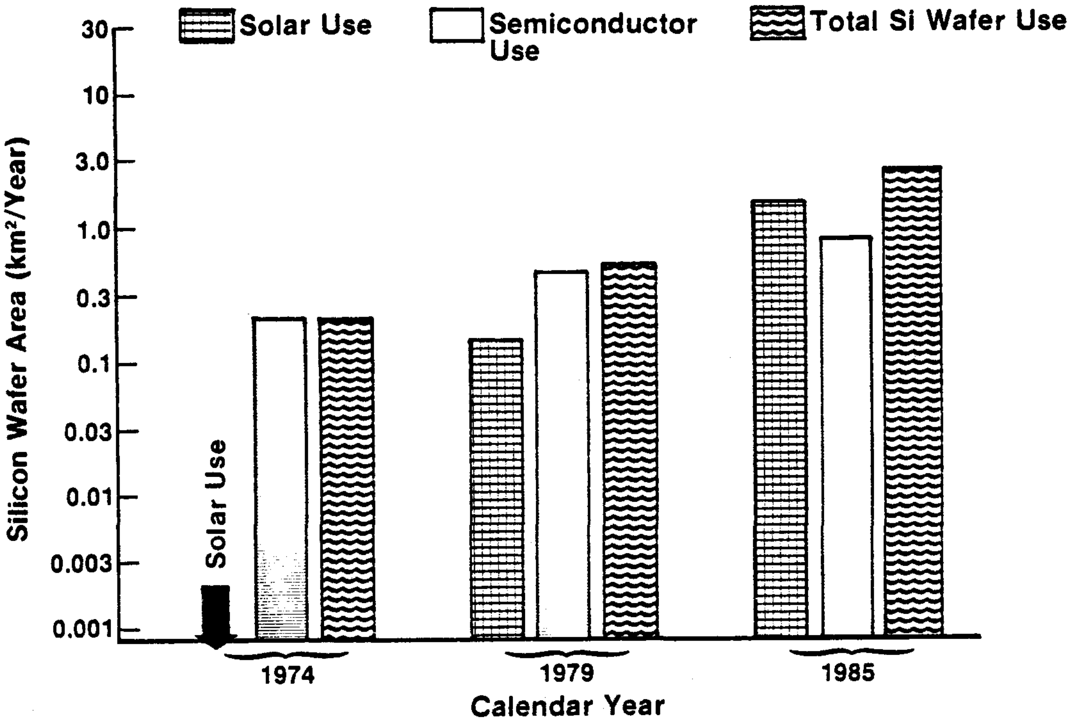

Figure 5. Czochralski Si Wafer Production Rate

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SECTION 3.0

ARRAY COST EVOLUTION: 1974-1979

On the basis of the cumulative production data presented in Tables 2 and 3, a straightforward learning curve extrapolation can be used to estimate the cost of wafer-based Si arrays in 1979 and 1985 [10-12]. One obvious credibility check for this procedure is that the predicted values for each of the major cost elements cannot go below a realistic limit for the direct materials cost associated with the process. This justification will be presented following the development of the specific estimates.

Table 4 presents a particular set of estimates for Si solar array costs in 1979, together with estimated "confidence levels" for these estimates. The assignment of estimated confidence level values is based on the sensitivity of the cost estimates to: (a) device technology improvement, as represented by the assumed peak output per m^2, and (b) the combination of different learning curve coefficients for the major cost components. This parameter represents a highly subjective judgment of the credibility for the various cost estimates in Table 4.

Table 4. Array Cost Estimates - 1979

		1974 Actual Costs ($/m²)	1979/1974 "Learning Ratio"	1979 Learning Curve Estimates @80% ($/m²)	@75% ($/m²)	@70% ($/m²)	"Mixed" ($/m²)
Constant 1974 $'s	Single-Crystal Si Wafers	290	2.0	232	218	203	232
	Solar Cell Processing	870	3.8	566	500	438	500
	Array Assembly & Encapsulation	1160	80.	283	188	122	122
	Total	$2320/m²	....	$1081/m²	$906/m²	$763/m²	$854/m²
	Peak Output	100W/m²	....	....	120W/m²	....	
	Factory Price per Peak watt	$23	....	$9.0	$7.6	$6.4	$7.1
	Confidence Level (Estimated)	....	....	90%	50%	10%	50%
	Factory Price per Peak watt (1979 $'s)			$12.6	$10.6	$8.9	$10.0

The three cost predictions detailed in Table 4 are presented in a normalized bar graph form in Figure 6. The dominant factor in all three estimates is "cell processing." The "array assembly and encapsulation" share has fallen sharply from the 1974 share (50%, see Figure 3) to a level of 16-21%, because of the significant increase in cumulative production for terrestrial arrays. Although there has as yet been no transition to direct-materials-cost limitation, the three estimates show a clear increase in the importance of Czochralski-Si wafer cost (21-27%) vis-a-vis the 1974 cost structure (about 12%, see Figure 3).

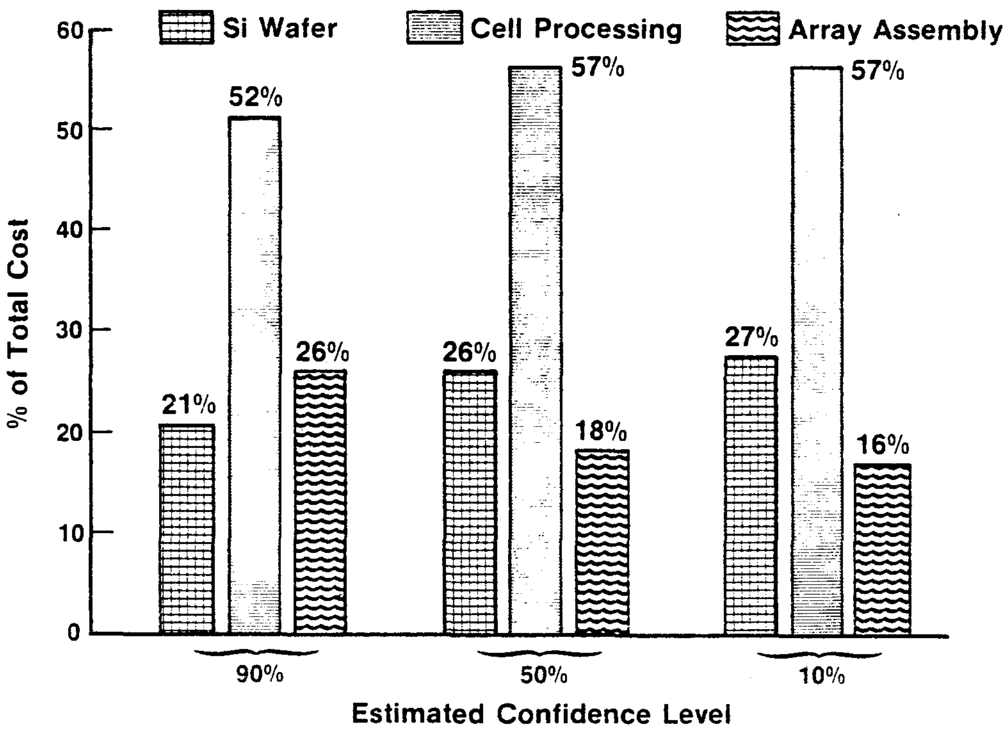

Figure 6. Terrestrial Arrays - 1979

SECTION 4.0

"ACTUAL" ARRAY COSTS: 1979

As with any other industrial or consumer product, the actual standard cost figures for solar cell arrays are held proprietary by the commercial manufacturers. However, in the latter part of 1979 and early 1980, a number of articles have reported on the basic price structure of the 1979 terrestrial solar cell array industry.

These reports can be summarized as follows [18,19,20,23,24]:

- the range of array prices is reported as $7 - $11 per peak watt.
- the "industry standard" price is $10 per peak watt, with one competitor quoting $7 per peak watt.

These prices are entirely consistent with the estimates forecasted in Table 4 and Figure 6, particularly the "industry standard" price of $10/W, which lies between the 10% and 50% confidence level estimates.

The one competitor selling at $7/W is perhaps practicing a "forward pricing" strategy based on anticipated learning curve cost reductions. This is a classic strategy for capturing a dominant market share in a rapidly growing market.

SECTION 5.0

ARRAY COST EVOLUTION: 1979–1985

Table 5 shows an equivalent set of array cost estimates for 1985, again based on the assumptions presented in Tables 2 and 3. The assignment of estimated confidence levels is based on the criteria discussed for Table 4. The estimates are presented in normalized bar graph form in Figure 7.

It is clear from Figure 7 that the Czochralski-Si-wafer cost has become a major cost element. In the case of the lowest cost prediction ($2.2/watt at 10% estimated confidence level), the Czochralski-Si wafer cost is approximately 50% of the total cost, and the combined direct materials cost approaches 60% of the total array cost.

Table 5. Array Cost Estimates - 1985

	1974 Actual Costs ($/m²)	1985/1974 "Learning Ratio"	1985 Learning Curve Estimates @80% ($/m²)	@75% ($/m²)	@70% ($/m²)	"Mixed" ($/m²)
Constant 1974 $'s:						
Single-Crystal Si Wafers	290	7.5	152	126	103	152
Solar Cell Processing	870	127.	183	117	72	117
Array Assembly & Encapsulation	1160	952.	127	68	34	34
Total	$2320/m²	....	$462/m²	$311/m²	$209/m²	$303/m²
Peak Output	100W/m²		....	135 W/m²	....	
Factory Price per Peak watt	$23	....	$3.4	$2.3	$1.5	$2.2
Confidence Level (Estimated)	....	...	90%	50%	10%	50%
Factory Price per Peak watt (1979 $'s)			$4.8	$3.2	$2.2	$3.1

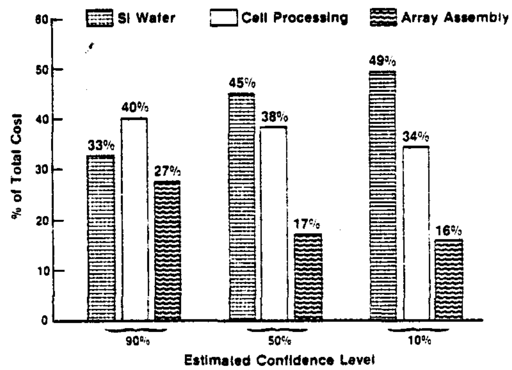

Figure 7. Terrestrial Arrays - 1985

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SECTION 6.0

ESTIMATED DIRECT MATERIALS COSTS

As indicated earlier, one obvious credibility check that must be applied to the learning curve estimates is the lower limit determined by the direct materials cost associated with each process task, since, strictly speaking, the classic learning curve technique can only be applied to that portion of costs attributed to labor cost displacement through automation or, more generally, through technological innovation leading to increased productivity [10,11].

In the case of the Czochralski-Si wafer, the direct materials cost for polysilicon is assumed to remain at about its present percentage of total single-crystal cost. Hence the poly-silicon is assumed to follow the same cost-reduction learning curve as the Czochralski growth process. No dramatic improvement in the current state of wafer production technology is assumed; i.e., ca. 250 micrometer wafer thickness and 250 micrometer total kerf and etch loss. The learning curve cost reduction will be associated with boule diameter increase, and boule length and growth rate improvement.

Estimates have been made for the direct materials costs of the cell-processing and array-assembly/encapsulation steps based on: (a) 1974 Factory technology [8], (b) a conceptual Advanced Technology process sequence [2,13] and, more recently, (c) a "strawman" 1986 LSA Factory [21]. These estimates are all summarized in Table 6, where they have been brought to a common cost basis in terms of 1979 $'s. This range of

Table 6. Direct Materials Cost Estimates

Assumed Technology	Cell Processing		Array Assembly & Encapsulation	
	(1974 $'s)	(1979 $'s)	(1974 $'s)	(1979 $'s)
• 1974 Factory [8]	$16/m² ➧	$22/m²	$29/m² ➧	$41/m²
• Advanced Technology [2, 13]	$1/m² ➧	$1.4/m²	$3.3/m² ➧	$4.6/m²
	(1975 $'s)		(1975 $'s)	
• 1986 LSA Factory [21]	$5.5/m² ➧	$7/m²	$10.6/m² ➧	$14/m²

costs includes widely differing assumptions: (a) the direct materials costs for the 1974 Factory are actual 1974 $'s for the real materials and real volume usage of that time; (b) the conceptual Advanced Technology process sequence assumes high material usage efficiency, lowest possible cost materials, and savings due to very high volume material usage; and, finally, (c) the 1986 LSA Factory assumes reasonable material usage efficiency, relatively low cost materials that have been proven feasible technically, and assumes materials costs based on annual production volumes in the range of 50 to 250 peak MW per year. In confidence level terminology, the 1974 Factory obviously has a 100% confidence level, the Advanced Technology is probably in the 1-10% range, and the 1986 LSA Factory is in the 30-70% range.

When the 1979 and 1985 cost predictions, presented in Tables 4 and 5, are measured against these lower limit materials costs, summarized in Table 6, there is no fundamental conflict with the total cell-processing or array-assembly cost predictions.

SECTION 7.0

INDUSTRIAL IMPACT

The rate of solar-cell-array production growth presented in Table 2 was specifically tied to the DOE/LSA Project production objectives [16]. In addition, it should be noted that it is generally consistent with the near-term outlook summarized in Exhibit 2, which represents one of the demand forecasts that have been developed for this product [3]. On this basis it is relevant to examine, at this point, the potential impact of such a demand within the context of the solar array business and the semiconductor device/materials industry for the period to 1985.

Exhibit 3 summarized this impact for the solar array business [1]. The low-cost terrestrial array share of the total Si solar array business is dominant on an annual market value basis by 1979, and increases its share to about 95% by 1985. It is clear that this market scenario represents an attractive growth situation for a small company involved in the solar array business.

	"Terrestrial" ($Millions)	"Space-Satellite" ($Millions)	Total ($Millions)	Terrestrial "% Share"
1974	$ 0.3	$7.5	$ 7.8	4%
1979	$17.1	$9.5	$26.6	64%
1985	$180	$12.	$192	94%

Exhibit 3. Si Solar Array Sales (Factory Price @ 50% Confidence Level)

In contrast, for the Czochralski-Si-wafer industry, the picture presented in Exhibit 4 [1,16,22], is by no means as attractive. In 1979 the solar share of the demand is about 3%, and only in 1985 does it become a dominant fraction of the total annual sales (i.e., 66%). This dominant share in 1985 depends, of course, on the solar cell array industry achieving a 100% annual increase in unit production rate for the period 1980-1985. It seems likely that Czochralski-Si suppliers will not consider resource commitment to a specialized "solar-grade Si" technology until this high-rate growth pattern is confirmed.

	"Semiconductor" ($Millions)	"Solar" ($Millions)	Total ($Millions)	Solar "Share"
1974	$61	$0.044	$61	<0.1%
1979	$102	$3.2	$105	3%
1985	$122	$234	$356	66%

Exhibit 4. Si Wafer Sales ($ Millions @ Factory Value Level)

Finally, in Exhibit 5 the potential impact of the Si solar array market is developed in the context of the general semiconductor market [1,14]. The solar array market represents less than 1% of the general market even in 1985, and on a cumulative basis it is an almost negligible factor for the time period of industrial planning significance. Additionally, the technology areas requiring major development for the Si solar array business—e.g., (a) the technology of large-area shallow junctions and large-area high-transparency contacts; and (b) the design of low-cost automated-cell-processing and array-assembly manufacturing facilities—are not relevant to the mainstream of the semiconductor growth business; namely, the dominant integrated circuit technology.

	Solar Cells	Total Semiconductor Devices & I.C.'s	Solar Cell "Share"
1974	$7.8	$4000	0.2%
1979	$26.6	$10600	0.25%
1985	$192	$34000	0.56%

Exhibit 5. Semiconductor Industry Sales ($ Millions @ Factory Value Level)

SECTION 8.0

OVERVIEW AND GENERAL R&D OUTLOOK

The overall conclusions from the preceding analysis are the following:

(1) Conventional new-venture-analysis indicates that the solar array business does not represent an attractive investment area for the major companies in the semiconductor materials or devices/integrated circuits industries. Significant resource commitments from these industrial sectors cannot reasonably be expected until the late-1980s, at the earliest.

(2) The solar array business represents a very attractive growth market for small companies presently in this market, but their intrinsic resource base, as derived from market sales, is too limited to support the required investment. In addition, the inherent risk attached to predictions of new-business markets, such as those presented in Exhibit 2 and Table 2, is too great for a small company to survive the results of forecast inaccuracies.

In brief, industrial sponsorship, by those companies presently in the semiconductor business, of the required research and manufacturing technology development is very unlikely during the time period through 1985.

A typical criterion for product development, tooling, and learning costs is from 5 to 10% of total product sales [15]. The cumulative production/sales goals of Table 2 and Exhibit 3 indicate that to reach the 1980-85 DOE/LSA growth objectives (which result in ca. $700 millions of cumulative sales for this period), a total R&D effort level of $50-100 millions is required over the 1980-85 period.

The question of technical effort focus is more difficult to evaluate with any degree of certainty. The analysis summarized in Table 5 and Figure 7 indicates that a major cost barrier is the Czochralski-Si-wafer cost, if the route taken is automation and technology improvement for wafer-based solar cell arrays.

In contrast, if an alternative route of development based on 100-micrometer thick Si ribbon/sheet/web technology is taken, then there is some expectation of about 5:1 reduction in cost per m^2 for the Si material. This assumes that: (1) the ribbon/sheet/web material is 100-micrometers thick, (2) the Si wafer is 250-micrometers thick with a total 250-micrometer kerf and etch loss, and (3) the ribbon/sheet/web technology has reached a sufficiently advanced state of the art that the ratio of poly-Si direct-materials-cost to crystal Si cost, is equivalent to the ratio for current Czochralski technology.

However, if this cost reduction is accompanied by a significant penalty in conversion efficiency vis-a-vis the Czochralski wafer devices (e.g., 10% terrestrial cell efficiency for ribbon/sheet/web vs. 16% for wafer cells at equivalent yields), then there would probably be a negligible reduction in <u>array cost</u> per peak watt.

Thus, a strong commitment to a ribbon/sheet/web-based array fabrication process is realistic if there is a reasonable expectation that the resulting solar cells will have conversion efficiencies approaching those of wafer-based cells, <u>or</u> if there is a high confidence level expectation that the direct materials costs associated with cell-processing and/or array-assembly-and-encapsulation will be substantially reduced vis-a-vis a wafer-based technology. This appears particularly unlikely for the cell-processing direct materials costs.

The significance of this appraisal vis-a-vis the fundamental effort focus for R&D is that the importance of the form of Si-crystal base-material chosen for emphasis (e.g., Czochralski-Si wafer vs. ribbon/sheet/web) is secondary to the emphasis that should be placed on the research and technology relevant to the reduction of cost for the input raw material common to all crystal growth processes—the high-purity polysilicon. This represents a "core" cost element that will impact all growth processes strongly, and a significant reduction in poly-Si cost (beyond that expected from the normal learning experience) might remove the Czochralski-Si-wafer cost barrier to economically viable photovoltaic solar arrays for large-scale applications.

SECTION 9.0

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15. Supplementary Notes

16. Abstract (Limit: 200 words)

A multipath learning curve model was proposed to characterize the price dynamics for terrestrial Czochralski-silicon solar cell arrays. This model was sucessfully tested against the actual price evolution over the period 1974-1979.

Based on the successful modeling of this historical period, the multipath learning curve model was then used to forecast the 1985 array price. This forecast utilized the (DOE/JPL) LSA Project production growth goals.

Finally, the impact of the resulting price and annual sales on the semiconductor and solar cell array industries was extrapolated, and the implications for industry structure and industrial R&D focus were developed.

17. Document Analysis

a. Descriptors Silicon Solar Cells ; Learning Curves ; Cost ; Estimation ; Industry ; Production ; Solar Cell Arrays ;

b. Identifiers/Open-Ended Terms Czochralski-Silicon Solar Cell Array

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