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ENERGY REQUIREMENT FOR THE PRODUCTION OF SILICON SOLAR ARRAYS

FINAL REPORT

JPL CONTRACT NO. 954606

SOLAREX REPORT NO. SX/111/4

DECEMBER 1977

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ENERGY REQUIREMENT FOR THE PRODUCTION OF SILICON SOLAR ARRAYS

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FINAL REPORT

SEPT. 21, 1977 TO DEC. 20, 1977

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Summary

This report documents the results of a study under JPL Contract 954606 to investigate the feasibility of manufacturing photovoltaic solar array modules by the use of energy obtained from similar or identical photovoltaic sources. The primary objective of this investigation was the characterization of the energy requirements of current and developing technologies which comprise the photovoltaic field. These energy requirements were subsequently compared to the energy production potential of a future solar power plant and, as a result, the concept of the SOLAR BREEDER was refined and manifested in a computer program. The breeder model allows to take the energy requirements for any photovoltaic technology into account and calculate its energy economics. It is thus a valuable tool to estimate the energy impact of developing technologies within the photovoltaic field.

The report documents the energy assessment of the prevailing technologies and many alternative technologies currently under development. For cross-checking the energies of prevailing technologies Solarex data were also used and the wide-range assessment of alternative technologies included different refinement methods, various ways of producing light sheets, semicrystalline cells, etc.

Finally, these energy data are utilized to model the behavior of a future SOLAR BREEDER plant under various operational conditions.

1. Introduction

This final report documents the results of a feasibility study of manufacturing photovoltaic solar array modules by the use of energy derived from similar or identical photovoltaic sources. In order to substantiate this "SOLAR BREEDER" concept an extensive assessment of the energy expenditures in the prevailing and potential manufacturing technologies of terrestrial photovoltaic cells and modules was carried out and compared to the energy producing capability of a photovoltaic power plant. The Solar Breeder concept relies on the fact that much less energy is expended in the making of solar arrays than can be reclaimed from them during their subsequent employment in solar power stations.

The energy assessment of the manufacturing technologies was carried out based on three major types of energy expenses as described in Appendix A. These energy costs were then compared to a typical solar cell as test vehicle and its energy payback capability was utilized to derive the term "payback time" for each process step within the photovoltaic production sequence.

Subsequently, a model plant could be developed in the form of a computer program which can simulate the energy management of a Solar Breeder as a function of its manufacturing technology. The model accepts any string of photovoltaic process steps and balances energy costs versus energy return of manufactured modules in order to compute the time after which such a plant would deliver net energy to society. The model as developed can thus be used to evaluate prevailing and potential photovoltaic technologies with respect to their energy effectiveness and thus is a tool of considerable predictive power for energy considerations.

The energy assessment within the framework of this contract was carried out in various ways. For the conventional photovoltaic production sequence an extensive investigation of the energy expenses of the processes practiced at the Solarex Corporation was carried out. This study indicates that in 1977 a non-concentrated, non-tracking panel under average conditions shows a payback time on the order of 6.4 years. This represents a considerable improvement from the payback time of 40 years estimated for space applications; payback times on the order of 1 year are terrestrial technology goals. Potential technologies were examined by direct communications with JPL contractors about their research efforts and from their reporting documents. In addition, this contract provided also for the energy assessment of Solarex's own efforts to develop a solar cell requiring low energy expenditure by means of silicon casting, a Solarex program which is now in its third year of development.

2. The Solar Breeder

2.1 Introduction

The Solar Breeder is an energy self-sufficient plant producing new energy in the form of solar electric panels which are available for external use or for Breeder growth to increase the direct energy input.

When the operation of the breeder begins it must borrow the energy that is inherent in the initial array. Energy must also be borrowed continually in the form of materials of production and equipment. This will be called non-direct energy to distinguish it from the direct energy available from the breeder's array. The borrowed energy is returned by the panels that are sold. When the total power generated from panels that have been sold exceeds the total non-direct energy used then the <u>cross-over time</u> has been reached. For a particular technology the payback time is a fixed number but the cross-over time depends on the dynamics of the breeder plant. In particular, the cross-over time depends on how much of the plant's panel production is added to the breeder array.

The cross-over time will be developed mathematically for the simple case where all the panels produced are sold. A computer program is used for the more complex case where panels are added to the roof and the breeder plant grows in production capacity. In this "open loop" case of selling all of production it is assumed that the panel lifetime is longer than the cross-over time so that the number of sold panels operating is simply the sum of the panels produced.

The borrowed energy, the energy debt, can be written

$$1)\quad \text{Debt}_{\text{total}} = \text{Debt}_{\text{initial array}} + \text{Debt}_{\text{non-direct}}$$

The non-direct debt grows at a constant rate since panels are produced at a constant rate.

(2) $$\text{Debt}_{\text{non-direct}} = (\text{Non-direct energy/panel}) \times (\text{panels/day}) \times (\text{time})$$

The production rate depends on the direct energy available.

(3)
$$(\text{Panels manufactured/day}) = \frac{(\text{insolation/panel-day}) \times (\text{breeder array size})}{(\text{direct energy/panel})}$$

The expression (insolation/panel-day) will be written henceforth (insolation).

We shall call the energy per panel E so we can write from equations (2) and (3).

(4) $$\text{Debt}_{\text{non-direct}} = \frac{E_{\text{non-direct}} \times (\text{insolation}) \times (\text{breeder array}) \quad \times (\text{time})}{E_{\text{direct}}}$$

The energy debt due to the array is simply the sum of the direct and non-direct energy.

(5) $$\text{Debt}_{\text{initial array}} = (\text{breeder array}) \times (E_{\text{direct}} + E_{\text{non-direct}})$$

so the total debt is

(6) $$\text{Debt}_{\text{total}} = (\text{breeder array}) \left[E_N + E_D + \frac{E_N}{E_D} \; (\text{insolation}) \times (\text{time}) \right]$$

The energy produced by the sold panels can be written as follows:

(7) $$\text{Energy credit} = (\text{Number of panels sold}) \times (\text{insolation})dt$$

Equation (3) gives the number of panels made each day so the total sold is the product of this number with time.

Equation (7) can then be written,

(8) $$\text{Energy credit} = \frac{(\text{breeder array}) \times (\text{insolation})^2 \; (\text{time}) \; dt}{E_D}$$

which can be integrated to obtain:

9) $$\text{Energy credit} = \frac{(\text{breeder array})(\text{insolation})^2\ (\text{time})^2}{2E_D}$$

The cross-over time can be found by equating the energy credit with the total debt, equations (6) and (9). After some algebra the equation becomes:

10) $$\frac{E_N}{\text{insolation}} + \frac{E_D}{\text{insolation}} + \frac{E_N}{E_D} \times (\text{time}) = \left(\frac{\text{insolation}}{E_D}\right) \left(\frac{\text{time}}{2}\right)^2$$

The ratio of energy needed to make a panel with the insolation per panel-day is the payback time so equation (10) can be written

11) $$(P_N + P_D)\ P_D + P_N\ (\text{time}) = \frac{(\text{time})^2}{2}$$

where P_I and P_D are the indirect and direct payback times.

The cross-over with no breeder-array growth can be written as follows:

12) $$\text{Cross-over time} = P_N + \ P_N^2 + 2P_NP_D + 2P_D^2$$

The implications of this formula can be seen from two examples. If the production is completely vertically integrated so that all materials and equipment are made in-house then the energy required is entirely direct. In that case, the cross-over time is about 1.4 payback time. The factor of 1.4 is due to the fact that the energy generated by the panels sold can only be realized over time as the panels operate. Another example is when the direct energy is one-third the total energy, then the cross-over time is twice the payback time.

The eventual net energy gain to society is determined by the payback time. The cross-over time is a systems parameter that indicates when the net energy flow to society is positive under conditions that the number of solar panels on earth grows. When the breeder plant grows in production capacity the equations are so complex that the system is best investigated with a computer model as described in the next section.

2.2 The Computer Model

A Computer model has been developed that can simulate a manufacturing facility that begins with silica and through a sequence of steps produces solar modules. In the model, the only source of direct energy is a solar array so that the process is self-sufficient in regards to direct energy. The model consists of a string of up to nine production steps as indicated in Figure 2.1. Each step is described by seven parameters. These parameters correspond to the data we have reported in the following chapters for the various conventional and alternative process steps. The parameters will be described fully in a later section.

The model contains shelves that act as a buffer to store manufactured products between steps so that the output of one step does not necessarily represent immediate input to the subsequent step. This allows great flexibility since some steps can be shut-down while others continue to run in response to varying insolation. The model uses insolation data which vary from day to day and as a result the impact of weather variations can be simulated. Battery storage is also included in the model with the battery capacity being an input parameter. There is a dynamic interaction between the solar insolation, the battery and the process steps so that energy during days of high insolation can be both stored in the battery and "stockpiled" as output products that are added to the shelves from individual production steps.

Another feature of the program is that it is possible to treat the panel lifetime as statistically distributed rather than as a step function whereby all panels expire exactly after a predetermined lifetime. Panel expiration occurs in the form

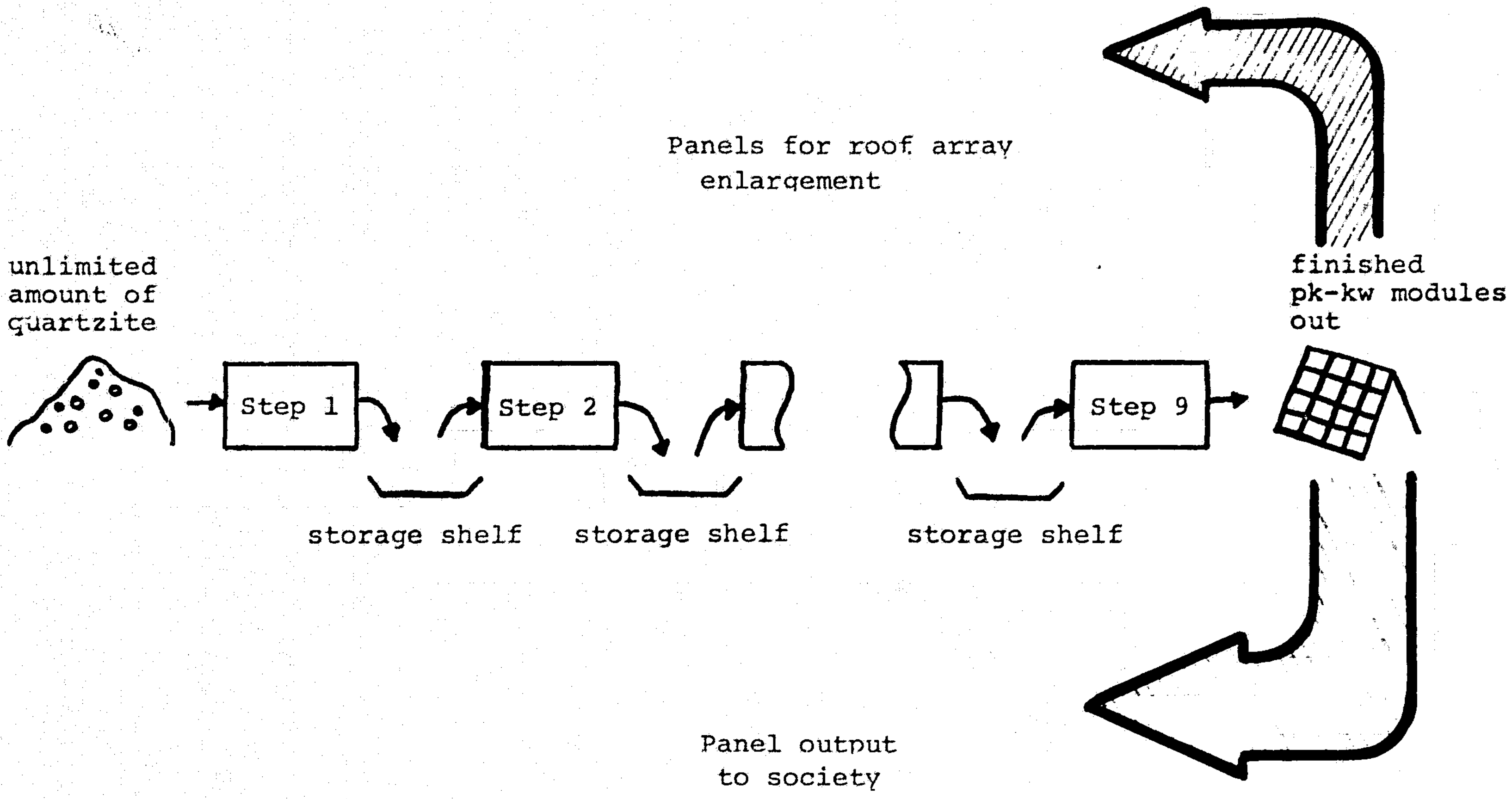


Fig. 2.1 BREEDER MODEL CONSISTING OF UP TO NINE PROCESS STEPS.

of a gaussian distribution with the mean and standard deviation as input parameters as described later in this chapter.

Process Step Characterization

Each process step within the manufacturing sequence is represented in the computer model as a system which transforms an input arriving from the preceeding step or shelf into an output to the subsequent step or shelf. A process step is diagrammed in Figure 2.2 For each step there are seven numbers that characterize the step.

1) C_1 : The first number is the input/output conversion factor denoted C_1. It specifies the quantity of input units needed to make one output unit. Since the program assumes that the output from one step is in the same unit as the input to the next step, it is not necessary to tell the computer the name of the units. For example, if 969 4" wafers are required to build a single peak-kilowatt module, then the input to the computer for the panel building step is simply the number 969. The program assumes that the output from the last step has the units of peak-kilowatt modules.

C_1 is the product of two factors, the physical conversion and the yield. For example, since a 4" wafer, 10 mils thick, weighs 4.72 grams the process of crystal growing and slicing has a physical conversion of 4.72×10^{-3} kg/wafer. However, due to losses in crystal growing and slicing, the yield is 55%, i.e. 1/.55 yield conversion. The overall conversion factor is $\frac{4.72 \times 10^{-3}}{.55}$.

2-4) C_2, C_3, C_4: These factors describe the respective energy usage to make one unit output. C_2 is related to the direct energy. C_3 is related to the materials energy and C_4

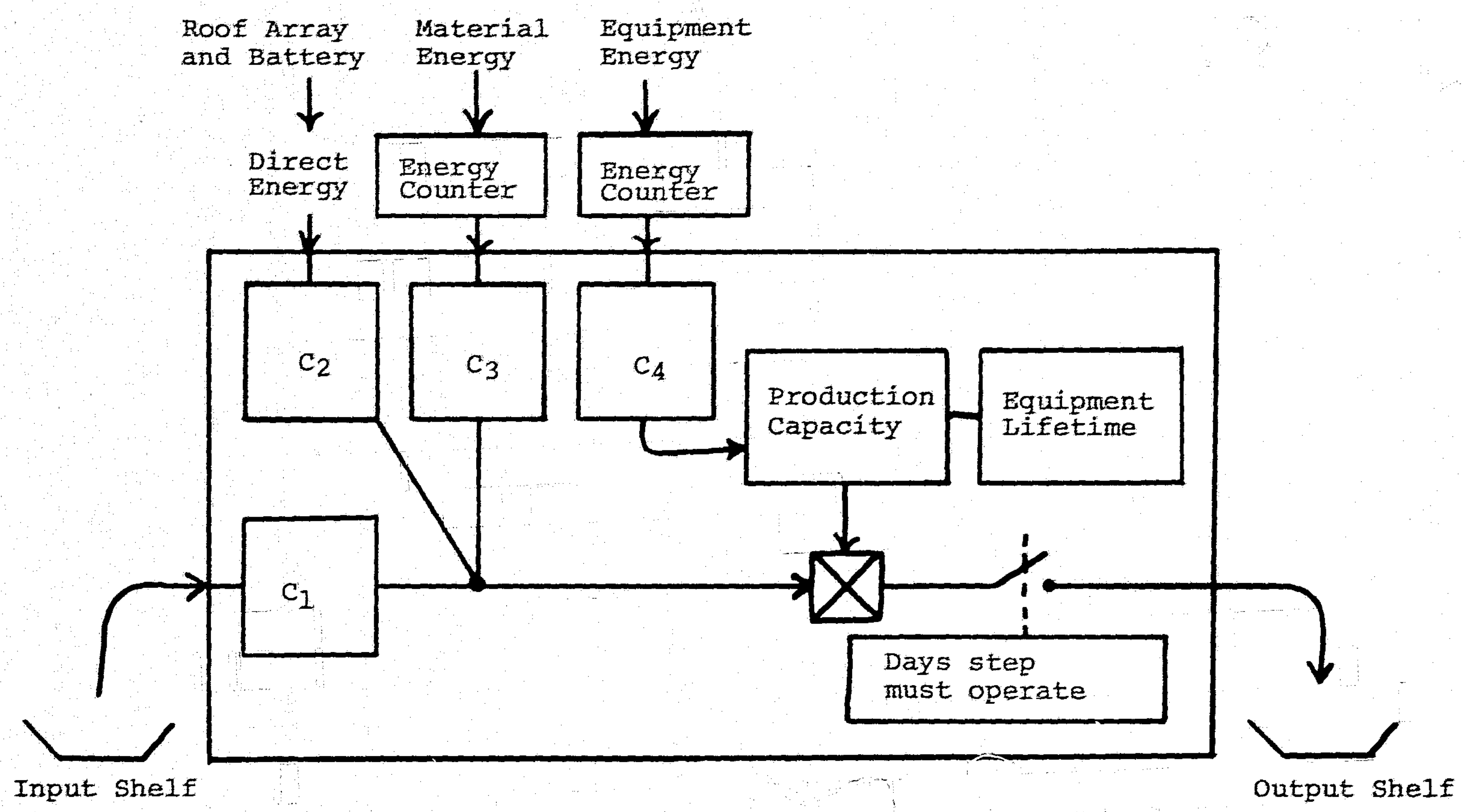


Fig. 2.2 CHARACTERIZING PARAMETERS OF A PROCESS STEP.

is related to equipment energy as described in Appendix A. These values are in kw-hr per output unit (kg silicon, wafer or module) and are basically the energies listed for the various conventional and alternative process steps with the following differences. The direct energy is obtained only from the panels assigned to the breeder facility, denoted the roof array. The equipment energy is determined solely by the amount of equipment that is introduced into a process step. The overhead energy can be obtained from the roof array, hence, is included as part of the direct energy. Furthermore, if vertical integration is introduced so that some of the indirect materials are made in-house then some of the indirect material energy can be direct energy instead.

5) Equipment lifetime: The equipment in each step is assigned a particular lifetime in years. As often as each year some of the equipment expires and must be replaced. Each process step can have its own equipment lifetime but within the step there is no further differentiation.

6) Operating days: Some process steps are allowed to be shut down at the end of each day while others cannot be turned off such as an arc furnace. The option of shutting down some of the process steps of the breeder facility allows leveling and distributing the load within the facility in response to the available daily insolation. At times of low insolation process steps that can operate a single day will be shut down first and steps which require more days to run, such as an arc-furnace, will remain operating.

The model has, as one of its modes, the option of a two-day weekend during which time process steps that can be shut-off will be off. The weekend-off mode allows the facility's battery to recharge.

7) Capacity: The capacity parameter determines the number of units which the particular process step can produce daily. It is set as an input parameter at the beginning of the breeder operation. At that time its proportion to the initial roof array size is determined. The production capacity increases with the roof array such that this ratio remains constant. At times of roof array reduction through expiration the production capacity does not immediately decrease. The correct proportion between capacity and roof array is regained when panels are added to the roof and/or some of the equipment expires. It is assumed that additional equipment is reliably available each year it is needed to maintain the proportion to roof array. Each time equipment is added the inherent energy is added to the equipment energy debt.

Energy, Debt and Credit

The materials and equipment are fed by a reliable source of supply from which they can be drawn according to the manufacturing needs. Then the amount of energy inherent in the material and equipment obtained is recorded by means of counters and added to the respective energy debts. Material energy is added daily to the energy debt while equipment is added yearly when the production capacity must increase due to the expanding roof array or to replace equipment that has expired. The total debt is the sum of equipment and material debt, the debt due to the battery (like an equipment debt) and the energy debt inherent in the initial roof array obtained prior to the start-up of the manufacturing facility.

Part of what the breeder produces is added to the roof and part is sold. The energy debt is offset by the panels sold.

The panels sold represent a potential energy of twenty years operating life. However, the energy credit is counted only as it is realized over the operational lifetime. It is as if all the panels sold are attached to a single watt-hour meter that shows the accumulated energy credit generated.

Process Step Operation

Each individual process step will conduct a survey prior to production start each day in order to determine whether it will be able to produce without systems complications. It will only run if the following conditions are met:

a) the input shelf of the process step contains enough product so that a full day's production of the particular process step is possible even if the preceeding process step does not generate an output. The exception is the first step for which enough sand or quartzite is always available.

b) the output shelf is not full, but rather contains enough storage space for the day's production.

c) enough energy is available from the storage batteries to supply itself and all the preceeding steps with energy during the time they have to be in operation. The energy required from the storage batteries for such a situation is calculated as follows:

$$\sum_{\substack{\text{all active} \\ \text{process step}}} \begin{pmatrix} \text{energy required} \\ \text{per day} \\ \end{pmatrix} \cdot \begin{pmatrix} \text{number of days the} \\ \text{process step must} \\ \text{operate} \end{pmatrix}$$

By not relaying on the present day's insolation, the system is unaffected by hourly variations.

At the beginning of the sensing activity, each process step assumes that all steps in the breeder chain are "active", i.e. ready to produce, and compares the required energy with the energy available in batteries. If not enough energy is available for a whole breeder cycle, then the last process step sets its production to zero and cancels its energy demand. As a result it will not be counted in the above sum as an active step. The remaining steps continue the sensing activity and the "last" active step declares itself inactive until a situation arises whereby the energy demands of the remaining string of production steps can be met from the batteries during a time span over which each step has to operate. The breeder then runs one day and the active steps convert items from the input shelves to output products on subsequent shelves.

Model Synthesis and Additional Inputs

The computer model of the breeder allows the simulation of a photovoltaic manufacturing facility consisting of up to nine individual process steps. The steps are interconnected such that buffering between the steps is possible in the form of temporary storage facilities (shelves) for semi-processed silicon material. The model is now believed to be flexible enough so that almost all operational situations of a breeder facility can be simulated.

In addition to the inputs required to describe the individual process steps the program calls also for input information which pertains to the production sequence as a whole.

These additional input parameters are:

1) The initial battery capacity expressed in kw-hrs. Similar to the equipment growth the battery capacity is expected to enlarge in constant proportion with the roof array.

2) The lifetime of the individual batteries. Similar to the equipment, a constant lifetime expressed in years is assumed for the batteries.

3) The energy debt of the battery per kW-hr of storage capacity. The installation of a battery bank into the breeder facility for energy storage constitutes an additional energy debt. This debt is accounted for and added to the total debt of the facility.

4) The initial roof array size expressed in peak kW at the beginning of breeder operation. The roof array size will increase by adding panels from the subsequent production.

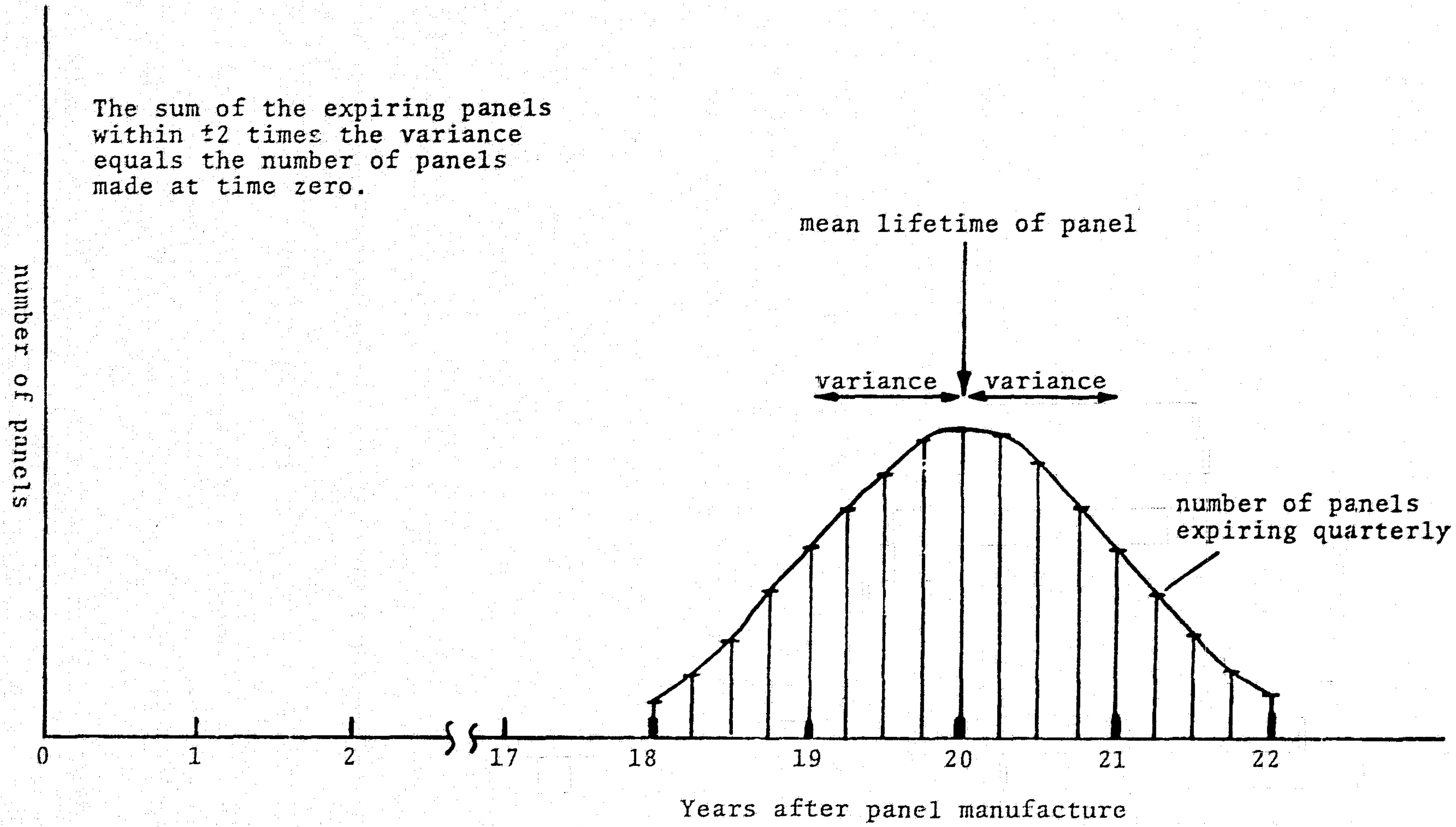
5) The number of panels from production which will be added to the roof quarterly. This number can either be a constant or be determined as a function of breeder operating time.

6) The panel expiration mode. The assumption is made that a set of panels does not expire momentarily at the end of the expected lifetime but that expiration of the set occurs according to a gaussian distribution curve as shown in Fig. 2.3 The mean of the distribution function can be set at the expected average panel expiration date. The variance of the distribution curve can be chosen to reflect a realistic range of lifetimes.

   Although panels are produced daily, they are installed in quarter year intervals. Thus, a set of panels in the above sense consists of the number of panels installed during a quarter year. Panels are assigned one of two functions, either on the breeder roof or in other applications after being sold.

7) The weekend-off option. The program runs in either one of two modes. One mode assumes that everyday of the year is a production day. The other mode allows equipment to be shut off during weekends. Process steps will only be shut down for the weekend if not conflict with the number of days they have to run is encountered. For example, an arc furnace which has to be in operation for 5 days will not be shut down if the smelting process began two days before a weekend. In this case the weekend mode will be overridden for that step.

   The weekend-off option is interesting from the system's reliability and production continuity point of view because



The sum of the expiring panels within ±2 times the variance equals the number of panels made at time zero.

Fig.2.3 PANEL EXPIRATION DISTRIBUTION (GAUSSIAN) For 20 ±1 year Lifetime periodic battery charge opportunities on weekends might allow the system to recover from occasionally occurring awkward operational situations.

8) Automatic Production Capacity Balance

At the start of the breeder operation, the determination of the capacity values for each process step is based on experience and estimation. In many instances the throughput values of the individual process steps are not optimally selected because the best estimated production rate of an individual step is not optimal when looked upon within the operation of the whole breeder system.

Our breeder model allows the automatic adjustment of the production capacities in each process step by means of iterative trial runs. The model assumes that all input parameters except the production capacities are well known, including the daily insolation data. In other words, the automatic capacity balance option provides the answer to the following question: Given all information on the individual process steps and thus having the breeder well defined with respect to the various manufacturing technologies, and given all the information on the local daily weather conditions, what should the individual production rates of the process steps be in order to make optimal use of the breeder system? We believe that this is an important question whose correct answer has significant consequences in any kind of production system which consists of individual process steps and between step buffering.

The meaning of the word "optimum" needs to be clarified. Within the scope of our model the system is optimally tuned if the idle capacity of each process step is a minimum.

Idle capacity is defined as the number of days the process step did not operate in a whole year divided by the number of available workdays in the year. Since we only consider workdays, the automatic capacity balance can also be carried out in the weekend-off mode.

In order to carry out an optimization procedure, initial production capacity values are assumed according to the best information available. The program is then run through 8 iterations, each one consisting of the first 2 years of breeder operation. Each iteration calculates the idle capacity (i.e. essentially the days during which the individual processes could not operate because of an inbalance resulting in a completely full or empty shelf or because of bad weather conditions) and formulates a decision with respect to proper changes in the individual production capacities. After 8 iterations the system has been stabilized and the optimal production capacities have been determined to the extent that additional iterations would only yield minor changes of the parameters. The breeder facility as a whole is now considered fine-tuned in its response to the demands of the individual production steps, their interfacing activity, and the available energy procurement either from the roof array or battery bank.

3. Semicrystalline Silicon

In the quest to circumvent the high cost of the conventional semiconductor grade silicon Solarex initiated already almost three years ago a program to obtain wafer material by means of unconventional preparation methods. One of them is the semicrystalline casting technique whereby large grained material is obtained which when processed into a solar cell yields cell efficiencies almost as high as single crystalline wafers. Early results of this research effort were presented at the latest Photovoltaic Specialists Conference.1)

Under the terms of this contract we manufactured cast semicrystalline wafers and processed some of them into solar cells in order to asses the energy expenditure. Twenty wafers and twenty cells including their IV characteristics were delivered to JPL for evaluation.

Typical IV curves of 2cm x 2cm type cells are shown in Figs. 3.1 and 3.2 The displayed efficiencies are 13.5% and 13.9%, respectively, under AM1 conditions at 25°C. Semicrystalline cells exhibiting the large grain structure are shown in Fig. 3.3

The purpose of the program under this contract was the evaluation of this potential alternative preparation technique in terms of the energy demands of the casting process. In order to assess energies and payback times a new test vehicle must be defined in order to account for new dimensions and expected production efficiencies as shown in Table 3.1.

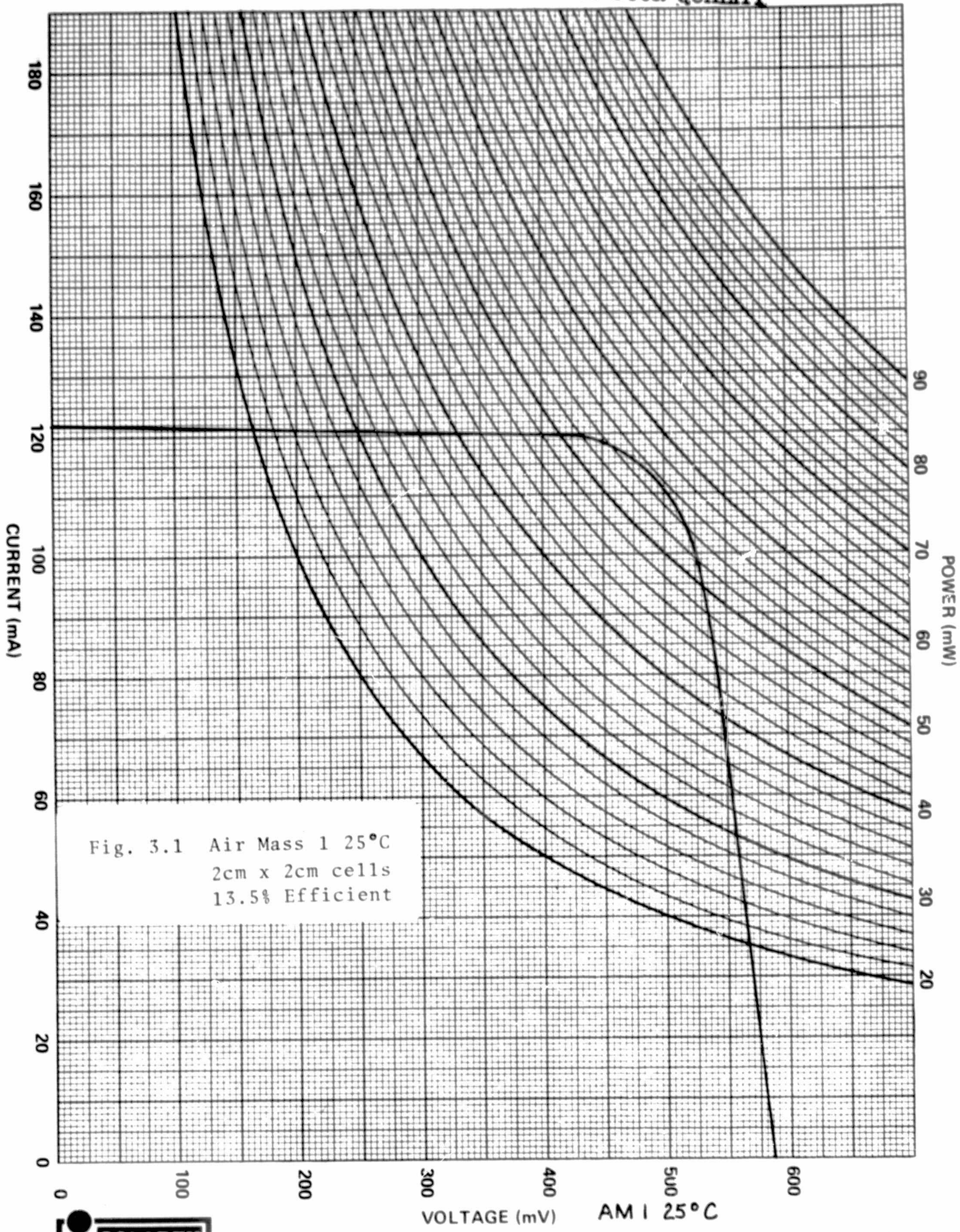


Fig. 3.1 Air Mass 1 25°C
2cm x 2cm cells
13.5% Efficient

AM 1 25°C

SOLAREX
ROCKVILLE, MARYLAND USA
FORM 11134

Cell Type 2X2 SEMI No. 55237-5 By DSL Date 11-18-77

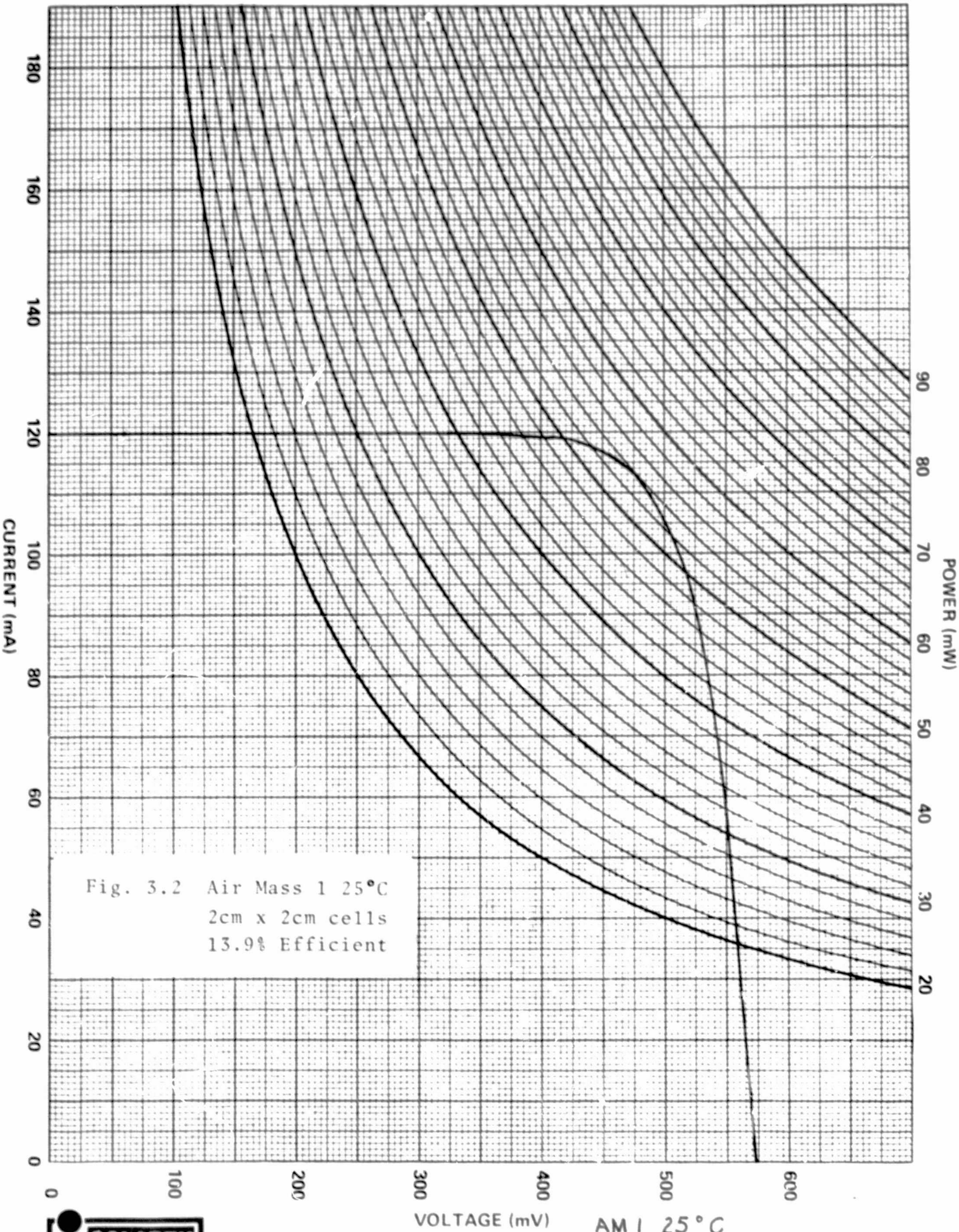


Fig. 3.2 Air Mass 1 25°C
2cm x 2cm cells
13.9% Efficient

AM I 25°C

SOLAREX
ROCKVILLE, MARYLAND USA
FORM 11134

Cell Type 2X2 SEMI No. 55237-13 By DSL Date 11-18-17

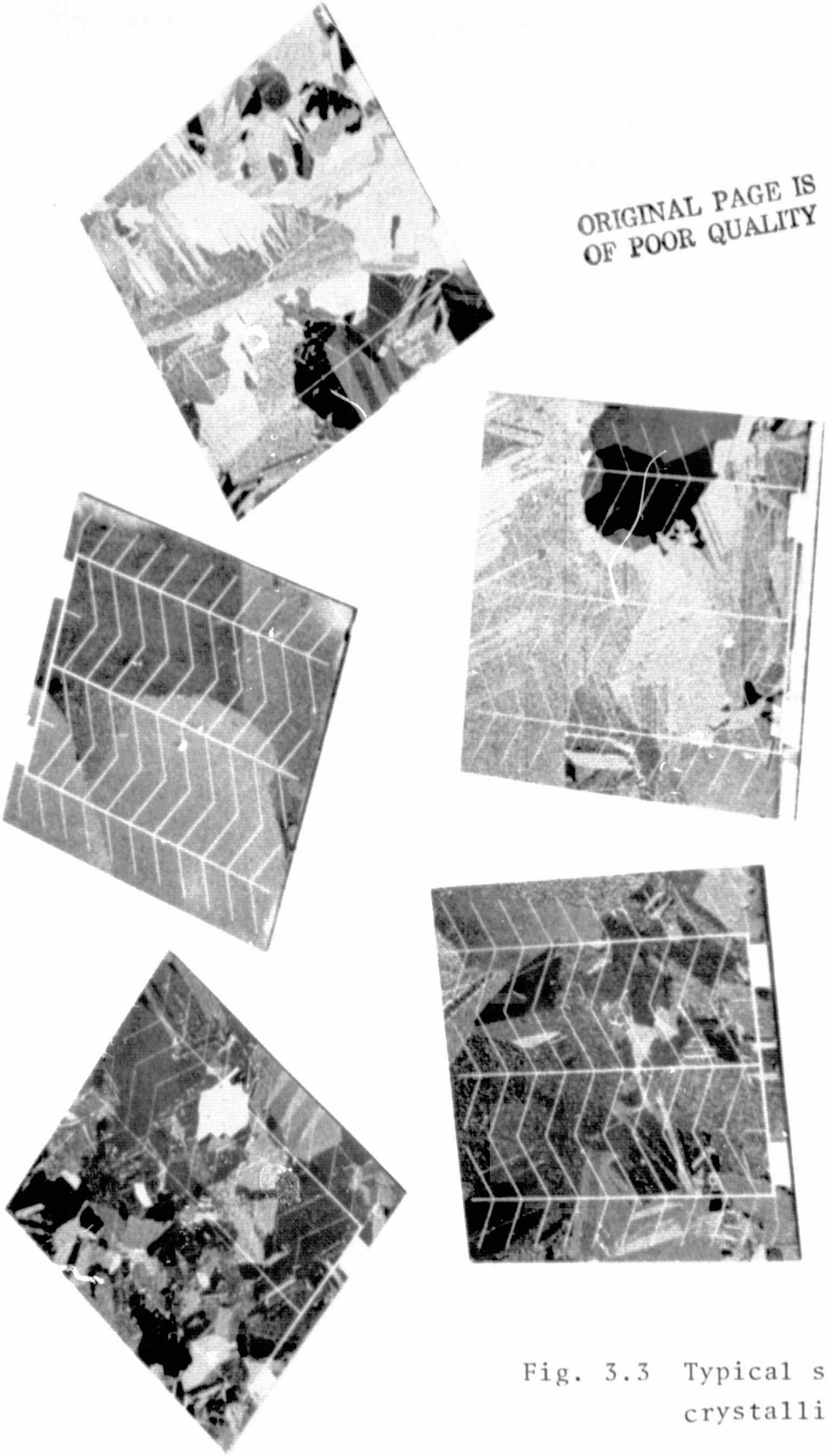


Fig. 3.3 Typical semi-crystalline cells

Table 3.1 Semicrystalline Test Vehicle

Material	SeG silicon
Cell dimensions	4" x 4" x 0.010"
Cell area	16in.^{2} (103.2cm^2)
Cell volume	.16in^3 (2.58cm^3)
Silicon mass	6.01gms @ p of 2.33gm/cm^3
Lifetime of cell	20 years
Efficiency	10%
Peak Power	1.032 W
Average insolation time per day	4.33 hours
Energy delivered in 20 years	32.6 kwh

In a scaled-up production facility, cell yield is expected to be as good as, if not better than, present Czochralski techniques. Hence, assuming 50% yield as in conventional techniques, the energy delivered in one year is:

Energy delivered per kg silicon
in 1 year at 50% yield = 167 kwh.

Case 1 - SeG as Starting Material

If SeG silicon is used as the base material, the same energy is expended reducing the metal to that purity and in re-melting the material as in the conventional technique. Melting will take place in readily available crucibles and be cast in ceramic molds of size 4" x 4" x 8". The charge of silicon is assumed to be approximately 5kg, 4.9kg of which is poured into a mold, 0.1kg of which is lost to the sides of the crucible.

The direct energy costs will appear as meltdown energy in producing the melt. Net yield of a 4" x 4" x 8" mold in the form of the defined test vehicle will be 400 wafers. Direct energy cost is, therefore, 0.125 kWh/wafer yielding a payback time of 0.077 years.

Indirect energy appears in materials costs of crucibles and molds. Crucibles could cost approximately $200.00 and last for 10 charges. The indirect energy requirement for crucibles will be approximately 0.33 kWh/wafer, yielding a payback time of 0.20 years. The molds must be replaced after each casting. At approximately $1.00 per mold, indirect energy costs will be estimated at 0.017 kWh/wafer, yielding a payback time of 0.01 year. Total indirect energy costs of SeG based semi-crystalline casting could be 0.34 kWh/wafer with a payback time of 0.21 years.

Estimates of equipment costs for the casting system for SeG based semi-crystalline silicon approach $60,000. Assuming a lifetime of 5000 days and 4 charges per day, equipment energy costs will be 0.05 kWh/wafer with a payback time of 0.031 years.

Table 3.2 Energies for SeG Semi-crystalline Casting

	kWh/"test cell"	Payback time in years
Direct energy	.125	.077
Indirect energy	.350	.210
Equipment	.050	.031
Total energy	.525	.318

The energy costs of SeG based semi-crystalline cells compares with conventional cells in the process steps of reduction through wafering as follows:

Table 3.3 Sheet Payback Time of Cells of Cast Process vs. Conv. Process

	Payback time in years
Conventional Process	4.46
SeG based Semi-crystalline Process	3.83

SeG based semi-crystalline silicon saves 6 months of payback time, but investigation of the use of MG as a starting material for semi-crystalline material illustrates the potential of the semi-crystalline casting technique.

Case 2 - MG as Starting Material

Direct energy costs will rise due to the increase in temperature needed to purify the MG silicon. The direct energy of melting the MG and maintaining the melt will be approximately 0.325 kWh/wafer yielding a payback time of 0.2 years.

Indirect energy costs involve crucible and molds as before but in addition is the cost of Cl_2 for greater purification. At a rate of 1 liter per hour and a cost of $1.00/liter, total indirect energy costs of MG semi-crystalline silicon could rise to 0.367 kWh/wafer and with a payback time of 0.22 years.

Equipment costs will rise to an estimated $160,000. Assuming a lifetime of 5000 days and a yield of 4 charges per day, equipment energy costs will approximately be 0.13 kWh/wafer yielding a payback time of 0.082 years.

Table 3.4 Energy for MG Semi-crystalline Casting

	kWh/"test cell"	Payback time in years
Direct energy	0.325	0.2
Indirect energy	0.367	0.22
Equipment	0.13	0.082
Total	0.822	0.502

There are no reduction-to-SeG costs.

The energy costs for cells prepared by conventional single crystal techniques, SeG based semi-crystalline silicon casting techniques, and MG Si based semi-crystalline silicon casting techniques compare as follows: (from Si reduction through wafering)

Table 3.5 Payback Times in Casting Technologies

	Payback time in years
Conventional Process	4.46
SeG Si Semi-crystalline Process	3.83
MG Si Semi-crystalline Process	0.80

Total energy payback time of a terrestrial solar cell could decrease from 6.4 years to 2.8 years by utilizing the MG Si semicrystalline process.

4. Energy Assessment of Prevailing Manufacturing Technologies

4.1 Introduction

The prevailing sequence used in the present-day manufacture is depicted in Fig. 4.1 introducing five basic operations. The prevailing processes within those operations are relatively well established. They are:

Reduction. - Quartzite pebbles are reduced to metallurgical grade (MG) silicon by means of carbon-containing agents in electric arc furnaces.

Refinement. - Conversion of MG silicon to high purity by means of trichlorosilane gas and subsequent silicon deposition of silicon in polycrystalline form. (Semiconductor grade, SeG)

Crystal. - The processing of SeG silicon into single crystal ingots (usually CZ) and subsequent slicing of the ingots into wafers.

Cell Processing. - The processing of blank silicon wafers into a finished solar cell.

Panel Building. - The process in which individual cells are inter-connected and encapsulated to form modules and panels.

The energy payback time will be calculated with the following assumptions:

a. Flat (non-concentrated) panel
b. Panel in fixed position facing true south at 45° angle.
c. Panel experiences the average U.S. insolation

After the payback time for the five basic operations has been calculated a section of this report will elaborate on the potential effects of alternative technologies.

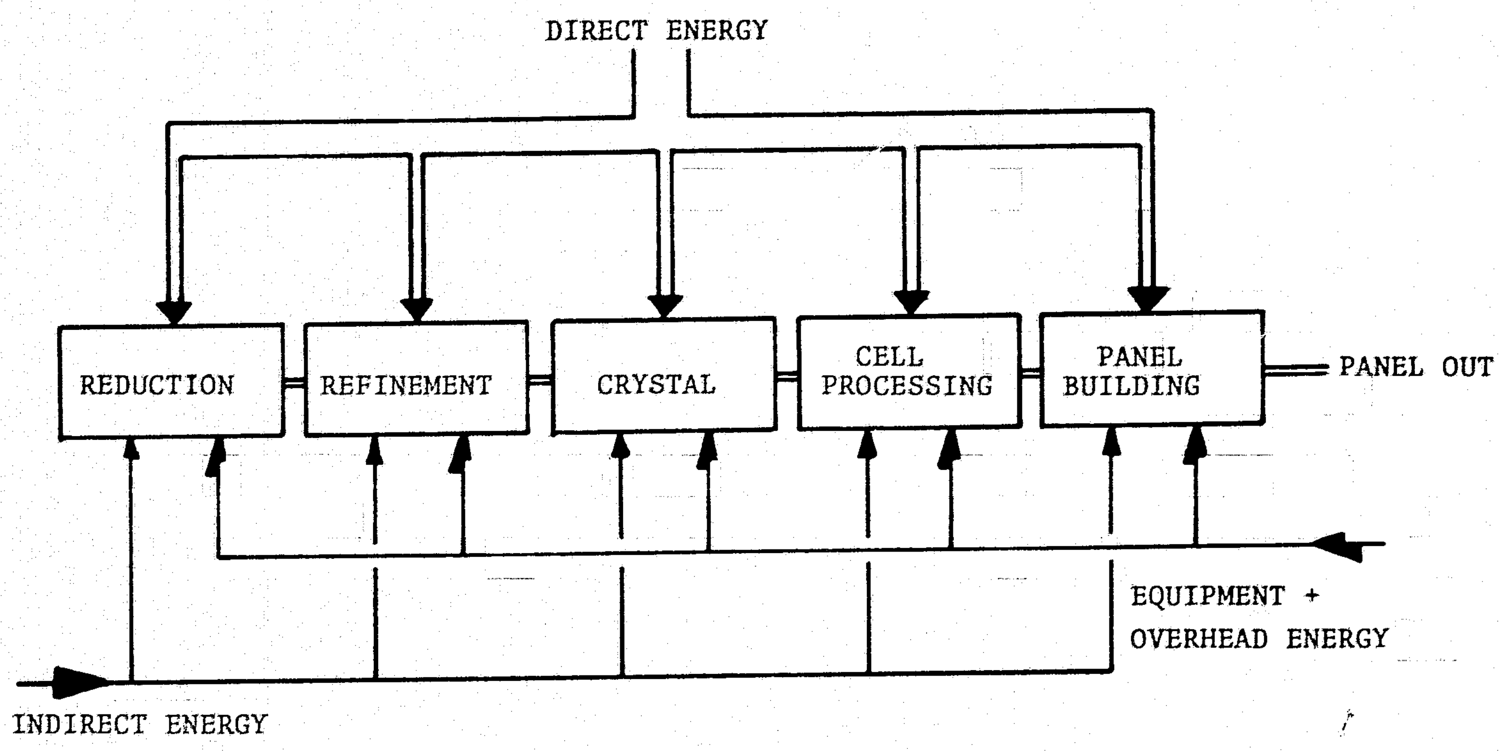


FIG.4.1 PANEL PRODUCTION SEQUENCE AND ENERGIES

4.2 Reduction of Silicon

Silicon manufacturing processes must resort to compounds such as silicon dioxide as the starting material. Because of high purity and general availability quartz pebbles became the dominant choice as the starting material for metallurgical grade silicon.

The manufacture of metallurgical grade (MG) silicon is carried out on a large scale by the reduction of quartzite with carbon-containing agents. The process occurs in huge electrode arc furnaces at high temperatures according to the overall equation:

$$SiO_2\ (s) + 2C\ (s) \rightarrow Si\ (l) + 2CO\ (g)$$

Silica melts at temperatures in excess of 1700°C. and reacts with the carbon-containing additives. In the reduction process the mix may reach temperatures as high as 3000°C, forming elemental silicon which accumulates at the bottom of the furnace crucible. The molten silicon can be withdrawn from the bottom of the furnace through a taphole either continuously or in regular intervals. Metallurgical grade silicon attains purity as high as 99.5%.

The yearly production of MG silicon in the United States has now exceeded 140,000 short tons.2) Most of it is used in the steel, aluminum and chemical industry. Approximately 1% of MG silicon is refined in a subsequent operation and channeled into the semiconductor and solar cell industry.

Direct energy is supplied to the smelting process in the form of electric power to the graphite arc electrodes. The electric energy consumption3) per gross ton is 13,952 kWh or 15.4 kWh per kg MG-silicon resulting in a payback time of 0.09 years.

Indirect energy is consumed in the form of mining efforts and rail transportation of the raw materials and in the form of the caloric content of some of the raw materials themselves. The amount of raw materials which constitute a typical mixture to yield 1 kg of MG silicon may be listed as follows:

Table 4.1 Raw Materials for Silicon Smelting.

	kg/kg Si	Caloric energy content (kcal)
quartzite	3.26	negligible
pet. coke briquettes	.17	1190
raw petr. coke	.66	4620
met. coal	.66	5082
wood chips	1.77	7080
remelts	.02	--
carbon electrodes	.17	1309
TOTAL		19281

The caloric energy content of the carbon-containing raw materials has been calculated using the following conversion units 4)

wood chips	4000 kcal/kg
pet. coke	7000 kcal/kg
met. coal	7700 kcal/kg

Thus, the combined caloric energy content expended in the carbon-containing raw materials is 19281 kcal which is equivalent to 22.4 kWh.

Additional energy is consumed in the mining, production and transportation process of the raw materials. According to a study by the Battelle Columbus Laboratories 5) these energies have been determined as follows:

Table 4.2 Energies in Smelting Materials.

	10^6 BTU per ton of item
silica pebbles, mining	.1
rail transportation (300 miles)	.2
coke, making	31.5
rail transportation (300 miles)	.2
coal, mining	.3
rail transportation (300 miles)	.2
wood chips, sawing and chipping	.02
truck transportation (50 miles)	.12

Using the conversion factors of 907.2 kg/ton and 3410 BTU/kWh the indirect energy content in the raw materials for the smelting process aside from their caloric value is

Table 4.3 Caloric Value of Smelting Materials.

	kWh/kg MG-Si
quartzite pebbles	.32
coke	8.51
coal	.11
wood chips	.08
TOTAL	9.02

The combined indirect energy content in the raw materials for the smelting process is 31.4 kWh which results in a payback time of 0.19 years.

Data for invested equipment and overhead energy cannot be readily found in the literature. An announcement of the National Metallurgical Corporation to expand the production capability of one of their plants from 4,500 tons to 13,000 tons annually at a cost of $5.5 million allows for an estimate of these energies.

Assuming a return of investment expenditures in 10 years during which time approximately 85,000 additional tons of MG-silicon are produced, the cost per kg silicon is \$0.071. The assumption that 5% of the invested cost constitutes an energy cost (which is high) and that this cost is converted into energy units at a rate of \$0.003/kWh the invested energy per kg MG-silicon is 1.18 kWh. The payback time for this energy amount is of the order of 7.0×10^{-3} years.

The total energy required to produce a kg of metallurgical grade silicon is relatively small. The energy cost of the reduction process is found below in Table I. The kWh/kg figure listed represents the energy actually used, while the energy payback time is related to present-day cell technologies.

Table 4.4 Energy in Reduction.

	kWh/kg MG Silicon	Payback Time in Years as of 1977
Direct Energy	15.4	0.09
Indirect Energy	31.4	0.19
Equipment + Overhead Energy	1.2	0.01
Total Energy	48.0	0.29

The payback times of less than 0.1 and 0.2 years for direct and indirect energy respectively are low. From the standpoint of the photovoltaic industry the current state of the silicon reduction process is considered satisfactory with respect to its energy balance and production capability and is not regarded as an obstacle.

4.3 Refinement

The need for ultrapure starting materials for device development in solid state electronics was recognized as soon as the influence of impurities on the electronic conduction process was understood and controlled doping techniques were developed. To fulfill this need, a number of alternative processes for the preparation of high purity silicon have been investigated internationally by various laboratories.

Up to the present time the preparation of semiconductor grade (SeG) silicon appears to be impossible without resorting to ultrapure gaseous silicon compounds from which the high purity silicon can be reclaimed. Amongst the many silanes which could be used for that purpose trichlorosilane is preferred worldwide because it can be employed at lower temperatures and faster rates. It is formed in high yields by the interaction of MG silicon powder and hydrochloric acid at a temperature of 300°C. The exothermic process occurs in a fluidized bed reactor according to the chemical reaction:

$$Si(s) + 3HCl\ (g) \rightarrow SiHCl_3(g) + H_2(g) \quad (1)$$

To obtain the desired purity trichlorosilane must be separated from metal chlorides and other silanes such as $SiCl_4$. Trichlorosilane has a low boiling point of 31.8°C which allows effective purification by means of fractionated distillation.

Ultrapure silicon is obtained from the purified trichlorosilane via chemical vapor deposition, whereby trichlorosilane reduces in the presence of hydrogen to silicon. Simply, the chemical reaction is the reverse of the fluidized bed reaction of Eq. (1). The reduction occurs at temperatures exceeding 1000°C on a resistance heated starting polyrod made from silicon having a purity comparable to the deposit. Due to demands for large wafer sizes polyrods now reach diameters of 4 inches and more during reaction times on the order of a hundred hours.

The production of trichlorosilane requires relatively little energy due to the exothermic nature of the fluidized bed reaction. However, direct energy is required in the distillation process for the purification of the gas. The value quoted 6) is 40 kWh per kg of SeG silicon. The dominant part of direct energy used in the refinement process is expended in the silicon deposition process which occurs on the current heated starting rod. 400 kWh per SeG silicon 9) is consumed in this process so that the total direct energy expended in refinement reaches 440 kWh per kg SeG silicon resulting in a payback time of 2.63 years.

The indirect energy is small compared to the direct energy expended. Most of the indirect energy is contained in hydrochloric acid and hydrogen gas. However, because the same chemical reaction is passed through in the forward and reverse direction little of the raw materials are actually expended in the whole process. In order to account for material losses we make the assumption that the indirect energy is approximately 5% of the direct energy or 22kWh resulting in a payback time of 0.13 year.

Equipment and Overhead energies were derived from industrial expansion estimates for the production of SeG silicon. Dow Corning expects to enlarge its production capability at a cost of $46 million. The typical output of polysilicon after such an expansion is 200 metric tons per year. Assuming a 10 year lifetime of such an investment the cost contribution to the price of 1kg SeG silicon would be $11.50 representing an equipment energy expenditure of 76.7 kWh which is equivalent to a payback time of 0.46 years.

The semiconductor industry developed manufacturing procedures whereby many chips are produced from a single wafer. Because the amount of silicon used in the chip is small, primary emphasis is placed on high purity starting material and homogeneous quality.

Cost played a lesser role and energy was not even considered. The installations for the production of ultrapure silicon reached sizes comparable to small oil refineries. Distillation columns for trichlorosilane are now several stories high and the reaction chambers for the silicon deposition accommodate rod lengths of up to 5 feet. In addition, the demand for cheap electrical power at high consumption rates led to strategical plant locations in the vicinity of power stations where reduced electricity rates could be negotiated.

The traditional refinement process as described above is not entirely suitable for the requirements of the photovoltaic industry. The amount of material used in a simple solar cell is high compared to the chip and, therefore, the material costs cannot be ignored and even constitute an obstacle for the development of the inexpensive cell. The solar industry is trying to circumvent the cost and energy expended in the silicon refinement process by orineting its research efforts towards the development of an inexpensive solar cell made from less pure material, such as semi-crystalline cost silicon.

The various energies of the refinement process are listed in Table 4.5

Table 4.5 Energy in Refinement.

	kWh/kg Seg Silicon	Payback Time in Years as of 1977
Direct Energy	440	2.63
Indirect Energy	22	0.13
Equipment + Overhead Energy	77	0.46
Total Energy	539	3.22

This energy component is large.

4.4 Crystal (Growth and Wafering)

The discovery of the transistor effect approximately thirty years ago marked the beginning of the semiconductor device technology based on the single-crystalline state. The single crystalline state gained predominance in solid state electronics not only because the crystalline state could be treated with mathematical rigor but also because of the early observations that electronic events were more controlled when the crystallinity was high. In addition, despite the high symmetry which semiconductors commonly exhibit, a prominent degree of anisotropy of certain physical phenomena remained which is exploited in semiconductor technology. The semiconductor device industry has specified from its infancy single-crystalline wafers and increased its demand for larger wafers of highest quality with respect to crystallinity and low dislocation density as transistors and microcircuits were developed.

Although germanium was the material of early semiconductor research it was soon replaced by silicon due to its more advantageous properties. Most growth methods are aimed at producing silicon in the single-crystalline form. Of the many methods developed the Czochralski pulling process gained worldwide industrial importance although in some instances crystals obtained by the typically more expensive float zone technique are preferred.

In the Czochralski pulling process the crystal is drawn from the melt which is contained in a quartz crucible. At the start of the process a small seed crystal of predetermined crystallographic orientation is lowered onto the melt surface. As the seed is subsequently pulled from the surface under a rotational motion additional silicon from the melt crystallizes above the liquid solid interface whereby the crystallographic orientation of the seed is maintained. Pulling times of 100 hours or more result in crystals exceeding 4 inches in diameter and over 30 inches long. The crystals are then sliced into thin wafers and sold to the semiconductor and photovoltaic industry. Direct energy requirements for the pulling of a crystal of 15 kg in weight are reported[4,7] to be 610 kWh or 40.7 kWh per kg SeG silicon. Approximately 7.4 kg of ingots can be processed in a typical slicing operation yielding 600 wafers in 16 hours. The energy required to power the 3/4 HP motor commonly installed in a slicing machine is 8.8 kWh or 1.2 kWh per kg silicon ingot. The total direct energy for pulling and wafering is thus 41.9 kWh per kg SeG silicon resulting in a payback time of 0.25 years.

Indirect energy is contained in materials such as argon, quartz crucibles, replacement parts, wafering blades and slurry. The costs of some of the materials have been reported to be:

Table 4.6 Costs of Crystal Growth Supplies

Argon	$ 1.21 /kg SeG-Silicon
Quartz Crucibles	6.25
Replacement Parts	4.55
	$12.01 /kg SeG-Silicon

Blades for wafering generally cost $80.00, however, most of the cost is due to wages in the assembly process and not due to the cost of the material. We assume that only 30% of the cost of the blades reflect material costs and since 4.4kg of ingots can be sliced with a set of blades the cost of the blades per kg of silicon is $3.24. Combined costs are therefore $15.25. The indirect energy expended is thus 101.7 kWh resulting in a payback time of 0.61 years.

Equipment and overhead energy is primarily contained in the cost of a Czochralski pulling machine whose purchase price is approximately $170,000. Assuming a lifetime of 20 years during which time 6,000 ingots at 15 kg each can be grown, the cost burden per kg silicon is $1.89 which relates to an equipment energy value of 12.6 kWh. In order to account for overhead energy we inflate this value to 15 kWh and obtain an estimated payback time of 0.09 years.

The data is summarized in Table 4.7

Table 4.7 Energy in Crystal

	kWh/kg SeG Silicon	Payback Time in Years as of 1977
Direct energy	42	0.25
Indirect energy	102	0.61
Equipment + Overhead energy	15	0.09
Total energy	159	0.95

CZ crystal and sawing are the prevailing technologies at this time.

4.5 Cell Processing

The cell production process starting with the blank pre-doped silicon wafer and ending with a finished cell can consist of several manufacturing steps, as listed below:

a) Surface preparation of the wafer. This is usually an etching process to remove the work damage caused by the saw and to clean the surfaces.
b) The formation of the junction typically by means of a diffusion process.
c) Removal of the back junction which can be done by etching or alloying an opposite dopant.
d) Formation of the back contacts which is usually done by evaporation techniques.
e) Formation of the front contacts. This is typically done by evaporation through a shadow mask or by application of photolithographic techniques.
f) Sintering to enforce contact adhesion.
g) Edge clean to eliminate junction shorting. It is conventionally done by an etching process.
h) AR coating of the front surface to reduce reflective losses.
i) Cell testing and quality control.

Each manufacturing step has been examined with respect to its direct and indirect energy expenditure. The direct energies were obtained by actually metering the energy input to each manufacturing step. Indirect energy contents of raw materials used in cell production were determined by either using published data of energy expended in their making or from the purchase price. The data are summarized in Table 4.8

Table 4.8 Energies in Cell Production

	DIRECT ENERGY		INDIRECT ENERGY	
Cell Processing Step	kWh/"Test" Cell	Payback times in Years	kWh/"Test" Cell	Payback Times in Years
Surf. prep.	0.0230	0.014	0.0464	0.029
Junction form.	0.1566	0.098	0.0993	0.062
Back junction rem.	0.1033	0.065	0.0208	0.013
Back contact	0.0245	0.015	0.2385	0.149
Front contact	0.0533	0.033	0.2433	0.152
Sintering	0.0050	0.003	none	none
Edge clean	0.0060	0.004	0.0080	0.005
AR coating	0.0495	0.031	0.0416	0.026
Testing	negl.	negl.	none	none
Total	0.4212	0.263	0.6979	0.436

Equipment energies were derived from the replacement cost of the equipment used in the production process whereby a lifetime of 20 years and the present cell production rate was assumed. This energy appears to be approximately 0.065 kWh per cell. Overhead energies were directly determined from the electrical meter readings for heating, lighting and airconditioning of the production floor. This value is 0.0135 kWh per cell. Thus, the total equipment and overhead energy amounts to 0.0785 kWh resulting in a payback time of 0.05 years. The data are summarized in Table 4.9

Table 4.9 Energy in Cell Processing.

	kWh/"test" cell	Payback Time in Years as of 1977
Direct Energy	0.42	0.26
Indirect Energy	0.70	0.44
Equipment + Overhead Energy	0.08	0.05
Total Energy	1.25	0.75

The conclusion that results from this analysis is that the cell making process is not energy expensive. The criticism that a predominant amount of energy is tied up in cell making originated at times when cells were made solely for space applications and were energy intensive. Major technological advances have been made in the last few years. For example, the diffusion process was always believed to require unusual amounts of electrical energy. As shown in Table 4.9 the whole diffusion process requires only about 0.16 kWh per cell burdening the payback time only by 0.1 years. Part of the data listed in Table 4.9 is the result of directly monitoring energy inputs to the Solarex production process and represent factual energy figures.

The apparent fact is that cell and panel processing has gone through many changes in the last three years, resulting not only in lesser cost, but also in great reduction of energy use. Ongoing development promises further energy reduction.

4.6 Panel Building

Major power from solar cells can only be derived from the integration of many cells into the solar panel. The backbone of the panel consists typically of a sheet of plastic or metal which is strong enough to provide structural support. Individual cells are arranged on this board with efficient area utilization and electrically interconnected. Silicone rubber is then poured over the whole surface covering the cells and, after curing, protecting them from future environmental exposure.

Direct energy is required to power various ovens for baking and curing operations during the panel production process. Approximately 0.090 kWh per cell is used for that purpose resulting in a payback time of 0.06 years. Indirect energy is contained in the raw materials consisting of the support structure, the silicon rubber encapsulant and connecting wires. This energy content is estimated to be 1,660 kWh resulting in a payback time of 1.04 years.

Equipment and overhead energy was estimated from the cost of equipment, mainly in the form of ovens for baking, tabbing and curing, and from actual energy used for heating, lighting and cooling of the panel production area. The combined energy amounts to approximately 0.170 kWh which yields a payback time of 0.11 years.

The energies and payback times for panel building are summarized in Table 4.10

Table 4.10 Energy in Panel Building.

	kWh/"test cell"	Payback Time in Years as of 1977
Direct Energy	0.09	0.06
Indirect Energy	1.67	1.04
Equipment plus Overhead Energy	0.17	0.11
Total Energy	1.93	1.21

Panel building requires little electrical energy which is reflected in the low payback times of direct and equipment plus overhead energy respectively. The relatively high payback time of the indirect energy is due to the calculated energy content in materials used to make the panel, although the total cost of these materials is a fraction of a dollar.

4.7 Summary of Energy Assessment

The overall payback time of our test vehicle is the sum of the individual payback times as derived in the preceding sections. In order to visualize their significance they are shown in Table 4.11 and Figure II in the form of a vertical bar pattern and in an accumulating fashion along the panel building train.

Table 4.11 Energies expended for Test Vehicle

	Payback Time in Years as of 1977
Direct energy	3.29
Indirect energy	2.41
Equipment + Overhead Energy	0.72
Total energy	6.42

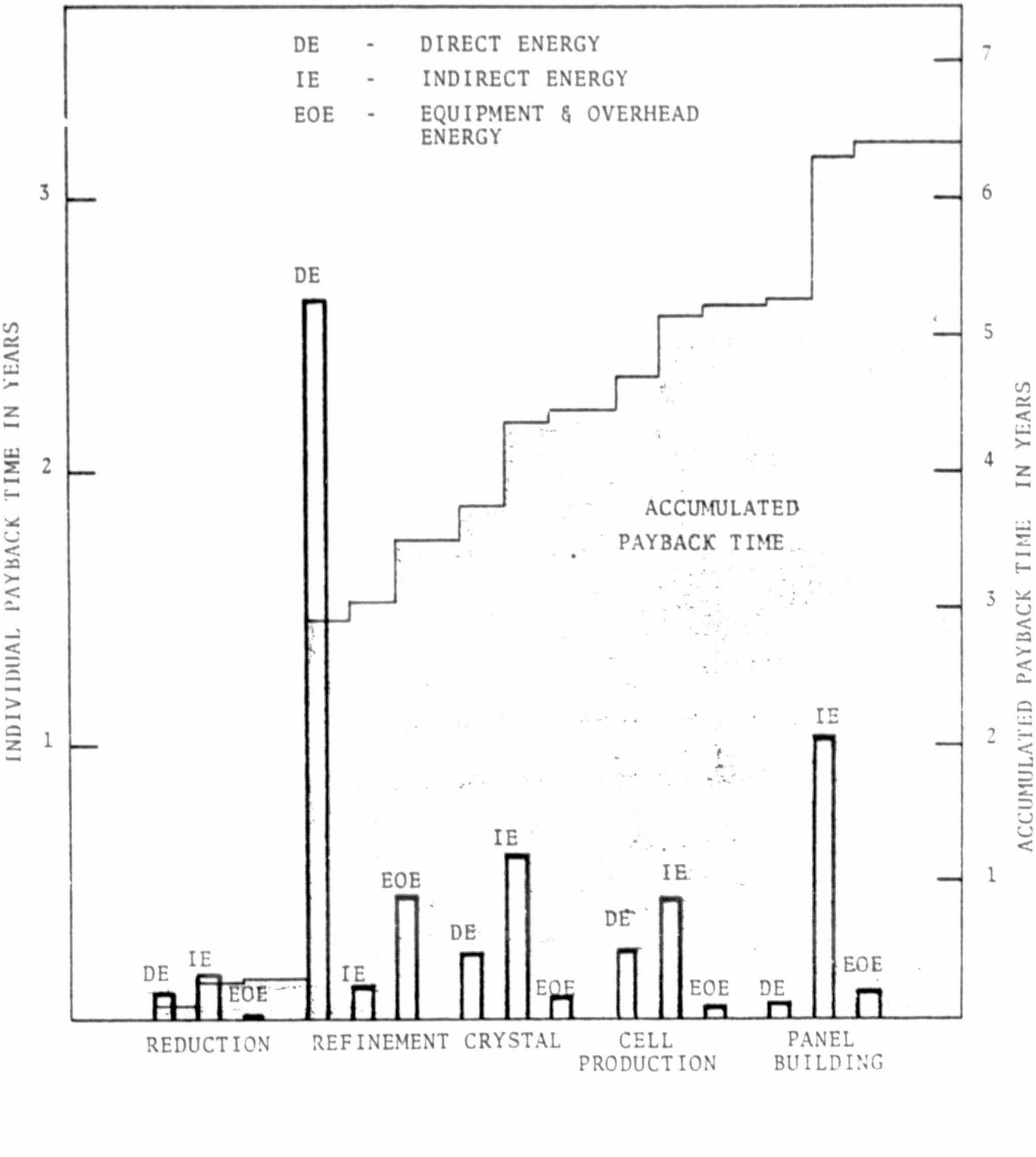


FIG. 4.2 PAYBACK TIME VS. PROCESS STEPS

4.8 Variations of Parameters

The appraisal of the energy payback time as documented in the preceding sections deals primarily with the details of the prevailing manufacturing process. In order to arrive at a quantitative value of the payback time we based our calculations on a well defined cell as a test vehicle and assumed certain operational conditions of the final panel. These assumptions were basically as follows:

cell efficiency is 12.5%
insolation per day is 4.33 sun hours
cell thickness is 10 mil
the packaging factor of the cells in the panel is about 70%
the flat panel is in a fixed position facing true south at 45° angle and concentration is not employed

Based on these assumptions we derived a payback time of 6.4 years. However, it is clear that this value can change as the above assumptions are allowed to vary. The payback time then becomes not only a function of the details of the manufacturing process but depends also on conditions surrounding the panel operation.

As can be seen in Exhibit C the daily average insolation in the United States varies with the location and can be as high as 6 sun hours. In addition, the 12.5% efficiency value of our test vehicle has risen as high as 15%. If only these two new data points are introduced into the former analysis the payback time would reduce to 3.8 years.

Further improvements with respect to shorter payback times will be introduced when a higher utilization of silicon in the form of thinner wafers becomes standard practice. In addition, the circular shape of the wafers limits area utilization in the panel. When rectangular cells find their way into the production process, a significant saving in indirect panel energy will occur. Of course, concentration and/or tracking would also reduce the energy payback time. In the following chapter, some potential technologies present still greater reductions in energy payback time.

In summary, the technology prevailing today project 6.4 years of energy recovery or as low as 3.8 years under favorable conditions.

5. Energy Assessment of Alternative Technologies

In this chapter, several potential alternate technologies are presented to show how their implementation would affect photovoltaic payback time. Not all potential processes are developed enough in order to be discussed here: the chosen topics for detailed discussion include: Multiple Wire Saw, Ion Implantation, Alternate Silicon Refinement Methods, and Solar Concentration and Silicon Ribbon Growth.

Semi-crystalline cast silicon, as discussed in Chapter 3, should be considered a potential technology and as seen can reduce energy payback times considerably.

5.1 Multiple Wire Sawing

General

Until the present time, the sawing of Czochralski-grown boules of silicon into wafers is still the prevailing method for obtaining large sheets of silicon for the manufacture of solar panels in considerable quantities. This slicing process is costly because almost half of the single crystalline material is lost. Several programs have been launched in the past to improved the sawing operation using conventional equipment, but have been only moderately successful.

The prevailing sawing procedures employ either a circular saw whereby individual wafers are cut on the inside diameter of the ring-shaped blade or a multiple blade saw which slices the ingot into many wafers in one operation. No advantage can be claimed at present by one technique over the other.

The state of the art of multiple blade slurry sawing was reviewed in a recent report[8]. The current technology cuts wafers approximately 10 mil thick with a kerf loss of 8 mil.

Since 22 wafers can be obtained per cm of ingot length, the conversion rate per weight of a 4" diameter boule is 0.94 m^2 of sheet material per kg of ingot. The total slicing time is approximately 29 hours. Although it is possible to slice faster, wafer thicknesses generally have to increase, and the ratio of wafer thickness to kerf loss deteriorates. Accordingly, less sheet area would be obtained per weight of ingot.

In addition, blade sawing always produces irregular wafer surfaces normal to the cutting stroke. This damage extends several mils into the material and is characterized by a high density of dislocation etch pits. This damaged layer must be removed by etching as the first step in the cell making process.

The Potential of the Multiple Wire Saw

A new multiple wire saw9) was recently introduced to the market. The saw was developed for large volume continuous production cutting of hard and brittle materials whereby close tolerances can be achieved. The saw includes a continuous wire which forms multiple wire loops around specially designed wire guides. In operation, the workpiece is positioned upon a platform and raised against the multiple wires. Machining is accomplished by oscillating the multiple wire loops across the workpiece and lapping away the kerf with an abrasive slurry. Due to a continuous supply of new precision diameter wire, it is claimed that exceptionally close thickness tolerances can be obtained with excellent surface finish and minimal subsurface damage. The work stage of the saw can accommodate ingots of up to 4" in diameter and 4" in length, which represent 1.92 kg of silicon material.

According to the distributor 333 wafers, with a thickness of less than 0.20mm and a kerf loss of 0.10mm can be obtained in approximately 30 hours. These 4" diameter wafers constitute a sheet area of 2.70m^2 which can be expressed as 1.41m^2 per kg of usable silicon ingot. This figure represents a 50% increase in the yield of sheet area per kg of ingot over conventional sawing and a 67% materials yield in form of wafers. It is claimed that the dimensional accuracy of the as-cut wafer is excellent, and that the subsurface work damage layer is thinner than in conventionally cut wafers so that less preparatory surface etching is required to obtain good solar cell performance.

Impact Upon Energy and Payback Time

The introduction of the multiple wire saw into the silicon wafering process potentially impacts the energy and payback time in two ways. Due to a materials yield of 67% in the sawing process more energy could be generated per weight of silicon leading to a potential reduction of the payback time.

Recent advancements in the solar cell manufacturing process already created the need for a wafering device with the potential capabilities of the multiple wire saw. Solarex has recently reported10) a technological advance in the thin cell production by developing a high efficiency thin silicon solar cell under NASA/JPL sponsorship. Several thousand ultra-thin (50 microns or less) solar cells exhibiting efficiencies as high as 15% under AM1 conditions and excellent power to weight ratios have been developed at Solarex with an acceptable yield and at reasonable cost. Consistent reproducibility and relative ease of processing as now developed forecasts that these cells can be made in high quantities in a production environment. Therefore, the potential combination of the thin slicing capabilities of the multiple wire saw and the increased efficiency of the thin cell will result in a considerable reduction of the overall payback time as shown in the following sections of this chapter.

Because of the potential change in the parameters, the characteristics of our test vehicle must be redefined as shown in Table 5.1

Table 5.1 Test Vehicle for Multiple Wire Saw

Material	SeG Silicon
Cell diameter	10.16 cm (4")
Cell thickness	0.05 mm (0.002")
Cell area	81.07 cm^2
Cell volume	0.40 cm^2
Silicon mass	0.94 g @ density of 2.33 g/cm^3
Efficiency	15%
Peak power	1.216 W
Average insolation time per day	4.33 hours
Energy delivered in one year (1,582 hr)	1.92 kWh
Lifetime of panel	20 years
Cell energy delivered in 20 years (31,630 hr)	38.4 kWh

When production yields are taken into account, the energy as delivered can be expressed by 1 kg of ingot material.

A sheet area of 1.41 m^2 can be obtained from 1 kg of ingot by utilizing the new saw technology. Assuming a terrestrial insolation of 100 mW/cm^2 (AM1) and a cell efficiency of 15%, the energy delivered in one year is now:

$$\text{energy delivered per kg of silicon in one year} = 334.4 \text{ kWh}$$

Reduction and Refinement

Having thus redefined the test vehicle, the payback times as derived in the first quarterly report need to be properly scaled to account for the potential new situation. Since sawing has no impact upon the energy expenditure in Reduction and Refinement, the payback times can simply be scaled by a factor of $\frac{167}{334.5} = .50$ due to the change in the yearly energy return of 1 kg of ingot, and may be listed as follows in Table 5.2

Table 5.2 Payback Times in Reduction and Refinement

	Payback Times in Years	
	Conventional Process	With Potential of Multiple Wire Saw
Reduction		
Direct Energy	0.09	0.04
Indirect Energy	0.19	0.10
Equipment and Overhead Energy	0.01	Negl.
Total Energy	0.29	0.14
Refinement		
Direct Energy	2.63	1.32
Indirect Energy	0.13	.06
Equipment and Overhead Energy	0.46	.23
Total Energy	3.22	1.61

A. Direct Energy

Direct energy is consumed in sawing in the form of electrical energy to the various motors of the multiple wire saw. In total, these motors consume 600 W. It takes about 30 hours of slicing time to cut a 1.92 kg piece of ingot into wafers. Therefore, the energy consumed in this operation per kg of ingot is 9.4 kWh. Combined with energy in crystal growth of 40.7 kWh, the total direct energy in Crystal is 51.1 kWh resulting in a payback time of 0.15 years.

B. Indirect Energy

Indirect energy is consumed in the sawing operation, mainly in the form of energy contained in the sawing wire. The energy content is derived from the purchase price of the wire. However, it must be assumed that this wire is a specialty item and that only about 1/3 of the wire cost represents materials cost from which the indirect energy should be derived. The purchase price of the wire is \$260; thus, \$87 approximately represent the energy expenditure in materials. Since at least 3 ingots with a combined silicon weight of 5.7 kg can be processed with one spool of wire, the relevant materials cost per kg of silicon is \$15.26. Materials cost for CZ-growth is \$12.01 per kg ingot as shown in the first report. Accordingly, the combined cost in materials for Crystal is \$27.27, resulting in expended indirect energy of 181.8 kWh and a payback time of 0.54 years.

C. Equipment and Overhead Energy

Equipment and overhead energy is primarily contained in the cost for the Czochralski pulling machine and the wire saw, which is \$1.89 per kg silicon.

The purchase price for a multiple wire saw is \$30,000. Assuming a 20 year saw life and the capability to process silicon ingots at a rate of 1.92 kg in 33 hours, 10,200 kg of silicon can be sliced within the life of the saw. Therefore, the cost burden per kg ingot due to the cost of the saw is \$2.94. This figure must be combined with costs due to the crystal growth station which becomes \$4.83 and relates to an equipment energy value of 32.2 kWh. In order to account for overhead energy, we inflate this value to 36 kWh and arrive at an estimated payback time of 0.11 years.

Payback time for Crystal may now be listed as in Table 5.3

Table 5.3 Payback Times in Crystal

	Payback Times in Years	
	Conventional Process	With Potential of Multiple Wire Saw
Direct Energy	0.25	0.15
Indirect Energy	0.61	0.54
Equipment and Overhead Energy	0.09	0.11
Total Energy	0.95	0.80

Cell Production and Panel Building

The energies expended in cell production and panel building are not affected by the introduction of a new sawing technology. However, as pointed out earlier, the payback times as listed in the first quarterly report must be properly scaled to account for the changes in our test vehicle. The scaling factor is $\frac{1.013}{1.216}$ = .83 due to the change in cell output power. The payback times are listed in Table 5.4

Table 5.4
Payback Times in Cell Production and Panel Building

	Payback Times in Years	
	Conventional Process	With Potential of Multiple Wire Saw
Cell Production		
Direct Energy	0.26	0.22
Indirect Energy	0.44	0.37
Equipment and Overhead Energy	0.05	0.04
Total Energy	0.75	0.63
Panel Building		
Direct Energy	0.06	0.05
Indirect Energy	1.04	0.87
Equipment and Overhead Energy	0.11	0.09
Total Energy	1.21	1.01

Summary of the Energy Assessment - Potential Impact of the Multiple Wire Saw

The present commercial solar cell technology still has to rely on a sawing operation to obtain high quality sheet material in large quantities. Conventional sawing produces a materials yield of only about 50% and relatively thick wafers at a time when the technology has advanced enough to accept ultrathin wafers as the starting material for solar cells. The recently developed multiple wire saw appears capable of cutting thinner wafers than was possible in the past and thus would be advantageous for the new thin cell technology. The potential of the new saw lies not only in its improved cost economy but also in its promise to reduce the overall payback time from 6.42 years to 4.19 years as depicted in Figure 5.1.

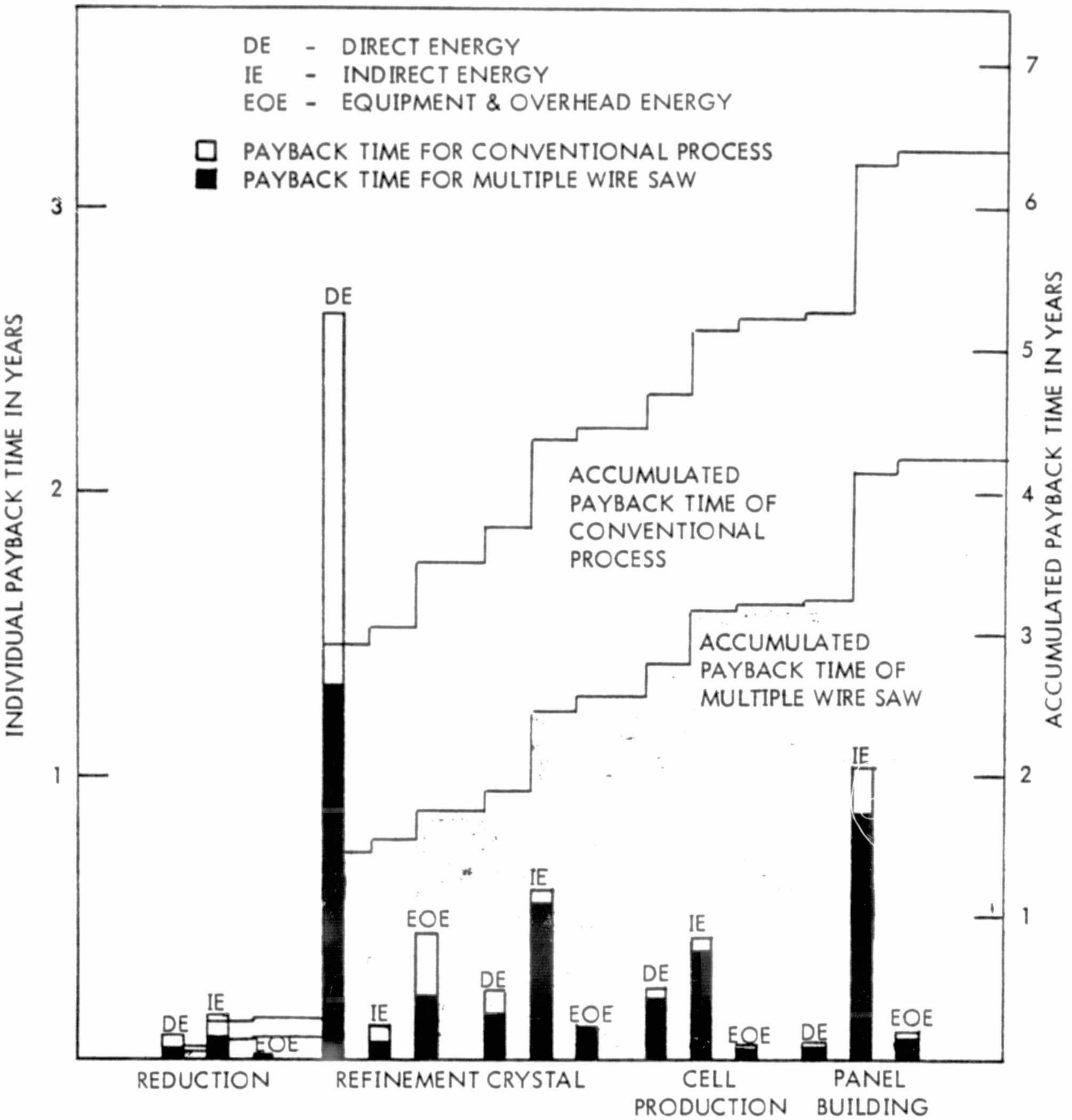


Fig. 5.1 PAYBACK TIME VS. TIME: POTENTIAL OF WIRE SAW

5.2 Ion Implantation

Ion implantation potentially offers an alternative to diffusion techniques for doping of terrestrial solar cells. A system implanting under vacuum can deliver 275 phosphorous doped three inch diameter or four inch diameter wafers per hour. Machines capable of practical large scale cell production with a processing potential of $10^7 cm^2$ of cell area per day (1.23×10^6 4 inch diameter wafers per day) are under design consideration.11)

A beam of phosphorous ions is directed at the silicon surface implanting the ions within the crystal material. To create the proper junction, the cell wafer must be implanted on the front and back surfaces and in order to electrically activate the ions, the cell must be annealed. An electron pulse anneal technique has been reported12) which elevates the implanted region to 1410°C for a sufficient time period (perhaps one microsecond). This technique could replace present furnace anneal techniques, typically running 750°C for 30 minutes.

This section analyzes the energy costs involved in the present ion implantation process and compares it to conventional diffusion technique energy costs.

Current Ion Implantation Technology

The machine which has been developed utilizes a continuous wall plug power of 10kW to produce a throughput rate of 275 wafers per hour. The cost of the system complete with vacuum pumps is approximately $350,000.

The direct energy accounting for wall plug power is approximately 0.04kWh/wafer yielding a payback time of 0.02 years.

Indirect energy costs involve the dollar costs of liquid nitrogen at the rate of one liter per hour and the cost of replacing filaments every two shifts. At approximately 50¢/liter for liquid nitrogen and $1.00 per filament, total indirect energy costs are estimated at 0.01kWh/wafer yielding a payback time of 0.01 years.

Equipment and overhead energy cost based on the dollar cost of the system and assuming a 5000 day life for machinery is approximately 0.21kWh/wafer which yields a payback time of 0.13 years.

These energies do not complete the case. The energy costs for annealing must be taken into account.

The direct energy of a 750°C, 30 minute anneal in a conventional belt furnace, with a 200 wafer/hour output approximates 0.02kWh/wafer yielding a payback time of .01 years.

There are no indirect energy costs to report for annealing.

Equipment energy expense calculated for a furnace which costs approximately $10,000 and has a 5000 day life is estimated at 0.01kWh/wafer yielding a payback time of 0.01 years.

The complete energy costs for ion implantation and annealing are tabulated below.

Table 5.5 Energy for Ion Implantation

	kWh/"test cell"	Payback Time in Years
Direct energy	0.06	0.03
Indirect energy	0.01	0.01
Equipment	0.22	0.14
Total energy	0.29	0.18

This energy would replace junction formation and back junction removal in cell production.

Payback time for conventional cell production: 0.76 years.

Payback time for ion implanted cell production: 0.71 years.

Total cell payback time would effectively not drop from the present 6.4 years.

Due to high equipment costs and low throughput rates, until a high throughput system is developed, ion implantation offers little incentive to switch from conventional diffusion techniques.

5.3 Solar Concentration Systems

Solar concentration systems are currently being studied as sources for energy with the potential of lower costs per power output. It is assumed that mirrors or lenses are usually much less expensive than the solar cells which they replace. We believe that in low concentration systems for which nontracking and passively cooled devices can be employed an immediate reduction in the payback time can be achieved. In larger concentration systems which need to be equipped with precise tracking mechanisms and liquid cooling the potential for short payback times is as yet untested in real life situations. Accordingly, we focus our analysis onto relatively low concentration systems for which reasonable data are already available.

Case 1. 5X Concentration

Equivalent Payback Times for Cells and Encapsulation

To approximate the power output of a concentrator system in terms of standard 4" diameter test vehicles a straightforward conversion technique is employed. The power of sunlight hitting the cells in a 5X concentrated system is approximately 0.5 W/cm^2. Assuming the cells to be 15% efficient, it takes approximately 13,400cm^2 of cell area to produce at least 1kW. If the maximum square area is cut from a test cell, then it will take an estimated 260 7.2cm x 7.2cm cells for one possible 5X concentrated system. The ratio of the power outputs of one 5X concentrated collector at 1kW to 260 4"D test cells at 260 watts is 3.8:1. 3.8 will be used as a constant factor to calculate equivalent energy payback times for the process steps of cells through paneling.

In this way, the effect of concentration power on energy expense can be shown in comparison to conventional flat plate collectors.

The <u>direct energy payback time</u> for the process steps of cells through paneling will be 0.88 years. Since passive cooling is employed, no direct energy costs due to pumping occur.

Indirect energy payback time will be 0.62 years for cells through paneling. The costs of a mirrored surface and heat sinks, estimated to be 25¢/watt, must be added. The total indirect energy payback time will be 1.62 years, accounting for the additional materials costs. Noteworthy is that since this is non-tracking, these are the complete materials costs.

Equipment energy payback time for cells and encapsulation will be .18 years.

Total payback times for a 5X non-tracked, passively cooled concentrator system are tabulated below:

Table 5.6 Payback times for 5X systems

	Payback Time in Years
Direct energy	0.88
Indirect energy	1.62
Equipment energy	0.18
Total energy	2.68

This would represent a substantial savings in payback time as compared to 6.4 years for current planar panel technology.

Case 2. 20X Concentrator

The approximate power of sunlight hitting the cells in a 20X system is 2 W/cm^2. Assuming 12% efficiency, there should be approximately 4200cm^2 of cell area to produce at least 1kW. A typical collector might contain 180 4.25cm x 5.5cm cells. Two of these cells can be cut from a standard 4" diameter test vehicle.

The ratio of the power outputs of one 20X concentrated collector at 1kW to 90 4" diameter test cells at 90 Watts is 11.1:1.

The equivalent direct energy payback time for the process steps of cells through paneling becomes 0.3 years. The direct energy of cooling the collectors over 20 years is based on the power required to run a 1/3 H.P. pump for four collectors (~4kW) maintaining a flow rate of 19 gallons/minute, over an average of 4 hours per day. Total direct energy payback time becomes 1.41 years.

The indirect energy payback time for cells through paneling becomes .21 years. Present system estimates for higher power concentration systems reportedly range from ~$1/Watt to >$4/Watt[13)] for collectors and tracking units. If scaled-up production (as now exists in the solar thermal industry) these costs could be reduced to 48¢/Watt to $2.70/Watt[14)].

Assuming that $1/Watt is a reasonable cost for future 20X systems, and that half of that would be tracking costs, the estimated indirect energy payback time would be 2.1 years.

Total indirect energy payback time is estimated to be 2.31 years.

Equipment energy costs will only be reflected in the process step cells through paneling. Equipment energy payback time will be approximately 0.06 years.

Total energy payback time for a 20X concentrator system becomes 3.78 years, as shown below:

Table 5.7 Payback time for 20X system

	Payback Time in Years
Direct energy	1.41
Indirect energy	2.31
Equipment energy	0.06
Total energy	3.78

Conclusions

We conclude from our analysis that immediate considerable payback time shorting can be achieved by employing concentration of the non-tracking, passively cooled kind in photovoltaic systems. As the concentration factor increases the payback time appears to become burdened by the additional need for tracking and active cooling devices and might follow a trend as shown in Fig. 5.2.

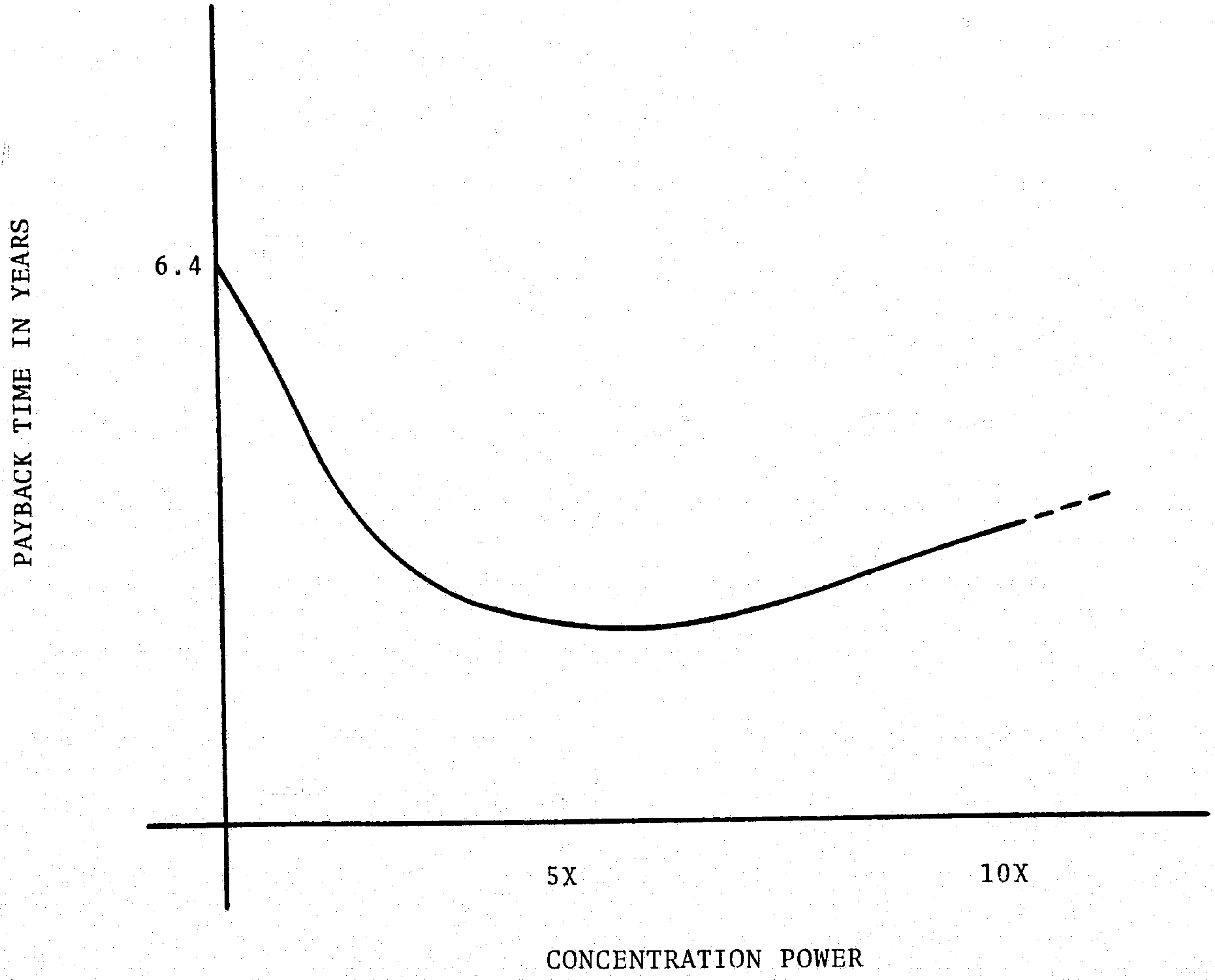


Fig. 5.2 Qualitative Behavior of Payback Time versus Concentration Today.

5.4 Silicon Ribbon Growth

Introduction

While extensive work leading to many technological advances and inexpensive procedures was carried out in cell production and module building, the procurement of silicon sheet in large quantities and low prices still represents a major problem. It is generally felt that price and limited quantity constitutes one of the principal factors that affects economically and technically the attainment of large-scale silicon photovoltaic systems.

Most of the research efforts aim at the development of processes which will deliver silicon sheets in large quantities directly from the melt and thus eliminate the high materials loss which is commonly experienced in sawing. Among the more promising sheet technologies appears to be the ribbon growth, although its ultimate success is far from being assured. Despite the fact that few details of the energy intensiveness of the processes are available, an attempt has been made to estimate the payback times by making reasonable assumptions concerning the energy expenditure in a production setting.

Silicon Ribbons

Silicon ribbon growth processes were initiated with the aim to obtain a high material utilization. They are crystallization techniques whereby a continuous solid ribbon of predetermined cross section is pulled from the melt. The techniques employ a die in the form of a capillary tube which is shaped in such a fashion that it determines the final dimensions of the grown ribbon. The die is customarily made from graphite. It is inserted vertically into the bulk of the melt from where it draws liquid up to the top due to the capillary action. A crystal seed is then lowered onto the liquid silicon forming a meniscus until contact is made. As the seed is subsequently withdrawn, material from the liquid solidifies and a continuous solid silicon ribbon is formed. The thermodynamics of the growth process appears to be largely under control so that continuous ribbons up to 2" wide and 8-10 mils thick can be grown at a speed of 3" per minute.15)

The silicon ribbons typically contain crystallographic defects and discrete inclusions. The crystallographic defects are mainly twins, dislocations and low and high angle grain boundaries. Because of the relatively high density of defects and the presence of lifetime reducing inclusions, the electrical characteristics of ribbons are not of the same quality as conventional Czochralski type crystals, and the resulting solar cells exhibit efficiencies of typically 6-10% or less.

Little is known about the present state of the art of the ribbon growth processes, and no clear assessment of their ultimate potentials can be made at present because none of the processes has yet been tested under production conditions. For the purpose of this energy assessment, this assessment represents an estimate based on the presently practised ribbon growth process implemented on the production floor. Measures to ensure high cell productivity, for instance, would include procedures to ensure a 70% materials yield as is commonly experienced by device manufacturers. As for the average efficiency of ribbon cells, 9% is assumed.

A. Direct Energy

We assume that a typical ribbon growth machine allows us to pull a silicon ribbon 2" wide and approximately 10 mil thick at a rate of 3" per minute. The energy expended in this process amounts to approximately 15 kW electrical power. During one hour, 360 square inches of sheet material can be obtained, which is equivalent to 2,323 cm^2. Under AM1 conditions and considering an average cell efficiency of 9%, this sheet area would produce 20.9 W. However, mainly because of breakage, the manufacturing yield is 70%; thus the effective energy obtained from ribbon material grown in one hour is 14.63 W. Since 15 kWh were expended in this process, the payback time amounts to 1435.1 hours. Again, we base our calculation on an average insolation of 4.33 hours per day; therefore, the payback time for direct energy is approximately 0.65 years.

B. Indirect Energy

Indirect energy is consumed in the form of the energy content of the materials and supplies expended in the ribbon growth process. Materials are used in the form of rare gases such as helium and argon and as high purity quartz and graphite. Because the high purity gases are not contained in a reasonably tight volume of the system, the throughput rate must be considered high, perhaps 4 times as high as in a conventional diffusion furnace. At a purchase price of approximately $0.25 per cubid foot of gas and an hourly throughput of typically 25 cubic feet, gases at a cost of $6.25 are consumed each hour. Similar estimates must be carried out in order to arrive at a reasonable cost value for expended parts. Although ribbons as long as 81 feet have been grown from one crucible charge, we assume that the typical ribbon length is 30 feet, resulting in 2 hours of operation. After each growth, the crucible and the die need to be replaced. Based on information used previously, we know that the quartz crucible costs $6.25 and that other parts made from high purity graphite amount to at least $4.00 in materials cost. Therefore, the assumption can be made that materials are expended at a cost rate of $5.00 per hour. The combined cost of $11.25 for gases and parts represents an energy value of 75 kWh which is expended during each hour of operation. In return, a finished solar cell made from ribbon material delivers 14.63 W from which a payback time for indirect energy of 3.24 years may be derived.

C. Equipment and Overhead Energy

As expected, equipment and overhead energies are small. If a 20 year life is assumed of a ribbon growth machine and the equipment operates on the average of 20 hours every day, total operating time is approximately 146,000 hours. A reasonable estimate of the materials value of the puller is $5,000. The hourly loading cost due to the puller material is, therefore, $0.034 which represents an energy value of 228 Wh. The finished cell made from ribbon grown during an hour delivers 14.63 W and, therefore, returns the expended energy in about 0.01 years. In order to account for overhead energy due to heating, lighting and cooling, we allow this value to double and arrive at a payback time of 0.02 years for equipment and overhead energy.

Table 5.8 Energies in Ribbon Growth

	kWh/kg Si	Payback Time in Years
Direct Energy	156	0.65
Indirect Energy	781	3.24
Equipment Energy	2	0.02
Total Energy	939	3.91

Under assumed conditions a payback time of 3.91 years was derived. The assessment did not include the cell making or module fabrication process of ribbon material because of the lack of pertinent formation on the energies expended in these processes. The ribbon growth process substitutes the conventional crystal category and exchanges a payback time of 0.95 years with 3.91 years. The resulting payback time of the whole sequence would then amount to 9.38 years which compares unfavorably with the 6.42 years of the wafer production sequence.

Ribbon growth process as practiced today is not yet energy competitive and that major technological breakthroughs and significant energy measures must be introduced in order to implement it into a production setting. In conclusion, it also may be noted that the successful ribbon crystallization process based on SeG silicon alone will not significantly reduce overall payback time because of its high contribution in silicon refinement. Only when efficient ribbons from unrefined material can be grown will the full advantage of ribbon growth come to light.

5.5 The Silicon Refinement Problem

As long as the production of refined silicon was intended solely for the conventional semiconductor industry, no incentives existed to modify the expensive refinement process by means of the established trichlorosilane technique. The semiconductor industry could easily absorb the high expenses of this elaborate and energy intensive process because the impact upon the final price of the small microelectronic chips is negligible.

The conventional silicon refinement process utilizes ultrapure gaseous silicon compounds from which the high purity silicon can be reclaimed. The most preferred gas, amongst the many possible silanes, is trichlorosilane because it can be used at relatively low temperatures and high rates. Trichlorosilane is formed in an exothermic process by the reaction of metallurgical grade silicon and hydrochloric acid. It is then purified by separating it from metal chlorides and other silanes by means of fractionated distillations.

Ultrapure silicon is obtained from the purified trichlorosilane by means of a chemical vapor deposition process whereby the silane undergoes a reduction to silicon. This reaction, which occurs at temperatures exceeding 1000°C on a resistance heated silicon rod of comparable purity, is energy intensive and requires long reaction times. The direct energy expended in this reduction process was reported previously in this study to reach values up to 400 kWh per kg SeG silicon and, transformed into a payback time component, contributes almost 2.4 years. The conventional refinement process is considered one of the major obstacles for the fulfillment of the demands of the solar industry.

The current reaction to the situation on the silicon front is expressed in the many novel approaches currently pursued to refine silicon economically in large quantities for a future solar cell material. Due to the infancy of these developments no winning technology can yet be predicted, however, a few processes seem developed enough so that their potential becomes visible and may be assessed.

Our energy investigations in terms of the earlier defined energy categories focus onto the following new refinement technologies:

A) Pure silicon via the metallic reduction of silicon tetrahalides
B) Synthesis of silane for solar grade silicon by means of catalytic redistribution of chlorosilanes
C) Refined silicon via a silicon fluoride polymer transport process
D) Purified silicon from upgraded conventional arc furnace processes.

Each of this alternative refinement technology will have its potential assessed in terms of expended energies and payback time. Most of these technologies are still in the formative stage and have not yet been tested outside the laboratory. This analysis, therefore, must be considered preliminary and is only capable of predicting the potential of an alternative refinement technology. The payback time calculation is based on the same test vehicle and 50% cell yield as defined in the first report although it is questionable whether a cell efficiency of 12.5% can be achieved in the near future when these technologies become established in the photovoltaic production process.

5.5.1 Pure Silicon via the Metallic Reduction of Silicon Tetrahalides

In order to avoid the energy intensive reduction of the gaseous trichlorosilane, several research efforts are currently undertaken to obtain pure silicon by the reduction of more suitable halides by means of metals. The reason for these efforts lies in the fact that certain metals react exothermically with silicon tetrahalides to form pure silicon and a metal salt. Most of the research attention focuses onto silicon tetrachloride ($SiCl_4$) as the gas to be reduced although silicon tetrafluoride (SiF_4) has also been suggested16) as a candidate gas. Silicon tetrachloride is produced exothermally in a fluidized bed reactor in a similar fashion as trichlorosilane. However, since the tetrachloride forming reaction does not require hydrogen, members of the family of the chlorosilanes are not produced and the resulting tetrachloride exhibits already a high starting purity.

The reduction of silicon tetrachloride to pure silicon requires an element which aids in breaking the bonds of the $SiCl_4$ molecule and forms a salt with the chlorine. At least two major research efforts are currently reported.

<u>Reduction of Silicon Tetrachloride by means of Sodium</u>

One research effort under JPL contract17) investigated the possible reductants H_2, Na, Mg and Zn. Thermochemical analyses were carried out for each of the candidate reductants and their theoretical reaction yields, energy requirements and molar feed ratios of reactants-to-products established. In order to aid in the selection of the most logical choice of reductant, a selection matrix, based upon economic and technological criteria, was established as shown in Table 5. 9. After evaluating the matrix,

Table 5.9 Criteria Matrix for Reductant Selection *)

(Basis: 1000 metric tons Si per year production)

Criteria	Reductant			
A. Economic	H_2	Na	Mg	Zn
Silicon yield	0.339	0.979	0.95	0.3
Arc heater power	9551 kW	1432 kW	1359 kW	91,833 kW
Total Process power	12,880 kW	6647 kW	6091 kW	104,954 kW
Direct operating costs/metric ton Si	$ 2921	$ 2225	$ 1751	$ 29,705
Indirect costs/ metric ton Si	$ 3310	$ 2552	$ 2278	$10,471
Total costs/ kg Si	$ 6.23	$ 4.78	$ 4.03	$ 40.18
B. Technological				
Reaction kinetics & equilibrium	Known for the gas-gas reaction. Large excess of H_2 required for the reduction.	Known for Na liquid reaction with $SiCl_4$. Very rapid reduction with sodium vapor. High yield reaction.	Not fully known, limited data-should be an analogous reaction compared to Na- high yield reaction.	Known; however large excess of Zn required & minimal yield of silicon predicted
Boiling pt. (metal Cl) vs. melting pt. of Si	Hcl/Si 188°K/1693°K	NaCl/Si 1686°K/1693°K	$MgCl_2$/Si 1685°K/1693°K	$ZnCl_2$/Si 1005°K/1693°K

(continued)

*) from M.G. Fey, Westinghouse Electric Corp., Quarterly Report #76/2 on JPL Contract No. 954589.

Criteria	Reductant			
	H_2	Na	Mg	Zn
Reductant and product purity	H_2 gas available in high purity. High purity graphite available for electrolysis. Minimum impurity source for silicon.	Available NA purity should be adequate. Electrodes for electrolysis of NaCl are normally graphite and copper. Minimal impurity source for silicon.	Available Mg purity not as high as Na. Electrolysis of $MgCl_2$ may be impurity source for silicon	Available zinc purity and electrolysis impurities remain to be determined.
Matls. handling problems	Minor problems anticipated, std. gas system; However corrosion by HCl by-product could be detrimental	Na melting pt. = ~98°C. All welded system required. Reactivity of liquid Na requires proper handling & safety. Na handling & systems well documented and state-of-the-art.	Mg melting pt. = 651°C. Very high temp. sys. required for liquid Mg handling. Safety practices also needed to prevent Mg fires.	Zn melting pt. = 419°C. High temp. system required for liquid Zn. Zn is a relatively safe matl. to handle.
Matls. of construction	Std. metal components such as stainless steel, nickel-base alloys, e.g. monel, inconel, etc.	Stainless steel normally used for liquid NA sys. However Fe and Cr are undesirable. Therefore Ni, monel or inconel should be used.	Std. steel equipment can be used for liquid Mg sys. However if Fe or Cr present a potential problem Mo or Ta can be used.	Limited info. available for liquid Zn sys. However, std. construction matls. should be adequate for containment.

(continued)

Criteria	Reductant			
	H_2	Na	Mg	Zn
Other problems	Hot HCl vapors very corrosive, large excess of H_2 req'd. for reactor, possible recycle problems after electrolysis of HCl .	Na is a very reactive matl., safety must be maintained to prevent Na fires or Na-H_2O reactions.	High temp. sys. needed to handle liquid Mg, safety req'd. to prevent Mg fires or reaction with H_2O .	Low reaction yield with Zn process. High temp. system required for liquid Zn. Large excess of Zn req'd. for reduction.
Other benefits	Gaseous H_2 injection and control instruments readily available. Room temp. H_2 injection, less impurity problems with H_2. By-product chloride is a vapor.	Na technology is well documented, systems are state-of-the art, a wealth of in-house expertise, also high reaction yield.	Mg is a relatively safe matl. to handle, high reaction yield for Mg reduction.	Zn is a quite safe matl. to handle in the liquid form.

sodium was chosen as the most promising reductant considering areas such as costs,yield, handling, safety, and state of the art technology.

The proposed reduction process will utilize an arc-heated plasma reactor which is maintained at a temperature of 2000°K to 2200°K. Liquid sodium which immediately vaporizes, will be injected together with silicon tetrachloride, and argon and hydrogen as arc heater gases. The subsequently occurring reaction produces liquid silicon and the salt sodium chloride in vapor form. The separation of the molten silicon from the sodium chloride vapors and arc heater gases takes place within a wet-walled-cyclonic separator.

The gaseous products exit from the top of the cyclone while liquid silicon accumulates at the bottom of the cyclone from which it can be tabbed and cast into ingots.

One feature of this process is the fact that most of the reaction products can be recycled. The sodium chloride vapors exiting the cyclonic separator with the arc heater gases can be cooled and the salt separated from the gases. The gases can be cleaned, cooled and reinjected into the arc heater. Sodium chloride will be channelled into cells for electrolysis into sodium and chlorine.

The sodium can be reused in the reduction process while the chlorine may be utilized in the production of silicon tetrachloride from silica.

Estimates of the energies of this process (as well as all following refinement processes) must be considered preliminary and subject to changes as the technologies progress.

From the available reports and direct communication with scientists associated with the project, we estimate the energies as follows:

The total electrical power requirements to produce 3,000 metric tons of silicon by means of the sodium reduction process per year, whereby one year contains 8,000 operating hours, has been reported18) to be 24,606 kW. However, about 1,000 kW must be added to this figure to account for the energy consumption of equipment such as pumps.

Thus, the direct energy per kg Si expended in the gas reduction can be calculated to

$$\frac{25{,}606 \text{ kW x } 8{,}000 \text{ h}}{3{,}000 \text{ metric tons}} = 68.3 \text{ kWh/kg Si}$$

However, this energy value does not include contributions due to the purification of silicon tetrachloride, a value which may be assumed to be similar to the energy required to purify trichlorosilane, namely 40 kWh/kg Si. Thus, the total direct energy for this refinement process may be assumed to be 108.3 kWh/kg Si leading to a payback time of 0.65 years.

The indirect energy for this specific process was not immediately available. However, because of the similarity of this process with the zinc reduction process to be described in the next section, it is assumed that the data for the indirect energy are essentially the same, namely 24 kWh/kg Si equivalent to a payback time of 0.14 years.

Estimates for equipment and overhead energies are, by necessity still very crude. Because of lack of any supporting data, we attempt to establish an upper bound. If the price for 1 kg of silicon is $10.00 and is reflected in the costs for capital equipment and overhead expenses, the energy would be 66.7 kWh/kg Si, equivalent to a payback time of 0.40 years.

Thus, the energies of the silicon tetrachloride reduction process, by means of sodium, may be listed as in Table 5.10.

Table 5.10 Energies in Sodium Reductant Process

	kWh/kg Silicon	Payback Time in Years
Direct Energy	108.3	0.65
Indirect Energy	24.0	0.14
Equipment + Overhead Energy	66.7	0.40
Total Energy	199.0	1.19

5.5.2 Zinc as a Reductant of Silicon Tetrachloride

Zinc was considered a possible candidate reductant of silicon tetrachloride within the work effort described in the preceeding section. It was eliminated from further consideration in favor of sodium.

Research efforts[19)] are currently undertaken, however, to develop zinc reduction of silicon tetrachloride in a fluidized bed process. This technique was tried in the early days of the semiconductor industry but was abandoned despite potential advantages of the fluidized bed in continuity of operation and in obtaining the end product in granular form.

The current experiments use purchased silicon tetrachloride which is purified by distillation. The tetrachloride meets the zinc reductant in a fluidized-bed reactor which is already seeded with small silicon particles of equivalent purity.

During the subsequent reaction between vaporized zinc and silicon tetrachloride at a temperature of about 930°C, elemental silicon and zinc chloride is formed according to the equation

$$2Zn + SiCl_4 \rightarrow Si + 2ZnCl_2$$

The elemental silicon deposits onto the available seeds which increase in size and can be continuously withdrawn from the fluidized bed. The zinc chloride is removed from the bed at a temperature of about 335°C and subsequently condensed and fed to an electrolysis cell where the metal can be recovered and recycled in the reduction process.

Realistic estimates of the direct energies involved may be obtained by summing up the positive energy values of the various process steps as reported in Table 1 of the 7th report of reference and adding 15% to account for inefficiencies.

Based on the yield of 3.6 kg silicon, these process step energies may be listed as follows:

$SiCl_4$ boiler	2.05 kWh
Fluidized bed reactor	0.27
Zinc molten storage	0.077
Zinc vaporizer	15.25
Zinc stripper A12	0.025
Zinc stripper B4	0.027
$SiCl_4$ reserve	0.06
Subtotal	17.759 kWh
and 15%	2.664
Expended direct energy per 3.6 kg Si	20.423 kWh
Expended direct energy per kg Si	5.673 kWh

The recovery of the metallic zinc from the chloride constitutes another direct energy component. The required energy for this process is 5.5 kWh/kg Zn. In order to obtain an estimate of the equivalent energy value per kg of silicon yield, the following consideration is made. As can be seen from the chemical equation of the reduction process two moles of zinc are required to yield one mole of silicon. In order to convert from the energy per kg zinc to the energy per silicon the expended energy needs to be scaled by the molecular weights as follows:

$$2 \frac{5.5 \text{ kWh}}{\text{kg Zn}} \cdot \frac{0.0654 \text{ kg Zn}}{\text{mole Zn}} = \frac{X \text{ (kWh)}}{\text{kg Si}} \cdot \frac{0.0281 \text{ kg Si}}{\text{mole Si}}$$

and X can be determined to be 25.6 kWh as the energy per kg silicon yield expended in the zinc recovery process.

Lastly, an energy value of 40 kWh/kg silicon must be added to the direct energy to account for energies expended in the purification of Silicon tetrachloride.

The combined direct energy for the zinc-process is thus 71.3 kWh/kg silicon leading to a payback time of 0.43 years.

Indirect energy is expended by replacing Zn metal lost at a rate of about 5% each cycle. The expended energy lies mainly in the mining and preparation processes of zinc. About 2 kWh/kg Si is estimated to be the indirect energy value contained in the zinc used for replenishment in each cycle. Gases used in the process are also recycled, however, losses occur and fresh gases must be added in small amounts at each cycle. It is estimated that the replenishment of these gases constitutes an energy cost of 22 kWh/kg Si so that the total indirect energy amounts to 24 kWh/kg Si and the corresponding payback time is 0.14 years.

The contractor estimates the cost for capital equipment and operating expenses to be $5.67/kg Si for a pilot plant capable of producing 100 MT/year. Based on our energy-cost formula described in the first quarterly report, these expenses represent about 37.8 kWh/kg Si. This energy content replaces equipment and overhead expenses for the conventional thermal deposition process but not equipment and overhead expenses for the purification equipment to clean the bases. These energies are approximately 40 kWh/kg Si so that the total equipment and overhead energy is 77.8 kWh/kg Si yielding a payback time of 0.47 years.

Table 5.11 thus compiles the energies in the silicon tetrachloride process by means of zinc as follows.

Table 5.11 Energies in Zinc Reductant Process

	kWh/kg Silicon	Payback Time in Years
Direct energy	71.3	0.43
Indirect energy	24.0	0.14
Equipment + Overhead energy	77.8	0.47
Total energy	173.1	1.04

5.5.3 Synthesis of Silane for Solar Grade Silicon by means of Catalytic Redistribution of Chlorosilanes

The purpose of this program[20)] is to establish the practicality of a process for the low cost, high volume production of high quality silane and its subsequent pyrolysis into semiconductor grade or solar grade silicon material.

The four step process to be considered can be described by means of the following equations:

Hydrogenation	$Si(MG) + 3SiCl_4 + 2H_2 \rightarrow 4HSiCl_3$
Redistribution	$4HSiCl_3 \rightarrow 2H_2SiCl_2 + 2SiCl_4$
Redistribution	$2H_2SiCl_2 \rightarrow SiCl_4 + SiH_4$
Pyrolysis	$SiH_4 \rightarrow 2H_2 + Si$

Net: $Si(MG) + 2H_2 \rightarrow Si(Pure) + 2H_2$

The overall reaction is a closed loop since the generated hydrogen and silicon tetrachloride can be recycled. The first three reactions generate also chlorosilanes other than the ones expressed in the formulas. These byproducts are separated and removed by distillation and ultimately fed back into the proper stage of the four step process. The distillations purify the gases.

The redistribution reactions are catalyzed by means of a macroreticular tertiary amine functional ion exchange resin. Because the reaction is catalytic the redistribution process does not need much energy. The cost of the exchange resin is negligible, approximately $2.50 per lb. whereby one pound of resin can process over a thousand pound of gases and practically never wears out.

However small amounts of metallic impurities in the gases destroy the resin.

The direct energy input to the redistribution steps has been estimated to be 2,500 BTU per pound of silane whereby this energy is mostly used in the distillation process. For the generation of trichlorosilane from silicon tetrachloride approximately 26,600 BTU per pound of silane is used. The direct energies involved in the pyrolysis of silane are negligible because silane decomposes readily. Thus, the total direct energy input is about 29,100 BTU per pound of silane which can be converted to 18.74 kWh per kg silane. Since one pound of silane produces 0.3573 kg silicon at an overall yield of 90% the direct energy is 23.86 kWh/kg Si which yields a payback time of 0.14 years.

Most of the indirect energy is contained in the gases, which are continuously recycled. In order to account for losses we use the same rationale expressed in our first report and assume that the indirect energy is not larger than 22.0 kWh/kg Si or that the payback time is not more than 0.13 years.

The equipment and overhead energy costs cannot be estimated yet, however, the assumption that they will not differ much from the equivalent costs in the conventional refinement process leading to 76.7 kWh/kg Si and a payback time of 0.46 years.

Thus the following Table 5.12 can be established.

Table 5.12. Energies in Catalytic Reduction Process

	kWh/kg Silicon	Payback Time in Years
Direct Energy	23.9	0.14
Indirect Energy	22.0	0.13
Equipment + Overhead Energy	76.7	0.46
Total Energy	122.6	0.73

5.5.4 Refined Silicon via a SiF_2 Polymer Transport Purification Process

This investigation[21)] examines the potential of obtaining refined silicon via a SiF_2 polymer transport purification process. It involves the reaction of low cost metallurgical grade silicon with SiF_4 to yield SiF_2 gas which is condensed to a polymeric form $(SiF_2)_x$.

Subsequent heating of the polymer to temperatures of about 400°C yields purified silicon, silicon tetrafluoride and higher order homologues.

Basically, the purification procedure consists of a three step process which can be written as follows:

$SiF_4 + Si(MG) \xrightarrow{1100^\circ C} 2SiF_2$ Step 1

$XSiF_2 \xrightarrow{-45^\circ C} (SiF_2)_x$ Step 2

$(SiF_2)_x \xrightarrow{400^\circ C} Si + SiF_4 + Si_yF_z$ Step 3a

$Si \xrightarrow{>730^\circ C} Si\ (crystalline) + Si_xF_y$ Step 3b

The reaction of silicon tetrafluoride with metallurgical grade silicon at high temperatures produces gaseous silicon fluoride according to reaction Step 1. The gas is then cooled in Step 2 and condenses to form a polymer. Subsequent heating of the polymer to moderate temperatures as indicated in Step 3a results in the release of amorphous silicon and gaseous silicon fluorides. The precipitated silicon is then again heated to temperatures above 730°C during which process the silicon crystallizes and any remaining fluorides are driven out of the silicon material.

The salient feature of this three step transport process is the fact that silicon undergoes purification in all three steps and, therefore, this technology is very effective in removing impurities and potentially viable for large scale silicon production. Laboratory tests identified only uncompensated phosphorous in concentrations below 3.6 ppm as the major impurity.

Although the technology is still in the laboratory stage, it is established enough to allow an assessment of the energies involved.

According to the investigators, direct energy is only used for the heating and cooling processes. The energies for heating are primarily used in Step 1 and are estimated to be 8.6 kWh/kg Si. The refrigeration Step 2 requires about 5.6 kWh/kg Si. Accordingly, the total direct energy is only about 14.2 kWh/kg Si and a payback time of 0.09 years results.

There are hardly any indirect energies because the whole process is essentially a closed reaction cycle. We have only to account for losses of SiF_4 which are estimated to be about 5% each cycle. High purity SiF_4 can be obtained in pressured cylinders for $60 per kg SiF_4. The estimated energy content is 1480 kWh/kg Si. However, unpurified SiF_4 can also be obtained as a by-product of the fertilizer industry for about $1.60 per kg of silicon which would indicate an energy content of 11.0 kWh/kg Si before purification. An intermediate value of approximately 100 kWh/kg Si can be achieved in large production quantities since the energy of purifying SiF_4 should be similar to the energy expended in refining $SiCl_4$. Since only 5% of the SiF_4 needs to be replaced each cycle the indirect energy is, therefore, estimated to be only about 5kWh/kg Si yielding a payback time of about 0.03 years.

The estimated equipment and overhead costs for a plant capable of producing 1000 MT per year is on the order of $15 Mio. Assuming a 10 year lifetime of such a facility the equipment and overhead costs would furden the silicon with $1.50 per kg silicon. This would indicate that the equipment and overhead energy is in the neighborhood of 10.0 kWh/kg Si and the payback time for this energy category is only 0.06 years.

Our results may be summarized as in Table 5.13.

Table 5.13 Energies in the Silicon Fluoride Polymer Process

	kWh/kg Silicon	Payback Time in Years
Direct Energy	14.2	0.09
Indirect Energy	5.0	0.03
Equipment + Overhead Energy	10.0	0.06
Total Energy	29.2	0.18

The total energy expenditure of about 30 kWh per kg refined silicon may prove to be an underestimate in the future. Yet the indication that this refinement is very energy inexpensive must be acknowledged.

5.5.5 Purified Silicon via an Improved Conventional Silicon Technology

The objective of this development program[22] is to render the refinement process in its conventional form and as practiced for semiconductor grade silicon unnecessary. The approach to this goal is based upon the use of material of higher-than-normal purity for the silicon smelting process. The silicon metal so obtained is expected to be pure enough that only a relatively simple additional refinement step in the form of a unidirectional freezing process will be required to yield silicon of solar grade quality and ready for use as cell material

A survey indicated that large deposits of quartzite gravel with purities as high as 99.5% SiO_2 are available in the United States and Canada as raw material for clean smelting. The major impurity contributors in the conventional process were the carbon supplying materials such as wood chips, coal and coke. They are replaced in the new smelting process by a high purity carbon source in the form of refined charcoal which was exposed to a halogen for several hours at high temperatures. The charcoal halogenation is carried out under high vacuum and reduces the levels of the most important impurities of boron and phosphorous to below the 15 ppmw figure. The effect of other impurities which are also affected by the halogenation process but are not specifically monitored is considered negligible. The halogenation occurs in specially designed box furnaces whose walls are lined with high purity ceramics, quartz and graphite materials.

The smelting of the silicon from higher purity materials is currently carried out in experimental furnaces with the goal to transfer the process later to large furnaces of similar design and quality as have been used in the past in the conventional process.

The silicon obtained under controlled purity conditions is subsequently subjected to a unidirectional solidification process for further refinement.

An important feature of the unidirectional solidification process is that in a liquid/solid phase system of silicon the impurities tend to accumulate in the liquid phase. Thus, if solidification of the melt occurs in a linear direction the impurities tend to remain in the melt rather than being incorporated into the newly formed crystal. As a result solidified material may be obtained from the melt with a lower impurity content than the starting material had before melting.

Several solidification schemes have been tested. Amongst them the Bridgman type growth technique and the Czochralski type pull. It appears that the CZ type pull yields the best results and shows the greatest promise for the future technology. The pull rate can be much higher than normally required to obtain single crystals because the resulting polycrystalline ingots exhibiting large grains will most likely be the cell material of the future.

An assessment of the involved energy expenditures of the proposed refinement approach must necessarily include the silicon reduction. Therefore, the estimated energies of the whole procedure under development need to be compared to the energies in reduction and refinement of the conventional processes as described previously.

We believe that the energies involved in the proposed refined silicon process are composed of the conventional reduction energies and the additional energies expended in the halogenation of charcoal and the unidirectional refinement.

The conventional reduction energies were listed in the first quarterly report as:

	kWh/kg Si
Direct energy	15.4
Indirect energy	31.4
Equipment and Overhead energy	1.2

To these data we have to add the energies expended in the halogenation process of charcoal. Although the temperatures employed in the box furnaces for halogenation reach values of 2000°C the energy usage per kg silicon is small because the process can be carried out in large furnaces with high throughput rates. The electrical energy required to halogenize 1 kg of charcoal is about 5.5 kWh. In relation to the silicon this value transforms to an energy expenditure of 2.4 kWh/kg Si. Thus, the total direct energy expenditure for the new reduction process is 17.8 kWh/kg Si yielding a payback time of 0.11 years.

The indirect energy cost of the halogenation depends upon the type of the used halogen. It is estimated that the indirect energy when a fluorocarbon is used will be approximately 20 kWh/kg Si and the total indirect energy of the reduction will, therefore, be 51.4 kWh/kg Si. The payback time based upon this value is then 0.31 years.

Accurate data on the energy expenditure in equipment and overhead for the box furnace is not available but assuming that it will be similar to the large conventional arc furnaces currently used. Therefore, we double the equipment and overhead energy for the conventional reduction process and arrive at 2.4 kWh/kg Si and a payback time of 0.01 years.

The assessed energies involved in the subsequent refinement step are based upon the Cz-type pull solidification. The energy estimate does account for the fact that about 35% of the silicon material will be lost in this process due to the fact that it represents the residual melt after each pull which contains the large part of the impurities. The energy values which are quoted are based on the 65% of usable silicon material after pull.

The direct energy required to pull a polycrystalline ingot is 33.8 kWh with an associated payback time of 0.20 years.

The indirect energy is estimated to be 7.7 kWh/kg Si based upon a materials cost of 75¢ per kg of unrefined silicon and 65% materials utilization. The associated payback time is, therefore, 0.05 years.

The costs for capital and maintenance is estimated to be $2.98 for 1 kg of unrefined silicon. Therefore, the equipment and overhead energy is about 30.6 kWh/kg Si for refined silicon with 65% materials yield. The resulting payback time is then 0.18 years.

The energies and payback times of the improved conventional silicon technology are summarized in Table 5.14.

Table 5.14 Energies in Improved Conventional Silicon Technology

	kWh/kg Si	Payback Time in Years
Reduction		
Direct Energy	17.8	0.11
Indirect Energy	51.4	0.31
Equipment + Overhead Energy	2.4	0.01
Total Energy	71.6	0.43
Refinement		
Direct Energy	33.8	0.20
Indirect Energy	7.7	0.05
Equipment + Overhead Energy	30.6	0.18
Total Energy	72.1	0.43

5.5.6 Summary of the Energy Assessment of the Refinement Process

The conventional refinement process is at present the most energy demanding and production limiting process tep within the photovoltaic manufacturing sequence. In its present form, the refinement process constitutes a major obstacle in the general efforts to reach the National Goal in the middle of the next decade. In view of this situation many different alternative refinement schemes are currently suggested and experimentally tested. At the time of this writing a winning technology cannot yet be predicted. The result of this assessment represents an indication rather than a prediction of which technology has the potential of being successful.

The major unknown parameter is the resulting cell efficiency and many technological developments will probably occur before final cell performance can be determined.

Based on a 12.5% efficiency the present payback times have been calculated and displayed in Fig. 5.3 Proper scaling will be required when the actual cell efficiencies based on the present alternative refinement processes are known.

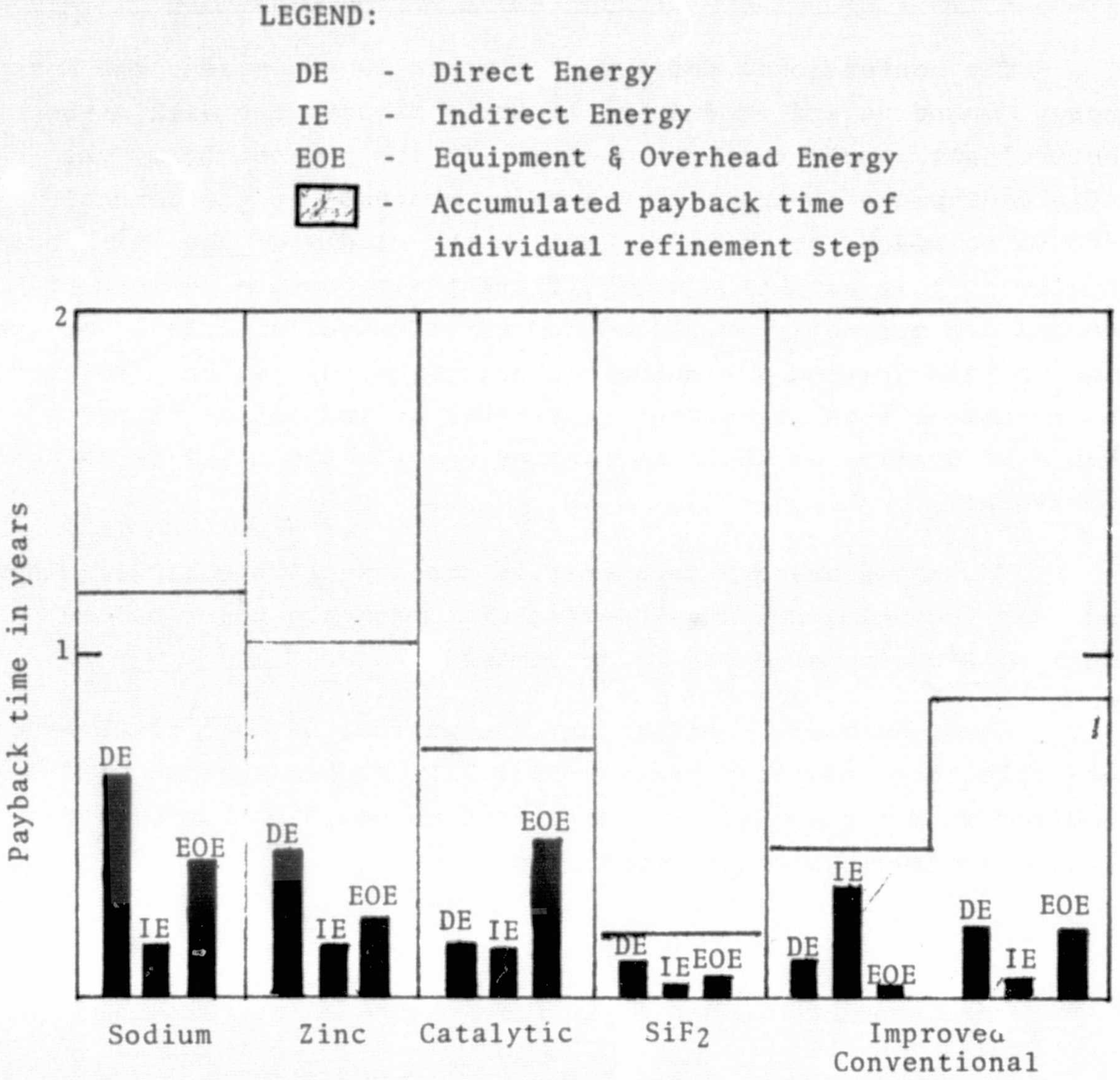


Fig. 5.3 PAYBACK TIMES OF ALTERNATIVE REFINEMENT PROCESSES.

LEGEND:

DE - Direct Energy
IE - Indirect Energy
EOE - Equipment & Overhead Energy
▨ - Accumulated payback time of individual refinement step

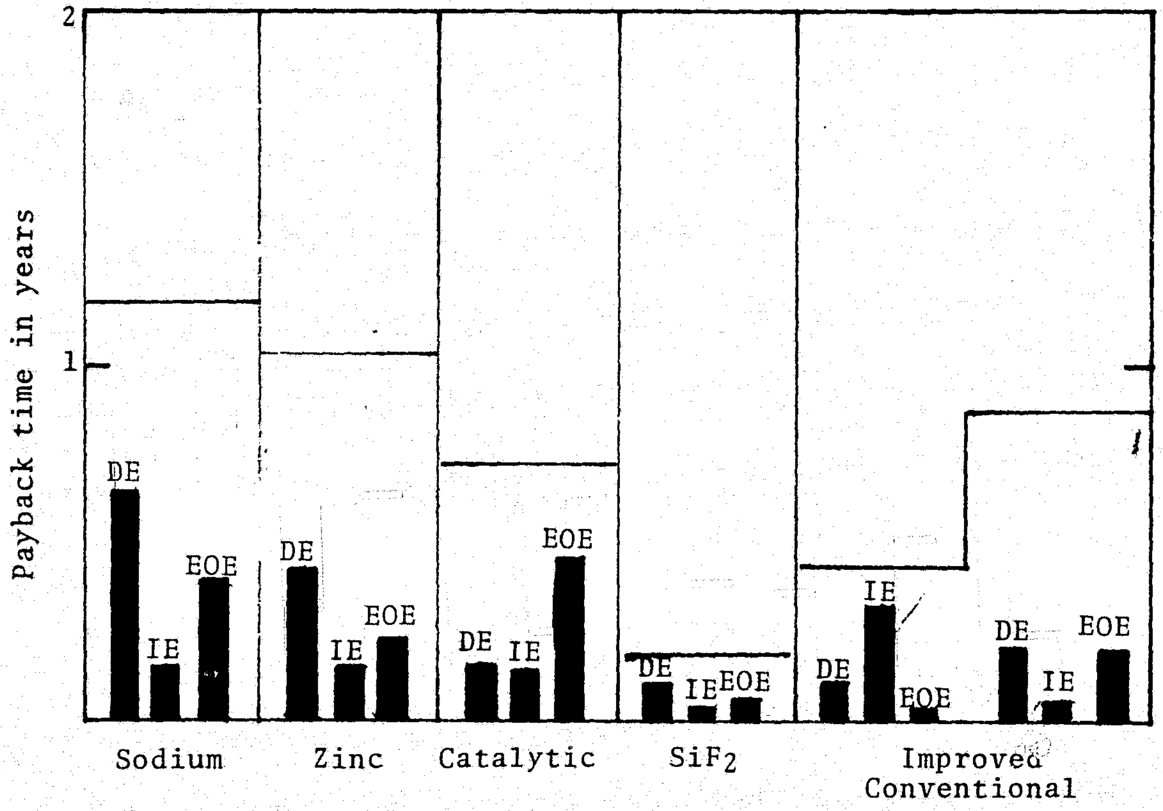


Fig. 5.3 PAYBACK TIMES OF ALTERNATIVE REFINEMENT PROCESSES.

6. Some Results of a Breeder Analysis

The Breeder model was applied to two photovoltaic technologies for simulation of Breeder growth, module output and net energy delivery. Breeder growth is achieved by directing part of the produced modules to the plant "roof" for increased energy input. Thus, its size is represented by the number of pk-kW modules which provide the sole power input. This number is compared in the same graph to the number of photovoltaic panels which have been produced and "sold" and are still "operating" in the field, i.e. panel expiration effects were taken into account. By multiplying the power of the externally employed panels by the elapsed time since their production a figure for their energy delivered to society can be derived and compared with the energy debt of the whole Breeder plant. As explained in section 4.0, the cross-over point between "Energy from Panels sold" to "Total Energy Debt" is a function of the payback time and other parameters inherent to the Breeder operation.

The two technologies to which the model was applied use

A) the conventional photovoltaic technology as typically practiced today;

B) a near term technology which could be implemented in the foreseeable future.

A) Conventional Technology

The conventional technology has been described in Chapter 4. It is comprised of the five process steps as defined earlier, and the relevant input data for the computer analysis are given in Table 6.1.

Table 6.1 Program Input Data for Conventional Technology

Process Step	Arc Furnace	Refinement	Crystal	Cell Processing	Module Building
1/yield	N/A	1.1	1.8	1.05	1.0
Physical Conversion	N/A	1.	$4.72x10^{-3}$ kg si/4" dia.wafer	1.	987. 4" dia.cells/ pk-kw module
C_1	N/A	1.1	.0085	1.05	987.
C_2 Direct Energy	(kw-hr/ kg Si) 15.4	(kw-hr/ kg Si) 440	(kw-hr/ wafer) .357	(kw-hr/ wafer) .42	(kw-hr/module) 88.8
C_3 Material	31.4	22.	.867	.70	1648.
C_4 Equipment	1.2	77.	.127	.08	168.
Lifetime of eqpt(yrs)	10.	10.	14.	20.	10.
Days must operate	5.	N/A	N/A	N/A	N/A
Initial production capacity	7.7kg Si/day	7.1kg Si/day	801.wafers/day	746 wafers/ day	.74 pk-kw modules/day
Initial Battery Capacity			12,000 kw-hr		
Battery Lifetime			5 years		
Battery Inherent Energy			200 kw-hr/kw-hr storage		
Initial Roof Array			1000 peak-kilowatts		
Continuous Operation (weekends not off)					
Panel Lifetime			20± 1 year		

The results of the computerruns for the conventional technology are shown in Figs. 6.1 to 6.4.

Fig. 6.1 shows the number of panels forming the roof array and the number of panels which have been sold to society and are operating, both as a function of Breeder time. In this figure as well as in the next the assumption is made that 20% of the module output is employed for roof panel enlargements.

Fig. 6.2 depicts the growth of energy derived from sold panels and the Breeder's total energy debt. Similar graphs are depicted in Figs. 6.3 and 6.4 under no-growth conditions of the Breeder. As the roof array dies after an assumed lifetime of about 20 years and panel production stops the number of panels in the field would decrease linearly in time, although the energy output from them would still continue to rise at least until the year 30. The cross-over point in the energy balance, however, is reached much earlier.

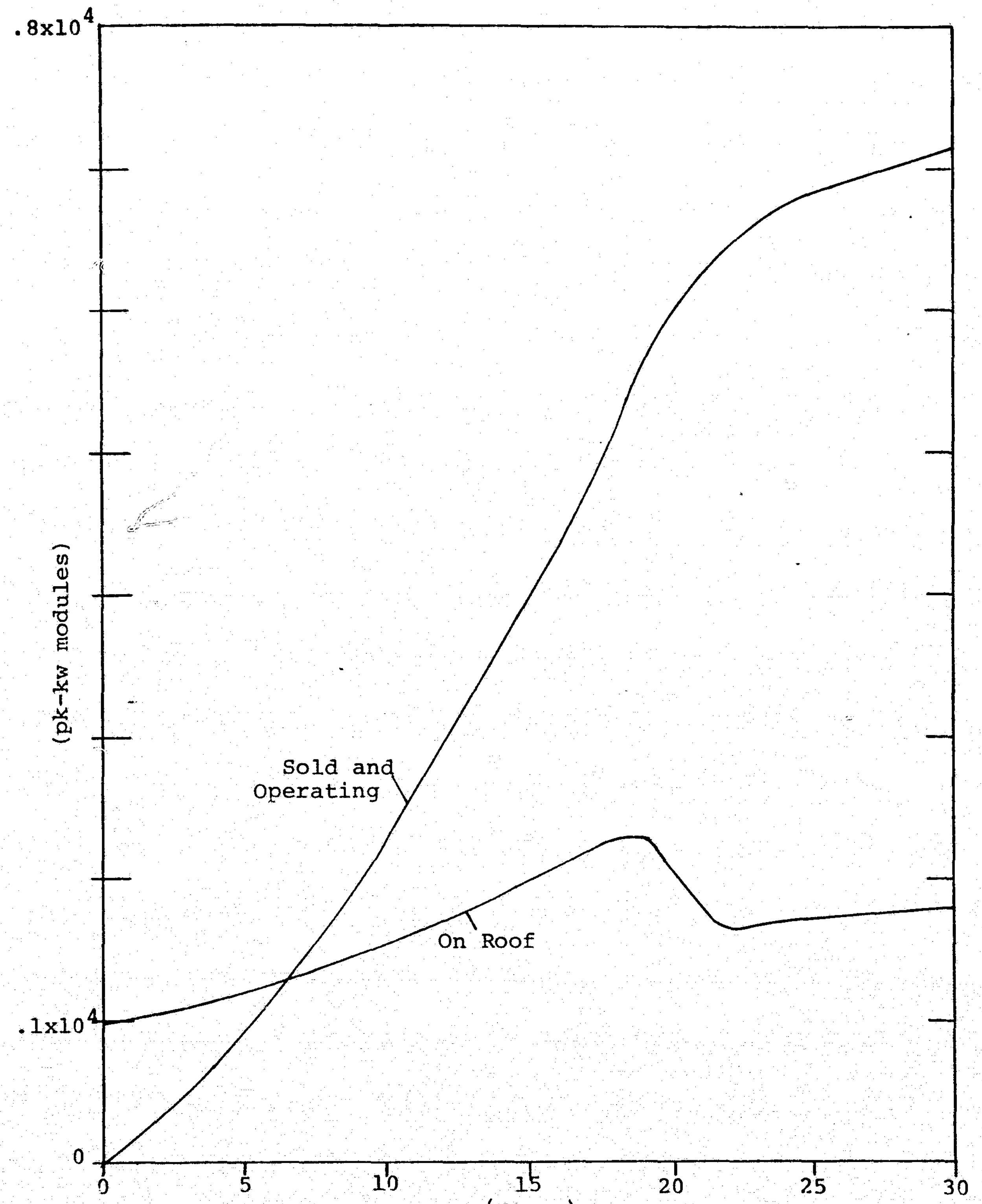


Fig. 6.1 Conventional Technology Growth: 20% to roof.

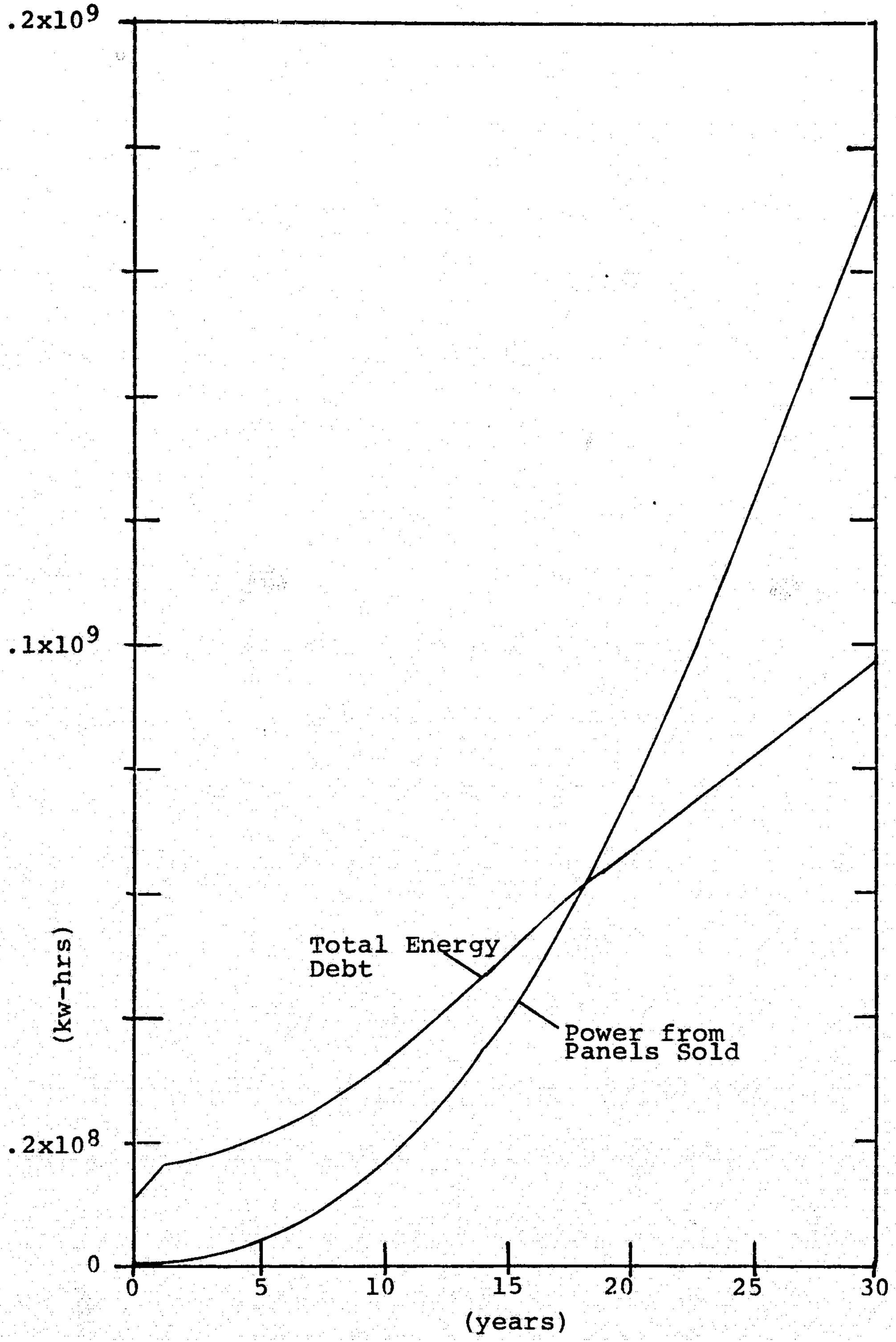


Fig. 6.2 Conventional Technology
Growth: 20% to roof.

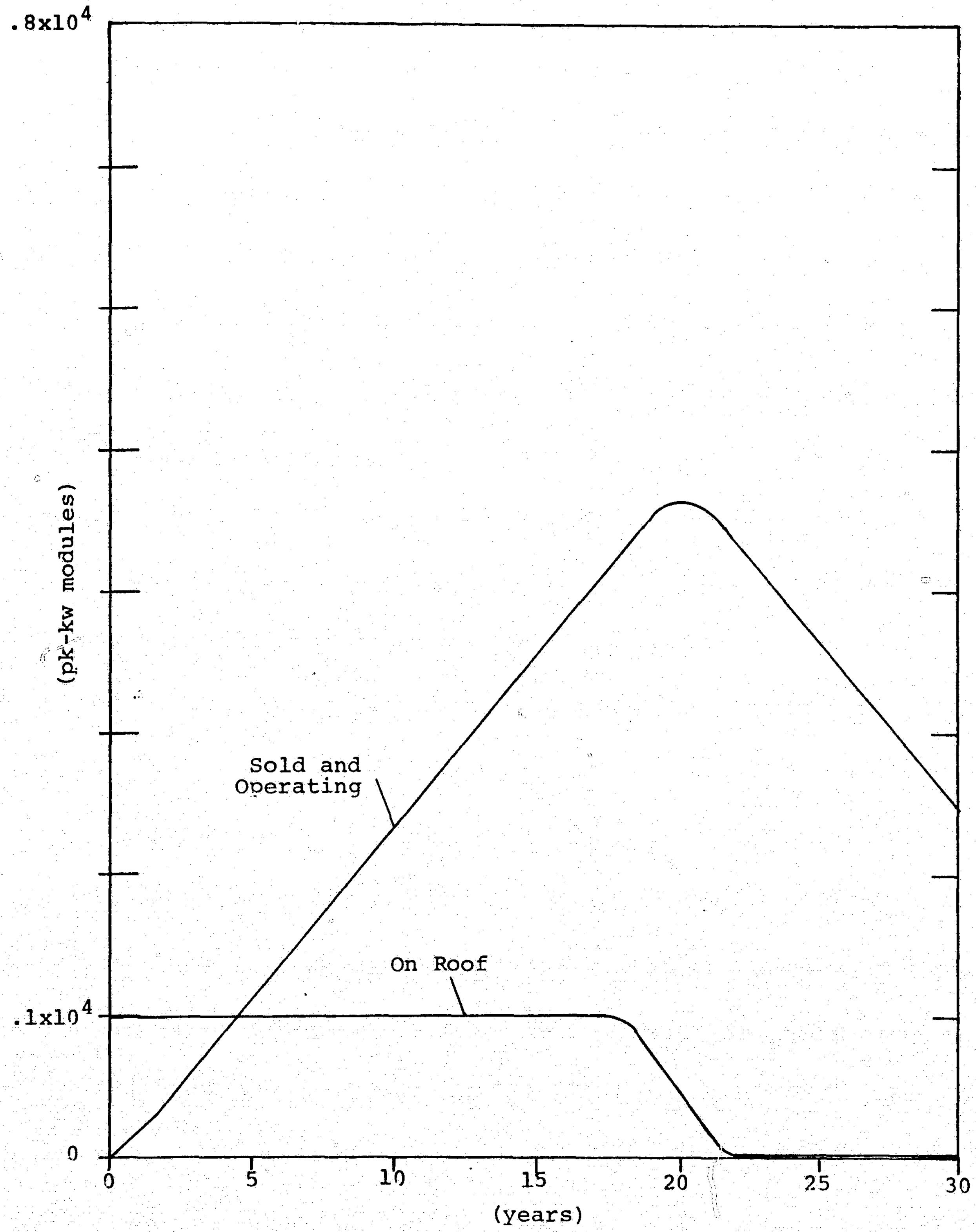


Fig.6.3 Conventional Technology
Growth: None.

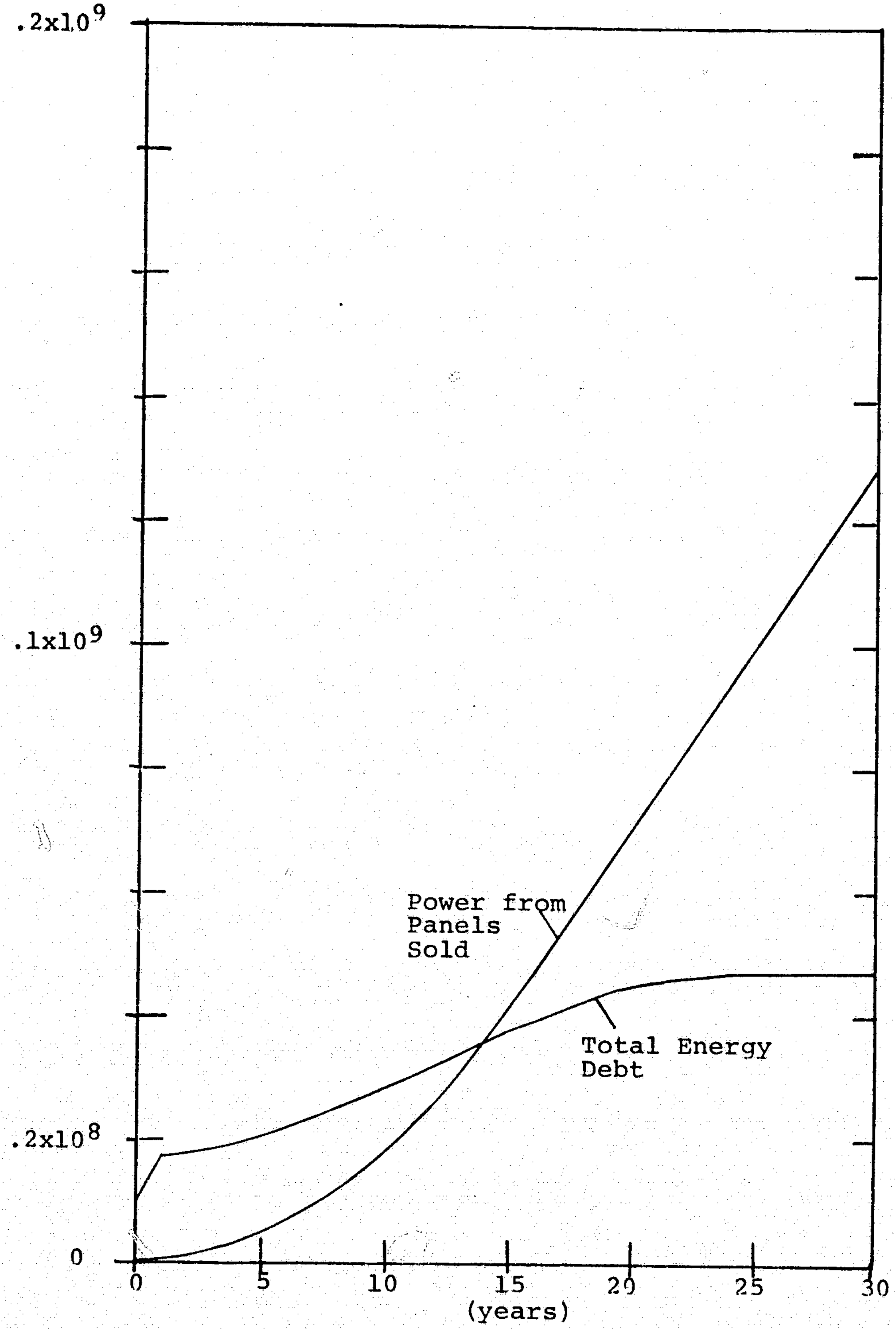


Fig.6.4 Conventional Technology

Growth: None.

B) Near Term Technology

Based upon current efforts to develop alternative technologies we have synthesized a photovoltaic production process which could impact the energy economics in the near future. The sequence is composed of individual production steps, mostly as described in section 5 of this report, as follows with respect to their energy demands

concentional arc furnace
an average energy demand based upon the four
  alternative chemical refinement processes with
  intermediate compounds
semicrystalline casting of silicon bricks with
  4" x 4" cross-section
wire saw cutting of the cast bricks
cell processing with similar energies as today
module fabrication with similar energies as today

The input data for this computerrun is shown in Table 6.2.

Table 6.2 Program Input Data for Near Term Technology.

Process Step	Arc Furnace	Improved Refinement	Casting	Wire Saw	Cell Processing	Module Building
1/yield	N/A	1.1	1.02	1.	1.05	1.
Physical Conversion	N/A	1.	1.	.00734 wafers /kg	1.	807.
C_1	N/A	1.1	1.02	.00735	1.05	807.
C_2 Direct Energy	(kw-hr/ kg Si) 15.4	(kw-hr/ kg Si) 54.4	(kw-hr/ kg Si) 10.23	(kw-hr/ wafer) .069	(kg-hr/ wafer) .42	(kw-hr/pk-kw module) 87.2
C_3 Material Energy	31.4	18.8	27.8	.746	.70	1618.
C_4 Equipment Energy	1.2	57.8	4.09	.144	.08	165.
Lifetime of equipment (years)	10.	10.	14.	20.	20.	10
Days must operate	5.	N/A	N/A	N/A	N/A	N/A
Initial Production Capacity	16.kg Si/ day	14.kg Si/day	14.kg Si/day	1920. wafers/ day	1810 wafers day	2.2 pk-kw modules/ day

Initial Battery Capacity	12,000 kw-hr
Battery Lifetime	5 years
Battery Inherent Energy	200 kw-hr/kw-hr storage
Initial Roof Array	100. peak-kilowatts
Continuous operation (weekends not off)	
Panel Lifetime	20 ± 1 year

This near term technology was utilized under various growth conditions. Figs. 6.5 and 6.6 depict results whereby a constant roof panel increase of 500 kW per year is assumed. As can be seen from Fig. 6.5 the roof array grows relatively slow during the initial breeder time equivalent to a panel lifetime and becomes approximately constant thereafter when new panels more or less replace expired ones. This steady state level is about ten times the initial array size.

Accordingly, panel sales to society increases rapidly as well as the energy sale compared to the Breeder energy debt in Fig. 6.6

If 20% of the yearly output is used to add to roof growth as shown in Figs. 6.7 and 6.8 roof growth is a non-decreasing function in time and expands faster than in the conventional technology. The accompanying effect is a relatively steep rising energy debt which tends to follow the energy sold to society.

The situation becomes more severe if the percentage of the yearly production which is added to the Breeder roof is increased to say 30% as in Figs. 6.9 and 6.10. The Breeder enters into a heavy energy borrowing mode through the purchase of materials for high production rates and the instantaneous energy debt is always larger than the energy recovered by society from produced panels.

No growth conditions are indicated in Figs. 6.11 and 6.12. Under that circumstances the net energy mode is reached already after a few years approximately after twice the payback time and initial energy output to society is high within the initial time span of a panel life but decreases rapidly thereafter. The situation is not much different from similar no-growth situations based on the conventional technology but because now all processes are more energy efficient more energy can be sold to society in form of modules before Breeder decline sets in.

Based upon these computerruns it is already apparent that the operation of a future Breeder can be tightly controlled by a few parameters once the underlying technology has been properly characterised.

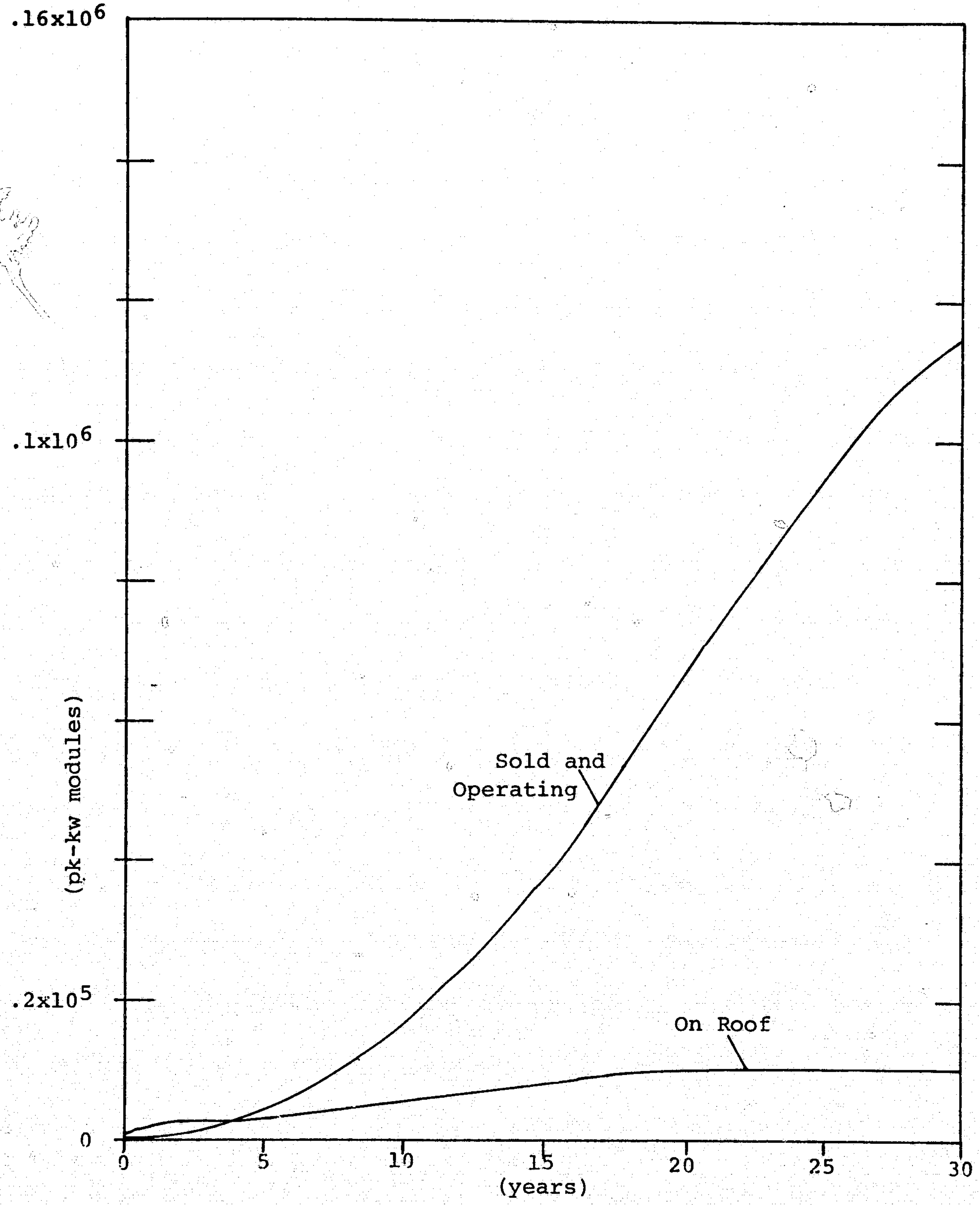


Fig. 6.5 Near Future Technology
Growth: 500 pk-kw each year to roof.

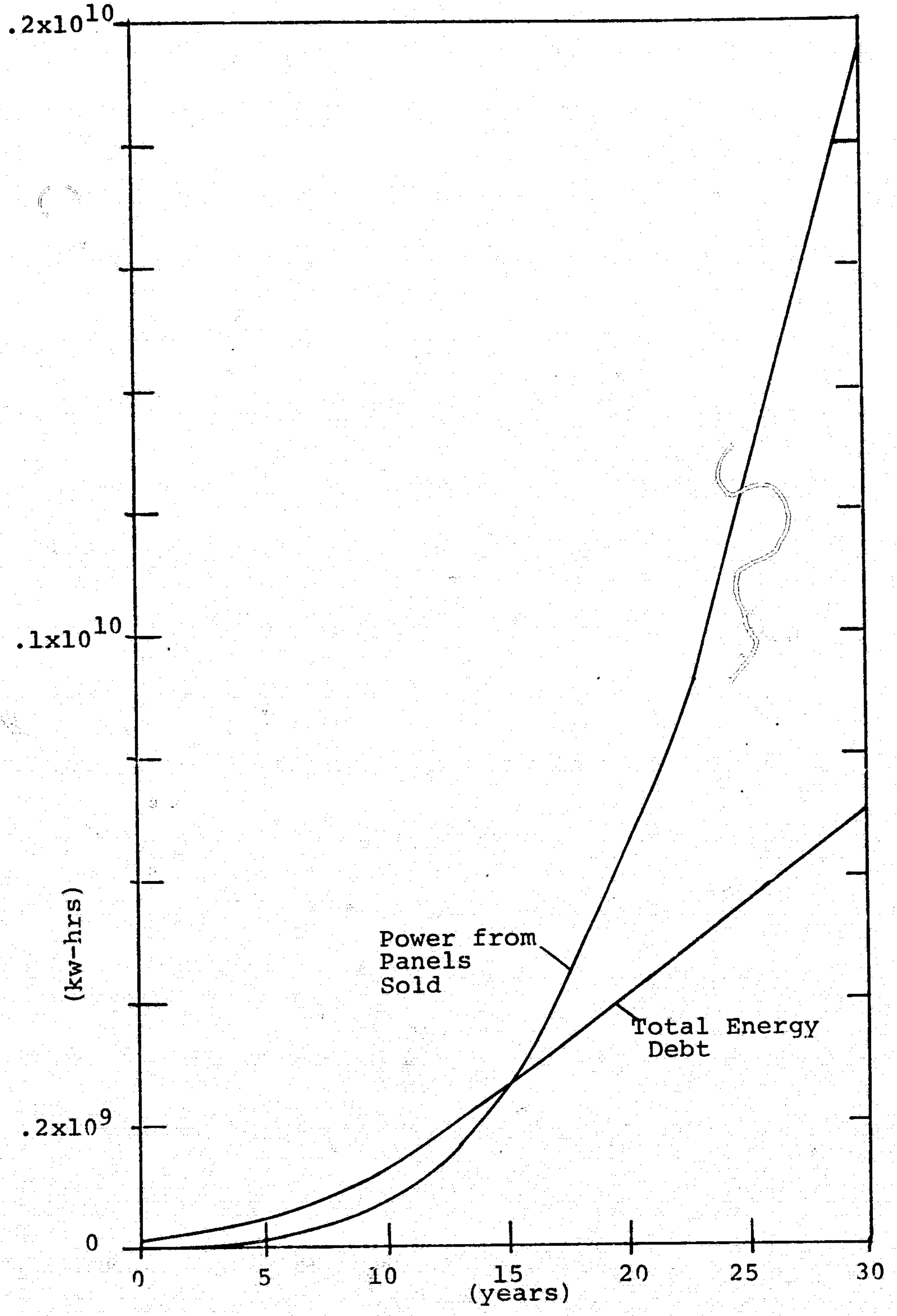


Fig. 6.6 Near Future Technology
Growth: 500 pk-kw each year to roof.

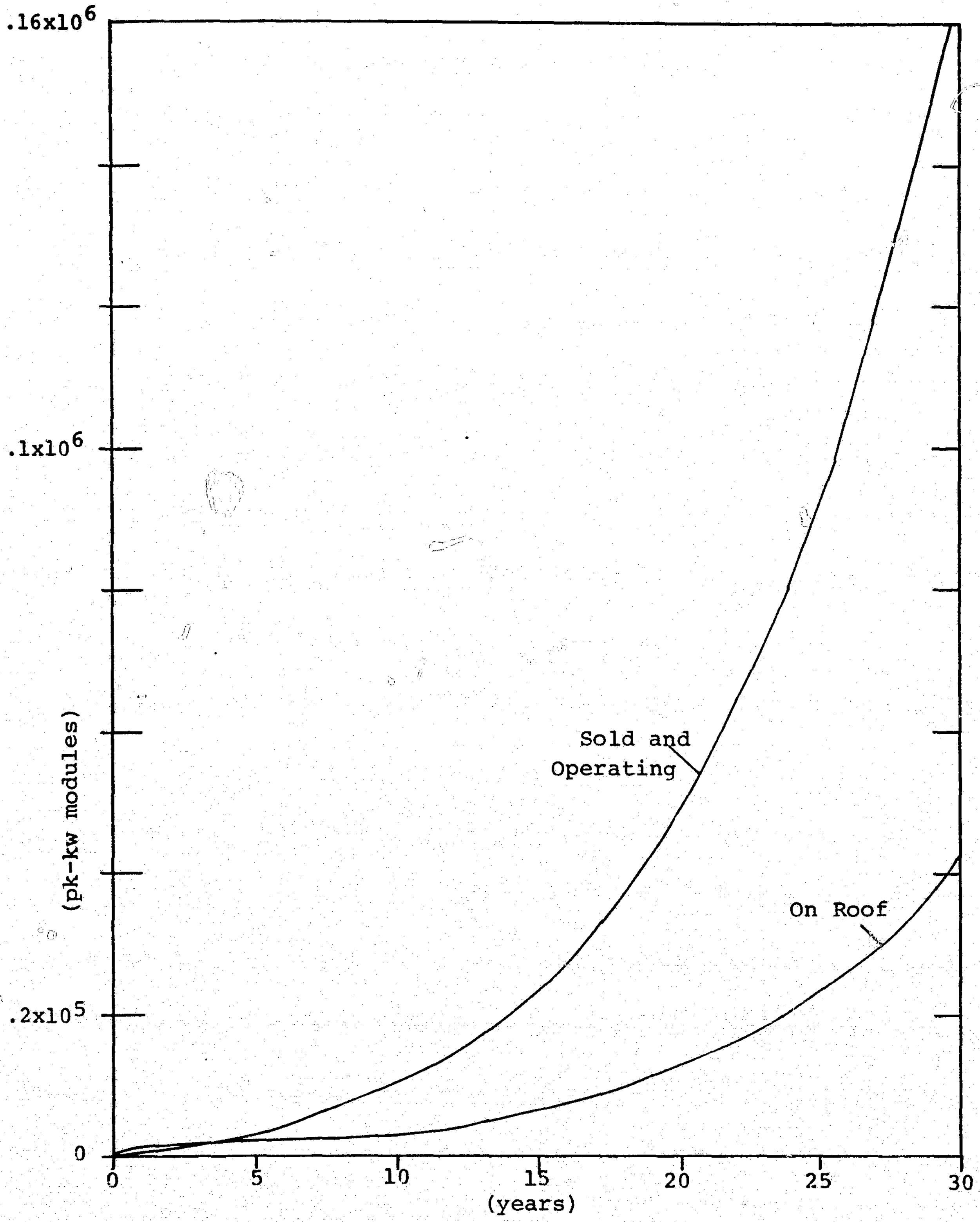


Fig.6.7 Near Future Technology
Growth: 20% to roof.

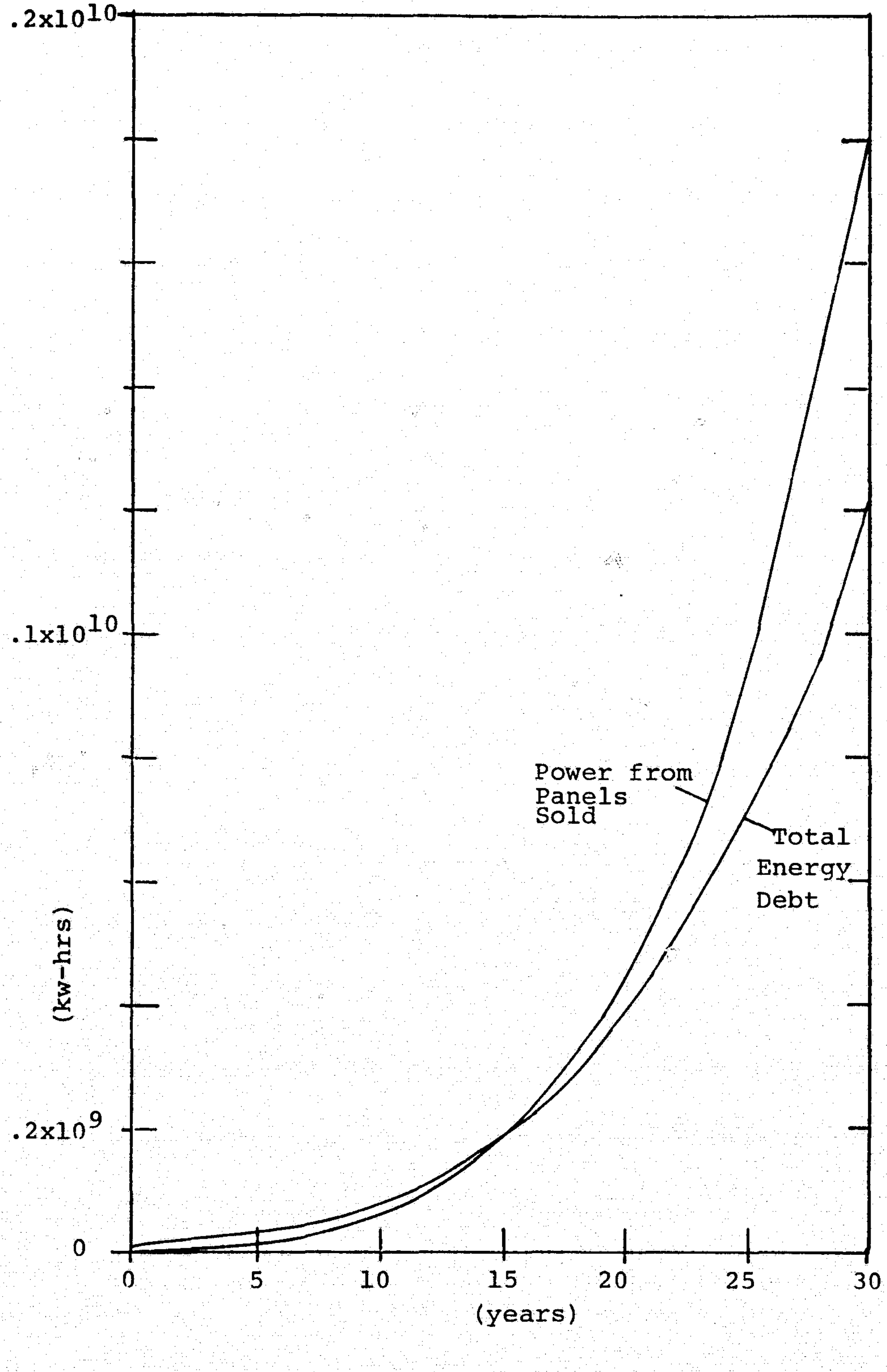


Fig. 6.8 Near Future Technology

Growth: 20% to roof.

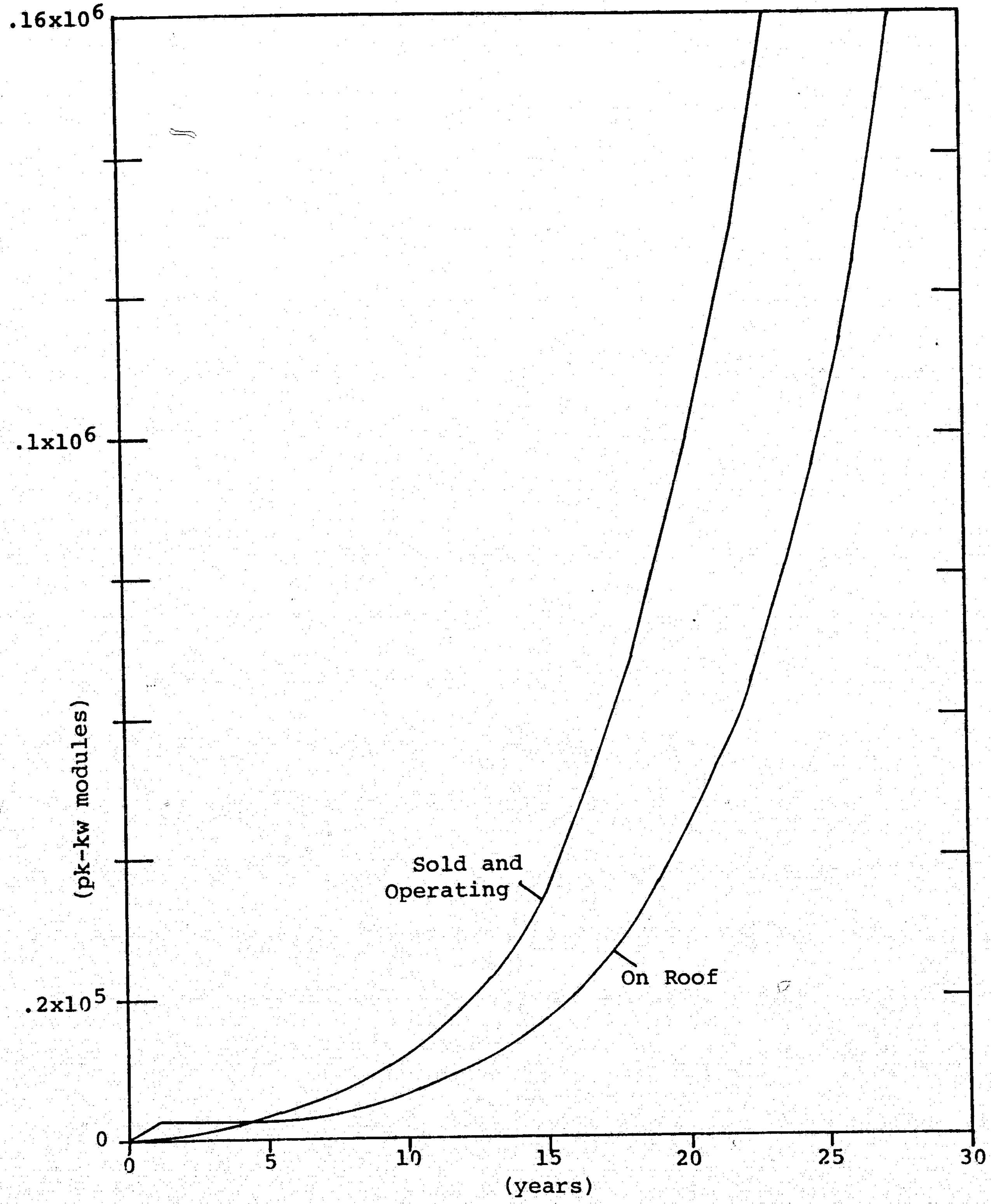


Fig.6.9 Near Future Technology
Growth: 30% to roof.

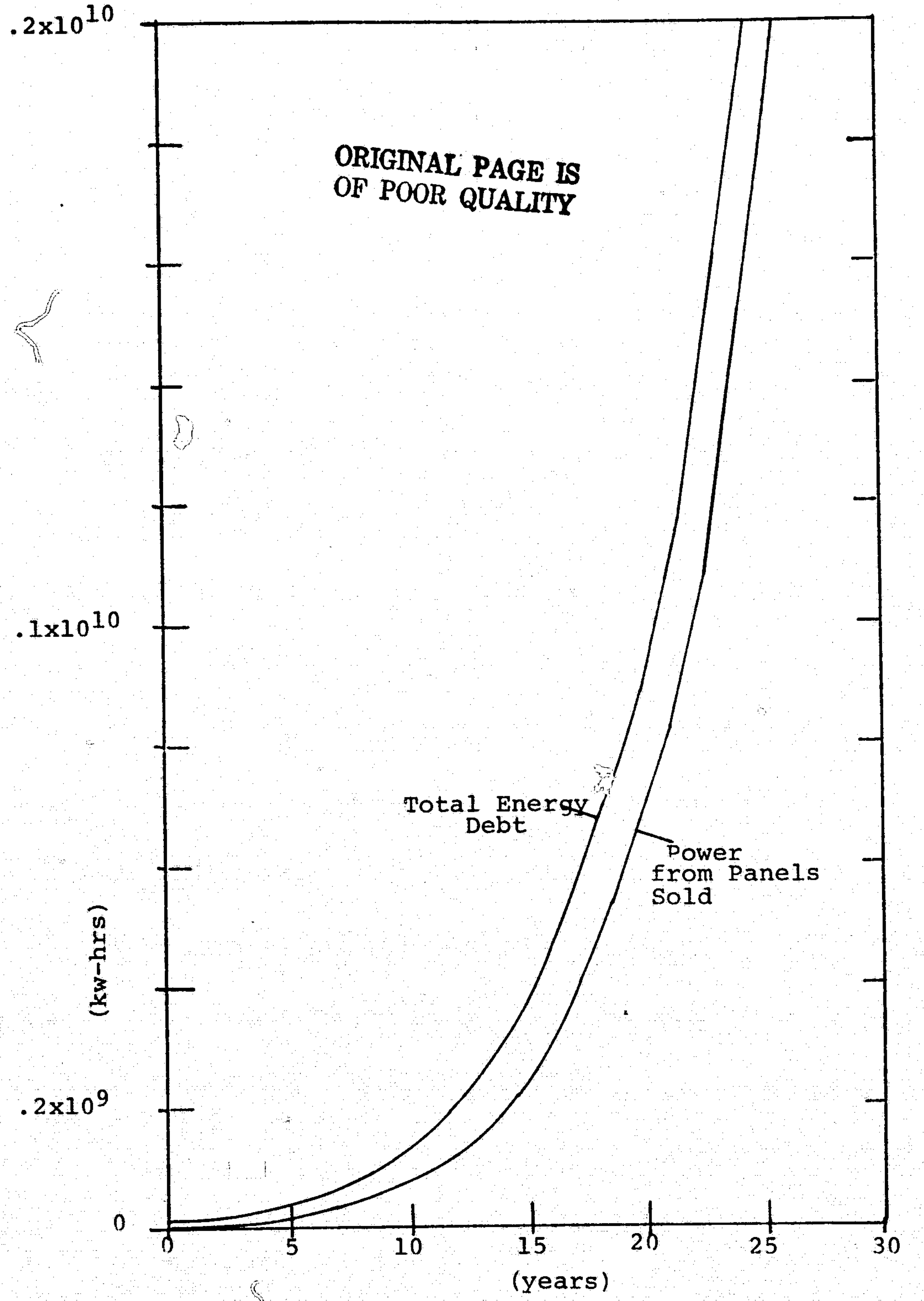


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Fig.6.10 Near Future Technology
Growth: 30% year to roof.

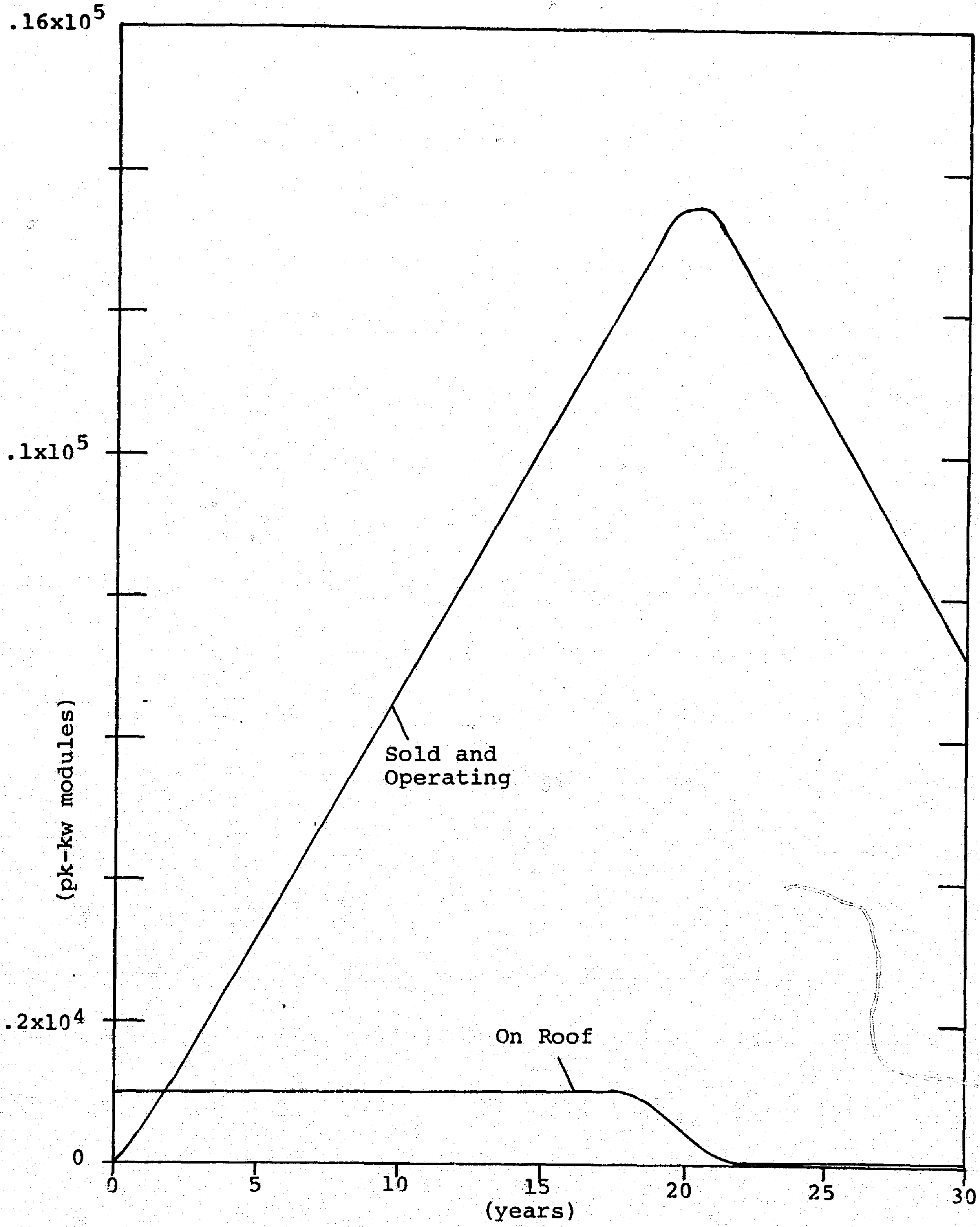

Fig. 6.11 Near Future Technology
Growth: None.

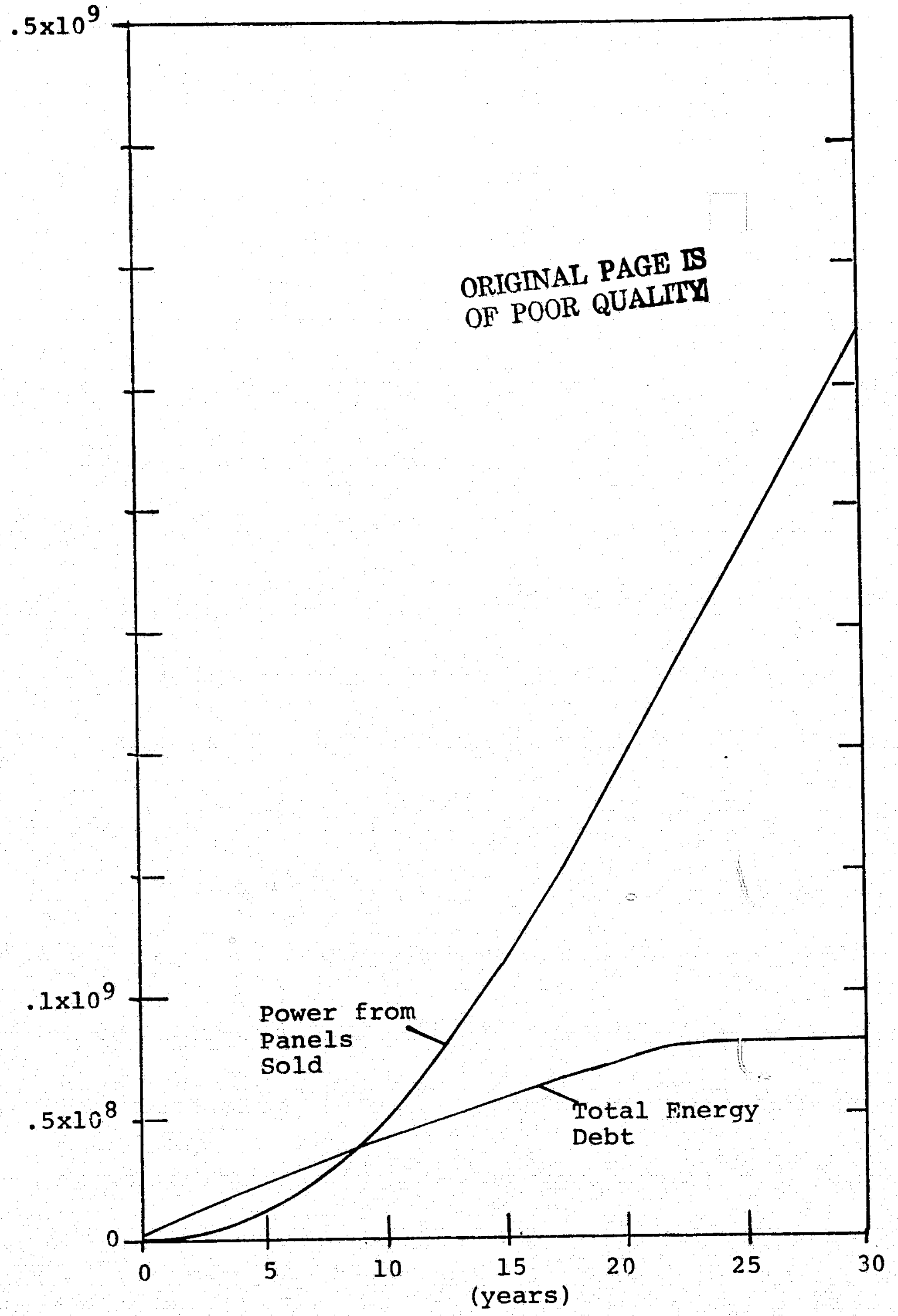

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Fig.6.12 Near Future Technology
Growth: None.

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Exhibit A - Energies, Test Vehicle, Payback Times

Energies

The energy expended during the production of photovoltaic panels has been broken up into three categories:

a) Direct Energy - The amount of energy expended during the actual production of the cells and panels; typically involving electrical energy.

b) Indirect Energy - The energy expended to make raw materials available for solar panel production. Under this heading we include also major energies expended in the mining and transportation processes of raw materials as well as their possible caloric content.

c) Equipment and Overhead Energy - The equipment energy is defined as the energy expended in the manufacture of the production equipment. Overhead energy is defined as the energy expended in lighting, heating and airconditioning of the manufacturing area.

Test Vehicle

As a test vehicle, a 4" diameter solar cell has been used as representative of the state-of-the-art. The following table lists the basic characteristics of a 4" cell:

Table I

Material	SeG silicon
Cell diameter	10.16cm (4")
Cell thickness	0.25mm (0.010")
Cell area	81.07cm^2
Cell volume	2.03cm^3
Silicon mass	4.72 g @ density of 2.33 g/cm^3
Lifetime of panel	20 years

Efficiency	12.5%
Peak Power	1.013W
Average insolation time per day	4.33 hours
Energy delivered in 20 years (31,630 h)	32kWh

The energy delivered by such a cell can be readily calculated for the average U.S. insolation. As for the lifetime we assume 20 years; however, this is not meant to imply that the cell has only this limited life. At the present time it is believed that the life of solar panels is controlled by the packaging materials in conjunction with the environment. In setting a 20 year life it becomes possible to express the energy collected per weight of silicon at the average U.S. location:

energy delivered per kg
silicon in 20 years at = 6,678 kWh
100% yield

Since production yields cannot be regarded as 100%, the following calculations will employ an overall yield of 50% of silicon usage. This means that certain conservation measures are taken, such as the silicon remaining after CZ growth is being reused and that the sawing operation is better than 50% efficient. In addition, it is estimated that the silicon material yield in cell production is approximately 90% as a certain portion of reject cells can be reprocessed and the silicon thereby reclaimed. (This reclamation is not energy intensive). While such yields may vary depending on individual company practices, it is convenient and reasonable to operate with an overall 50% yield for silicon. Accordingly, at 50% yield the energy delivered for one year is:

energy delivered per kg
silicon in 1 year at = 167 kWh
50% cell yield

Payback Times

Energy payback time has been developed as a convenient way to understand the utilization of energy in a particular manufacturing process step. Payback time is the number or fraction of years required for a process step to return the expended energy in production to society. The numbers are based on the power delivered by a test cell in one year. The cell becomes the manufacturing function's payback mechanism by generating electricity for consumption.

Exhibit B - Estimation of Energies from Product Price

The determination of indirect and equipment energies could involve detailed analyses which lead in too many directions in the search for expended energy. In order to cut off such side roads the purchase price of a product has been frequently used for guidance of its energy content. We base the validity of this procedure on the results of a research document[23)] which reports that on the average, 2% of the purchase price of items such as equipment or materials reflect the cost of energy expended in the manufacturing of the item.

This assumption determines the cost of the expended energy in equipment and materials but not the energy value itself. The missing conversion factor of energy vs. price was taken from a recently published study[24)] where it is pointed out that the composite price per million BTU is $0.879. The word composite means that the quoted price is composed of the prices of various energy sources weighted by the relative importance of the individual source. In practical terms the average cost for one kWh is thus $0.003.

Based on these two assumptions it is now possible to derive an energy value from the equipment or material purchase price at a rate of 6.67 kWh per price dollar. This procedure has been adopted except in cases where this simple formula does not apply. For example, the price for photoresist is based largely on initial research costs, quality control and "on the fact that practically only one manufacturer has succeeded in making it" as we were informed. In cases like this derived energy was approximated from appropriate percentages of the purchase price.

Exhibit C - Average Insolation in the United States

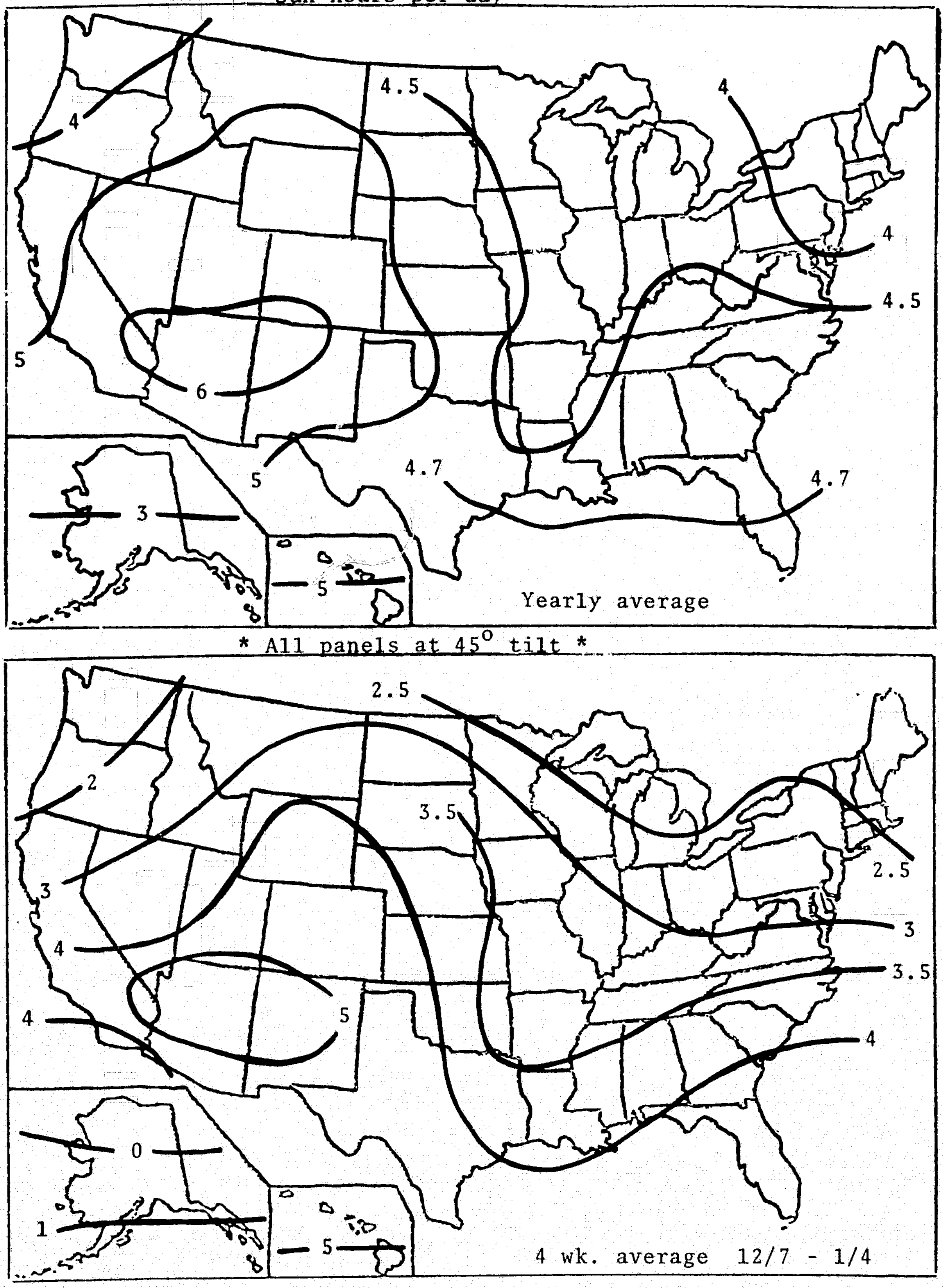
The accompanying maps in Figure VII show the average solar energy available in the United States. Solar radiation data obtained from various weather stations throughout the U.S. were analyzed in terms of average daily sun hours available on a surface facing true south and tilted 45° up-upwards from the horizon.

A sun hour is a measure of incident solar energy. It is defined as the insolation of 100 mW/cm^2 for one hour. The term sun hour does not imply that it is only used for full sunshine unobscured by clouds. For example, reduced insolation of 50 mW/cm^2 for two hours is also considered one sun hour for photovoltaic purposes.

The upper map, Figure B.1 depicts the distribution of the yearly average insolation in the United States. For example, in most of Arizona and New Mexico the average daily energy available from the sun amounts to 6 or more sun hours.

The lower map shows the daily insolation averaged over four winter weeks. The northern part of the U.S. experiences only 2-1/2 sun hours daily during that time while the daily insolation in the southwest is as high as 5 sun hours.

Sun hours per day



* All panels at 45° tilt *

Fig B.1 Average insolation across the United States

Exhibit- D - Breeder Program Documentation

A flow-chart is provided which is keyed to a list of algorithms that explain how the various program steps are accomplished. After the flow-chart is explained, the format of the input data is described and an example is provided. Finally, the FORTRAN computer program is listed.

Flow-Chart

The program structure is shown in Figures D.1 and D.2.

The computer program consists of a main program and a subroutine called BRDYR. The main program performs operations that occur once a year such as the change in equipment and battery size. The subroutine simulates the operation of the breeder manufacturing facility for 365 days.

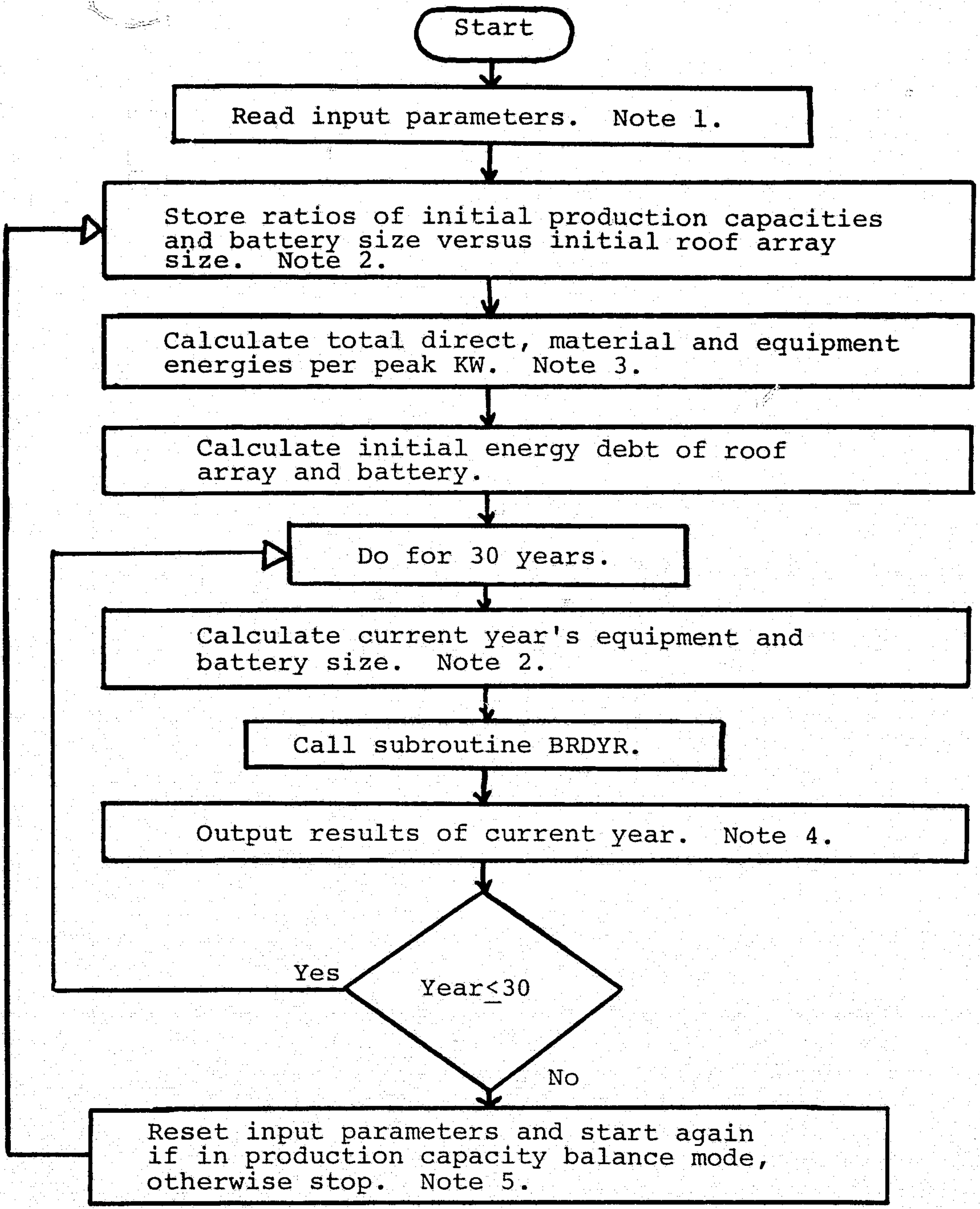


Fig. D.1 FLOW CHART MAIN PROGRAM

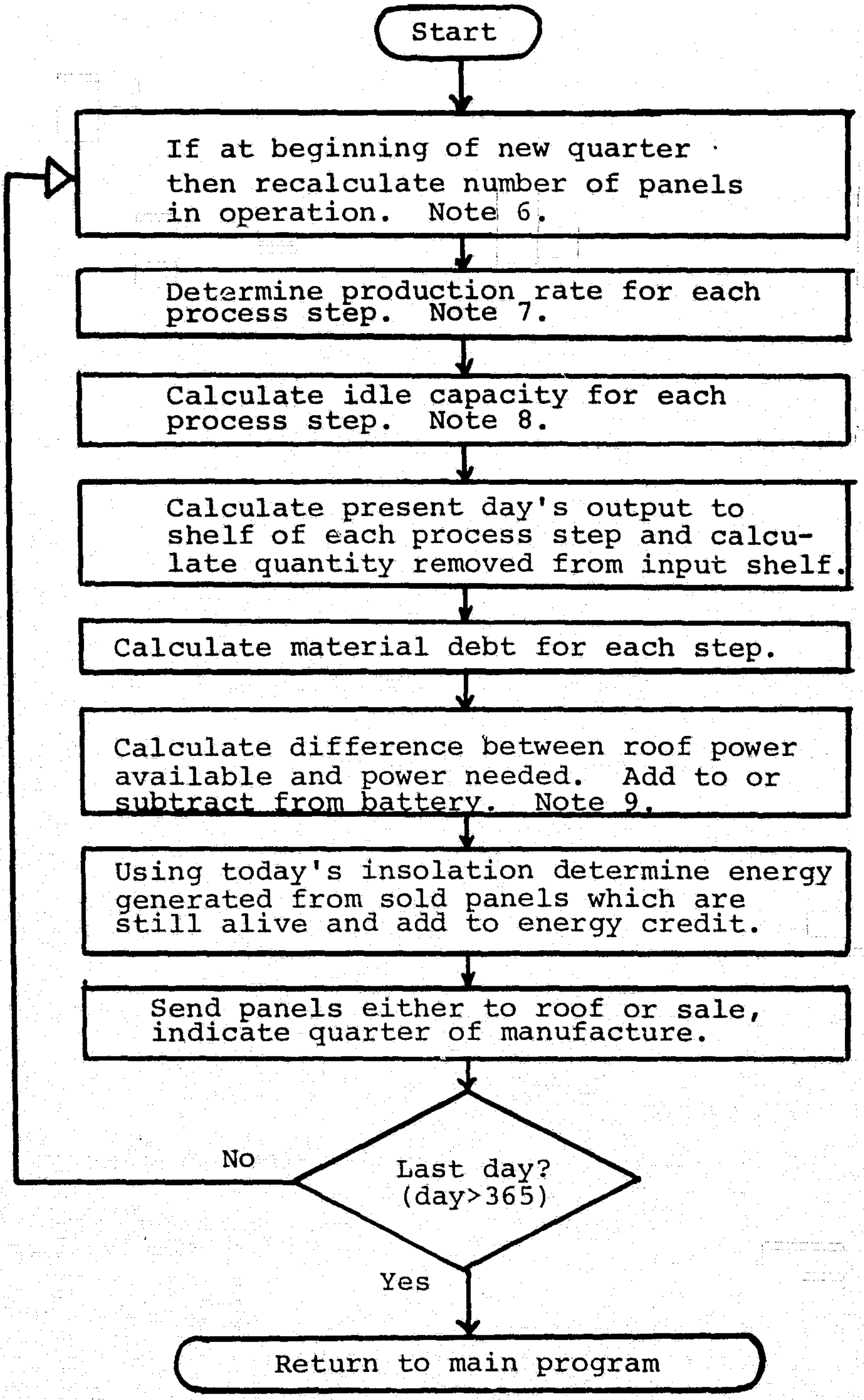


Fig.D.2 FLOW CHART
SUBROUTINE BRDYR

Notes on Flow Chart.

1) The input parameters are discussed in detail in the next section.

2) Determination of equipment and battery size:

The ratio of equipment size (as expressed as units per day for each process step) and battery size to the roof array each year remains the same as the initial year by adding equipment or battery capacity to match the roof array growth.

For each process step the equipment added is logged into a numerical array indexed by the year. The equipment available from previous years is the sum of the L-1 previous years where L is the lifetime of the equipment. To this is added equipment if the proportion to roof array dictates. Equipment is not immediately subtracted if the roof array is reduced in size but will eventually become less as the older ones expire, i.e. are not included in the sum of L-1 previous years.

This procedure of size adjustment is also applied to the battery.

3) Energy debt per peak-kilowatt:

The total energy debt per peak-kilowatt depends on both the step energies and the step yields. For example, when given the amount of energy needed to run an arc furnace to produce a kilogram of metallurgical grade silicon the amount of this energy that goes to produce a peak-kilowatt depends on how many kilograms are ultimately used to produce a peak-kilowatt. The sum of the three energy debts per peak kilowatt is used to determine the energy debt due to the initial roof array.

The energy debt is calculated with the following formula.

$$(\text{Energy debt})_k = \sum_{i=1,\ \text{last step}} \left(E_{ki} \prod_{j=i+1,\ \text{last step}} C_{1j} \right)$$

where E_{ki} is the energy (k = direct, material, or equipment) per one unit output for the i^{th} step and C_{1j} is a conversion factor describing the number of units from the previous step needed to make one unit of the j^{th} step.

It is assumed that the units of the last step are one pk-kw panels.

4) Output yearly results:

The four most important results from this program are the size of the breeder manufacturing facility, the amount sold, the total energy debt and the energy credit produced by the panels sold. These values are written out at the end of each year.

The size of the manufacturing facility is shown in terms of the size of the roof array since the equipment and battery grow in proportion to the roof array size. (The term roof array does not mean that all the panels are necessarily on the roof of the building, the term is used to distinguish the panels tied into the breeder from the panels sold.)

The total energy debt is from materials, equipment, batteries and the initial array. It does not include, of course, direct energy since that is the one type of energy that does not have to be provided externally.

5) Balancing the line, an example of varying input parameters:

An example of the outer loop that changes input parameters is the procedure for automatically balancing the production line. The production capacities for the first run are estimated. In this procedure only the first two years are run. At the end of the second year the idle capacity is subtracted from a number, such as 1.2. Then if the idle capacity is greater than .2, for a particular step the capacity is reduced by multiplying the capacity by the difference between the idle capacity and the present number. If the idle capacity is less than .2, the difference is greater than one and the capacity is increased. This causes the line to become balanced because equipment can be idled by too much on its output shelf or too little on the previous shelf, in either case the step is too large for its neighbors. (Equipment can also be idled by insufficient power available.)

The equipment size for each step is pushed to its maximum by starting with a present number of 1.5 and reducing it to 1.1 over a period of eight loops. Then not only is the line balanced but the overall size is the maximum that has less than 10% idle capacity.

6) Number of Panels in operation:

The lifetime of the panel is a variable usually set to twenty. The lifetime can be given a gaussian distribution of variable width, sigma. Sigma is set at the start of the program as is the panel lifetime.

For a group of panels made during a given year, Y, the output of that group follows the error function, the integral of a gaussian distribution, displaced by the lifetime, L. For an error function of width one year this means that about 68% of the panels undergo a transition from operating to inoperative during the period (Y+L-1) to Y+L+1).

The number of panels operating is the sum of error functions each displaced from the other by the initial date of installation. The installation date is accurate to the quarter year and the number of panels operating on the roof or still operating among those sold is recomputed each quarter year. This is described mathematically below.

Number of panels =

Σ (Panels made k^{th} quarter) x [ERF(index)]
$k = 1$, present quarter

where Index =

[(Present quarter-k) - panel lifetime]/sigma

and where

ERF is the integral of the gaussian distribution.

7) Algorithm for deciding production rate of each step:

Set a flag for each process step to zero. If a flag is reset greater than one then the step must run today.

For process steps two through last do the following. Calculate quantity of material needed from previous step for one day's operation. That is, the amount of input needed for one unit output, C_1, multiplied by the current production capacity. Set tentative production rate to 1 if production will not deplete input shelf (that is, output shelf of previous step) during time this step must run. Otherwise, set tentative production rate to zero. For process step one, the rate is set to 1 because it is assumed there is always enough silicon dioxide.

For all the process steps do the following. If it is a weekend, i.e. day modulo 7 = 0 or 1, and if the program is in 'the weekend off' mode then the tentative rate is reset to zero. Divide units on output shelf by daily capacity. This is the number of days production is backlogged between two steps. If the backlog is greater than 20 days then the tentative rate for that step is set to zero.

If the "days yet to run" variable for a particular step is greater than zero then the tentative rate is reset to 1, the days yet to run is reduced by 1, and the "must run" flag is set to greater than 1.

Otherwise, i.e. no days yet to run, consider if step is one which if started must run for more than one day. If yes, and if tentative rate is 1 then "days yet to run" is set to the full value minus one. If no, set days yet to run to zero.

Sum up the total energy commitment and see if the needed energy is in battery. Either run facility today or if there is insufficient energy storage begin turning off steps in the order of last step first. The procedure is to turn off one step at a time unless the flag is set greater than 1, in which case the step cannot be turned off. After each reduction of need, see if enough energy can now be supplied by the battery.

8) Calculate idle capacity:

The idle capacity for each process step at the end of the year is the number of days each step did not run. The values returned to the main program are the number of idle days divided by 365 if weekends are not days off or divided by 260 if weekends are days off.

9) The daily insolation and battery storage:

The insolation values used in the computer program change each day for 365 days. The same 365 values are used each year. The insolation is derived from daily measurements taken at Solarex for a panel tilted at 45°. The data is normalized so that the average insolation each month equals the monthly insolation averaged over many years. That is, the day to day variation reflects the actual random aspect of insolation while the overall average reflects many years of observation.

Using the present amount of peak-kilowatts on the roof, the insolation is converted to power. If the power is in excess of the day's need, the extra power is stored in the battery after being reduced by 30%. If the power is not sufficient, the difference is drawn from the battery. The battery is never allowed to charge beyond its full rated capacity. Any power entering the battery is multiplied by 0.7 in order to account for storage losses.

The production rate for a particular day is set so as to need no more energy (both today and the "must run" future) than is already in the battery at the start of the day. Since the production does not depend on the present day's insolation, hourly variations need not be considered.

Format of Input Data

Line	Description	Format
1	Number of process steps, N.	Integer in first space
2 to N+1	One line of 7 decimal numbers per process step:	Spaces:
	C_1, input/output	1 - 6
	C_2, kw-hr direct energy/output	7 - 12
	C_3, kw-hr material energy/output	13 - 18
	C_4, kw-hr equipment energy/output	19 - 24
	Lifetime of equipment	25 - 30
	Days unit must run	31 - 36
	Initial capacity, output units/day	37 - 42
N+2	7 decimal numbers on one line:	Spaces:
	Initial battery size	1 - 10
	Lifetime of battery	11 - 20
	Battery storage energy debt, kw-hr debt/kw-hr storage	21 - 30
	Size of initial roof array in kw-hr	31 - 40
	F, fraction of production added to roof	41 - 50
	A, constant number of panels added to roof	51 - 60
	B, number of panels added to roof in proportion to year number	61 - 70

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Note, the number of panels added to the roof array follows one of two formulas. In the first case the number added is a percentage of those produced. The input for this case is through variable F which is set to a number between zero and one. The variables A and B are set to zero in the first case. In the second case the number of panels added to the roof follows the formula A + B · (year). In this case F is set to zero.

N+3	Four items of information:	Spaces:
	Weekends off? 0=No, 1=Yes	1
	Number of years to run cycle, usually 30. An input of 02 tells the computer to optimize the daily capacities of each process step.	2 - 3
	Average panel lifetime	4 - 8
	Standard deviation of panel lifetime	9 - 13

An example is shown below.

```
//GO.SYSIN DD *
5
 1.    15.4 31.4   1.2    10.    5.   25.
 1.1   54.4 18.8   57.8   10.  0.    22.
.01082 .125 .35    .05    14.  0.    2100.
 1.05  .42   .7    .08    20.  0.    1900.
 969.  872. 1618.  165.   10.  0.    2.
12000.     5.        150.      1000.     0.0        500.        0.
030  20.  1.0
/*
```

Main Program Listing

```
//FORT.SYSIN DD *
C MAIN PROGRAM READS INPUT, OUTPUTS RESULTS,
C VARIES PARAMETERS, AND INCREASES PRODUCTION CAPACITY.
      DIMENSION SUN(365), UNIT(9,20),VNIT(9,20), PNLSLD(200)
      DIMENSION PNLRF(200),EQUIP(9,50),BATYR(50),ERF(17)
      DIMENSION ERF2(17)
      COMMON /BR/ UNIT,BAT,BATCAP,PNLSLD,PNLRF,LF,PSOLD,PRF,PSD,
     1 NUNIT,SUN,PCTRF,MW5,PNLQL,SIGQ,ERF,A2,B2
      DIMENSION S1(91),S2(91),S3(92),S4(91)
      DATA S1  /3.7,
     1 3.5,0.8,3.8,3.3,3.9,3.7,2.9,3.9,1.7,3.4,3.3,0.8,3.8,2.6,2.0,
     1 3.9,0.6,0.8,0.5,1.4,4.1,3.8,3.9,1.8,3.7,4.0,1.5,3.5,2.5,0.8,
     1 0.4,1.6,4.7,0.9,2.3,2.7,4.2,4.9,2.1,4.8,2.2,1.0,4.3,5.1,2.8,
     1 1.4,0.8,0.7,5.9,5.3,6.1,6.1,2.3,0.6,4.6,5.9,4.8,5.3,5.6,4.8,
     1 4.7,5.3,5.5,6.1,1.5,5.3,6.0,1.6,1.3,0.7,3.3,0.7,5.9,5.3,5.3,
     1 3.3,0.7,6.1,6.4,1.3,5.5,0.7,5.3,5.9,4.0,4.6,2.6,4.0,6.1,6.8/
      DATA S2   /6.9,
     1 3.9,5.7,2.9,6.2,5.7,6.6,6.4,3.9,3.4,6.2,5.0,5.6,0.6,6.2,6.7,
     1 1.7,6.7,0.6,6.7,2.8,5.6,1.1,3.9,5.0,3.9,2.2,5.6,5.6,6.4,1.9,
     1 6.8,5.6,3.7,4.3,6.4,4.3,4.3,3.7,2.5,4.3,6.8,5.6,6.2,6.2,3.6,
     1 1.1,3.6,5.5,6.2,4.9,3.4,3.7,2.5,6.6,6.2,6.2,4.3,5.6,6.7,4.3,
     1 6.7,5.5,1.8,0.6,6.1,6.1,6.7,3.7,5.5,6.1,6.1,6.7,6.1,5.7,5.6,
     1 5.7,4.7,1.8,0.6,4.7,3.5,5.7,6.3,6.7,5.8,4.3,6.7,5.8,3.6,4.8/
      DATA S3  /5.4,3.2,
     1 4.2,4.2,1.2,2.4,3.0,4.2,3.0,5.6,4.8,4.2,5.6,5.6,5.6,5.4,1.8,
     1 6.2,5.6,5.4,6.2,5.6,5.7,6.2,5.6,5.8,5.6,4.2,4.8,1.6,3.3,3.4,
     1 5.2,4.2,6.1,6.3,6.5,4.0,3.4,4.6,2.8,6.8,6.3,3.7,5.0,5.1,5.6,
     1 3.9,6.1,4.0,6.1,2.4,3.4,5.1,6.3,2.7,6.5,5.5,0.6,1.5,2.5,2.2,
     1 3.5,3.1,6.1,6.4,3.5,5.0,6.1,2.8,4.3,5.2,5.6,3.7,6.3,6.4,6.6,
     1 4.2,6.3,6.5,2.1,3.7,5.4,6.3,5.3,3.2,4.7,5.9,4.6,6.0,4.6,5.2/
      DATA S4   /0.9,
     1 0.6,2.9,6.4,6.1,6.4,6.4,2.3,0.6,6.4,0.6,3.5,6.1,6.0,6.0,0.6,
     1 2.3,1.2,1.7,5.2,4.6,6.0,6.1,5.8,5.2,4.6,4.6,3.9,4.2,3.1,3.8,
     1 3.6,1.5,3.8,0.5,1.5,2.1,3.9,3.8,3.6,3.7,3.6,3.8,2.6,2.9,3.5,
     1 1.6,4.4,1.6,4.2,3.4,1.9,4.1,3.9,3.4,4.4,3.6,3.5,3.4,1.5,1.6,
     1 3.1,3.5,2.6,1.8,1.9,1.6,3.5,4.5,4.6,3.5,3.9,0.8,3.8,3.4,3.7,
     1 2.1,0.6,2.7,1.1,0.5,0.7,1.1,2.7,0.6,2.7,2.0,1.0,2.0,1.8,3.1/
      DATA ERF2 /1.,.96,.93,.89,.84,.77,.69,.6,
     1 .5,.4,.31,.23,.16,.11,.07,.04,0./
      DO 10 I=1,17
10    ERF(I)=ERF2(I)
      DO 302 II=1,91
      II2=II+91
      II3=II2+91
      II4=II3+92
      SUN(II)=S1(II)
      SUN(II2)=S2(II)
      SUN(II3)=S3(II)
      SUN(II4)=S4(II)
302   CONTINUE
      SUN(274)=S3(92)
```

```
C READ LIST OF UNITS
        READ(5,510) NUNIT
510     FORMAT(I1)
        DO 210 I=1,NUNIT
        READ(5,511) (VNIT(I,K),K=1,7)
511     FORMAT(7F6.1)
        VNIT(I,17)=20.
210     CONTINUE
C READ INITIAL BATTERY(KW-HR), BATTERY LIFE, ENERGY DEBT/KW-HR,
C INITIAL ARRAY SIZE(PK-KW), PERCENTAGE TO ROOF
        READ(5,512) BCHOLD,BLHOLD,BEHOLD,PRHOLD,PCTRF,A2,B2
512     FORMAT(7F10.3)
        A2=A2/4.
        B2=B2/4.
C EXPIRATION SIGMA
        READ(5,514) MW5,LASTY,QLFP,SGHOLD
514     FORMAT(I1,I2,F5.0,F5.1)
        ICASE=1
C ECHO INPUTS
751     WRITE(6,660)
660     FORMAT(///' SOLAR BREEDER MODEL'///
      1 11X,'IN',10X,'D',8X,'M',8X,'E',7X,'LF',7X,'OP',
      2 6X,'CAP','  SHELF LIM')
        DO 150  M=1,NUNIT
150     WRITE(6,661) M,(VNIT(M,L),L=1,7),VNIT(M,17)
661     FORMAT(' STEP ',I1,1X,8(1X,E8.3))
        WRITE(6,662) BCHOLD,BLHOLD,BEHOLD,PRHOLD,PCTRF,A2,B2
662     FORMAT('    BATCAP,       BATLIF,    BATENG,',
      1 ' INITIAL RF,OUTPUT*PCT OR  A    +  B*YR=+RF(QRT)'/1X,7F10.3)
        WRITE(6,663) QLFP,SGHOLD
663     FORMAT(' PNL LF ',F4.1, ' +- ',F4.2)
        IF(MW5.EQ.0) WRITE(6,665)
        IF(MW5.EQ.1) WRITE(6,666)
665     FORMAT(/' CONTINUOUS OPERATION')
666     FORMAT(/' WEEKENDS OFF')
```

```
C START 30 YR OPERATION
750    DO 110 I=1,200
       PNLSLD(I)=0.
110    PNLRF(I)=0.
       DEBTB=0.
       PSOLD=0.
       DO 801 I=1,9
       DO 801 J=1,20
801    UNIT(I,J)=0.
       DO 820 I=1,NUNIT
       UNIT(I,17)=VNIT(I,17)
       DO 820 K=1,7
820    UNIT(I,K)=VNIT(I,K)
       SIGQ=SGHOLD*4.
       IF(SIGQ.LT..001) SIGQ=.001
       PNLQL=QLFP*4.
       BATCAP=BCHOLD
       BATLIF=BLHOLD
       BATENG=BEHOLD
       PNLRF(1)=PRHOLD
       DO 115 I=1,NUNIT
115    UNIT(I,16)=UNIT(I,7)/PNLRF(1)
       BAT=BATCAP
       BATG=BATCAP/PNLRF(1)
C CALCULATE INITIAL EQUIPMENT & BATTERY, SIZE & DEBT
       DO 124 K=1,50
       DO 125 I=1,9
125    EQUIP(I,K)=0.
124    BATYR(K)=0.
       DO 126 I=1,NUNIT
       EQUIP(I,1)=UNIT(I,7)
       UNIT(I,9)=UNIT(I,7)
126    UNIT(I,11)=UNIT(I,11)+(UNIT(I,7)*UNIT(I,5)*365.*UNIT(I,4))
       BATYR(1)=BATCAP
       DEBTB=DEBTB+(BATCAP*BATENG)
C CALCULATE INITIAL DEBT DUE TO PANELS
       A=1
       DBD=0.
       DBM=0.
       DBE=0.
       DO 200 I=1,NUNIT
       K=NUNIT+1-I
       J=K+1
       IF(J.GT.NUNIT) GO TO 201
       A=A*UNIT(J,1)
201    DBD=DBD+(A*UNIT(K,2))
       DBM=DBM+(A*UNIT(K,3))
       DBE=DBE+(A*UNIT(K,4))
200    CONTINUE
       DEBTI=DBD+DBM+DBE
       DEBTI=DEBTI*PNLRF(1)
       WRITE(6,620) DBD,DBM,DBE,DEBTI
620    FORMAT(/10X,' DEBT/PK-KW'/' DIRECT   MATERIAL   EQUIPMENT',
     1 '      INITIAL FOR ROOF'/1X,3F10.2,5X,E12.4)
```

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```
C LOOP YEAR BY YEAR
      DO 700 NYR=1,LASTY
C CALCULATE EQUIPMENT & BAT SIZE AND ADD TO DEBTB,UNIT(-,11)
      IF(NYR.LT.2) GO TO 702
      DO 180 I=1,NUNIT
      GOTE=0.
      LFTM=UNIT(I,5)+.01
      IF(LFTM.LT.2) GO TO 130
      L1=NYR-LFTM+1
      L2=NYR-1
      IF(L1.LT.1) L1=1
      DO 135 KK=L1,L2
135   GOTE=GOTE+EQUIP(I,KK)
130   ATEMP=(UNIT(I,16)*PRF)-GOTE
      IF(ATEMP.LE.0.) GO TO 180
      EQUIP(I,NYR)=ATEMP
      UNIT(I,11)=UNIT(I,11)+(ATEMP*UNIT(I,5)*365.*UNIT(I,4))
      GOTE=GOTE+ATEMP
180   UNIT(I,9)=GOTE
      GOTE=0.
      LFTM=BATLIF+.01
      IF(LFTM.LT.2) GO TO 140
      L1=NYR-LFTM+1
      L2=NYR-1
      IF(L1.LT.1) L1=1
      DO 145 KK=L1,L2
145   GOTE=GOTE+BATYR(KK)
140   ATEMP=(BATG*PRF)-GOTE
      IF(ATEMP.LE.0.) GO TO 181
      BATYR(NYR)=ATEMP
      DEBTB=DEBTB+(ATEMP*BATENG)
      GOTE=GOTE+ATEMP
181   BATCAP=GOTE
      BAT=BATCAP
```

```
C CALL BRDYR FOR ONE YEAR CYCLE
702     CALL BRDYR(NYR,JOKE)
        IF(JOKE.EQ.1) GO TO 701
        WRITE(6,650) JOKE
650     FORMAT(1X,'ERR(J)= ',I1)
        GO TO 760
C OUTPUT RESULTS OF YEAR
701     DEBTM=0.
        DEBTE=0.
        DO 810 I=1,NUNIT
        DEBTM=DEBTM+UNIT(I,10)
810     DEBTE=DEBTE+UNIT(I,11)
        TOTDEB=DEBTM+DEBTE+DEBTI+DEBTB
C WRITE OUTPUT
        IF(NYR.EQ.1) WRITE(6,960) DEBTB
960     FORMAT(/' BAT DEBT ',E10.4//
     1 ' YR  BAT SIZE   FULL RATE USE   TOT DEBT   P FROM SOLD
     2 ' ON ROOF  TOT SLD&OPRT')
        TEMCAP=0
        DO 720 I=1,NUNIT
720     TEMCAP=TEMCAP+(UNIT(I,9)*UNIT(I,2))
        WRITE(6,630) NYR,BATCAP,TEMCAP,TOTDEB,PSOLD,PRF,PSD
630     FORMAT(1X,I3,6(2X,E10.4))
        WRITE(6,962) (UNIT(I,12),I=1,NUNIT)
700     CONTINUE
C RUN OTHER CASES
760     ICASE=ICASE+1
        IF(LASTY.GT.2) GO TO 979
C HERE TO BALANCE LINE
        WRITE(6,962) (UNIT(I,12),I=1,NUNIT)
962     FORMAT(' IDLE ',9(1X,F5.3))
976     IF(ICASE.GT.8) STOP
        LASTY=2
        DO 978 I=1,NUNIT
        IF(JOKE.GT.1) VNIT(I,7)=UNIT(I,7)*.9
        IF(JOKE.GT.1) GO TO 978
        VNIT(I,7)=UNIT(I,7)*((1.5-(ICASE/18.))-UNIT(I,12))
978     CONTINUE
        GO TO 751
C HERE FOR OTHER CHANGES
979     LASTY=30
        IF(ICASE.EQ.2) STOP
        IF(ICASE.GT.2) STOP
        GO TO 751
        END
```

Subroutine BRDYR Listing

```
      SUBROUTINE BRDYR(NYR,JOKE)
      DIMENSION SUN(365),UNIT(9,20),PNLSLD(200),PNLRF(200)
      DIMENSION ERF(17)
      COMMON /BR/ UNIT,BAT,BATCAP,PNLSLD,PNLRF,LF,PSOLD,PRF,PSD,
     1 NUNIT,SUN,PCTRF,MW5,PNLQL,SIGQ,ERF,A2,B2
      JOKE=1
      DO 396 I=1,NUNIT
396   UNIT(I,12)=0.
C LOOP DAY BY DAY
      DO 310 NDY=1,365
      NQT=NDY/92.
      NQ=((NYR-1)*4) + NQT + 1
      IF(NDY.EQ.1.OR.NDY.EQ.93) GO TO 311
      IF(NDY.EQ.185.OR.NDY.EQ.277) GO TO 311
      GO TO 312
C PANELS EXPIRE
311   PSD=0.
      PRF=0.
      IDXQ=NQ-1
      IF(IDXQ.LT.2) GO TO 314
      PMADE=PNLSLD(IDXQ)+PNLRF(IDXQ)
      RUF=A2+(B2*NYR)
      IF(RUF.LT.1.) GO TO 314
      IF(RUF.LT.PMADE) GO TO 320
      PNLRF(IDXQ)=PMADE
      PNLSLD(IDXQ)=0.
      GO TO 314
320   PNLRF(IDXQ)=RUF
      PNLSLD(IDXQ)=PMADE-RUF
314   DO 315 NQQ=1,NQ
      ALFQ=((NQ-NQQ)-PNLQL)/SIGQ
      IDXQ=(ALFQ*4)+9
      IF(IDXQ.LT.1) IDXQ=1
      IF(IDXQ.GT.17) IDXQ=17
      PSD=PSD+PNLSLD(NQQ)*ERF(IDXQ)
      PRF=PRF+PNLRF(NQQ)*ERF(IDXQ)
315   CONTINUE
```

```
C SET TODAY'S PRODUCTION RATE
C CONSIDER IF STEP MUST RUN AND
C IF THERE IS ENOUGH INPUT FROM PREVIOUS STEP
312    DO 350 I=1,NUNIT
       UNIT(I,18)=0.
       TEST=UNIT(I,1)*UNIT(I,9)*(UNIT(I,6)+1.)
       K=I-1
       IF(K.LT.1) RATE=1.
       IF(K.LT.1) GO TO 360
       RATE=0.
       IF(UNIT(K,8).GE.TEST) RATE=1.
360    MWN=MOD(NDY,7)
       IF(MWN.LT.2.AND.MW5.EQ.1) RATE=0.
       FULL=UNIT(I,8)/UNIT(I,9)
       IF(FULL.GT.UNIT(I,17)) RATE=0.
       IF(UNIT(I,15).LT..9) GO TO 365
       UNIT(I,14)=1.
       UNIT(I,15)=UNIT(I,15)-1.
       UNIT(I,18)=2.
       GO TO 350
365     IF(UNIT(I,6).LT..9) GO TO 366
       IF(RATE.GT..9) GO TO 367
       GO TO 366
367    UNIT(I,14)=1.
       UNIT(I,15)=UNIT(I,6)-1.
       GO TO 350
366    UNIT(I,14)=RATE
       UNIT(I,15)=0.
350    CONTINUE
C SUM ENERGY NEED AND COMPARE TO STORAGE
373    DO 372 I=1,NUNIT
       K=NUNIT-I+1
       ENEED=0.
       DO 375 J=1,NUNIT
375    ENEED=ENEED+(UNIT(J,2)*UNIT(J,9)*UNIT(J,14)*(UNIT(J,15)+1.))
       IF(ENEED.LT.BAT) GO TO 380
       IF(UNIT(K,6).GT..9) GO TO 371
       UNIT(K,14)=0.
       GO TO 372
371    IF(UNIT(K,18).GT.1.) GO TO 372
       UNIT(K,14)=0.
       UNIT(I,15)=0.
372    CONTINUE
C CALCULATE IDLE EQUIPMENT
C IDLE CAPACITY DOES NOT INCLUDE WEEKENDS IF MW5=1
380    IF(MWN.LT.2.AND.MW5.EQ.1) GO TO 381
       DO 390 I=1,NUNIT
390    UNIT(I,12)=UNIT(I,12)+(1.-UNIT(I,14))
```

```
C RUN PRODUCTION ONE DAY
381   ENEED=0.
      DO 382 I=1,NUNIT
      K=I-1
      WIDGET=UNIT(I,9)*UNIT(I,14)
C ADD TO SHELF
      UNIT(I,8)=UNIT(I,8)+WIDGET
C REMOVE FROM PREVIOUS SHELF
      IF(K.LT.1) GO TO 383
      UNIT(K,8)=UNIT(K,8)-(UNIT(I,1)*WIDGET)
      IF(UNIT(K,8).GE.0.) GO TO 383
      JOKE=3
      RETURN
C ADD TO MATERIAL DEBT
383   UNIT(I,10)=UNIT(I,10)+(UNIT(I,3)*WIDGET)
C ADD TO DIRECT ENERGY NEEDED
      ENEED=ENEED+(UNIT(I,2)*WIDGET)
382   CONTINUE
      FLOW=(SUN(NDY)*PRF)-ENEED
      PSOLD=PSOLD+(PSD*SUN(NDY))
      IF(FLOW.GE.0.) BAT=BAT+(.7*FLOW)
      IF(FLOW.LT.0.) BAT=BAT+FLOW
      IF(BAT.GT.BATCAP) BAT=BATCAP
      IF(BAT.GT.0.) GO TO 385
      JOKE=4
      RETURN
C DISTRIBUTE PANELS MADE
385   PNLSLD(NQ)=PNLSLD(NQ)+(UNIT(NUNIT,8)*(1.-PCTRF))
      PNLRF(NQ)=PNLRF(NQ)+(UNIT(NUNIT,8)*PCTRF)
      UNIT(NUNIT,8)=0.
      IF(NYR.NE.38.OR.NDY.LT.351.OR.NDY.GT.359) GO TO 310
      WRITE(6,971) NYR,NDY,SUN(NDY),BAT
971   FORMAT(' YR',I2,' DAY',I3,' SUN ',F3.1,
     1 ' BAT LEVEL ',E10.4/' STEP SHELF      TODAY RATE')
      DO 972 I=1,NUNIT
972   WRITE(6,973) I,UNIT(I,8),UNIT(I,14)
973   FORMAT(1X,I2,3X,E10.4,1X,F5.3)
310   CONTINUE
      DO 395 I=1,NUNIT
      IF(MW5.EQ.1) UNIT(I,12)=UNIT(I,12)/260.
      IF(MW5.EQ.0) UNIT(I,12)=UNIT(I,12)/365.
395   CONTINUE
      RETURN
      END
//GO.SYSIN DD *
```

Exhibit E - Battery Storage Energy Consideration

The Solar Breeder does have in its programming a consideration of the energy costs involved with energy storage. In that light, the determination of energy cost is as follows:

Active materials cost:[1]

Lead-acid	\$8.50/kW-hr.
Iron-Redox	\$1.00/kW-hr.
Sodium-Sulfur*	\$0.49/kW-hr.

Total costs for a large scale system are estimated at:

Lead-acid	\$50/kW-hr.
Iron-Redox	\$18/kW-hr.

On this basis energy debt becomes:

Lead-acid	333kW-hr/kW-hr of storage
Iron-Redox	120kW-hr/kW-hr of storage

As a reasonable estimate for energy costs of storage the program employs a 200 kW-hr/kW-hr of storage and a five year life of the storage system.

* Sodium-Sulfur does have a low-cost but appears to be impractical due to a high operating temperature of 300-350°C.