Assessment of Solar Options for Small Power Systems Applications

Volume IV

Comparative Ranking of Concepts

J. W. Currie
M. Jannol

July 1980

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Richland Washington 99352

FOREWORD

Under the sponsorship of the U.S. Department of Energy's Division of Central Solar Technology, the Pacific Northwest Laboratory performed a comparative analysis of solar thermal conversion concepts that are potentially suitable for development as small electric power systems (1 to 10 MWe). Cogeneration and total energy systems were beyond the scope of this study.

Seven generic types of collectors, together with associated subsystems for electric power generation, were considered. The collectors can be classified into three categories: 1) two-axis tracking (with compound-curvature reflecting surfaces), 2) one-axis tracking (with single-curvature reflecting surfaces), and 3) nontracking (with low-concentration reflecting surfaces). All seven collectors were analyzed in conceptual system configurations with Rankine-cycle engines. In addition, two of the collectors (the Point Focus Central Receiver and the Point Focus Distributed Receiver) were analyzed with Brayton-cycle engines, and the latter of the two also was analyzed with Stirling-cycle engines. With these engine options, 10 systems were formulated for analysis.

This is the fourth volume of a five-volume report on the work performed to analyze the alternative concepts, and the results obtained. Included in this volume are descriptions of the methodology used with, and concept ranks obtained from, potential users and R&D fund allocators. The five volumes are:

- Volume I Executive Summary
- Volume II Identification and Characterization of Concepts for Analysis
- Volume III Analysis of Concepts
- Volume IV Comparative Ranking of Concepts
- Volume V SOLSTEP - A Computer Model for Solar Plant System Simulations

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ASSESSMENT OF SOLAR OPTIONS
FOR
SMALL POWER SYSTEMS APPLICATIONS
VOLUME IV
COMPARATIVE RANKING OF CONCEPTS

1.0 INTRODUCTION

Under the sponsorship of the U.S. Department of Energy's (DOE) Division of Central Solar Technology, the Pacific Northwest Laboratory (PNL) performed a comparative analysis of solar thermal conversion concepts for small electric power applications. This is the fourth volume of the PNL report on the work performed. Volume I is the Executive Summary. Concept identification and evaluation are reported in Volumes II and III, respectively.

The primary objective of the task reported in this document was to rank the principal solar thermal conversion concepts that have the potential for achieving commercial success as small electric power systems in the 1- to 10-MWe range. A secondary objective was to identify concept attributes that are most important to potential users. These results will serve as guidance for DOE to make decisions on which concepts and technological attributes warrant priority attention in further technology development.

1.1 RELATIONSHIP OF RANKING TASK TO OTHER PROJECT TASKS

The relationship of the ranking task, reported in this volume, to other project tasks is shown in Figure 1.1. The numbered boxes within the shaded boundary form the research outline for the ranking task. Step 1 was to develop a concise statement of the ranking task objectives in a manner consistent with, and complementary to, the project objectives.

The second step in the ranking task was to identify decision makers whose preferences would be used in determining the concept ranks. Possibilities included the ultimate users of small solar power systems, the electric power industry, and DOE program managers.

FIGURE 1.1. Relationship of Ranking Task to Other Project Tasks

Step 3 was to identify attributes (characteristics) of small power concepts that were important to the decision makers. This required obtaining general information on the concepts to be evaluated, as well as interfacing with the decision makers to identify attributes important to them. Knowing which attributes (e.g., levelized energy cost, capacity factor) were the most important to the decision makers was essential in characterizing the solar concepts.

In Step 4, the methodology used to rank the concepts was chosen. Survey data were required to rank the concepts. This necessitated developing a survey questionnaire in Step 5. To accomplish this, input was required from the systems analysis task. To evaluate each concept, the achievable range for each attribute had to be known.

In Step 6, the questionnaire was used in personal interviews to collect data on decision makers' values and preferences.

The ranks were determined in Step 7. This was done by combining the best technical estimate of the attribute level for each concept with decision makers' preferences for that attribute level. This resulted in a final score for each concept. The concept scores were used to ordinally rank the concepts.

Step 8 comprises the conclusions and recommendations for this task. Conclusions from this and the other tasks were ultimately combined to produce the project conclusions and recommendations in Laity et al. (1979).

1.2 VOLUME IV SCOPE

Steps 2 through 8 are discussed in detail in the following sections of this report. The ranking task conclusions and recommendations are presented in Section 2.0. Section 3.0, Methodology, addresses Steps 2 through 5. Step 6, determining decision maker values, and Step 7, calculating the concept scores and ranks, are discussed in Section 4.0.

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2.0 CONCLUSIONS AND RECOMMENDATIONS

Several conclusions and recommendations based on the concept ranking task are highlighted in this section. Conclusions derived from analyses of concept ranks and decision maker preferences are presented first, followed by conclusions on the methodology used in this study. Recommendations address both the results of the ranking process and the method used.

2.1 CONCLUSIONS

Statistical analysis of the concept scores and ranks, and of decision maker preferences, led to eight conclusions.

- The Point Focus Central Receiver with Rankine power conversion and the Point Focus Distributed Receiver with Brayton and Stirling power conversion consistently ranked high.
- The Line Focus Distributed Receiver with a tracking receiver and the Line Focus Central Receiver consistently ranked low.
- The concept ranks for a sample of electric power industry decision makers were not statistically significantly different from the ranks for a sample of DOE R&D managers.
- The concept ranks at low (<0.4) capacity factor were not statistically significantly different from ranks at high (0.8 to 0.9) capacity factor. However, decision makers were willing to pay the cost of storage to have the higher capacity factors.
- The concept ranks using all seven attributes [levelized energy cost (LEC), capacity factor (CF), fixed cost as a percentage of levelized energy cost (FIX), forced outage rate (FO), plant flexibility (FLEX), environmental and safety effects (ENV), and public investment in R&D necessary for commercialization (R&D)] were statistically significantly different from the ranks using only LEC, CF, and FIX.
- When only the three more traditionally compared attributes of LEC, CF, and FIX were considered, concepts using central receiver subsystems ranked above those with distributed receivers. In addition,

concepts with thermal storage ranked above those with electric storage at higher capacity factors (>0.4). Finally, two-axis tracking concepts ranked above one-axis tracking concepts, which, in turn, ranked above the nontracking concept.

- When all seven attributes were considered, the point focusing, distributed generation concepts ranked highest. The central receiver concepts dropped in ranking, primarily because of higher forced outage rates, and the central receiver Brayton concept incurred an additional penalty for higher R&D costs. Distributed line focusing and nontracking concepts moved up in rank, particularly at high capacity factors, due primarily to relatively low R&D costs.
- Statistically, LEC was the most important attribute and CF the second most important attribute to both the utility and DOE samples. R&D was statistically the least important attribute to the utility sample.

Two conclusions were made regarding the multiattribute utility method used in this study.

- The method is applicable to a broad array of energy decision makers and requires, on average, 35 minutes of contact time for a typical interview.
- The behavioral assumptions required to implement the method were shown to be valid by internal consistency checks during the interview process.

2.2 RECOMMENDATIONS

Three recommendations resulted from this work. The first follows from the conclusions on ranking analysis.

- Utility decision makers indicated that plant flexibility, forced outage rate, and environmental and safety effects affect the commercialization potential of solar concepts. Therefore, research, development, and demonstration programs should include provisions for establishing these plant characteristics.

Two recommendations for improving the method used are listed below.

- Research should be undertaken to build more theoretical rigor into the method while limiting the interview time to less than 45 minutes.
- Experiments should be conducted to determine the consistency of ranks under varying degrees of theoretical rigor in the method used. The purpose of the experiments would be to produce the most cost-effective procedure to yield consistent results.

3.0 METHODOLOGY

In choosing the ranking methodology, it was hypothesized that users will select small power systems on the basis of certain attributes. If these attributes and their importance could be identified, this information could be used to decide how to allocate R&D investment funds among technological concepts and attributes.

One possible way to identify attributes and determine their relative importance would be to use small power systems sales data to statistically estimate a demand function for the attributes. This would present several problems. First, the available sales data may be limited. In the case of power systems in the 1- to 10-MWe range, very few units were purchased by the electric power industry in the Southwest between 1967 and 1977 (Aerospace 1978). Even if extensive sales data were available, it would be necessary to estimate the level of the attributes used to describe the technology. When using secondary data, user expectations of product quality are important. Determining these expectations would require interviews with users, vendors, or both.

After considering these problems, and noting that the Jet Propulsion Laboratory (JPL) had assembled an initial list of important attributes, it was decided not to use a method requiring secondary data. Instead, a direct inquiry technique, multiattribute utility methodology (MAUM), would be used. This general method assumes that consumers derive utility from the attributes, or characteristics, of a particular good. In this study, the good in question is a small power system. Potential users of the technology could be questioned about the attributes in a way that would allow the analyst to combine user responses with technical estimates of attribute levels to arrive at a preferential rank for each concept under consideration.

The remainder of this section addresses issues related to Steps 2 through 5 shown in Figure 1.1. The identification of relevant decision makers (Step 2) is discussed first. Then, attribute identification (Step 3) is described. Next, the choice of MAUM version (Step 4) is documented and the conceptual

framework is presented. Finally, the manner in which elements of the conceptual framework were used to develop the questionnaire (Step 5) is discussed.

3.1 DECISION MAKER IDENTIFICATION

The first methodological issue to be addressed was identifying the decision makers. Two groups were easily identified.

The first group, composed of ultimate users of new small solar thermal power systems, was the electric power industry. After a system is supplied to the marketplace, its ability to effectively compete with substitute systems (coal, oil, other solar) depends on the attributes of all competing systems, as well as on the industry's preferences for these attributes and willingness to act on these preferences. Obtaining preferences from electric power industry decision makers was of utmost importance. It was also deemed important to identify those decision makers within the electric power industry who had the highest probability of using small solar thermal concepts. These were believed to be utility executives in the far West, Southwest, and Southeast.

A second group of decision makers--DOE program managers--was also identified as important in this study. The DOE manager allocates resources to research and develop new technology for ultimate use by the electric power industry. Because the DOE managers' objective is to expedite the commercialization process, it is necessary that they allocate resources to improve the performance of those attributes viewed as most important to the ultimate users of the technology. This allocation would occur if the attribute preferences of DOE and electric power industry managers were not significantly different. Data from both groups of decision makers--the allocators of R&D funds and the ultimate users--were required to test this hypothesis.

3.2 ATTRIBUTE IDENTIFICATION

After identifying the relevant decision makers, it was necessary to identify important technology characteristics or attributes on which decision makers would discriminate when choosing among small thermal power systems. However, before the attributes could be identified, the small solar power systems to be

evaluated had to be selected. The systems were selected by identifying those concepts that best represented the most advanced generic types currently being proposed. The configurations selected for analysis were classified on the basis of two major characteristics--method of tracking and thermodynamic cycle. Table 3.1 presents the seven generic concentrator systems, and includes the nomenclature used to identify the individual concepts. A detailed discussion of these concepts and why they were chosen is presented in Volume II of this report (Laity et al. 1980b).

TABLE 3.1. Concepts Selected for Analysis

<u>Concept</u>	<u>Energy Conversion Subsystem</u>	<u>Symbol</u>
<u>TWO-AXIS TRACKING</u>		
Point Focus Central Receiver	} Rankine } Brayton	PFCR/R
		PFCR/B
Point Focus Distributed Receiver	} Rankine } Brayton } Stirling	PFDR/R
		PFDR/B
		PFDR/S
Fixed Mirror Distributed Focus	Rankine	FMDF
<u>ONE-AXIS TRACKING</u>		
Line Focus Central Receiver	Rankine	LFDR
Line Focus Distributed Receiver		
• Tracking Concentrator	Rankine	LFDR-TC
• Tracking Receiver	Rankine	LFDR-TR
<u>NONTRACKING</u>		
Low-Concentration Nontracking	Rankine	LCNT

After choosing the concepts to be evaluated, the important attributes were identified (Step 3, Figure 1.1). According to Feinberg et al. (1979), the attributes identified should have the following properties:

- differentiation - The attributes should reflect actual differences among the alternative technologies being considered. For example, if the choice were between two systems with identical capacity factors, then capacity factor would not be a basis for choosing either concept.

- importance - Each attribute should represent a significant factor in the value model of the decision makers.
- familiarity - Each attribute should be recognizable and understandable to the decision maker.
- measurability - The attribute can be subjectively or objectively measured with data that can be attained within the time and resources available for the decision analysis.
- independence - Changes within certain limits in the level of one attribute should not affect preference for other attributes. This can be a very restrictive assumption. For example, within a given range, variations in the level of environmental impacts should not affect the importance a decision maker places on capacity factor.

Furthermore, the attributes chosen should be common to all small power systems currently in use. This will help ensure that the attributes are both important and familiar to the decision maker. This commonality also creates a more realistic situation because small solar thermal systems will be competing with the systems currently in use.

The attribute selection process began by generating a list of over 20 possible attributes. Input to the list was provided by electric power industry personnel, DOE managers, and R&D scientists from the Jet Propulsion Laboratory, the Solar Energy Research Institute, and the Pacific Northwest Laboratory. Continued interaction among these groups resulted in several revisions in which many attributes were combined with others or deleted. The final list of seven attributes is shown in Table 3.2. With one exception, the levels of all the attributes were hypothesized to vary significantly among the 10 solar concepts as well as be important to decision makers in choosing small power systems.

Levelized energy cost (LEC) was hypothesized to be the most important attribute. It includes all fixed and variable costs and is measured in mills per kilowatt-hour produced. Holding the level of all other attributes constant, decision makers were expected to prefer lower levelized energy costs. Levelized energy costs were expected to vary significantly among concepts.

TABLE 3.2. Attributes and Units of Measurements

<u>Attribute</u>	<u>Unit of Measurement</u>
Levelized Energy Cost (LEC)	mills/kWh (1978 dollars)
Fixed Cost as a Percentage of Levelized Energy Cost (FIX)	% Fixed Cost
Plant Capacity Factor (CF)	% Capacity Factor (excluding forced outage)
Forced Outage Rate (FO)	% Forced Outage Rate
Plant Flexibility (FLEX)	0 to 10 Subjective Scale (A score of 10 would indicate maximum flexibility. A score of 0 would indicate flexibility similar to that of a coal-fired base load power plant.)
Environmental and Safety Effects (ENV)	0 to 10 Subjective Scale (A score of 10 would indicate minimum environmental and safety effects. A score of 0 would indicate environmental and safety effects similar to those of an oil-fired steam plant using low-sulfur oil.)
Public Investment in Research and Development Necessary for Commercialization (R&D)	0 to 10 Subjective Scale (A score of 10 would indicate the public investment in research and development necessary to commercialize geothermal energy. A score of 0 would indicate the public investment in research and development necessary to commercialize fusion energy.)

Fixed cost was expected to be important. Holding the level of all other attributes constant, it was not hypothesized if decision makers would prefer lower or higher fixed costs. High fixed cost as a percentage of levelized

energy cost implies low variable cost and, thus, low (or no, as in the case of solar) fuel costs. However, it also suggests high relative costs in shutting the plant down or retiring it early. In other words, with high fixed cost, most of the total costs are known in advance, regardless of how much electricity is ever produced by the plant. This attribute was not expected to vary significantly among the 10 generic concepts. However, it does vary significantly among the small power concepts currently available. For example, FIX for small hydro is significantly higher than for a gas turbine plant. Therefore, the FIX attribute was included.

Plant capacity factor was also hypothesized to be one of the most important attributes. Measurement was in percentage of capacity factor excluding forced outages. Holding the level of all other attributes constant, it was hypothesized that decision makers would prefer a higher to a lower capacity factor. With storage, a wide range of capacity factors is available for each concept.

Forced outage rate was thought to be important and was, therefore, not evaluated as part of capacity factor. It was measured as the percentage of time the plant was forced to be out of operation. Considerable variation in the forced outage rate was expected between central and distributed solar concepts. It was expected that, holding the level of all other attributes constant, decision makers would prefer a lower forced outage rate.

Plant flexibility is one of three attributes measured on a subjective scale. The measure combines siting flexibility in general with the modularity of small power concepts. It was expected that, holding the level of all other attributes constant, decision makers would prefer more plant flexibility.

Environmental and safety effects were also measured on a subjective scale. Variation in ENV was expected among the concepts. However, the range over which ENV was measured (Table 3.2) suggested it would be one of the less important attributes. It was expected that, holding the level of all other attributes constant, decision makers would prefer fewer environmental and safety effects.

The final attribute listed is the public investment in research and development necessary for commercialization. This attribute, measured on a subjective scale, is not important to decision makers in choosing among available technologies. Therefore, it was hypothesized to be of relatively minor importance to the electric power industry. However, it was hypothesized to be important to DOE managers in choosing how to allocate R&D funds among technologies. Significant variation among the concepts was expected in R&D. For example, it was expected that the LCNT would be shown to have low R&D costs while the Stirling and Brayton systems would require relatively high R&D costs.

3.3 RANKING METHODOLOGY SELECTION AND REFINEMENT

After the important attributes were identified, the 10 solar concepts were technically described. While this characterization was underway, the specific form of MAUM for producing the concept ranks was chosen (Step 4).

3.3.1 Ranking Methodology Selection

The use of MAUM is well documented in the literature. Feinberg and Miles (1978) present a detailed bibliography of theoretical and experimental research. The use of MAUM ranges from theoretically rigorous applications requiring relatively long and complex interviews to relatively simple approaches requiring only a few questions.

The more rigorous approaches use a multiplicative utility function. Decision makers must respond to a series of questions to ascertain their indifference among different levels of the attributes. The questions involve explicit considerations of changes in probabilities of attaining different attribute levels.

Examples of the more rigorous approach can be found in Keeney and Robilliard (1977) and Woodward-Clyde Consultants (1975). This approach has been applied primarily to problems where there is either a single decision maker or, at most, very few decision makers. The decision being addressed is usually an important problem to the decision maker, i.e., the decision maker has a vested interest in the decision. Finally, the decision maker generally wants the decision process to work. In other words, he is willing to devote

the time and concentration necessary to complete the procedure in a consistent manner. Moreover, the decision maker normally is a high level manager or technical person and has the capacity to comprehend the complexity of the procedure.

In fact, in the two studies cited above, the decision analysts actually assumed the role of decision makers. While it may be a convenient way of using a relatively complex and lengthy interview process, this procedure leaves no assurance that the recommended decisions represent the values of the real decision makers.

The less rigorous methods use an additive utility function. This means that the utility or level of satisfaction a user derives from only one attribute of the technology is added to the utility derived from each of the other attributes. Examples of this procedure can be found in Edwards (1977) and Litchfield et al. (1976).

The interview procedure for this approach is relatively straightforward and requires much less contact time than does the more rigorous approach. It was hypothesized that the approach could be easily applied to a broad array of decision makers, many of whom may have little immediate interest in the decision problem of the PNL study but could be potential users of the technology.

The more rigorous approach was compared to the less rigorous approach for this problem. A theoretically rigorous approach requires a relatively long and complex face-to-face interview. If the decision maker being interviewed had the incentive and capacity to give the procedure his full attention and concentration, it was hypothesized that high-quality, relatively costly data would be collected. On the other hand is the approach that lacks the theoretical rigor of the first approach and requires a relatively short and straightforward face-to-face interview. Because the interview is significantly shorter than that required by the more rigorous approach, it was hypothesized that there is a higher probability of commitment and concentration to the shorter than to the longer interview. However, without extensively testing both approaches on random samples drawn from the same population over which actual decisions are to be observed, there appear to be no conclusions that can be drawn on the quality of data (in terms of predictive ability) obtainable with either approach.

For these reasons, pretests were conducted on science and engineering staff at PNL using different versions of each approach. It was found that the interview length for the more rigorous approach ranged from 45 minutes to just over 2 hours, with the mean well over 1 hour. The interview length for the less rigorous approach ranged from 20 minutes to 1 hour. Also, a higher percentage of individuals criticized the more rigorous approach for being too complex than criticized the less rigorous approach for being too simplistic.

During the pretests several candidate decision makers within the electric power industry and DOE were contacted. They were told that PNL was assessing small power systems for DOE and had developed an interview procedure for eliciting decision maker preferences. They were asked to participate in an interview and an attempt was made to schedule a time and place. The decision makers contacted were generally high level managers. Most expressed interest in the study but hoped the process would take no more than an hour. Their reasons were twofold. First, as expected, they were busy people. Second, in the case of the electric power industry decision makers, several did not expect to be seriously considering small power systems in the immediate future. Because the candidate decision makers preferred the total length of contact time to be less than 1 hour and because they were less than enthusiastic about small power systems in the 1- to 10-MWe range, the more rigorous approach was discarded in favor of the less rigorous approach.

3.3.2 Ranking Methodology Refinement

The procedure used to derive the concept ranks is presented below. A description of the variables is presented first. The way in which the variables would then be combined in equation form to calculate the concept scores and ranks is described next.

3.3.2.1 Variable Description

The variables used in the methodology are defined below.

PF = preference function

ps = preference score

cs = concept score

cr = concept rank

a = attribute level
 w = importance weight
 w^* = normalized importance weight
 i = i th attribute
 j = j th decision maker in a group
 k = k th group of decision makers
 l = l th small solar thermal concept.

3.3.2.2 Rank Calculation

The objective was to derive, for each decision maker group, a concept score, cs , which represents each group's preferences for each concept. The concept scores for each group could then be ordered by magnitude to determine the concept ranks. The data available to calculate the ranks were the importance weight, w_{ijk} , and the preference function, PF_{ijk} , from the interview process and the attribute level, a_{i1} , from the systems analysis task.

The importance weight, w_{ijk} , is a weight between 100 and 0, which represents the relative importance of each attribute, given its respective range. In this study, for example, this information would answer the question, "How important to the decision maker is the range of levelized energy cost compared to the range of forced outage rate?"

The preference function, PF_{ijk} , represents the relative importance of changes in the level of an attribute. An example of the type of question this information would answer is, "How important to the decision maker are changes in levelized energy cost over its respective range?"

The attribute level, a_{i1} , is the best technical estimate of the level of each attribute for every concept. An example of a_{i1} would be the best estimate of the forced outage rate for the PFCR/B.

To calculate the ranks, normalized importance weights are calculated first as shown in Equation (1).

$$w_{ijk}^* = \frac{w_{ijk}}{100} \quad (1)$$

where

$$0 \leq w_{ijk} \leq 100$$

$$0 \leq w_{ijk}^* \leq 1$$

This was done to aid in interpreting the final results by restricting the concept scores to two-digit numbers.

The next step is to derive ps_{ijk1} :

$$ps_{ijk1} = f(PF_{ijk}, a_{i1}) \quad (2)$$

where

$$0 \leq ps_{ijk1} \leq 10$$

An example of how ps_{ijk1} is derived is shown in Figure 3.1. The curve representing PF_{ijk} is determined from the decision maker interview. The a_{i1} estimate is generated in the systems analysis task. The ps_{ijk1} estimate is read directly off the graph.

FIGURE 3.1. Derivation of the Preference Score, ps_{ijk1}

The next step is to calculate the concept score for each decision maker. Equation (3) indicates that the satisfaction (concept score) from each attribute is the preference score (ps) multiplied by the normalized importance weight (w^*).

$$cs_{jk1} = \sum_{i=1}^n \left(ps_{ijk1} \right) \left(w_{ijk}^* \right) \quad (3)$$

Equation (3) also assumes that the total satisfaction (concept score) from a given concept can be determined by adding the satisfaction or utility an individual derives from each attribute. This is true only within the relevant attribute range for each decision maker. It was determined by pretests (and confirmed in the interview process) that, if for any concept the estimated attribute level (i.e., a_{i1}^* in Figure 3.1) results in a ps_{ijk1} of zero, then cs_{jk1} equals zero. This means that, even if all other attributes are set at their most favorable values within the technologically possible range, the concept is unacceptable to the decision maker because the level of one of the attributes is outside his minimum acceptable value. This condition can be stated as a constraint to Equation (3) or,

$$\text{if } ps_{ijk1} = 0 \text{ for any } i=1,n, \text{ then } cs_{jk1} = 0$$

Use of Equation (3) also assumes that the satisfaction or utility a decision maker derives from a given attribute is independent of the levels of all other attributes over the relevant attribute range. It is important to provide internal consistency checks when implementing the procedure to see if this assumption is justified.

The group concept score is determined from

$$cs_{k1} = \frac{\sum_{j=1}^m cs_{jk1}}{m} \quad (4)$$

Use of Equation (4) assumes that equal weight is given to individual decision maker preferences and that cs_{k1} is simply the mean of the individual concept scores.

Finally, the cs_{k1} values for each attribute are ordered in terms of descending magnitude to produce the concept rank, cr_{k1} , for each decision maker group.

3.4 QUESTIONNAIRE DEVELOPMENT

After choosing and refining the ranking methodology, it was necessary to develop a questionnaire (Step 5, Figure 1.1) and procedure for obtaining the importance weights, w_{ijk} , and preference functions, PF_{ijk} , from the decision makers. A copy of the questionnaire used is found in Appendix A.

It was necessary to estimate the range within which the level of an attribute over all concepts would fall. The attribute range was used in determining both the importance weights and the preference functions.

3.4.1 Determining Importance Weights

The attribute range was first used to completely describe each attribute to the decision maker, to assist him in assigning an importance weight, w_{ijk} , to that attribute. The attribute ranges, along with complete attribute descriptions, were assembled on 5 x 7 cards. Seven 5 x 7 cards were developed, one for each attribute. Each decision maker was asked to read all of the cards except that describing the attribute on R&D requirements for commercialization. The decision maker was then asked to order the cards in terms of importance. He was asked to assign an importance weight (w_{ijk}) of 100 to the card depicting the most important attribute and numbers less than or equal to 100 but not less than zero to the other cards to represent the relative importance of the other attributes to the most important attribute. A key to the relative importance of an attribute is the possible range of values that attribute can take on. The decision maker was encouraged to concentrate on the attribute ranges. The 5 x 7 cards used in the procedure are reproduced in Appendix A.

3.4.2 Determining Preference Functions

The second way in which the attribute range was used was in developing graphic representations of decision maker preference functions, PF_{ijk} , for each attribute (see Figure 3.1). To accomplish this, seven blank graphic aids were developed, one for each attribute. For a given attribute, a preference score, ps , of 10 was assigned to the most favorable attribute value within the technically possible attribute range. The decision maker was then asked to assign a preference score to the least favorable attribute level. Preference scores were then assigned to enough intermediate attribute levels to form a curve depicting the preference function, PF_{ijk} . The shape of the PF_{ijk} curve depended heavily on the attribute range. The blank graphic aids used in determining the individual preference functions are shown in Appendix A.

3.4.3 Other Important Data

Additional information on w_{ijk} and PF_{ijk} was collected to determine if 1) the independence-among-attributes assumption was justified, 2) major differences existed between solar and nonsolar systems, and 3) the attribute describing R&D requirements to commercialize small solar thermal power systems was useful.

An important assumption in implementing the ranking methodology is that the individual decision maker's preference function for an attribute is independent of the level of all other attributes. Pretests showed that, for the attributes and attribute ranges used in this study, the assumption appeared justified. However, additional evidence could be gathered during the data collection process by deriving the PF_{ijk} while holding the level of other attributes at the most favorable and least favorable values.

Literature reviews and discussions with electric power industry consultants indicated that, in general, the industry probably would not be optimistic about the immediate contribution that could be made from solar thermal power systems. This meant that industry managers might not be as committed to concentrating on the questionnaire as they would be if the topic were merely small thermal power systems with no mention of solar. It was hypothesized that, if technological choices are really made on the attributes, then the process would

lead to higher quality data on w_{ijk} and PF_{ijk} if no mention of solar were made in the interview. After gathering the data, the decision makers were asked whether they would alter any w_{ijk} or PF_{ijk} if they had known solar thermal electric systems were being evaluated.

Because the purpose of this study was to provide information to DOE for use in allocating R&D funds, it was deemed important to assess the importance of this attribute to both DOE and electric power industry decision makers. Therefore, after telling the decision makers that the first application of the method would be to assess small solar power systems, they were asked for all their w_{ijk} and PF_{ijk} on the attribute describing R&D requirements to commercialize small solar thermal power systems.

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4.0 ANALYSIS AND RESULTS

This section presents the analysis and results of the concept ranking task. The data used in the analysis are described first, followed by a statistical analysis of the decision makers' values. Finally, the concept scores and ranks are presented along with the results of statistical tests.

4.1 DATA DESCRIPTION

It was shown in Section 3.0 that the data required to calculate the individual concept score, cs_{jk} , are the importance weights, preference functions, and estimated level for each attribute.

4.1.1 Importance Weights and Preference Functions

The decision makers' importance weight, w_{ijk} , and preference function, PF_{ijk} , for each attribute were produced by administering the questionnaire, in an interview format, to the decision makers.

The questionnaire was administered to two different groups. First, 37 separate interviews were conducted with managers representing 13 different electric power industry entities in the far West, Southwest, and Southeast. This industry sample was chosen specifically to concentrate on those entities that would most likely use solar electric power systems and be familiar with and interested in small power systems. The questionnaire was also administered to 15 DOE managers involved in R&D allocation decisions on electric power systems.

In gathering w_{ijk} and PF_{ijk} data, it was important to check the legitimacy of the assumption that the level at which all other attributes are set does not significantly affect any PF_{ijk} . Of the 52 decision makers interviewed, four made changes in at least one PF_{ijk} when the levels of all other attributes were changed from their most favorable to least favorable values. These changes did not affect the final concept ranks.

It was also deemed important to determine if the decision makers would change w_{ijk} and PF_{ijk} if they knew the purpose of the study was to rank small solar concepts. No effect by these changes on the final concept ranks would

provide one indication that no "solar bias" was present in the decision makers' original responses. Greater confidence could be given to w_{ijk} and PF_{ijk} in that they represent an objective measure of the decision makers' preferences for the attributes of small thermal power systems. Of the 52 decision makers interviewed, three made changes in at least one w_{ijk} or PF_{ijk} when they were told that small solar thermal systems were being analyzed. These changes did not affect the final concept ranks.

The results of these two consistency checks indicated that, although the method employed for eliciting decision maker preferences was not the most theoretically rigorous available, there was reason to believe that the data were of sufficient quality to undergo statistical analysis.

4.1.2 Estimated Level for each Attribute

Figure 3.1 indicates that, to calculate the group concept score, cs_{k1} , and ultimately group concept rank, cr_{k1} , it was necessary to have data on the estimated level for each attribute, a_{i1} . The a_{i1} data were output from the systems analysis task, as indicated by Figure 1.1.

Information was generated on the seven attributes discussed earlier in this report and described in detail in Table 3.2 and Appendix A. These are levelized energy cost (LEC), plant capacity factor (CF), fixed cost as a percentage of levelized energy cost (FIX), plant flexibility (FLEX), forced outage rate (FO), environmental and safety effects (ENV), and public R&D investment required for commercialization (R&D). For each of the 10 solar concepts, the engineering team performing the systems analysis produced the best technical estimate of the level of each attribute for each concept (i.e., a_{i1}). Tables B.1 through B.3 in Appendix B show the a_{i1} data generated from the systems analysis task. A detailed description of how these data were generated is found in Volume III of this report (Laity et al. 1980a).

4.2 DECISION MAKER PREFERENCES

The data collected on decision maker preferences were judged to be of high enough quality to warrant statistical analysis. The w_{ijk} data analysis is presented first, followed by an analysis of the PF_{ijk} data.

4.2.1 Group Importance Weight Analysis

Group importance weights, w_{ik} , were calculated for both the DOE and electric power industry samples using Equation (5).

$$w_{ik} = \frac{\sum_{j=1}^n w_{ijk}}{n} \quad (5)$$

Thus, w_{ik} is the mean importance weight for each attribute in each decision maker group. It is important to note that the only purpose for calculating w_{ik} is to analyze decision maker preferences and that w_{ik} is not used in calculating the concept scores, cs_{kl} .

Difference in means tests were conducted to determine significant differences 1) among attributes within a group and 2) between the two groups for each attribute.^(a) The results are shown in Table 4.1.

The dotted lines in Table 4.1 show where there are statistically significant differences (0.05 level) among the mean importance weights. For example, the levelized energy cost importance weights for both the utilities and DOE are significantly different from the importance weights assigned to capacity factor. However, there is no significant difference between the levelized energy cost importance weights assigned by the utilities and those assigned by DOE.

Table 4.1 shows that the utility and DOE subjects placed the same importance on levelized energy cost and capacity factor and that the importance placed on each of these attributes was significantly different from all other attributes. Thus, for both the utilities and DOE, levelized energy cost is clearly the most important attribute and capacity factor is clearly the second most important attribute when considering capacity additions in the 5- to 10-MWe range.

(a) Tests among attributes within a group were for correlated samples. Tests between groups were for independent samples.

TABLE 4.1. Attribute Mean Importance Weights for Utility and DOE Samples

Attribute	Mean Importance Weights (w_{ik}) ^(a)	
	Utilities (n = 37)	DOE (n = 15)
Levelized Energy Cost (LEC)	97.4	94.0
Capacity Factor (CF)	77.0	74.0
Plant Flexibility (FLEX)	62.1	60.7
Forced Outage Rate (FO)	60.3	59.3
Environmental and Safety Effects (ENV)	53.2	33.7
Fixed Cost as a Percentage of Levelized Energy Cost (FIX)	52.2	37.5
Public Investment in Research and Development Necessary for Commercialization (R&D)	11.2	34.7

(a) The dotted lines delineate boundaries of statistically significant differences among the w_{ik} (nondirectional, 0.05 significance level).

The utility and DOE samples showed no significant differences in the importance weights assigned to plant flexibility and forced outage rate. Also, there was no significant difference between these two attributes.

There were significant differences between the utility and DOE samples on the importance of environmental and safety effects (ENV), fixed cost as a percentage of levelized energy cost (FIX), and public investment in research and development necessary for commercialization (R&D). Department of Energy respondents assigned a relatively low importance weight to ENV because the range of impacts was narrow and rather benign. However, the utility industry knows, through experience, that regardless of the level of environmental impacts, there can be major costs from the environmental impact statement and hearing process. Thus, they are acutely sensitized to environmental and safety effects.

Fixed costs were more important to the utility sample than to the DOE sample. The two samples showed no difference in preferences for high fixed costs as a percentage of levelized energy cost. Seventy percent of the utility sample preferred higher to lower fixed costs, as opposed to 67 percent of the DOE sample. Finally, R&D was clearly the least important attribute to the utility sample. The ENV, FIX, and R&D attributes were clearly the least important to the DOE sample. As hypothesized, R&D was significantly more important to the DOE than it was to the utility sample.

4.2.2 Group Preference Function Analysis

Group preference functions, PF_{ik} , were calculated for both the DOE utility samples using Equation (6).

$$PF_{ik} = \frac{\sum_{j=1}^n PF_{ijk}}{n} \quad (6)$$

Thus, PF_{ik} is the mean preference function for each attribute in each group. As with w_{ik} , the only purpose in calculating PF_{ik} is to make comparisons among attributes within a group and between the two groups.

Graphs of the PF_{ik} are presented in Figures 4.1 through 4.7. There are significant similarities between the DOE and utility samples. What differences exist are, for the most part, related to the w_{ik} assigned by the two groups. For example, the greater the w_{ik} , the greater is to be expected the slope of PF_{ik} . This can be seen by comparing the slope of PF_{ik} for LEC, the most important attribute, with PF_{ik} for R&D, the least important attribute. Note also that the DOE sample judged R&D to be significantly more important than did the utility sample. This is reflected in the relative slopes of the PF_{ik} for this attribute.

Statistical tests of differences among the PF_{ik} would require 1) statistically estimating the functions and 2) tests involving the coefficients of the dependent variables. These are not necessary to draw the important conclusions

FIGURE 4.1. Levelized Energy Cost Group Preference Function (PF_{ik})

FIGURE 4.2. Plant Capacity Factor Group Preference Function (PF_{ik})

FIGURE 4.3. Plant Flexibility Group Preference Function (PF_{ik})

FIGURE 4.4. Plant Forced Outage Rate Group Preference Function (PF_{ik})

FIGURE 4.5. Environmental and Safety Effects Group Preference Function (PF_{ik})

FIGURE 4.6. Fixed Costs as a Percentage of Levelized Energy Cost Group Preference Function (PF_{ik})

FIGURE 4.7. Public Investment in Research and Development Necessary for Commercialization Group Preference Function (PF_{ijk})

regarding decision maker preferences, which are

- LEC and CF are clearly the most important attributes.
- The only potentially important difference between the DOE and utility samples is that R&D is clearly the least important attribute to the utility sample and the importance attached to it by the utility sample is significantly different from the importance given this attribute by the DOE sample.

Given this evidence, it was hypothesized that the concept scores and ranks would not differ significantly between the two groups.

4.3 CONCEPT SCORES AND RANKS

Data on decision maker preferences, w_{ijk} and PF_{ijk} , were used with the best technological estimates of the attribute levels for each concept, a_{ij} , to calculate the concept score, cs_{kj} , and concept rank, cr_{kj} , for each group. The

concept scores, cs_{k1} , were then subjected to a statistical analysis from which conclusions about the concept ranks, cr_{k1} , were drawn.

Sensitivity tests were conducted on all cr_{k1} to determine the degree to which changes in key parameters influenced both the utility and DOE sample ranking decisions. Where important differences occurred, a more detailed analysis of the cs_{k1} was undertaken.

4.3.1 Sensitivity Analysis

The sensitivity analysis included three dimensions. First, tests were conducted to determine how sensitive the concept ranks were to the decision maker group data being used. Second, the importance of using storage was addressed by comparing all cr_{k1} resulting from different capacity factors. Third, the impact of totally excluding certain attributes from the ranking process was analyzed.

4.3.1.1 Decision Maker Group

As shown earlier, no major differences existed in preferences between the two decision maker groups. This led to the hypothesis that no differences in the concept ranks, cr_{k1} , between groups would exist. This hypothesis was tested as part of the sensitivity analysis.

4.3.1.2 Storage

Each of the 10 concepts can be operated with or without storage. The addition of storage capacity increases a concept's capacity factor at some additional cost. Because capacity factor was found to be an important attribute over which the user has control (through additional storage), cs_{k1} were calculated over a broad range of storage and associated capacity factors. The capacity factors ranged from less than 0.3 for no-storage cases to 0.9 for high storage cases. For each concept the capacity factor that produced the highest concept score was termed the optimal capacity factor and the concept score the optimal cs_{k1} . The optimal capacity factor was either 0.8 or 0.9 for every concept. Thus, the decision makers would be willing to pay the cost of storage to obtain higher capacity factors.

In the sensitivity analysis, concept scores and ranks were analyzed for optimal as well as 0.4 capacity factors. Although a 0.4 capacity factor was

not optimal for any concept, project ground rules required that concept ranks be produced at 0.4 capacity factor.

4.3.1.3 Deleting Selected Attributes

The best technological estimates for a_{ij} , the attribute level for each concept, was an output of the systems analysis task. For each concept, only three attributes had variable levels. These were LEC, CF, and FIX. These three attributes are functionally related and, therefore, vary together. Attributes FLEX, FO, ENV, and R&D were invariant with respect to the concept. For example, any given concept may have a wide range of possible capacity factors but only one forced outage rate.

Relatively more resources were allocated to estimating the levels of LEC, CF, and FIX than to the other four attributes, for two reasons. First, discussions with electric power industry representatives early in the project suggested that LEC and CF would be found to be significantly more important than would the other attributes. Second, limited data were available for estimating the levels of FLEX, FO, ENV, and R&D. In fact, three of these attributes are measured on a subjective scale (Table 3.2), while the levels of LEC, CF, and FIX were estimated from a detailed computer model. As a result, there is a higher degree of confidence in the estimated levels of LEC, CF, and FIX relative to the other four attributes. Therefore, it is important to appreciate the sensitivity of the concept ranks to changes in the levels of FLEX, FO, ENV, and R&D. If the ranks are extremely sensitive to changes in these attributes, then caution should be used in drawing conclusions on the ranking process. Also, this would suggest to DOE that relatively more resources should be allocated to research on one or more of these four attributes in future system studies.

For this exercise the ranks for a "best" case were compared with ranks for the "worst" case. The best case included all seven attributes. For the worst case, it was assumed that, for each decision maker, the levels of FLEX, FO, ENV, and R&D were unacceptable. Thus, these four attributes contributed nothing to the cs_{k1} and cr_{k1} .

4.3.2 Spearman Rank Correlation Tests

Sensitivity was determined using the Spearman rank correlation test. This test, applicable to ordinal, or rank order, data, was used to determine the degree of correlation between two different sets of concept ranks, cr_{k1} . Implementing the test resulted in a test statistic called Spearman's Rho (ρ) (Ferguson 1966). The calculated value of ρ can be compared with critical values of ρ to determine statistical significance between two sets of ranks.

Tables 4.2 through 4.4 present the results of three sets of tests conducted.^(a) Table 4.2 shows the degree of correlation between the ranks, cr_{k1} , assigned by the utility and DOE samples. A value of ρ greater than 0.746 is termed highly significant (0.01 level). This means that there is only one chance in 100 of being wrong if it were concluded that there is no difference between the concept ranks. Four tests were conducted between the cr_{k1} of the two groups; Spearman's ρ was highly significant in all four cases. Thus, the ranks showed no significant differences at optimal and 0.4 capacity factor for both the three- and seven-attribute cases. This confirms the hypothesis that the ranks assigned by the two groups are not significantly different.

Table 4.3 shows the degree of correlation between the ranks at the optimal and 0.4 capacity factor. Three of the tests produced highly significant correlations. The fourth test involving the DOE sample and seven attributes produced a Spearman's ρ of 0.721, which is significant at the 0.05 level. The results in Table 4.3 indicate that the cr_{k1} were not sensitive to the capacity factor. The concept ranks at a 0.4 capacity factor were not significantly different from those produced at the optimal capacity factor.

Table 4.4 shows the degree of correlation between the cr_{k1} at three attributes (LEC, CF, FIX) and the full seven attributes. All four tests produced statistically insignificant Spearman's ρ s. For example, the concept ranks at three attributes for the utility sample and optimal capacity factor were virtually perfectly uncorrelated with the ranks at seven attributes ($\rho = 0.009$). This means that one or more of the four attributes on which limited

(a) An example of how the test is applied is shown in Appendix C.

TABLE 4.2. Spearman's Rho Between Utility and DOE Samples(a)

	<u>Three Attributes</u>	<u>Seven Attributes</u>
Optimal cf	0.973**	0.797**
0.4 cf	0.988**	0.858**

(a) $\rho_{0.01} = 0.746^{**}$, $\rho_{0.05} = 0.564^{*}$

TABLE 4.3. Spearman's Rho Between Optimal and 0.4 Capacity Factors(a)

	<u>Three Attributes</u>	<u>Seven Attributes</u>
Utility Sample	0.821**	0.815**
DOE Sample	0.930**	0.721*

(a) $\rho_{0.01} = 0.746^{**}$, $\rho_{0.05} = 0.564^{*}$

TABLE 4.4. Spearman's Rho Between Three and Seven Attributes(a)

	<u>Utility Sample</u>	<u>DOE Sample</u>
Optimal cf	0.009	0.245
0.4 cf	0.339	0.009

(a) $\rho_{0.01} = 0.746^{**}$, $\rho_{0.05} = 0.564^{*}$

information was available (FLEX, FO, ENV, and R&D) are potentially very important in determining the commercial success of small solar thermal power concepts.

4.4 CONCEPT SCORE ANALYSIS

The Spearman rank correlation tests showed that significantly different ranks were assigned when FLEX, FO, ENV, and R&D were at levels unacceptable to decision makers. Setting these four attributes at unacceptable levels means that they simply are not considered in the ranking process. Therefore, the resulting ranks are based on only three attributes--LEC, CF, and FIX. Because significant differences existed between the three- and seven-attribute cases, analyses of the importance of the relative differences among concept scores were carried out for both the three- and seven-attribute cases.

4.4.1 Ranks Using Three Attributes

Figure 4.8 shows the ranks at a capacity factor of 0.4 and at the optimal capacity factor (that which produced the highest score for each concept) for the utility sample. The solid horizontal lines represent statistically significant differences (0.05 level) among the concepts above and below the line. Concepts falling within the cross-hatched areas were not significantly different from adjacent concepts. A Spearman's ρ of 0.821 (Table 4.3) indicates that the overall groupings changed little between 0.4 and optimal capacity factors. However, the decision maker preferences and attribute ranges used in this study generally produced higher concept scores as capacity factor increased.

Point Focus Central Receiver systems were ranked significantly higher than all other systems. Furthermore, the ranks were grouped according to tracking capability; two-axis tracking systems were ranked at the top, followed by one-axis tracking systems. The Low Concentration Nontracking concept was ranked the lowest. Finally, at higher capacity factors, concepts using thermal storage ranked higher than those using electric storage.

4.4.2 Ranks Using Seven Attributes

As with the three-attribute case, the general trend of higher ranks with higher capacity factors was present. This trend is indicated in Figure 4.9

FIGURE 4.8. Utility Sample Concept Ranks Resulting from Concept Scores Using Three Attributes (LEC, CF, and FIX)

for the utility sample. A Spearman's ρ of 0.721 (Table 4.3) indicates that the ranks between 0.4 and optimal capacity factor are highly correlated but not to the degree of the ranks in Figure 4.8.

As shown in Table 4.4 ($\rho = 0.009$ and 0.339), the ranks appearing in Figure 4.8 are not well correlated to the ranks in Figure 4.9. In comparison to the three-attribute case, the general conclusions are that the Point Focus Distributed Receiver systems have significantly improved, relative to the Point Focus Central Receiver systems. The primary reason for this is the lower projected forced outage rates for the distributed Brayton and Stirling

FIGURE 4.9. Utility Sample Concept Ranks Resulting from Concept Scores Using All Seven Attributes

systems relative to the central receivers. The line focus and nontracking concepts showed significant improvement relative to the three-attribute case. This is partially due to the relatively low R&D costs associated with these two concepts.

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APPENDIX A

RANKING METHODOLOGY QUESTIONNAIRE AND STIMULI

APPENDIX A

BATTELLE, PACIFIC NORTHWEST LABORATORIES SMALL ELECTRIC POWER SYSTEMS

RANKING METHODOLOGY QUESTIONNAIRE

1. Interviewer and interviewee meet. Interviewer informs interviewee of the length of interview and proceeds:

"Thank you for participating in this project. Your responses to our questions will assist DOE in its funding decisions on research, development and demonstration of emerging energy technology."

2. Pause:

"The Department of Energy is interested in determining which types of electric power systems in the 5 to 10 MWe range should receive federal research and development funds over the next 10-20 years. The goal is to fund those systems which are likely to be commercially competitive by 1990 to 2000. We have identified attributes which are applicable to all types of small electric power systems and should form the basis of selection of desirable systems. Your task will be to make judgments concerning these attributes. You will be engaging in a decision-aid which has proved helpful in choosing among several complex and technical alternatives. If at any time during this exercise you have a question, please simply stop and ask it."

3. Pause:

"The attributes are shown on these cards."

4. Short pause. He continues:

"Considerations making up each attribute are listed. Recall that we are considering these attributes in the range of 5 to 10 MWe electric power systems."

5. Short pause. (Interviewer hands interviewee large index cards.)
"Please read these cards very carefully. We want you to have a good understanding of the attributes and especially their ranges. All the systems we are interested in fall within these attribute ranges."
6. (Interviewer waits until interviewee begins to read "Fixed Cost as a % of Levelized Energy Cost.")
For this attribute please read the card and tell me which of the two values listed here you most prefer." (The preferred value becomes the 'most favorable' value and is identified with a check (✓) mark.)
7. Interviewer waits for interviewee to finish reading cards. He proceeds:
"Please place the cards, in a row, on the table."
8. Cards are placed on the table. Pause:
"Now, imagine you are planning to invest in a small electric power system. You have several power system choices which together cover the full range on all the attributes. We want to know how important each attribute is to you. We'll begin by setting each attribute at its least favorable value."
9. (Interviewer gives examples.) Pause:
"Please indicate which attribute you would most prefer to move from its least favorable value to its most favorable value."
10. Pause:
"Pull out the appropriate card from the row and place it face down to the side."
11. Pause:
"Repeat this process with the remaining cards until all are placed face down, one on top of the other."
12. (Interviewer waits for interviewee to finish.) Continue:
"Turn the stack of cards over and reexamine their order. Change any cards you believe you may have misordered."

13. (Interviewer waits for interviewee to finish.) Pause:

"Now, please tell us how important each attribute is relative to the others. Do this by writing an "importance value" of 100 in the box in the upper right corner of the top card."

14. Pause:

"Now, assign a number to the second card indicating the relative importance of the second attribute to the first attribute on the first card. For example, if you believe the second attribute is 90% as important as the first, write the number 90 in the upper right corner of this card. If you believe it is half as important write in the number 50. Continue to assign 'importance values' in this manner to the remaining attributes as they relate to the most important attribute. Please focus on the ranges available for the attributes when considering their relative importance.

15. (Interviewer waits for interviewee to finish.) Continue:

"Review all the numbers you have recorded. Make any changes necessary to have the numbers reflect the relative importance of the attributes given the range available on each attribute."

16. (Interviewer waits for interviewee to finish.) Pause:

"Now, we are interested in determining how important changes in the value of each attribute are to you, assuming the levels of all other attributes are held constant. We have provided graphs to facilitate your judgements. The range on each attribute can have preference scores falling between a maximum of 10 and a minimum of zero (0). A score of zero means unacceptable. Thus, you would not accept a small electric power system at this attribute level regardless of the levels of the other attributes."
(Point this out to interviewee on graph.)

17. (Interviewee displays graphs.) Pause:

"Let's begin by arbitrarily assigning a preference score of 10 to the most favorable value. Now that _____ is assigned a preference score of 10, what score do you assign to _____, the least favorable value?" (If zero:

What preference score do you assign to ____? If still zero, repeat process to find value where preference score becomes non-zero.) What preference score do you assign to ____ (the resulting midpoint)?" (If the interviewee wants to know at what level are the other attributes, tell him that all the attributes are assumed to be at their "most favorable" values. Complete the exercise, then elicit his utility functions assuming the other attributes are at their "least favorable" values. If the interviewee was indifferent between the high and low value for "Fixed Costs as a % of Levelized Energy Costs," assign 95% a preference score of 10.)

18. (The interviewee thus provides utility functions for each attribute. After the interviewee finishes this task, the interviewer continues:) "Thank you. Suppose, of the electric power systems we have been discussing, the first systems under consideration would be solar thermal electric systems in the 5 to 10 MWe range.

If the first systems under consideration were solar thermal electric, do you think it would have affected any of your judgments?"

19. If no, go to 20; if yes, continue:

"Go back over the 'importance values' you gave the attributes and the 'preference score' you gave on each of the attributes to see if you think you would like to change anything assuming the first systems under consideration are solar thermal electric. The 'most favorable' and 'least favorable' values accurately reflect the attribute ranges of the solar thermal plants being considered."

20. "When deciding on capacity additions, what size units would you consider?"

smallest _____
largest _____

21. "In doing this exercise, were you evaluating the small power systems as:"

peaking _____

base load _____

neither _____

other _____

22. "Can you think of any attributes that would be more important to you than the ones we have used?"

(If "yes", list these. If "no", continue.)

23. "Relative to the other attributes, what weight would you assign to the amount of public research and development costs required to commercialize 5 to 10 MWe solar thermal electric power systems by 1990 to 2000?" (If the weight is greater than zero, determine the utility function, then go to 24. If the weight is zero, go to 24.)

24. "Are you familiar with the various types of solar thermal electric systems?"

25. If no, go to 26. If yes, present the seven concepts and solicit an ordinal ranking from the interviewee.

26. Ending:

"This ends the interview. Thank you for your cooperation."

**ATTRIBUTE:
LEVELIZED ENERGY COST**

1978 DOLLARS FOR SYSTEMS THAT
WILL COME ON-LINE BETWEEN
1990 AND 2000

IMPORTANT COMPONENTS:

- A) CAPITAL COST
- B) OPERATIONS & MAINTENANCE COSTS
- C) ACTUAL AND RATED CAPACITY FACTORS
- D) CONSTRUCTION TIME (INTEREST DURING CONSTRUCTION)
- E) FIXED CHARGE RATE

ESTIMATE OF MOST FAVORABLE VALUE: 75 MILLS/kWh

ESTIMATE OF LEAST FAVORABLE VALUE: 275 MILLS/kWh

**ATTRIBUTE:
PLANT CAPACITY FACTOR**

IMPORTANT COMPONENTS:

- A) ANNUAL SCHEDULED OUTAGE RATE
- B) MAINTENANCE SCHEDULE
- C) PLANT OUTPUT RAMP RATE
- D) MINIMUM LOAD AND PART LOAD EFFICIENCY
- E) START-UP POWER REQUIRED
- F) REMOTE OPERATIONS AND CONTROL

ESTIMATE OF MOST FAVORABLE VALUE: 95% CAPACITY FACTOR

ESTIMATE OF LEAST FAVORABLE VALUE: 25% CAPACITY FACTOR

ATTRIBUTE:
**FIXED COSTS AS A % OF
LEVELIZED ENERGY COST**

IMPORTANT COMPONENTS:

- A) CAPITAL COST
- B) OTHER FIXED COSTS
(i.e. INSURANCE AND PROPERTY TAXES)
- C) INTEREST DURING CONSTRUCTION

ESTIMATE OF HIGHEST VALUE: 95% OF LEVELIZED ENERGY COST

ESTIMATE OF LOWEST VALUE: 45% OF LEVELIZED ENERGY COST

ATTRIBUTE:
PLANT FORCED OUTAGE RATE

IMPORTANT COMPONENTS:

- A) ANNUAL FORCED OUTAGES NOT INCLUDING
SCHEDULED MAINTENANCE.

ESTIMATE OF MOST FAVORABLE VALUE: 2% FORCED OUTAGE RATE

ESTIMATE OF LEAST FAVORABLE VALUE: 12% FORCED OUTAGE RATE

**ATTRIBUTE:
PLANT FLEXIBILITY**

IMPORTANT COMPONENTS

- A) CO-GENERATION POTENTIAL
- B) FLEXIBILITY OF APPLICATIONS, INCLUDING CAPACITY FACTOR AND LOAD FOLLOWING CHARACTERISTICS, AND SUITABILITY FOR REMOTE OPERATIONS
- C) SITE FLEXIBILITY, INCLUDING WATER, LAND, TRANSPORTATION, AND MAINTENANCE REQUIREMENTS
- D) CONSTRUCTION FLEXIBILITY, INCLUDING THE TIME AND INFRA STRUCTURE REQUIRED DURING CONSTRUCTION

ESTIMATE OF MOST FAVORABLE VALUE 9 ON FLEXIBILITY SCALE

ESTIMATE OF LEAST FAVORABLE VALUE 5 ON FLEXIBILITY SCALE

A SCORE OF 10 ON THE FLEXIBILITY SCALE WOULD INDICATE MAXIMUM FLEXIBILITY ON ALL OF THE ABOVE LISTED COMPONENTS, AND A SCORE OF 0 WOULD INDICATE FLEXIBILITY SIMILAR TO THAT OF A COAL FIRED BASE LOAD POWER PLANT

**ATTRIBUTE:
ENVIRONMENTAL AND SAFETY EFFECTS**

IMPORTANT COMPONENTS:

- A) MATERIAL ACQUISITION AND CONSTRUCTION, INCLUDING MATERIAL AND LAND REQUIREMENTS AND EFFLUENTS
- B) POWER GENERATION, INCLUDING CHEMICAL HAZARDS AND OTHER BYPRODUCTS OF GENERATION
- C) WASTE DISPOSAL, INCLUDING DECOMMISSIONING AND MAINTENANCE BYPRODUCTS

ESTIMATE OF MOST FAVORABLE VALUE 9 ON ENVIRONMENTAL AND SAFETY EFFECTS SCALE

ESTIMATE OF LEAST FAVORABLE VALUE 7 ON ENVIRONMENTAL AND SAFETY EFFECTS SCALE

A SCORE OF 10 ON THE ENVIRONMENTAL AND SAFETY EFFECTS SCALE WOULD INDICATE MINIMUM ENVIRONMENTAL AND SAFETY EFFECTS ON ALL THE ABOVE LISTED COMPONENTS, AND A SCORE OF 0 WOULD INDICATE ENVIRONMENTAL AND SAFETY EFFECTS SIMILAR TO THOSE OF AN OIL-FIRE STEAM PLANT USING LOW SULFUR OIL.

**ATTRIBUTE:
PUBLIC INVESTMENT IN RESEARCH
AND DEVELOPMENT NECESSARY
FOR COMMERCIALIZATION**

IMPORTANT COMPONENTS:

- A) MANUFACTURING FACTORS, INCLUDING EASE OF MASS PRODUCTION;
"LEARNING" CAPABILITY; AVAILABILITY OF SPECIALIZED MATERIALS,
AND ALTERNATE USES OF COMPONENTS.
- B) TECHNOLOGICAL FACTORS, INCLUDING TECHNICAL BREAKTHROUGH
REQUIRED; STANDARD COMPONENT UTILIZATION; AND POSSIBILITY OF
DESIGN OPTIMIZATION.

ESTIMATE OF HIGHEST VALUE: 8 ON THE PUBLIC RESEARCH AND
DEVELOPMENT SCALE

ESTIMATE OF LOWEST VALUE: 4 ON THE PUBLIC RESEARCH AND
DEVELOPMENT SCALE

A SCORE OF 10 ON THE PUBLIC RESEARCH AND DEVELOPMENT SCALE WOULD
INDICATE THE PUBLIC INVESTMENT IN RESEARCH AND DEVELOPMENT NECESSARY
TO COMMERCIALIZE GEOTHERMAL ENERGY ON ALL OF THE ABOVE LISTED
COMPONENTS, AND A SCORE OF 0 ON THE PUBLIC RESEARCH AND
DEVELOPMENT SCALE WOULD INDICATE THE PUBLIC INVESTMENT
NECESSARY TO COMMERCIALIZE FUSION ENERGY.

**ATTRIBUTE:
LEVELIZED ENERGY COST**

**1978 DOLLARS FOR SYSTEMS THAT
WILL COME ON-LINE BETWEEN
1990 AND 2000**

IMPORTANT COMPONENTS:

- A) CAPITAL COST
- B) OPERATIONS & MAINTENANCE COSTS
- C) ACTUAL AND RATED CAPACITY FACTORS
- D) CONSTRUCTION TIME (INTEREST DURING CONSTRUCTION)
- E) FIXED CHARGE RATE

ESTIMATE OF MOST FAVORABLE VALUE: 75 MILLS/kWh

ESTIMATE OF LEAST FAVORABLE VALUE: 275 MILLS/kWh

**ATTRIBUTE:
PLANT CAPACITY FACTOR**

IMPORTANT COMPONENTS:

- A) ANNUAL SCHEDULED OUTAGE RATE
- B) MAINTENANCE SCHEDULE
- C) PLANT OUTPUT RAMP RATE
- D) MINIMUM LOAD AND PART LOAD EFFICIENCY
- E) START-UP POWER REQUIRED
- F) REMOTE OPERATIONS AND CONTROL

ESTIMATE OF MOST FAVORABLE VALUE: 95% CAPACITY FACTOR

ESTIMATE OF LEAST FAVORABLE VALUE: 25% CAPACITY FACTOR

ATTRIBUTE:
FIXED COSTS AS A % OF
LEVELIZED ENERGY COST

IMPORTANT COMPONENTS:

- A) CAPITAL COST
- B) OTHER FIXED COSTS
(i.e. INSURANCE AND PROPERTY TAXES)
- C) INTEREST DURING CONSTRUCTION

ESTIMATE OF HIGHEST VALUE: 95% OF LEVELIZED ENERGY COST

ESTIMATE OF LOWEST VALUE: 45% OF LEVELIZED ENERGY COST

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PLANT FORCED OUTAGE RATE**

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**A) ANNUAL FORCED OUTAGES NOT INCLUDING
SCHEDULED MAINTENANCE.**

ESTIMATE OF MOST FAVORABLE VALUE: 2% FORCED OUTAGE RATE

ESTIMATE OF LEAST FAVORABLE VALUE: 12% FORCED OUTAGE RATE

**ATTRIBUTE:
PLANT FLEXIBILITY**

IMPORTANT COMPONENTS:

- A) CO-GENERATION POTENTIAL.
- B) FLEXIBILITY OF APPLICATIONS, INCLUDING CAPACITY FACTOR AND LOAD FOLLOWING CHARACTERISTICS, AND SUITABILITY FOR REMOTE OPERATIONS.
- C) SITE FLEXIBILITY, INCLUDING WATER, LAND, TRANSPORTATION, AND MAINTENANCE REQUIREMENTS.
- D) CONSTRUCTION FLEXIBILITY, INCLUDING THE TIME AND INFRA-STRUCTURE REQUIRED DURING CONSTRUCTION.

ESTIMATE OF MOST FAVORABLE VALUE: 9 ON FLEXIBILITY SCALE

ESTIMATE OF LEAST FAVORABLE VALUE: 5 ON FLEXIBILITY SCALE

A SCORE OF 10 ON THE FLEXIBILITY SCALE WOULD INDICATE MAXIMUM FLEXIBILITY ON ALL OF THE ABOVE LISTED COMPONENTS, AND A SCORE OF 0 WOULD INDICATE FLEXIBILITY SIMILAR TO THAT OF A COAL FIRED BASE LOAD POWER PLANT.

**ATTRIBUTE:
ENVIRONMENTAL AND SAFETY EFFECTS**

IMPORTANT COMPONENTS:

- A) MATERIAL ACQUISITION AND CONSTRUCTION, INCLUDING MATERIAL AND LAND REQUIREMENTS AND EFFLUENTS.
- B) POWER GENERATION, INCLUDING CHEMICAL HAZARDS AND OTHER BYPRODUCTS OF GENERATION.
- C) WASTE DISPOSAL, INCLUDING DECOMMISSIONING AND MAINTENANCE BYPRODUCTS.

ESTIMATE OF MOST FAVORABLE VALUE: 9 ON ENVIRONMENTAL AND SAFETY EFFECTS SCALE

ESTIMATE OF LEAST FAVORABLE VALUE: 7 ON ENVIRONMENTAL AND SAFETY EFFECTS SCALE

A SCORE OF 10 ON THE ENVIRONMENTAL AND SAFETY EFFECTS SCALE WOULD INDICATE MINIMUM ENVIRONMENTAL AND SAFETY EFFECTS ON ALL THE ABOVE LISTED COMPONENTS, AND A SCORE OF 0 WOULD INDICATE ENVIRONMENTAL AND SAFETY EFFECTS SIMILAR TO THOSE OF AN OIL-FIRE STEAM PLANT USING LOW SULFUR OIL.

ENVIRONMENTAL AND SAFETY EFFECTS SCALE

**ATTRIBUTE:
PUBLIC INVESTMENT IN RESEARCH
AND DEVELOPMENT NECESSARY
FOR COMMERCIALIZATION**

IMPORTANT COMPONENTS:

- A) MANUFACTURING FACTORS, INCLUDING EASE OF MASS PRODUCTION;
"LEARNING" CAPABILITY; AVAILABILITY OF SPECIALIZED MATERIALS;
AND ALTERNATE USES OF COMPONENTS.
- B) TECHNOLOGICAL FACTORS, INCLUDING TECHNICAL BREAKTHROUGH
REQUIRED; STANDARD COMPONENT UTILIZATION; AND POSSIBILITY OF
DESIGN OPTIMIZATION.

ESTIMATE OF HIGHEST VALUE: 8 ON THE PUBLIC RESEARCH AND
DEVELOPMENT SCALE

ESTIMATE OF LOWEST VALUE: 4 ON THE PUBLIC RESEARCH AND
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TO COMMERCIALIZE GEOTHERMAL ENERGY ON ALL OF THE ABOVE LISTED
COMPONENTS, AND A SCORE OF 0 ON THE PUBLIC RESEARCH AND
DEVELOPMENT SCALE WOULD INDICATE THE PUBLIC INVESTMENT
NECESSARY TO COMMERCIALIZE FUSION ENERGY.

APPENDIX B

ATTRIBUTE LEVELS

TABLE B.1. Five-MWe Least-Cost Generic Concepts - Levelized
Energy Costs (mills/kWh)

<u>Concept</u>	<u>No- Storage (cf)</u>	<u>Capacity Factor (cf)</u>							<u>Lowest Cost (cf)</u>
		<u>0.3</u>	<u>0.4</u>	<u>0.5</u>	<u>0.6</u>	<u>0.7</u>	<u>0.8</u>	<u>0.9</u>	
PFCR/R	136 (0.25)	135	112	101	95	89	87	93	87 (0.77)
PFCR/B	92 (0.25)	109	105	105	105	106	108	118	92 (0.25)
PFDR/R	157 (0.28)	155	136	126	120	116	117	132	115 (0.78)
PFDR/B	114 (0.29)	127	126	130	133	136	143	161	114 (0.29)
PFDR/S	114 (0.29)	126	126	129	133	136	143	161	114 (0.29)
FMDF	168 (0.26)	145	127	118	112	109	111	126	108 (0.68)
LFDR	243 (0.22)	190	165	152	146	141	142	169	139 (0.78)
LFDR-TC	209 (0.22)	173	156	148	143	140	140	164	139 (0.74)
LFDR-TR	218 (0.21)	184	167	158	151	147	148	207	146 (0.74)
LCNT	235 (0.21)	200	182	171	165	159	158	178	157 (0.74)

TABLE B.2. Five-MWe Least-Cost Generic Concepts - Fixed Costs as a Percentage of Levelized Energy Cost

<u>Concept</u>	<u>No-Storage</u>	<u>0.4 Capacity Factor</u>	<u>0.7 Capacity Factor</u>	<u>Least Cost</u>
PFCR/R	0.88	0.89	0.89	0.88
PFCR/B	0.87	0.87	0.87	0.87
PFDR/R	0.89	0.89	0.89	0.89
PFDR/B	0.83	0.86	0.86	0.83
PFDR/S	0.85	0.87	0.87	0.85
F MDF	0.89	0.89	0.90	0.90
LFCR	0.92	0.92	0.92	0.92
LFDR-TC	0.83	0.82	0.76	0.75
LFDR-TR	0.88	0.87	0.87	0.87
LCNT	0.90	0.90	0.90	0.90

TABLE B.3. Level of Invariant Attributes for Each 5-MWe Least-Cost Generic Concept

<u>Concepts</u>	<u>Attributes</u>			
	<u>FLEX</u>	<u>FO</u>	<u>ENV</u>	<u>R&D</u>
PFCR/R	7.5	9.0	8.0	5.6
PFCR/B	9.0	12.0	7.6	4.7
PFCR/R	7.7	7.2	7.3	6.1
PFDR/B	8.9	2.3	8.6	4.7
PFDR/S	8.9	2.3	8.0	4.0
F MDF	5.4	7.3	7.3	7.1
LFCR	5.4	11.7	7.4	6.1
LFDR-TC	6.4	5.7	8.2	7.3
LFDR-TR	5.0	7.5	7.2	5.4
LCNT	8.5	6.0	8.0	7.5

APPENDIX C

SAMPLE SPEARMAN RANK CORRELATION TEST

APPENDIX C

SAMPLE SPEARMAN RANK CORRELATION TEST

Table C.1 presents the Spearman rank correlation test between DOE and utility ranks at optimal capacity factor with seven attributes.

TABLE C.1. Sample Spearman Rank Correlation Test

<u>Concept</u>	<u>Ranks</u>		<u>Difference (DOE - Utility)</u>	<u>Squared Difference (Δ^2)</u>
	<u>DOE</u>	<u>Utility</u>		
PFDR/R	1	4	3	9
PFDR/B	2	1	-1	1
LCNT	3.5 ^(a)	5	-1.5	2.25
PFDR/S	3.5	3	0.5	0.25
LFDR-TC	5	6	-1	1
PFCR/R	6	2	4	16
F MDF	7	8	-1	1
LFDR-TR	8	7	1	1
PFCR/B	9	10	-1	1
LF CR	10	9	1	1

$$\Sigma \Delta^2 = 33.50$$

$$\rho = 1 - \frac{6 \Sigma \Delta^2}{N(N^2 - 1)}$$

$$\rho = 1 - \frac{6(33.5)}{10(99)}$$

$$\rho = 0.797^{**}$$

Because $\rho_{0.01} = 0.746$, we do not reject the null hypothesis of no significant difference between the DOE and utility ranks at optimal capacity factor and using seven attributes.

(a) In the case of ties among the concept ranks, the average of the two (or more) concepts that are tied is assigned to both concepts.

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