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ENERGY REQUIREMENT FOR THE PRODUCTION OF SILICON SOLAR ARRAYS

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SECOND QUARTERLY REPORT

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MARCH 21, 1977 TO JUNE 20, 1977

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TABLE OF CONTENTS

1. Summary

In the first quarterly report, we reviewed the prevailing solar module manufacturing sequence in terms of its energy demands. The expended energies were subsequently compared to the energy delivering capability of a typical solar cell, and a payback time of 6.4 years was derived for the average U.S. location employing a flat panel without concentration.

This report contains an assessment of potential changes and alternative technologies which could impact the photovoltaic manufacturing process. The recent introduction of a new multiple wire saw into the market could impact the prevailing production sequence in the near future. A review of the potential of the saw indicates that upon its implementation into the wafering process, the overall payback time would be reduced to 4.2 years.

The quest for a higher silicon utilization led to the development of ribbon growth techniques which allow the growth of silicon sheet directly from the melt. Thus, the conventional CZ-growth process and the subsequent wafering procedure could be circumvented. Ribbon growth has so far only been practiced in the laboratory. In order to arrive at a fair assessmnet of this alternative technology, we assumed that certain measures would be taken to increase its economy in a production-like setting. However, despite these measures, we conclude that the technology has not yet matured enough to impact the prevailing photovoltaic industry. If ribbon growth would be introduced now into the module manufacture, the overall payback time would increase to 9 years. Although the future viability of a ribbon growth process is not denied, important changes and improvements need to be undertaken in order to reach its intended goal.

In order to circumvent the energy demanding crystal growth process, Solarex is currently conducting experiments in silicon casting and efforts to estimate the energy expenditure. An exposé of semicrystalline solar cells obtained from casted silicon is contained in this report.

Finally, we report the development of a computer model of a future large-scale solar power plant. The model allows us to simulate the input-output behavior of a solar breeder facility under various growth conditions and to arrive at preliminary conclusions with respect to its energy benefit to society. For testing purposes, we operated the computer model under the assumption of the prevailing module manufacturing sequence. However, we do not imply that we advocate the operation of a future breeder by utilizing today's technology because the average payback time is still too high. Solarex believes that novel technologies will emerge in the near future which are energy inexpensive and yield a much shorter payback time. When these technologies are at hand, then the full potential of the breeder concept can be put to test in a real time application. The next quarterly report will already contain information on breeder operations based on shorter payback times as a result of the potential of the new sawing technology.

2. Introduction

One of the principal features by which new and potential energy sources must be judged is their capability to contribute net energy to society. Photovoltaics, a new and promising technology in the quest for alternate energy sources for terrestrial applications, has only recently become the subject of an extensive assessment in terms of its net energy potential. As documented in the first quarterly report of this contract, we examined the prevailing photovoltaic manufacturing process in terms of its energy intensiveness. According to its structure, we have divided the prevailing manufacturing sequence into five major operations:

Reduction - In the conventional process, quartzite pebbles are being 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 - 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 interconnected and encapsulated to form modules and panels.

Each of these production steps was evaluated in terms of their energy demands whereby the energy was broken up into three well-defined 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 also include 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 air conditioning of the manufacturing area.

Each of the five basic production operations were assessed for their energy expenditure in terms of direct, indirect, and equipment and overhead energies. These energies were then compared to the energy delivering capability of a typical solar cell. As a test vehicle, we chose a 4" diameter cell as a representative of the state of the art. The basic characteristics of this test vehicle may be listed as follows in Table 1.

Table 1

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	4.72g @ density of 2.3 g/cm^3
Lifetime of panel	20 years
Efficiency	12.5%
Peak power	1.013 W
Average isolation time per day	4.33 hours
Energy delivered in 20 years (31,630h)	32 kWh

The energy output of this test vehicle was calculated for the average U.S. insolation of 4.33 hours per day for an elapsed time of 20 years. In assuming a time span of 20 years, it becomes possible to derive the energy collected per weight of silicon at the average U.S. location:

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

Since production yields cannot attain 100%, an overall materials yield of 50% was assumed in the assessment of the first quarterly report. It was noted that most of the silicon loss occurred in the sawing operation. Accordingly, the energy delivered during one year at 50% materials yield was calculated to:

energy delivered per kg silicon in one year at 50% materials yield 167 kWh

In comparing the energy consumed in making the photovoltaic array to the energy which the array subsequently delivers, the term "payback time" can be introduced. It is defined as the time span over which the array of the cell has to deliver energy back to society to balance the energy expended in its making. As we pointed out in the first report, the payback time is one of the important operational parameters of a photovoltaic production plant such as the Solar Breeder. In Fig. 1 we show the individual payback times under average conditions for each process step which accumulate currently to 6.4 years.

It should be emphasized that judging a technology in the photovoltaic field by its energy consumption is by no means less important than assessing its economical viability. Economical viability for photovoltaics will be reached automatically if the progressive depletion of our fossil energy sources continues, and the price of conventional energy increases until economical parity with solar energy is achieved. However, the photovoltaic technology would not serve avail for society when this situation is reached if it cannot disclose considerable energy profit. Therefore, potential changes and alternative processes and sequences must not only be introduced into the present photovoltaic technology with the aim of reducing expenses and prices but also to shorten the overall payback time.

Most of the silicon sheet which is currently used in large quantities for production is procured in the form of SeG wafers. The photovoltaic industry has recognized the cost and energy factors associated with conventional refinement and crystal growth techniques and began a search for alternative procedures to obtain large sheets of silicon under more economical conditions.

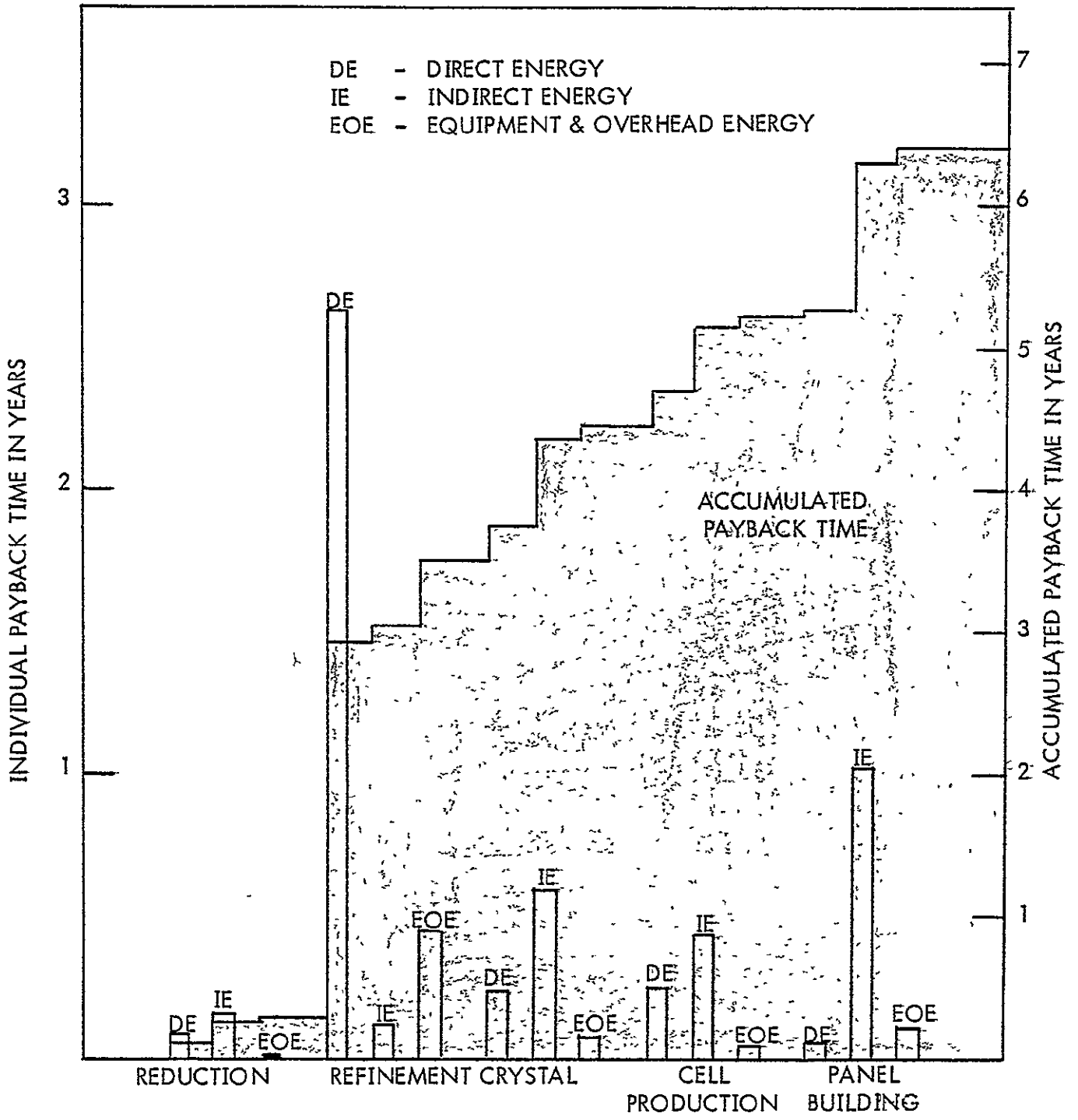

FIG. 1. PAYBACK TIME VS. TIME FOR CONVENTIONAL PROCESS

However, it soon became apparent that the silicon question constitutes a problem of high complexity for which no easy and immediate solutions can be found in order to reach the national goal by 1986. In recognition of this fact, the U.S. government through ERDA/JPL instituted a large-scale support to the industrial and academic community in order to aid in attacking the silicon problem on many fronts. Some of the task forces aim at the development of alternate technologies to produce less pure silicon suitable for solar cells and means to convert it into large sheets, both under energy and cost inexpensive conditions. As a result, extensive efforts are currently carried out with the goal to specify and develop solar cell grade silicon material, and to investigate new growth processes in the form of ribbons and sheets. The experimental activities to find refinement processes either by modifying the conventional silane process or by developing new purification techniques have not yet led to a situation whereby a winning technology can be predicted. In addition, the physical implications of the higher impurity level in solar cell grade silicon have not yet been the subject of thorough tests.

The incentive for the search for alternative growth processes stems from the desire to utilize silicon at yields close to 100% and thus to eliminate the inherently lossy sawing process. Current efforts aim at the growth of large silicon sheets by drawing ribbons directly from the melt or from laser heated liquid zones, and by chemical vapor depositions. Despite extensive research activities in the past, these processes have not yet been tested in a production-like environment.

In view of the relatively early development of the mentioned research fields to date, we address in this report few technological areas which could impact the photovoltaic field in the near future in its use of semiconductor grade silicon.

The recent availability of a newly developed multiple wire saw does upon its implementation constitute a potential change in the conventional sawing technology inasmuch as it promises a higher materials yield with the benefit of a reduction in the overall payback time. A detailed assessment of the potential impact upon the energy is contained in this report.

Although the technology of ribbon growth has not yet matured enough to replace the CZ-wafer, an early assessment of its energy demands appears possible and approximate payback times can be derived. We have examined the ribbon growth process as an example of an alternative photovoltaic process. Mention also will be made of current efforts at Solarex to free itself from the limited and expensive CZ-wafer supply by casting silicon under controlled conditions to obtain semicrystalline material exhibiting large grains. The feasibility of converting large grained sheet into cells displaying 10% efficiencies or more has already been demonstrated at Solarex and others in the past.

The importance of cost and energy economical considerations within the photovoltaic field becomes apparent when the issue of future large-scale power plants is addressed. These plants must not only be cost effective but also provide a net energy gain to society. Fortunately, by utilizing a computer simulated model of such a plant called the Solar Breeder, we are able to demonstrate that the net energy mode can be easily achieved and maintained. The basic operational features of the Solar Breeder have been described in the first quarterly report. The unique significance of the breeder concept lies in the fact that the sun whose energy capacity may be considered infinite provides an inexhaustible supply of energy for which society is not required to expend any development efforts. In principle, society is only required to

make initial energy from conventional sources available to build the breeder plant. Once in operation, the breeder will convert solar energy into electric energy and pay back its energy debt to society. Part of the electric energy derived from the breeder will be used to manufacture solar modules to enlarge its own production capacity and to provide panels which may lead to the construction of additional breeders. Thus, society will ultimately be the beneficiary of the vast and inexhaustible supply of solar energy.

3. Multiple Wire Sawing

3.1 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 must be considered technologically awkward because almost half of the high quality single crystalline material which had been obtained under extensive financial and energy expense is lost. Several programs have been launched in the past to improve the sawing operation using conventional equipment, but only moderate success can be claimed in terms of improved materials yield.

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 [1]. The current technology allows to obtain 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. Along the blade stroke the surface is relatively flat; large undulations, however, characterize the surface in directions approximately normal to the cutting stroke. Accordingly, saw-induced damage to the subsurface layer of the semiconductor material occurs. 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.

3.2 The Potential of the Multiple Wire Saw

A new multiple wire saw[2] was recently introduced to the market. The saw was specifically developed for large volume continuous production cutting of hard and brittle materials whereby close tolerances can be achieved. The characteristic features of the saw include 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.

3.3 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. We have already pointed out that due to thinner wafers and an improved ratio of wafer thickness to kerf loss, a materials yield of 67% in the sawing process appears feasible, resulting in a larger and thinner sheet area. Accordingly, more energy could be generated per weight of silicon leading to a potential reduction of the payback time.

In addition, 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 reported[3] a technological breakthrough 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 were developed recently at Solarex with an acceptable yield and at reasonable cost. Consistent reproducibility and relative straightforwardness of the process as now developed forecasts that these cells can be made in high quantities in a production-like 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 report.

Because of the potential change in the parameters, the characteristics of our test vehicle must be redefined as shown in Table 2.

TABLE 2

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, it becomes possible to express the energy as delivered by 1 kg of ingot material.

As we pointed out earlier, 1.41 m^2 of sheet area could 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

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

3.4 Reduction and Refinement

Having thus redefined our 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 3.

TABLE 3. 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	0.29	0.14
REFINEMENT		
Direct energy	2.63	1.32
Indirect energy	0.13	.06
Equipment and overhead energy	0.46	.23
Total	3.22	1.61

3.5 Crystal

Because the introduction of the wire saw constitutes a different production procedure, the energies expended in this manufacturing process need to be reexamined as far as wafering is concerned. The energy expenditure of crystal growth remains the same.

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. We derive this energy content from the purchase price of the wire, a procedure which is thoroughly discussed in the first quarterly report. 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. In the first quarterly report, we arrived at a cost burden due to the purchase price of a CZ-growth puller of $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 the burden due to the crystal growth station, so that we arrive at a combined cost of $4.83 which 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 4.

TABLE 4. 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	0.95	0.80

3.6 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. Therefore, the payback times may be listed as in Table 5.

TABLE 5
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	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	1.21	1.01

3.7 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 to be 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 2.

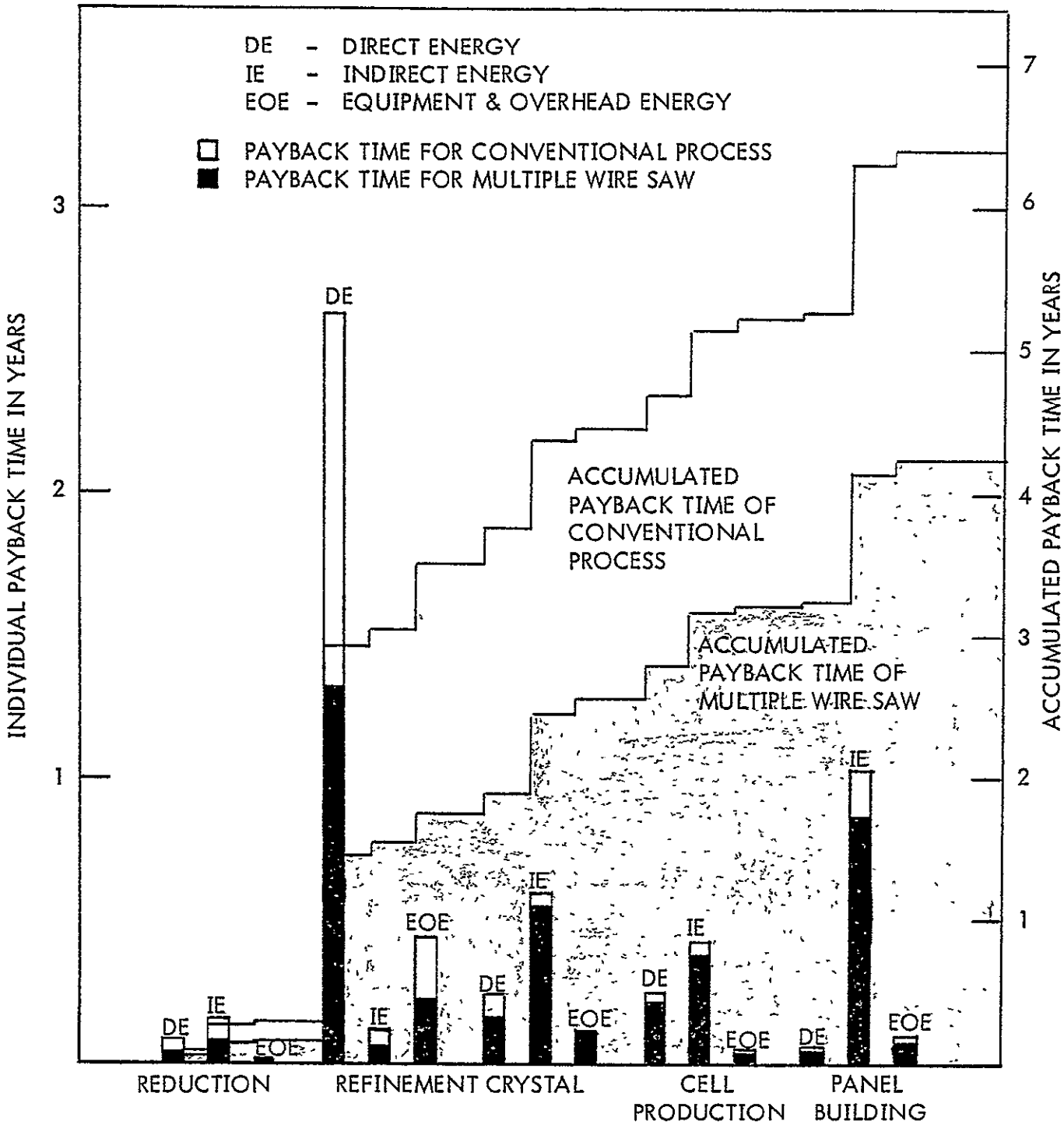

FIG. 2. PAYBACK TIME VS. TIME: POTENTIAL OF WIRE SAW

4. Alternative Processes

4.1 General

Basically, the photovoltaic production process consists of:

a) Production or procurement of silicon sheet material
b) Cell production
c) Module building

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 constitutes a major problem. Currently, most of the available silicon is derived from semiconductor grade silicon in the form of high quality ingots or wafers. It is generally felt that their price and limited quantity constitutes one of the principal factors that affects economically and technically the attainment of large-scale silicon photovoltaic systems. In view of this situation, the photovoltaic community initiated ERDA/JPL supported research programs with the aim to become less dependent on the semiconductor grade silicon and develop sheet material according to their own technical and economical needs.

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 process are available, we attempt to estimate the payback

times by making reasonable assumptions concerning the energy expenditure in a production type setting.

In the continuing search for alternative answers to the silicon problem, Solarex and others have posed the question of whether it is indeed necessary to resort to single crystalline silicon in order to produce an efficient solar cell. Preliminary experiments demonstrated that this question need not be answered positively, and that cells exhibiting reasonable efficiencies can be made from large grained silicon which can be obtained by controlled casting. This technique constitutes another means to circumvent the elaborate CZ-growth process. Research in silicon casting is one of the development projects currently emphasized at Solarex.

4.2 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.[4]

The silicon ribbons typically contain crystallographic defects and discrete inclusions. The crystallographic defects are mainly twins, dislocations and low and high angle grain boundaries. The discrete inclusions are clusters of SiC particles. 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. Because of these circumstances, the future yield and cell performance is conjectural. For the purpose of this energy assessment to date, we are envisioning the presently practised ribbon growth process implemented on the production floor. Under this circumstance, we grant that measures to ensure high cell productivity would be taken which are currently not observed in the laboratory. These measures, for instance, would include procedures to ensure a 70% materials yield as it is commonly experienced by device manufacturers. As for the average efficiency of ribbon cells, we assume 9%. Corrections to the tentative energy and payback times can be made by proper scaling when data derived under actual production environments become available.

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 rate 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 cubic 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 in the first quarterly report, 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. As described in the first quarterly report, we

derive the energy content of materials from their purchase price using the conversion factor of 6.67 kWh per purchase price dollar. Accordingly, 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.

4.3 Summary of the Energy Assessment of Ribbon Growth

The development of the ribbon growth process was initiated with the aim of obtaining a crystallization technology which would yield silicon in large sheets for immediate availability for cell production. The successful development of this technology would allow high materials' yields by circumventing the CZ-type boule growth and the subsequent materials loss in the sawing operation. To date, the ribbon

growth process is still carried out in a laboratory environment and has not yet been tested under production conditions. Breakage, for instance, is currently far higher than could be tolerated on the production floor. In order to estimate the energies and payback times of the silicon ribbon growth process, we have viewed the current technology against a production-like background with the assumption that the materials yield of 70%, as commonly experience by device manufacturers, is attained. Under these conditions we arrived at a payback time of 3.91 years. Our assessment did not include the cell making or module fabrication process of ribbon material because of the lack of pertinent information on the energies expended in these processes. We are, therefore, assuming that the energy expenditure in the ribbon cell and module fabrication process is equivalent to the energy expense in cell and module based on the 4" diameter wafer, and that the payback times are also alike. Under these assumptions, 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 highly unfavorably with the 6.42 years of the wafer production sequence.

In view of this fact, it must be concluded that the 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 like setting. In conclusion, it also may be noted that the successful ribbon crystallization process based on SeG silicon alone will not significantly reduce the overally payback time because its highest contribution is in the silicon refinement. Only when efficient ribbons from unrefined material can be grown will the full advantage of ribbon growth come to light.

4.4 Semicrystalline Solar Cells

In the continuing quest for alternative answers to the silicon problem, we have for some time posed the question of whether it is indeed necessary to resort to single crystalline silicon in order to produce an efficient solar cell. Early experiments at Solarex demonstrated that sheet material obtained by casting semiconductor grade silicon could be processed into cells which exhibited high efficiencies. The silicon obtained from the casting process is characterized by a structure consisting of grains with sizes of the order of a few millimeters. Such a structure has been termed "semicrystalline"[5] to distinguish it from other morphologies such as small grain poly-material. The experience gained at Solarex provides evidence that cells with grain sizes of a few millimeters can yield efficiencies higher than 10% and that the resulting silicon cell is less sensitive to impurities. This behavior led to the assumption that cell efficiency is mainly a function of the grain size and that impurities preferentially segregate at the grain boundaries where their influence on the cell operation is reduced.

The potential advantage of being able to manufacture high efficiency cells from other than single crystalline material is intriguing and is of great consequence, although the solar cell industry might experience temporary difficulties in raising the efficiencies of cell material, composed of grains and grain boundaries with defects and impurities, to similar levels as displayed by single crystalline material. However, a clear technical and economical gain will be obtained by freeing oneself from the expensive CZ-supply. Then, not only can the elaborate crystal growth process be circumvented, but the development can even be carried further by introducing material of less purity than SeG.

We are currently in the process of assessing the energy expenditure of the silicon casting technologies and will describe our findings in the next quarterly report.

5. The Solar Breeder Model

5.1 Model Description

The generation of electrical energy by means of the photovoltaic effect is a potentially powerful approach to satisfy our energy needs in the future. At present, most of the attention of the scientific and industrial photovoltaic community focuses on the immediate technological problems of cell making and module fabrication and, therefore, no effort is undertaken to study the inherent operational correlations and long range potentials of large scale solar power systems.

In order to stimulate the general interest in solar power plants, we are developing a conceptual model of a photovoltaic manufacturing plant based on detailed energy balance considerations between the total energy expended in the module fabrication process and the potential energy return, and hope that such a model will lead to a general awareness of future large scale power systems based on solar energy.

The model will allow a study of the synergistic effects of manufacturing processes that comprise the photovoltaic industry, and an estimate of energy benefits to society.

In its first approximation, the breeder model is based on the energy balance between the total energy consumed to make solar panels and the potential energy return of the finished modules. The model simulates a manufacturing plant in which the whole production sequence from the quartz reduction to the final module fabrication is exercised. Each of

the five conventional manufacturing steps is linked to its adjacent step such that the output of one step is the input to the next. By this we mean that we envision a continuous production belt running through the sequence with no provision for storage or buffering of energy (panels) between steps. The situation is depicted in Figure 3 where the five major production steps are shown as interacting gears with no allowance for slippage.

The only energy input to the system occurs by means of solar energy via a bank of panels mounted on the roof of the production facility. The initial size of 1 MW of this array is part of the input parameters. A 20 year life of all panels is assumed in this computer simulation. Additional input data are the daily insolation which assumes a new value every month, the percentage of produced monthly panels that will be added to the roof to increase power input, and the payback times.

The payback times have been regrouped to be:

Direct Energy Payback Time which describes all electrical power needed to operate the manufacturing sequence. This also includes energies which were previously listed under overhead energies such as air conditioning, lighting and heating;

Supply Energy Payback Time which is the previously defined payback time for indirect energy; and

Equipment Energy Payback Time, derived from the earlier defined equipment and overhead energy and describing energy expenses for manufacturing equipment.

The payback times constitute important parameters in the computer program from which dynamic situations such as production

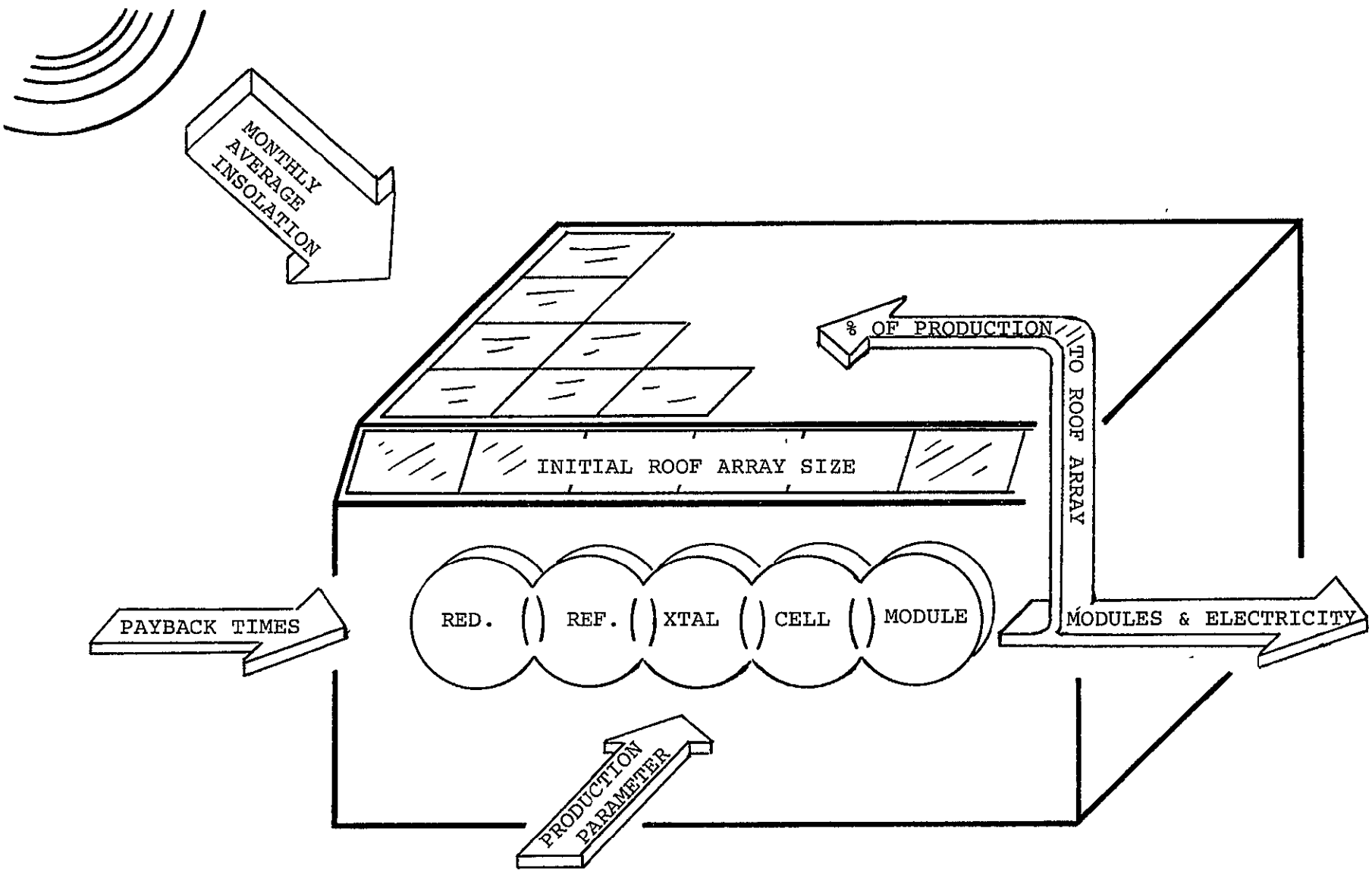

FIG. 3. SOLAR BREEDER MODEL

capacity, number of monthly panels made, number of panels sold, etc., will be calculated.

The output of the breeder consists of power sold in the form of panels and of excess electricity during the summer when the breeder operation runs under full production capacity.

Production capacity represents installed manufacturing equipment to make a certain number of panels provided the power is available. The model assumes that the production capacity is never decreasing and is set at a constant value at the beginning of each year based upon the roof array size and the external production capacity parameter. The setting of the production capacity to a constant value for the year means that part of the equipment will be idle in winter due to reduced insolation, and excess energy from the roof array will have to be sold when more energy than required for full production is available during the summer months. It is felt that this trade off is necessary in order to prevent the continuous installation and removal of equipment which would be required if the production capacity is supposed to track the monthly insolation.

The structure of the computer program representing the breeder model and the underlying algebra is described in the appendices. Already at this stage of the model development, interesting conclusions concerning future breeder operations can be drawn.

5.2 Trial Run of Breeder Model

We have used the breeder model as currently developed to simulate the prevailing module fabrication sequence characterized by a total payback time of 6.4 years. The breeder model derives its input power from the roof array which is initially set at 1 MW. The monthly insolation data are those which Solarex typically experiences at its location in Rockville, Maryland. The production capacity is characterized by a production parameter, p, of 3.9 sun-hours per day, approximately the average daily insolation averaged over the year. Breeder operations are simulated at zero and increasing growth rates of the plant as expressed by the increasing percentage of monthly manufactured panels which are added to the roof array. The percentage data used range from 0% to 50% in steps of 10%.

Accordingly, the input data may be listed as in Table 6.

TABLE 6. Breeder Input Parameters

Initial roof array	1 MW					
Payback times						
Total	6.4 years					
Direct energy	3.6 years					
Supply energy	2.4 years					
Equipment energy	0.4 years					
Average daily sun-hours	Jan.	Feb.	March	April	May	June
	2.9	3.5	4.1	4.5	4.6	4.8
	July	Aug.	Sept.	Oct.	Nov.	Dec.
	4.6	4.5	4.3	4.0	3.1	2.7
Production capacity parameter	3.9 sun-hours					
Percentage of the monthly produced panels added to roof	0%,	10%,	20%,	30%,	40%,	50%

The model response is illustrated in the following figures. Figures 4 to 9 show the balance between energy debt of the breeder and energy return. Energy debt includes the energy expended in making the initial roof array plus the energies contained in materials and in installed manufacturing equipment. These energies are originally supplied by the society from conventional sources. In return, the breeder delivers finished panels which when multiplied with their operating hours over their lifetime represent the energy which is paid back to society. The curves show the accumulated energy values during the first 30 years of breeder operation. As expected from the breeder equations in the first quarterly report, net energy delivery of the plant at zero growth sets in at about twice the payback time. Figure 4 shows that after 13 years, more energy has been sold than was invested.

As the roof array is allowed to grow at increasing rates, the breeder enters into the net energy mode at progressively later times, as shown in Figures 5 to 8, until the energy sold does not balance the invested energy within the first 30 years of plant operation as depicted in Figure 9. At the growth rate at which 50% of the production is used to increase the roof array, the breeder invests so much in energy in form of materials and equipment that production can hardly keep up balancing the energy investment.

Figure 10 depicts the growth of the roof array. At zero growth, all panels expire at the end of their life of 20 years. If 10% of the production is added to the roof array, the array experiences modest growth over the first 20 years but its size reduces abruptly in the 21st year when the initial 1,000 panel expire. However, the growth rate was too small to have twice the initial array size available shortly before the initial 1,000 panel expire. Therefore, the roof array in the 21st year is small and does not allow a large enough production so that

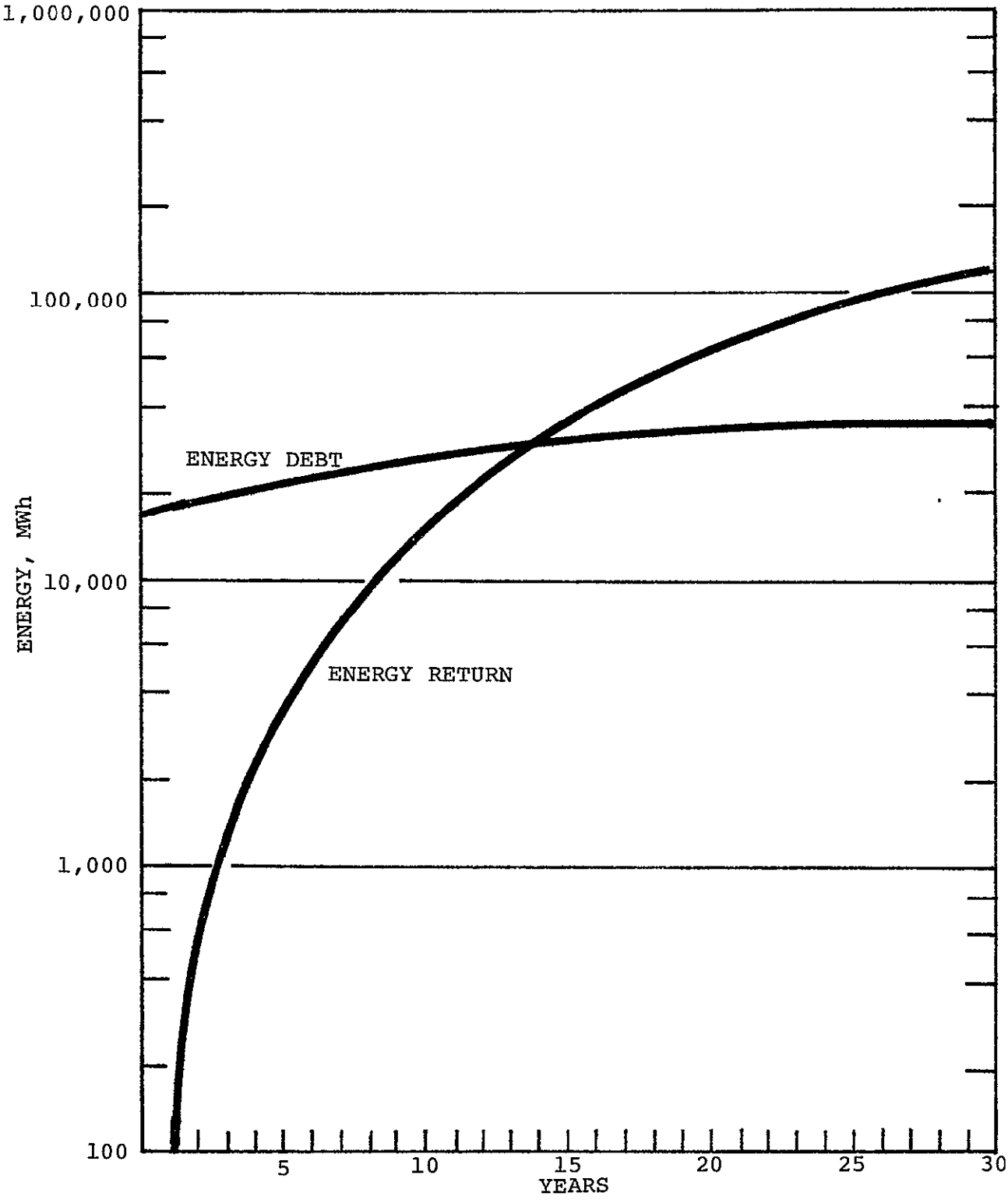

FIG. 4. ZERO BREEDER GROWTH: ENERGY DEBT AND ENERGY RETURN. ACCUMULATED VALUES.

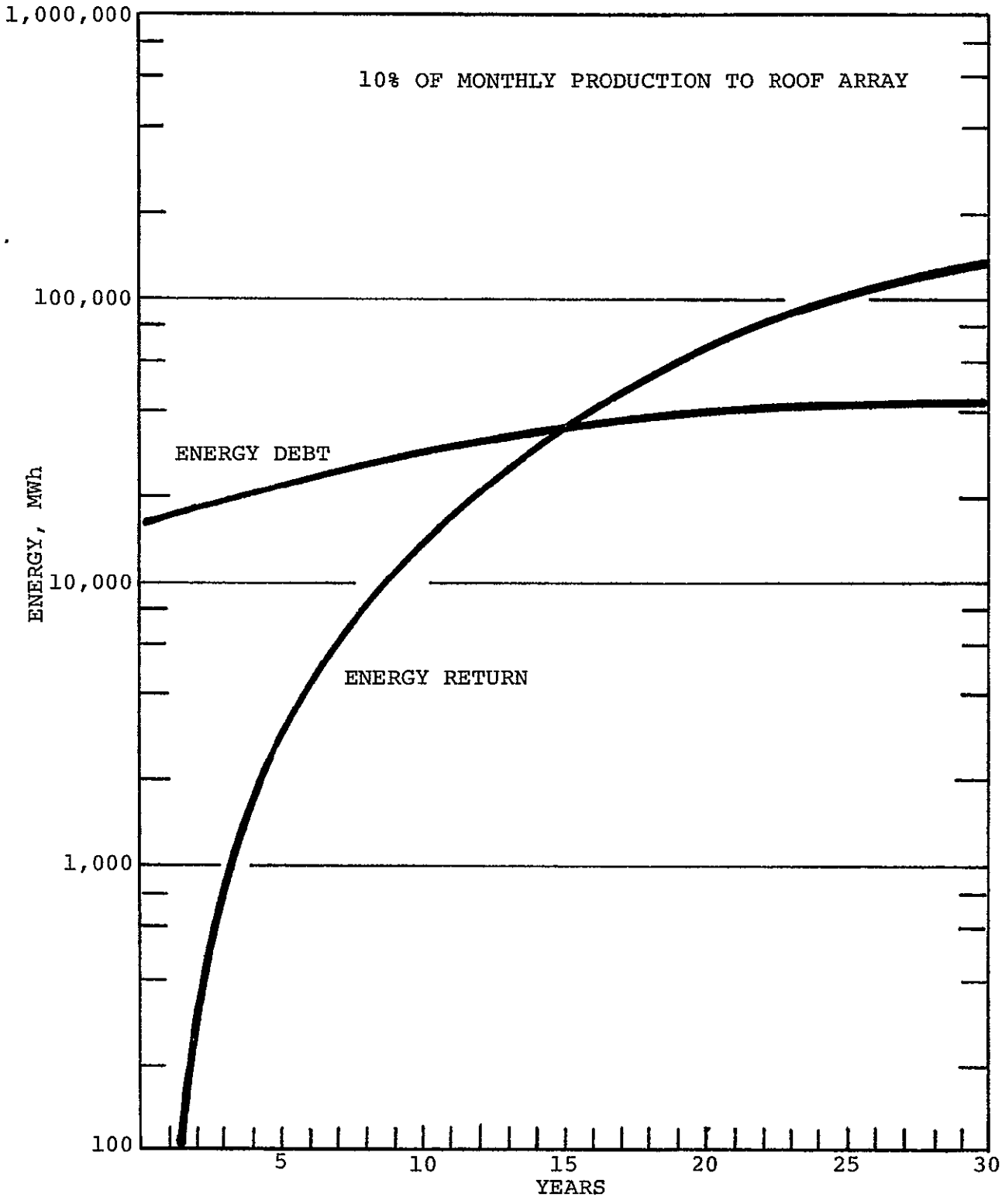

FIG. 5. BREEDER GROWTH: ENERGY DEBT AND ENERGY RETURN. ACCUMULATED VALUES.

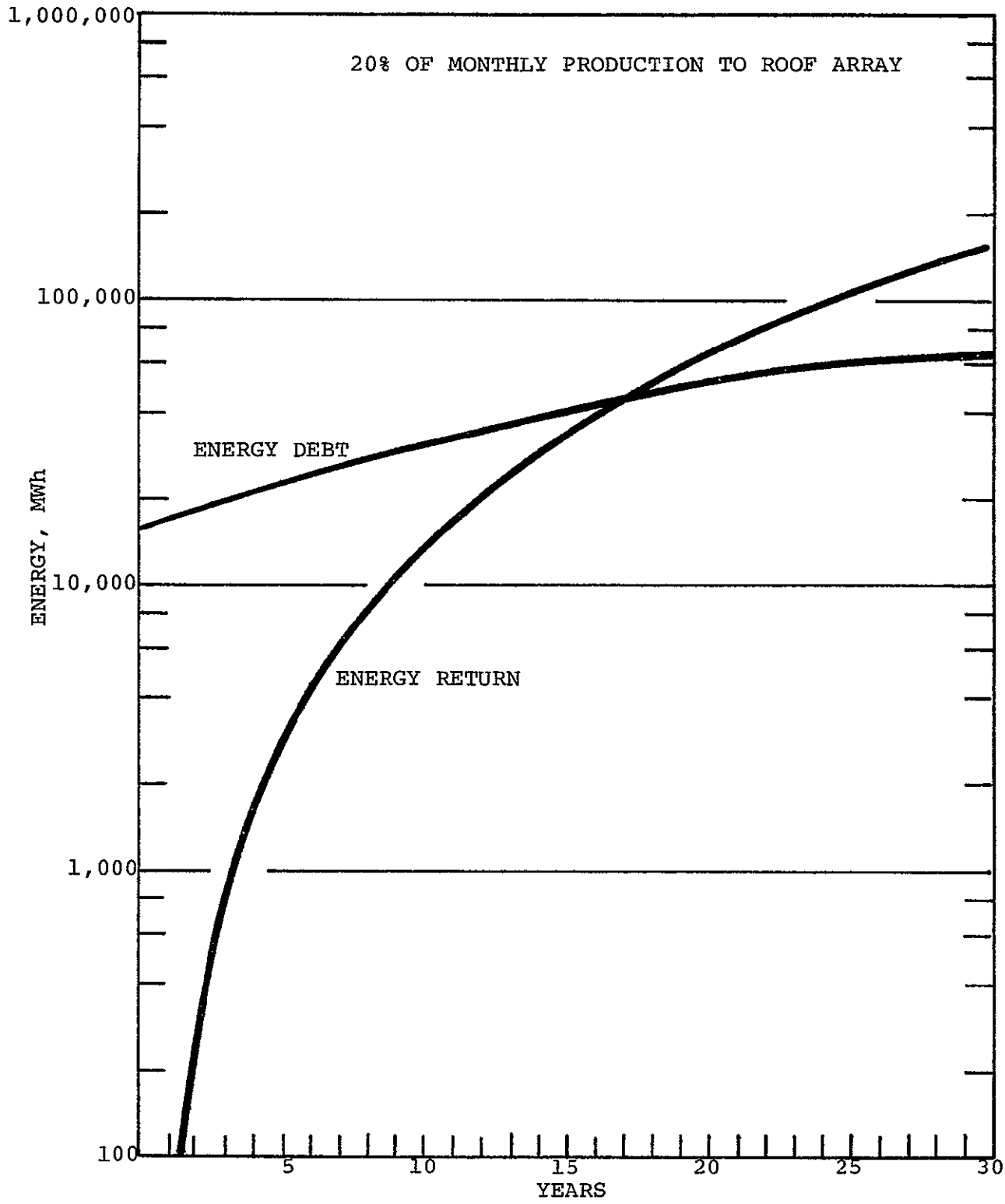

FIG. 6. BREEDER GROWTH: ENERGY DEBT AND ENERGY RETURN. ACCUMULATED VALUES.

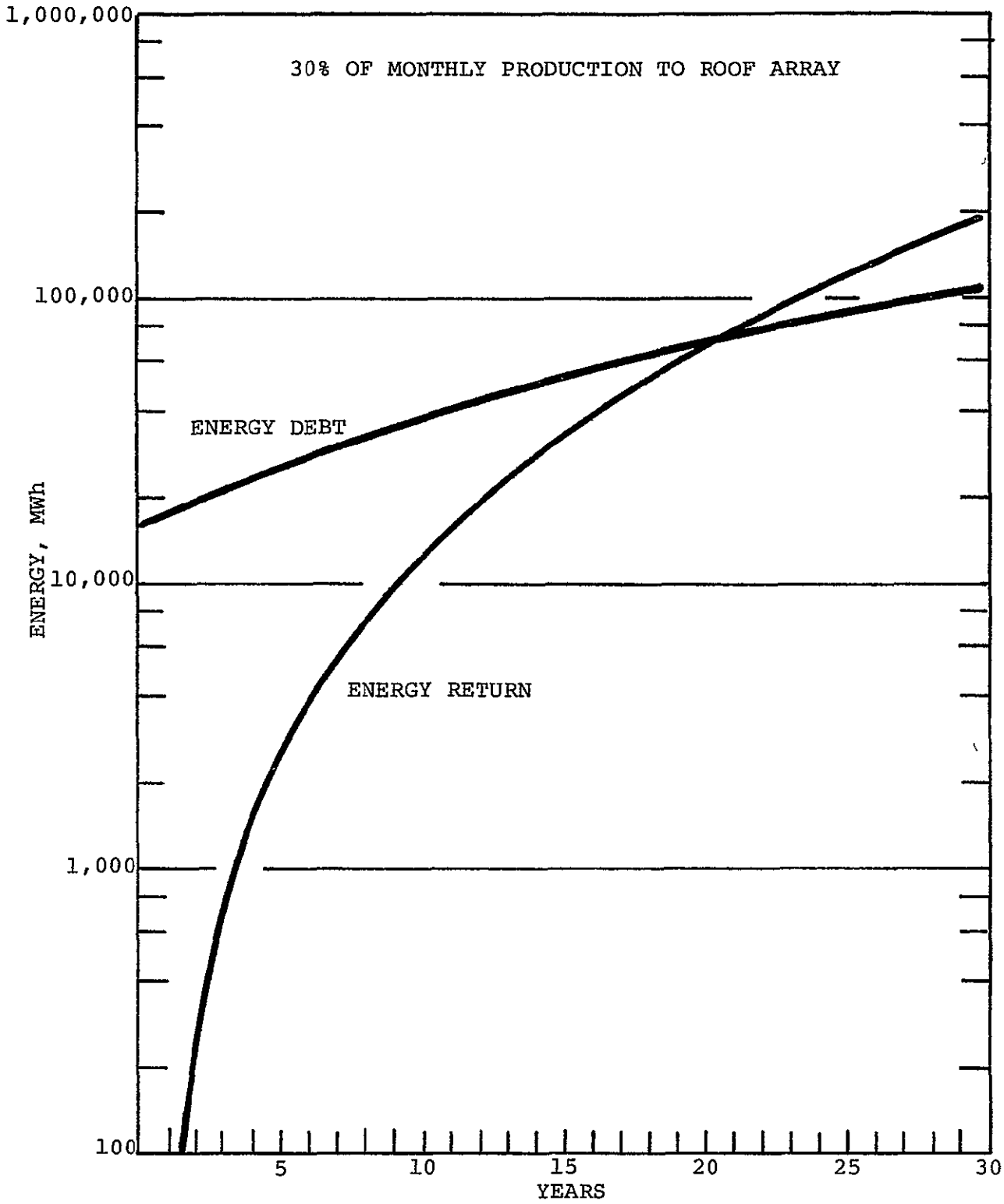

FIG. 7. BREEDER GROWTH: ENERGY DEBT AND ENERGY RETURN. ACCUMULATED VALUES.

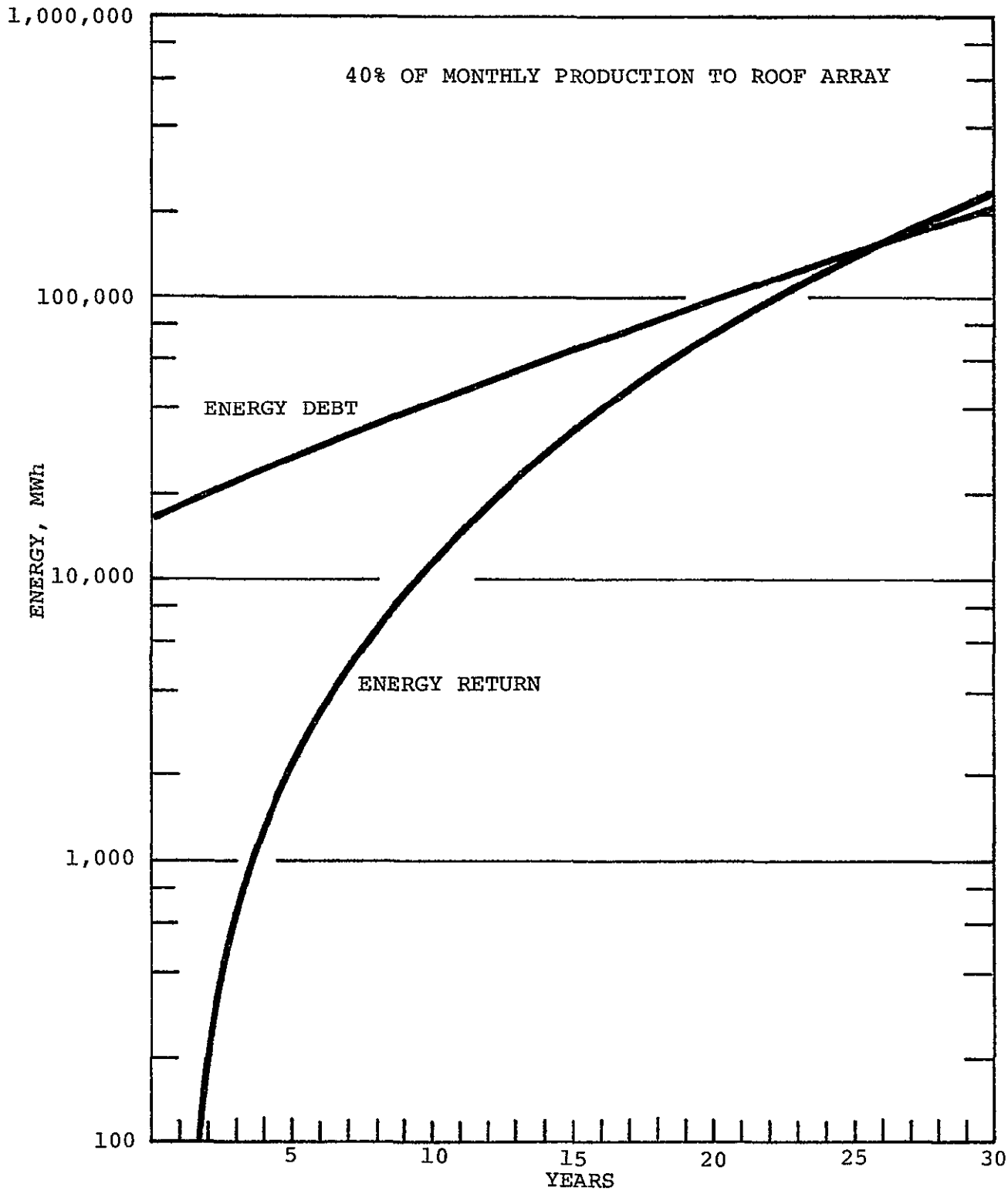

FIG. 8. BREEDER GROWTH: ENERGY DEBT AND ENERGY RETURN. ACCUMULATED VALUES.

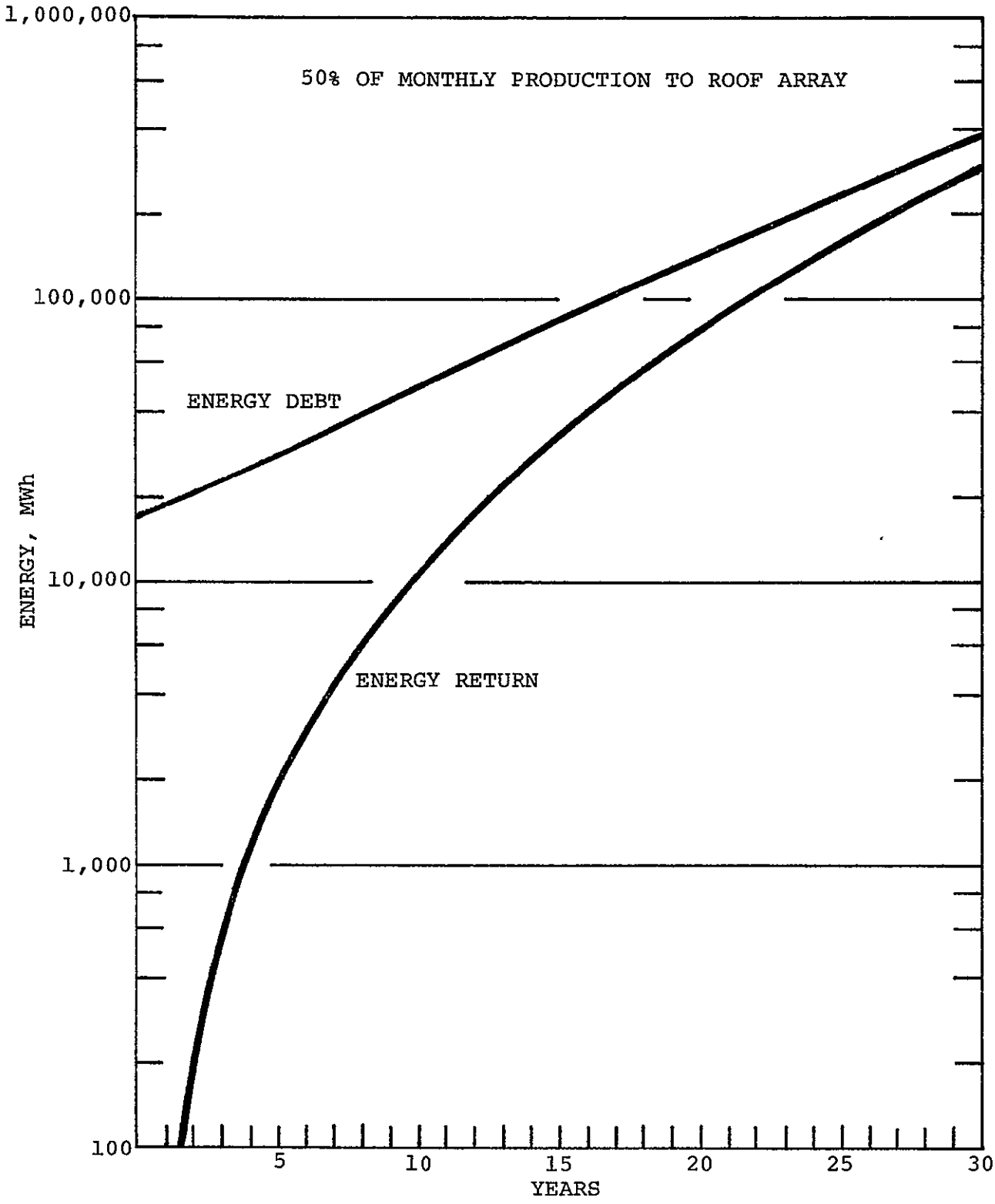

FIG. 9. BREEDER GROWTH: ENERGY DEBT AND ENERGY RETURN. ACCUMULATED VALUES.

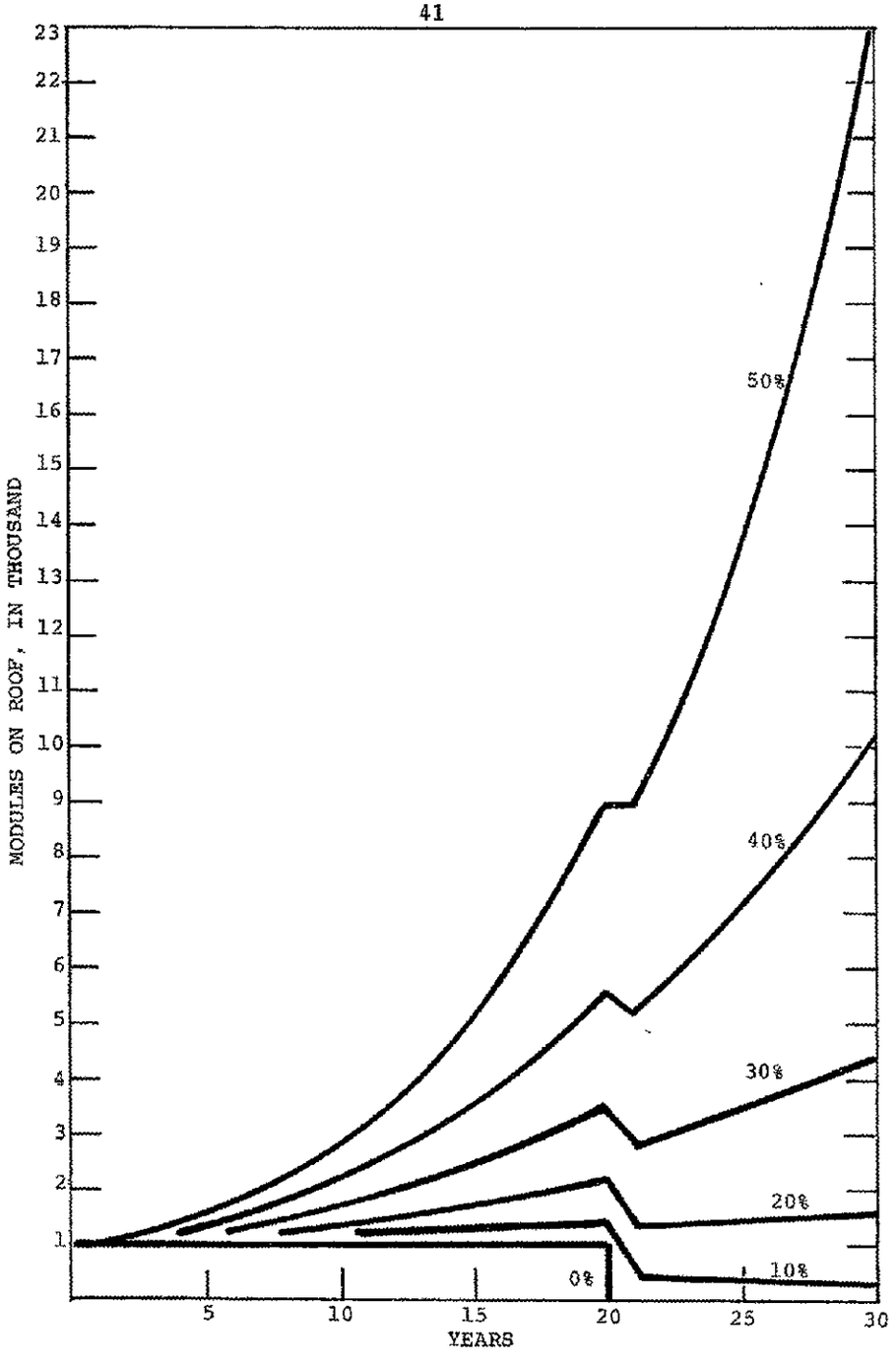

FIG. 10. ROOF ARRAY GROWTH AS A FUNCTION OF THE PERCENTAGE OF PRODUCTION WHICH IS MONTHLY ADDED TO ARRAY.

10% of it can replace expiring roof panels. The result is a progressively smaller roof array leading to a possible halt of breeder operation. If 20% or more of the production is used to enforce the roof array, this accident can be prevented and the array on the roof continues to grow after the 21st year.

Figure 11 shows the yearly rate of module sale to society. The situation here is similar to the roof array growth. Again, at constant roof array size, the array expires during the 20th year and production and sale comes to a halt for lack of input power. At modest growth (10% of production to roof) the sales rises during the first 20 years, but declines thereafter because production decreases with the roof array. At higher growth rates, the yearly sale of modules increases accordingly. The yearly sale during the first few years becomes smaller if the percentage of manufactured panels which are used to enlarge the roof array increases.

The excess amount of electrical energy which needs to be sold every year due to high insolation and saturated production capacity during the summer months is depicted in Figure 12. At zero growth this value is a finite constant during the first 20 years and zero thereafter due to the expired roof array. In all other roof array growth situations, electricity sales rises exponentially during the first 20 years of breeder operation. However, at modest roof array growth rates (10% and 20% of produced panels to roof) no excess electricity will be sold between the 21st and 30th year. The reason for this situation lies in the fact that the production capacity increased during the first 20 years to such a volume that the recovering roof array size during the years 21 and 30 can not provide enough input power to achieve production saturation even in summer. Only when at least 30% of the manufactured panels are placed on the breeder roof will the sale of excess electricity

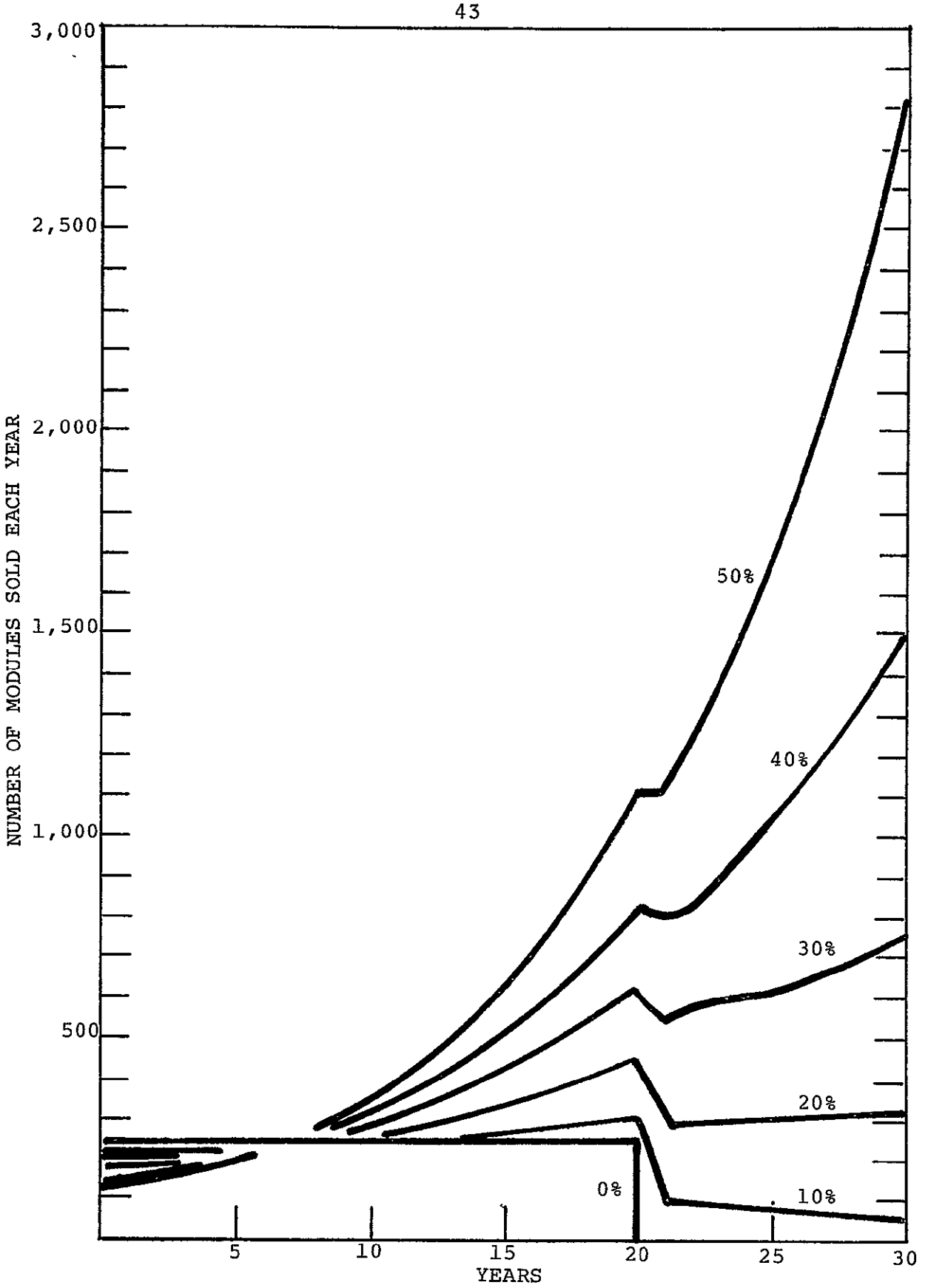

FIG. 11. NUMBER OF MODULES SOLD EACH YEAR AS A FUNCTION OF THE PERCENTAGE OF PRODUCTION WHICH IS MONTHLY ADDED TO THE ARRAY.

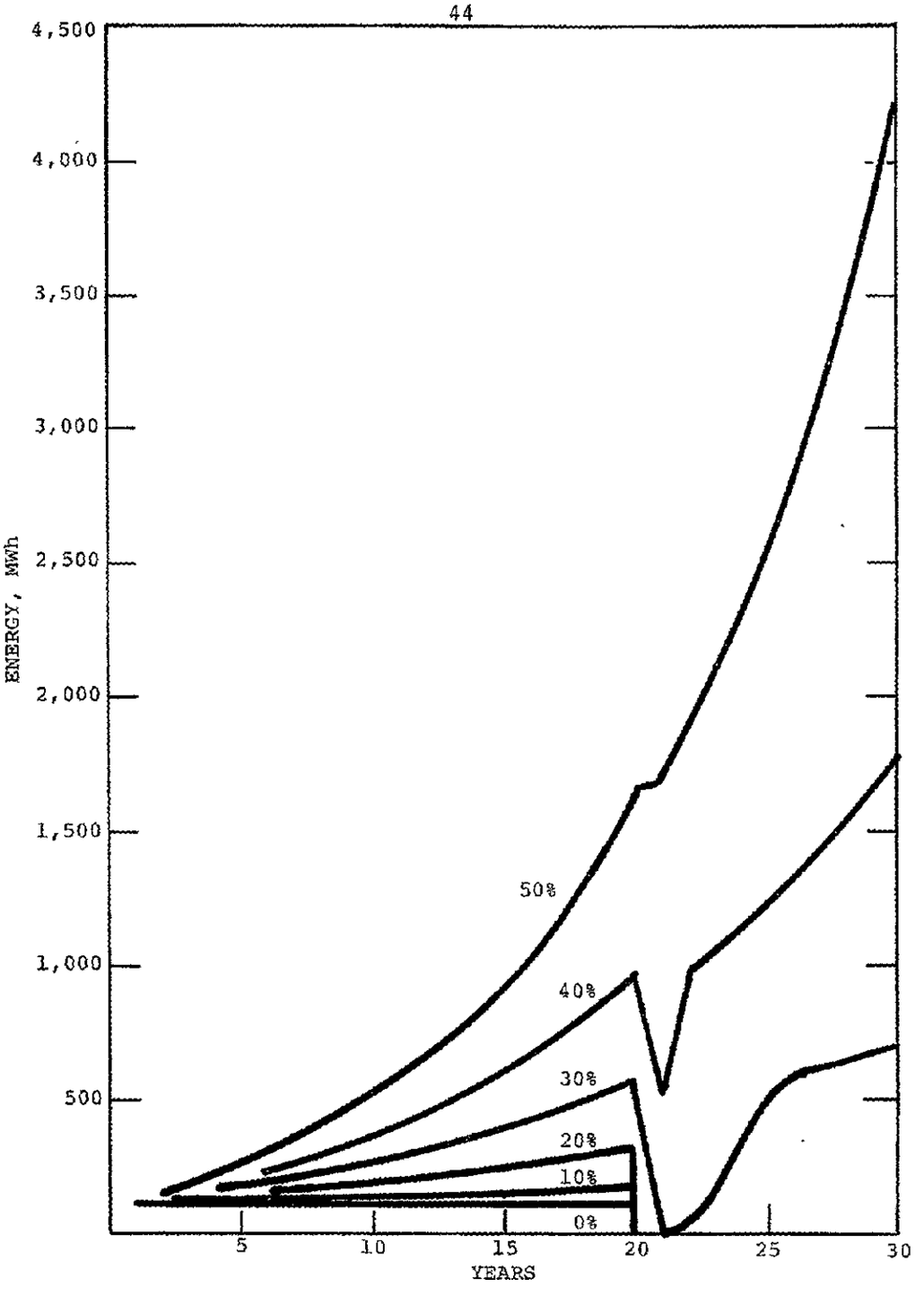

FIG. 12. EXCESS ELECTRICAL ENERGY SOLD EACH YEAR AS A FUNCTION OF THE PERCENTAGE OF PRODUCTION WHICH IS MONTHLY ADDED TO THE ARRAY.

increase again in the 22nd year of breeder operation. At higher percentages (40% and 50%) the rate of electricity sale experiences a temporary discontinuity in the 21st year, but increases again exponentially during the following years.

Figure 13 shows the behavior of idle capacity over the first 30 years of the breeder operation. Idle capacity is expressed in the number of panels which can not be manufactured each year because of insufficient input power either due to low insolation during the winter months or due to an insufficient roof array size.

At zero roof array growth, the idle capacity assumes a small and constant value during the initial 20 years. Afterwards, this value is high and again constant because the roof array expired and all production equipment becomes idle.

We have seen earlier that in the case where 10% of the monthly panel production is added to the roof, the array size actually declines after the 20th year. As a result, the available input power declines too and the idle capacity soon exceeds the value it assumed in the zero growth case.

When panels are added to the roof array at a higher rate (20% to 40% of produced panels to roof) the idle capacity, although momentarily high in the 21st year, declines for a few years thereafter and after passing through a minimum, rises again. This is the situation where the roof array size, although small, starts to increase again after the 21st year. However, the production capacity remained constant for a few years and therefore the idle capacity decreases during that time until it reaches a minimum. Afterwards, the roof array size grows faster than the production capacity and as a result the idle capacity increases again.

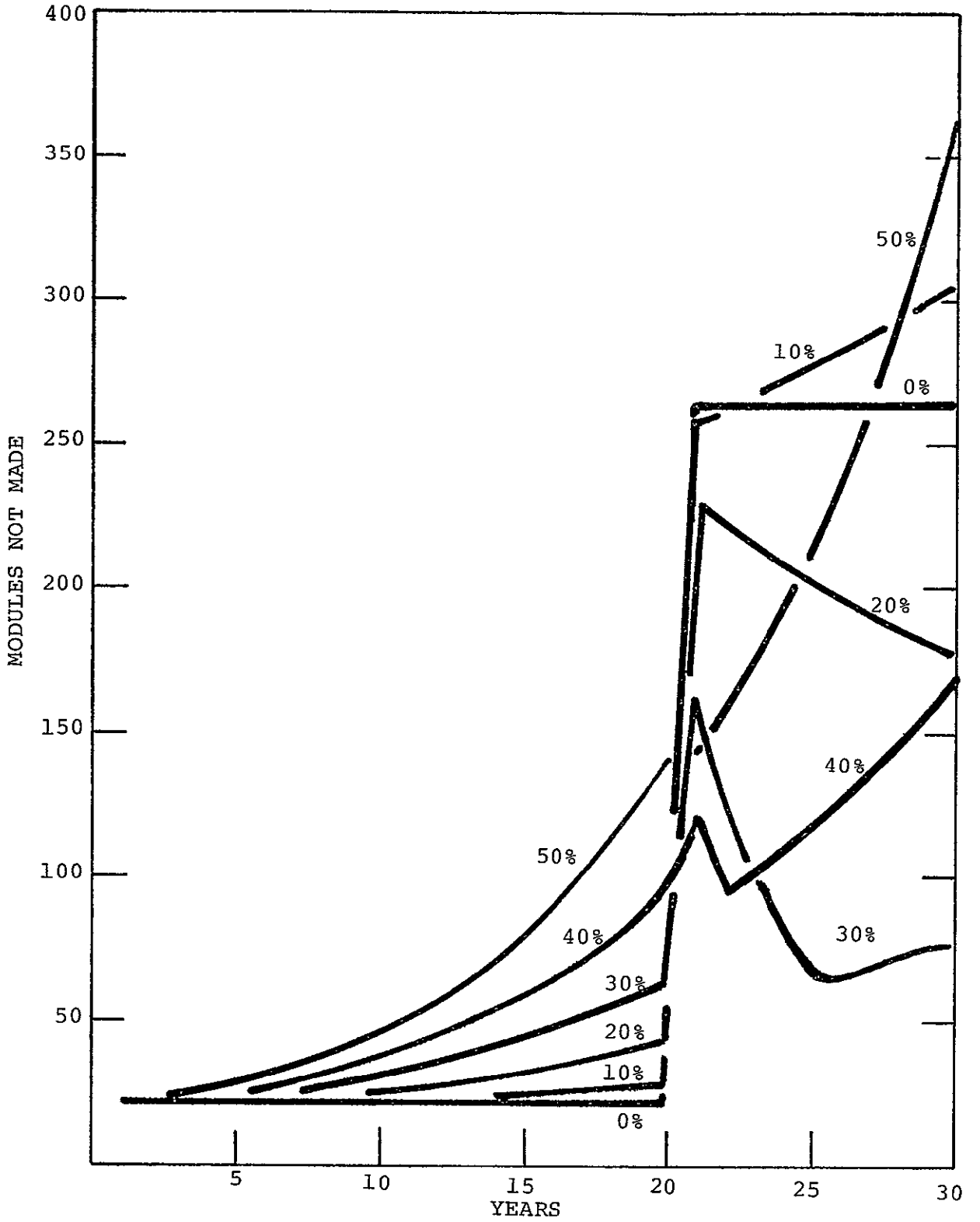

FIG. 13. IDLE CAPACITY EXPRESSED AS THE NUMBER OF MODULES PER YEAR WHICH COULD NOT BE MANUFACTURED. PERCENTAGE VALUES INDICATE THE FRACTION OF THE PRODUCTION WHICH IS MONTHLY ADDED TO ARRAY.

When 50% of the monthly production is added to the roof array its size increases so fast during the first 20 years that the number of expiring panels in the 21st year, and later, hardly causes a change in the array size. As a result, the finite panel life causes only a minor perturbation in the growing breeder operation.

5.3 Summary of the Breeder Model

We have modeled a photovoltaic breeder facility under varying growth conditions in order to gain an approximate understanding of the input-output behavior of future large-scale solar power systems.

Our results indicate that if the achieval of self-sufficiency of the breeder is of primary concern, the facility has to operate under zero growth conditions. In this case, the breeder will enter into the net energy mode after an elapsed time of approximately twice the total payback time of the underlying manufacturing sequence. However, zero growth also means that the breeder operation comes to a halt at the end of the first cycle which is equal to the panel lifetime.

If the breeder is allowed to grow by directing a certain percentage of the manufactured panels to the roof array, the growth rate must be large enough to assure that the array can at least double in size during the first cycle. Under this condition, the breeder operation will continue to grow after the first cycle. The breeder will enter into the net energy mode at progressively later times but its output in form of panels and excess electrical energy increases exponentially.

When the growth rate, however, becomes large, as in the case where 50% of the production is used to increase the input

array, the breeder begins to invest so heavily in energy in form of materials, supplies and equipment that the energy production barely balances the investment. All breeder responses, such as roof array size, yearly sale of panels and excess electrical power, and idle capacity, follow very closely an exponential growth curve. However, as shown in Figure 9, the energy debt curve and the energy sale curve tend to meet asymptotically, and the net energy benefit to society appears to be significantly delayed.

From the behavior of the breeder model, we draw the conclusion that modest growth as represented by typically allocating 30% to 40% of module production for roof array expansion, yields an optimal energy return to society. When novel technologies with little energy demands and yielding much shorter payback times become available, the full potential of the breeder concept can be tested in real time applications with a net energy delivery after only a few years.

6. References

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Appendix A: Program Structure

The structure of the computer program is shown in Figure 14.

The calculation starts with the reading of the input data comprised of the initial array size on the roof, average sun hours per day for each month, the percentage of panels produced each month which will be added to the roof, the payback times, and a parameter that characterizes the production capacity at the beginning of each year.

After the initial energy debt of the facility has been calculated, the program enters into a yearly loop. It calculates the number of panels which power the facility and derives the production capacity and equipment energy debt with the help of the payback times. The program flow then enters into a monthly loop due to monthly changes in insolation and calculates the number of panels made during the current month and the mismatch between the capacity and the available energy, and adds panels to the roof and to the sales volume. At the end of the year, the power sold in the form of manufactured panels and the supply energy debt are determined. Data are printed out at the end of each year of the breeder operation. The detailed description of the underlying algebra can be found in Appendix B.

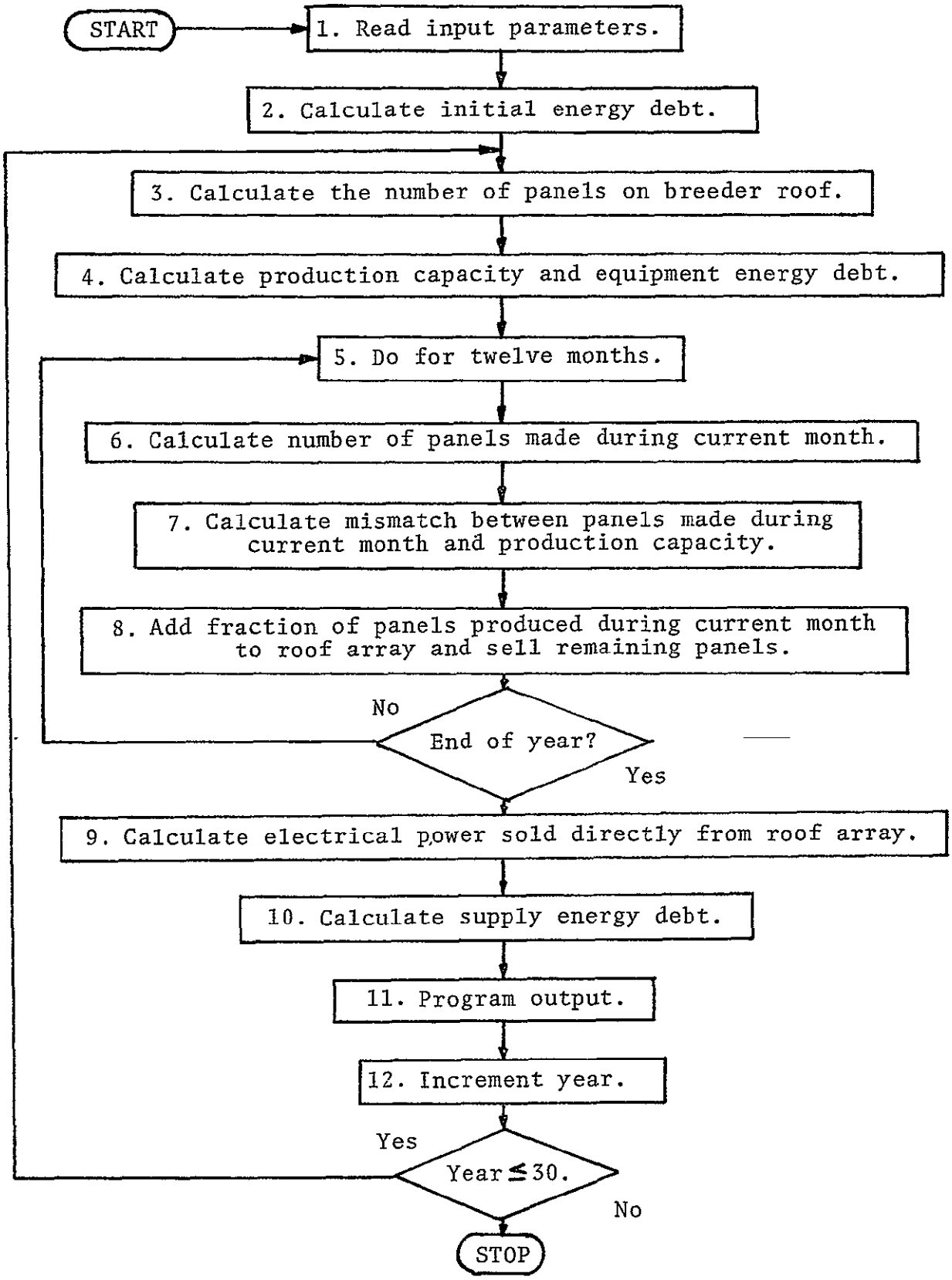

FIG. 14. PROGRAM STRUCTURE

Appendix B: Program Algebra

This appendix describes the algebra which comprises the internal structure of the computer program simulating the breeder. The section numbers refer to the program steps as outlined in Figure 14.

1. Read input parameters

The input parameters are:

a) Initial array size expressed in peak kW
b) Payback times, redefined as
   Direct energy payback time
   Supply energy payback time
   Equipment energy payback time
   and expressed in years.
c) Percentage of panels produced monthly which are added to the roof. This parameter can assume a new value each year.
d) Daily sun-hours averaged over each month. One value for each month.
e) Production capacity parameter expressed in sun-hours. This parameter is numerically chosen to be within the range of the monthly average sun-hours.

2. Calculate initial energy debt

The initial energy debt results from the energy expended in manufacturing the initial roof array. The debt

is determined by the total payback time, τ_B, and the panel lifetime, τ_L, according to

$$\begin{matrix}\text{initial} \\ \text{energy debt}\end{matrix} = \begin{matrix}\text{initial number of} \\ \text{modules on roof}\end{matrix} \times \frac{\tau_B}{\tau_L}$$

Initial energy debt is expressed in the number of panels of one peak kW size. Their energy value is determined by their peak power multiplied with the sun-hours over their lifetime.

3. Calculate the number of panels on breeder roof

Each month a percentage of the manufactured panels is added to the roof array to increase the energy input to the breeder. The panels, however, are tagged with the year in which they were made and are later removed from the roof when their lifetime, τ_L, has been expired. Therefore, at any time, only panels which were manufactured during the preceeding τ_L years provide input energy to the breeder.

4. Calculate production capacity and equipment energy debt

The production capacity is an expression for available manufacturing equipment during the year. It is determined at the beginning of each year by a parameter, p, and assumed to be constant during the year. Production capacity is expressed as the number of panels which can be manufactured due to invested equipment provided enough energy is available. The monthly production capacity is derived by dividing the yearly capacity by 12. The meaning of the monthly production capacity may be explained as follows: at times of reduced energy

inputs, such as during the winter months, panel production per month will not reach the monthly capacity, and part of the equipment will be idle. In summer, on the other hand, more energy is available than the monthly production capacity can utilize, and the excess energy will be sold. The production capacity is a non-decreasing function of time of the breeder operation. It is set to a constant value throughout the year in order to avoid the continuous removal and installation of manufacturing equipment if production capacity were to track the monthly insolation.

The production capacity is calculated as

$$\begin{array}{l}\text{production capacity}\\ \text{in number of panels}\\ \text{which can be made}\\ \text{per current year}\end{array} = \frac{\begin{array}{c}\text{number of panels}\\ \text{on roof at the}\\ \text{beginning of year}\end{array}}{\begin{array}{c}\text{direct energy}\\ \text{payback time}\end{array}} \times \frac{\text{p (sun-hours)}}{\begin{array}{c}\text{daily average}\\ \text{sun-hours}\end{array}}$$

The first term on the right hand side constitutes the number of panels which can be made during the year assuming average daily insolation. This follows from the definition of the payback time which is based on daily average sun-hours. The production capacity is expressed in units of this average insolation production and scaled by the production parameter, p, which has the dimension of sun-hours. The production parameter must be divided by the average sun-hours to make the second term on the right hand side unity when p assumes the average sun-hour value.

The production parameter, p, can assume any value within the range of the sun-hours per month. Setting p to the lowest sun-hour per month (winter month) means that the production capacity is small throughout the year and excess energy must

be sold during all months of higher insolation. In contrast, if p is set to the highest monthly sun-hour of the year, the production of panels will reach full capacity only during one summer month, and part of the equipment will be idle during most of the year.

Therefore, the production parameter allows us to simulate the trade-off between the effect of idle equipment in winter and insufficient equipment in summer.

Energy has been expended in the making of the production equipment. The amount of this energy can be determined from the production capacity since it is a function of the equipment size. It can be shown that the equipment energy debt as a function of production capacity is

$$\begin{matrix}\text{equipment}\\ \text{energy debt}\end{matrix} = \frac{\begin{matrix}\text{equipment}\\ \text{payback time}\end{matrix}}{\text{panel lifetime}} \times \text{capacity} \times \begin{matrix}\text{equipment}\\ \text{lifetime}\end{matrix}$$

Our model assumes an equipment lifetime of 30 years. For each production capacity value calculated at the beginning of every year, the equipment energy debt can be calculated.

5. Do for twelve months

At this point, the program enters into 12 loops according to the 12 months of the year. The program takes the various values of the monthly average sun-hours into account and uses them to calculate the monthly production. At the end of the 12 months, the production data will be added and printed out as yearly values.

6. Calculate number of panels made during current month

The number of panels made during the current month is defined as the number of panels which can be made from the available power disregarding any limiting production capacity. Therefore, the number of panels made during the current month is strictly a function of the roof array size and the average insolation during the current month. Assuming daily insolation averaged over the year, the monthly average of produced panels is

$$\frac{1}{12} \times \frac{\text{number of panels in roof array}}{\text{direct energy payback time}}$$

To account for the monthly changes in insolation, the above expression must be multiplied with the insolation (number of sun-hours) of the current month scaled by the average daily insolation to yield

$$\text{number of panels made during current month} = \frac{1}{12} \times \frac{\text{number of panels in roof array}}{\text{direct energy payback time}} \times \frac{\text{daily sun-hours averaged over current month}}{\text{daily sun-hours averaged over year}}$$

7. Calculate mismatch between panels made during current month and production capacity

The yearly production capacity has been calculated earlier. By dividing it by 12, a monthly production capacity can be arrived at. If the number of panels made during the current month is smaller than the monthly capacity, the whole amount of produced panels is listed as production of the current month, and the difference to the capacity is expressed as

panels not made and thus represents idle equipment. On the other hand, if the number of panels made during the current month exceeds the monthly capacity, only a number of panels equivalent to the monthly capacity is treated as production of the month, and the excess is represented as electrical energy which must be sold.

8. Add fraction of panels produced during current month to roof array and sell remaining panels

The percentage of panels produced each month which is allocated to be added to the roof array is an input parameter. Accordingly, these panels increase the input power available from the roof array for all following months. The remaining part of the current monthly production is sold and leaves the breeder facility.

9. Calculate electrical power sold directly from roof array

In the previous program step 7, the number of panels made during the current month which exceeded the production capacity and, therefore, represents excess electrical energy has been determined. To convert from the number of panels to electrical energy, the panel power must be multiplied by the operating hours during the direct energy payback time. Since one panel represents one peak kW, the monthly power produced may be calculated as

$$\text{monthly power produced} = \text{monthly excess panels made} \times \text{daily sun-hours averaged over year}$$

$$\times \text{ days per year} \times \text{direct energy payback time in years}$$

10. Calculate supply energy debt

The supply energy debt is the energy component contained in the supplies and materials which are used in the module manufacture. This debt is calculated from the number of panels made during the current year as

$$\begin{matrix}\text{supply}\\ \text{energy debt}\end{matrix} = \begin{matrix}\text{number of panels}\\ \text{made during year}\end{matrix} \times \frac{\text{supply payback time}}{\text{panel lifetime}}$$

11. Program Output

The program prints out accumulated values of energy debt and energy return as well as the yearly roof array size, module and excess electrical energy sale and the yearly idle capacity.