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DECISION ANALYSIS: A TOOL TO GUIDE THE R&D SELECTION OF ALTERNATIVE ENERGY SOURCES

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DECISION ANALYSIS: A TOOL TO GUIDE THE R&D SELECTION OF ALTERNATIVE ENERGY SOURCES

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ABSTRACT

The array of alternative energy sources which are vying for the federal government's R&D dollar is formidable when compared to the politically acceptable amount which can be used to fund the research. To guide how these funds should be dispersed, a rational, defensible procedure is needed which can repeatedly be applied as new technologies and new information become available. The procedure advanced in this paper is a decision analysis technique known as multi attribute decision analysis (MADA) and its use is illustrated in an evaluation and ranking of solar thermal electric power generating systems. Since the ultimate purchase decision is made in the market place, the preferences of potential users have been sampled and brought to bear on the ranking. The focus of this description is on the formulation of the problem structure and the decision model, the treatment of uncertainty, and how the results relate to the questions asked by and of the Department of Energy, which funded the study. A final note proposes how decision analysis can be used to address the broader questions of choice among competing technologies with cautions concerning misuse of the procedure.

INTRODUCTION

The Department of Energy is the primary manager of the United States national energy policy. DOE must judiciously use its funds to set & achieve energy goals consistent with broad policy statements. In this time of rapidly increasing shortage of supply and increase both in prices and problems with conventional sources of energy, interest has been renewed in alternative sources. DOE is faced with a selection of potential sources, which range from synthetic fuels to direct use of the sun's energy. Throughout DOE, this general problem is mirrored at lower levels where funding decisions must be made for specific technologies. One such area is the Thermal Power Systems Branch of the Division of Central Solar Technology. Within this branch lies the responsibility to allocate funds for the research, development and demonstration of solar thermal electricity generation. The Thermal Power Systems Branch asked the Solar Energy Research Institute (SERI) to evaluate and compare selected solar thermal designs to determine those with the most potential to be accepted into the market place in the mid 1990s. A similar study [1] has concurrently been done by Battelle, Pacific Northwest Laboratories (PNL). The Jet Propulsion Laboratory (JPL) was charged with coordinating the efforts of SERI and PNL. This paper examines the work done at SERI in this, the Small Power Systems Study (SPSS).

The main objective of the SPSS is to project the mid 1990 cost and performance of selected generic solar thermal electric power systems according to criteria important to future commercial acceptability. The study incorporates the preferences of potential users by soliciting from them the criteria against which the systems will be judged. Such an energy purchase decision involves a complex interaction of cost, performance, and technological impacts complicated by significant uncertainty. To model this decision process, JPL, SERI, and PNL agreed upon the use of the techniques of decision analysis, a rapidly growing field which examines complex decision problems. Several techniques such as the Delphi procedure, goal programming, and simple pair wise comparisons were examined. However, the Multi Attribute Decision Analysis (MADA) approach proposed by Ralph Keeny and Howard Raffa [2] proved to be most appropriate. MADA has successfully been applied to other similar energy related decision studies. Among them is an environmental assessment of solar energy system alternatives done by the Electric Power Research Institute [3]. Keeney and Nair [4] apply MADA in the ranking and selection of nuclear power plant sites in the Northwest United States. Hax and Wiig [5] examine the use of decision analysis in capital investment problems.

While the specific decision examined herein may be of parochial interest within DOE, the setup and solution procedure has wider implications. This paper will concentrate on those aspects of the problem which illustrate how similar problems might be handled. The issues which are examined in detail include: (1) the problem structuring and overall approach to the comparative evaluation, (2) formulation of the decision analysis model, (3) Treatment of uncertainty, and (4) presentation of results. The SPSS is to be viewed as a case study in the use of decision analysis, but this paper is liberally annotated with comments on its more general use.

PROBLEM STRUCTURE

The overall approach followed in this study involved the following steps:

- Choice of solar thermal systems
- Definition of groundrules and assumptions
- * Problem structuring
- Selection of evaluation tool
- Generic system design
- Development of performance simulation model
- * Development of decision model
- Selection and interview of potential users
- Evaluation and ranking of systems
- * Sensitivity analyses
- * Presentation of results

The *'d items are examined in detail. This section deals with the formulation of the problem structure with a brief preliminary comment on the study groundrules.

The first requirement for a comparative evaluation and the heretofore missing aspect of previous comparisons is the establishement of common groundrules and assumptions. The old adage about comparing apples and oranges is indeed true concerning the mixed bag of fruit represented in the selected solar thermal technologies. The study examines solar ponds and other non-concentrating systems, line focusing and point focusing systems, and the central receiver or "power tower" concept. The ground rules which place these disparate technologies on a common basis include:

- Geographic location
- Forecasting assumptions (such as inflation)

- System size
- Insolation data (profile of sun's usable energy)
- Performance simulation code
- Financial and tax groundrules
- Selection of potential users categories

These groundrules focus the study on a specific, though representative case.

Achievement of the study's objectives requires two distinct, but interrelated developments. The first path of development includes system selection and design, together with a forecast of system cost and performance in the 1995 time frame. The second path includes development of the decision model, choice and interviews of the potential users, and ranking of the selected systems. Overhanging both paths are the constant problems of data uncertainty and how to evaluate its effect on the final ranking. The primary interface between the two paths is the requirement to design and evaluate the systems in such a manner that the data needed in the decision model are available. In other words the problem needed to be structured so that the decision criteria could be identified.

The following problem setup not only identifies the attributes which comprise the decision model, but it provides the needed framework for any comparative evaluation. Figure 1 provides a schematic of the important considerations in the decision to purchase a solar thermal power system. This schematic was developed in conference with the user market identified, small and medium sized electric utilities. The structure splits the main objective into a set of independent criteria which can be measured by quantitative or subjective attributes. Attributes are selected which: (1) are of major importance to the decision; (2) are independent; (3) are measurable; (4) are differentiable between options; and (5) are familiar to the decision maker. To illustrate how these rules lead to a concise set of decision criteria, the evolution of the structure represented in Figure 1 to the structure given in Figure 2 is reviewed. The two structures are for separate parts of the study: phase 1 in which 1-10MW systems are examined; and phase 2 in which .1-1MW systems are studied.

The first point to be noted in Figure 1 is the exclusion of reliability as a decision criterion. This occurs indirectly because of violation of property (3), that a criterion must be measurable. Reliability is usually calculated by testing the system or the components comprising the system. However, some of the components have not been tested, not even built yet. Forecasting performance or reliability is difficult enough under these circumstances, but SERI finds itself in a Catch 22 position here. System reliability depends in part on the number and length of demonstrations which in part depends on the funding provided by DOE. To close the loop, the funding depends partly on the results of this study. Consequently, reliability could not be included as a measurable criterion.

To illustrate how the other properties behind the choice of criteria effect the problem structure, the difference in setup between the two parts of the evaluation will be examined. Figure 2 presents the problem structure for the .1-1MWe evaluation. Users for such smaller size plants include: small communities; military bases; small institutions, such as universities and prisons; and remote mining operations. Because of the shift in users and the experience gained during evaluation of the larger systems, the problem structure is different.

A comparison of Figures 1 and 2 reveal four changes. Market potential has been dropped because the criteria are unimportant in the 1-10MWe study and appeared less so to the smaller size users. Negative impacts are relatively unimportant and the differences between solar thermal systems are even less important. The only significance to the impacts is as a go/no go filter with regard to existing regulations. Consequently the safety and environmental concerns entered into the study ground rules as follows: when a choice between two alternative system designs of roughly equal cost and performance had to be made, the more acceptable of the two systems was chosen. This type of subjective comparison was made in choosing the generic designs preliminary to system comparison. Next, the performance characteristics measured by hours of storage in Figure 2 is the same one measured by capacity factor in Figure 1. The change in label reflects the need to talk the language of the decision makers. Utilities deal with capacity factors (fraction of the rated solar output produced annually) while the smaller users understand number of hours of electricity per day. Finally, O & M costs are not as important to small towns and mining engineers as payback,

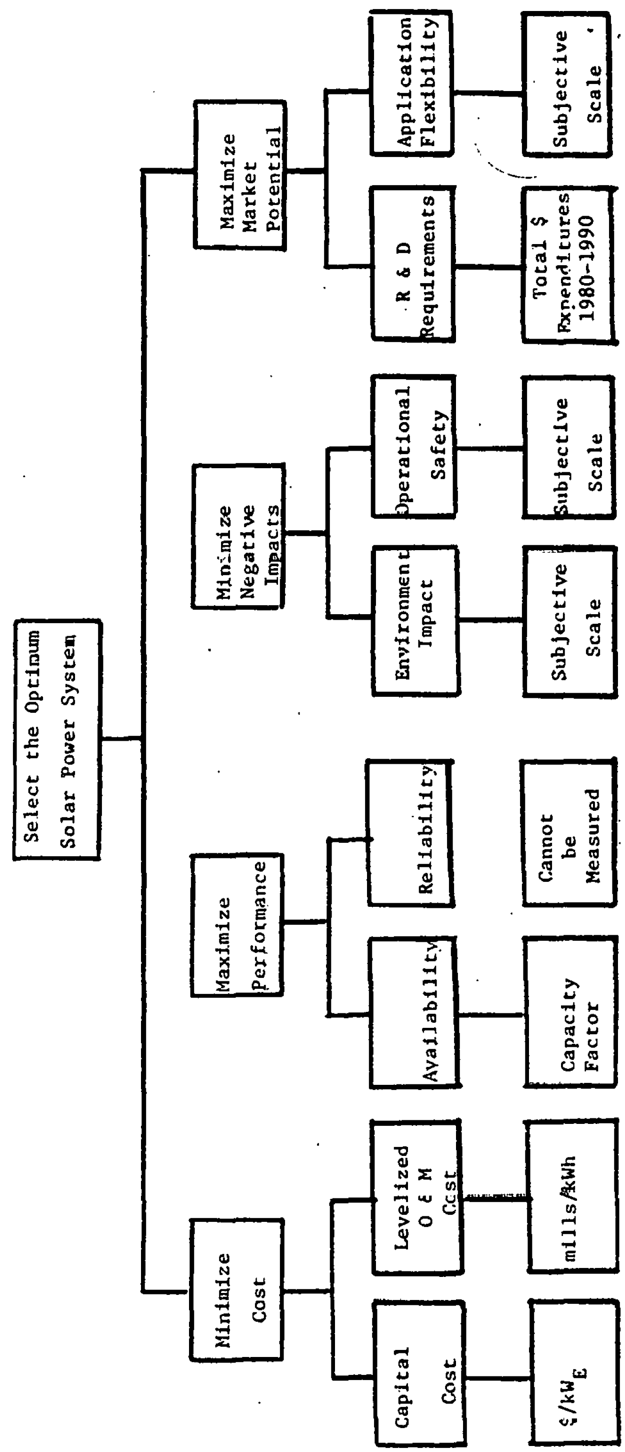

Figure 1. Problem Structure (1-10MW)

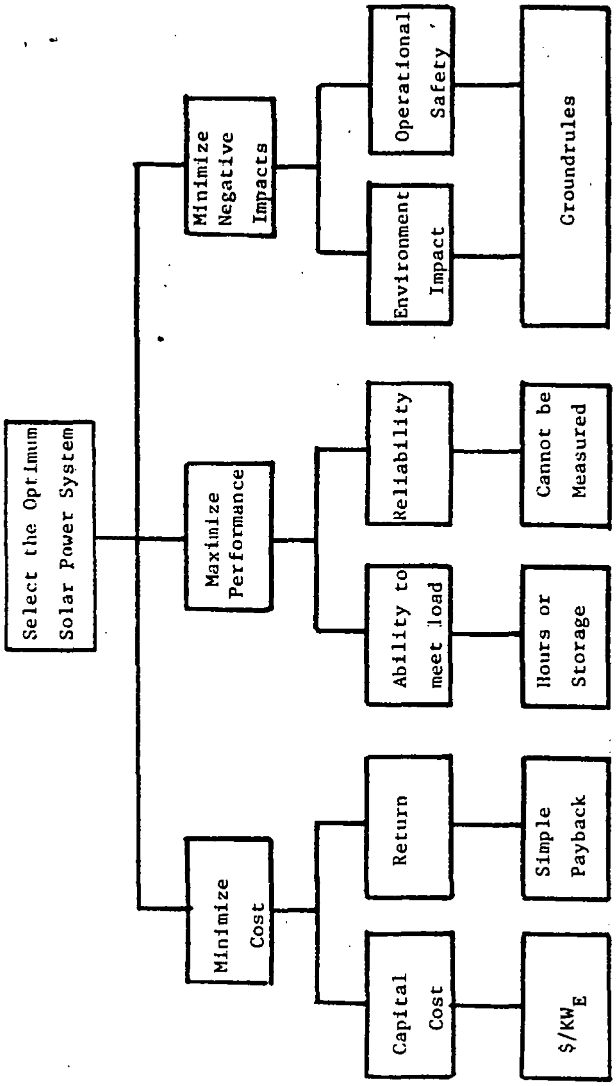

Figure 2. Problem Structure (.1-1 MW)

hence, the substitution. One note on the independence of attributes. It is not necessary that attributes be unrelated. Obviously payback and capital cost are closely related. It is necessary, however, that a single attribute and tradeoffs between pairs of attributes can be evaluated independent of the level of other attributes in the model. For further information on the issue of independence see chapter 3 of [2].

At this point much has been accomplished even without the use of the mathematical decision model. A logical, systematic framework has been defined for evaluating alternatives. Even if only a pair wise comparison were to be done with the structure in Figure 1 or Figure 2, a much more intelligent comparison could be done. The decision maker understands better his own decision process!

DECISION MODEL

Once the decision is structured as discussed in the previous section, why not calculate the value of the attributes for each system and allow the decision maker to choose among the alternatives? If the decision were a one time event based on certain data, this would be the way to proceed. However, a decision model allows for: evaluation on a repeated basis, testing of the uncertainty associated with the system values, comparisons of far more alternatives than the decision maker has time or patience to evaluate, and handling of more attributes than a decision maker can effectively handle at one time. Further, the model can be exercised without the decision maker present as new data is collected.

The central concept of the MADA model is its ability to calculate a single unitless value called a utility value or preference score for each system. This utility value measures the usefulness or preference which the decision maker has for the system. The higher the system's utility value, the more the decision maker prefers that system. This provides the basis for a straightforward ranking of the systems! Construction of the utility function from which these utility values are calculated is not a simple task, but neither is it a highly complex problem. The primary mechanism for combining such widely disparate units of measure as dollars and hours of storage is the single attribute utility function (SAUF). The SAUF expresses the relative preferences of a decision maker for the values of that attribute. Obviously a low cost is more preferred than a high cost, but the SAUF measures how much it is preferred. Equally important, the function provides the basis for evaluation of tradeoffs between values of conflicting attributes, e.g., how much extra cost is a user willing to pay for an increase in system performance?

A SAUF for the systems's payback is illustrated in Figure 3. Payback is the time required to recoup the initial investment through savings from use of the solar system. The range of values along the horizontal axis is important in the accurate formulation of the function. The best value (that corresponding to a utility of 1) must be at least as good as the best value for any of the systems to be evaluated. The worst value should be a reasonable estimate of the worst value the decision maker would consider. The choice of 30 years in Figure 3 is an approximation of the maximum payback which small users would be willing to consider for an energy system. The sample payback curve can be constructed in two ways. The first involves lottery type questions as described by Drake and Keeney [6] which find the payback (for the example in Figure 3) corresponding to various midpoints along the vertical axis. The second way to determine the curve is simply to ask the decision maker to draw one.

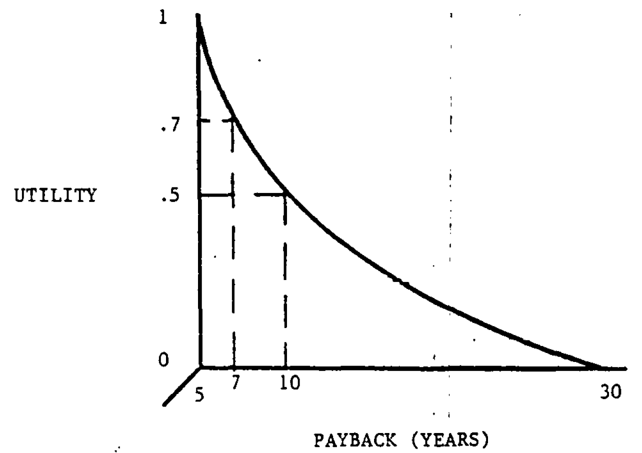

FIGURE 3. SINGLE ATTRIBUTE UTILITY FUNCTION

The next step in the construction of the system utility function is determination of the weights or relative importance of the decision criteria. The importance of each criterion must take into account the range of values. To illustrate this point, consider the importance of payback when candidate systems vary from 5 to 30 years relative to the importance when all systems pay back in 5 to 6 years. The smaller range makes payback play a less important role in the decision.

Many approaches to establishing these weights have been used. The simplest is to subjectively assign weights. An approach which is easily understood and probably more accurate has been used since long before the invention of money. In fact, the very concept of money as a medium of exchange embodies this approach. In this method the attribute (called the reference attribute) which is chosen as most important, keeping in mind the defined range of values, becomes the standard for the measure of importance. For example, if the decision maker chooses payback as the reference attribute, then the importance of hours of storage and capital cost can be judged on the basis of a tradeoff against years of payback. The more years traded away to improve another attribute, the more weight that attribute carries in the decision. A simple example should clear up this point.

Suppose the range of values to be considered for capital cost is between $1400 and $3400/KW and that the hours of storage varies from none to ten hours. Suppose further that Figure 3 is the SAUF for payback and that payback is the reference attribute for the sample decision maker, Mr. Henry Ford. In discussions with Mr. Ford, it is found that he is willing to increase payback on his solar energy system from 5 years to 10 years, if he can reduce his capital cost from $3400 to $1400/KW. However, Henry will only give up two years of payback, from 5 to 7 years, to increase his storage capacity from none to 10 hours. As indicated in Figure 3, he has given up one half of his payback utility for the capital cost improvement, but only 30% of the utility to increase the storage. Consequently, the capital cost is approximately one and two thirds times as important as storage to Mr. Ford given the ranges of interest.

The details for determining the single attribute utility functions and the criteria weights can be found in Drake and Keeney [6] and as they apply in the SPSS in Fineburg, Kuehn and Miles [7]. It should be noted that the weights are the most important aspect of the decision, after the choice of attributes. Consequently the weights should not be assigned by analysts doing the study, but rather should be solicitated from the decision maker.

This discussion has been purposely non-mathematical. The intent of the discussion is to pass along the flavor of the model rather than the mechanics. The formula for calculating the system utility or preference score is included here for those who feel more comfortable with equations and to tie together what has been said in this section in a concise form.

$$\text{SYSTEM UTILITY} = \frac{1}{k}\left(\prod_{i=1}^{n}(1 + kk_i u_i(x_i)) - 1\right)$$

where

- x_i = value of attribute i for the system
- u_i = single attribute utility function
- k_i = weight of attribute i in the decision
- k = scaling factor to normalize the function
- n = the number of attributes

Fineberg and Miles [8] give details on the form and calculation of this function. Another form often used in MADA, but requiring more stringent conditions on the independence of the attributes, is the additive form:

$$\text{SYSTEM UTILITY} = \sum_{i=1}^{n} k_i u_i(x_i)$$

The first of these, the multiplicative form is used in the SPSS.

UNCERTAINTY

Uncertainty plays a significant role in a study which relies on forecasts of energy prices and technological advance. Uncertainty arises as cost and performance estimates and forecasts are made to the end of the century. The solicitation of the data for the decision model also provides ample room for uncertainty. Decision analysis deals explicitly and clearly with this type of uncertainty. When reasonable error bounds can be estimated for system data, these values can be put into the model in place of the base estimates as is done in any parametric analysis. When estimates are not available, the error which would cause a system to be ranked equal with the system above or below it can be backed out of the model. It is often easier to judge whether a 50% error in cost is within reasonable error bounds then to state what reasonable error bounds are. Over and above estimates of cost and performance lies the fact that many of the solar thermal systems require much of the same hardware: heliostats, piping, turbines, to name a few. To take advantage of these similarities, in light of the comparative aspects of the evaluation, a philosophy of comparative costing has been adopted. Systems whose characteristics are known with more certainty provide the basis for costing of other similar systems. More advanced technologies are evaluated on the basis of comparison to the known systems. In this manner, if the costs are misestimated, all similar systems are either overestimated or underestimated. If an unanticipated technological breakthrough occurs in efficiency of reflective material, for example, many systems will perform better. All these examples illustrate how part of the inevitable error in forecasting will wash out in the face of such a comparative analysis as this. More importantly, the final ranking will most likely remain stable throughout these sorts of changes, but of course not always.

In addition to uncertainty arising from system forecasts, the decision model itself may be inaccurate. Decision rationale changes over time, from company to company and even from individual to individual within a single corporation. The individual differences can be examined by interviewing many decision makers and comparing resulting rankings. Major emphasis shifts can be examined if the decision criteria do not change, but rather the shift can be captured as a change in the weights associated with each criterion. Decision makers can be hypothesized with extreme points of view. For example, a potential user could be imagined whose primary concern is environmental and safety concerns and one whose sole concern is cost. The difference between the rankings for two such opposing points of view can be determined by appropriately choosing the attribute weights in the decision model, then using the model to reevaluate the systems. This approach can identify shifts in attitude which result in significant variations in the resulting ranking. Further analysis can then be used to evaluate the likelihood of attitude shifts of this sort.

The collective use of these sensitivity studies provided SERI with the confidence to propose rankings which are defensible in both phases of the SPSS.

RESULTS PRESENTATION

The catalyst which prompted the SPSS was a need for rationale to assist DOE in allocating their R&D funds in the solar thermal power program. How have the results of the study answered DOE's needs? The primary answer which the study provides consists of two rankings of selected solar thermal power systems according to future commercial acceptability. A supporting, but equally important, result is an analysis of the sensitivity of these rankings to uncertainty. A secondary result of the study is identification of the strengths and weaknesses which cause systems to rank high or low. Two reports summarize in detail the results of the work. The first report [9] is an overview of the work done in the part of the study analyzing 1 - 10 MW plants. The second report [10] presents the total project with supporting detail and is an excellent source for readers who would like more information on the system designs. A separate paper by Thornton [11] addresses the system strengths and weaknesses.

The final rankings are summarized in Tables 1 and 2. These rankings represent the concensus opinions of approximately twenty decision makers in each case. The systems are grouped into three categories in both rankings. Group I consists of the systems most preferred by the sampled users. Group III includes those systems which fall consistently short of the others according to user opinion. The remaining systems, in Group II show promise, but

Group I

Point-focus central receiver with Ranking-cycle power conversion
Parabolic dish collectors with distributed Stirling engines

Group II

Parabolic dish collectors with central Rankine power conversion
Parabolic dish collectors with distributed Brayton engines
Point-focus central receiver with Brayton power conversion
Parabolic trough system with central Rankine power conversion
Low concentration, non-tracking CPC system

Group III

Line-focus central receiver system
Fixed mirror, distributed focus bowl system
Segmented trough with tracking receiver system and central Rankine power conversion
Shallow solar pond system

Table 1. 1 - 10 MW Ranking

Group I

Parabolic dish collectors with distributed Stirling engines

Group II

Parabolic dish collectors with distributed Brayton engines
Point-focus central receiver with central Stirling power conversion
Point-focus central receiver with Brayton power conversion
Point-focus central receiver with Rankine power conversion
Parabolic dish collectors with distributed Rankine engines
Parabolic dish collectors with central Rankine power conversion

Group III

Parabolic trough system with central Rankine power conversion
Fixed mirror, distributed focus bowl system
Low concentration, nontracking CPC system

Table 2. .1 - 1 MW Ranking

overall are not outstanding. The data uncertainty and the results of the sensitivity analysis dictate use of a coarse grouping. Systems within each group are ranked according to user preference, but differences are not significant. Breaks between groups are judged to be significant.

Sensitivity analyses identify several important uncertainties. In both rankings the uncertainty surrounding capital cost is significant. The analysis uncovers the need for firmer estimates of O&M costs. The decision model sensitivity analyses indicate the rankings are stable with a single general exception in each ranking. The ranking of Table I changes if an extreme social impact point of view is postulated, in which environmental and safety concerns dominate. However, no decision maker interviewed expressed such concerns. The ranking in Table 2 changes when emphasis is placed on the storage attribute of Figure 2. This attribute is displayed by a minority of users interviewed, who in general are concerned with availability of conventional power sources.

More detailed analysis of why systems ranked higher or lower revealed two trends.

- Optical efficiency losses for central receivers at small sizes cause those systems to rank lower.
- Systems with thermal rather than electrical storage are ranked higher when storage is important to the user.

These results illustrate how decision analysis can answer the questions originally postulated, provide a feel for the sensitivity of the ranking and give insights into why systems are preferred. This package is for more comprehensive and useful than a straightforward choice among alternatives.

CONCLUSION

This paper blends a specific case study and a general summarizing approach. This tack is taken to present each section on a level appropriate to the probable readers of the article. The problem structure and results presentations are tuned to the specific solar case study. The decision model and sensitivity analysis are presented on a more general level because the flavor and overall intent of these sections is more important to managers faced with problems similar to those expressed here than is the technical detail. Details are provided for those interested enough to pursue the references cited.

The broader question of evaluating competing technologies such as synthetic fuels, geothermal and solar can be addressed using decision analysis. The key to this generalization is the proper formulation of the problem structure. Once the important decision criteria are identified, the appropriateness of decision analysis will be clear.

Decision analysis is not a panacea. Even when it is useful, pitfalls exist which must be avoided. Experienced managerial judgment should be used to review results. If the analysis counters experienced intuition perhaps the problem structure is inappropriate or the data has grave errors. Secondly, results are not absolute. Action should not be undertaken based on a set of untested assumptions and data whose uncertainty is not taken into account. When data is significantly uncertain, more effort should be put into resolving this uncertainty. When decisions must be made in the face of such unknowns they should be made cautiously and they should be reviewed as more is discovered about the values of important decision criteria.

ACKNOWLEDGEMENT

The author would like to acknowledge Ken Brown for his pioneering work in constructing the decision model and James Gresham for his constant and valuable critiques. John Thornton, as task leader for the SPSS, has borne the brunt of the attacks launched by advocates of systems which fared both well and poorly in this study. His survival is a testimony to the effectiveness of the decision analysis and the success of the study in general.

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