SENSITIVITY ANALYSIS FOR SOLAR PANELS

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The Project Analysis and Integration (PA&I) task of the Flat-Plate Solar Array (FSA) project has prepared economic evaluation methods and analyses of emerging photovoltaic (PV) technology since 1976. The purpose of this paper is to apply this type of analysis to the silicon research portion of the PV Program in order to determine the importance of this research effort in relationship to the successful development of commercial PV systems.

This analysis addresses all four of the generic types of PV that use silicon. The first generic type of PV is the one that uses the most silicon, where crystalline silicon ingots are grown either by the Czochralski method or by some sort of ingot casting method. The second type of PV uses ribbons that are pulled directly from molten silicon, thus avoiding material losses associated with sawing wafers from an ingot. The third type of PV device is an amorphous silicon thin film, which attempts to achieve low cost by minimizing silicon material utilization. A fourth type of PV device is the concentrator system, which can use high concentration lenses (500x to 1000x) to minimize silicon material utilization. This last type of PV technology can be analyzed very simply because the amount of silicon used will be roughly 500 to 1000 times less per unit of PV energy produced than would be the case with the first generic type of PV.

SILICON COST RANGE

In order to show the value of the silicon research program, it is first necessary to construct a hypothetical range of silicon prices that would occur if there had been no program. In 1975, at the start of the program, the price of semiconductor grade polycrystalline silicon was $50/kg. In order to standardize financial units, this cost figure (and all subsequent cost figures in this paper) will be inflated to 1982 dollars. Inflation over that period was a factor of 1.68, thus if the price of silicon had increased with inflation it would now be $84/kg in 1982 dollars. However, the market price of silicon fluctuates due to changes in supply and demand, so that a price range of $50/kg to $120/kg in 1982 would be appropriate.

However, a silicon manufacturing research program has been conducted since 1975, which is expected to have a significant impact on future silicon price. L. Reiter (Ref. 1) conducted a study where PV prices were projected for the 1990s. In this study, price was defined as the revenue required to meet all direct and indirect costs, including the after-tax return on investment that is normally obtained by the chemical industry. Three technologies were analyzed: the Union Carbide fluidized bed reactor process, the Hemlock process, and the Union Carbide Komatsu process. The major components of each process were assessed in terms of the costs of capital equipment, labor, materials, and utilities. These assessments were encoded as the probabilities assigned by experts for achieving various cost values or production rates. The result was a combined probability curve of silicon cost. This is a reasonable approach because of the uncertainties inherent in a research program and in projections of the future. The 1st and 99th percentiles of the resulting probability curve were approximately $10/kg and $30/kg (in 1982 dollars), respectively. These values are used in this analysis as the range of silicon prices that may be found in the industry in the 1990s, due to the silicon research program.

The impact of silicon research on PV costs is determined not only on the two cost ranges described above, but also on the amount of silicon needed to construct a PV device. This amount will vary with different types of PV technology.

INGOT AND RIBBON PHOTOVOLTAICS

Ingots require the greatest amount of silicon per square meter of PV cell. The thickness of the wafer must be increased by the size of the kerf loss, which varies with different types of saws. Silicon utilization is also reduced by ingot growth losses, slicing losses, and cell manufacturing yields. Table 1 provides representative values for each of these parameters, and shows that between 1.6 and 2.8 kilograms of silicon are required for every square meter of PV cell area.

Table 1. Ingot PV Silicon Mass per Square Meter of Cell

Thickness (mils)	Saw Type	Representative Yields (%)				Kiligrams of Silicon per Square Meter of Cell
		Growth	Slice	Cells	Cumulative	
16	Wire	95	70	85	57	1.68
20	Wire; ID MBS	95	90	85	73	1.63
24	ID MBS	95	95	85	77	1.85
28	ID MBS	95	95	85	77	2.16
32	ID MBS	95	95	85	77	2.47
36	ID MBS	95	95	85	77	2.78

One of the major reasons for the development of ribbon technology is to reduce the amount of silicon that must be utilized to manufacture PV cells. Table 2 shows the thickness associated with four types of ribbon. Typically these range from 4 mils to 14 mils of crystal thickness, with no kerf loss. As a result, the number of kilograms of silicon per square meter of cell is reduced significantly.

Table 2. Ribbon PV Silicon Mass per Square Meter of Cell

Thickness (mils)	Ribbon Type	Representative Yields (%) Growth	Cells	Cumulative	Kiligrams of Silicon per Square Meter of Cell
4		90	85	77	0.31
6	Web, LASS	90	85	77	0.46
8		95	85	81	0.59
10	EFG	95	85	81	0.73
12	ESP	95	85	81	0.88
14		95	85	81	1.03

The results of Tables 1 and 2 can be combined with the silicon cost ranges developed previously to show the contribution of silicon to PV module cost. This is done in Table 3, where the contribution to PV module cost is expressed in 1982 $/sqm. In these units it is possible to compare those results with the DOE Program goal for modules, which is $90/sqm. It can be seen immediately that without a silicon research program that ingot PV would have no chance of meeting the DOE goal, particularly when it is realized that part of that goal must be allocated to the costs of ingot growth and slicing, cell fabrication, and module encapsulation (Ref. 2,3). In the latest published set of Allocation Guidelines (pg 502, Ref. 3), the allocation for silicon and sheet fabrication (including costs associated with labor, investment, and utilities, as well as for materials) for an advanced, 15% efficient module is $31 per square meter in 1982 dollars. Because of the silicon research program, ingot technology may have some chance of meeting the DOE energy cost goal, particularly if cell efficiencies can be increased above 15%, but only if silicon utilization rates are minimized and silicon price comes in at the low end of the probability range, and reductions in the other costs of sheet production (ingot growth and slicing) are realized.

Ribbon technology has what appears to be a more realistic chance of achieving the DOE energy cost goal because it uses less silicon. The silicon cost reduction research program still plays an important role in the development of this technology, however, because it provides potential cost reductions that range from $14/sqm to $106/sqm of cell.

Table 3. Silicon Contribution to Ingot PV cost

Sheet Type	Kilograms of Silicon per Square Meter Cell	Silicon Cost (1982 $/kg)					
		10	20	30	50	84	120
Ribbon	0.30	3	7	10	17	28	41
	0.45	5	10	15	25	43	61
	0.60	7	14	20	34	57	81
	0.75	8	17	25	42	71	102
	0.90	10	20	30	51	85	122
	1.05	12	24	36	59	99	142
Ingot	1.60	18	36	54	90	152	217
	2.00	23	45	68	113	190	271
	2.40	27	54	81	135	227	325
	2.80	32	63	95	158	265	379

A burden rate of 20% and a cell-to-module area ratio of 0.94 are assumed.

AMORPHOUS SILICON PHOTOVOLTAICS

Amorphous silicon is grown from silane. High efficiency is required, and in order to obtain high efficiency, it is likely that only very pure (device grade) silane can be used. At this time, device grade silane costs from $500/kg to $2000/kg. In industrial quantities this cost range might go down to $200 to $500/kg. However, a spinoff from the silicon research program is a Union Carbide method to produce very pure silane at a cost of $5/kg to $10/kg.

An important feature of thin film photovoltaics is the fact that very little material is used. Material requirements will be proportional to device thickness, silane utilization rates, and module yield. In this analysis, a nominal thickness of 0.7 microns is used, along with a range of silane utilization rates of 2% to 40%. Module yield is not known at this time, but for purposes of this analysis a range of 50% to 100% is used. The 50% figure was selected as a lower bound because it is unlikely that amorphous silicon would be commercially viable at lower yields, due to the costs of module encapsulation materials and processing (Ref. 4).

Table 4 shows the amount of silane used per square meter of cell area, based on the figures described above. It can be seen that material utilization is indeed lower for this technology. The worst case amorphous silicon material requirement is a factor of 2 less than the lowest silicon material requirements for ribbon technology, and in most cases it is a great deal lower.

Table 4. Amorphous Silicon Silane Mass per Square Meter of Cell

Kilogram Silane per Square Meter of Cell	Silane Cost ($/kg)			
	5	10	200	500
0.005	0.03	0.06	1.13	2.82
0.010	0.06	0.11	2.26	5.64
0.020	0.11	0.23	4.51	11.28
0.030	0.17	0.34	6.77	16.92
0.040	0.23	0.45	9.02	22.56
0.050	0.28	0.56	11.28	28.20
0.100	0.56	1.13	22.56	56.40
0.150	0.85	1.69	33.84	84.60

A burden rate of 20% and a cell-to-module area ratio of 0.94 are assumed.

These low silane material requirements are combined with the rather large silane cost range in Table 5, to obtain silane contribution to the cost of an amorphous PV module, in 1982 dollars per square meter of module. It can be seen immediately that the lower silane costs that may result from the silicon research program significantly reduces the sensitivity of silane utilization rate on module cost, and thus may simplify the development of this technology considerably. If silane cost were to remain at $500/kg, then material utilization rates would be a critical parameter which might conceivably compromise the achievement of other targets that must be met in order to commercialize this form of PV.

Table 5. Silane Contribution to Module Cost (1982 $/sqm)

Utilization Rate	Module Yields					
	50	60	70	80	90	100
0.02	0.143	0.119	0.102	0.089	0.079	0.071
0.05	0.057	0.048	0.041	0.036	0.032	0.029
0.10	0.029	0.024	0.020	0.018	0.016	0.014
0.15	0.019	0.016	0.014	0.012	0.011	0.010
0.20	0.014	0.012	0.010	0.009	0.008	0.007
0.25	0.011	0.010	0.008	0.007	0.006	0.006
0.30	0.010	0.008	0.007	0.006	0.005	0.005
0.35	0.008	0.007	0.006	0.005	0.005	0.004
0.40	0.007	0.006	0.005	0.004	0.004	0.004

IMPACT ON PHOTOVOLTAIC ENERGY COST

There are a number of ways that PV energy cost can be derived from module cost and other factors that need to be considered. The standard approach of the DOE PV research program is described in the Five Year Photovoltaic Research Plan (Ref. 5), and a discussion of how to best implement that approach can be found in JPL's sensitivity analysis of central station photovoltaic systems (Ref. 6). While there are many factors to be considered such as insolation levels, tracking options, and system lifetime; two very important factors are module cost and module efficiency (page 2, Ref. 6).

The DOE energy cost goal is $0.15/kWh. Using the DOE energy cost equation and JPL's recommended parameter values for a fixed flat plate system a rough rule of thumb can be calculated to determine the sensitivity of energy cost to changes in module cost. If the module is 15% efficient, then a $10/sqm change in module cost will result in a $0.01/kWh change in system energy cost. This rule of thumb can be used for both ingot and ribbon technology. If the module is 10% efficient, then a $6.6/sqm change in module cost will result in a $0.01/kWh change in system energy cost. This rule of thumb can be applied to future thin films or to low efficiency (e.g., cast ingots using lower grade silicon) types of PV modules.

Successful silicon research and commercialization will reduce the cost of energy from ingot PV by about $0.15/kWh. This represents critical progress towards viability for this type of PV module. Without silicon research, the energy cost from this type of PV approach would be at least double the DOE goal.

Energy cost from ribbon PV is reduced by about $0.03/kWh for the thinner ribbons (web), and by about $0.05/kWh for the thicker ribbons (EFG, ESP). Successful silicon research has been very impprtant for this type of PV approach. Without that research, energy costs would be at least 20% to 30% above the DOE goal.

Energy cost from amorphous silicon systems will be reduced by about $0.01/kWh to $0.04/kWh if silane utilization is on the order of 10% to 2%, respectively. Successful silane R&D will make it unnecessary to achieve high material utilization rates, and thus is an important step in the development of viable commercial amorphous silicon PV.

Energy cost from concentrating systems is 2 to 3 orders of magnitude less sensitive to the cost of silicon than flat plate ingot technology, and therefore this research program will not be a factor in the successful commerciallization of this particular technology. However, all of the flat plate varieties of PV that use silicon have benefited greatly by the success of this part of the DOE PV research Program.

CONCLUSION

A successful silicon research program will play a major role in the effort to reduce the cost of energy derived from photovoltaic systems. This is particularly true for today's commercial technology, which is ingot-based, and will remain true for the major flat plate PV options of the foreseeable future.

References

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5. U. S. Department of Energy, National Photovoltaics Program, Five-Year Research Plan 1984-1988: Photovoltaics: Electricity from Sunlight, DOE/CE-0072, May, 1983.

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DISCUSSION

SCHMIDT: You used a comparison between ingot and ribbon, and I would like to comment on that. Typically, there isn't a lot of segregation in ribbon processes and, therefore, the quality of the silicon material used for ribbon should be much higher than for an ingot process. There is very effective segregation using a good ingot process and lower quality material could be used, and the overall cost would be about the same or maybe even less.

ASTER: Thank you for that comment. There are a lot of tradeoffs between material use and efficiency. It's difficult to predict what the ultimate answer is for that comparison.

HUANG: You presented data for ribbon and amorphous-silicon technologies. What is the position in your calculations for the combination of solar-grade silicon with a casting process?

ASTER: I'm not sure what solar-grade silicon is. If metallurgical-grade silicon is used, the module efficiencies are too low to be commercially useful.

HWANG: I don't mean metallurgical-grade silicon. I mean solar-grade silicon as it is conventionally defined.

ASTER: Well, when the FSA Project started, there was a belief that a solar-grade silicon could be produced that would be significantly less costly than semiconductor-grade silicon, and part of the Project had a goal of developing those processes. I used the data for the Union Carbide and Hemlock Semiconductor processes in my calculations. I assumed $10 to $30/kg for those processes. There may be other, less expensive processes producing silicon adequate for cells. Please comment on them, if you will.

HWANG: This morning, the NEDO processes for semiconductor-grade silicon and solar-grade silicon were described. Where would be the position of that type of solar-grade material coupled with a casting process in your calculations on the assumption of 10% module efficiency?

ASTER: I would use the same technology as I used for semiconductor-grade silicon, since it applies to casting as well as for Czochralski ingots. Then, I would use the $\$7/m^2$ of module cost which is equivalent to $0.01/kWh; I think this percentage/kilowatt hour is appropriate. Of course, usefulness of the solar-grade silicon for 10% cells would have to be demonstrated.

PELLIN: Amorphous silicon requires a substrate, whether it be plastic, glass, or stainless steel. How would the amorphous silicon compare when the cost of the substrate is included?

ASTER: Well, the best way to compare the cost of rather different photovoltaic technologies is on the basis of energy cost. There have been attempts to do it in many other ways. The basis of dollars/square meter is probably not appropriate, because efficiency is important. We do know the cost of the substrate, the metallization of amorphous silicon, and so forth, will probably be about $3/m^2$ in any event, even if the photovoltaic system is free. The comparisons have to be made on a common basis to be valid. The best common basis is energy cost, and I believe the program goal of about $50/m^2$ for 10% amorphous-silicon modules is roughly equivalent to $90/m^2$ for a 15% module in terms of energy cost.

LEIPOLD: I have a comment rather than a question. When considering other elements of amorphous-silicon cost (for example, the silane utilization of 2 to 5%), the need to dispose of the other 95 to 98% of the unutilized silane may, in fact, cost more than the product that is put in.

ASTER: I think that, eventually, the maturity of research in that area will allow us to look at the effluent cost and other aspects of the cost, and then we can do a complete cost analysis of that technology. I think it's too early to do that at this point.

WRIGHT: We are in the process of completing a paper for the Electric Power Research Institute that will be published some time in December or January. In the paper, we go over the four technology areas that you have commented on. Effluent disposal in amorphous-silicon production was accounted for in our cost model. I'm not prepared to present our results at this time, but I feel you might be interested in looking at the published paper.