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JPL- 5103-47

Thermal Power Systems
Small Power Systems Applications Project

Decision Analysis for Evaluating and Ranking Small Solar Thermal Power System Technologies

Volume II - The Criteria and Methodology for Evaluation and Ranking

January 15, 1979

Prepared for
U.S. Department of Energy
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103

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ABSTRACT

This report describes the criteria, their attributes, and the decision analysis methodology developed to evaluate and rank technology alternatives for small (1-10 MWe) solar thermal power systems applications. The emphasis of the report is on the development of the specific criteria and their attributes to be used, and on the application--rather than the theory--of the decision analysis methodology. The decision analysis methodology uses the Keeney formulation of the multiattribute utility equation. Several assumptions are introduced to simplify the procedures for interviewing representatives of organizations and segments of society which have an interest or responsibility with respect to electrical power systems. Graphical material to be used in the interviews are presented and their use is explained.

OBJECTIVE = GOALS = CRITERION

FOREWORD

This report, Volume II of a three volume series, has been prepared to describe the criteria, their attributes, and the decision analysis process developed to evaluate and rank technology alternatives for small (1-10 MWe) solar thermal power systems applications. The primary focus of this report is on the development of the specific criteria and their attributes, and on the application--rather than the theory--of the decision analysis methodology. The specific technology alternatives will be described in detail in other reports of the Small Power Systems Applications (SPSA) Project.

A non-technical introduction to the concepts involved in multiattribute decision analysis is provided by Volume I of this series, "A Brief Introduction to Multiattribute Decision Analysis," by Abe Feinberg and Ralph F. Miles, Jr., issued in June, 1978. This document, formerly published as JPL Internal Report 5030-222, has been revised and is now JPL Publication 79-12. The third, and final volume in this series will cover the interviews and subsequent analysis for evaluating and ranking the SPSA technology alternatives. Volume III is presently scheduled for completion in May, 1979.

ACKNOWLEDGMENTS

Many people at the Jet Propulsion Laboratory, Battelle-Pacific Northwest Laboratories of Richland, Washington, and the Solar Energy Research Institute of Golden, Colorado, have provided invaluable assistance throughout this project. In particular, the authors wish to acknowledge the support of Alan T. Marriott and Robert Ferber at the Jet Propulsion Laboratory, and the cooperation of J. William Currie of Battelle-Pacific Northwest Laboratories, and Ken Brown of the Solar Energy Research Institute.

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SECTION I

INTRODUCTION

The Small Power Systems Applications (SPSA) Project is presently examining several different technology alternatives for small (1 to 10 MWe) solar thermal electric power systems applications. This Report develops the criteria, their attributes, and a decision analysis process for evaluating and ranking these technology alternatives.

The decision analysis paradigm can be summarized in terms of the components of the diagram of Figure I-1. A set of alternatives are identified, and then described by means of a System Model. The System Model must be defined in sufficient detail that the Value Model can establish a preference ordering between the systems and their resultant outcomes. The System Model must also incorporate any uncertainty that is present in the outcomes. Uncertainty could arise from a specific system or from the selection of a specific alternative. The output of the System Model is a set of possible outcomes with associated probabilities of occurrence. Separate outcomes with varying probabilities will result from the selection of different alternatives. The Value Model describes the goals and a value structure of the decision maker in terms of (1) criteria that quantify the goals, (2) attributes that provide a means of measuring the extent to which each of the criteria are satisfied, and (3) a method for aggregating the attributes into a preference ordering for the outcomes and their associated probabilities of the System Model. Finally, the output of the Value Model is a preference ordering of the original alternatives.

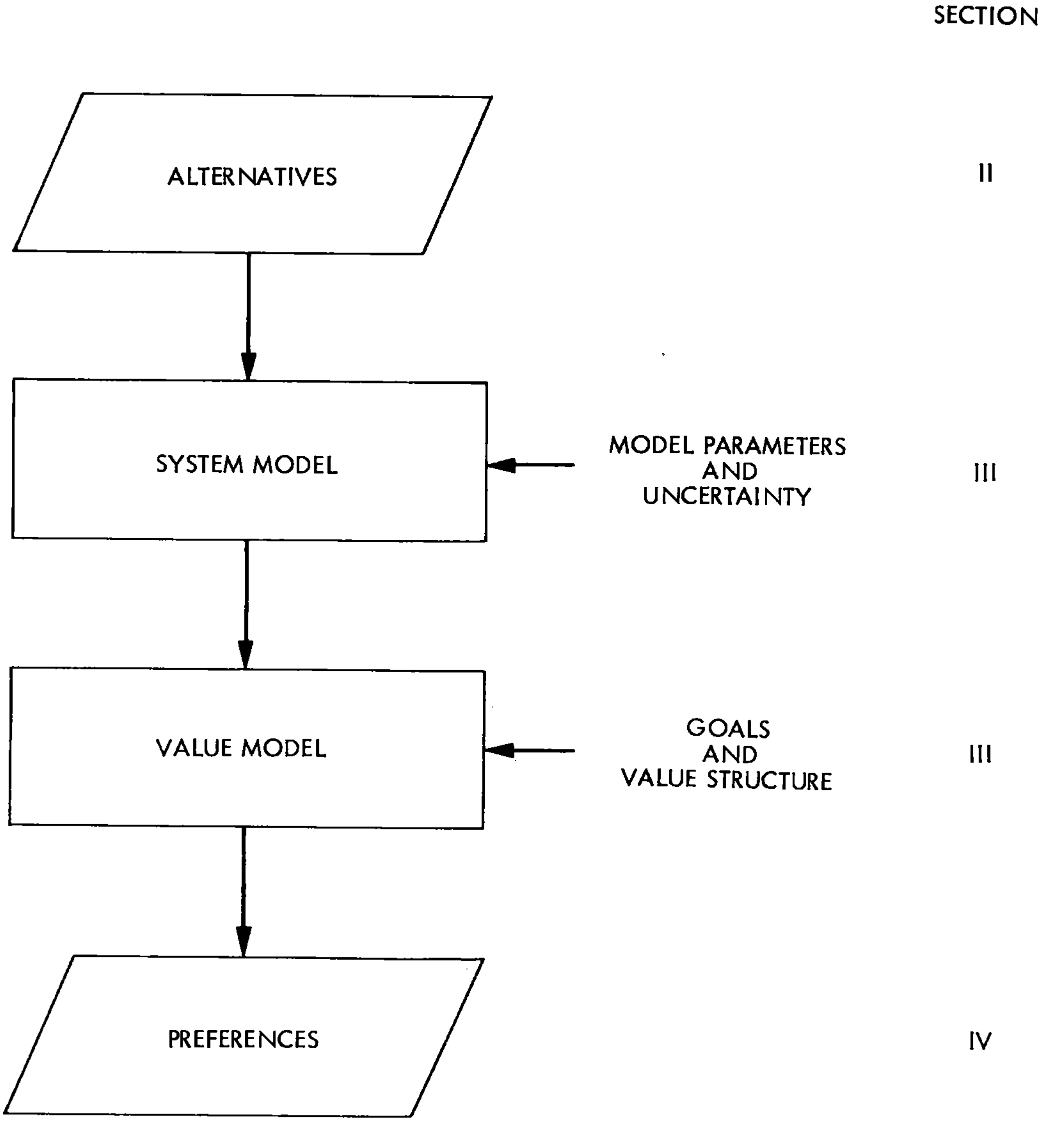


Figure I-1. A Diagram of the Decision Analysis Paradigm

The development and execution of the decision analysis process are given in Table I-1, with emphasis on the Value Model component. Step 1 through Step 6 develop the methodology and data necessary to conduct the interviews of Step 8. The interviews conducted in Step 8 will be with members of organizations or segments of society with an interest in or responsibility for the development, implementation, and operation of electrical power systems. Step 9 through Step 11 analyze the results of the interviews, and develop the implications for the design and development of the technology alternatives.

This decision analysis process is derived from the theoretical formulation of Keeney and Raiffa (14). Some additional assumptions have been introduced concerning the preference structures--the value models--of the interviewees in order to simplify the interviews in Step 8 (24). These assumptions and methods are discussed in Section IV of this Report.

Seven technology alternatives have been defined by the SPSA Project for examination (Step 1). This Report specifically addresses Steps 2, 3, and 4, and touches on Step 5. Subsequent steps of the decision analysis process will be presented in the third Volume of this series of reports. Following this introductory section, Section II gives a description of the problem setting and the technology alternatives for the decision analysis process (Step 1). Section III describes the criteria and their attributes that will be used in the evaluation and ranking of the technology alternatives (Steps 2-3). Section IV presents in detail the decision analysis methodology (Step 4). Section V describes the purpose and samples of graphical material to be used in the interviews (Step 5). Section VI is a brief summary.

Table I-1. Steps in the Decision Analysis Process

STEP	PROCESS
1	Select the technology alternatives.
2	Specify the criteria for evaluating and ranking the technology alternatives.
3	Select attributes and their units of measurement for each of the criteria.
4	Develop a methodology for aggregating the attribute measurements so that the technology alternatives can be rank ordered in preference.
5	Develop the procedures and graphics for the interview process.
6	Analyze the engineering and economic data to define each of the technology alternatives in terms of the selected attributes.
7	Identify and select persons who represent organizations or segments of society which have an interest in or a responsibility with respect to the technology alternatives.
8	Conduct interviews with those selected persons to assess their preferences.
9	Analyze the interview results to determine the preferences of the relevant parties.
10	Perform a sensitivity analysis to determine the sensitivity of the preferences to variations in key parameters.
11	Write a report which discusses the results of Steps 8, 9, and 10 with the implications for the design and development of the technology alternatives.

SECTION II

THE PROBLEM SETTING AND THE TECHNOLOGY ALTERNATIVES

A. SMALL POWER SYSTEMS APPLICATION PROJECT

The United States Department of Energy is pursuing a variety of solar thermal power options. These include research and development on various devices and components, and engineering designs for several types of systems. The DOE Solar Program is designed to tap all of the appropriate skill resources of the nation including: academic, industrial, and government research laboratories; production industries; architectural and engineering firms; and utilities.

The Small Solar Power Systems Applications Project (SPSA Project) is one of three solar thermal projects being managed for the Department of Energy by the National Aeronautics and Space Administration at the Jet Propulsion Laboratory of the California Institute of Technology. The project includes the examination of potential applications for small power systems. It has already been determined that users who could most benefit from distributed solar thermal power systems tend to be dispersed and somewhat removed from the existing utility grids. These include:

1) Small communities and utilities
2) Special isolated facilities (such as scientific, military or industrial complexes)
3) Outlying or rural communities or islands
4) Mines and light industrial parks
5) Agriculture
6) Developing countries

The approach taken most often in the research and development process is to determine several alternative solar thermal system concepts and assess each alternative with respect to the feasibility constraints. The most promising alternatives are chosen for further in-depth analysis. The best are chosen for experimental testing and possibly demonstrations. Full-scale production and commercialization is the ultimate goal.

The research and development of solar thermal power systems is just beginning. Many types of solar thermal system concepts have been identified and are being analyzed throughout the country. However, at this stage, it is still unclear as to which designs are the most effective and producible. The primary difficulty in these assessments is not determining a system's performance, but in determining accurate cost estimates of designs and potential production cost reduction scenarios. Thus, research and development decision makers are presently unable to make appropriate trade-offs in cost, performance, and production designs. For these reasons the Department of Energy and the Jet Propulsion Laboratory's SPSA Project initiated a general systems study program to evaluate and rank the most promising approaches.

B. GENERAL SYSTEM STUDY OF SMALL SOLAR THERMAL POWER SYSTEMS

In order to provide an objective assessment of the many proposed approaches for solar thermal power plants, a technology comparison study involving JPL and the two other independent agencies, Solar Energy Research Institute and Battelle-Pacific Northwest Laboratories, was recently initiated by DOE. The purpose of this study is to compare, on a relative basis, seven generic types of solar thermal power plant concepts. The types selected for study, as described in the following subsection, are:

1) Point focus distributed receiver 3

✓ 2) Point focus central receiver

3) Line focus distributed receiver - tracking collector

✓ 4) Line focus distributed receiver - tracking receiver

✓ 5) Line focus central receiver

✓ 6) Fixed mirror distributed focus

✓ 7) Low concentration nontracking

The intent of the comparative systems studies is to find the most appropriate long term ranking of solar thermal technologies for small electric power applications in the 1-10 MWe range. The ranking must include considerations of system performance and cost, as well as social, institutional, and environmental impacts. The problem facing the systems analysts is to assess and quantify the importance of key system attributes to develop a ranking. To determine this it is imperative that the decision makers, from the R&D sponsor to the ultimate user of such systems, be part of the ranking process and that the system ranking results reflect their preferences. Therefore, a formal decision analysis involving the decision makers will be utilized in the study to assist in ranking the various systems under consideration. This will insure consistent and detailed interpretation of the technology ranking, and will document the methodology, assumptions, and data by which the study recommendations were derived. Some of the criteria to be considered for the general systems analysis of small power systems are given in Table II-1 below as outlined in the original study plan (2).

The original study plan also specified that, for each of the selected technology alternatives, 1, 5, and 10 MWe power plants with an annual load factor of 0.4 are to be analyzed. Systems analysis shall be directed toward

Table II-1. Criteria for System Selection

Criteria	Description
1	Comparatively low capital and energy costs (implying low O&M costs).
2	The system concept should use or contribute directly to the eventual concepts and systems that are likely to achieve commercial success in the era 1990 to 2000.
3	High degree of modularity. It is desired that the system can be used in a wide range of power level applicatons (1 to 50 MWe) without major changes in system configuration (other than power level).
4	Reliability approach existing commercial power plants.
5	Easily integratable with applications for small power systems (i.e., little or no problems associated with safety hazards, aesthetics, environment, etc.).
6	Technology with high probability of achieving successful development.

optimizing the system selected with respect to the criteria given in this report. The information to be obtained for each selected alternative includes system and subsystem descriptions, performance assessment, and estimation of capital costs and levelized energy costs. A sensitivity analysis is to be conducted on the systems with regard to rated power and annual load factor.

In short, the general systems analysis must provide a first order ranking of solar thermal electric alternatives and encompass attributes that lead to a cost-effective route to successful commercialization. The scope of the general analysis is primarily limited to a comparative evaluation of seven specific power plants.

C. ALTERNATIVE SOLAR THERMAL TECHNOLOGIES

Several types of solar thermal electric power systems are undergoing research and development, a few types are already in commercial production. Basically, a solar thermal electric power (STEP) system consists of four subsystems called the collector, power conversion subsystem, the energy transport subsystem and the energy storage subsystem. Figure II-1 illustrates a STEP system and its subsystems.

The collector and power conversion subsystems are the major determinants of the cost and performance of the system. Thus, they may be used to differentiate solar thermal power systems for analysis. Collectors consist of a concentrator and receiver. The concentrator, using mirrors or lenses, gathers and concentrates sunlight on the receiver. The receiver, a specially shaped heat exchanger, absorbs the light and converts it to thermal energy. The power conversion subsystem, which consists of a heat engine and electrical generator, then converts the thermal energy to electricity.

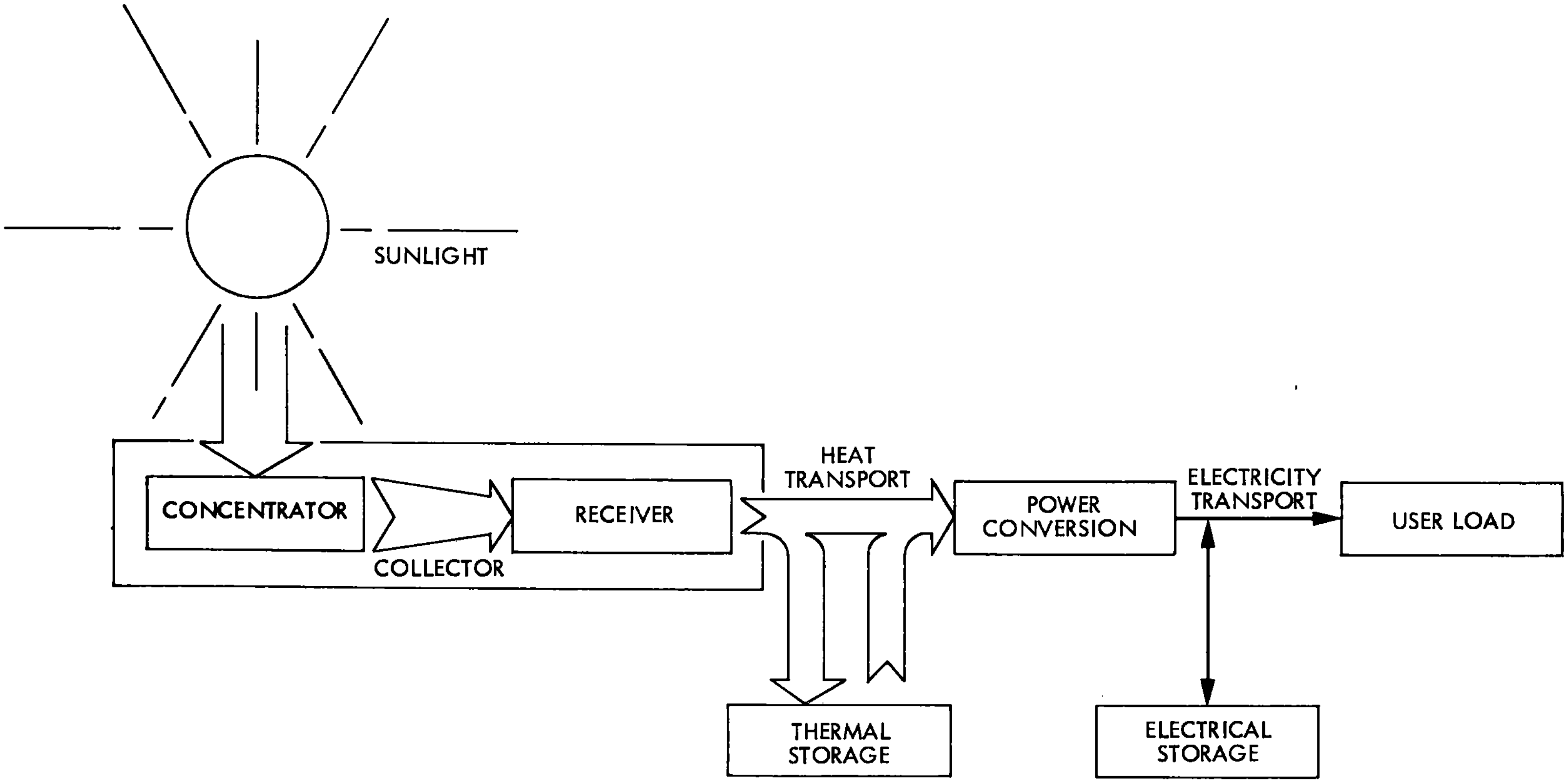


Figure II-1. A Solar Thermal Electric Power System

1) Two major areas of collector designs currently being examined are the central receiver and distributed receiver designs. Central receiver systems are comprised of a large field of sun tracking mirrors (heliostats) which focus sunlight on a centralized receiver. Distributed receiver systems consist of a field of many smaller concentrator-receiver modules. There is a trade-off between central and distributed receiver systems: the mass (fixed) production of many small concentrator-receiver modules may provide better cost reductions than the operational economies of scale provided by large central receivers. A further dimension by which collector designs may be differentiated is in the type of sun tracking mechanism employed. Collectors may be fixed, one axis tracking, or two axis tracking. Fixed collectors are usually flat plate or low concentration devices producing low temperatures (150-300°F) and low system efficiencies (5% - 10%). One axis systems employ higher concentration ratios and linear receivers for higher temperatures (300-800°F) and efficiencies (10-18%). Two axis collectors provide point focusing capabilities with high temperatures (800-2000°F) and the highest system efficiencies (15%-30% or better). The tradeoff here is between the higher cost, greater complexity and higher performance of two axis systems, versus the lower cost, greater simplicity and lesser performance of one axis or fixed systems.

2) Again, in power conversion subsystems, differentiation occurs between central and distributed power conversion. Central conversion involves the collection of thermal energy from the collector at one large, central heat engine-generator. Distributed power conversion involves many smaller heat engine-generators located near the receivers. Naturally, distributed power conversion is only possible with distributed receiver systems. Again, the

major trade-off is between the cost reduction potential of mass production of many small units versus the operational economies of scale of using one large unit.

The other dimension for differentiating solar thermal power systems involves the type of heat engine conversion cycle employed. The conversion cycles most often considered are the Rankine cycle, Brayton cycle, and Stirling cycle. Rankine cycle engines are limited to lower temperature ranges (150°F-1100°F) and have lower expected efficiencies (20% to 35%) than other conversion cycles of equivalent engine size (very large units in the 300-500 MWe range achieve conversion efficiencies of 42%). However, commercially available Rankine cycle power systems currently exist and future cost-performance estimates are fairly certain. Rankine cycle engines may be applied to either large central conversion systems or to small distributed conversion systems. Brayton cycle power systems require high temperature gas technology (1500°F). Efficiencies for Brayton cycle engines are potentially better than Rankine cycle engines (35% to 45%), but they require more complex, higher temperature collectors and further engine development. Furthermore, although large central Brayton cycle engines are possible in solar thermal applications, most development is focused on small engines for distributed conversion systems. Stirling cycle engines offer the best performance potential. Existing engines have achieved 40% efficiency and advanced engines are expected to achieve efficiencies in the 50% to 60% range. It appears that Stirling cycle engines are best suited to distributed systems where their small size and high temperature (1500°F) needs are better matched. In summary, the trade-off in selecting conversion cycles is one of choosing higher performance, increased complexity, and development costs, versus lower performance, less complexity and current availability.

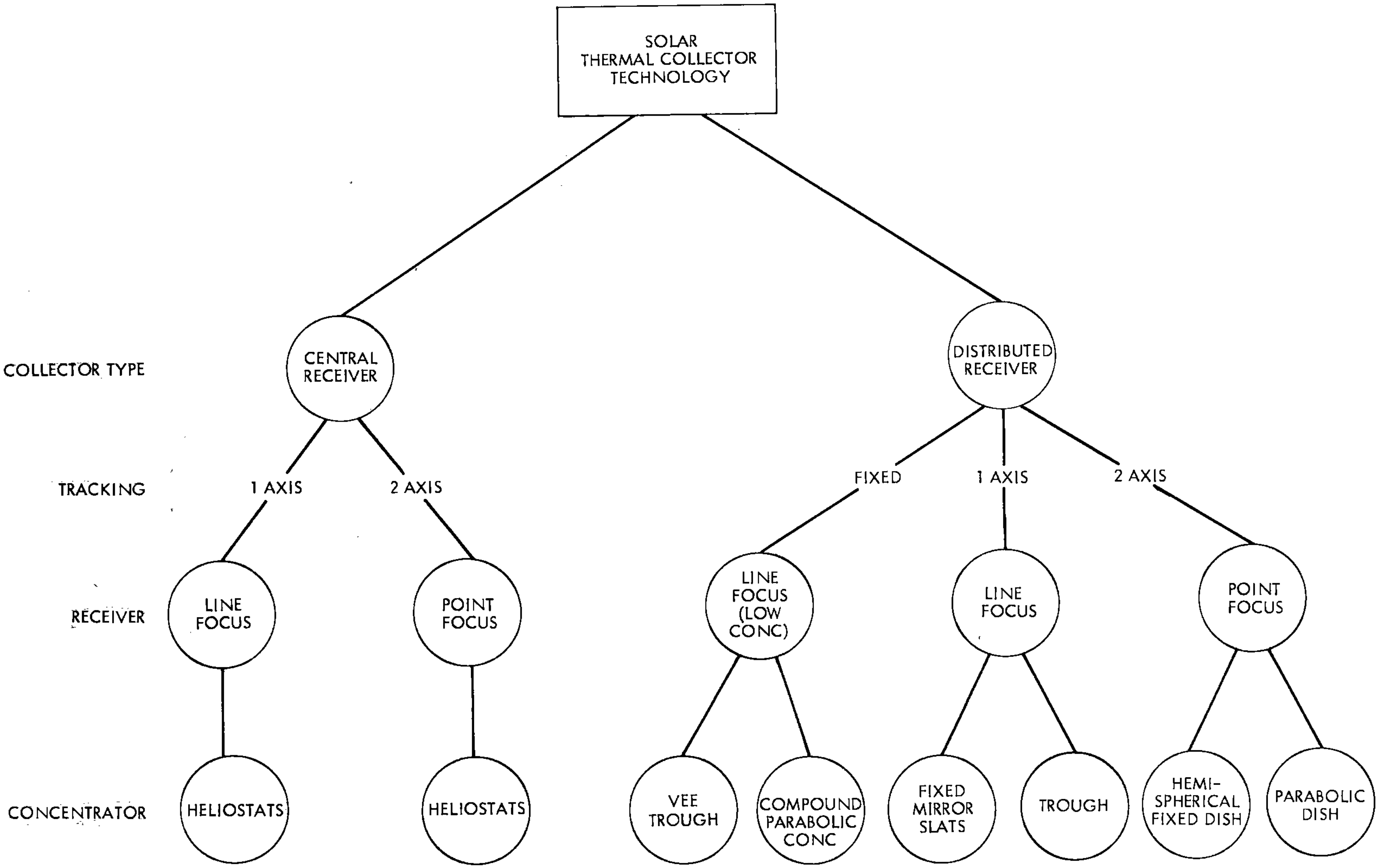


Figure II-2a. Breakdown of Solar Thermal Collector Technology Alternatives Considered in General System Studies (Conversion Cycles Alternatives Not Shown)

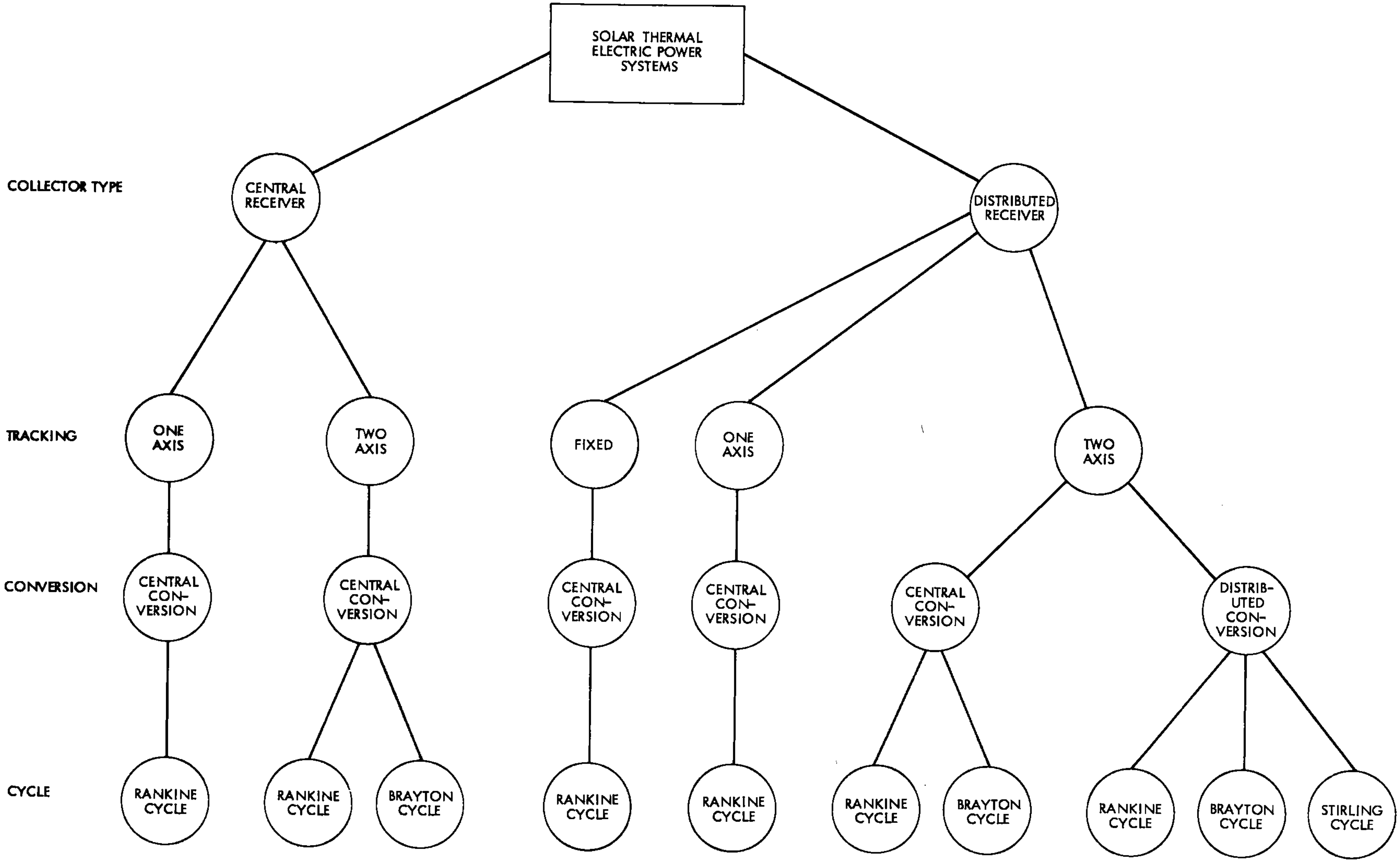


Figure II-2b. Alternative Solar Thermal Energy Conversion Cycles

Altogether, these four dimensions permit classification of the solar thermal electric technologies into many alternative system concepts. Figures II-2a and 2b illustrate a few of the possible configurations for combining the different solar collectors and energy conversion alternatives. Previous assessments of most of these alternatives have been based on necessarily rough cost estimates and have not definitively identified any specific system as having the best potential for development.

D. DECISION MAKING IN A SYSTEMS ANALYSIS CONTEXT

When the decision analysis becomes closely linked to the systems analysis, the central challenge is to develop criteria and attributes that are detailed enough to satisfy the systems analyst and concise enough to satisfy the decision maker. In this case, the process of developing a consensus on criteria and attributes takes on considerable importance. In order to arrive at this consensus, a hierarchical set of criteria and attributes must be developed in at least three iterative stages. First, a basic set of solar power plant requirements must be defined in order to provide a framework of minimum performance standards for the specification of a reference design for each power plant to be compared. Second, the ground rules, assumptions, and boundary conditions for the systems analysis must also be defined. Third, a concise set of decision analysis criteria and attributes must be selected. This approach is required in order to insure that the value model and the systems model are adequately defined.

The decision analysis framework must ultimately present to the DOE the appropriate information, so that informed decisions can be made via the normal political and institutional process. Any decision analysis framework must satisfy several requirements:

1) It must be capable of generating a set of attributes sufficiently well defined so that policies and systems providing alternative solutions can be described. The attributes must be quantifiable at least to the extent that attribute states can be rank ordered in preference. The set of attributes must be complete, in that it must include all of the factors that could significantly influence the decision.

2) The alternative policies and systems must be feasible. They must satisfy all of the absolute constraints--technical, economic, legal, and social--that are required for commercial feasibility.

3) It must be possible to generate a value model that will permit the attributes to be aggregated into a form that yields a rank ordering in preference for the alternative policies and systems. This aggregation requires the consideration of trade-offs. A trade-off is the amount by which the state of one attribute must be changed to compensate for a change in another attribute.

The selection of ranking attributes depends not only on the purpose of the ranking exercise, but also the availability of information on which the rankings will be based. The requirements for the decision analysis methods described in this document will change over the course of the small power systems applications project. For instance, it will be necessary to rank order solar thermal electric power systems at different stages of the project in order to:

A. Narrow the field of system altenatives to those which show the greatest potential for successful development

B. Select appropriate systems for construction of successful experimental systems

C. Select the optimal commercial system for specific combinations of applications and sites

D. Select applications and sites

For instance, the attributes used to rank experimental systems that embody present state-of-the-art technology might be quite different from the attributes of the ultimate commercial systems. A successful experimental system would be judged with R&D costs in mind as well as the contribution to advancing SPSA technology towards the overall objective of commercialization. On the other hand, ranking of a successful commercial system must be primarily based on the economic and institutional feasibility of such systems.

Relatively little is known about the cost, performance, and applicability of such systems. Given the most elementary criteria, development of a realistic system model under these conditions becomes a difficult task. As a result, the need for decision analysis criteria and attributes becomes closely tied to the definition of system requirements, assumptions, and boundary conditions of the systems analysis. Therefore, considering the technical issues and analytical problems that will be encountered, it is important that criteria and attributes be developed carefully. In this way, the ranking criteria and attributes for ranking can be coordinated with the systems analysis. The following two sections provide a more detailed exposition of the process of developing the criteria and attributes to be used, and of the decision analysis methodology.

SECTION III

CRITERIA AND ATTRIBUTES FOR EVALUATION

A. SELECTING CRITERIA AND ATTRIBUTES

The objective of the decision analysis is to rank order the alternative technical approaches to small solar thermal power plant design in terms of their technical, economic, and commercialization potential. As discussed in Section II, three overall constraints are imposed on the selection of appropriate ranking criteria and attributes. First, the criteria must conform to the purposes of the general systems studies that the decision analysis is supporting and, conversely, provide guidelines for the systems analysts. Second, technical information may be limited by the early stage of conceptual development of small solar thermal power systems. Third, the final list of criteria and attributes must be satisfactory to each institutional participant in the general systems study, in order to provide a consistent and standardized methodology required to compare the results of these independent systems analyses.

In addition to these three general constraints, the set of attributes to be employed when ranking technological alternatives must meet several technical standards. It must be complete enough to include all of the factors that could significantly influence the decision, yet not so large as to overwhelm the evaluator. As a rule, attributes should be carefully selected to avoid redundancy or double counting of the system characteristics. The attributes selected should also differentiate between systems by measuring only important advantages and disadvantages inherent in the different types of technologies being considered. For instance, many of the cost factors are represented by a single calculation of levelized energy cost. Other attributes should measure major indicators such as environmental, social, or institutional factors that impinge on the choice of technologies.

The primary criteria and attributes selected should have the following properties:

1) Differentiation - the attributes should reflect actual differences between the alternative technologies being considered

2) Importance - each attribute should represent a significant factor in the value model of the decision makers

3) Familiarity - each attribute should be recognizable and understandable to the decision maker

4) Measurability - the criteria or attribute can be subjectively or objectively measured with data that can be attained within the time and resources available for the decision analysis

5) Independence - changes within certain limits in the value of one attribute should not affect preferences or trade-offs between other attributes

In order to limit the set of criteria and attributes and to satisfy the needs for comprehensive systems analysis, sets of primary and secondary attributes were developed as shown in Table III-1. The primary attributes attempt to satisfy the properties listed above, while the secondary set provides data required to evaluate the primary attributes in some depth. The primary set is intended to satisfy the needs of an evaluator or a decision maker by providing a familiar and limited set of attributes. The secondary set of attributes provides definitions and data requirements needed to develop the systems model, and should satisfy the systems analyst's needs for detailed guidelines.

The criteria and attributes were developed iteratively in order to satisfy these standards and to meet the requirements of each institution participating in the general system study. A series of draft criteria and attribute sets were developed and reviewed by each participant in the general system study until a final list was agreed upon. This careful negotiation process took place over a six month period, permitting refinement of the ranking criteria as both the knowledge of the systems and decision analysis method was improved. The following discussion begins with the initial set of primary and secondary criteria proposed by JPL. Section C presents the final set selected.

B. MULTIPLE CRITERIA AND ATTRIBUTES FOR RANKING SMALL POWER SYSTEMS

The multiattribute aspect of decision analysis appears because, for complex systems, the outcomes must be evaluated in terms of several objectives (also called goals or criteria). Objectives of a decision analysis are stated in terms of properties, either desirable or undesirable, that determine the decision maker's preferences for the outcome. For the design of a solar power plant, several objectives might be: (a) to minimize cost, (b) to maximize performance, (c) to minimize negative impacts, (d) to maximize industrial and commercial potential. The purpose of the value model is to take the outcomes of the systems model, to determine the degree to which the outcomes satisfy each of the objectives, and then make the necessary trade-offs between the objectives to arrive at a ranking for the outcomes that correctly expresses the preferences of the decision maker. The value model is developed in terms of a hierarchy of objectives and sub-objectives as shown in Figure III-1 for the design of a small solar thermal power plant.

In order to quantify the value model, a unit of measure must be assigned to each of the lowest items in the objectives hierarchy. These measurable items are called "attributes", and they are scaled in convenient units to measure the degree to which the associated objective is satisfied. In Figure III-1, seven attributes are used to quantify the value model. The results of the associated systems model would be expressed as a 7-component vector, with the components corresponding to the attributes, i.e., $X = (x_1, x_2, x_3, x_4, x_5, x_6, x_7)$ where x_i is the value of the ith attribute of the value model. A specific occurrence of an attribute is called a "state" of the attribute. An attribute state for the objective "minimize cost" might be $x_1 = 70$ mills per kilowatt hour. The criteria and attributes shown in Figure III-1 are discussed in the following sections.

The first set of attributes proposed by JPL for the decision analysis is given in Table III-1. These attributes fall within the scope of the general systems studies. They attempt to provide measures of the criteria listed in Table III-1, using data and expert judgment developed in the

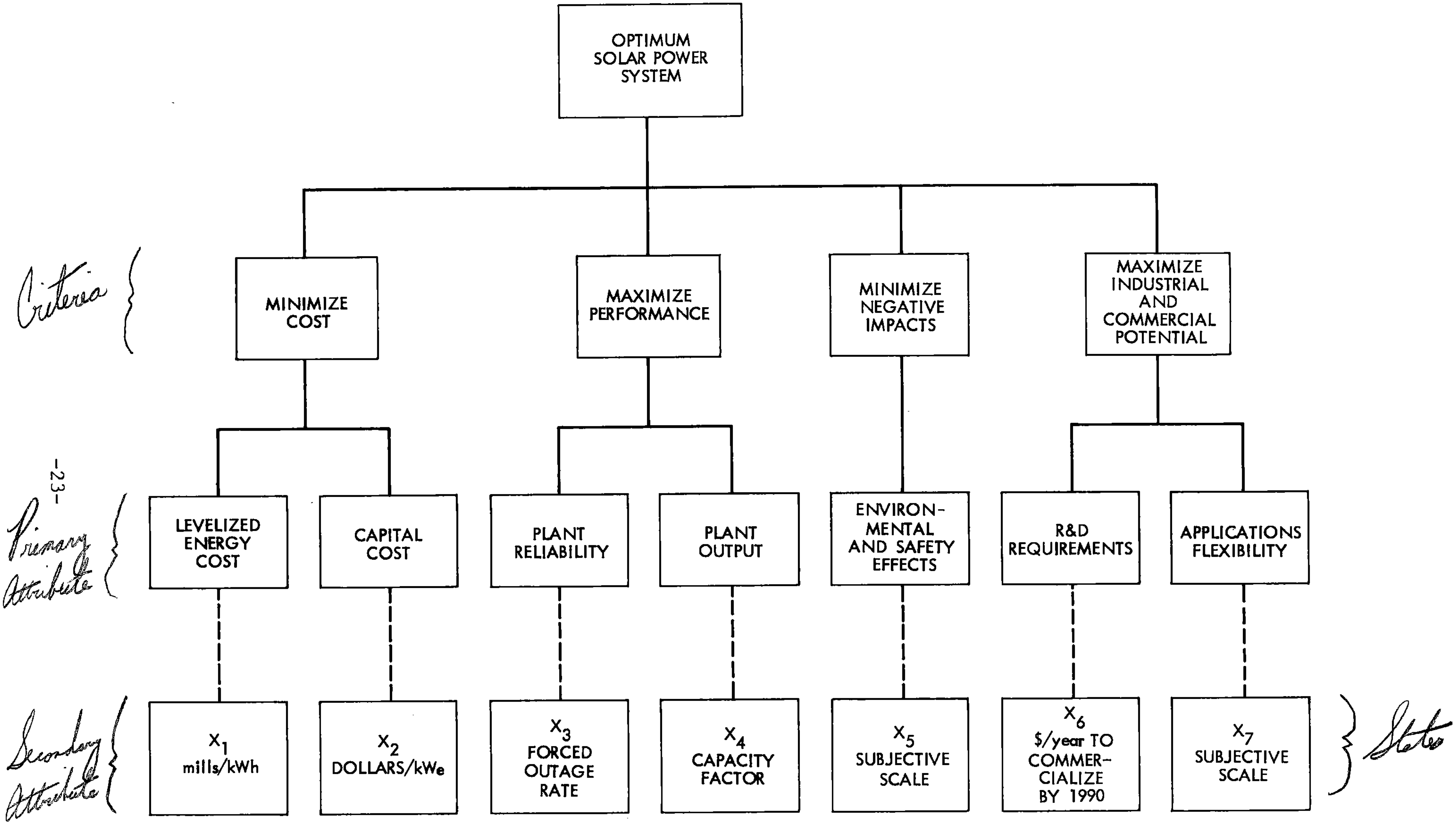


Figure III-1. Hierarchy of Criteria and Attributes for Ranking Small Solar Thermal Electric Power Systems Technology Alternatives

Table III-1. Proposed Criteria and Attributes for Ranking Small Solar Thermal Power System Alternatives

Criteria	Primary Attribute	Unit of Measure	Secondary Attributes and Requirements	Systems Analysis Assumptions and Ground Rules
Cost	Levelized energy Cost	mills/kWhr	Capital cost of 1 MWe plant operations and maintenance cost Fuel costs (if any) Actual capacity factor Nominal capacity factor Construction time (interest during construction) Fixed charge rate	Calculation of levelized energy cost assumes modular construction and start-up over three years. Assumes that each system has been optimized to lowest levelized energy cost under a defined set of minimum performance, operations and maintenance requirement that are suitable for a utility application.
	Capital cost	$/kW	Capital cost of unit Energy output of unit (MWe) Operations and maintenance cost Fuel costs (if any) Actual capacity factor Nominal capacity factor Installation time	Assumes that mass-production rate of modules captures most economies of scale for that specific type of plant.
Performance	Plant reliability	Forced outage rate	Annual forced outages Remote operations Back-up power requirement	Assumes that plant meets minimum requirements
		Percent capacity output	Annual scheduled outage rate (%) Back-up power requirement Maintenance schedule Day-time maintenance consideration Plant output ramp Rates kWe/sec Sunrise/sunset Blockage/return	Scheduled maintenance procedure for each type of system optimizes O&M cost. Small modular systems may permit cost-effective daytime maintenance and also reduce the impact of forced outage due to single unit failure

Continued

Criteria	Primary Attribute	Unit of Measure	Secondary Attributes and Requirements	Systems Analysis Assumptions and Ground Rules
			Storage Part load efficiency (percent) Minimum load (percent) Start-up power required (kWe)	Assumes that plant meets minimum requirements including remote operation and control and, power grid interface and;
			Power grid interface and electrical performance Remote operations and control	Operations, maintenance and storage procedures each type of system are optimized with captial and O+M costs.
Impacts	Safety and environmental effects	Subjective scale	Occupational health and safety (Man-days lost due to accidents/year/MWh) Probability of unsafe event Fatalities or services injuries/year/MWh	Assumes that plant meets minimum health and safety codes and; Includes effects of accidents and health injuries to visitors and local inhabitants as well as employees and;
			Environmental safety toxic and hazardous materials inventory Probability of environmental pollution event	Risk analysis is performed by systems analyst study
			Natural environmental effects Effluents and Contaminants Local ecology (geo, hydro, bio and atmosphere) Socio-Economic effects demand for social services aesthetics Resource Use Land-use Water-use	Only environmental effects of a single plant on locality are to be considered in this systems study. Subjective scale will be developed after key issues are identified during the study -- based on actual impacts that are anticipated.

Continued

Criteria	Primary Attribute	Unit of Measure	Secondary Attributes and Requirements	Systems Analysis Assumptions and Ground Rules
Industrial and Commercial Potential	Research, development & industrial requirement	$/year to commercialize by 1990	Cost of R&D program Probability of meeting cost/ performance targets Probability of accelerating/ surpassing goal Cost of manufacturing development Mass production volume required Capital cost and savings of new tooling	Commercialization assume sufficient demand for mass production and competition energy costs in 1990. R&D cost includes automation and tooling projects Moderate manufacturing development program includes application of more cost-effective techniques tooling available in 1990.
	Applications and design flexibility	Subjective scale	Subsystems cost sensitivity and tradeoffs Load factor and plant size sensitivity Hybrid and storage flexibility Siting and applications flexibility Dry/wet cooling flexibility Number of potential applications Ease of manufacture Ease and timing of installation, maintenance and replacement Marketability Economies of scale Transportability	Subjective scale to be developed after key issues are identified. Flexibility refers to ability to change design to meet specific applications or site requirements and achieve satisfactory costs and performance. Assumes that plant is replacing oil & gas capacity except for hybrid operations. Assume that module size is optimum for each technology with respect to levelized energy cost. Assumes that given a module size at the optimum for at technology, preferences for module sizes reflect the secondary attributes listed.

general systems analysis studies. Table III-1 shows a hierarchy of criteria, primary attributes, and secondary attributes. Some of the key assumptions and ground rules for the systems analysis associated with the selected attributes are summarized in the Appendix to this report. The significance of each of these criteria is briefly described below. In order to aid in understanding the context of the following criteria, it may be helpful for the reader to refer to the brief discussion of the systems alternatives under consideration given in Section II.

1. Energy and Capital Costs Criterion

The general systems analysis will include trade-off studies which optimize the levelized energy cost based on a thirty-year plant life. The analysis will be based on a nominal 1 MWe (rated) power plant having a 0.4 load factor. A standard methodology developed at JPL by Doane et al (4) will be used to estimate energy cost.

The levelized energy cost was selected for the primary ranking attribute because it represents a simple means to compare numerous cost factors including operations and maintenance, capital cost, fuel cost and other economic factors under realistic economic assumptions. The costing methodology to be used provides a consistent approach to deriving a levelized cost of power in mills per kilowatt hour. The formula is shown below:

$$\overline{BBEC} = \frac{\overline{FCR} \cdot CIpv + \overline{OM} + \overline{FL}}{CF \cdot CAP \cdot 8760}$$

where

$\overline{\text{BBEC}}$ = the levelized cost of energy in mills/kWh

$\overline{\text{FCR}}$ = the levelized fixed charge rate

CIpv = the present value of capital costs

$\overline{\text{OM}}$ = the levelized operations and maintenance costs

$\overline{\text{FL}}$ = the levelized fuel costs (if any)

CF = the "attained" capacity factor as a proportion of "rated" capacity

CAP = the rated capacity factor

8760 = the number of hours in a year

Systems performance factors such as the attained capacity factor (CF), and the rated capacity (CAP) are related to the cost of energy in a highly structured form as shown in the above formula. Subjective estimates of trade-offs between subfactors are unnecessary since satisfactory quantitative attributes can be used. We can calculate the precise trade-off between CF and CIpv, if there is a target levelized energy cost ($\overline{\text{BBEC}}$) that is preferred. The data developed for calculating levelized energy cost can also be used to construct other equations that describe the structural relationship between cost and performance characteristics of different systems.

One of the key differences between systems being considered is the degree of utilization or the number of power modules that make up a 1 megawatt power plant. For instance, the point-focusing-distributed-receiver concept provides decentralized energy conversion with small heat engines and electric generators associated with individual collectors. The central receiver on the other hand involves a centralized energy conversion plant with the field of heliostats concentrating sunlight on a central receiver. The distributed concept requires a number of electrical generating modules to make up a single 1 megawatt power plant. Modularity permits adding additional capacity to a power plant in response to incremental power demands. Thus, the levelized energy cost of modular plants may be relatively less than central plants because capital investments can be made in increments with shorter construction lead times, smaller interest payments during construction, and greater rates of return on investments.

The capital cost of the power plant is suggested as a separate attribute in order to differentiate systems under consideration. The number, size, and cost of power units making up a modular power plant may provide additional data needed to assess the financial attributes of alternative systems. A utility or other buyer of the solar system could purchase no more plant capacity than required in the near term with the modular system. This could be an advantage in tight capital markets.

2. Plant Performance Criterion

The criteria selected to compare the performance of small power systems are plant capacity factor and forced outage rate performance. These criteria represent a large range of important factors in the viewpoint of future users. The operational and maintenance characteristics of small power systems must not only meet the requirements of the user, but address major issues and concerns related to the adoption of solar energy.

Plant performance is very important to the user and encompasses several considerations. These include the annual forced and planned outage rates, as well as the output of the plant relative to its capacity. Plant reliability can be measured by the forced outage rate, while the plant output can be measured by capacity factor.

Several issues must be considered in calculating forced outage rates, including the impact of remote operations, backup power availability, and the associated maintenance schedules and procedures. For instance, central and distributed conversion systems may have different plant reliabilities. In the distributed system, only a small percentage of power conversion units would be expected to fail at any one time, and maintenance can be performed on a module without taking the entire plant off-line. Maintenance schedules of distributed systems will allow daytime maintenance of individual units without affecting plant reliability or planned outage rates. Backup power requirements may also be quite different between distributed and central conversion technologies. A central power plant may require less total maintenance time, because only one central power conversion and generator unit is required. The central plant could have less complicated maintenance schedules and procedures.

The analysis of plant performance must assume that each plant type has been optimized for maintenance scheduling, and that backup power requirements and other minimum performance requirements have been determined and included in the levelized energy costs.

Many of the desirable operational performance characteristics of a solar power plant are listed in the Appendix, "Requirements for Reference Solar Thermal Power Plant." For example, one of the unique operational problems presented by solar energy conversion are the variations in solar insolation due to passing clouds, weather changes, or time of day. These variations are known as operational transients and are examples of especially important secondary attributes that can be measured by the start-up time or response time of the power plant to changes in insolation or storage output. Insolation will vary throughout the day from plant start-up at sunrise to drawing on storage toward sunset. Also, clouds and other weather changes may effect available insolation throughout the day. A profile of the effects of operational transients on power plant output is shown in Figure III-2. These plant output ramp rates could be calculated for each solar technology. Since this is a complex systems problem beyond the resources of present systems analysis, a subjective scale could also be used.

Another example of important operational characteristics is the partial load efficiency of the energy conversion subsystem under reduced insolation conditions. An illustration of the evaluation of partial load efficiency is given in Figure III-3. Given that solar plants will be subject to operational transients in the amount of solar energy available to the engine, the partial load efficiency of the engine is important in determining the maximum amount of solar energy converted to electric or shaft power. Each solar power plant technology has known theoretical limits to response times, based upon the thermal mass and size of each system. Small heat engines may have different part load efficiency and faster ramp rates than large heat engines.

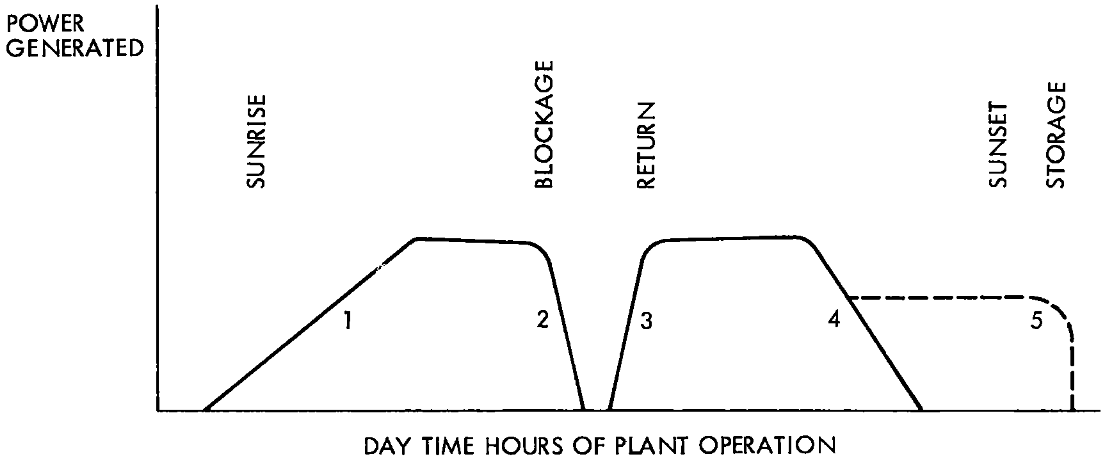
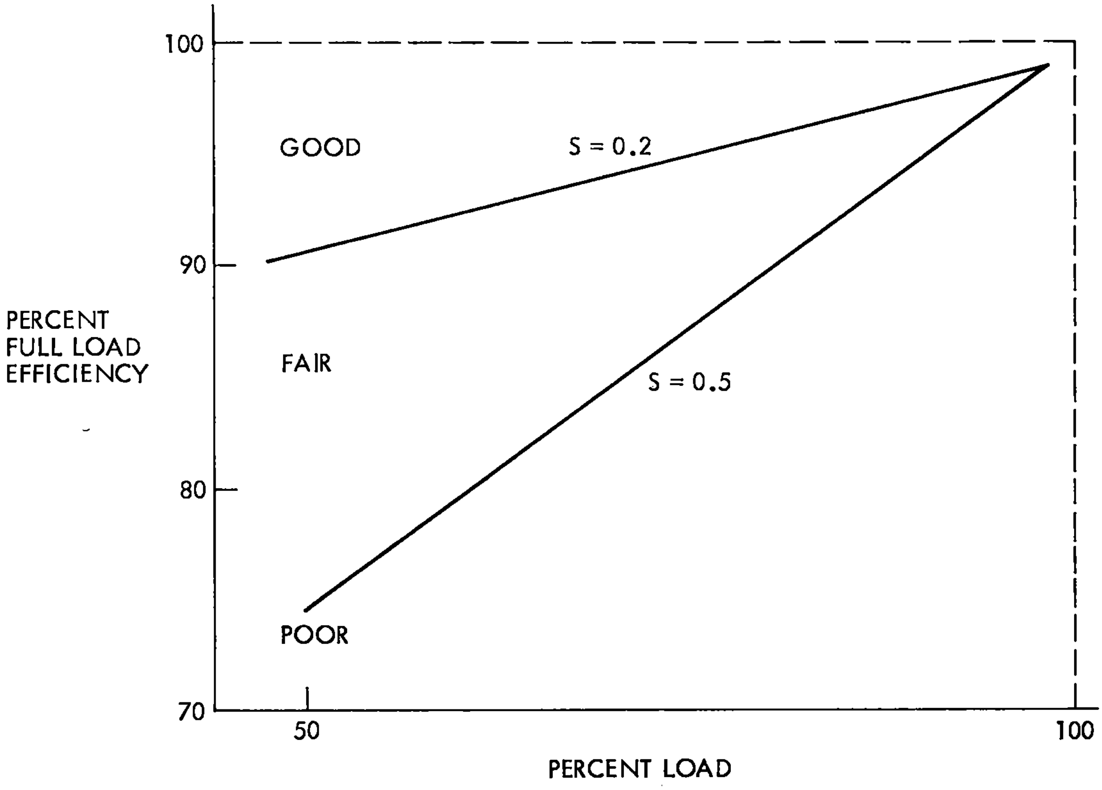


Figure III-2. Operational and Transient Performance



S = PARTIAL LOAD EFFICIENCY.
SEE THE APPENDIX FOR A DETAILED DEFINITION.

Figure III-3. Evaluation of Partial Load Efficiency

Partial solar load efficiency can be calculated as the average slope(s) of the efficiency versus load curve. For the purpose of this criterion, the average slope will be defined as:

$$S = (1 - N^*/N_{FL})/(1 - P^*/P_{FL})$$

P_{FL} and N_{FL} are the power and efficiency at full load, while P^* and N^* are evaluated at 50 percent load ($P^*/P_{FL} = 0.5$) or at the minimum load if the unit cannot get down to 50 percent load. However, to keep the evaluation as straightforward as possible, the primary attribute could also be a subjective scale that considers both the ramp rate and part load efficiency of each solar technology. At this time data on partial load and transient performance are not available and outside the scope of the general systems study. Thus, plant capacity factor and forced outage rate were selected as the ranking attributes.

3. Plant Impact Criterion

This criterion may pose the most difficult problems for the general systems analysis, since relatively little information is presently available. A subjective scale to calculate impacts is suggested to measure plant impacts. The attribute selected is safety and environmental effects. This includes both social and ecological factors.

It is not anticipated that safety will be a significant problem in the final commercial systems. Most of the anticipated problems can be solved through routine engineering development. However, there are some important differences between the technologies being considered that must be identified and considered. In particular, hazards are presented by the use of toxic chemicals as heat transfer fluid, storage media, high temperatures and pressures presented in heat transfer pipes, and the potential exposure of plant personnel to various concentrations of sunlight. The choice as well as design of systems must be cognizant of the relative safety hazard presented by these systems. Since comprehensive risk analysis is outside of the scope of presently funded general systems analysis, a subjective scale will be used to evaluate safety considerations. The scale will represent a number of important secondary attributes of safety including occupational health and safety and environmental safety.

Environmental effects must also be considered. For the present, a single subjective scale will be used to evaluate both ecological and socio-economic effects. Detailed environmental impact analysis is outside the scope of presently funded studies. However, the solar thermal power systems presently being considered will not be greatly differentiated by environmental effects. They are expected to be similar for all types of plants. Detailed environmental analysis will be conducted at a later date to minimize the environmental impacts of the highest ranked systems. For the purpose of general systems studies, only environmental effects of a single plant on the locality are to be considered. Several important secondary attributes must be considered: environmental pollution, community effects, and resource use, as well as other factors outlined in Table III-1.

Land-use and water-use are two resource criteria that can be calculated easily. Socio-economic effects on a local community may differ given the size and modularity of a system. Contaminant characteristics of each technology may have very different effects on the local ecology. For instance, the requirements for dry or wet cooling associated with each technology may have different microclimate effects. These include fog or haze caused by the cooling towers or albedo changes.

In summary, the relative environmental advantages and disadvantages of solar plants under consideration should include some major differentiating factors such as the toxicity of the heat transfer and storage media, material requirements and resource use, and the cooling requirements. A subjective rating scale can be developed based on specific impacts, but it is important to fully document the rationale for subjective ratings such as these, and to back up conclusions with available data.

4. Industrial and Commercial Potential Criterion

The overall goal of the SPSA project is to maximize the potential for the industrialization and commercialization of small solar thermal electric power systems technology. Accomplishment of these goals requires successful transfer of technology from government sponsored RD&D into industrial production. Ranking of the systems options must therefore consider the feasibility of developing a technology to the point where it is ready for industrial production and possesses economically viable markets.

The two attributes selected for evaluating the industrial and commercial potential of each system are (a) the research, development, and industrial expenditures that will be required to commercialize the systems by the year 1990 and (b) the application flexibility of the system, as a subjective indicator of the market penetration potential. For the purposes of this decision analysis, commercialization is defined as: "The total megawatts of solar power plant capacity installed per year beginning in 1990 must be of sufficient volume to justify industrial investment in mass-production facilities for collectors, concentrators, receivers and engines, plus assembly plants as required by the technology." In other words, to be commercialized, the cost and performance goals must be met, in order that the technology be competitive with other forms of energy production. The R&D required for commercialization then, is that amount necessary to make the technology competitive.

Applications flexibility is defined in reference to market penetration potential. In this case, market penetration is assumed to be a function of both direct and indirect marginal cost of energy. It is assumed that market penetration will vary over a wide range of competitive levelized energy costs depending on specific geographic considerations, user requirements, and constraints faced by each market sector. The inherent flexibility of each system design will permit greater competition in also meeting the specific requirements of diverse markets.

Industrialization factors that are regarded as especially important are the mass production requirements and the R&D cost associated with the development of a given technology. The economies of scale of manufacturing will vary greatly between distributed and central energy conversion, versus the cost savings through mass production of a large number of small units. However, beyond the cost effects, the number of units that must be made to capture these economies of scale may create barriers or incentives to industrialization. For instance, the development of an industry to mass produce a large number of small modules for a distributed receiver system may require greater capital expenditures than a central receiver industry requiring fewer batch-produced components. If a large volume of production is required to bring the cost of the system into competitive range, the industrialization process may be more critical and require greater incentives. The mass production assumptions used to estimate systems cost must be explicit and realistic, reflecting the actual economies of scale of each technology.

The cost of research and development is another important measure of the industrialization potential. Since reliable technology forecasts are not available, it may be difficult to estimate the R&D costs required. However, it is important to develop such estimates using the best available information, and at least ascertain the relative R&D cost for each solar technology. These estimates will necessarily be judgmental and rely on the expert knowledge of the analyst. Conclusions should be carefully documented and justified.

There are at least two possible approaches to assessing commercialization potential. First, an estimate of the total demand or market penetration for each type of solar technology for specific market sectors would provide a definitive measure of commercial potential. However, detailed market and applications studies of small power systems are not available. Further, competition, cost, prices, and acceptance of these systems are not known. In addition, market factors may not differentiate well between different solar technologies, since the market penetration will depend on the levelized energy cost rather than the systems configuration.

A second approach (the one adopted in this methodology) is to compare the marketability of each technology in terms of the advantages and disadvantages for competing in a very wide variety of market sectors. Here the applications flexibility of the generic system design to be modified to meet the requirements of specific users could be a decisive advantage. Also, the flexibility afforded by the system in siting in a variety of applications may be an important competitive advantage. For the most part, flexibility refers to the ability to change the system design to meet specific applications or site requirements and still achieve satisfactory cost and performances.

Applications or site flexibility can refer to a number of secondary attributes related to the size, site constraints, and/or degree of modularity of each technology. For instance, the use of wet cooling (rather than dry cooling) would limit power plants to sites with adequate water supplies. Modular designs could be accommodated by irregularly sized plots of land, while central power plants require large, contiguous sites.

Flexibility of applications can also refer to the generality of the system for use in residential, commercial, or central station applications. One possibility is that the minimum efficient scale of a particular system is small enough that it could be used in all of the above applications. Larger systems would be generated by replicating the smaller efficient units. The potential market for such a system will be greater than systems with less flexibility.

The transportability of a system may provide additional flexibility to deliver the system to a remote site. For example, installation costs may be kept to a minimum if the technology permits prefabrication. The investment risk to owners may be reduced if they are able to remove or resell the system should the firm fail or leave a specific location. Eventually, the transport characteristics could be included in the initial costs or in the salvage value.

Industrial and commercial energy systems must assume the same risk on energy investments as is applied to their primary activities if these systems cannot be moved. Transportability of the solar thermal system would reduce the investment risk by separating the useful life of the solar thermal system from the operation life of a plant location or even the firm itself.

The grade of heat from the system is also a characteristic which may eventually produce benefits which do not currently show up in the cost of power calculations. Obviously higher temperatures are reflected in the cost of power calculations, but high grade heat may permit further improvements in systems cost which are not possible today. One possibility is that engines with greater efficiency at higher temperatures will be developed. Another possibility is that the systems producing higher grade heat are more likely to have residual heat useful for cogeneration arrangements.

Thus, there are a number of secondary attributes that will be included subjectively in the evaluation of application flexibility. Some of the secondary attributes treated include:

Ease of Manufacture
Ease and Timing of Installation, Maintenance, and Replacement
Marketability
Economies of Scale
Transportability
Grade of Heat

All of these secondary attributes reflect the benefit of handling a large number of relatively small units or the disadvantages of a small number of relatively large units that comprise a plant.

C. FINAL SELECTION AND SCALING OF PRIMARY ATTRIBUTES

The final set of attributes to be used for the initial ranking of technology alternatives was developed by consensus among the organizations conducting the general systems analysis. A standard methodology and a set of attributes provides an important means to assure that the results and the conclusions are comparable, once these analyses are completed. The proposed list of primary and secondary attributes given in Table III-1 evolved over a period of several months, as the requirements for the reference solar power plants were developed. There were six months of discussion and analysis among Jet Propulsion Laboratory, Solar Energy Research Institute, and Battelle-Pacific Northwest Laboratories' representatives endeavoring to select a small number of attributes that capture the essence of the problem. The final set of criteria and primary attributes is shown in Figure III-1, leaving only the step of scaling the ranges of expected values within which all of the solar plant technology alternatives will fall.

The four criteria and seven primary attributes which resulted have been selected to mesh well with the methodology covered in the next section. The units of measure have been chosen to allow careful expression of a decision maker's preferences, yet not place unreasonable requirements for system data. The upper and lower bounds for the attribute scales given in Table III-2 are based on a number of assumptions that are given in the notes immediately following the table. The bounds reflect current estimates of future technology.

TABLE III-2. SPSA Technology Alternatives Criteria and Attributes with Tentative Scales(1)

Criteria	Primary Attributes	Tentative Scale	Notes
Cost	Levelized energy cost	70-120 mills/kWh in 1978 $ for 1990 startup	(2)
	Capital cost	$1800-3000/kWe in 1978 $ for 1990 startup	(2)
Performance	Plant output	20-80% Capacity factor (depending on insolation and storage)	(3)
	Plant reliability	0-10% for Forced outages (due to hardware failures)	
Impacts	Safety and environmental effects	0-10 Subjective scale 0 = Effects similar to oil fired steam plant 10 = Environmentally neutral	
Industrial and Commercial Potential	Research development and industrial requirement	10-50 $ Million/year in 1978 $ to commercialize by 1990 for 1 technology	
	Applications flexibility	0-10 Subjective scale 0 = Few applications 10 = Wide applicability	

Notes on Attribute Scales

(1) Nearly all systems ratings and therefore attribute scales are affected by hybrid systems, year of startup, and intended market penetration (utility or non-utility, intermediate or base load). Non-utility applications (e.g., military, foreign) may be important in the 1985-1990 time period.

(2) These cost ranges reflect current goals for competitive systems. These ranges are sensitive to insolation data and to the use of storage. For further detail, see (23) and (30).

(3) This range includes allowances of 0-10% for mechanical forced outages. With hybrid firing, a modular plant could theoretically go to 100%.

SECTION IV

THE DECISION ANALYSIS METHODOLOGY

A. INTRODUCTION TO THE METHODOLOGY

The purpose of this section is to describe the multiattribute decision analysis methodology used in this study. The approach presented here generally follows the work of Keeney and Raiffa, as described in Reference (14). The methodology is chosen for its relative ease of use, solid theoretical foundation, and previously successful applications. The reader not familiar with this methodology should read References 11, 12, 14, 21, 24, and 29. Reference 29 is Volume I of this series and provides a management-oriented introduction to multiattribute decision analysis.

Following this introduction, this section continues with an exposition of the current approach to multiattribute decision analysis. Some previous applications of multiattribute decision analysis then are listed. Next, the form of the utility function used in this application is described followed by the steps used. Discussions of pratical and theoretical considerations precede an example of the determination of an attribute utility function. This example concludes the section.

B. CURRENT APPROACH TO MULTIATTRIBUTE DECISION ANALYSIS

In the past decade, the field of multiattribute decision analysis (also called decision making with multiple criteria) has burgeoned from a few scattered papers and brief coverage in a pioneering book by Raiffa (19), into a field with national and international conferences and proceedings. The recent publication of Keeney and Raiffa's book (14) has provided in one source both an up-to-date survey and a mathematically supported framework for multiattribute decision analysis.

There are several assumptions made for the current orthodox approach to multiattribute decision analysis under uncertainty as exemplified in References 9 through 14.

These assumptions (see Keeney and Raiffa (14, Chapter 6)) are:

1) There is a single decision maker who is undecided about the course of action to be taken with a particular problem. The problem has been identified, and the feasible alternative actions are given.

2) The decision maker structures the problem by answering questions such as:

   a) What choices can be made now?

   b) What choices can be deferred?

   c) What information can be gathered and used?

3) The answers to these questions are organized in the form of a decision tree, with decision points or nodes under the decision maker's control and chance nodes not under his control or knowledge.

4) The decision maker is able to assign probabilities to the branches emanating from the chance nodes, using data based on the results of stochastic models, expert testimony, and the decision maker's own judgment.

5) The decision maker is able to quantify his preferences by assigning utility numbers to the possible outcomes associated with paths through the tree, which implies:

   a) The decision maker must be able to express his relative preferences for lotteries over these outcomes. As a simple example of a lottery, he could state whether he prefers $50 for sure or a fifty-fifty chance at 0 or $100.

   b) The decision maker must exhibit some form of independence among the multiple attributes of the outcomes, in order to permit assessment of his utilities for these outcomes to be based upon assessment of his utilities for each of the attributes.

   c) The decision maker must have a value model, which can be specified in an algebraic form that allows the attribute utilities to be aggregated into preferences for multiattributed outcomes.

6) After the decision maker structures the problem, assigns probabilities, and utilities, he can determine the optimal strategy that maximizes his expected utility (i.e., the sum of the products of his probabilities and utilities).

C. PREVIOUS APPLICATIONS OF MULTIATTRIBUTE DECISION ANALYSIS

The method of decision analysis just described has been used by a number of analysts on a wide variety of decision problems. For example, Woodward-Clyde Consultants of San Francisco employed decision analysis for studies on nuclear power plant siting (13). It also has been used for airport site evaluation (10), R&D planning (9), and evaluating corporate policy (12). A variety of applications of multiattribute decision analysis is given in Table IV-1 (adapted from (22)).

There are other, less formal approaches to treating multiattribute outcomes under uncertainty. For illustration of these, see Corman (3) and Edwards (6).

D. THE FORM OF THE UTILITY FUNCTION USED IN THE METHODOLOGY

The methodology uses the Keeney multiplicative form (21) of the decision maker's utility function for multiattribute alternatives. This form is:

$$U(X) = \frac{1}{k} \left\{ \prod_{i=1}^{n} \left[1 + kk_i u_i(x_i) \right] - 1 \right\} \tag{1}$$

where $X = (x_1, x_2, \ldots, x_n)$ is a mathematical expression for the alternative X with n attributes, U(X) is the utility value for the alternative X, $u_i(x_i)$ is the attribute utility value for the state x_i, where U and the u_i's are scaled 0 to 1, $0 \leq k_i \leq 1$, and k is a non-zero scaling constant greater than minus one which can be calculated from the k_i's. The k_i's are scaling constants for each of the n attributes. If the sum of the scaling constants is equal to one, i.e.,

$$\sum_{i=1}^{n} k_i = 1,$$

Table IV-1. Previous Applications of Multiattribute Decision Analysis Methodology

Problem	Sponsor	Analyst
Selection of suitable sites for new large-scale nuclear generating stations in Washington and Oregon	Washington Public Power Supply System	Woodward-Clyde
Airport development strategy for Mexico CIty	Ministry of Public Works, Mexico	Woodward-Clyde
Ranking of proposed pumped storage sites in Arizona	Arizona Public Service Co.	Woodward-Clyde
R&D planning strategy for a private corporation	Whirlpool Corp.	D. L. Keefer (now with Gulf Oil)
Environmental assessment of solar energy system alternatives	EPRI	Woodward-Clyde
Optimal blood bank inventory policies	Cambridge Hospital	J. B. Jennings
Optional U.S. foreign policies toward the Mid-East	U.S. State Department	Decisions & Designs, Inc.
Corporate policy review	Woodward-Clyde	Woodward-Clyde
Comparing underground vs. surface siting for nuclear power plants	Sandia	Woodward-Clyde
Assessing New York City Fire Department operations	N.Y.C.F.D.	R. L. Keeney
Alternative strategies for forest pest management	Canadian Government	University of British Columbia
Selecting optimal strategies for the transport of hazardous materials	American Institute of Chemical Engineering	Arthur D. Little
Solar Total Energy System Selection	Sandia	Woodward-Clyde

then it can be shown that U(X) takes the weighted additive form (see Reference (14) or (21)):

$$U(X) = \sum_{i=1}^{n} k_i u_i(x_i).$$

E. STEPS IN THE DECISION ANALYSIS METHODOLOGY

Miles (24) has proposed several assumptions appropriate to the SPSA decision analysis that retain the rigor of the Keeney and Raiffa approach, yet substantially reduce the number of questions that must be asked in the interviews needed to carry out Step 8 of Table I-1. The steps to the simplified approach are:

1) Assess the utility function for each attribute by asking but one lottery question for each attribute. Ascertain that these responses do not vary with the state of the other attributes.

2) Ask the interviewer which attribute he would most prefer to change from its least-preferred to its most-preferred state. If possible, this attribute would then be designated as the reference attribute.

3) Assess trade-offs between the reference attribute and each of the other attributes, in order to provide the data necessary to determine scaling constants for the other attributes.

4) Assess the scaling constant for the reference attribute by asking a single lottery question.

5) Use the assessed data for each technology alternative to perform the calculations necessary to determine a utility value for each technology and rank them accordingly.

These five steps require that the total number of lottery questions asked be one greater than the number of attributes. (More precisely, each question is a series of questions that converge to the desired question.) The total number of questions asked is one greater than three times the number of attributes (one for each attribute to determine its utility function, one for each attribute to assure its utility independence of the other attributes, one for each attribute to determine its scaling constant, and one additional question to determine the reference attribute). Thus, with seven attributes, the total number of questions would be 22.

F. PRACTICAL CONSIDERATIONS IN APPLYING THE METHODOLOGY

This decision analysis process is designed so that the interviewee has to understand only a limited number of concepts and has to respond to only a minimum number of questions concerning his preferences between alternatives and between attribute states. The steps of the interview are arranged so that each step builds on the concepts and responses of the preceding steps.

The concept of utility independence (14) between attributes is neither explicitly presented nor discussed. Utility independence does appear in Step 1 of the simplified approach, but it is not discussed as such. The concept of preference independence (14) and its associated assessment of trade-off curves never appear at all. In this simplified process, it is not even required in theory.

In Step 1, the assessment of all attribute utility functions requires the consideration of only one lottery per attribute. The independence test can be simply answered yes or no. (If the answer is no, then a more detailed modeling would be required.) Step 1 requires only explicit consideration of lotteries over single attributes. Step 1 will acquaint the interviewee with his preferences for states of each attribute, without consideration of states of other attributes (assuming the independence condition is valid).

In Step 2, the most-preferred and least-preferred states of each of the attributes are compared. The reference attribute is determined by asking the interviewee which attribute he would most prefer to have changed from its least-preferred state to its most-preferred state.

Step 3 builds on Step 1 and Step 2 in requiring the interviewee to quantitatively state the degree to which each attribute can influence the preference ordering relative to the reference attribute. Only two attributes, one of them the reference attribute, need be considered in each assessment.

Step 4 is the last question presented to the interviewee, and is the most difficult indifference relation to determine, because all the attributes are varied. This step quantitatively determines the degree to which the reference attribute influences the rank ordering of the alternatives.

This completes the interview part of the decision analysis process. All of the calculations to determine the preference ordering of the alternatives can be done without further interaction with the interviewee.

G. THEORETICAL CONSIDERATIONS

All of the comments made in this Section are made in the context of the SPSA decision analysis for ranking small solar thermal power system alternatives. The alternatives are to be ranked by consideration of seven attributes: Levelized energy cost, capital cost of modules, plant reliability, plant output, environmental and safety effects, R&D requirements, and applications flexibility.

The independence tests of Step 1 theoretically justify the attribute utility functions $u_i(x_i)$ being independent of the states of the other attributes. The independence tests also provide theoretical justification for a multiattribute utility function of a form which Keeney and Raiffa call a "multilinear utility function" (14). However, the multilinear form is too unwieldy for practical use and would require the assessment of 126 scaling constants for 7 attributes.

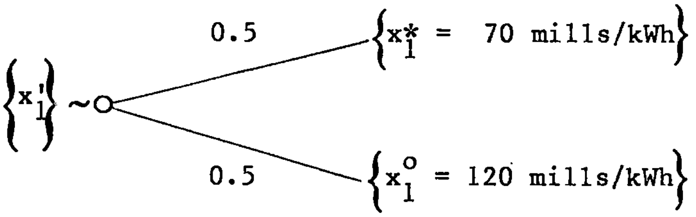
The theoretical justification for the simplified approach taken here lies in Theorem 6.2 of Keeney and Raiffa (14), which gives alternative independence conditions for the "multiplicative" form use to be valid. The detailed discussion of the theory is given in Miles (24).

The assumption that, for continuous variables, the attribute utility function has the form $u_i(x_i) = a_i + b_i e^{c_i x_i}$ needs discussion. All of the 7 attributes can be assumed to yield monotonic attribute utility functions. As long as the state ranges of the attributes are sufficiently restricted so that no breakpoints or regions occur where the preferences of the interviewee are altered such as to change the sign of the second derivative of the utility function, then $u_i(x_i) = a_i + b_i e^{c_i x_i}$ should be a reasonable approximation. Utility function of this form exhibit a property called constant risk aversion. See Keeney and Raiffa (14) for a discussion of this property. The derivation of the constants a_i, b_i, and c_i, based on the assessed data, is given in Miles (24).

An example is given in the next section for determining the attribute utility function for a continuous attribute, given the assessment of the certainty equivalent for only a single lottery (i.e., given only x_i).

H. AN EXAMPLE OF THE DETERMINATION OF AN ATTRIBUTE UTILITY FUNCTION

This final Section presents an example of the determination of an attribute utility function for a continuous attribute, given only the certainty equivalent of a single lottery. The attribute to be considered is that of levelized energy cost, and the attribute state range to be considered is 70-120 mills/kWh. The interviewee is presented with the following indifference relation, and asked to state his value for x_1' (x_1 = levelized energy cost in mills/kWh).



Let us assume that the interviewee responds by stating that x_1 = 105 mills/kWh. Using x_1^o = 120 mills/kWh, x_1' = 105 mills/kWh, and x_1^* = 70 mills/kWh, one obtains for the three constants a_1, b_1, and c_1:

$a_1 = 1.198$

$b_1 = -0.01589$

$c_1 = 0.03602$

These values yield the attribute utility function:

$$u_1(x_1) = 1.198 - 0.01589\ e^{(0.03602)x_1}$$

This function is presented in Figure IV-1.

Graphical aids to help the interviewee respond to questions such as determining x_1' have been found quite useful. Examples of these graphical aids are given in the next section.

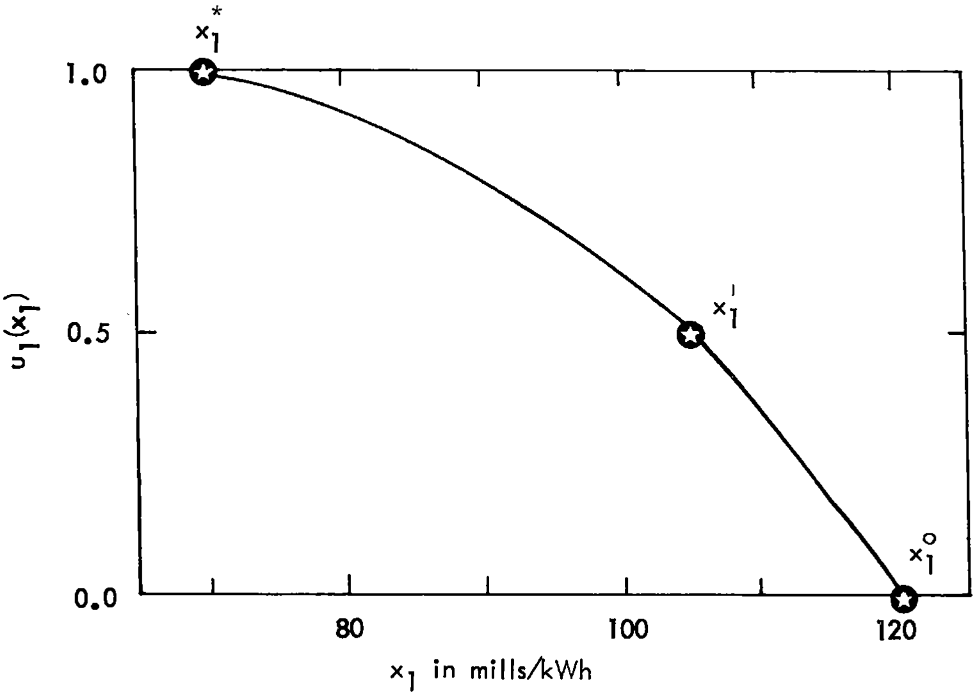


Figure IV-1. An Example of an Attribute Utility Function for Levelized Energy Cost

SECTION V

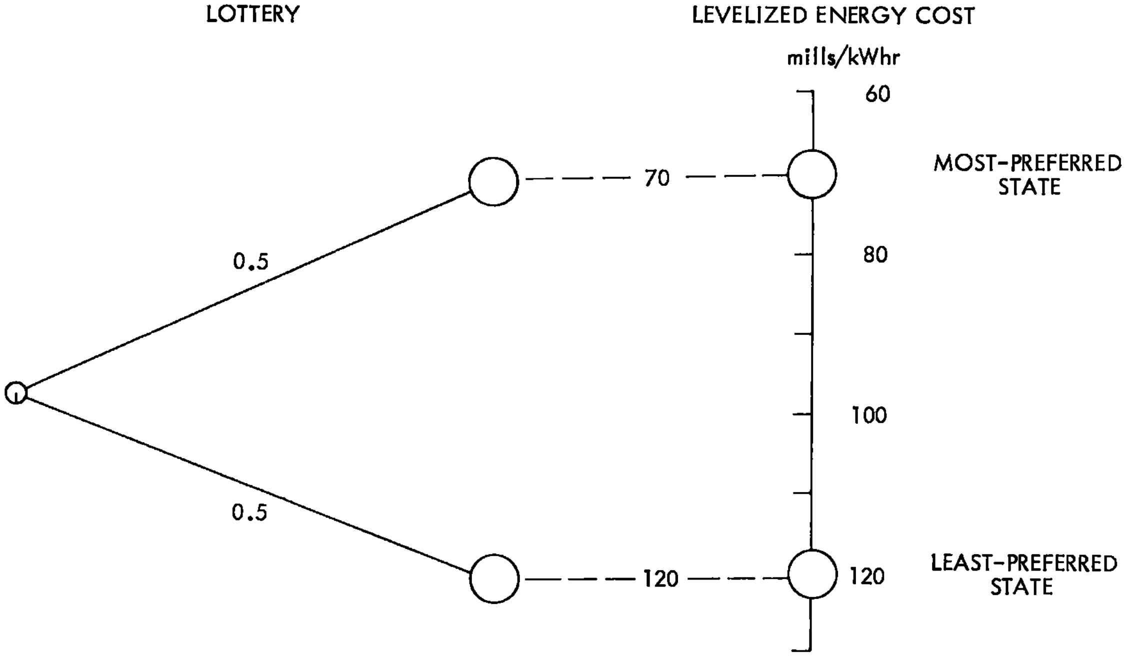
GRAPHICAL AIDS FOR THE INTERVIEWS

In the previous section, the four steps of the simplified multiattribute decision analysis methodology were described. In order to facilitate accurate responses to the questions that will be posed to interviewees, graphical aids have been developed. Hence, this section discusses four figures that are characteristic of the set of figures that will be required in the SPSA interview process (1) to assess attribute utility functions, (2) to select a reference attribute, (3) to assess the scaling constants for attributes other than the reference attribute, and (4) to assess the scaling constant for the reference attribute.

A. ASSESSING THE ATTRIBUTE UTILITY FUNCTION

Figure V-1 is used for assessing the attribute utility function for Levelized Energy Cost. The diagram asks, "For what state of Levelized Energy Cost are you indifferent to the lottery?" A 50/50 lottery between the most-preferred and least-preferred attribute states is shown on the left, and a graduated scale over the attribute state range is shown on the right.

The indifference point to the lottery is determined by asking the interviewee a series of questions that converge to his indifference point. The questions start by asking whether the most-preferred state or the lottery is preferred. (Obviously, the most-preferred state is preferred). The next question asks whether the least-preferred state or the lottery is preferred.



FOR WHAT STATE OF LEVELIZED ENERGY COST ARE YOU INDIFFERENT TO THE LOTTERY?

Figure V-1. Typical Figure for Assessing Attribute Utility Functions

(Obviously, the lottery is preferred.) These first two questions provide assurance that the interviewee understands the responses that are required of him. In the third question, the interviewer picks a point on the graduated scale near the most-preferred state and asks whether the selected state or the lottery is preferred. The rest of the questions are tailored to the responses of the interviewee and are selected so as to bracket and converge on the interviewee's indifference point. When a point or a bracketed range is reached where the interviewee can no longer make a choice, then this point or range is identified as his indifference point or indifference range. It is helpful, as the questions proceed, to mark the interviewee's preferences on the graduated scale so as to leave a trail which converges to the indifference point. The letter L (for lottery) can be used to indicate states for which the lottery is preferred, the letter S for states preferred to the lottery, and finally I for the indifference point or indifference range.

Several other similar figures and sets of questions will be required to determine the other attribute utility functions for attributes with continuous states. For continuous attribute utility functions, this single 50/50 lottery will serve to uniquely determine an attribute utility function that has constant risk aversion (14, 24). HP-25 and HP-97 programmable calculator programs have been documented (25) and (26) which will calculate these attribute utility functions. For attributes with discrete states, this technique may or may not work, and the matter needs further analysis.

Figure V-2 is a table used to determine a suitable reference attribute. The figure displays in a table the least-preferred states and the most-preferred states of all the attributes. The question is then asked, "If you could change only one attribute from its least-preferred state to its most preferred state, which attribute would you change?" If the attribute selected is not an attribute with continuous states, then that attribute is deleted and the question is repeated for the remaining attributes. This process is continued until an attribute with continuous states is selected that would be a suitable reference attribute. An attribute is suitable for use as a reference attribute when the interviewee can understand or has sufficiently well formulated opinions about the attribute to be able to make trade offs between states of that attribute and states of the other attributes. Thus Levelized Energy Cost, measured in mills/kWh, would be a logical candidate for a reference attribute.

C. ASSESSING SCALING CONSTANTS FOR ATTRIBUTES OTHER THAN THE REFERENCE ATTRIBUTE

Figure V-3 is typical of those for assessing scaling constants for attributes other than the reference attribute. It assumes that Levelized Energy Cost is the reference attribute, and that Levelized Energy Cost is more "important" than Capital Cost--more important in that it is assumed for this example that changing from A to C is preferred to changing from A to B. A graduated scale is drawn between points A and C along a line of constant Capital Cost.

The first question asked with respect to Figure V-3 is whether point A or point B is preferred. Obviously B is preferred to A, since for the same

IF YOU COULD CHANGE ONLY ONE ATTRIBUTE FROM ITS LEAST-PREFERRED STATE TO ITS MOST-PREFERRED STATE, WHICH ATTRIBUTE WOULD YOU CHANGE?

ATTRIBUTE	LEVELIZED ENERGY COST	CAPITAL COST	PLANT RELIABILITY	PLANT OUTPUT	ENVIRONMENTAL AND SAFETY EFFECTS	R&D FOR COMMERCIALIZATION	APPLICATIONS FLEXIBILITY
UNIT OF MEASUREMENT	mills/kWhr	$/kWe	FORCED OUTAGE	CAPACITY FACTOR		$/yr	
MOST-PREFERRED STATE			0	80	NONE		MANY
LEAST-PREFERRED STATE			10	20	OIL-FIRED STEAM PLANT		FEW

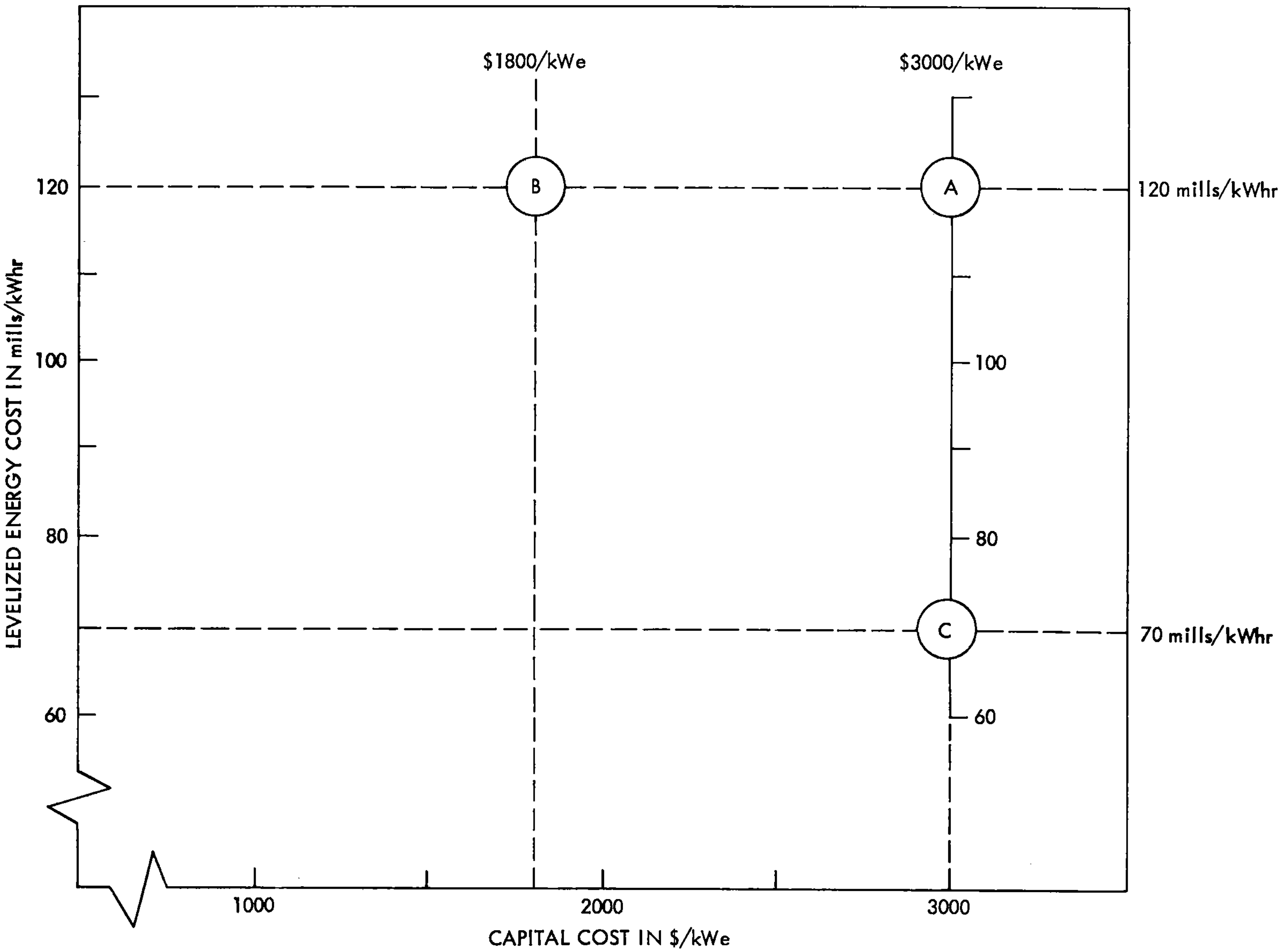


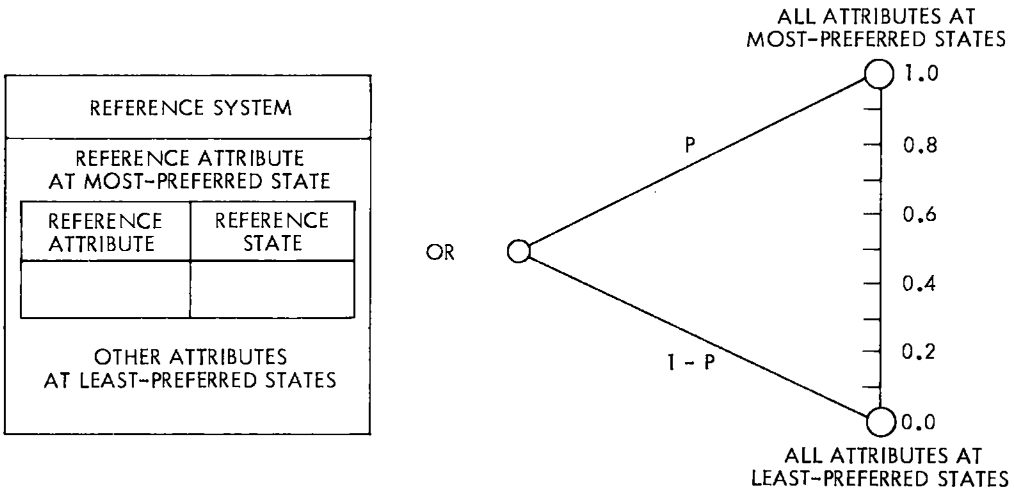
Figure V-3. Figure for Assessing the Scaling Constant for Capital Cost

Levelized Energy Cost, Capital Cost is reduced. The second question asks whether point C or point B is preferred. If, as has been assumed, Levelized Energy Cost is more important than Capital Cost, then changing from A to C is preferred to changing from A to B, and therefore C is preferred to B. The answers to these two questions will provide assurance that the interviewee understands the responses that are required of him and that he is consistent.

Since A is less preferred than B and C is more preferred than B, there must be a point of indifference on the graduated scale of constant Capital Cost between A and C. The questions that are then asked determine this indifference point in a manner analogous to the set of questions used with Figure VI-1. The theory for determining the values of the attribute scaling constants from these indifference relations is given in Reference (27).

D. ASSESSING THE SCALING CONSTANT FOR THE REFERENCE ATTRIBUTE

Figure V-4 is a figure used for assessing the scaling constant for the reference attribute. The reference system is shown as a box in the upper left of the figure. The reference attribute and its most important state are written in the box. All other attributes are at their least-preferred states. A lottery is shown in the upper right of the figure. The lottery yields with probability P a system for which all attributes are at their most-preferred states or it yields with probability 1-P a system for which all attributes are at their least-preferred states. The bottom of the figure reproduces the table of Figure V2-2, so that the interviewee has the relevant states of the attributes displayed before him. Figure V-4 asks the question, "For what probability P are you indifferent between the reference system and the lottery?" The series of questions that are asked to determine P are



FOR WHAT PROBABILITY "P" ARE YOU INDIFFERENT BETWEEN THE REFERENCE SYSTEM AND THE LOTTERY?

ATTRIBUTE	LEVELIZED ENERGY COST	CAPITAL COST $/kWhr	PLANT RELIABILITY % FORCED OUTAGE	PLANT OUTPUT % CAPACITY FACTOR	ENVIRONMENTAL AND SAFETY EFFECTS	R&D FOR COMMERCIALIZATION $/yr	APPLICATION FLEXIBILITY
MOST-PREFERRED STATE	70	1800	0	80	NONE	10×10^6	MANY
LEAST-PREFERRED STATE	120	3000	10	20	OIL-FIRED STEAM PLANT	50×10^6	FEW

Figure V-4. Figure for Assessing the Scaling Constant of the Reference Attribute similar in approach to those asked with respect to Figures V-1 and V-3.

These four figures, extended to include all the attributes and modified as necessary for the appropriate reference atrribute, are all that are needed to assess the interviewee's preferences for alternative small solar thermal power system technologies. The engineering and economic data developed for each of the alternative technologies can be transformed into attribute utility function values. These values, along with the assessed scaling constants, can be entered into the Keeney multiplicative utility function (14, 21) to determine utility values for each of the alternative technologies. An HP-97 programmable calculator program has been written and documented to expedite this calculation (28).

SECTION VI

SUMMARY

This Report, Volume II, has described the criteria, their attributes, and a decision analysis methodology developed to evaluate and rank technology alternatives for small (1-10 MWe) solar thermal power systems applications. The primary focus of the report has been on the development of the specific criteria and their attributes and on the application--rather than the theory--of the decision analysis methodology. An example of each of the types of graphical material to be used in the interviews has been presented. The technology alternatives to be evaluated and ranked were defined but they are described in greater detail in other SPSA Reports. A follow-on report, Volume III, will further expand on the graphical material to be used in the interviews. It will describe the interview procedures and results in detail.

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APPENDIX

REQUIREMENTS FOR REFERENCE SOLAR THERMAL POWER PLANT

Criteria	Design Requirement
Plant Capacity	1 MWe Nominal 0.5 - 5 MWe Design Range 5 - 50 MWe Sensitivity Range
Annual Plant Factor	$0.2 \leq$ Plant Factor ≤ 0.7 0.4 Nominal Plant Factor 0.2 Minimum Value for zero storage Plant Factor = $\frac{\text{Total Plant Output/Year (kWh)}}{8760 \times \text{Plant Rating}}$
Energy Storage	Thermal and Thermochemical Storage: Storage output rating = 0.7 x Plant Rating Storage efficiency = 0.7 Electric Storage: Remote location permitted Plant + Storage rating decoupled Assume Storage Rating = Plant Rating Assume Storage Efficiency = 0.7
Operational Transient	Plant Output Ramp Rates 1. Sunrise : Rise Time ≤ 30 min to Full Power 2. Blockage: Fall Time ≥ 5 min to Zero Power 3. Return : 2 min $\leq$ Rise Time ≤ 10 min to Full Power 4. Sunset : Same as 2 5. Storage : Same as 2
Power Grid Interface	o Voltage Regulation . ~ 5% 0 to Full Load . Time constant ≤ 2 cycles o Frequency Regulation by Line Synchronization o 0.7 Lag $\leq$ Effective Power Factor Range ≤ 1.0
Plant Reliability	o Central Conversion with Thermal Storage . Plant Availability ≥ 0.85 . No more than 1 wk/yr scheduled maintenance o Distributed Conversion (one engine per collector) . Plant availability ≥ 0.95 . No more than 2 days/yr forced outage for individual engines

Criteria	Design Requirement
Part Load Efficiency	Part Load Efficiencies = $0.2 \leq S \leq 0.5$ Part load efficiency will be calculated as the average slope (S) of the efficiency versus load curve. For the purpose of this criterion the average slope will be defined as $S = (1 - N^*/N_{FL})/(1 - P^*/P_{FL})$ where P_{FL} and N_{FL} are the power and efficiency at full load, while P^* and N^* are evaluated at 50 percent load ($P^*/P_{FL} = 0.5$) or at the minimum load if the unit cannot get down to 50% load.
Minimum Load	Plant can operate 20 percent of full load rating
Forced Outage Rate	0.1 day/year = loss of load probability for total plant forced outage rate ≤ 5 percent
Scheduled Outage	Scheduled outage rate ≤ 10 percent
Start-up Power	Starting Power from Electric Grid ≤ 5 percent rated capacity
Operations and Maintenance	o Plant Lifetime 30 years o Unattended operation required from Central Dispatch Area
Safety	o Pressure Vessels - ASME Codes o Toxic/Hazardous Materials o Performance Monitoring/Fault Isolation o Probability of Unsafe Event = 10^{-3} o Fatalities or serious injuries/year for 1000 MWe $\leq 10^{-6}$
Environmental	o Cooling + Blowdown Water 1000 Gal/Day - MW o Wind . Survive to 40 M/S . Operate to 13 M/S o Hail o Blowing Sand typical of Albuquerque, NM o Meets 1985 Water and Air Quality Standards
Plant Installation Time	Construction 2 years (per plant module)