PHOTOVOLTAIC DECISION ANALYSIS

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ABSTRACT

This paper is concerned with the development and implementation of a methodology that analyzes information relating to the choice between flat plate and concentrator technologies for photovoltaic development. A Decision Analysis approach is used to compare and systematically evaluate the two photovoltaic energy conversion systems. This methodology provides a convenient framework for structuring the decision process in an orderly sequential fashion via decision trees, incorporating information on subjective probabilities of future outcomes, and focusing attention on critical options and uncertainties.

A significant tenet of the analysis is that any set of energy technologies must be compared on the basis of the cost of generated energy rather than simply on the basis of the cost of hardware production. As a result, the cost analyses presented focus on a comparison of energy generated by the photovoltaic systems in units of $/kWh, rather than on a comparison based on units of $/peak kW. The criterion for choice between the alternative technologies is chosen to be minimization of expected cost per unit of energy generated.

After presenting the decision tree framework used to structure the problem, including a classification of the components of the competing technologies, a detailed procedure for calculating the system cost per kilowatt-hour for each path through the decision tree is described for each technology and methods for assessing subjective probability distributions are discussed.

PREFACE

The research discussed in this paper reflects work undertaken by the author as part of the Planning and Analysis for Development of Photovoltaic Energy Conversion Systems project, supported at the MIT Energy Laboratory by the U.S. Department of Energy (formerly the U.S. Energy Research and Development Administration).

The author would like to express his gratitude for the extremely helpful suggestions of Dr. Richard D. Tabors.

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I INTRODUCTION

Solar photovoltaic conversion systems offer a potential for providing significant quantitites of electrical energy from an inexhaustible resource. If these systems can generate electricity economically, over a wide range of applications, enormous benefits to society can result from the reduced dependence on fossil fuel resources.

The government's Photovoltaic Program has been structured to reduce rapidly the cost of photovoltaic systems over the next two decades, and to promote rapid expansion of production and use. The program has set price and production goals through the end of this century. If these goals are achieved, photovoltaic systems will be economically competitive with alternative energy sources for dispersed on-site applications as well as for central station power generation. Several technological options that are potentially economically viable in the early to mid 1980's are presently being pursued in parallel. These options range from flat plate single-crystal silicon systems to highly concentrating systems that require compound semiconductor solar cells such as gallium arsenide. The goals of the program, rather than being technology specific, are systems goals that can be met by any of the competing photovoltaic technologies. Important issues such as how the government's Research and Development (R&D) resources can best be allocated both across and within the technology options, what the criterion or criteria are on which technology choice decisions should be based, and which methodologies can best be used to model the decision process, have not yet been clearly addressed by the government's program planners.

In this paper we are concerned with the development and implementation of a methodology that analyzes information relating to an important Photovoltaic Program decision: the choice between flat plate and concentrator technologies for photovoltaic development. A significant tenet of the analysis is that one must compare any set of energy technologies on the basis of the cost of generated energy rather than on the basis of the cost of hardware production alone. As a result, the cost analyses within this report focus on a comparison of energy generated by the photovoltaic systems in units of \$/kWh, rather than on comparisons based either on units of \$/peak kW or \$/unit area.

A Decision Analysis approach has been chosen for the comparison and systematic evaluation of the two photovoltaic energy conversion systems. Formal decision analysis not only forces meaningful structure on informal reasoning, but provides a convenient framework for structuring a decision process in an orderly sequential fashion, incorporating information on subjective probabilities of future outcomes, and focusing attention on critical options and uncertainties. The methodology also facilitates the clear definition of data and information required for use within the decision framework. The basis of choice between the alternative technologies, i.e., the objective function, is chosen to be minimization of <u>expected</u> discounted cost per unit of energy generated (\$/kWh), for a system manufactured in 1986 and beginning its operation in the following year.[1] The year 1986 represents the Photovoltaic Program's major milestone year for achievement of 'mid-term' goals. Other milestone years such as 1982 or 2000 could also be used.

In Sections II and III, the decision tree framework used to structure the problem is shown to depict a series of technological and economic decision and chance nodes unfolding sequentially within the 1986 time frame. In this way, component characteristics of the competing technologies are specified along with probability distributions on future costs and efficiencies. The subjective probability distributions will be conditional, not only upon a well defined decision path, but also upon a specific, given, R&D budget allocation scenario across major technology tasks from 1976 to 1986. A detailed procedure for calculating the outcome measure, total discounted cost per kilowatt-hour, for each path through the decision tree, is then presented for each technology, along with complete lists of the system parameters that must be assessed to perform these calculations. A uniform cost account structure is thereby developed which allows the two systems and system elements to be compared on an equivalent basis.

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[1] If it is decided not to include estimates of operation and maintenance costs, the choice will still be made on the basis of minimizing expected discounted annualized costs, in units of \$/kWh, (rather than simply on the basis of minimizing expected capital costs of hardware production in units of \$/peak kW), since the two system lifetimes will be different.

Also, unless otherwise noted, all costs considered in this paper are 1986 costs in 1976 dollars.

In Section IV, we discuss the implementation of Decision Analysis. First, methods for assessing and aggregating subjective probability distributions, the final inputs to the decision analysis, are presented. Once the required subjective probability distributions on costs and efficiencies have been assessed, and the outcome measure for each path through the decision tree has been calculated, the straightforward decision tree technique of 'averaging out and folding back' can be employed to yield an expected discounted cost for each of the competing systems.[2] An optimal strategy can then be identified and its robustness tested via sensitivity analyses. The procedure of folding back the decision tree is outlined in this section.

Section V presents concluding remarks on the nature of decision trees, and on the future direction of our decision analysis work.

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[2]A basic introduction to the fundamentals of decision analysis can be found in the text by Howard Raiffa [1].

II FLAT PLATE SYSTEM

A. Classification of Components

The following components of a flat plate photovoltaic conversion system are considered in our analysis (note that the first five components make up a generic flat plate module):

1. Silicon Material - Semiconductor Grade vs Solar Grade Silicon.
2. Crystal Growth - Sheet/Ribbon Growth and Cutting vs Ingot Growth and Slicing.
3. Automated Cell Fabrication - Includes etching surface macrostructure, junction formation, metallization, antireflective coating, etc.
3. Encapsulation Material - Polymer vs Glass.
5. Automated Module Assembly and Encapsulating - Includes substrate, superstrate, interconnection, assembly and testing, etc.
6. Support and Wiring - Includes support structure, foundations, array wiring (not intra-module), and land.
7. Installation.
8. Operation and Maintenance.

The direct conversion of light energy to electrical energy is accomplished by a silicon photovoltaic semiconductor device called a solar cell. A non-concentrating flat plate module consists of a series of encapsulated solar cells mechanically and electrically combined. An array is formed by joining modules in various series-parallel combinations to meet designed power needs and attaching a support structure. The solar cells are the major cost driver in the manufacture of flat plate arrays.

To develop reliable, efficient, low-cost silicon solar arrays, the Energy Research and Development Administration (ERDA) has created the Low-Cost Silicon Solar Array Project (LSSA). The Jet Propulsion Laboratory (JPL) is managing this flat plate silicon program for ERDA.[3]

Silicon solar cells are presently fabricated from extremely pure semiconductor-grade silicon, using processes that are quite costly and labor-intensive. Silicon material studies and experiments are presently pursuing improved low-cost refinement processes for semiconductor-grade silicon. Other studies are also exploring the feasibility of utilizing silicon material that has a higher level of impurities. Such material, termed 'solar-grade' silicon, may yield lower performance efficiencies than semiconductor-grade silicon but will be much less expensive to process.

Further cost reductions in silicon cell manufacture are possible if the necessity to grow and slice large cylinders or ingots of monocrystalline silicon into thin wafers could be avoided. While methods are presently being evaluated for reducing the cost of silicon wafer fabrication from ingots, development work is also progressing on processes for growing continuous ribbons of crystalline silicon and on other processes for producing crystalline sheets. These methods introduce unwanted impurities into the silicon and are not yet as rapid as traditional ingot growth and slicing, but they can dramatically reduce both cost and the waste of silicon in the crystal growth stage. Although

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[3] For detailed information about the LSSA project see [2].

all of the ribbon and sheet growth techniques still must be regarded as uncertain, it is hoped that one or more of these processes will become a cost-effective means of fabricating efficient solar cells.

A low-cost flat plate system also requires an economical module encapsulant that has a high demonstrated reliability and a long life expectancy (say, 20 years) in terrestrial environments. In addition to transmitting a maximum amount of sunlight to the solar cells, the encapsulant must protect the cells and electrical conductors from the detrimental effects of a variety of environmental conditions. Several studies in progress are examining various polymers and glasses as potential encapsulant materials.

The projected high costs of material for installing arrays has caused increased efforts toward improving module and cell conversion efficiency. Such performance improvements would reduce the area and amount of installation material required per unit of power output, and thereby reduce the installed cost of arrays in the field.

In general, it seems that the prospects for the future cost reduction of flat plate systems depend more on the application of mass-production methods to known techniques than on fundamental technological breakthroughs or new concepts.

B. Decision Tree

A prototype decision tree structure for the flat plate system is displayed in Figures 1 and 2. The concentrator section of the tree is continued on later figures. Note that a □ represents a decision node and a ○ represents a chance node. Considerations of various silicon material processes to produce the different grades of silicon, various sheet and ribbon growth methods, and other complicating features, can readily be handled, if necessary, by inserting additional forks in the body of the tree. Subjective probability distributions at all chance nodes will be assessed from experts in a systematic way, to be described in Section IV.

In our decision trees, for both the flat plate and concentrator systems, each chance event fork is symbolically represented by a probability fan. This schematically indicates the potential occurrence of a large number of event possibilities, i.e., a many-event probability distribution on cost or efficiency. One way of dealing with such multiple possibilities, as described later, is to represent them in the decision tree model by simplified few-event distributions. Note that subsequent decisions are always dependent upon the branch followed at the simplified schematic event fork. Also, probability distributions assessed for any chance event fork must be assessed conditionally upon all of the chance events and decisions preceding this fork and, in our problem, upon a specific, given, R&D budget allocation scenario.

C. System Parameters

Although not appearing explicitly in the flat plate decision tree, the values of several important system parameters must be assessed for each path through the tree:

1. Encapsulated cell efficiency, η_{ec}.
2. Geometrical module packing factor efficiency, η_{pf}.

3. Wiring and mismatch efficiency, η_{wm}.

4. Fractional silicon yield losses (see [3]):

   a. Silicon to wafer yield, Y_w.

   b. Silicon not lost through etching wafer during cell fabrication, Y_{etch}. (Note that the surface area of the wafer remains approximately the same.)

   c. A yield from breakage and testing, from cell fabrication through module assembly, Y_{mfg}.

5. Silicon density in kg/m^3, D.

6. Expected cell thickness in the module in meters, TH. (1 mill = 2.54×10^{-5} meter)

7. System capacity factor, CF. (location and device specific)

8. Annualized average insolation, I_{ave}, in average kW/m^2;
   OR the ratio average kW/peak kW = δ, $\delta < 1$.
   Both I_{ave} and δ are location and device specific.
   Note that $I_{ave} = \delta\ kW/m^2$ and $I_{peak} = 1\ kW/m^2$.

9. Expected flat plate system lifetime in years, T_F.

10. Discount rate, r.

11. Either a nominal fixed charge rate, FCR; OR a captial recovery factor, CRF, calculated using T_F and r.

D. Cost Analysis

As we discussed earlier, the unit of comparison for the photovoltaic systems was chosen to be dollars per unit of energy generated ($/kWh). A procedure for converting flat plate system component costs from their generic units into units of $/kWh is described in this section. First, capital costs, in $/unit area, are summed for each path through the decision tree. These sums are then converted into units of $/peak kW,

\$/average kW, and \$/rated kW, before the final conversion to \$/kWh is made. The basic unit area for the flat plate system is taken to be a unit of module area. Recall that all capital costs considered in our analysis are 1986 costs in 1976 dollars.

Let:

C_1 = silicon material cost, in \$/kg-Polysilicon.

C_2 = value added crystal growth cost, in $\$/m^2$-wafer.

C_3 = value added cell fabrication cost, in $\$/m^2$-cell.

C_4 = value added encapsulant cost, in $\$/m^2$-module.

C_5 = value added module assembly and encapsulating cost, in $\$/m^2$-module.

C_6 = support and wiring cost, in $\$/m^2$-module.

C_7 = installation cost, in $\$/m^2$-module.

$SCUA_F$ = total flat plate system capital cost per unit area, in $\$/m^2$-module.

PCAP = total flat plate system capital cost, in \$/peak kW.

ACAP = total flat plate system capital cost, in \$/average kW.

RCAP = total flat plate system capital cost, in \$/rated kW.

Converting each component cost into units of $\$/m^2$-module and summing, we have:

$$SCUA_F = C_1 \left[(D \cdot TH) \frac{\eta_{pf}}{Y_w \cdot Y_{etch} \cdot Y_{mfg}} \right] + C_2 \left(\frac{\eta_{pf}}{Y_{mfg}} \right) + C_3 (\eta_{pf}) + C_4 + C_5 + C_6 + C_7$$

where:

$$\eta_{pf} = \frac{m^2\text{-cell}}{m^2\text{-module}} \quad , \frac{\eta_{pf}}{Y_{mfg}} = \frac{m^2\text{-wafer}}{m^2\text{-module}} ,$$

and

$$(D \cdot TH) \frac{\eta_{pf}}{Y_w \cdot Y_{etch} \cdot Y_{mfg}} = \frac{\text{kg-Polysilicon}}{m^2\text{-module}} .$$

Letting

$$\eta_{sys} = \eta_{ec} \cdot \eta_{pf} \cdot \eta_{wm}$$

be the flat plate system efficiency, we can convert $SCUA_F$ into units of \$/peak kW, \$/average kW, and \$/rated kW, as follows:

$$PCAP = \frac{SCUA_F}{I_{peak} \cdot \eta_{sys}} , \text{ where } I_{peak} = 1 \text{ kW/m}^2 ;$$

$$ACAP = \frac{SCUA_F}{I_{ave} \cdot \eta_{sys}} ; \text{ and}$$

$$RCAP = \frac{CF \cdot SCUA_F}{I_{ave} \cdot \eta_{sys}} .$$

Note that average kW = (CF) · rated kW for a system with no storage, and $ACAP = \frac{1}{CF} RCAP = \frac{1}{\delta} PCAP$.

For each path through the decision tree, the payoff or outcome measure, total discounted cost per kWh, is determined in the following way. The total system capital cost for the path, in \$/average kW, is annualized and converted into units of \$/kWh. After adding the path Operation and Maintenance (O&M) cost, also converted into units of \$/kWh (either from \$/rated kW/yr or \$/average kW/yr), the new total, which represents a uniform annualized energy cost in constant 1976 dollars, is then discounted for convenience to the base year, $t_0 = 0$, i.e., 1976. The result is the present value of the system's first year energy cost to be used as our outcome measure. This procedure is outlined below.

Recurrent O&M costs are incurred over the expected system lifetime of T_F years, beginning in year $t_{sm} + 1$, the first year of system operation, assumed to be 1987. (Recall that the system is manufactured in 1986.) Assume that the O&M cost stream is constant over this period.

Let:

$\overline{OM}$ = annualized O&M costs in \$/rated kW/yr given in base year 1976 dollars over the T_F years: $t_{sm} + 1$ through $t_{sm} + T_F$.
(It is possible that these annualized costs will be assessed in \$/average kW/yr.)

TSC = total discounted system cost in \$/kWh -- represented by the present value of the system's first year energy cost from a uniform annualized cost stream in constant 1976 dollars.

Capital costs are annualized by multiplying either by a capital recovery factor, CRF (based on a system life of T_F years and a discount rate r), or by a nominal fixed charge rate, FCR. Although CRF is less than FCR, (CRF does not take account of insurance premiums and taxes), it does not matter which factor is used in the flat plate/concentrator system comparison as long as consistency is maintained.

Calculating CRF, given T_F and r, we have:

$$\frac{1}{CRF} = \sum_{t=1}^{T_F} \frac{1}{(1+r)^t} \Rightarrow CRF = \frac{r}{1-(1+r)^{-T_F}}$$

The total discounted system cost is then given by:

$$TSC = \left[\frac{ACAP \cdot CRF + (\overline{OM}/CF)}{8760 \text{ hr/yr}}\right] \cdot \frac{1}{(1+r)^{t_{sm} - t_o}},$$

where $t_{sm} - t_o = 10$.

Note that: if O&M costs are assessed in units of \$/average kW/yr, the CF term should be omitted; RCAP/CF can be substituted for ACAP; and if deemed more appropriate, a nominal FCR can be substituted for CRF. It should also be pointed out that if O&M costs are not included in the analysis, total system capital costs for each path through the decision tree should still be annualized and converted into units of \$/kWh, since the flat plate and concentrator system lifetimes will be different.

III CONCENTRATOR SYSTEM

A. Classification of Components

The components of a concentrator photovoltaic conversion system that are considered in our analysis are as follows:

1. Concentrator Solar Cells (fully encapsulated) - Silicon vs Compound Semiconductor.
2. Concentrator Optics - Low vs Medium vs High Concentration Ratio Ranges.
3. Tracking - Periodic Seasonal Adjustment vs 1-Axis vs 2-Axis.
4. Support and Wiring - Includes support structure, foundations, array wiring and land.
5. Automated Array Assembly and Testing.
6. Cooling System - Passive vs Active.
7. Installation.
8. Operation and Maintenance.

Concentrating photovoltaic systems reduce the area of the presently very expensive solar cells that are required to produce a unit of electrical power. High-cost solar cell area is then effectively replaced by equivalent areas of presently lower-cost reflective or refractive materials. The economics of concentrating systems are thereby very attractive, at least for the short run. To reduce the future costs of concentrator arrays, emphasis will be placed in two areas: improving the cell conversion efficiency and reducing the cost of the concentrator optics. Cell performance will have a higher priority than cell cost. Two cell technologies are being pursued: silicon cells for application in low- and medium-concentration ratio ranges; and high-cost compound semiconductors, such as gallium arsenide (GaAs) -- now as much as ten times as expensive as silicon -- for application in high concentration ranges where higher temperatures must be tolerated. In the latter case, cell encapsulation schemes must be devised which are capable of withstanding potentially very high temperatures and thermal shock.[4]

A large number of designs for concentrator optics (see Figure 3, adapted from [4]) are being evaluated to determine which interface most effectively with solar cells and have the potential for low-cost mass production. In the low-concentration ratio range of 2 to 10, V-troughs and compound parabolic concentrators (CPCs) are being considered. These devices require only periodic seasonal adjustment. Linear parabolic reflectors and cylindrical Fresnel lenses are being considered for use in the medium-concentration range of 10 to 100. These line-focusing devices require one-axis tracking of the sun. In the high-concentration range of 100 to 2000, reflecting paraboloids and circular Fresnel lenses, both point-focusing and requiring two axes of tracking, are the main devices under consideration. Note that the tracking requirements of all but the low-concentration range optical systems, may limit their eventual use in some applications.

Passive cooling systems utilizing finned structures and natural ambient air convection are heavy and use a considerable amount of material. Active systems utilizing a pumped fluid or forced-air con-

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[4]The concentrator systems development program is under the technical management of Sandia Laboratories for ERDA.

vection are more complicated and more expensive, but offer the advantage of operation at constant temperatures, lower than that of passive systems. At this time, passive systems appear to be more reliable, but in the high-concentration ratio range where very high temperatures are produced, active cooling systems may be required since the performance of photovoltaic devices degrades as temperatures increase. In such cases it may be advantageous to utilize the thermal energy collected by the flowing coolant for space heating, air conditioning, and water heating.

It should be noted that due to insufficient hardware experience very little is presently known about installation and operations and maintenance of either concentrator or flat plate systems. Subjective probability distributions on the future costs of these components will likely be the most difficult to assess and the least reliable.

B. Decision Tree

A prototype decision tree structure for the concentrator system is displayed in Figures 4 to 7. Nominal concentration ratio values have been chosen as representative of each of the low, medium, and high ranges. Many complicating features, such as consideration of various cell production processes for either silicon or gallium arsenide, can be accommodated, if necessary, by inserting additional forks in the decision tree. Again, subjective probability distributions at all chance nodes will be assessed from experts in a systematic way, to be described in Section IV.

C. System Parameters

Important system parameters that must be assessed for each path through the concentrator decision tree are:

1. Geometrical concentration ratio, X.
2. Encapsulated cell efficiency, η_{ec}.
3. Total optical efficiency of concentrator, η_{op}, including losses due to geometry of optics, shadowing and blocking, mirror reflectivity, receiver absorption, etc.
4. Wiring and mismatch efficiency, η_{wm}.
5. System capacity factor, CF.
6. $I_{ave} = \delta$ kW/m^2, defined earlier.

   (Items 5 and 6: These parameters are both location and device specific.)
7. Expected concentrator system lifetime in years, T_C.
8. Discount rate, r. (same as for the flat plate system)
9. Fixed charge rate, FCR; OR a capital recovery factor, CRF, calculated using T_C and r.

D. Cost Analysis

In this section we discuss the procedure to be followed in converting concentrator system component costs from their generic units into units of \$/kWh. First, capital costs, in \$/unit area, are summed for each path through the decision tree. The basic unit area for the concentrator system is taken to be a unit of aperture area.

Let:

C_1 = encapsulated cell cost, in \$/m^2-cell.

C_2 = concentrator optics cost, in \$/m^2-aperture.

OC = sum of all other capital costs, each measured in \$/m^2-aperture.

$SCUA_C$ = total concentrator system capital cost per unit area, in $/m^2$-aperture.

Converting all component costs into units of $/m^2$-aperture and summing, we have:

$$SCUA_C = \frac{C_1}{X} + C_2 + OC$$

where: $X = m^2\text{-aperture}/m^2\text{-cell}$.

Using the concentrator system efficiency, defined as

$$\eta_{sys} = \eta_{ec} \cdot \eta_{op} \cdot \eta_{wm},$$

$SCUA_C$ can be converted into units of $/peak kW, $/average kW, and $/rated kW, in the same way as described earlier for the flat plate system. The procedure for calculating total discounted system costs, in $/kWh, for each path through the decision tree also remains the same.

By the procedures described in Sections II D and III D, the framework of a uniform cost account structure has been developed which will allow the two photovoltaic conversion systems and system components to be compared on an equivalent basis.

Before closing this section we must note that certain system costs have been ignored in our flat plate/concentrator comparison. These include:

1. Storage
2. Power Conditioning

3. Indirect Costs:

Architectural and Engineering Fees

Contingencies and Spare Parts

Shipping

Interest during Construction

Exclusion of these system costs should not affect the relative choice between the two photovoltaic technologies.

Another important consideration is that our analysis not only depends on location but may also be application-dependent, since various component costs of each system may well depend on whether the application is residential, commercial/industrial, or central power station. In the event that application dependence is determined to be a major consideration, a decision analysis can be done for each considered application.

IV IMPLEMENTATION OF DECISION ANALYSIS

A. Subjective Probability Assessment

In our decision tree model there are many uncertain quantities -- costs and efficiencies -- that could take any of a large number of possible values. These multiple possibility situations have been schematically represented by many-event probability distributions at each chance node. A cumulative probability approach can be used to approximate such distributions by simplified few-event distributions described by chance nodes having only three, four, or five branches. This type of simplification both cuts assessment effort and greatly reduces the number of end points in the tree for which outcome measures must be evaluated.

The simplest procedure is to assess five points on a cumulative distribution (values of the uncertain variable corresponding to cumulative probabilities of 0, .25, .50, .75, and 1.0) that divides the range of possible values of the uncertain variable into four intervals, in each of which it is felt that the actual value of the variable is equally likely to fall. A four-event probability distribution is then constructed simply by assigning a .25 probability to each of the values of the variable corresponding to the midpoints of the four equally likely value ranges. If we adopt the letter C, with a subscript representing the probability assessed, as a notation for cumulative probability values of the uncertain variable, then this procedure would assign a probability of .25 to each of four events or values:

$$.5(C_0 + C_{.25});\ .5(C_{.25} + C_{.50});\ .5(C_{.50} + C_{.75});\ .5(C_{.75} + C_{1.0}),$$

where C_α is the value assessed as corresponding to the cumulative probability of α, $0 \leq \alpha \leq 1$.

Simplifed formulas are also available that make it acceptable to use three or five branches on each chance event fork in the decision tree [5]. These formulas produce more accurate probability distributions than the four-event distribution method described above, because they assign differing probabilities to each of the specified three or five events, rather than the same probability to each. To use the three-event formulas only the C_0, $C_{.50}$, and $C_{1.0}$ cumulative probability values must be assessed. The five-event formulas require more assessment effort as well as greater computational effort.

A number of studies have shown that subjective probability distributions can be substantially improved by averaging together the assessments of several experts rather than relying on a single expert. These studies have also shown that from a practical standpoint there is no evidence to suggest that the use of methods other than simple averaging to aggregate assessments (such as Delphi procedures) will improve the quality of the resulting subjective probability distribution [6].

B. Folding Back the Decision Tree

As we mentioned earlier, once the required subjective probability distributions on costs and efficiencies have been assessed, and the outcome measure (total discounted cost per kWh) for each path through the decision tree has been calculated, an 'averaging out and folding back' procedure can be employed to yield an expected discounted cost for each of the competing photovoltaic systems. This procedure calculates, in a backward fashion, the expected cost looking ahead into the future, if we were to arrive at any specific node on the decision tree. Expected value calculations are performed at chance nodes, and at each decision node the branch associated with the lowest expected cost is selected. Working backwards to the beginning of the tree by successive use of these devices allows an optimal strategy to be identified.[5] Sensitivity analyses can then be used to test the robustness of such a strategy. Note that the 'averaging out and folding back' process is often referred to as the process of backward induction in the theory of dynamic programming.

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[5]For simple examples of this procedure see the texts by H. Raiffa [1] or R.V. Brown et al. [5].

V. CONCLUDING REMARKS

Decision trees that exhibit the structures of real problems have a habit of getting rapidly out of hand -- branches proliferate and the tree never seems to stop growing. In point of fact, in most realistic problems, as in ours, one cannot possibly begin to chart out all the possible sources of uncertainty, future decisions, and action alternatives. Compromises must be made. Omission or deletion of many possible occurrences and choices -- thinning or pruning of the tree -- has been essential to reduce our complicated problem to both manageable and comprehensible dimensions. Still further refinement will be necessary.

The future direction of our decision analysis work will involve extensive interaction with the prime contractors of the Photovoltaic Program in order to: further develop our information and data base (including the determination of nominal values of system parameters); obtain technological advice as an aid to further refinement of the decision tree structure; construct several plausible alternative R&D budget allocation scenarios across major technology tasks, given a total prospective budget for each technology from 1976 to 1986; and identify experts who can help us assess the required subjective probability distributions. The next step will be to assess these distributions, calculate path outcomes via methods described earlier, and then fold back the decision tree. By assessing the probability distributions conditional on an R&D budget allocation, we can evaluate the effects of different R&D scenarios in reducing the future system costs of each technology.

It is our hope that focusing upon the flat plate vs concentrator decision structure will provide support for critical technology and program planning issues associated with the Photovoltaic Program over the next several years.

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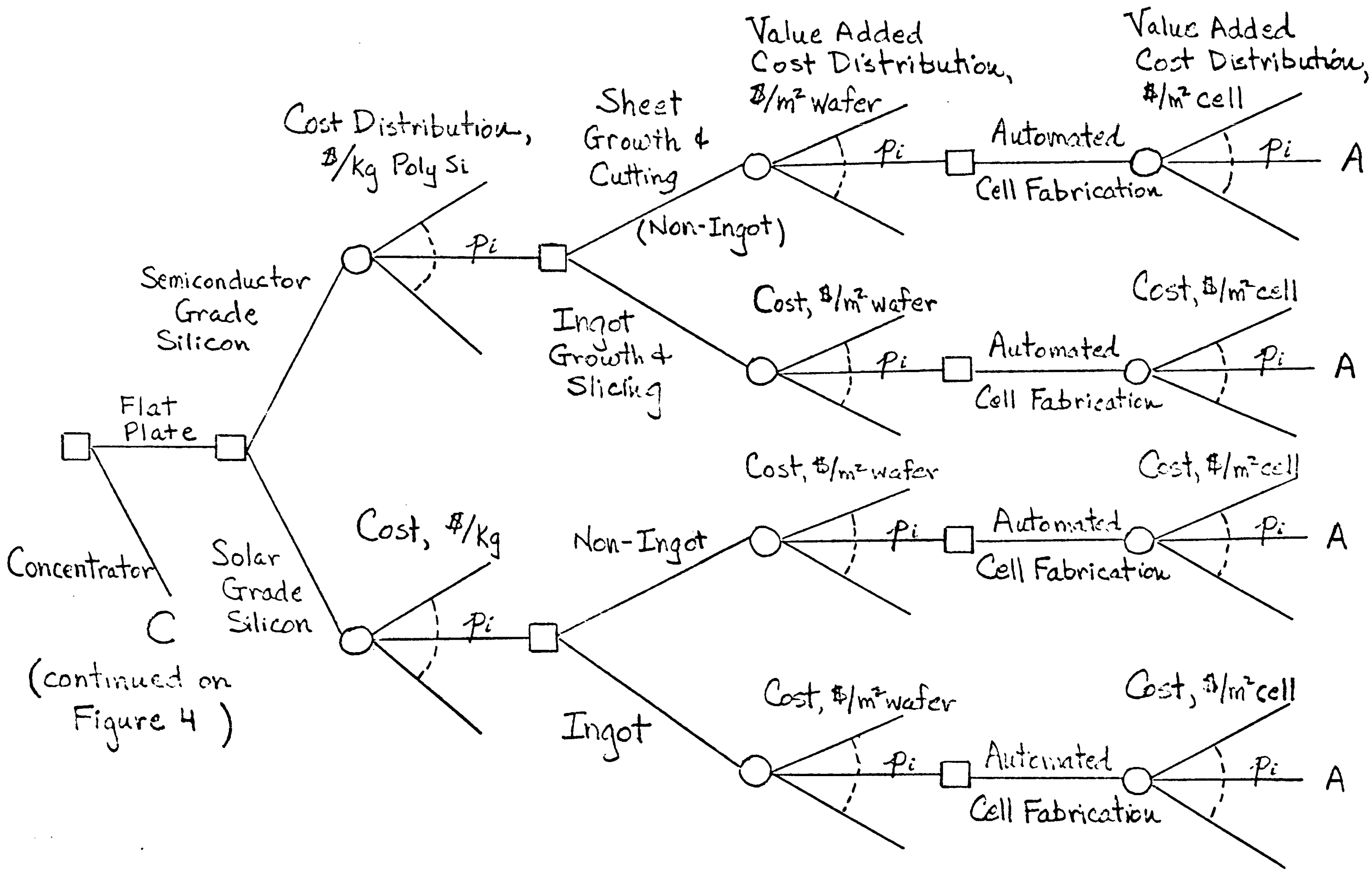

Figure 1

DECISION TREE FOR FLAT PLATE SYSTEM

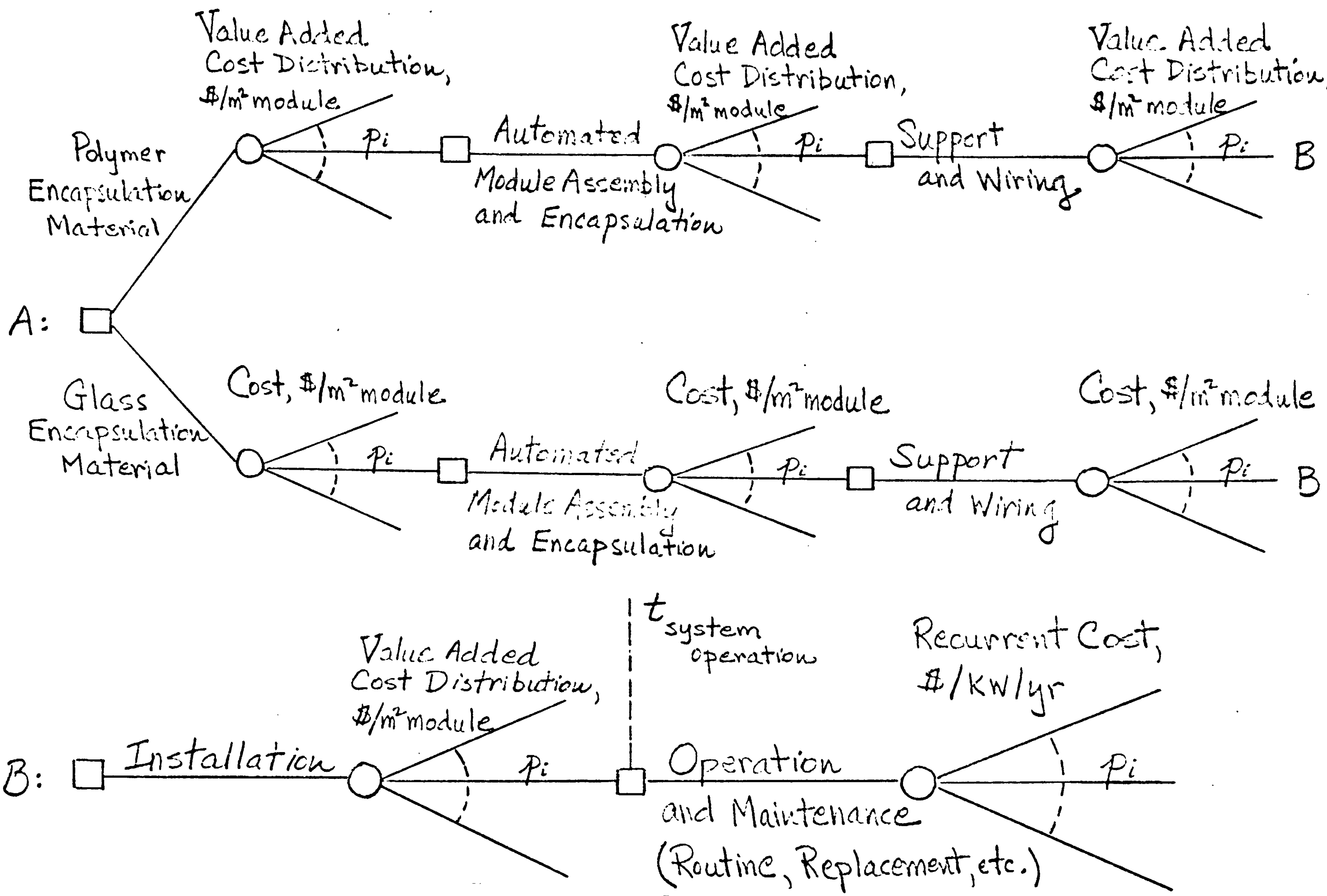

Figure 2
DECISION TREE FOR FLAT PLATE SYSTEM (continued)

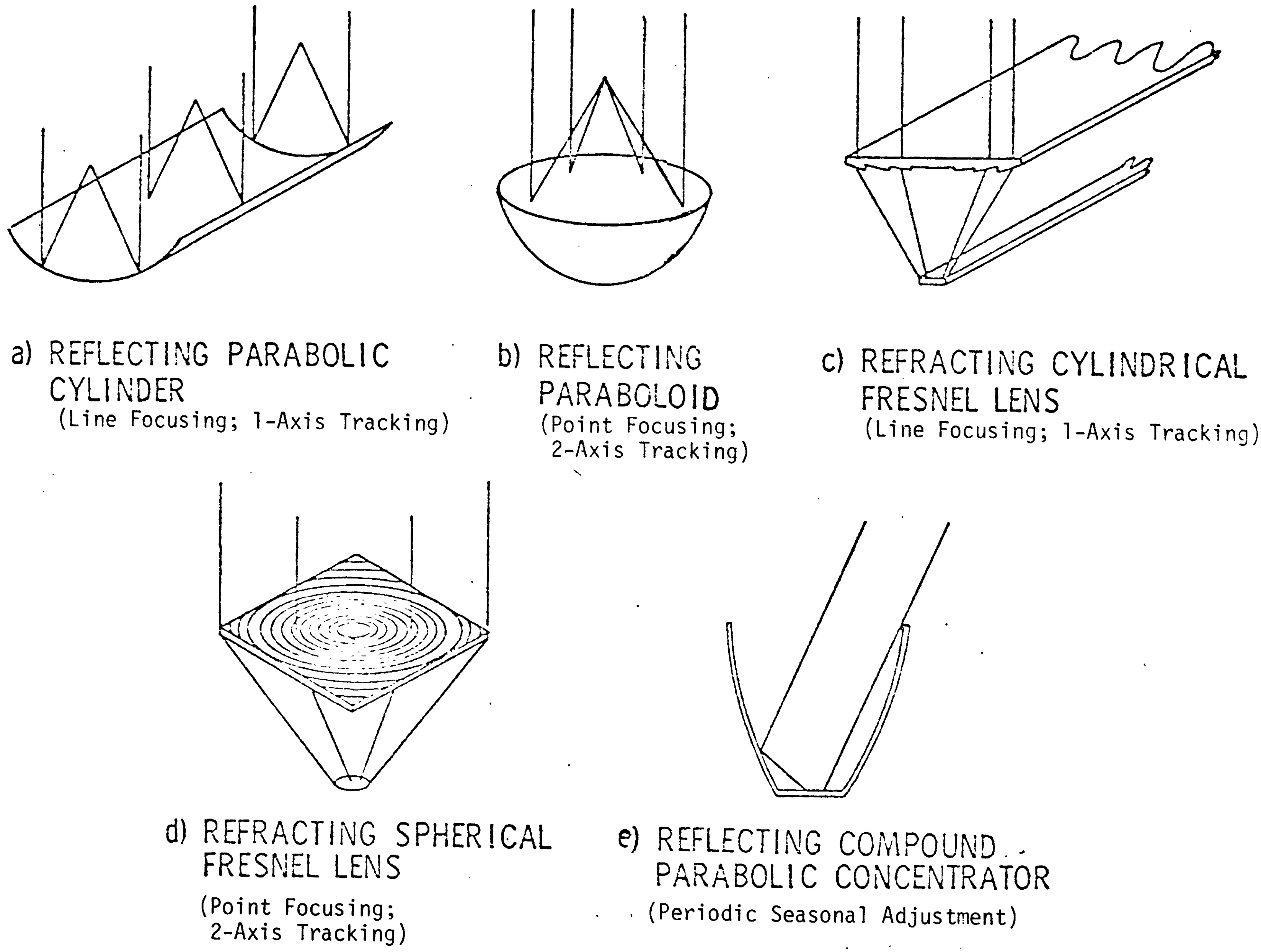

Figure 3

CONCENTRATING OPTICS UNDER CONSIDERATION
FOR PHOTOVOLTAIC APPLICATIONS (Adapted from [4])

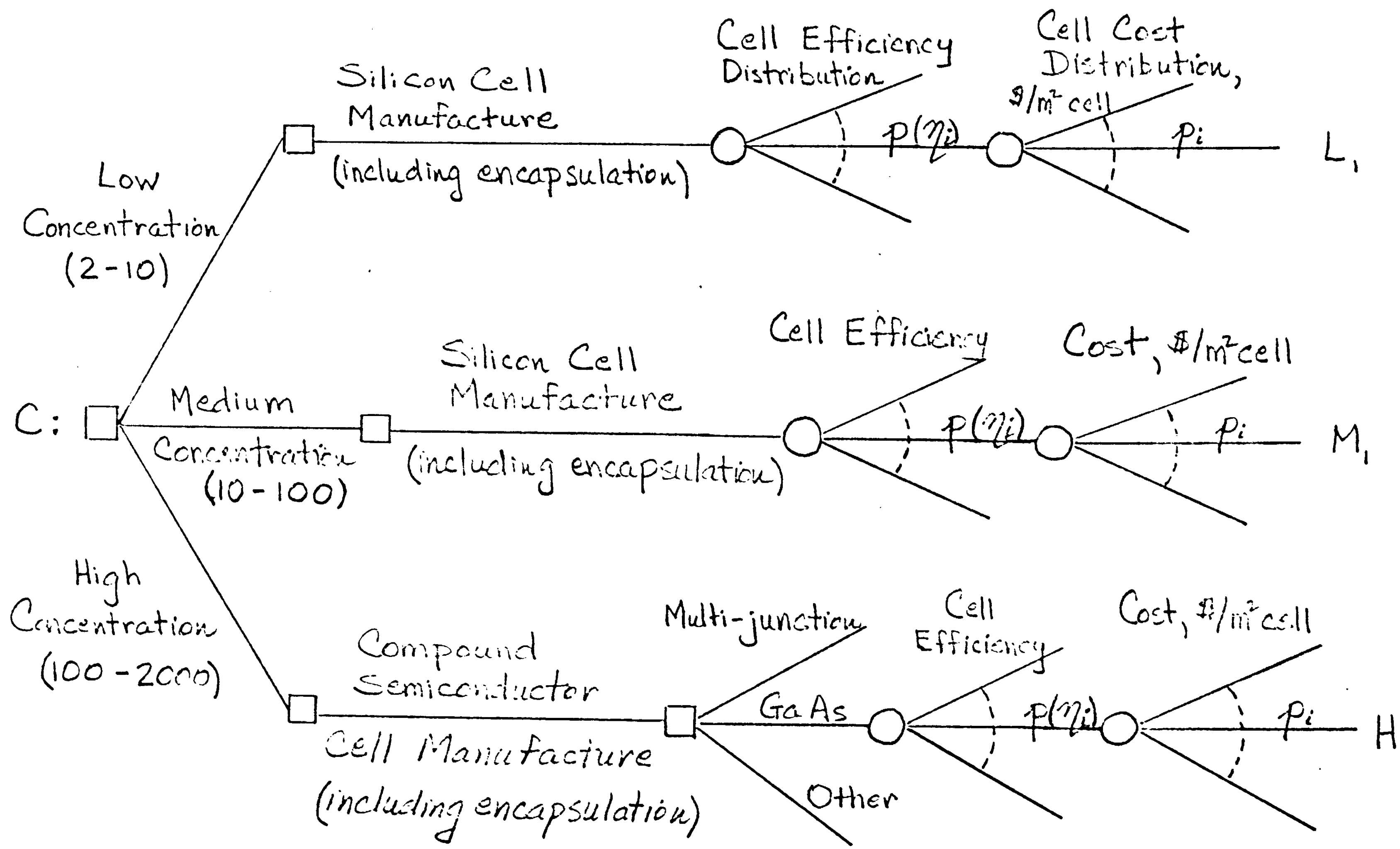

Figure 4
DECISION TREE FOR CONCENTRATOR SYSTEM

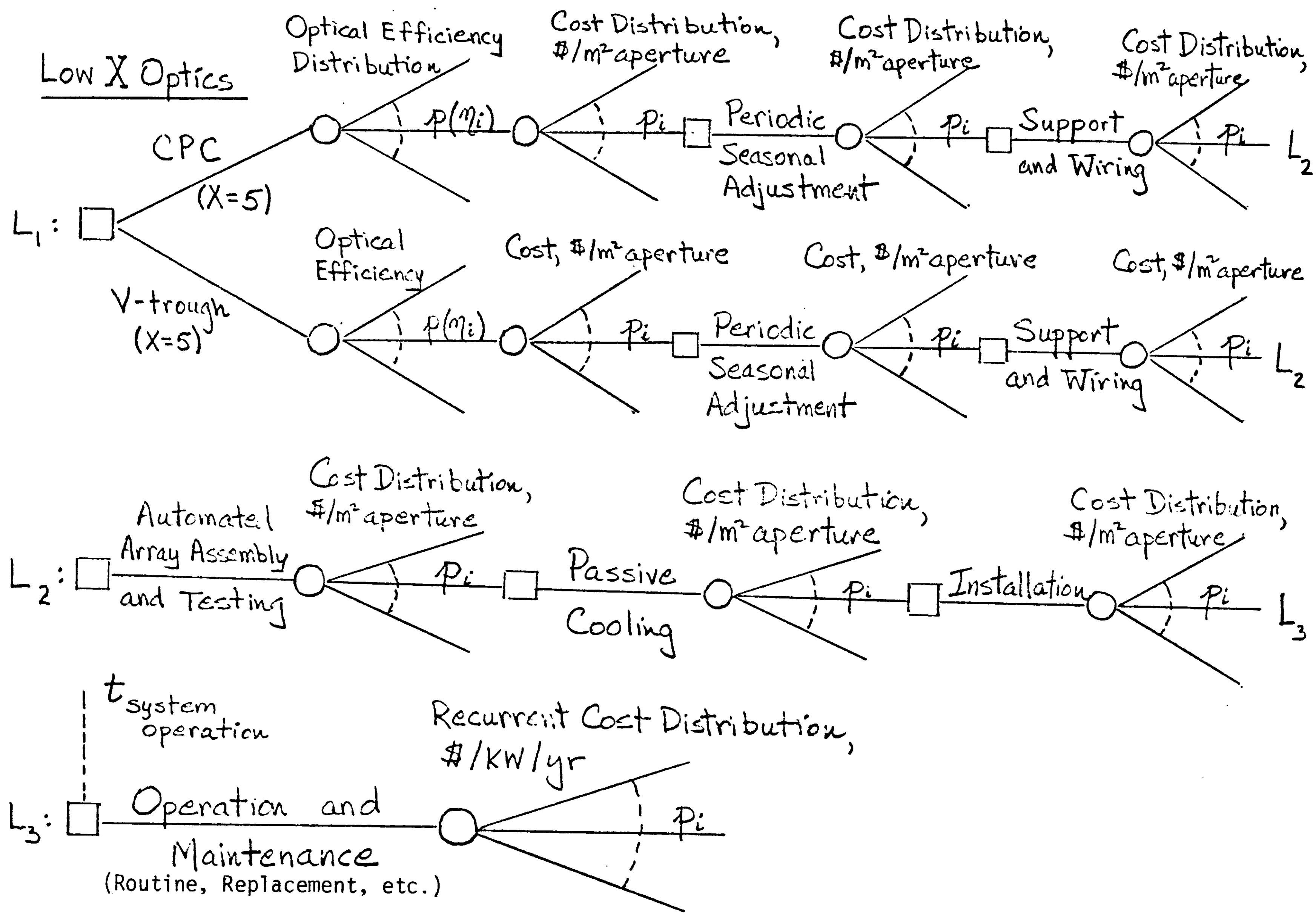

Figure 5

DECISION TREE FOR CONCENTRATOR SYSTEM (continued from Figure 4)

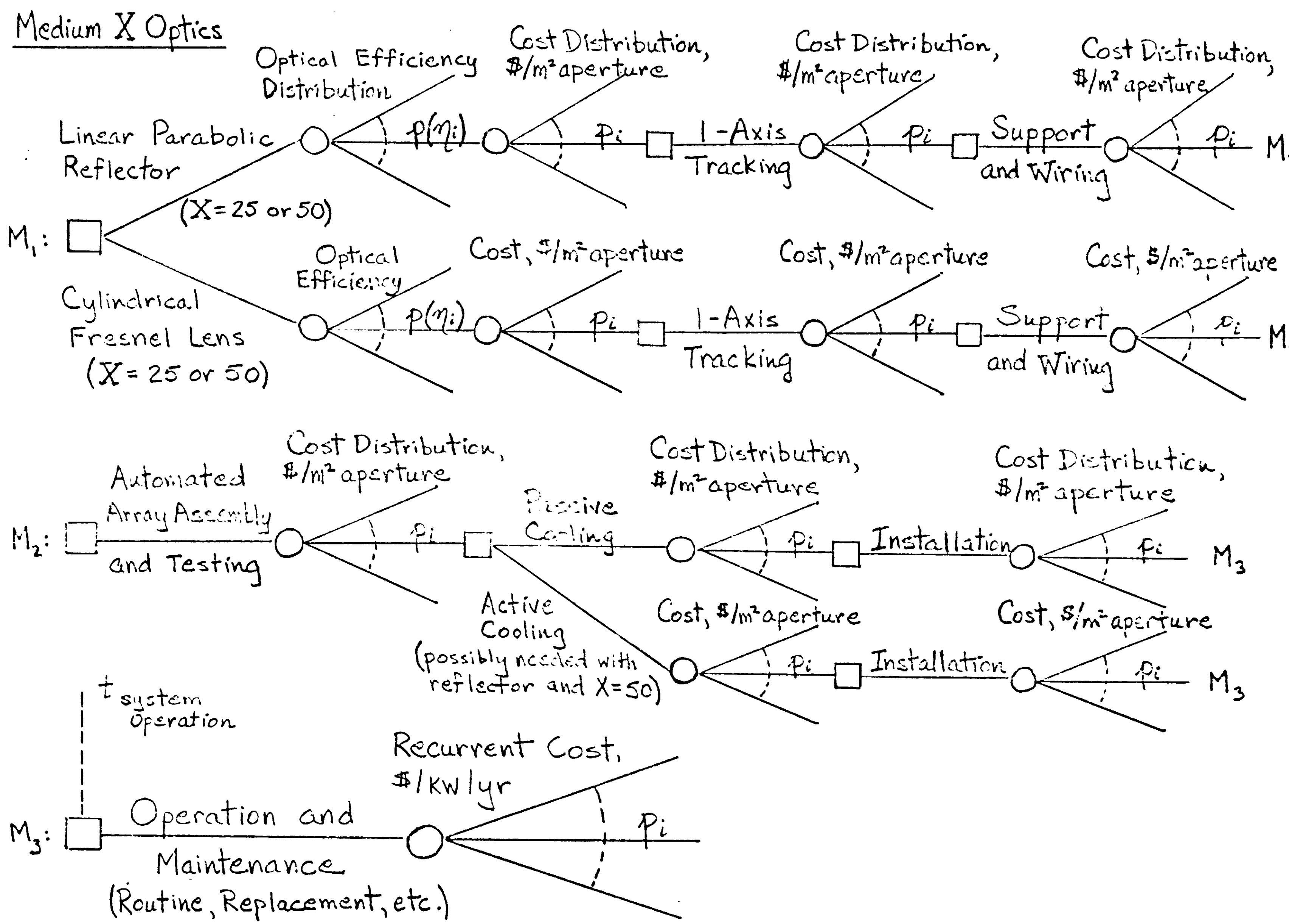

Figure 6

DECISION TREE FOR CONCENTRATOR SYSTEM (continued from Figure 4)

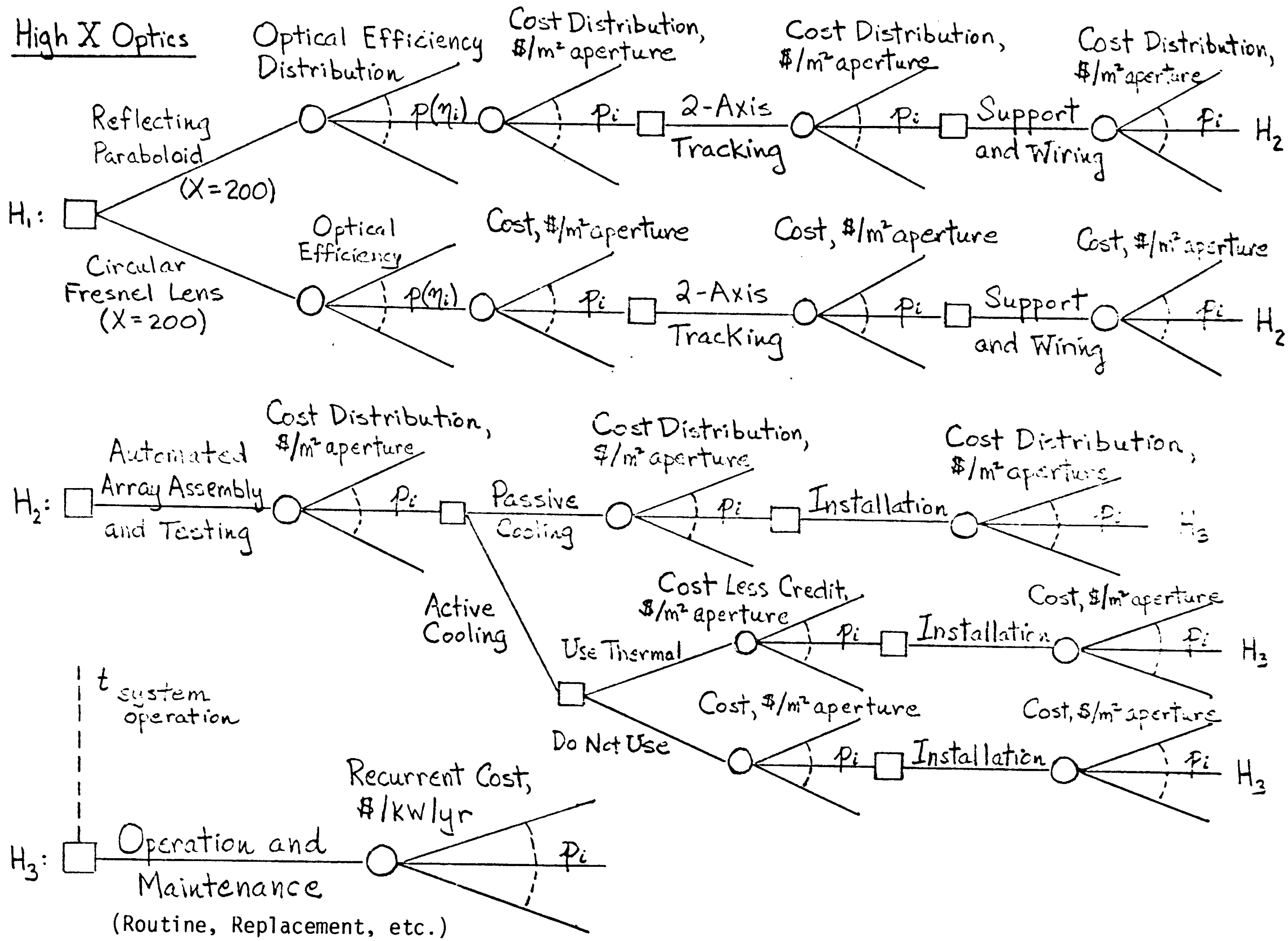

Figure 7

DECISION TREE FOR CONCENTRATOR SYSTEM (continued from Figure 4)