SOME TRADEOFFS IN INGOT SHAPING AND PRICE OF SOLAR PHOTOVOLTAIC MODULES

Taher Daud

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, California 91109

ABSTRACT

Conventionally, silicon sheet is produced by growing single-crystal ingots from semiconductor-grade polysilicon and slicing them into wafers. Wafers are processed to make solar cells and, after interconnection in strings, are encapsulated to form a working module.

Growth of round ingots is cost-effective for sheets but leaves unused space when round cells are packed into a module. This reduces the packing efficiency, which approaches 95% for square cells, to about 78%. This reduces the conversion efficiency of the module by the same ratio. Shaping these ingots into squares with regrowth of cut silicon improves the packing factor, but increases growth cost.

By considering shaping ingots in stages from full round to complete square, a study of the cost impact on solar cell modules has been made. The sequence of module production with relevant price allocation guidelines is outlined. The effect of silicon utilization on sheet price is illustrated. Trade-offs due to shaping of ingot are discussed. Sheet and module prices are calculated for various slicing and material utilization scenarios. Effect of balance of system is outlined.

INTRODUCTION

The objective of the Low-Cost Solar Array (LSA) Project is to develop technologies for achieving a goal of \$0.70/peak watt (W_p)* for flat-plate photovoltaic modules by 1986. The working module evolves from silicon material formed into sheets. Conventionally, it is produced by growing cylindrical single-crystal ingots using Czochralski growers and slicing the ingot into circular wafers. These wafers are then processed to produce photovoltaic cells and are interconnected in close-packed flat strings with series-parallel combinations for electrical output. Encapsulation and module assembly is then done to provide rigidity, reliability and long life.

The price goal of \$0.70/W_p is broken down for each stage of module manufacture in Reference 1, based on performance criteria of material usage, process yields, efficiencies, etc., expected to be achieved during technology development.

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*All figures are in 1980 dollars.

Conversion efficiency of a module is important in determining its price. When packed, circular cells leave spaces that reduce module efficiency in direct ratio. Shaping ingots into square cross-sections, and recycling trimmed silicon, improves packing density but increases ingot growth cost. Other factors, such as cost of slicing circular vs square wafers, achievable thickness of wafers, and amount of kerf loss also affect the cost.

Sequence of Module Production

Multiple single-crystal Czochralski (Cz) ingots, of 15-cm. dia., can be grown from a single crucible with a growth yield of 92% to 94%. The resulting ingots are generally cropped at the seed and the tang end and are ground to uniform-diameter cylinders. Cropping and grinding yields of 85% to 90% are achievable.

Slicing of the ingot into wafers 10 to 15 mils thick (d), with kerf loss (k), of 6 to 12 mils gives a material utilization of about 15 to 25 wafers/cm of ingot length. Wafer breakage during this operation results in a slicing yield of 95%, which translates into 0.6 to 1.0 m^2/kg (corresponding to $d + \kappa$ of 27 to 16 mils). This results in a combined silicon-to-wafer yield (Y_{sh}) of about 81%. A similar loss of cells during processing with 95% cell yield (Y_c) and subsequent 99.5% module yield (Y_m) is expected.

These circular cells, when interconnected and arranged flat in a module, leave areas between cells. This results in a packing efficiency, (η_p) of only about 78%. Thus, the encapsulated cell efficiency (η_e) of 15% would give a module efficiency ($\eta_m = \eta_e \cdot \eta_p$) of 11.7%. Square cells on the other hand, can be closely packed, leaving very little unused sp The value of η_p then approaches 95% with the module efficiency η_m increasing to 14.25%.

Table 1 gives relevant projected price breakdowns and the criteria for Cz-type of photovoltaic (PV) modules.

Ingot Diameter, Growth, and Slicing

As seen from Table 1, the add-on price allocation for ingot growth and slicing is $27.4/$m^2$. Growth cost in $/kg can be reduced by increased throughput obtained by increasing ingot diameter.

Economic analysis for growth of different diameter ingots indicates the possibility of achieving add-on price as given in Table 2 (Reference 2). This analysis assumes multiple ingot growth from a single crucible. Estimates based on various slicing results (Reference 3) show that for a 10-cm-dia or a 10-x-10-cm cross-section ingot, material utilization of 25 slices/cm of ingot length is obtained ($d + k = 16$ mils). However, for a 15-cm-dia ingot, 17 slices/cm ingot length only has been achieved ($d + k = 23$ mils).

Table 1. Price Allocation Guidelines for Cz-Type PV Module

Price Allocations (add-on)	Silicon	\$/kg	14.0		
		$\$/W_p$		0.126	
	Sheet	$\$/m^2$	27.4		Ingot diameter 15 cm d + k 17.5 mils (slices/cm. 22.5)
		$\$/W_p$		0.193	Y_{sh} 0.810
	Cell	$\$/m^2$	21.0		
		$\$/W_p$		0.141	Y_c 0.950
	Encapsulation material	$\$/m^2$	14.0		η_p 0.780
		$\$/W_p$		0.120	η_e 0.150
	Module assembly	$\$/m^2$	14.0		Y_m 0.995
		$\$/W_p$		0.120	η_m 0.117
Goal	Module price	$\$/W_p$		0.700	

Table 2. Growth Prices for Ingots of Different Diameters

Ingot diameter (cm)	Add-on Growth Price (\$/kg)
10.0	28.00
11.0	25.14
12.0	22.28
13.0	19.42
14.0	16.56
15.0	13.70

Effect of d + k on Price Allocation

Because variation of d + k affects material use, it must influence the silicon material price and the growth price. The add-on price allocation for a sheet of \$27.4/m^2 can be divided equally between growth and slicing for the given d + k of 17.5 mils (Table 1). A 95% slicing yield then gives a sheet conversion of 0.92 m^2/kg of ingot, requiring a growth add-on of

$12.6/kg. With this price of growth, the effect of variation of d + k on allowable slicing price is shown in Figure 1. It shows a material price of $17.9/m^2 ($Y_{sh}$ = 81%) with an add-on sheet price of $27.4/m^2 split equally between growth and slicing, for 22.5 slices/cm of ingot length. Corresponding values of d + k (in mils) are also given for ease of conversion. For a total sheet price (including silicon material cost) of $45.3/m^2, the allowable slicing cost reduces drastically for increasing d + k. Thus, e.g., at 17 slices/cm (d + k = 23 mils), the price goal can be met only if the slicing cost is brought down to $3.30/m^2. If, however, one can achieve at least 20 slices/cm, a slicing cost of about $10/m^2 is able to meet the allocated price of the sheet.

Shaping

One way to avoid this high penalty for larger d + k would be to shape the larger diameter ingot into a square cross section of reduced dimensions. This would result in reduced d + k. However, the cut-away silicon will have to be regrown as ingot with additional expense. There will be a tradeoff between regrowth cost of shaved-off silicon and the savings due to reduced d + k and improved packing factor.

As shown in Figure 2, circular ingot of diameter D can be shaped anywhere from full circle (no shaping) to a complete square with parallel faces C a distance D/ 2 apart. The four hatched areas of cut-away ingot are recycled silicon, given by

$$X = D^2 \cos^{-1}\left(\frac{C}{D}\right) - C\sqrt{\left(D^2 - C^2\right)} \qquad (1)$$

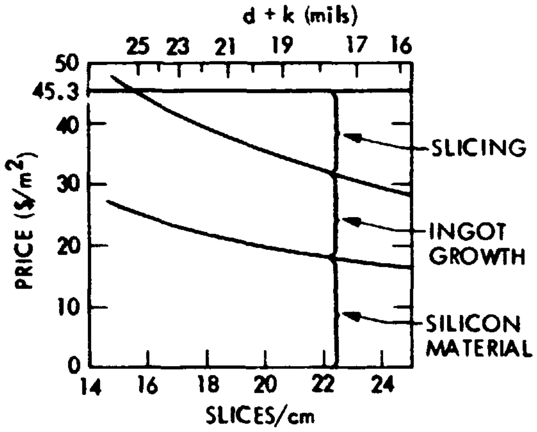


Fig. 1. Effect of Material Utilization on Ingot Growth and Slicing

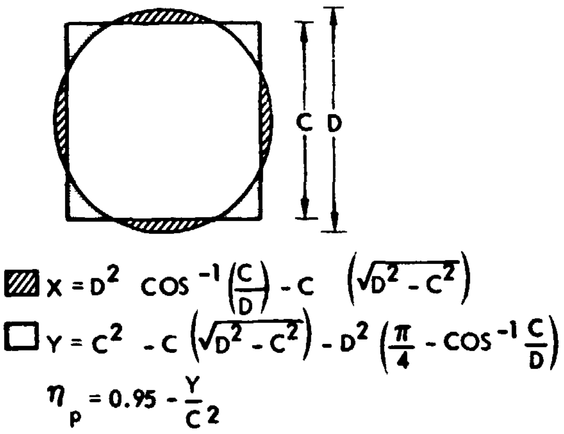


Fig. 2. Calculation of Recycled Silicon and Packing Factor with Ingot Shaping

The cross-hatched areas contribute to the modification of the packing factor. This is given by

$$Y = C^2 - C\sqrt{\left(D^2 - C^2\right)} - D^2\left(\frac{\pi}{4} - \cos^{-1}\frac{C}{D}\right) \tag{2}$$

and the resulting packing factor as

$$\eta_p = 0.95 - \frac{Y}{C^2} \tag{3}$$

For a solar insolation I ($1000\ W/m^2$), a general relationship between $\$/W_p$ and $\$/m^2$ is obtained as

$$(\$/m^2) = (\$/W_p)\cdot I\cdot\eta\cdot Y \tag{4}$$

where η and Y refer to the conversion efficiency and the process yield, respectively. Table 3 lists formulas used in this analysis.

Improved Packing and d + k versus Recycled Silicon

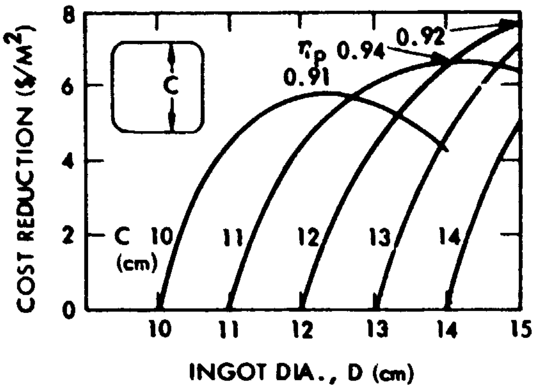
For a given parallel face distance C, the ingot diameter can be varied from D = C to D = 2.C. For a given C, the value of d + k is obtained by linear interpolation, with the end values fixed as 16 mils for C = 10 cm, 20 mil for C = 15 cm. By comparing the new allowable add-on sheet price to the new growth price, inclusive of recycled silicon, the advantage due to shaping is obtained as shown in Figure 3. For a given C, say 10 cm, the ingot growth add-on decreases with an increase in D (see Table 2). Further, the allowable sheet price increases due to better packing. Thus, a 12-cm-dia ingot gives a price advantage of about $\$6/m^2$ with η_p of 0.91. However, beyond a 12-cm-dia the growth cost reduction is compensated by increased recycling of silicon, and the advantage is lost. A maximum cost saving of nearly $\$8/m^2$ is obtained for a 15-cm-dia ingot with shaping, given C = 12 cm and $\eta_p = 0.92$.

Slicing Cost

The cost of slicing greatly depends upon cross-sectional dimensions of the ingot being cut. Three different cost scenarios are considered in the present analysis:

Case (i): For an ingot with larger cross-sectional dimensions, the slicing speed may be lower and the blade life may be inferior. The cost of the machine may also be higher than that for an ingot with smaller dimensions. Based on these assumptions the add-on slicing cost will increase with increasing C [Figure 4, Case (i)].

Case (ii): The parameter may be adjusted so a constant add-on cost may be attainable regardless of ingot dimensions [Figure 4, Case (ii)].



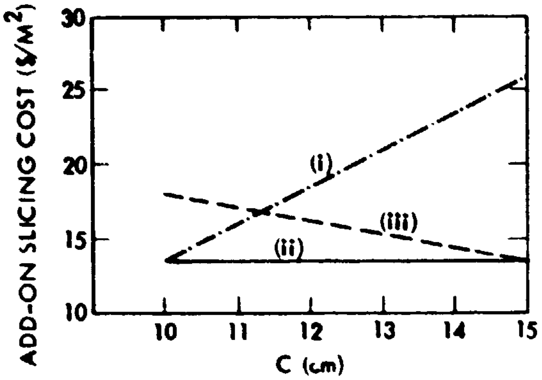


Fig. 3. Cost Saving Due to Shaping as a Function of Ingot Diameter

Fig. 4 Three Scenarios of Slicing Cost as a Function of Depth of Cut, C

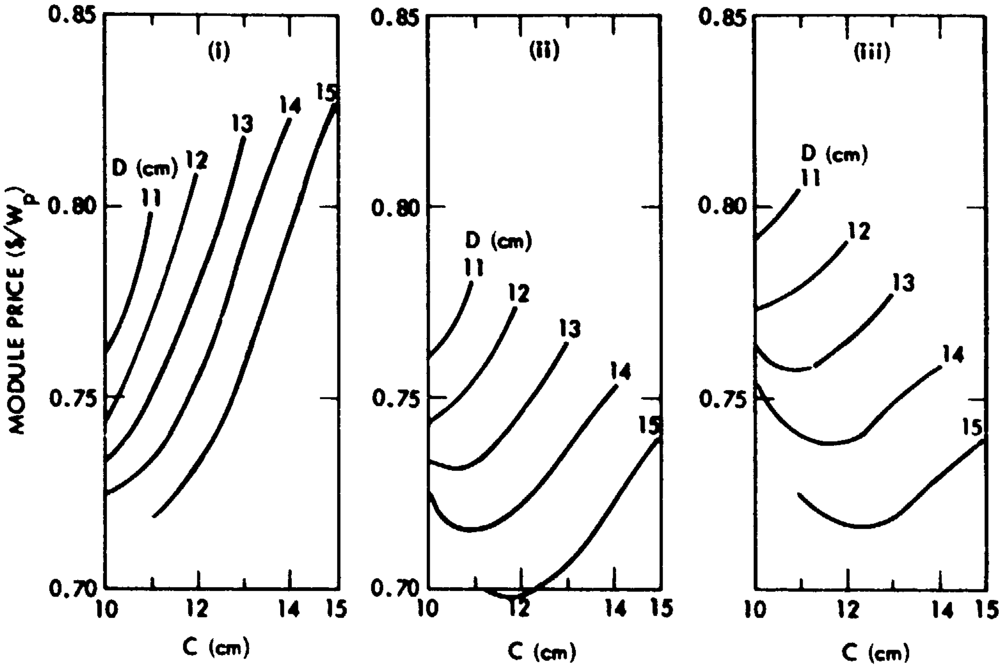


Fig. 5. Module Price as a Function of C for the Slicing Scenarios, Cases (i), (ii), and (iii), of Figure 4

Case (iii): With proper development efforts, increased blade life and slicing rate can be achieved. Automation will result in reduced labor cost. Thus, increased throughput due to larger diameter will result in reduced add-on slicing cost [Figure 4, Case (iii)].

In addition, a rough estimate of shaping cost, based on IPEG analysis (Reference 4) using an outer diameter (OD) saw, gives an add-on cost of \$1.80/m of ingot length. This can be done by one blade, or two parallel blades, with the ingot rotated 90° after completion of each cut.

Figure 5 shows the module price in $\$/W_p$ for the three slicing scenarios. The price of the module is least for the largest-diameter ingots. As expected, Case (i) shows maximum advantage due to shaping of a 15-cm-dia ingot to a

Table 3. List of Formulas

Module Price	$\$/W_p$ (module)	p_m
	$\$/m^2$ (module)	$P_m = p_m \cdot I \cdot \eta_m$
Encapsulation Materials Add-on	$\$/m^2$ (module)	C_{m1}
	$\$/W_p$ (module)	$c_{m1} = C_{m1}/I \cdot \eta_m$
Module Assembly Add-on	$\$/m^2$ (module)	C_{m2}
	$\$/W_p$ (module)	$c_{m2} = C_{m2}/I \cdot \eta_m$
Cell Price	$\$/m^2$ (cell)	$P_c = \left[P_m - \left(C_{m1} + C_{m2}\right)\right] Y_m/\eta_p$
	$\$/W_p$ (module)	$p_c = p_m - \left(c_{m1} + c_{m2}\right)$
Cell Fabrication Add-on	$\$/m^2$ (cell)	C_c
	$\$/W_p$ (module)	$c_c = C_c \cdot \eta_p/I \cdot \eta_m \cdot Y_m$
Sheet Price	$\$/m^2$ (sheet)	$P_{sh} = \left(P_c - C_c\right) Y_c$
	$\$/W_p$ (module)	$p_{sh} = p_c - c_c$
Silicon Price	$\$/m^2$ (sheet)	$C_{si} = [0.0591 \cdot (d + k) \cdot Si]/Y_{sh}$ Si is silicon price, \$/kg
	$\$/W_p$ (module)	$c_{si} = C_{si} \cdot \eta_p/I \cdot \eta_m \cdot Y_m \cdot Y_c$
Sheet Add-on	$\$/m^2$ (sheet)	$C_{sh} = P_{sh} - C_{si}$
	$\$/W_p$ (module)	$c_{sh} = p_{sh} - c_{si}$

complete square of $C \approx 11$ cm. Cases (ii) and (iii) show that in general there will be a value of C between full circle and full square, resulting in minimum module price. A saving of about 2 to 10 ¢/W_p is obtainable by shaping, depending upon the slicing scenario used.

A similar calculation is done for a 15-cm-dia ingot with two different d + k values at C = 15 cm of 24 mils and 20 mils. However, the d + k value is kept constant at 16 mils for C = 10 cm. Linear interpolations have been done for intermediate C values for both cases. The resulting module prices are shown by the two curves in Figure 6. This shows that the module price will be higher for larger d + k as expected, but the advantage of shaping will be even greater.

Array Installation

Increased packing factor and the consequent improved module efficiency has an added advantage when array installation costs are considered (Reference 5). Thus, a 10% efficient, \$0.70/W_p module will need \$0.60/W_p add-on for a \$60.0/m^2 array installation, resulting in a total installed price of \$1.30/W_p. With the same total array installed price of \$1.30/W_p, one could afford to pay more than \$0.70/W_p for the module if its efficiency is greater than 10%. The module price, p_m, in \$/W_p would then be shown as:

$$p_m = 1.30 - 60/I \cdot \eta_m \qquad (5)$$

Based on this premise, Figure 7 shows the savings (p_m - module price per watt with shaping) as a function of C with D as a parameter. Considerable saving is obtained with ingot shaping for all values of D from 10 cm to 15 cm. A maximum advantage of about 15¢/W_p is achievable by squaring a 15-cm dia ingot.

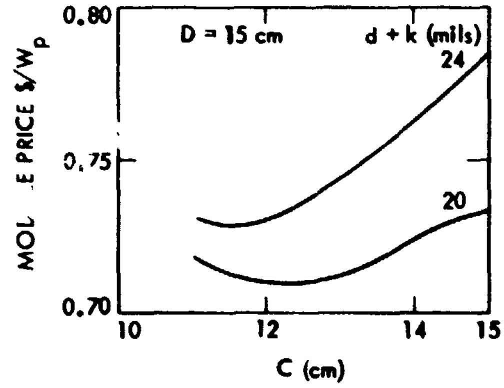


Fig. 6. Effect of d + k and Shaping on Module Price

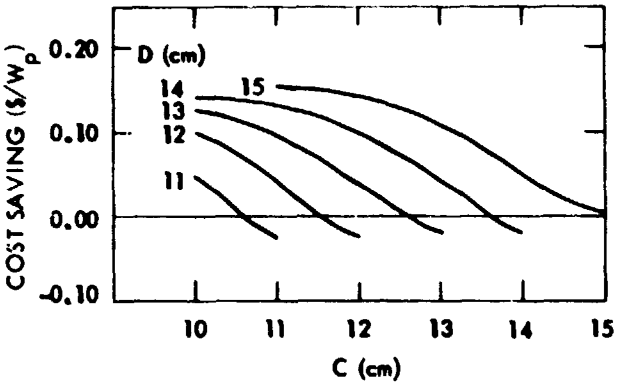


Fig. 7. Effect of Array Installation and Shaping on Module Price

DISCUSSION

Shaping ingots for solar photovoltaic modules affect module price in various ways. Slicing thinner pieces and reducing kerf saves polysilicon material and reduces the ingot growth cost. Similarly, improvement in packing factor reduces encapsulation cost. These cost benefits are, however, offset to a certain extent by regrowth cost of cut silicon and the shaping costs involved. Additional cost benefits occur in the balance of the system because of a more efficient module.

There may be other advantages of shaping, such as ease in slicing of multiple ingots and processing of square cells, etc. Incomplete squares with rounded corners may have the advantages of less chipping of corners during slicing and available spaces for interconnects.

Cost reduction in slicing of large-diameter ingots may make shaping less attractive. High shaping costs and poor ingot growth yields will also have a similar effect.

CONCLUSION

The severe penalties in add-on price due to increasing slice thickness and kerf are presented. Trade-offs between advantages of improved packing efficiencies and material use and disadvantages of recycling silicon and shaping costs are developed for different slicing scenarios. It is shown that shaping results in cost saving of up to 21% for a 15-cm dia ingot.

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5. Wolf, M., private communication.

DISCUSSION:

SCHMID: What kind of cost did you assume for the actual shaping itself, which would probably be a band-sawing operation?

DAUD: I did a rough IPEG, and compared it with the grinding. I came out with about $1.80 per meter length of the shaping. That's what I have assumed here.

ROBERTS: What effect do you think that shaping of the ingot is going to have on edge-chip and surface damage and so forth?

DAUD: Depending upon what kind of mask you are using, you may be able to accommodate slight variation in the edge chipping. Another thing I have not included is the etching of the silicon that is cut and which is to be regrown. If you include that cost, the picture may be a little different.

WOLF: I would like to mention that this is really not new technology. In the fabrication of space cells in the early 60s, this was done. At the time, about 2-1/2-inch-diameter ingots were grown that did not have regular diameter, and the cells fabricated were usually 2-x-2-centimeter and 1-x-2-centimeter. What existed at the time were templates that production girls could hold over the ingots, and see how many 2-x-2s and 1-x-2s they could cut out of it. Then the ingot was sectioned length-wise into 2-x-2 and 1-x-2 sections, and the outside parts of the ingots were etched and remelted in the next load in the crystal pulling furnace. The square and rectangular sections were then sliced, at that time on OD slicing machines, later on multi-blade slicing machines. So this is a practical technology.

ILES: I think the conclusions are good; I think you should include the practical case for modules where normally we use textured glass and reflecting back surface to somewhat offset that low packing density. It goes from 78%, to something like 85% or 88% effective packing density because of back reflection from bottom of the textured glass back onto the cells. I think at least for the next year or two that looks like it's sort of standard technology.