HIGH-EFFICIENCY CRYSTALLINE SILICON TECHNOLOGY DEVELOPMENT

U.S. DEPARTMENT OF ENERGY

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I have been asked to give the rationale for pursuing high-efficiency crystalline silicon technology research and development activities.

Let me start by quoting the purposes of the National PV Program from the latest Five-Year Research Plan.

"In accordance with legislative mandates and recent policy guidance, the National Photovoltaics Program sponsors high risk, potentially high payoff research and development in photovoltaic energy technology which will result in a technology base from which private enterprise can choose options for further development and competitive application in U.S. electrical energy markets."

In order for the private sector to compete in the U.S. electrical energy markets, photovoltaic energy systems must be able to produce electricity at or about the same cost as other competing energy systems such as oil, gas, coal, nuclear or any other source of energy. PV may be able to command a slightly higher price than some of the other sources because of its safety, non-pollution and other benefits. However, this premium should not blind us to the brutal fact that cost is the main driving force in our society in selecting its energy sources.

Energy cost analysts at JPL, Sandia, EPRI and the Aerospace Corp. have come up with essentially the same results regarding the necessary costs that must be reached. The 30-year levelized cost of electricity must get down to about 15¢/kWh, or at today's cost about 7¢/kWh.

The analysis has ended up with several graphs (which are in the Five-Year Plan) that relate module costs (in $/m^2$ and in $/W_p$), module efficiency and levelized electricity costs (¢/kWh). These graphs have been made w th many assumptions that differ in some parameters for flat-plate modules and concentrator modules

These parameters include system life, the ratio of system efficiency to module efficiency, capacity factor, average peak insolation, annual O&M costs, indirect cost multiplier, present worth factor, fixed charge rate, capital recovery and balance-of-system costs, both area-related and power-related. I refer to the Plan appendix which describes all of these parameters in detail and gives numerical data for them. I personally have some questions about some of the numbers, but the differences do not significantly change the results. Let us look at two of the figures from the Plan.

The first figure is for flat-plate PV systems with $75/m^2$ for area-related BOS costs (Figure 1). As you can see, in order for the PV system to meet the 15¢/kWh line, the module efficiency must be greater than 15%, and

even then the module cost must be less than $35/m^2$ (or approximately 20¢/watt). If the module efficiency can be increased to 20%, the cost of the module in the system can be up to $75/m^2$ (or about 37¢/watt). Thus, one can start to see the pressure on obtaining high efficiency.

Figure 2 shows similar information for a concentrator system with $125/m^2$ area-related BOS cost. In this case, one can see that the minimum meaningful cell efficiency is 25%, which will allow a module cost of $50/m^2$ of aperture. The $50/m^2$ level will be extremely difficult to meet. A more realistic set of numbers is efficiency of 35% and module cost of $135/m^2$ of aperture.

Thus, it is necessary to get to flat-plate module efficiencies of approximately 20% (and thus cell efficiencies of 22%) and concentrator cell efficiencies of about 35%. Also, you now have a better idea of what some of our problems are in designing the PV program within the limited budgets that we have been working with during the past few years. It is possible to trade off lower BOS costs to allow lower cell and module efficiencies, but unless some breakthrough is made in the BOS area of work, I believe the BOS costs assumed above will be difficult to beat. Besides the PV Five-Year Plan, I recommend that you read the EPRI Report AP-3351 titled "PV Power Systems Research Evaluation," especially Section 2, if you are interested in more detailed information on the economic requirements for PV systems.

The Program Office has, with the help of the three lead laboratories, come up with a set of activities that, we believe, will help industry reach these high efficiencies. This set includes work on silicon devices, single-junction multielement devices, multijunction thin-film devices (for flat-plate modules) and multijunction structures for concentrator modules.

Data on single-junction cells are shown in Figure 3. These data are for laboratory devices. The expected near-term efficiencies are given in the right hand columns. As you can see, none of these single-junction cells will ever meet the 35% efficiency needed for the concentrator module. Only a couple of materials have the potential for meeting the flat-plate cell efficiency of 22% or more. In the near term, tying costs with efficiency results in the fact that single-crystal silicon is the strongest contender for a single-junction device that may meet the objectives discussed above.

As most of you know, it is possible to obtain higher efficiencies by stacking more than one cell on top of another to make better use of the solar spectrum. Several analyses have been made that indicate that the efficiency can be increased to over 55% with about 10 to 20 junctions of different materials stacked upon one another. However, the difficulties of developing such a structure are so horrendous that we can only think in terms of two-cell and three-cell stacks at this time. These smaller stacks obtain the major increase of efficiency over the single-junction device efficiencies in any case. Figure 4 shows what is possible theoretically for single-junction, two-cell stack, and three-cell stack material systems for flat-plate modules and 500X concentrator modules. This chart also shows the optimum band gaps that should be used. Note the bottom line combination which uses silicon as the lower cell. Figure 5 (from John Fan) shows that the band-gap selection is not very critical. Thus many combinations of materials are possible that will meet both the flat-plate module and concentrator-module requirements.

50

To build successful stacks with these efficiencies, it is necessary for each cell in the stack to be efficient in its own right. Thus, again, silicon appears to be a relatively near-term component for a useful system, and it must be highly efficient.

Now that I have developed the rationale for the need to maximize the efficiency of crystalline silicon PV devices, let me very briefly set the background for the other speakers of this morning's program.

Figure 6 lists many of the factors that must be considered in the design of a high-efficiency device. Many of these factors can only be optimized at the expense of other factors, and it is this complex overall optimization that has given us difficulties over the past many years. However, we are gradually closing in on the optimal trade-offs, and as you know cells with over 19% have been obtained for silicon.

The last figure (Figure 7) shows how many of these factors fit in the conceptual photovoltaic cell.

Figure 1. Module Costs and Efficiencies vs 30-Year Levelized Electricity Costs for Flat-Plate Photovoltaic Systems (175/m^2 Area-Related BOS)
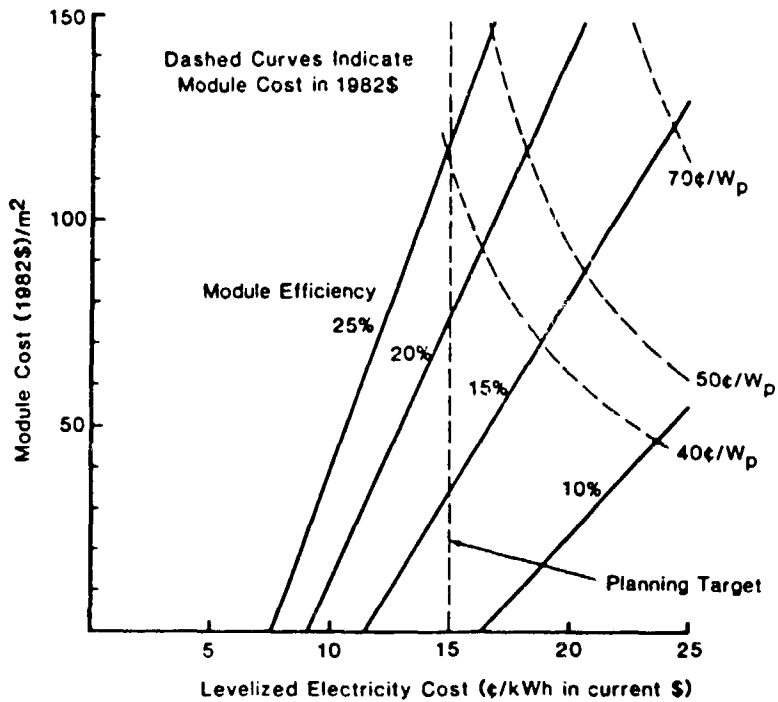
Figure 2. Module Costs and Cell Efficiencies vs 30-Year
Levelized Electricity Costs for Concentrator
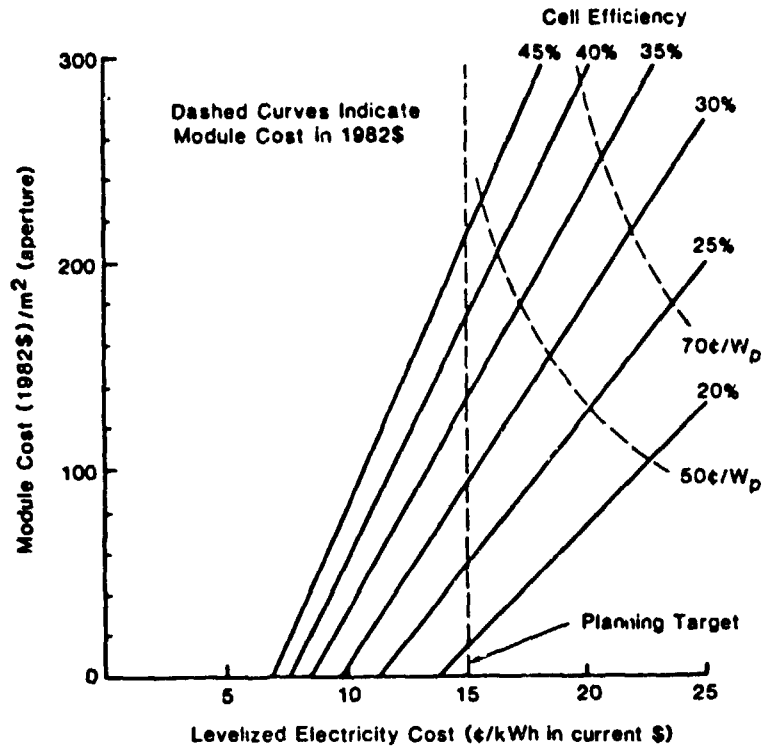Photovoltaic Systems ($125/m^2 Area-Related BOS)

Figure 3. Single-Junction Photovoltaic Cells

CELL MATERIALS	LABORATOR CELL EFFICIENCY (%)*			
	η (1983)	η (THEORY)	η (1986-8)	η (1990's)
SINGLE-CRYSTAL				
SILICON	19	25	20-21	22
SILICON (500X)	20	28	21-23	26
GaAs THIN FILM (THICK)	17(23)	28	20-24	25
GaAs (500X)	24	32	26-28	30
AMORPHOUS SILICON	10	20	12-14	15
$CuInSe_2/CdS$ **	11	25	14-17	19
$CdTe/CdS$ **	11	28	14-19	22

*CONCENTRATION RATIO = 1 SUN (1X) UNLESS DESIGNATED OTHERWISE
(500 SUN CONCENTRATION RATIO = 500X)

**POLYCRYSTALLINE THIN FILM CELLS

Figure 4. Theoretical Efficiencies

	OPTIMAL BANDGAP(S) (TOP TO BOTTOM)	η (THEORY) 28°C
SINGLE-JUNCTION CELL (1 SUN)		28%
SINGLE-JUNCTION CELL (500X)	1.45 EV	32%
TWO-CELL STACK (1 SUN)		35%
TWO-CELL STACK (500X)	1.6 ⟶ 0.95 EV	40%
THREE-CELL STACK (1 SUN)		42%
THREE-CELL STACK (500X)	2.0 ⟶ 1.5 ⟶ 0.95 EV	47%
TWO-CELL STACK (1 SUN) (LOWER CELL-SILICON)	1.8 ⟶ 1.1 EV	34%

Figure 5. Two-Junction Photovoltaic Converter Iso-Efficiency Lines
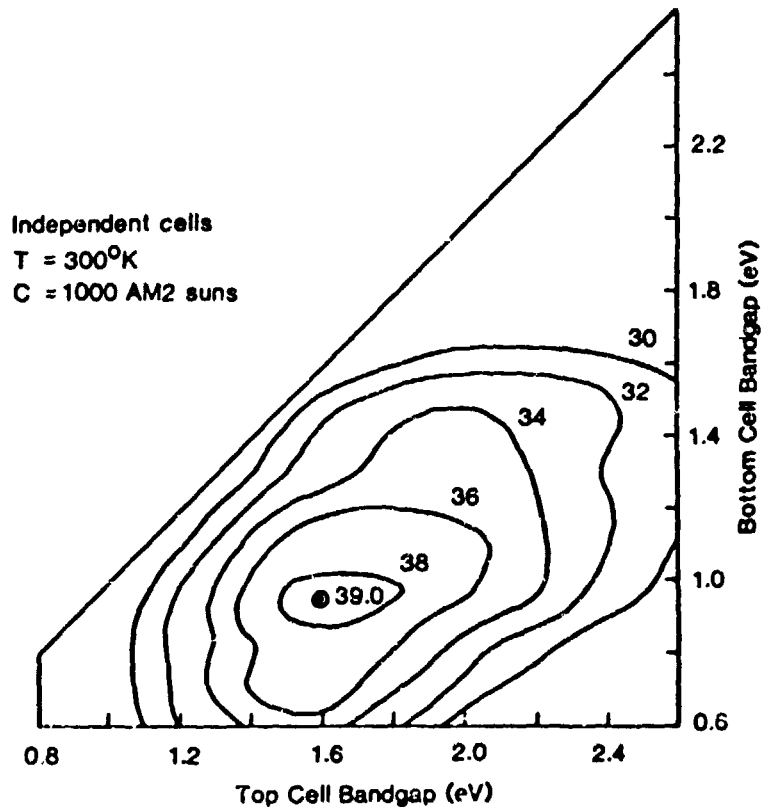

Independent cells
T = 300°K
C = 1000 AM2 suns

Figure 6. Factors Affecting Efficiency

MECHANICAL FACTORS

Depth of Junction (w)
Thickness of Wafer (d)
Series Resistance (contact geometry)
Front Surface Roughness (light trapping)
Contact Shadowing
Operating Temperature

PHYSICAL FACTORS

Base Resistivity

$(\tau_n, D_n, \mu_n, L_n, n_p)$

Emitter Impurity Distribution

$(\tau_{p_{eff}}, \mu_{p_{eff}}, p_{n_{eff}})$

Back Surface Impurity Distribution

Recombination and Scattering Centers
in Base and Emitter

DEVICE FACTORS

Surface Recombination Velocity (front,
back, under contacts)

Reflecting Back Surface

AR Coating

High Eg Window (oxide, etc)

Series Resistance

Shunt Resistance

Reverse Saturation Current
(I_0)

55

Figure 7