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SOLAR BREEDER
ENERGY PAYBACK TIME FOR SILICON PHOTOVOLTAIC SYSTEMS

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JOSEPH LINDMAYER, ET AL

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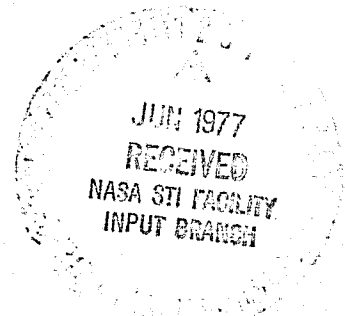
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ENERGY PAYBACK TIME FOR SILICON PHOTOVOLTAIC SYSTEMS

APRIL 1977

FIRST QUARTERLY REPORT
DECEMBER 20, 1976 TO MARCH 20, 1977

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1. SUMMARY

The primary objective of this program of research is the characterization of the energy requirements and energy production potentials of the "Solar Breeder" concept. This quarterly report documents the results of a careful and extensive study undertaken at the SOLAREX CORPORATION to assess the energy expenditures of the prevailing manufacturing technology of terrestrial photovoltaic cells and panels. The five major production processes in the current technology are: silicon reduction, silicon refinement, crystal growth, cell processing and panel building.

One of the most important results of this study is the fact that the energy payback time for a typical solar panel produced by the prevailing technology is only 6.4 years. Furthermore, this value drops to 3.8 years under more favorable conditions. Since energy payback times as high as 40 years have been estimated for space cells, this relatively short payback time reflects the rapid progress made in terrestrial photovoltaic manufacturing. Moreover, since the major energy use reductions in terrestrial manufacturing have occurred in cell processing, this payback time directly illustrates the areas where major future energy reductions can be made -- silicon refinement, crystal growth, and panel building.

The comprehensive research approach used in this study includes the examination in detail of the major production process and sequences of the current technology and the assessment of each of the steps of energy expenditures. Energy expenditures include direct energy, indirect energy and energy in the form of equipment and overhead expenses. Payback times were developed using a conventional solar cell as a "test" vehicle which allows for the comparison of its energy generating capability with the energies expended during the production process. Finally, the Solar Breeder is described from a systems viewpoint and the significance of payback time and panel lifetime as important systems parameters are pointed out.

2. Introduction

A comprehensive evaluation of any energy source requires an assessment of that source's net energy contribution to society. In the past, photovoltaics, an important alternate energy source, has not been properly appraised for its potential in terms of net energy. ERDA's National Photovoltaic Development Program, which calls for photovoltaic panels with a twenty-year lifetime, will also require the use of technologies that allow for energy recovery (or payback time) in a fraction of those twenty years. Early assessments of photovoltaic energy payback time were based on examinations of space solar cell production; a business that is very periodic and extremely inefficient in terms of net energy. Analysis has shown that the payback time for space solar cells manufactured under space-demand controlled situations may be in the neighborhood of forty years.¹ With the advent of terrestrial production, and the introduction of new technologies and business practices in 1973, the energy payback time began to decline sharply. The amount of change, however, was not quantized to determine what the actual situation was. This is the first quarterly report of a study directed to the examination of the energy payback time as it evolves in terrestrial manufacturing.

This first report documents that the energy payback time of terrestrial photovoltaic manufacturing has declined substantially below that of space production. The conclusion is that in the early part of 1977 the energy payback time for terrestrial production is less than 6-1/2 years. It is expected that the energy payback time will continue to drop as new technologies and improved production techniques are introduced. It is actually expected that the payback time will ultimately drop below one year. Figure 1 provides a general overview of the energy payback time as a function of real time projecting to less than one year recovery by the 1980s.

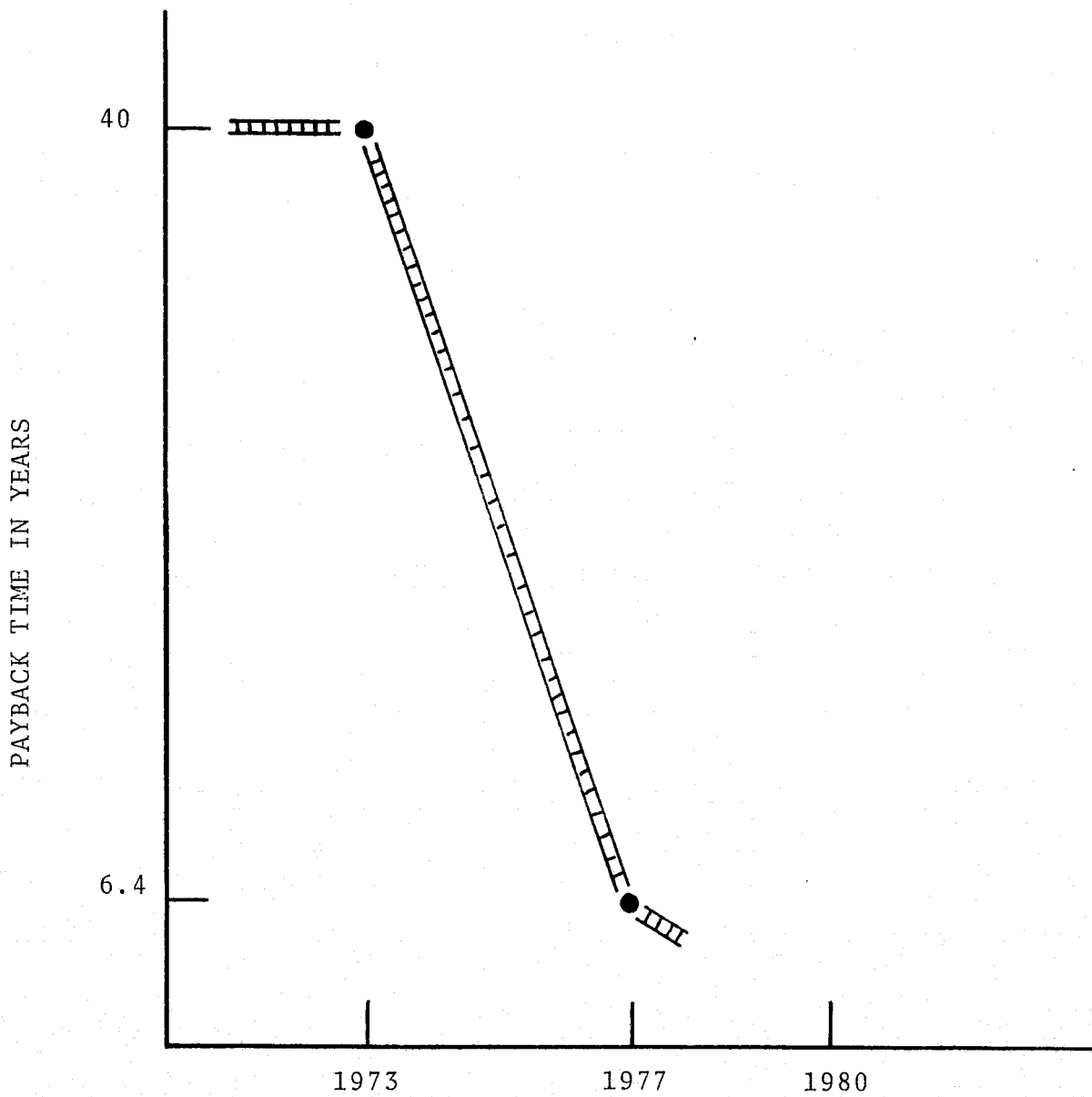


FIG. I. PAYBACK TIMES IN PANEL PRODUCTION PROCESS

The potentially low energy payback time of photovoltaic systems coupled with the expected long-life of solar panels allow for the development of nearly energy-independent photovoltaic manufacturing plants. These considerations lead to the Solar Breeder principle which was first proposed by J. Lindmayer in testimony before the Senate Committee on Finance in January 1974.² It was pointed out that a photovoltaic panel manufacturing plant can be made energy independent by using energy derived from its own roof using its own panels. Such a plant becomes not only energy self-sufficient but a major supplier of new energy, hence the name Solar Breeder.

The second part of this report deals with the basic principles of a Solar Breeder system in which context the energy payback time can be re-named as "breeding time." This report will establish certain mathematical relationships for the Solar Breeder clearly indicating that a vast amount of net energy is available from such a plant for the indefinite future. It should be pointed out that if solar electric plants would be built based on the Solar Breeder principle, their operation as a net energy source would be automatically assured. That is to say, a Solar Breeder facility would not be able to function if it is unable to produce net energy thereby introducing an automatic safeguard to assure that it is serving the needs of society.

This first report assesses the net energy situation for the early part of 1977. Later reports will appraise the modifications in general that can be made to reduce the energy payback time further. Still later reports will deal with the energy situation related to new photovoltaic technologies as they will be expected to come on line at later times. Later reports are also expected to refine the operational mode of the Solar Breeder.

This first report documents not only that there have been major improvements in the energy payback time, but describes specifically where the improvements have been made and points out weaknesses that need further attention. This view of the photovoltaic production from an energy domain also provides a new perspective for certain policy decisions in photovoltaic development.

3. Definitions for Energy and Payback Time

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

- a) Direct Energy.- This quantity is defined as the amount of energy expended during the actual production of the cells and panels; typically involving electrical energy.
- b) Indirect Energy.- This component contains 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 process 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 itself. Overhead energy is defined as the energy expended in lighting, heating and airconditioning of the manufacturing area.

The study will show that the largest energy component arises from direct energy. However, the indirect energy is also very significant. The equipment & overhead energy is usually the smallest. The determination of indirect and equipment energies is not always a simple matter because detailed analyses could ultimately lead to the question of how much energy was used to create the world. In order to cut off such side roads we have frequently used the price of the material for guidance of its energy content.

The prevailing sequence used in the present-day manufacture is depicted in Figure II, introducing five basic operations. The prevailing processes within those operations are relatively well established. Those are:

Reduction. - In the conventional process quartzite pebbles are being reduced to metallurgical grade (MG) silicon by means of carbon-containing agents all 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. - This involves the processing of SeG silicon into single crystal ingots (usually CZ) and subsequent slicing of the ingots into wafers.

Cell Processing. - This consists of the processing of blank silicon wafers into a finished solar cell.

Panel Building. - A 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 basic payback time has been calculated a section of this report will elaborate on the potential effects of

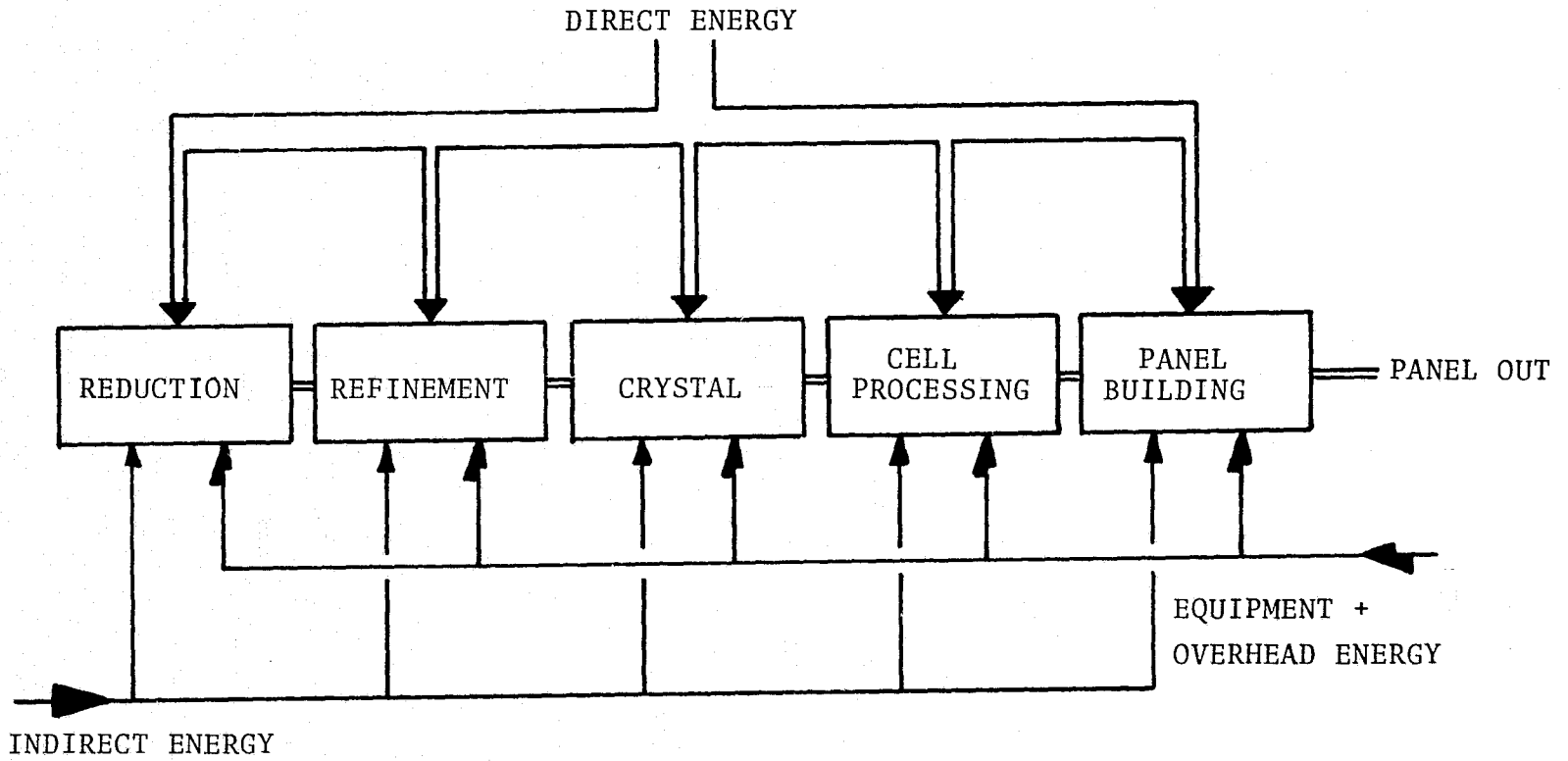


FIG. II. PANEL PRODUCTION SEQUENCE AND ENERGIES

increased efficiency, tracking, concentration, packaging density, and geographical location. From this point we will proceed to estimate the energy payback times of the five basic operations and three energy components.

4. Energy Assessment of Prevailing Manufacturing

4.1 Test vehicle

This section will assess the five basic operations for their energy expenditure in terms of direct, indirect, and equipment plus overhead energies. As a test vehicle we will frequently use a 4" diameter solar cell 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	10.16 cm (4")
Cell thickness	0.25 mm (0.010")
Cell area	81.07 cm ²
Cell volume	2.03 cm ³
Silicon mass	4.72 g @ density of 2.33g/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 (31,630h)	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 = 6,678 kWh
 at 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 we recognize that such yields may vary depending on individual company practices, we find it convenient and reasonable to operate with an overall 50% yield for silicon. (Deviations from this 50% yield can always be accommodated by a simple scaling factor of the payback times as will be apparent later). Accordingly, at 50% yield the energy delivered for one year is:

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

4.2 Reduction of Silicon

Although silicon is very abundant on the earth's crust, it cannot be found in elemental form. Silicon manufacturing processes, therefore, must resort to compounds such as the oxide 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 reduction of the oxide is carried out in huge electrode arc furnaces by means of carbon containing agents at high temperatures. Metered amounts of quartz pebbles, coal, coke and wood

chips are loaded into the furnace crucible which may be as large as 8 meter in diameter and 3.5 meter high. Heat is supplied to the mix by application of electric power to submerged graphite electrodes. As the temperature increases silica passes through several modifications until it finally melts at temperatures in excess of 1700° C and reacts with the carbon containing additives. In the reduction process the mix may reach temperatures up to 3000° C, forming elemental silicon which accumulates at the bottom of the furnace crucible. The oxygen from the oxide combines with the carbon to form carbon monoxide gas. The molten silicon can be withdrawn from the bottom of the furnace through a taphole either continuously or in regular intervals. It may be blown with oxygen or an oxygen chlorine mixture to reduce the content of metals such as aluminum, calcium or magnesium. Metallurgical grade silicon as it is called after the reduction process attains thus a purity as high as 99.5%.

Most of this metallurgical grade silicon is used in the steel and aluminum industry and in the chemical industry. Approximately 1% of metallurgical grade silicon is refined in a separate operation and channeled into the semiconductor and solar cell industry.

The reduction of silicon as described has been practiced for many years by the heavy industry and is therefore a highly developed process which is largely independent of the needs and demands of the semiconductor industry. Because silicon is produced in a quantity of approximately 12 tons per day in a typical plant the necessity to have inexpensive energy available for that process had been recognized by the industry. Traditionally these plants have been strategically located in the vicinity of power stations so that the costs for transmitting energy over longer distances could be largely eliminated.

The amount of energy required to make a kg of metallurgical grade silicon is relatively small. Direct energy is expended in the form of electrical power to the graphite electrodes in the amount of about 15 kWh per kg of MG silicon. A more detailed energy examination is to be found in Exhibit B. The indirect energy comprises the mining and transportation efforts expended in the procurement of the raw materials and in the caloric content of the carbon containing agents. The indirect energy value is about 31 kWh per kg of MG silicon.

Data for invested equipment and overhead energies were estimated from plant costs. As Exhibit B indicates the equipment plus overhead energy is quite low, in the order of 1 kWh per kg of silicon. This results in a negligible payback time, a very small fraction of a year.

Based on calculations to be found in Exhibit B, we can summarize the energy cost of the reduction process 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 I. 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 quite low. Since equipment plus overhead energy is negligible, a total payback time of less than 0.3 years for a present-day cell is most agreeable. Thus, 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 the 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 by various laboratories throughout the world. However, it appears that only the chemical vapor deposition technology whereby a gaseous compound of silicon is utilized found its way into a larger scale production operation. Trichlorosilane is the gas that is used world-wide today. It is formed by the reaction of hydrogen chloride and MG silicon at a temperature of approximately 300° C. The low boiling point of trichlorosilane at 31.8° C allows a very effective purification of the gas by means of fractionated distillation. Practically every impurity displays a relatively low volatility so that even in large scale production processes the final content of electrically active impurities is typically less than one part per billion atoms.

The preparation of semiconductor grade silicon is carried out now for over two decades by the reduction of ultrapure trichlorosilane with hydrogen on a resistance heated silicon substrate at temperatures exceeding 1000° C. A silicon rod of typically 3/4" to 1" thickness is heated directly by current to temperatures of about 1400° C in a gaseous atmosphere

containing a mixture of trichlorosilane and hydrogen. Trichlorosilane reduces on the hot rod to pure silicon and hydrochloric acid is formed with the hydrogen.

The development of the silicon refinement technology was influenced by the demands of the semiconductor device industry. This 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. Questions with regard to cost played a lesser role and energy was not even considered. In this economical environment 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.

It is now recognized that 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. In realization of this fact the solar industry tries to circumvent the cost and energy expended in the silicon refinement process by orienting its research efforts towards the development of an inexpensive solar cell made from less pure material.

At the present time, however, the photovoltaic industry still uses the same silicon as the integrated circuit manu-

facturer. As might be expected, high energy values and payback times result from this practice. Details may be found in Exhibit C. The direct energy is quoted to be 440 kWh per kg of SeG silicon which alone results in a payback time of about 2.6 years. Equipment plus overhead energies may be estimated from typical capital investments for refinement plants. The cost burden per kg of SeG silicon is approximately \$11.50 which points to an equipment plus overhead energy of 77 kWh and a payback time of 0.46 years. The indirect energy is mainly contained in chemicals used during refinement. Because the same chemical reaction is passed through in the forward and reverse direction, namely the formation of pure trichlorosilane from MG silicon and the subsequent reduction of the silane back to silicon, little of the material is expended in the overall process which cannot be recovered. It is estimated that the indirect energy is of the order of 5% of the direct energy or approximately 22 kWh per kg SeG silicon resulting in a payback time of 0.13 years. We have listed the various energies of the refinement process in Table 2

Table 2. 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	539	3.22

Again, we have to emphasize that this energy component is quite large and will require continuous attention.

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. This 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 the device technology. It is therefore not surprising that the device industry requested single-crystalline wafers already at the time of its infancy and increased its demand for larger wafers of highest quality with respect to crystallinity and low dislocation density as transistors and microcircuits were developed. Because many chips could be manufactured from a single wafer cost was of secondary nature and energy considerations nonexistent. Under these circumstances crystal growth industries encountered a highly beneficial environment for research on growth methods and subsequent economical expansion to today's multimillion dollar business.

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.

The Czochralski pulling process starts with a small silicon seed crystal of predetermined orientation which is lowered into a molten silicon-containing crucible until it touches the melt

surface. As the seed crystal is subsequently pulled from the liquid surface under rotational motion silicon from the melt crystallizes above the solid-liquid interface maintaining the crystallographic orientation of the seed. After approximately 14 hours of operation a single crystal of up to 4" diameter and weighing 15-20 kg is obtained. The crystal is subsequently sliced into thin wafers which are then used by the semiconductor industry as the starting material for its devices.

The photovoltaic industry is still using the same silicon wafers in large amounts for the manufacture of individual cells. However, present wafer costs impede the development of the inexpensive cell. While solar cells can be made on less orderly and pure silicon, the present solar industry can only be supplied from the established CZ technology. In fact, no other form of silicon is available in quantity in early 1977.

The growth and slicing procedures are now so well established that their energy requirements can be easily evaluated. Direct energy is consumed in the pulling process and in the sawing operation at a combined rate of 42 kWh per kg of crystal resulting in a payback time of 0.25 years. Indirect energy is expended in the form of chemicals, replacement parts, crucibles and blades for sawing at a rate of 102 kWh leading to a payback time of 0.61 years. Equipment plus overhead energy is primarily contained in the cost of Czochralski crystal pulling equipment at approximately 15 kWh resulting in a payback time of less than 0.1 years. We summarize these data in Table 3 and refer to Exhibit D for details of the energy analysis.

Table 3. 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	159	0.95

We should emphasize again, that CZ crystal and sawing are the prevailing technologies in early 1977. This does not imply that significant changes will not occur in this area.

4.5 Cell Processing

The cell production process starting with the blank pre-doped silicon wafer and ending with a finished cell consists commonly 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 diffusion processes.
- 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

We have examined each manufacturing step with respect to its direct and indirect energy expenditure and listed what we believe are typical industrial values in Exhibit E . We accounted for a direct energy value of 0.42 kWh per standard cell resulting in 0.26 years of payback time and an indirect energy value of 0.70 kWh/"test" cell pointing towards a payback time of 0.44 years. Equipment plus overhead energies were derived from an estimate of the replacement cost of actual production equipment and from energy expended for heating, cooling and lighting of the production area. The combined energy value is approximately 0.08 kWh leading to a payback time of 0.05 years. The data are summarized in Table

Table 4. 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	0.08	0.05
Total	1.25	0.75

The important conclusion that results from this analysis is the fact that the cell making process is not energy expensive. The criticism that a predominant amount of energy is tied up in the cell making and which is still prevailing originated at

times when cells were made solely for space applications and were indeed very energy intensive. However, major technological advances have been made in the last few years which changed the situation dramatically. For example, the diffusion process was always believed to require unusual amounts of electrical energy. As we show in Exhibit E the whole diffusion process requires only about 0.16 kWh per cell burdening the payback time only by 0.1 years. In addition, we believe that the full potential of the diffusion process has not yet been completely utilized in a production environment. The same is true for other processes in the cell manufacture. Part of the data listed in Exhibit E is the result of our directly monitoring energy inputs to the Solarex production process and therefore represent factual energy figures. It is expected that the energy balance of the cell making process will further improve, however, at the present time a large part of the blame for high energy expenditures of the overall panel production process rests mostly with silicon refinement and crystal growth.

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.

4.6 Panel Building

The individual cell is well equipped to fulfill its energy delivering task but major power can only be derived from the formation 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 in a geometric fashion 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 impact.

The direct energy expended in the manufacture of a typical panel is approximately .09 kWh per standard cell equivalent to our test vehicle yielding a payback time of less than 0.1 years as shown in Exhibit F. The indirect energy expended in the form of panel hardware and encapsulant amounts to approximately 1.67 kWh per cell which may be converted into a payback time of 1.0 years. Equipment plus overhead energy are typically 0.17 kWh per cell pointing towards a payback time of 0.11 years. As can be seen from these data which are listed in Table 5.

Table 5. Energy in Panel Building

	kWh/"test cell"	Payback Times 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	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 Figure III in the form of a vertical bar pattern and in an accumulating fashion along the panel building train.

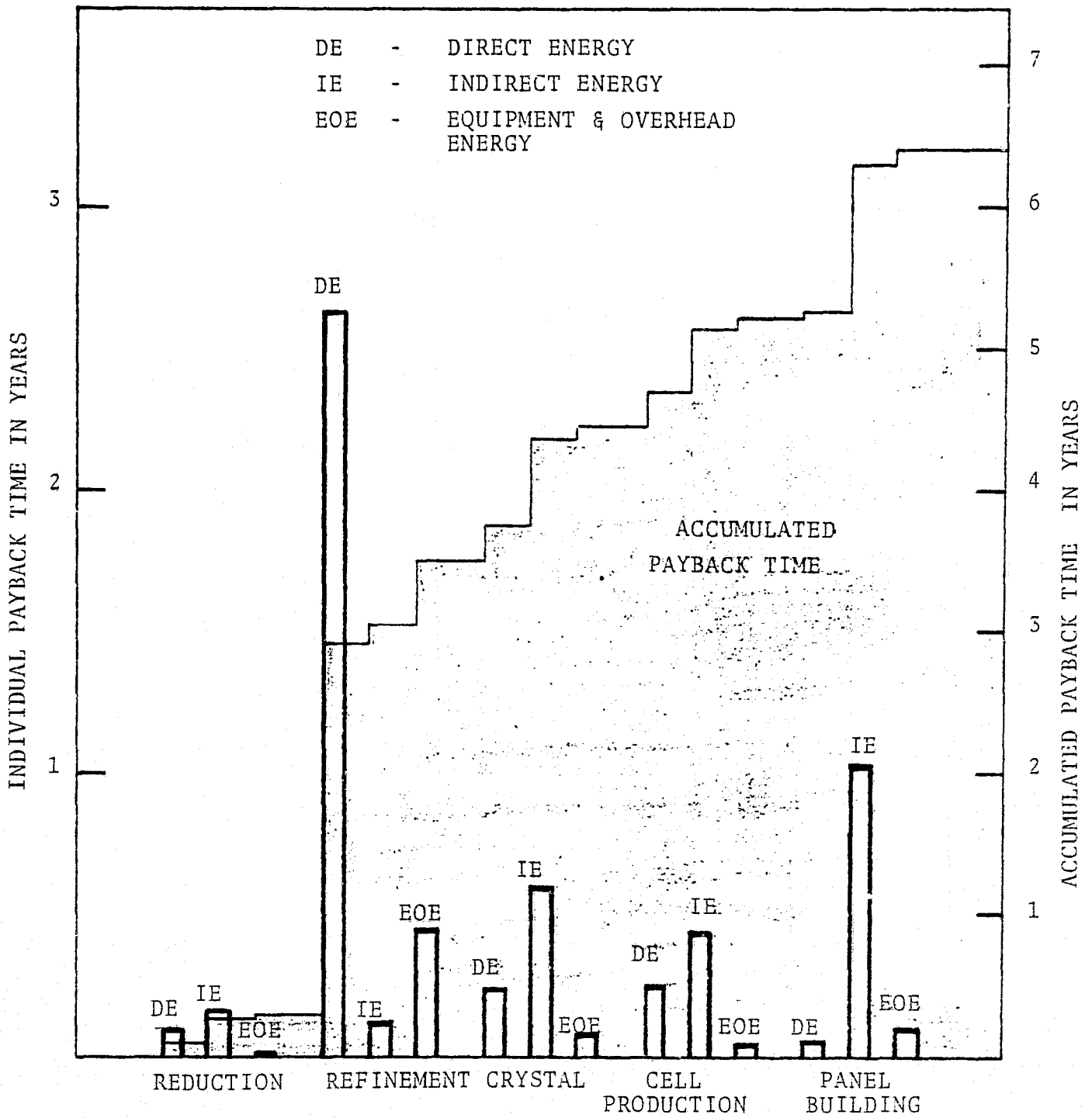


FIG. III. PAYBACK TIME VS. TIME

5. 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 G 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 may rise as high as 15% under certain manufacturing conditions. If only these two new data 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 or tracking would also reduce the energy payback time.

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

6. Comments

Appraisal of the energy payback time for the early part of 1977 reveals some interesting facts. Most of all, it clearly demonstrates that those areas of production technology that were heavily cultivated by the terrestrial photovoltaics manufacturers are the areas where tremendous reductions in energy consumption have occurred. This is surely the case for solar cell processing; the terrestrial production that began in 1973 was extremely sensitive to the energy question and abruptly reduced its energy consumption when compared to the frequently quoted 20-30 year energy recovery in space cell processing. At the same time, however, not much energy reduction occurred in the basic silicon production as it remained essentially the same as for the semiconductor industry. The solar cell manufacturers have not practiced the production of inexpensive silicon for their own use; accordingly, they inherited a high energy process from the semiconductor industry. Therefore, we believe that the key to future reductions in energy consumption (and cost reduction) is the extension of their sensitivity for low energy/low cost processing techniques to all aspects of production technology.

The basic processes today can be broken up into three major categories: Production of silicon sheet, cell production and encapsulation. In an overview they rank as follows:

- a) Sheet Production. The whole technology as practiced today is inherited from the semiconductor industry. The inexpensive and low energy demanding reduction into MG silicon is completely distorted by the high energy cost of the refinement. The trichlorosilane process is basically unacceptable not only for its high price, but also for its high energy content. Even if every gram of silicon

can be utilized, it requires an energy payback time of 1.6 years. Clearly, new approaches in refinement must be introduced and practiced in terrestrial production,

- b) Cell Production. With the introduction of terrestrial production, major changes occurred in this area. The payback time has been reduced dramatically when compared to the previous space cell production. We can see an order of magnitude reduction (at least at this company) in this area; so much so that the indirect material energy now exceeds the direct energy used in cell production. Cell production is clearly in good shape as far as energy is concerned and further improvements will occur.

- c) Panel Building. Terrestrial panel building is a new activity and is distinctly separate from space panel building. It is now becoming clear that certain terrestrial environments are more hostile than the space environment and, therefore, this area will experience continued changes. The present study indicates that the packaging materials contribute a significant amount of indirect energy, even though the direct energy is small. The energy requirement of the packaging materials is a new parameter to consider in the development of high reliability panels. It should be noted that the present circular cell requires a disproportionate amount of packaging material and energy; therefore, close packing is a basic requirement also. from the energy point of view.

It is expected that as time goes by the technology will change, resulting in a continuously decreasing payback time. We propose that new technologies must be appraised for their energy content, particularly in the silicon refinement and packaging areas.

7. SOLAR BREEDER

The Solar Breeder is an energy self-sufficient plant producing new energy in the form of solar electric panels that are available for external use. This section discusses some general relationships for such a Solar Breeder. Clearly, the critical parameters that play important roles in the Solar Breeder operation are the lifetime of the panel, τ_L , and the energy pay-back time which in the present context can be called the τ_B or the breeding time.

For convenience, the basic process is represented by five operations as shown in Figure IV. For simplicity, the energy is subdivided into two main parts; the direct and indirect components. While in the previous text a term "overhead energy" is also used, this component is relatively small and can be included into the indirect energy component. The breeder plant is operated as a vertically integrated unit where all operations are based on direct electrical energy. It will be clear that the lifetime of the panels, τ_L , must exceed the breeding time, τ_B , in order to produce net energy to society.

When the operation of the breeder begins it must borrow energy from conventional sources. The power flow can then be formulated as

$$P_{\text{external}} = P_{\text{utility}} + \frac{\Delta E_{\text{indirect}}}{\Delta t} \quad (1)$$

where P_{utility} represents the direct use of energy while Δt has the dimension of power representing all indirect energies. Based on a constant production rate the Solar Breeder will reduce its external power needs linearly in time as its own power supply increases. Accordingly, we may write (for a closed feedback loop in Figure IV)

$$P_{\text{external}} = P_{\text{utility}} + \frac{\Delta E_{\text{indirect}}}{\Delta t} - Rt \quad (2)$$

where R is the rate of production in units of power per time.

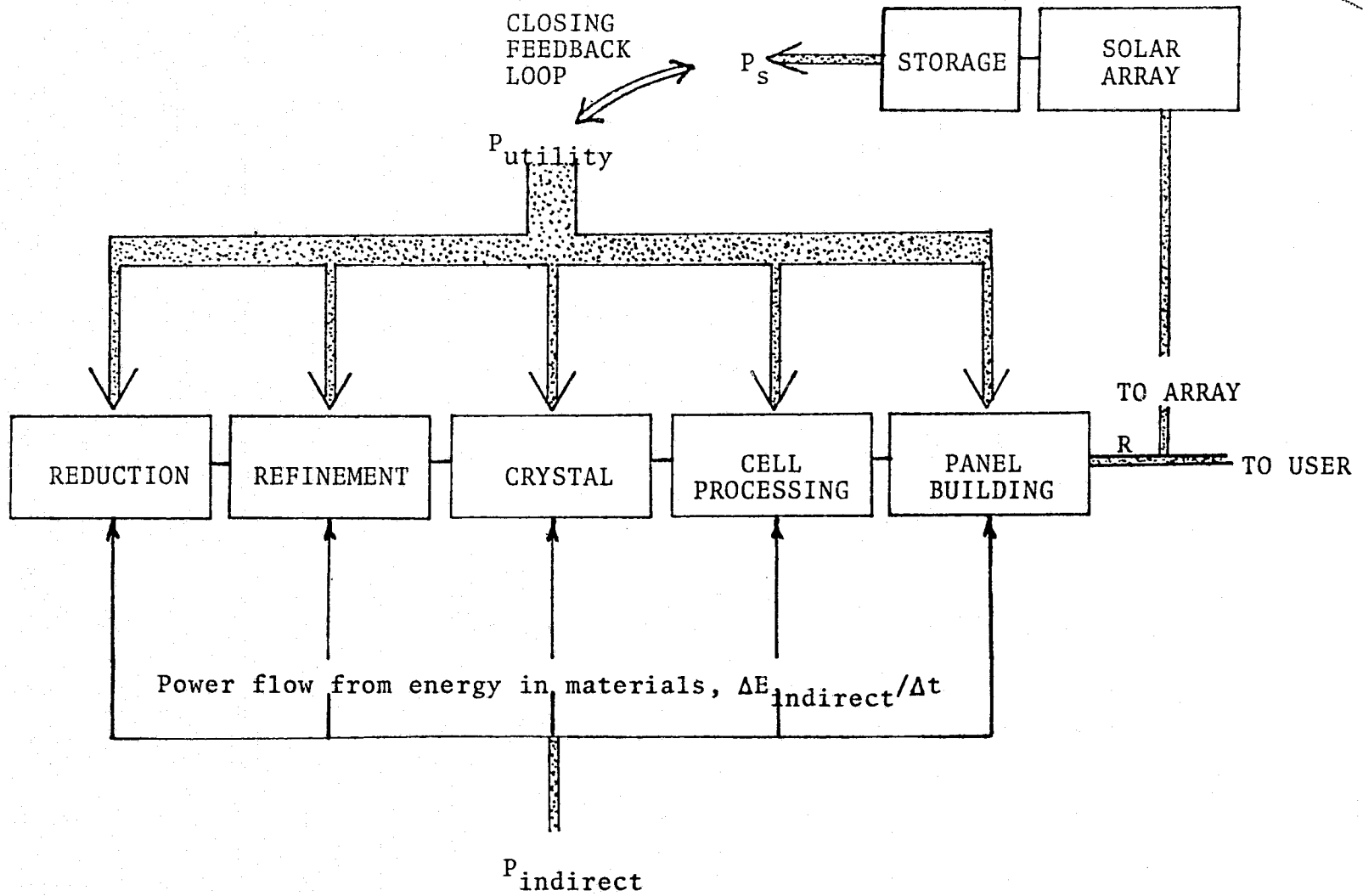


Fig.IV. Schematic Diagram for Solar Breeder.

Self-sufficiency will be reached when P_{external} reaches zero. At that time $t = \tau_B$ where τ_B is the breeding time. To a first approximation, it may be said that the utility and indirect power components are proportional to the rate of production R . If all quantities are redefined as power/unit production rate and denoted by T (having time units) we find from (2)

$$T_e = T_u + T_i - t \quad (3)$$

and when power independence is achieved T_e will be zero and therefore

$$\tau_B = T_u + T_i \quad (4)$$

In other words, the breeding time is determined by

$$T_u = \frac{P_{\text{utility}}}{R} = \frac{P_{\text{utility}} \Delta t}{\Delta W \text{ (solar)}} = \frac{\text{electrical energy used}}{\text{solar watts produced}} \quad (5)$$

plus

$$T_i = \frac{\Delta E_{\text{indirect}}}{\Delta W \text{ (solar)}} = \frac{\text{indirect energy}}{\text{solar watts produced}} \quad (6)$$

The relationships in (5) and (6) allow us to write the breeding time as

$$\tau_B = \frac{\text{direct energy} + \text{indirect energy}}{\text{solar watts produced}} \quad (7)$$

At the average U.S. location, the peak sun power is available for 4.33 hours/day. In 7 days, 30.31 hours are available; assuming an 80% interface efficiency, we can calculate with 24.2 sun hours/week. A 40 hour work-week yields 0.6 W (peak) solar power, which factor allows us to express the breeding time in W (peak) units:

$$\tau_B = 1.65 \frac{\text{direct energy} + \text{indirect energy}}{W \text{ (peak) produced}} \quad (8)$$

It is apparent that in order to have a reasonably short breeding time, such as a few years, not more than a few kWh energy can be invested in producing one W(peak) solar power.

The breeding time is the length of time required to reach self-sufficiency when the photovoltaic production plant is put into the breeder or "closed feedback loop" mode of operation. The meaning of breeding time remains the same even if the manufacturing plant is allowed to operate in the "open loop" mode of operation; i.e., when it does not retain any of its produced panels, but delivers them to users outside of the plant. Accordingly, the breeding time is a basic operational parameter of any photovoltaic production plant.

The importance of the breeding time assumes even more serious dimensions when the question of net energy is raised. It is obvious that a new energy source should be developed only if it has the potential of becoming a net energy source. Since solar energy is continuously derived from previously produced panels, their lifetime is of great importance. Denoting the lifetime of a panel by τ_L , let us examine Figure V. This plot shows power as a function of time. On the time scale, two important points are denoted, τ_B for the breeding time and, τ_L , for the panel lifetime. For a constant production rate the power needed by the facility is constant, while the solar power increases linearly as panels are produced at a constant rate, R . The following calculations can be derived from Figure V if we write the solar power, P_S , supplied by the panels as:

$$P_S = Rt \quad (9)$$

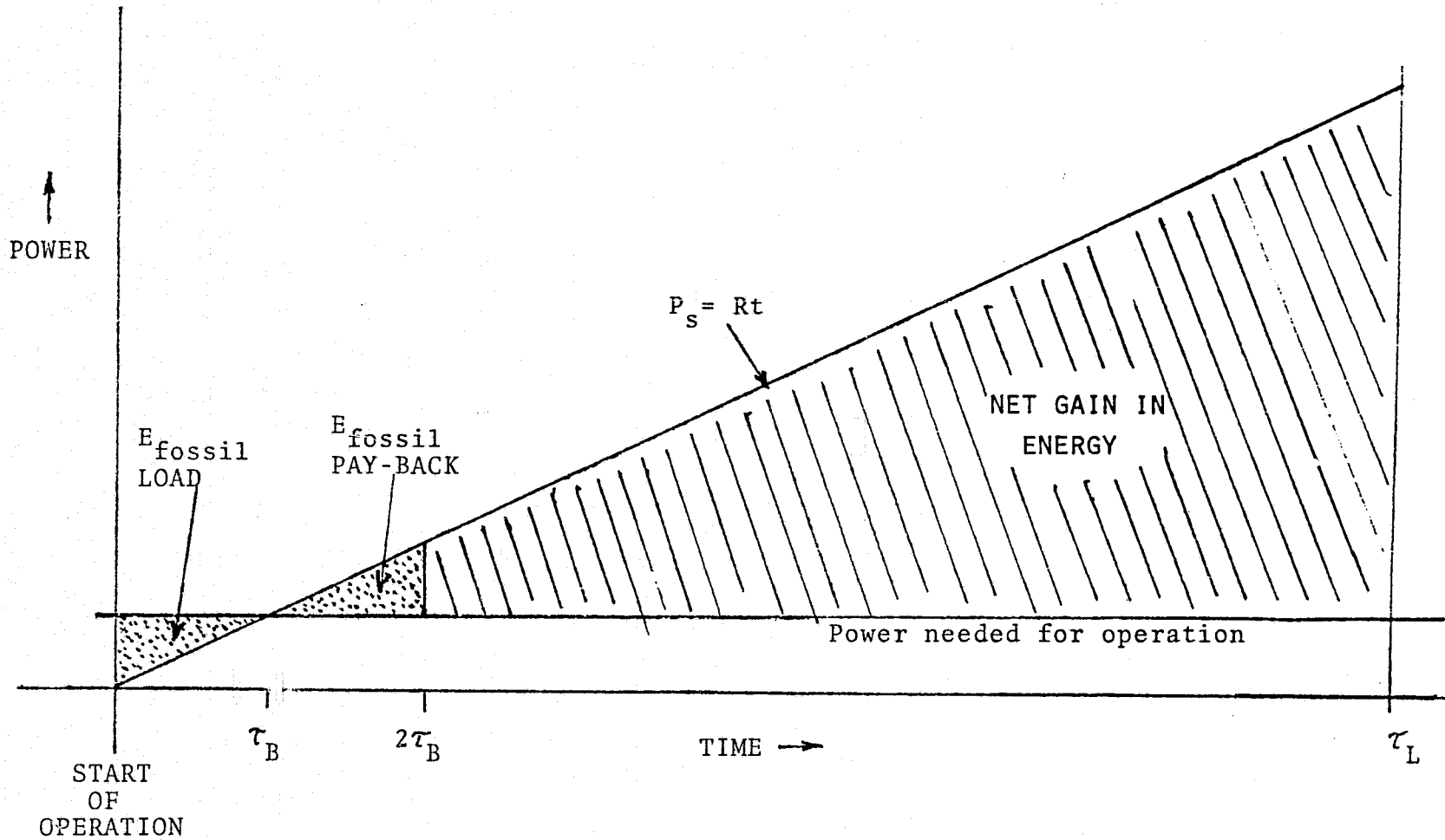


Fig. V. Power and Energy for Calculating Energy Gain.

The net energy supplied by the facility is represented by the area shown in Figure V, which excludes the fossil fuel investment and all energies required to operate the facility. The net energy in the first cycle of operation is:

$$E_{\text{net}} = \int_{\tau_B}^{\tau_L} R t \, dt - E_{\text{fossil}} = \frac{R}{2} (\tau_L^2 - \tau_B^2) - E_{\text{fossil}} \quad (10)$$

The invested fossil energy is readily available from Figure V also

$$E_{\text{fossil}} = \int_0^{\tau_B} R t \, dt = \frac{R \tau_B^2}{2} \quad (11)$$

The net energy gain in the first breeder cycle defined as τ_L is

$$\frac{E_{\text{net}}}{E_{\text{fossil}}} = \frac{\tau_L^2 - 2\tau_B^2}{\tau_B^2} \xrightarrow{\text{short } \tau_B} \left(\frac{\tau_L}{\tau_B} \right)^2 \quad (12)$$

In order to be in the net energy mode it is required that

$$\tau_L > \sqrt{2} \tau_B \quad (13)$$

Equation 12 shows a delightful conclusion: The Solar Breeder in its first cycle of operation will reproduce the invested energy many times. For example, if the panel life is 20 years and the breeding time is one year, the solar breeder

will produce in its first cycle 400 times the energy invested! In its second cycle of operation, it must reproduce its own panels, but in the above example, it will take only a small fraction of its energy output to do this. In other words, the net energy gain is already very large in the first cycle of operation and even beyond that the energy produced grows quadratically, ad infinitum. Clearly, the solar breeder is a tremendous source of new energy.

The solar breeder approach is a method in a new type of system analysis in evaluating photovoltaic production plants. The breeder employs a feedback principle to test the inherent characteristics of the facility. In the open loop situation, it simply remains a production facility to the outside world, but its inherent characteristics remain unchanged.

Let us also examine briefly the intermediate situation, namely when the loop is only partially closed. If the solar breeder is allowed to be the only panel user, it will go into the self-supporting state in τ_B time and then abruptly appears on the market with its excess capacity. This is shown in Figure VI. If, on the other hand, the facility is allowed to sell a portion of its products within τ_B , self-sufficiency is delayed beyond τ_B , but its products can appear on the market more gradually. This is also shown in Figure VI. While none of the basic system parameters change, the solar breeder operational mode offers a new degree of freedom in planning market entry. Its mode of operation actually allows proportioning external and internal use of panels at will. The only restriction is that after self-sufficiency all but a small fraction of its produced panels must go to external users.

↑
PANEL
DELIVERY
RATE TO
MARKET

GRADUAL & ABRUPT MARKET ENTRY

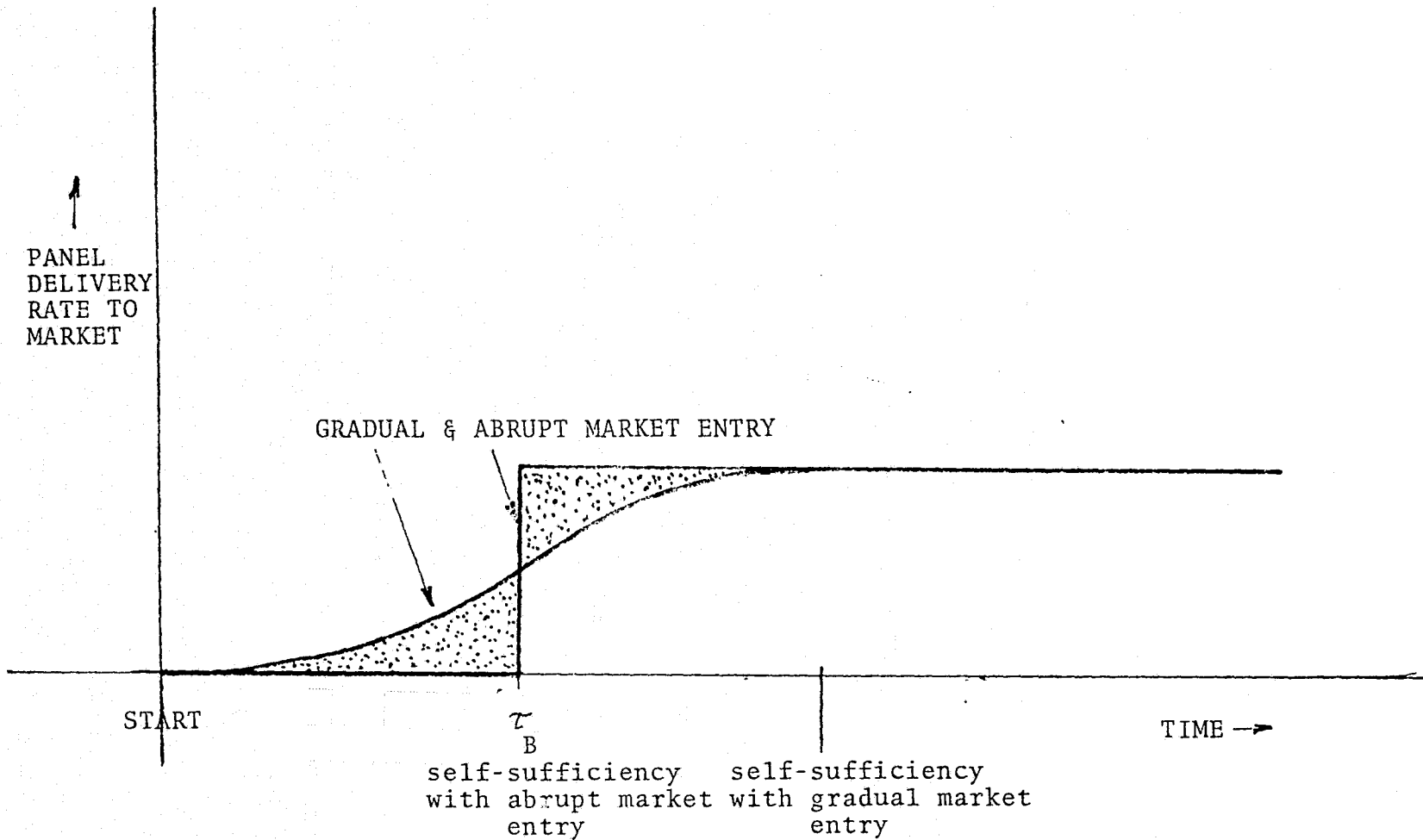


Fig.V1. Abrupt and Gradual Market Entry of Solar Breeder

There are clearly further sophistications and generalities in the solar breeder. We will pursue this new type of system analysis and expand on its scope and dimensions. It may well be that large scale expansion of manufacturing should indeed be based on the solar breeder approach which will assure delivery of net energy to society.

8.1 EXHIBIT A - Estimation of Indirect Energy from Product Price

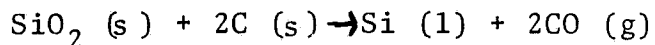
The determination of indirect and equipment energies is not always a simple matter because detailed analyses lead in too many directions in the search for expended energy. In order to cut off such side roads we have frequently used the purchase price of a product for guidance of its energy content. We base the validity of this procedure on the results of a research document³⁾ 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.

Equipped with this assumption we could determine 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 study⁴⁾ 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 more 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. We have adopted this procedure frequently except in cases where we were aware that 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 we derived energy from approximately one-third of the purchase price.

8.2 EXHIBIT B - Reduction to 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



Metered amounts of quartz pebbles, coal, coke and wood chips are loaded into the furnace crucible which may be as large as 8 meter in diameter and 3.5 meter high. Heat is supplied to the mix by application of electric power to submerged graphite electrodes. As the temperature increases silica passes through several modifications until it finally 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, as it is called after the reduction process, attains thus a purity as high as 99.5%.

The yearly production of MG silicon in the United States has now exceeded 140,000 short tons.⁵⁾ 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 consumption⁶⁾ 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:

	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
		<hr/>
		19281

The caloric energy content of the carbon-containing raw materials has been calculated using the following conversion units⁷⁾:

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 Laboratories⁸⁾ these energies have been determined as follows:

	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

	kWh/kg MG-Si
quartzite pebbles	.32
coke	8.51
coal	.11
wood chips	.08
total	<u>9.02</u>

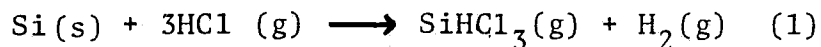
The combined indirect energy content in the raw materials for the smelting process is thus the sum of 22.4 kWh and 9.0 kWh, i.e., 31.4 kWh which results in a payback time of 0.19 years.

Data for invested equipment and overhead energy cannot be readily found in the literature. However, an announcement of

the National Metallurgical Corporation⁵⁾ 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 us to estimate these energies. If we assume a return of their investment in 10 years during which time approximately 85,000 additional tons of MG-silicon are produced, the cost per kg silicon is \$0.071. If we further make 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.

8.3 EXHIBIT C Refinement

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



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 a very effective purification by means of fractionated distillation due to the fact that all other byproducts display low volatilities.

Ultrapure silicon is obtained from the purified trichlorosilane via chemical vapor deposition, whereby trichlorosilane reduces in the presence of hydrogen to silicon. Simply speaking, 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 rod (poly-rod) 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 quoted⁹⁾ 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 silicon⁹⁾ 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 of the order of 5% of the direct energy or 22 kWh 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 energy expenditure of 76.7 kWh which is equivalent to a payback time of 0.46 years.

8.4 EXHIBIT D Crystal (Growth and Wafering)

The prevailing method for the production of single-crystalline silicon is based on the Czochralski pulling process whereby the crystal is drawn from the melt 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 ^{7,10)} 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:

argon gas	\$1.21 /kg SeG-silicon
quartz crucibles	6.25
replacement	
parts	4.55
	<hr/>
	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 4.4 kg 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 Gzochralski 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.

8.5 EXHIBIT E Cell Processing

The cell production process starting with the blank pre-doped silicon wafer and ending with a finished cell consists commonly 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

We have examined each manufacturing step 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, when this information was not available, from the purchase price. The data are summarized in Table 6.

Table 6. Energies in Cell Production

Cell Processing Step	DIRECT ENERGY		INDIRECT ENERGY	
	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 & overhead energy amounts to 0.0785 kWh resulting in a payback time of 0.05 years.

8.6 EXHIBIT F Panel Building

The panel building process consists of the integration of individual solar cells into a solar cell array from which large amounts of energy can be drawn. The cells must be electrically interconnected and arranged on a suitable support structure which is typically a sheet of plastic or metal. Silicone rubber is then poured over the cell array to serve as an encapsulant and to protect the cells from environmental impact.

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.

8.7 EXHIBIT G Average insolation in the United States

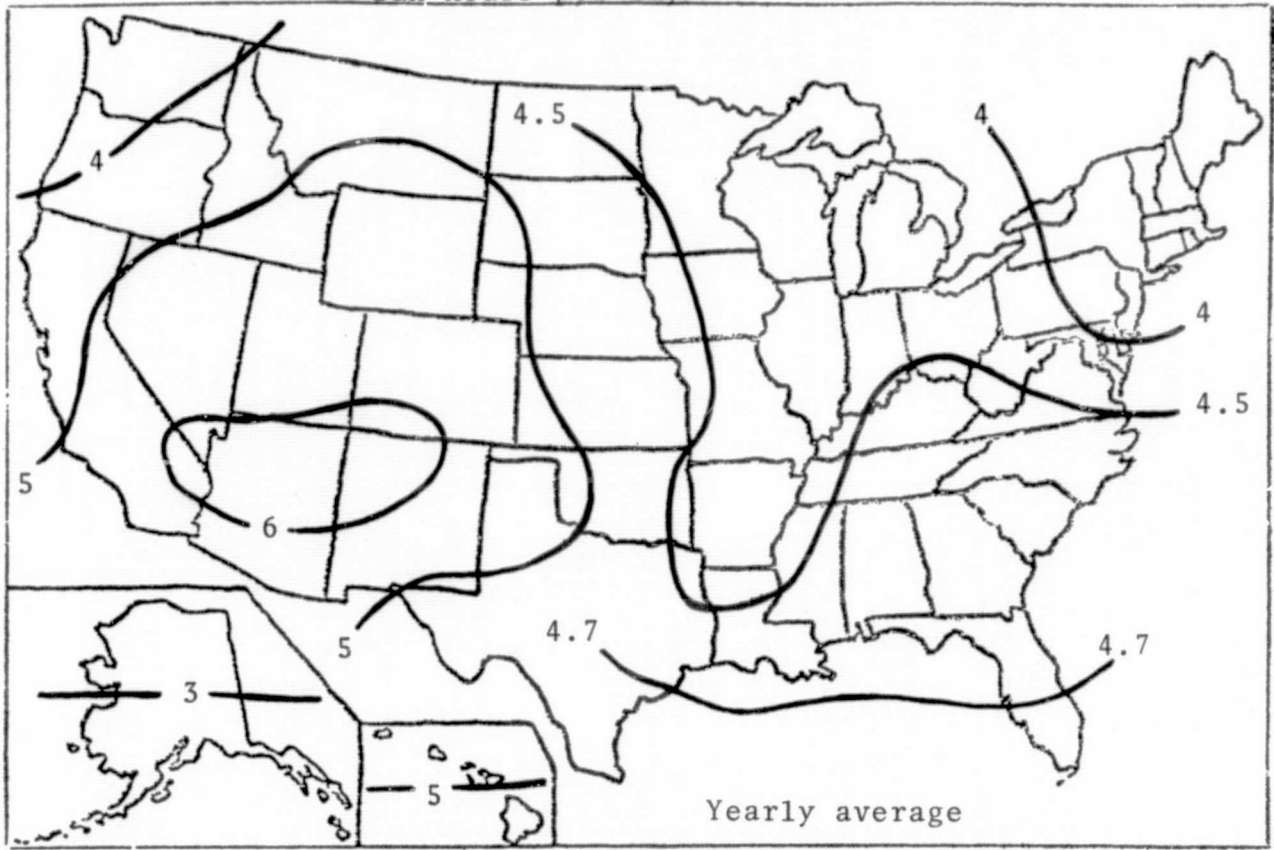
The accompanying maps in Figure VII show the average solar energy available in the United States. Solar radiation data obtained from various weather stations throughout the U.S. were analyzed in terms of average daily sun hours available on a surface facing true south and tilted 45° upwards from the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

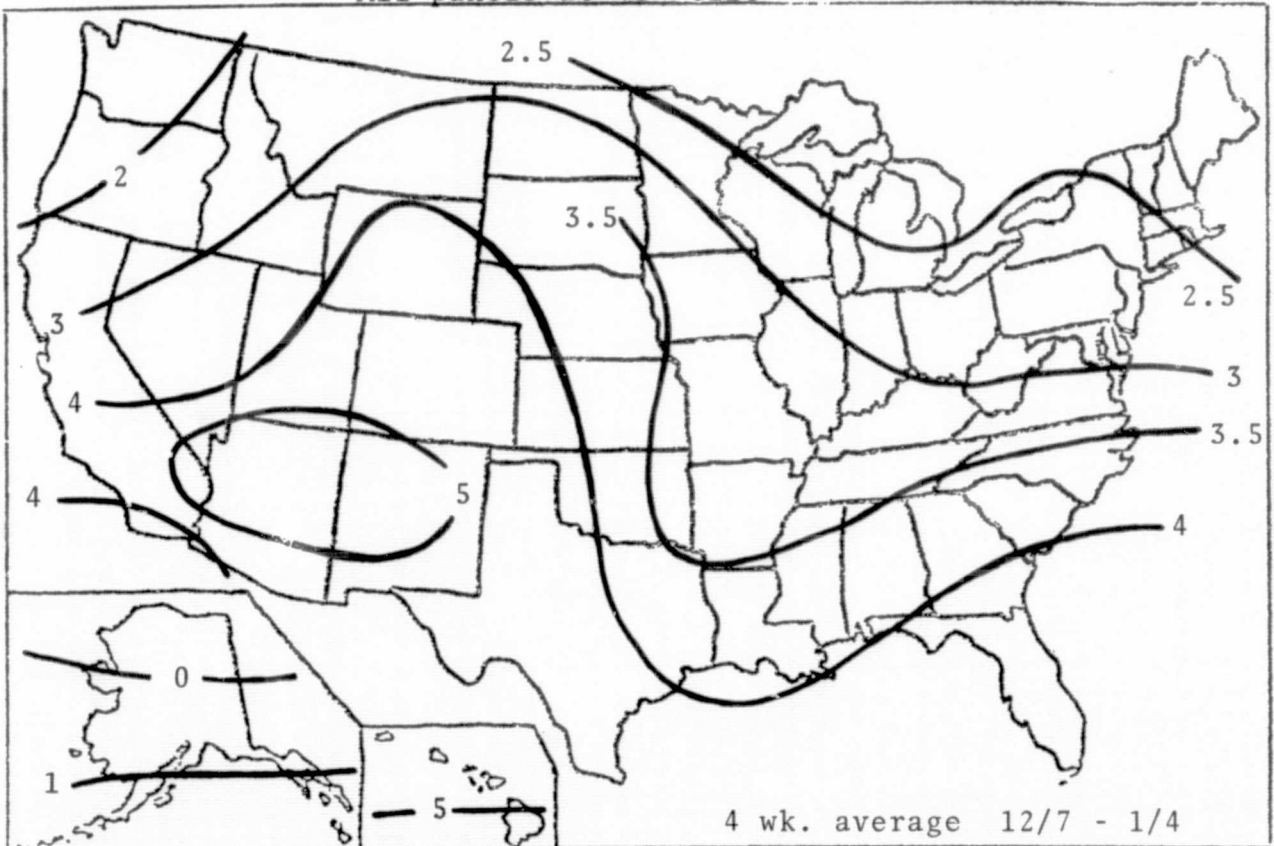


Fig. VII Average insolation across the United States

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