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Assessment of Solar Options for Small Power Systems Applications Volume I Executive Summary

W. W. Laity
D. T. Aase
W. J. Apley
S. P. Bird
J. W. Currie

M. K. Drost
M. Jannol
S. C. Schulte
A. M. Sutey
T. A. Williams

September 1979

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Pacific Northwest Laboratory
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ASSESSMENT OF SOLAR OPTIONS FOR SMALL
POWER SYSTEMS APPLICATIONS

VOLUME I

EXECUTIVE SUMMARY

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Richland, Washington 99352

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ABSTRACT

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 electric 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.

Conceptual designs developed for the 10 systems were based on common assumptions of available technology in the 1990 to 2000 time frame. No attempt was made to perform a detailed optimization of each conceptual design. Rather, designs best suited for a comparative evaluation of the concepts were formulated. Costs were estimated on the basis of identical assumptions, ground rules, methodologies, and unit costs of materials and labor applied uniformly to all of the concepts.

The computer code SOLSTEP was used to analyze the thermodynamic performance characteristics and energy costs of the 10 concepts. Year-long simulations were performed using meteorological and insolation data for Barstow, California as input to the code. Results for each concept include levelized energy costs and capacity factors for various combinations of storage capacity and collector field size.

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For all 10 concepts, subjective values were estimated for four additional power plant characteristics: plant flexibility, forced outage rate, environmental and safety effects, and R&D necessary for commercialization.

Multiattribute utility methodology was used to rank the 10 concepts. To quantitatively establish the importance to decision makers of each plant characteristic (attribute) used in the ranking, 37 interviews were conducted with personnel from the Electric Power Research Institute, Edison Electric Institute, and nine utilities in the Southeast and Southwest. Value indexes for the 10 concepts were calculated and used to rank the concepts and to determine concept groupings with statistically significant differences.

Results of this study led to the following conclusions:

- When only the three more traditionally compared attributes of leveled energy cost, capacity factor, and fixed costs were considered, concepts using central receiver subsystems ranked above those with distributed receivers; concepts with thermal storage ranked above those with electric storage at higher capacity factors (>0.4); and two-axis tracking concepts ranked above one-axis tracking concepts which, in turn, ranked above the nontracking concept.
- When all seven attributes were used for ranking, the central receiver concepts dropped to a significantly lower group, primarily because of higher forced outage rate. In addition, the central receiver Brayton concept was penalized for higher R&D costs. Distributed line focus and nontracking concepts moved up in ranking, particularly at high capacity factors, due primarily to relatively low R&D costs.
- Utility decision makers indicated that plant flexibility, forced outage rate, environmental and safety effects, and R&D requirements significantly affect the commercialization potential of solar concepts.

- The Point Focus Central Receiver with Rankine power conversion and the Point Focus Distributed Receiver with Brayton or Stirling power conversion consistently ranked high.
- The Line Focus Distributed Receiver with a tracking receiver and the Line Focus Central Receiver consistently ranked low.

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CONTENTS

ABSTRACT	iii
FIGURES	ix
TABLES	x
1.0 INTRODUCTION	1.1
1.1 STUDY PURPOSE	1.1
1.2 STUDY SCOPE	1.1
1.2.1 Principal Tasks	1.2
1.2.2 Limitations	1.3
1.3 EXECUTIVE SUMMARY SCOPE	1.3
2.0 CONCEPTS ANALYZED	2.1
2.1 TWO-AXIS TRACKING	2.2
2.1.1 Point Focus Central Receiver (PFCR)	2.2
2.1.2 Point Focus Distributed Receiver (PFDR)	2.5
2.1.3 Fixed Mirror Distributed Focus (FMDf)	2.7
2.2 ONE-AXIS TRACKING	2.9
2.2.1 Line Focus Central Receiver (LFCR)	2.9
2.2.2 Line Focus Distributed Receiver - Tracking Receiver (LFDR-TR)	2.11
2.2.3 Line Focus Distributed Receiver - Tracking Concentrator (LFDR-TC)	2.11
2.3 NONTRACKING CONCEPT	2.14
3.0 APPROACH FOR ANALYZING AND RANKING CONCEPTS	3.1
3.1 FORMULATION OF SYSTEM CONFIGURATIONS	3.1
3.1.1 Engineering Ground Rules and Assumptions	3.1
3.1.2 Design Constraints	3.2
3.2 ESTIMATION OF COSTS	3.3
3.2.1 Economic Ground Rules and Assumptions	3.3
3.2.2 Capital Investment Cost Estimating	3.3
3.2.3 Capital Replacement Cost Estimating	3.8
3.2.4 Operating and Maintenance Cost Estimating	3.8
3.3 MODELING CONDITIONS FOR LEAST COST CONCEPTS	3.9

3.4	COMPUTATIONAL PROCEDURES	3.11
3.4.1	Concentrator Optics	3.11
3.4.2	Receiver Performance	3.14
3.4.3	Solar Plant System Simulation	3.15
3.5	RANKING METHODOLOGY	3.19
3.5.1	Systems Analysis	3.20
3.5.2	Decision Makers' Values	3.20
3.5.3	Concept Rankings	3.22
4.0	RESULTS	4.1
4.1	ATTRIBUTES	4.1
4.1.1	Levelized Energy Cost and Plant Capacity Factor	4.1
4.1.2	Fixed Costs as a Percentage of Levelized Energy Cost	4.6
4.1.3	Plant Flexibility	4.7
4.1.4	Forced Outage Rate	4.9
4.1.5	Environmental and Safety Effects	4.11
4.1.6	Public Investment in Research and Development Necessary for Commercialization	4.12
4.2	COMPARATIVE RANKING OF CONCEPTS	4.13
4.2.1	Decision Maker Preference	4.13
4.2.2	Concept Rankings	4.15
4.3	COMMENTS AND CONCLUSIONS	4.19
4.3.1	Comments	4.19
4.3.2	Conclusions	4.20
REFERENCES		Ref.1

FIGURES

2.1	Point Focus Central Receiver	2.3
2.2	Point Focus Central Receiver Heliostat	2.4
2.3	Point Focus Distributed Receiver	2.6
2.4	Fixed Mirror Distributed Focus Concept	2.8
2.5	Line Focus Central Receiver	2.10
2.6	Line Focus Distributed Receiver - Tracking Receiver	2.12
2.7	Line Focus Distributed Receiver - Tracking Concentrator	2.13
2.8	Nontracking Compound Parabolic Concentrator	2.16
3.1	Collector Cost Estimating Methodology	3.7
3.2	Sample Plot of Energy Cost Versus Capacity Factor	3.18
3.3	Solar Concept Ranking Process	3.20
4.1	Sample Plot - Locus of Zero Storage Points	4.2
4.2	Comparison of Concepts on Basis of Levelized Energy Cost in Mills/kWh (1978 \$)	4.5
4.3	Relative Effect of Varying Plant Size on Lowest Levelized Energy Cost	4.6
4.4	Initial Capital Investment Costs (1978 \$)	4.7
4.5	Replacement Capital Costs (1978 \$)	4.8
4.6	Operating and Maintenance Costs (1978 \$)	4.8
4.7	Rankings by Concept Score of 5-MWe Concepts-- Three-Attribute Case (LEC, CF, FIX)	4.17
4.8	Rankings by Concept Score of 5-MWe Concepts-- Seven-Attribute Case	4.18

TABLES

2.1	Concepts Selected for Analysis	2.1
3.1	Economic Ground Rules and Assumptions	3.4
3.2	Generic Concept Configuration Parameters	3.10
3.3	Thermal Losses for System Concepts	3.16
3.4	Attribute Information	3.21
4.1	5-MWe Least-Cost Generic Concepts - Levelized Energy Costs (mills/kWh)	4.4
4.2	5-MWe Least-Cost Generic Concepts - Fixed Costs as a Percentage of Levelized Energy Cost	4.9
4.3	5-MWe Least-Cost Generic Concepts - Plant Flexibility	4.10
4.4	5-MWe Least-Cost Generic Concepts - Forced Outage Rate	4.10
4.5	5-MWe Least-Cost Generic Concepts - Environmental and Safety Effects	4.11
4.6	5-MWe Least-Cost Generic Concepts - Public Investment in Research and Development Necessary for Commercialization	4.12
4.7	Attribute Importance Weight Means	4.14

ASSESSMENT OF SOLAR OPTIONS
FOR
SMALL POWER SYSTEMS APPLICATIONS
VOLUME I
EXECUTIVE SUMMARY

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 executive summary is the first volume of the PNL report on the work performed.

1.1 STUDY PURPOSE

The primary purpose of this study is to provide DOE with an independent, objective assessment of 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. This assessment was performed concurrently with a similar assessment by the Solar Energy Research Institute (SERI). The results of these assessments will serve as guidance for DOE to make decisions on which concepts warrant priority attention in further technology development.

1.2 STUDY SCOPE

Seven generic types of collectors, together with associated subsystems for electric power generation, were considered in this study. 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).

These collectors can be combined with energy transport, energy storage, and power conversion subsystems in a wide variety of ways to formulate conceptual systems for electric power generation. In this study, attention was restricted to configurations that are potentially suitable for development as small power systems (1 to 10 MWe) in the long term (1990 to 2000), with initial commercialization by the mid-1980s. Cogeneration and total energy systems were beyond the scope of this study.

All seven types of collectors were analyzed in conceptual system configurations with Rankine-cycle engines. Because they can operate at particularly high concentration ratios, two of the collectors (the Point Focus Central Receiver and the Point Focus Distributed Receiver) were also analyzed with Brayton-cycle engines. In addition, the latter of the two was analyzed with Stirling-cycle engines. With these engine options, 10 conceptual systems were formulated for analysis.

1.2.1 Principal Tasks

The four principal tasks included in this study are as follows:

- Task 1 - Determination and Characterization of Concepts for Analysis:
The objectives of this task were to determine the solar thermal concepts that would be analyzed, and to acquire and evaluate the literature available on each.
- Task 2 - Systems Analysis: Each of the alternative concepts selected in Task 1 was analyzed to determine the levelized energy cost required for operation at a nominal power level of 5 MWe with an annual capacity factor of 0.4 and with costs amortized over 30 years.
- Task 3 - Sensitivity Analysis: The effect on each of the alternative concepts of varying rated power and annual capacity factor was determined.
- Task 4 - Concept Ranking: The alternative concepts were ranked on the basis of seven attributes considered in the analyses performed as part of Tasks 2 and 3, together with preference data for the attributes obtained from interviews of managers representing the utility industry and DOE. Multiattribute utility methodology was used to perform the ranking.

1.2.2 Limitations

Within the constraints imposed by the performance characteristics of the solar collector subsystems, the operating conditions (e.g., turbine inlet temperature) for alternative concepts that work on the same cycle (e.g., Rankine) were the same. This facilitated the identification of differences among concepts that could be attributed to the different collector subsystem designs. No attempt was made to perform a detailed optimization of each conceptual design. Rather, designs best suited for a comparative evaluation of the concepts were formulated.

1.3 EXECUTIVE SUMMARY SCOPE

The highlights of this study are summarized in the following three sections. In Section 2.0, the seven generic collector types analyzed are briefly described and illustrated. Section 3.0 summarizes the approach used to analyze and rank the concepts. The primary results and conclusions are presented in Section 4.0.

2.0 CONCEPTS ANALYZED

The initial step in evaluating the alternative solar thermal power systems was to identify those concepts that best represented the most advanced generic types currently being proposed. The configurations selected for analysis can be classified on the basis of two major characteristics--method of tracking and thermodynamic cycle. Table 2.1 presents the seven generic concentrator systems, and includes the nomenclature used to identify the individual concepts. Because the Brayton thermodynamic cycle was considered for the Point Focus Central Receiver, and the Brayton and Stirling cycles were also included for the Point Focus Distributed Receiver, 10 generic concepts were actually analyzed as part of the overall performance and economic evaluation. Several different configurations of each of the 10 generic concepts were evaluated. The descriptions given in the following sections are for those configurations that resulted in the lowest energy cost. Information on other configurations of these concepts is presented in Volume II of this report.

TABLE 2.1. 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

2.1 TWO-AXIS TRACKING

Two-axis tracking concepts use concentrators and receivers that can be oriented individually or collectively to enable focusing of the sun's image. The capability to track the sun's diurnal motion in both azimuth and altitude allows for very high concentration ratios. The availability of high concentration ratios means that higher system working fluid temperatures may be obtained, producing better Rankine-cycle efficiencies and allowing the use of alternative thermodynamic cycles (Brayton and/or Stirling). Three two-axis tracking concepts were considered: the Point Focus Central Receiver, the Point Focus Distributed Receiver, and the Fixed Mirror Distributed Focus.

2.1.1 Point Focus Central Receiver (PFCR)

Point Focus Central Receiver concepts employ a large array of mirrors that track the sun in two axes, redirecting the incident radiation onto a receiver located on the top of a fixed tower. The generic system is shown in Figure 2.1; however, it is important to note that the field shape can change dramatically when smaller plants or cavity receivers are considered. In the latter cases, the fraction of heliostats located in the southern portion of the field is reduced. The same heliostat and support assembly were used for all PFCR cases. The selected design was very similar to both the Solaramics and McDonnell Douglas (MDAC) prototype heliostats shown in Figure 2.2, sized to a 49-m² aperture area. Each heliostat has an individual tracking mechanism and foundation.

Three thermodynamic cycles were considered for the Point Focus Central Receiver: Rankine, Brayton, and Stirling. Because of the lack of available information on large Stirling engine performance and cost, only the Rankine and Brayton cycles were analyzed.

2.1.1.1 PFCR/Rankine Cycle

The Rankine-cycle PFCR used a cavity receiver with molten draw salt as both the heat transport and thermal storage fluid. The energy conversion subsystem used a heat exchanger/boiler assembly to produce steam for driving a conventional turbine. Full rated power was available at all times because the molten salt extracted from storage was at the same temperature (1000°F) as

FIGURE 2.1. Point Focus Central Receiver

McDONNELL DOUGLAS ASTRONAUTICS CORP.
PROTOTYPE HELIOSTAT

SOLARAMICS PROTOTYPE HELIOSTAT

FIGURE 2.2. Point Focus Central Receiver Heliostat

that coming from the field. The storage subsystem used a combination of molten salt and rock, arranged to form a thermocline. The medium is contained in an insulated tank.

2.1.1.2 PFCR/Brayton Cycle

The Brayton-cycle PFCR employed a cavity receiver with air as the energy transport medium. Receiver exit temperature was maintained at 1500°F. A cavity receiver was required to reduce the attendant thermal losses caused by operating at the higher temperatures associated with a closed-cycle Brayton system. The heated air was supplied to a gas turbine located immediately adjacent to the receiver at the top of the tower. Electric storage was

provided by an advanced Redox battery subsystem. This subsystem consists of anode and cathode fluids (chromium- and iron-chloride) separated by a sheet of membrane material. The fluid reactants are stored in tanks and pumped to the flow cells when needed.

2.1.2 Point Focus Distributed Receiver (PFDR)

The Point Focus Distributed Receiver concepts employ an array of parabolic dishes that track the sun in two axes, redirecting the incident radiation onto individual cavity-type receivers located at the focal point of each separate parabolic concentrator. A generic plant concept (JPL) is shown in Figure 2.3. Rankine, Brayton, and Stirling cycles were evaluated. For the Rankine cycle, a transport fluid was circulated through the receivers and piped to a central power generating facility. The Brayton and Stirling concepts used small engines mounted as part of the individual receiver assemblies. The same parabolic concentrator (100-m^2 aperture area) and support assembly were used for all Point Focus Distributed Receiver cases. However, some reinforcement was necessary for concepts with an engine as well as the receiver mounted at the focal point.

2.1.2.1 PFDR/Rankine Cycle

The Rankine-cycle PFDR used molten draw salt as both the heat transport and thermal storage fluid. The heated molten salt was piped to a central energy conversion facility where a heat exchanger/boiler assembly was used to produce steam to drive a conventional turbine. Full rated power was available at all times because the molten salt extracted from storage was at the same temperature (850°F) as that coming from the field. The use of molten draw salt at this temperature eliminated the need for stainless steel piping. This resulted in a substantial cost saving in the large piping system required for the PFDR/Rankine-cycle concept. The storage subsystem used a combination of molten salt and rock, arranged to form a thermocline. This medium is contained in an insulated tank.

2.1.2.2 PFDR/Brayton Cycle

The Brayton-cycle PFDR used a small closed-cycle turbine with 1500°F air as the working fluid. An optimal turbine size of 17.5 kWe was determined.

FIGURE 2.3. Point Focus Distributed Receiver (Jet Propulsion Laboratory)

The electricity generated at the collector was transported by the electric energy transport subsystem to a central power conditioning station and then to the demand grid. Electricity generated above demand levels was then used to charge a central Redox electrochemical storage device that used fully soluble anode and cathode fluids separated by a selective ion exchange membrane. The reactants are stored in tanks and, when needed, are pumped through flow cells where the electrochemical reactions take place at separate inert porous carbon felt electrodes.

2.1.2.3 PFDR/Stirling Cycle

The Stirling-cycle PFDR consisted of a 17.5-kWe free piston engine coupled to a linear alternator. A liquid metal receiver was used to produce a hot-end external temperature of 1500⁰F.

The electricity generated at the collector was transported by the electric energy transport system to a central power conditioning station and then to the demand grid. Electricity generated above demand levels was used to charge a central Redox electrochemical storage device, identical in all respects to the Redox battery used in the Brayton-cycle PFDR.

2.1.3 Fixed Mirror Distributed Focus (FMDf)

The Fixed Mirror Distributed Focus concept is a large bowl-like structure consisting of individual mirror panels attached to a criss-cross concrete frame. The entire bowl is canted 15⁰ to the south. A boom/crane assembly is used to maintain the tube-wound, cylindrical receiver within the moving focal region of the bowl during all daylight hours. Each bowl is 200 feet in diameter. The generic plant, as developed by Texas Tech University and E-Systems, Inc., includes a number of distributed bowls as shown in Figure 2.4. The energy is extracted from receivers and piped to a central electric generating facility.

The Rankine-cycle FMDf used molten draw salt as both the heat transport and thermal storage fluid. Brayton and Stirling cycles were not analyzed due to large receiver thermal losses at the high temperatures that would be required by the power conversion cycle. The heated molten salt was piped to a central energy conversion facility where a heat exchanger/boiler assembly was used to produce steam for driving a conventional turbine. Because the molten

FIGURE 2.4. Fixed Mirror Distributed Focus Concept

salt extracted from storage was at the same temperature (850°F) as the salt coming from the field, full rated power was available at all times. The use of molten draw salt at this temperature eliminated the requirement for stainless steel piping. Consequently, considering the large piping system necessary for the FMDF/Rankine-cycle concept, a considerable cost saving was possible. The storage subsystem used a combination of molten salt and rock, arranged to form a thermocline, contained in an insulated tank.

2.2 ONE-AXIS TRACKING

One-axis tracking concepts use linear concentrators that can rotate around one axis to track the sun's diurnal motion. In general, one-axis tracking does not achieve the very high concentration ratios available with the two-axis tracking concepts. However, one-axis tracking requires a less complicated and potentially less expensive collector. Three one-axis tracking concepts were considered: the Line Focus Central Receiver concept, the Line Focus Distributed Receiver with a Tracking Receiver, and the Line Focus Distributed Receiver with a Tracking Concentrator.

2.2.1 Line Focus Central Receiver (LFCR)

The Line Focus Central Receiver concept (Figure 2.5) uses an array of rectangular single-axis heliostats to focus incident solar radiation on an elevated line central receiver. The heliostats are arranged in a concentrator field on the north side of the receiver. The heliostats, which have adjustable focal lengths, track the sun automatically and concentrate the insolation on the receiver.

The cavity-type line receiver is mounted on towers, with sufficient length to absorb the energy collected in the heliostat field. Molten draw salt is supplied to the receiver sections by the transport subsystem piping network, then returned at 850°F to the central generation facility. By restricting the maximum molten salt temperature, it was possible to use carbon steel rather than more expensive stainless steel piping. This proved cost-effective for the extensive LFCR transport and storage piping subsystems. At

FIGURE 2.5. Line Focus Central Receiver

the central generation facility, a heat exchanger/boiler assembly was used to produce steam for driving a conventional Rankine-cycle turbine. Full rated power was available at all times, because the molten salt extracted from storage was at the same temperature as that coming from the field. The storage subsystem used a combination of molten salt and rock, arranged to form a thermocline, contained in an insulated tank.

2.2.2 Line Focus Distributed Receiver - Tracking Receiver (LFDR-TR)

The Line Focus Distributed Receiver - Tracking Receiver concept uses a fixed mirror concentrator that produces a sharp line focus regardless of the sun's position (see Figure 2.6). The receiver is moved in a circular arc to track the focal line. The concentrator is a concave array of long, narrow, flat mirror facets fixed to a concrete support. The movable receiver consists of a selectively coated enclosed receiver tube with a compound parabolic secondary concentrator.

Molten draw salt is supplied to the receiver sections by the transport subsystem piping network, then returned at 850°F to the central generation facility. By restricting the maximum molten salt temperature, it was possible to use carbon steel rather than more expensive stainless steel piping. This proved cost-effective for the extensive LFDR-TR transport and storage piping subsystems. At the central generation facility, a heat exchanger/boiler assembly was used to produce steam to drive a conventional Rankine-cycle turbine. Full rated power was available at all times, because the molten salt extracted from storage was at the same temperature as that coming from the field. The storage subsystem used a combination of molten salt and rock, arranged to form a thermocline, contained in an insulated tank.

2.2.3 Line Focus Distributed Receiver - Tracking Concentrator (LFDR-TC)

The Line Focus Distributed Receiver - Tracking Concentrator concept uses a collector segment consisting of a single-curvature concentrator that focuses solar insolation on a fixed linear receiver. The concentrator is rotated around one axis to track the sun's diurnal motion. The concentrator is a parabolic trough; the receiver consists of a glass-enclosed, selectively coated receiver tube as shown in Figure 2.7.

FIGURE 2.5. Line Focus Distributed Receiver - Tracking Receiver

FIGURE 2.7. Line Focus Distributed Receiver - Tracking Concentrator

The collector segments are placed in standard modules arranged to form the collector field. Energy is transported from the collector field by a heat transfer oil, Caloria HT45®. The transport subsystem consists of the piping, pumps, and accessories necessary to transport the oil to the collector field, then return the heated oil to the central energy conversion facility. The returning oil has a temperature of 580°F.

Energy collected in the field can be either stored in the thermal storage subsystem or immediately used in the energy conversion subsystem. The thermal storage subsystem uses a mixed-media oil and rock thermocline storage.

The energy conversion subsystem is a steam Rankine cycle where steam is generated in a heat exchanger/steam generator assembly that uses the hot oil as a heat source. The hot oil can be supplied either directly from the field or from storage. Because the oil extracted from storage is at the same temperature as that coming from the field, there is no reduction in performance efficiency or power output when operating from storage. The energy conversion subsystem includes the turbine, generator, air-cooled condenser, feedwater heaters, pumps, steam auxiliaries, and miscellaneous equipment.

2.3 NONTRACKING CONCEPT

Nontracking systems, such as flat plate collectors, are capable of producing maximum operating temperatures ~200°F greater than ambient. Because higher temperatures are required to enable more efficient electric power production, some form of concentrating mirror must be included as part of a stationary collector. While several different nontracking configurations have been proposed, the compound parabolic concentrator (CPC) collector with a Rankine energy conversion subsystem appears to provide the highest operating temperature with the smallest number of seasonal axial tilt changes.

The CPC collector uses a compound parabolic concentrator to redirect incident solar radiation onto a selectively coated tubular vacuum receiver.

® Trademark of the Exxon Corporation.

The CPC is a nonimaging concentrator, allowing a more precise concentration than do conventional mirrors. However, there is also a corresponding trade-off between achievable concentration ratio and number of tilt adjustments required per year. The system used in this study is a truncated 7.2x CPC with an effective net concentration of 5.25, requiring only twelve tilt adjustments per year. Because of significant increases in thermal losses at higher operating temperatures, the CPC collector heat transfer fluid was constrained to an exit temperature of 450°F. The specific collector design is based on similar nonimaging concentrators being developed at the University of Chicago.

As shown in Figure 2.8, the CPC segments are placed in standard modules arranged to form the collector field. Energy is transported from the collector field by Caloria HT45® heat transfer oil. The transport subsystem consists of the piping, pumps, and accessories necessary to transport the oil to the collector field, and then return the heated oil to the central energy conversion facility.

Energy collected in the field can be either stored in the thermal storage subsystem or immediately used in the energy conversion subsystem. The thermal storage subsystem uses a mixed-media oil and rock thermocline storage. Because the same oil is used for the transport and storage subsystems, heat exchangers are not required for charging storage.

The energy conversion subsystem is a steam Rankine cycle in which steam is generated in a heat exchanger/boiler assembly that uses the hot oil as a heat source. The hot oil can be supplied either directly from the field or from storage. Because the oil extracted from storage is at the same temperature as that coming from the field, there is no reduction in performance efficiency or power output when operating from storage. The energy conversion subsystem includes the turbine, generator, air-cooled condenser, feedwater heaters, pumps, steam auxiliaries, and miscellaneous equipment. This system design allows for full power production from both the field and storage. Therefore, no configurations employing different heat transport or storage fluids were included in this analysis.

SMALL ARRAY OF CPC MODULES

FIGURE 2.8. Nontracking Compound Parabolic Concentrator

3.0 APPROACH FOR ANALYZING AND RANKING CONCEPTS

As noted in the introduction, the primary objective of this study was to rank the generic collector systems that have been proposed for commercial small power systems applications. This section briefly describes the methods PNL used to determine the cost and performance of each generic collector type, as well as the ranking methodology employed. Primary emphasis throughout was to use common bases in developing both cost and performance parameters in analyzing the systems.

3.1 FORMULATION OF SYSTEM CONFIGURATIONS

Section 2.0 described the generic collector systems considered in the PNL study. This subsection describes the engineering ground rules, assumptions, and design constraints used in formulating the system configurations for analysis.

3.1.1 Engineering Ground Rules and Assumptions

Four key ground rules and assumptions were established at the outset of this study. They were selected to ensure that the small power systems ranked by PNL were comparable to those analyzed by SERI in its parallel study.

First, it was agreed that small power systems of 5 MWe would be compared. Sensitivity of the ranking to plant sizes of 1 MWe and 10 MWe would also be determined.

Second, all plants were to be designed to have a capacity factor of 0.4. Capacity factor was defined as

$$CF = \frac{\text{Net energy generated annually (kWh)}}{\text{Rated capacity (kW) x number of hours in year}}$$

The net energy generated, used to calculate capacity factor, does not include forced outages. The sensitivity of the ranking at capacity factors of 0.7 and the optimum, i.e., lowest levelized energy cost, for each concept was also to be determined. As part of the sensitivity study, the concepts were also to be

compared at capacity factors corresponding to zero storage for each system. By specifying capacity factor, the plants were compared at equivalent energy output, as well as at equivalent rating (power).

The third ground rule was that all the small power systems would be connected to a utility grid. This eliminated the need to match specific daily and seasonal load characteristics. The utility grid was assumed large enough to take the small power system's output and to supply power for specific peaks that would occur in any real load situation.

The fourth ground rule was that insolation data from Barstow, California would be used to determine plant output. The 1976 data collected by Aerospace Corporation were provided by the Jet Propulsion Laboratory.

3.1.2 Design Constraints

In addition to the four ground rules, PNL imposed several constraints in formulating the systems to be studied. The purposes of the additional constraints were to limit the scope of the engineering effort involved and to ensure that all concepts were evaluated on the same technological bases.

A description of collector components (concentrator and receiver) was selected from designs proposed for each generic concept. Description selection was based on how typically the design represented the generic concepts, as well as on the availability of design information. The descriptions were then modified to reflect proposed advances in structures, optical coatings, selective surfaces, and other features that would reflect the state-of-the-art in the 1990s.

Common subsystems and components were used as much as possible in formulating the small power systems representing each generic concept. Subsystems such as thermal and electrical storage and power conversion were standardized and used as appropriate with the generic collector concepts.

The PNL studies minimized the subsystem optimization of design and operating parameters. Previous studies were relied on to establish appropriate operating temperatures and other parameters for this study. Exceptions were necessary for the small plant sizes. In these instances, some changes, such

as field layout for central receiver concepts for small fields, are appropriate. Temperatures can be adjusted when cavity receivers are substituted for open receivers. No attempt was made, however, to perform extensive suboptimization, even when changes from previous designs were made.

3.2 ESTIMATION OF COSTS

Costs of constructing and operating solar thermal power plants consist of capital investment costs, capital replacement costs, and operating and maintenance costs. Capital investment costs are incurred before initial plant operation, and consist of all plant construction costs. Capital replacement costs are incurred as a result of major equipment replacement during the plant's operating lifetime. Operating and maintenance costs are expenses required for plant operation and routine maintenance, and occur at regular intervals throughout the plant's operating lifetime.

3.2.1 Economic Ground Rules and Assumptions

Realistic comparisons of small power systems can be achieved only when a uniform set of economic ground rules and assumptions is used to analyze all concepts. There are four primary types of ground rules and assumptions:

- those concerning the solar industry in general
- those concerning collector manufacturing
- those concerning small power systems operation and maintenance
- those concerning economic and financial parameters for the utility company operating the power system.

The uniform economic ground rules and assumptions used in this study are summarized in Table 3.1.

3.2.2 Capital Investment Cost Estimating

Reported capital investment costs consist of many individual cost elements related to solar thermal power plant construction. These costs are discussed herein under the broad categories of collector costs and balance-of-plant costs. Collector costs are installed costs for concentrators and

TABLE 3.1. Economic Ground Rules and Assumptions

Category	Ground Rules and Assumptions
Solar Industry	<ul style="list-style-type: none"> • Concepts are analyzed assuming the power system operates as part of a commercial electricity production industry. • Capital investment costs for concepts are estimated assuming sophisticated fabrication, assembly, construction, and installation techniques. • Technological and economic risk as they may affect investment decisions for solar thermal small power systems are not considered. • R&D costs, development subsidies, and all other costs associated with solar thermal industry commercialization are not included. • Cost estimates do not include the effects of investment tax credits or other incentives. • Power plant decommissioning costs are not included in estimates.
Collector Manufacturing Process	<ul style="list-style-type: none"> • Concentrator costs are estimated assuming a reference production rate of $1.2 \times 10^6 \text{ m}^2/\text{year}$ concentrator reflective aperture area. • Collector manufacturing facilities are assumed to consist of highly automated processes, thereby minimizing production labor. Manufacturing process technology is assumed to be current state-of-the-art. • Collector cost estimates include manufacturing facility indirect costs, overhead, and allowances for a required return on investment. • Allowances for sales taxes, working capital, and manufacturing facility personnel training are included. • Manufacturing facility lifetime is 15 years. • Effective state and federal income tax rate burdened on manufacturing facility profits is 0.52. • Effective other taxes burdened on manufacturing facility profits are 0.02.
Small Power Systems Plant Operation and Maintenance	<ul style="list-style-type: none"> • Unscheduled maintenance requirements are assumed to be minimal. • Concentrator cleaning is performed weekly. • Plant control schemes are highly automated, requiring little interface with plant operators. • One operator is required for plant operations, and is present whenever the plant is operating. Operators perform scheduled maintenance when not actively involved in plant operations. • Owner home office expenses are not included in cost estimates. • All required maintenance is performed using subcontracted labor. Full-time maintenance crews are not used. • Small power systems are assumed to not require security personnel.
Economic Inputs	<ul style="list-style-type: none"> • Levelized energy costs are calculated using methodologies described in Doane et al. (1976). • Power licensing, construction, and start-up periods are assumed to be 4 years. • Capital recovery factor = 0.094 • Fixed charge rate = 0.157 • Nominal capital escalation rate = 0.06 • Nominal O&M expense escalation rate = 0.07 • Nominal general inflation rate = 0.06 • Cost of capital = 0.086 • Power system lifetime = 30 years • First year of power system commercial operation = 1985 • Base year of price levels = 1978

receivers and, in general, tend to account for approximately half of the total capital investment costs. Balance-of-plant costs are composed of capital investment costs for all other plant equipment.

3.2.2.1 Collector Cost Estimating

Concentrator and receiver components, jointly referred to as collectors, are the major cost element of the total capital investment costs for all solar thermal small power systems analyzed. Due to this element's significant impact on capital investment costs, considerable effort was spent to obtain realistic collector cost estimates. Rather than simply extract collector cost estimates directly from available literature, PNL independently constructed collector manufacturing and field installation cost estimates for each concept. This approach is highly desirable because it ensures that all costs are estimated by a single estimator, resulting in identical assumptions, methodologies, ground rules, and unit costs of materials and labor for all concept evaluations. Without this uniform or "normalized" assessment of collector costs, collector cost comparisons would be uncertain at best.

Assumptions regarding collector cost estimating are listed in Table 3.1. Standardizing unit costs ensures that estimated costs for materials and labor for each concept are obtained using a consistent data base. Unit costs for conventional items and tasks were developed from construction cost estimating guidebooks, vendor quotes, equipment cost guides, and other industry cost information. In cases where component unit cost was highly dependent upon the specific applications of the component, unit costs were developed for each alternative application or location. An example of this is field-installed reinforced concrete, where the unit costs developed ranged from \$70 to \$450/yd³, depending upon the complexity of the concrete placement. Some collector elements such as tracking units have not been produced in the quantities that would be required in an established solar thermal industry; therefore, unit costs at the increased production levels are somewhat uncertain. Several methods were used to establish unit costs for these items. In instances when manufacturers were able to estimate their selling cost at different production levels, these estimated unit cost measures were used. When

these estimates were not available, they were made by comparing system components with other components of like size and configuration that do have cost information available.

The methodology developed to estimate collector costs was designed to obtain realistic collector cost estimates for each of the designs analyzed. In analyzing collector concepts, primary attention was given to major cost elements such as materials and labor cost. Less attention was given elements that contribute little to cost differences between collector concepts, such as manufacturing plant overheads, capital costs for constructing manufacturing facilities, and manufacturing facility return on investment requirements.

An overview of the major steps in the collector cost estimating methodology is shown in Figure 3.1. In general, eight steps are involved in applying the methodology. To begin the process, a reference collector design is chosen and characterized, and an overall assembly/installation scenario devised. Costs for materials and assembly, as well as the manufacturing plant capital cost, are then estimated and combined. These combined costs are then used to calculate the selling price of the manufactured collector. Field installation/construction costs are estimated, and added to the manufactured collector selling price, determining the total installed collector cost.

Costs for concentrators accounted for the majority of collector costs for all concepts, and were generally estimated in greater detail than receiver component costs. In some cases receiver design information was insufficient to allow complete application of the collector cost estimating methodology in determining receiver manufacturing costs. Receiver costs were then estimated based upon information from manufacturers, collector concept proponents, and prior solar cost studies.

3.2.2.2 Balance-of-Plant Cost Estimating

In addition to collector costs, capital investment costs were estimated for energy transport subsystems, instrumentation and control subsystems, spare parts, plant structures, energy conversion, energy storage, land, and indirect and contingency expenses. With the exception of energy storage and energy conversion subsystems, all subsystems consist of conventional components

FIGURE 3.1. Collector Cost Estimating Methodology

(i.e., components that could be bought off the shelf today) with well-established cost information. Costs for these conventional subsystems were developed using detailed subsystem descriptions.

Energy conversion and energy storage subsystems use advanced technology components. For the most part, these components are not currently being produced in large quantities. For this reason, estimated costs are sensitive to the number of components assumed to be produced each year. Costs for energy

conversion and energy storage subsystems were estimated on the basis of subsystem component production rates that would match the assumed number of solar collectors installed each year.

3.2.3 Capital Replacement Cost Estimating

Capital replacement costs are capital expenses incurred during the plant operating lifetime that result from required replacement of major capital components with lifetimes less than the plant lifetime. Examples of capital replacement components are engines or collectors. Costs for replacing minor components, such as valves, are considered maintenance costs.

Capital replacement costs were determined as a function of the component replacement cost and expected component lifetime. Component lifetimes were determined using manufacturers' data, information available from industry, and other studies. Replacement costs were determined by escalating original installed equipment cost estimates to the year of replacement price levels.

3.2.4 Operating and Maintenance Cost Estimating

Operating and maintenance costs are defined as noncapital annual expenses required for operating the power systems. These expenses consist of:

- direct operating costs
- maintenance costs
- overhead costs.

Direct operating costs are costs required for daily plant operations, such as salaries for an operating crew. Maintenance costs consist of both labor and materials expenses for scheduled and unscheduled equipment maintenance. Overhead costs include overhead burdens and administrative expenses.

3.2.4.1 Direct Operating Costs

Costs for plant operators are considered direct operating costs. The magnitude of the costs is largely independent of plant size, because operating requirements for automated plants would not vary significantly over the ranges considered as small power systems. In estimating plant operating requirements it was determined that one operator would be required during plant startup, operating, and shutdown phases. In addition to providing for safe plant operation, operators would perform scheduled maintenance as time permits.

3.2.4.2 Maintenance Costs

Scheduled maintenance consists of all maintenance activities expected to be performed at regular intervals. This includes mirror cleaning, subsystem inspection, and minor repair or replacement of items such as valves or controls. Expected frequency and manpower requirements were estimated for these activities, and used to determine yearly scheduled maintenance requirements.

Unscheduled maintenance is necessary due to unexpected component failure. Unscheduled maintenance costs were estimated assuming systems have been designed to minimize component failure, making allowances for unscheduled maintenance costs small.

Maintenance cost estimates were developed assuming maintenance is performed by subcontractors or by available labor force within the utility. A permanent maintenance staff is not employed.

3.2.4.3 Overhead Costs

Overhead costs include plant payroll burdens, administrative costs for operating and maintenance crews, and employee fringe benefits. These costs were estimated based on information for similar industries.

3.3 MODELING CONDITIONS FOR LEAST COST CONCEPTS

Ten generic solar thermal power concepts were identified and described in Section 2.0. All of the base cases and alternative configurations were analyzed using the SOLSTEP computer code to determine which systems should be employed for each concept. The configurations that demonstrated the lowest obtainable levelized energy cost are presented in Table 3.2. Included with the concept descriptions in Table 3.2 are three parameters frequently used in comparing configurations: energy conversion efficiency, annualized collector efficiency, and concentrator cost.

The energy conversion efficiency includes the engine or turbine efficiency, generator losses, pumping requirements, condenser effects, and applicable parasitic loads. Annualized collector efficiency is a SOLSTEP code output, not an input. It incorporates the optical and receiver efficiencies, including the thermal losses. The concentrator cost in $\$/\text{m}^2$ does not

TABLE 3.2. Generic Concept Configuration Parameters

Generic Concept	Thermal Cycle	Working Fluid	Storage Type	Maximum Working Fluid Temperature °F	Energy Conversion Efficiency	Annualized Collector Efficiency	Concentrator Cost \$/m ²
PFCR	Rankine	Draw Salt	Sensible heat thermocline	1000	0.31	0.55	80
	Brayton	Air	Redox battery	1500	0.40	0.49	80
PFDR	Rankine	Draw Salt	Sensible heat thermocline	850	0.29	0.63	116
	Brayton	Air	Redox battery	1500	0.32	0.59	116
	Stirling	Noble Gas	Redox battery	1500	0.35	0.59	116
FMDF	Rankine	Draw Salt	Sensible heat thermocline	850	0.29	0.41	65
LFCR	Rankine	Draw Salt	Sensible heat thermocline	850	0.29	0.38	72
LFDR-TC	Rankine	Caloria HT45 Oil	Sensible heat thermocline	580	0.28	0.42	67
LFDR-TR	Rankine	Draw Salt	Sensible heat thermocline	850	0.29	0.29	70
LCNT	Rankine	Caloria HT45 Oil	Sensible heat thermocline	450	0.23	0.40	62

include the receiver. Energy transport efficiencies have not been included because they are strongly dependent on the particular field size, and not on just the particular generic concept. Sensible heat thermocline storage systems have throughput efficiencies exceeding 99%, while the Redox battery system has an expected throughput efficiency approaching 75%. In all cases, however, these efficiency estimates are compilations of SOLSTEP inputs. The actual code inputs were detailed numbers that allowed for cost and performance information to be made a function of the applicable variable. For example, thermal losses from a thermocline storage system were made a function of not only storage size (kWe rating) and storage capacity ($\text{kW}_{\text{th}}\text{-hr}$), but also of operating history (Was the system running? How long had it been secured?). Using this level of detail allows for a more specific and therefore more accurate real-time analysis. All 10 generic solar thermal power concepts were evaluated with the same in-depth technical analysis. Thus, the results are internally consistent, allowing for an effective relative comparison.

3.4 COMPUTATIONAL PROCEDURES

Three computational procedures particularly important to the accurate analysis of the generic solar thermal plant concepts are presented in this section: concentrator optical efficiency, receiver thermal losses, and the overall plant performance simulation. Development of these procedures was a prerequisite for accurately modeling the semi-transients that affect the overall power plant performance. These transients, which include insolation, time of day, time of year, wind speed, and ambient air temperature, must be included in determining the cost of alternative concepts. The need for this level of detail was demonstrated when two of the concepts were evaluated for a point analysis (equinox, 2:00 p.m., 600 W/m^2 , $T_{\text{ambient}} = 70^\circ\text{F}$, wind speed = 10 mph) as well as for an annual simulation using SOLSTEP. Not only were the resulting absolute energy cost numbers notably different, but the two concepts' positions with respect to lowest overall cost were reversed.

3.4.1 Concentrator Optics

For every generic concept the optics must be determined for different field arrangements, ground cover ratios, tower heights, N-S and E-W mirror

separation distances, and tilt angles. The particular configuration can then be costed and simulation runs conducted until optimal performance and cost numbers are obtained. Economics and optical performance are not independent quantities; although the optical performance directly determines the system cost, the cost of individual subsystems and services will also determine the positioning, cleaning frequency, potential tracking accuracy, and, therefore, the overall optical efficiency. Because the economic and performance simulation was conducted based on data for 1976 at Barstow, California, collector optics calculations were required at that location for all expected altitude and azimuth angles.

3.4.1.1 Point Focus Central Receiver

Concentrator optical performance for the Point Focus Central Receiver was calculated with the assistance of a team at the Solar Energy Laboratory, University of Houston under the direction of Dr. Lorin Vant-Hull. Using component performance and cost data provided by PNL, concentrator optical performance for optimally configured heliostat fields and tower heights was determined. Analyses were performed for 1-, 5-, and 10-MWe plants using both cavity and open-type receivers. For comparison, the field layout and optical performance of an identical central receiver plant operating at the same power level was obtained from Sandia (Albuquerque), where it had been developed using the MIRVAL computer code (Leary and Hankins 1979).

3.4.1.2 Point Focus Distributed Receiver

Concentrator optical performance for the Point Focus Distributed Receiver systems was determined by a PNL-developed computer code SHADE (Selection of Heliostat Arrangement for Distributed Engines). The same optical efficiencies were not obtained for all Point Focus Distributed Receiver concepts. Parabolic concentrators employing small Brayton or Stirling heat engines at the focal point are interconnected by electrical wiring, while the Rankine concept, which heats the working fluid at the receiver and then transports the fluid to a central electric generating facility, uses an extensive network of piping. Because piping is more expensive than wiring, Brayton and Stirling heat engine concentrators can be located farther apart for the same cost. The farther apart the individual concentrators, the higher the optical efficiency.

3.4.1.3 Fixed Mirror Distributed Focus

Concentrator optical performance for the Fixed Mirror Distributed Focus concept was obtained from the major proponents of the Crosbyton Project (Texas Tech University and E-Systems, Inc.). Two methods were used to validate the predictions made by the major concept proponents:

- An independent assessment (Clausing 1976) of a stationary reflector with a tracking absorber was compared to the information obtained from Texas Tech University and E-Systems, Inc.
- PNL staff evaluated the optical performance models used by Texas Tech University and E-Systems, Inc.

3.4.1.4 Line Focus Central Receiver

Concentrator optical performance for the Line Focus Central Receiver concept was determined using a PNL-developed computer program. The PNL calculations for the same field size examined by FMC Corporation provided results that compared favorably with data generated by the FMC Line Focus Central Receiver Code. Only one major difference in optical efficiency was determined between the PNL and conventional line focus central receiver designs. The mirror fields were reoptimized by PNL to reduce the adverse economic impact of the end or "butterfly" sections of the fields. This led to fewer mirror rows for smaller plant sizes (10-MWe plant, 27 rows; 5-MWe plant, 26 rows; and 1-MWe plant, 20 rows).

3.4.1.5 Line Focus Distributed Receiver - Tracking Concentrator

Concentrator optical performance for the Line Focus Distributed Receiver - Tracking Concentrator concept was determined using a PNL-developed computer program. North-south, east-west, and polar axis orientations were analyzed. The N-S system provided for the most economic energy absorption within the constraints of this study. This conclusion was supported by similar analyses by Honeywell and Black and Veatch (Powell et al. 1974, p. 67). A parabolic trough design closely resembling the Hexcel Solar Collector was chosen because that collector was the most efficient yet tested at the Sandia Collector Module Test Facility, effective March 1978 (Dudley and Workhoven 1978, p. 21). Calculations by the PNL code were compared with theoretical determinations by

JPL (Caputo 1975, p. 12) and Black and Veatch (1977, p. 3.2 and 17), as well as with the experimental results obtained at the Sandia Test Facility.

3.4.1.6 Line Focus Distributed Receiver - Tracking Receiver

Concentrator optical performance for the Line Focus Distributed Receiver - Tracking Receiver concept was determined using a PNL-developed computer program. The Fixed Mirror Solar Concentrator (FMSC) design proposed by General Atomic was used for this study. PNL code calculations were compared with theoretical determinations by General Atomic (Russell et al. 1976, p. 31) and experimental performance testing at the Midtemperature Solar Systems Test Facility (Dudley and Workhoven 1978, p. 20).

3.4.1.7 Low Concentration Nontracking

Optical performance for the Low Concentration Nontracking concept was determined using a PNL-developed computer program. A 5.25x compound parabolic concentrator (CPC) similar to one proposed by Argonne National Laboratory and Arthur D. Little was evaluated as the base system (Cole, Schertz, and Teagan 1977a). Calculations by the PNL code were compared with theoretical determinations by Argonne National Laboratory and Arthur D. Little (p. 12) and, with modifications, were similar to experimental results obtained by Argonne National Laboratory for a 1.5x concentrator (Cole et al. 1977b, p. 11).

3.4.2 Receiver Performance

The thermal efficiency of the receivers used for the generic systems has a major effect on the overall system performance. Thermal losses are strongly dependent on the working fluid temperature, and only secondarily affected by power level. Therefore, for a particular system configuration, the thermal loss is more a fixed quantity than a fixed percentage. This means that thermal losses have a much larger percentage impact during early morning or late afternoon operation when total incident energy is less.

As with the concentrator subsystems, every attempt was made to use actual heat loss data or to compare PNL-determined thermal losses with other calculated or experimentally derived information. In addition, similar assumptions regarding available receiver material absorptivities, emissivities, and heat

transfer coefficients were made. If special selective absorbers were considered for some receiver designs, they were considered for all applicable designs. To better match actual operating conditions, the receiver losses (convection, radiation, and conduction) were included in the simulation code as functions of ambient temperature and wind speed. Also, because thermal losses are not linearly proportional to system operating temperature, calculated thermal loss values were determined by integrating losses along the receiver length, not by selecting some arbitrary average temperature or evaluation point.

The system concepts, working fluid, maximum working fluid temperature, PNL-calculated thermal loss at 850 W/m^2 ($T_{\text{ambient}} = 70^\circ\text{F}$, wind speed = 10 mph), and comparisons with other calculational or experimental determinations are displayed in Table 3.3. Receiver losses determined by PNL were found to be comparable to both calculated and experimentally derived thermal performance data obtained from other sources.

3.4.3 Solar Plant System Simulation

An important step in the evaluation of the generic concepts was a simulation of each plant's performance over a 1-year period using actual solar insolation and meteorological data. This evaluation required a computer code that could be used to perform a thermodynamic simulation and economic analysis of a solar thermal plant design under a wide variety of operating conditions. The code had to meet three major criteria:

- general applicability to model a diversity of solar thermal plant designs
- flexibility to allow an analysis of a design over a range of collector field and storage configurations
- low cost to provide analysis of numerous plant designs at reasonable expense.

The code developed at PNL to fulfill these needs is SOLSTEP (Simulation of Localized Solar Thermal Electric Production). It is based on the framework of computer programs used in earlier solar thermal studies. Specifically,

TABLE 3.3. Thermal Losses for System Concepts

CONCEPT	RECEIVER TYPE	WORKING FLUID	MAXIMUM WORKING FLUID TEMPERATURE	PNL THERMAL LOSS CALCULATION	COMPARABLE THERMAL LOSS DETERMINATION	EXPERIMENTAL (E) OR CALCULATED (C)	SOURCE OF COMPARISON DATA
PFCR/R	CAVITY RECEIVER	MOLTEN SALT	1000°F	0 TO 5% LOSSES	0 TO 5% LOSSES	C	CARLI AND ZOSCHAK (1978, p. 1635)
	OPEN RECEIVER	WATER/STEAM	1000°F	10 TO 15% LOSSES	10 TO 15% LOSSES	C	HALLET AND GERVAS (1977, p. 2-14)
		MOLTEN SALT	1000°F	10 TO 15% LOSSES	10 TO 15% LOSSES	C	HALLET AND GERVAS (1977, p. 2-14)
PFCR/B	CAVITY RECEIVER	AIR	1500°F	5 TO 10% LOSSES	5 TO 10% LOSSES	C	CARLI AND ZOSCHAK (1978, p. 1635)
PFDR/R	CAVITY RECEIVER	WATER/STEAM	1000°F	5 TO 10% LOSSES	5 TO 10% LOSSES	C	WU AND MEN (1978, p. 3.2)
		MOLTEN SALT	850°F	0 TO 5% LOSSES	0 TO 5% LOSSES	C	WU AND MEN (1978, p. 3.2)
PFDR/B	CAVITY RECEIVER	AIR	1500°F	5 TO 10% LOSSES	5 TO 10% LOSSES	C	WU AND MEN (1978, p. 3.2)
PFDR/S	CAVITY RECEIVER	HELIUM	1500°F	5 TO 10% LOSSES	5 TO 10% LOSSES	C	WU AND MEN (1978, p. 3.2)
FMDF	OPEN RECEIVER	WATER/STEAM	1000°F	10 TO 15% LOSSES	10 TO 15% LOSSES	C	TEXAS TECH UNIV (1977, p. IV-23)
		MOLTEN SALT	850°F	5 TO 10% LOSSES	5 TO 10% LOSSES	C	TEXAS TECH UNIV (1977, p. IV-23)
LFCR	CAVITY RECEIVER	WATER/STEAM	1000°F	10 TO 15% LOSSES	10 TO 15% LOSSES	C	FMC CORP (1978, p. 3-54)
		MOLTEN SALT	850°F	5 TO 10% LOSSES	5 TO 10% LOSSES	C	FMC CORP (1978, p. 3-54)
LFDR-TC	—	WATER/STEAM	650°F	5 TO 10% LOSSES	5 TO 10% LOSSES	E	DUDLEY AND WORKHOVEN (1978, p. 19)
		OIL	580°F	5 TO 10% LOSSES	5 TO 10% LOSSES	E	DUDLEY AND WORKHOVEN (1978, p. 19)
LFDR-TR	—	WATER/STEAM	1000°F	10 TO 15% LOSSES	10 TO 15% LOSSES	C, E	EGGERS et al. (1976, p. 25); WORKHOVEN AND DUDLEY (1978, p. 29)
		MOLTEN SALT	850°F	10 TO 15% LOSSES	10 TO 15% LOSSES	C, E	EGGERS et al. (1976, p. 25); WORKHOVEN AND DUDLEY (1978, p. 29)
LCNT	—	OIL	450°F	0 TO 5% LOSSES	0 TO 5% LOSSES	C	COLE, SCHERTZ, AND TEAGAN (1977a, p. 7)

0 TO 5% LOSSES

5 TO 10% LOSSES

10 TO 15% LOSSES

these were a set of programs developed by the Aerospace Corporation (1975) that were subsequently consolidated and modified at the California Institute of Technology's Jet Propulsion Laboratory (Caputo 1977; Fujita et al. 1977; El Gabalawi et al. 1978).

The code simulates the operation of a solar thermal plant design on a macroscopic, subsystem basis. Concentrator, receiver, energy transport, electric power generation, and energy storage subsystems are considered in simple, yet complete models. The code accounts for collector optical performance variations with respect to the time of day and time of year. Other aspects of concentrator and receiver performance can be treated as functions of component power level, ambient air temperature, and wind speed. The power generation subsystem model accounts for the effects of ambient air temperature, partial load operation, auxiliary power demands, and engine standby and startup energy requirements. Both central and distributed generation systems may be modeled using either electric or thermal energy storage systems.

In this study the plant designs were analyzed using the 1976 Barstow, California solar insolation and meteorological data compiled by the Aerospace Corporation. The code does, however, have the capability to use a large number of insolation data formats for numerous sites throughout the United States. The simulations are conducted on a time step basis, performing steady-state computations at a number of discrete time steps to attain an approximate estimate of the plant's transient performance over the total analysis period.

Following the thermodynamic simulation, an economic evaluation of each plant design is performed. The costing methodology calculates capital costs for the component subsystems and equipment replacements and determines annual operation and maintenance charges. An economic analysis following the Doane methodology (Doane, et al. 1976) then combines the lifetime plant costs and yearly plant electrical production to determine a levelized busbar energy cost.

An important requirement of the study was to determine plant performance over a range of capacity factors. To achieve this, the code actually analyzes a matrix of collector field sizes and storage capacities for each nominal plant design. The various combinations of field and storage yield an array of

plant capacity factors and levelized energy costs. Typical results for an analysis of this type are presented in Figure 3.2. The series of adjacent curves represents the results for each specified field size. Points on each curve correspond to the array of storage capacities (in terms of hours of storage) considered. Each point on the graph depicts an energy production figure, specified in terms of a plant capacity factor, and a levelized energy cost for a particular plant configuration. Note that at smaller field sizes only the smaller storage capacities are represented. This is because the economic analysis considers one field size at a time and calculates the economic performance at increasing storage capacities. When it is clear that the

FIGURE 3.2. Sample Plot of Energy Cost Versus Capacity Factor

addition of further storage capacity yields no increase in plant output and, therefore, is not cost-effective, the calculation for that field size is completed and the next field size is considered, again starting at the lowest storage capacity.

The significant portion of the plot in Figure 3.2 is the broad curve across the bottom of the matrix. This envelope represents the locus of field and storage combinations that yields the minimum levelized energy costs over the range of capacity factors. These are the plant designs in which field size and storage capacity are matched to achieve optimal performance. This curve has a number of uses: it shows how levelized energy cost varies with capacity factor for a concept; it may be used to select the least-cost field and storage combination at a specific capacity factor; or used to select the overall least-cost plant design and the corresponding capacity factor and levelized energy cost.

Because no solar thermal power plant has yet been built, it is difficult to verify the accuracy of SOLSTEP. As an approximate check, a comparison was made with the STEAEC computer program developed by researchers at Sandia Laboratories, Livermore (Woodard 1976). The STEAEC code is a more detailed, more expensive algorithm developed to analyze central receiver plant designs. For a year-long simulation of a 100-MWe central receiver plant, SOLSTEP predicted a capacity factor of 0.39, compared to a value of 0.37 calculated by STEAEC.

3.5 RANKING METHODOLOGY

Multiattribute utility methodology (MAUM) was selected to rank the ten solar thermal electric concepts. The process, shown in Figure 3.3, consists of three components: systems analysis, decision makers' values, and rankings procedure.

FIGURE 3.3. Solar Concept Ranking Process

3.5.1 Systems Analysis

Seven attributes were defined and quantitatively estimated for each least-cost concept. The attributes, units of measurement, and ranges are listed in Table 3.4. The range was defined by the highest and lowest estimates for each attribute over all the concepts.

Attribute information was used in two ways. First, the attribute ranges were used in developing a questionnaire to elicit decision makers' values. The attribute levels for each concept were then combined with decision makers' values to calculate the rankings.

3.5.2 Decision Makers' Values

A questionnaire was developed to elicit from each decision maker:

- a weight between 100 and 0 that represents the relative importance of each attribute, given its respective range - In this study, for example, such 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?"
- preference scores between 10 and 0 that represent the relative importance of changes in the level of each 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?"

TABLE 3.4. Attribute Information

Attribute	Unit of Measurement	Range
Levelized Energy Cost	Mills/kWh (1978 dollars)	75 to 275 mills/kWh
Plant Capacity Factor	% Capacity Factor	25 to 95% Capacity Factor
Plant Flexibility	Subjective Scale	5 to 9 on Flexibility Scale (A score of 10 would indicate maximum flexibility. A score of 0 would indicate flexibility similar to that at a coal-fired base load power plant.)
Outage Rate	% Forced Outage Rate	2 to 12% forced outage rate
Environmental and Safety Effects	Subjective Scale	7 to 9 on Environmental and Safety Effects 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.)
Fixed Costs as a Percentage of Levelized Energy Cost	% Fixed Cost	45 to 95% Fixed Costs
Public Investment in Research and Development Necessary for Commercialization	Subjective Scale	4 to 8 on Public Research and Development 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.)

This questionnaire design has several important aspects. First, the decision maker need not know which concepts are being analyzed. This prevents respondent bias for either solar systems in general or a particular solar concept from entering into the ranking process. In the PNL study, the decision makers were told only that "small electric power systems in the 5- to 10-MWe range" were being investigated.^(a) In addition, after the values were revealed, each decision maker was asked if his values would change if the concepts being analyzed were small solar thermal electric. No significant change in values was hypothesized.

3.5.3 Concept Rankings

The systems analysis output was combined with decision makers' values to calculate the rankings. For a given concept, this was accomplished as follows:

- From the systems analysis, seven attributes were quantitatively estimated in the units given in Table 3.4.
- For a given decision maker, the preference score associated with each attribute level was found from data gathered in the interview process.
- Each of the seven preference scores was then adjusted by the relative importance weights assigned to each attribute by the decision maker.
- The seven adjusted preference scores were then summed.
- The resulting concept score determined the rank for the given concept by the particular decision maker.
- The mean of the concept scores calculated for each decision maker determined the rank for the given concept.

(a) Questionnaire pretests indicated that the levelized energy cost estimates for the 1-MWe systems were unacceptably high to the decision makers; therefore, 1-MWe systems were not ranked.

4.0 RESULTS

Following a discussion of each attribute and the value(s) of that attribute for each of the 10 least-cost concepts, a comparative ranking of the concepts is presented. This comparative assessment includes both a three-attribute and seven-attribute ranking. Summary comments and conclusions are given after the final concept ranking results.

4.1 ATTRIBUTES

Each of the least-cost concepts was evaluated on the basis of seven attributes: levelized energy cost (LEC), plant capacity factor (CF), fixed costs as a percentage of levelized energy cost (FIX), plant flexibility (FLEX), forced outage rate (FO), environmental and safety effects (ENV), and public investment in research and development necessary for commercialization (R&D). The first three attributes were calculated using the SOLSTEP code, and are based on detailed analysis and extensive calculations. The other four are based on much more speculative data and, therefore, within the context of this study, it is only possible to establish a set of relative values for those attributes.

4.1.1 Levelized Energy Cost and Plant Capacity Factor

Interpolative routines in SOLSTEP, as described in Section 3.4.3, allow levelized energy costs to be determined for three variables of interest:

- capacity factor - Energy costs can be determined at any capacity factor, but are normally presented for values of 0.1 to 0.9.
- zero storage - Figure 4.1 shows that the locus of zero storage points has a minimum that normally occurs between capacity factors of 0.2 and 0.3. The higher the concept's efficiency, the higher the concept's capacity factor for its lowest cost no-storage point. This is important when comparing concepts on a no-storage basis. Concept A may have a less expensive no-storage LEC than Concept B because A's efficiency has allowed optimization at a higher capacity

FIGURE 4.1. Sample Plot - Locus of Zero Storage Points

factor. However, if Concepts A and B are considered over the entire range of capacity factors, Concept B may always be less expensive.

- minimum levelized energy cost - The lowest LEC occurs at different capacity factors, strongly dependent upon whether the concepts use central or distributed power generating subsystems and what method of energy storage is employed. SOLSTEP will determine the absolute minimum LEC, the exact capacity factor, and what combination of field and storage size has produced that capacity factor. When

comparing concepts on the basis of lowest levelized energy cost, it is always extremely important to remember that the minima may occur at significantly different capacity factors.

The values of levelized energy cost for the 5-MWe plants are shown numerically in Table 4.1 and, for relative comparison, on bar charts in Figure 4.2. Capacity factors below the no-storage case are not included because, in all cases, the levelized energy costs are much higher than those for the no-storage cases.

The nature of storage costs has a dominating effect on how levelized energy cost varies with capacity factor. Storage costs are composed of both a fixed and variable cost. The fixed cost (\$/kWe) includes the storage equipment, materials, and plant interfaces that depend on the rated electrical capacity, irrespective of the length of time the power will be required. The added storage components and elements dependent on the length of time the rated power will be needed form the variable cost (\$/kWe-hr). Because electric storage systems have a higher variable cost than thermal systems, the PFCR/B, PFDR/B, and PFDR/S tend to have their lowest levelized energy costs at lower capacity factors (usually at the no-storage point). One reason for the higher variable costs for electric storage subsystems is that, unlike thermal storage concepts, additional storage capacity requires additional energy conversion equipment. The other seven concepts tend to have their lowest LECs at higher capacity factors.

Fixed and variable storage costs also help explain the marked jump in LEC between the no-storage and 0.3 capacity factor cases for those concepts using electric storage. Because the fixed charge must be included no matter how little storage is added, a dramatic increase in LEC takes place although only a very small change in capacity factor is achieved. Because the fixed, as well as variable, charge for thermal storage is less than that for electric storage, a smaller displacement is observed between the no-storage and 0.3 capacity factor case for the seven generic concepts using thermal storage.

Results for levelized cost and capacity factor have been shown for the 5-MWe least-cost cases. The ten generic concepts were also analyzed at 1 and

TABLE 4.1. 5-MWe Least-Cost Generic Concepts - Levelized Energy Costs (mills/kWh)

Concept	No-Storage (CF)	Capacity Factor (CF)							Lowest Cost (CF)
		0.3	0.4	0.5	0.6	0.7	0.8	0.9	
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)
LFCR	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)

10 MWe to determine the sensitivity of cost to power rating. The analysis indicated that, while there is a small effect of power plant size between 5 and 10 MWe, the change between 1 and 5 MWe is dramatic. Figure 4.3 shows the relative change in levelized energy cost found when decreasing plant size from 10 to 1 MWe. Concepts using central station receivers (PFCR/R, PFCR/B, LFCR) are subject to significant scaling problems because of fixed costs for towers, increased optical losses for smaller field sizes, and the need for smaller mirrors or more accurate mirror focusing and tracking. Those concepts have higher relative increases in energy cost than do the other distributed collector concepts when plant size is decreased from 5 MWe to 1 MWe.

A large portion of this marked increase in levelized energy cost in going from the baseline 5-MWe case to the 1-MWe plant size is due to operation and maintenance expenses. It is clear that a 1-MWe plant must be highly automated

NOTE: CAPACITY FACTOR (cf) DOES NOT INCLUDE FORCED OUTAGES

FIGURE 4.2. Comparison of Concepts on Basis of Levelized Energy Cost in Mills/kWh (1978 \$)

FIGURE 4.3. Relative Effect of Varying Plant Size on Lowest Levelized Energy Cost

to effectively achieve reasonable energy costs. In addition to operation and maintenance expenses, so many fixed costs are associated with certain plants that 1-MWe power levels may not be practical with current configurations. New approaches to the design and operation of small solar thermal power plants will be required to reduce the costs of 1-MWe plants relative to larger plant sizes.

4.1.2 Fixed Costs as a Percentage of Levelized Energy Cost

The FIX attribute is determined by SOLSTEP as that fraction of the total levelized energy cost that is due to the initial capital investment, shown in Figure 4.4. Capital replacement and operation and maintenance costs represent those contributions that reduce the fraction, and are shown in Figures 4.5 and 4.6. A low fixed cost percentage would mean a reduced initial investment and increased subsequent charges during the life of the plant. Table 4.2 shows

FIGURE 4.4. Initial Capital Investment Costs (1978 \$)

the percentage fixed costs of the ten least-cost concepts at 5 MWe for the no-storage, 0.4 capacity factor, 0.7 capacity factor, and least-cost cases.

4.1.3 Plant Flexibility

Plant flexibility (FLEX) is the first of four attributes determined by a qualitative evaluation. Its major components include:

- co-generation potential
- flexibility of applications, including capacity factor and load following characteristics, as well as suitability for remote operations

FIGURE 4.5. Replacement Capital Costs (1978 \$)

FIGURE 4.6. Operating and Maintenance Costs (1978 \$)

TABLE 4.2. 5-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
FMDF	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

- site flexibility, including water, land, transportation, and maintenance requirements
- construction flexibility, including the time and infrastructure required during construction.

The FLEX attribute values given for the 5-MWe least-cost concepts in Table 4.3 are based on a relative scale. In theory, a score of 10 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.

4.1.4 Forced Outage Rate

The second of four attributes determined by a qualitative evaluation is forced outage rate (FO). The values shown in Table 4.4 are estimates based on an annualized average and do not include scheduled maintenance.

TABLE 4.3. 5-MWe Least-Cost Generic Concepts - Plant Flexibility

<u>Concept</u>	<u>Plant Flexibility Values</u>
PFCR/R	7.5
PFCR/B	9.0
PFDR/R	7.7
PFDR/B	8.9
PFDR/S	8.9
F MDF	5.4
LF CR	5.4
LF DR-TC	6.4
LF DR-TR	5.0
LCNT	8.5

TABLE 4.4. 5-MWe Least-Cost Generic Concepts - Forced Outage Rate

<u>Concept</u>	<u>Forced Outage Rate (%) Values</u>
PFCR/R	9.0
PFCR/B	12.0
PFDR/R	7.2
PFDR/B	2.3
PFDR/S	2.3
F MDF	7.3
LF CR	11.7
LF DR-TC	5.7
LF DR-TR	7.5
LCNT	6.0

4.1.5 Environmental and Safety Effects

Environmental and safety effects (ENV) is the third of four attributes determined by a qualitative evaluation. Its major components include:

- material acquisition and construction, including material and land requirements and effluents
- power generation, including chemical hazards and other byproducts of generation
- waste disposal, including decommissioning and maintenance byproducts.

The ENV attribute values given for the 5-MWe least-cost concepts in Table 4.5 are based on a relative scale. In theory, a score of 10 would indicate minimum environmental and safety effects on all the above listed components. A score of 0 would indicate environmental and safety effects similar to those of an oil-fired steam plant using low sulfur oil.

TABLE 4.5. 5-MWe Least-Cost Generic Concepts -
Environmental and Safety Effects

<u>Concept</u>	<u>Environmental and Safety Effects Values</u>
PFCR/R	8.0
PFCR/B	7.6
PFDR/R	7.3
PFDR/B	8.6
PFDR/S	8.0
FMDf	7.3
LFCR	7.4
LFDR-TC	8.2
LFDR-TR	7.2
LCNT	8.0

4.1.6 Public Investment in Research and Development Necessary for Commercialization

The public investment in research and development necessary for commercialization (R&D) represents the last of four attributes determined by a qualitative evaluation. Its major components include:

- manufacturing factors, including ease of mass production; "learning" capability; availability of specialized materials; and alternative uses of components
- technological factors, including technical breakthrough required; standard component utilization; and possibility of design optimization.

The R&D attribute values given for the 5-MWe least-cost concepts in Table 4.6 are based on a relative scale. In theory, a score of 10 would indicate the public investment in research and development necessary to commercialize geothermal energy on all of the above listed components. A score of 0 on the public research and development scale would indicate the public investment necessary to commercialize fusion energy.

TABLE 4.6. 5-MWe Least-Cost Generic Concepts - Public Investment in Research and Development Necessary for Commercialization

<u>Concept</u>	<u>Research & Development Values</u>
PFCR/R	5.6
PFCR/B	4.7
PFDR/R	6.1
PFDR/B	4.7
PFDR/S	4.0
FMDF	7.1
LFCR	6.1
LFDR-TC	7.3
LFDR-TR	5.4
LCNT	7.5

4.2 COMPARATIVE RANKING OF CONCEPTS

The results from implementing the ranking methodology are presented and interpreted in this section. The results from analyzing decision maker preferences for the seven attributes are discussed first, followed by the concept ranking results.

4.2.1 Decision Maker Preferences

PNL researchers interviewed 37 decision makers from the utility industry. The sample consisted of upper-level management from the Electric Power Research Institute, the Edison Electric Institute, the American Public Power Association, and nine separate utilities located in the far West, Southwest, and Southeast. In addition, 15 U.S. Department of Energy managers were interviewed representing divisions of Resource Applications, Policy and Evaluation, Energy Research, and the Bonneville Power Administration. The two different groups were sampled to test the hypothesis that the utility and DOE samples were not significantly different in preferences. No differences in preferences would indicate no differences in concept rankings using preference data from either group.

Each decision maker first assigned an importance weight between 100 and 0 to each attribute. This weight represented the importance to the decision maker of each attribute and its range relative to all other attributes and their ranges. The means of the importance weights for the 37 utility subjects and the 15 DOE subjects are shown in Table 4.7.

The dotted lines in Table 4.7 show where there are statistically significant differences 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.

The data in Table 4.7 show that the utility and DOE subjects were not different in the importance they placed on levelized energy cost and capacity factor. Further, the importance placed on each of these attributes was

TABLE 4.7. Attribute Importance Weight Means

Attribute	Importance Weight Means ^(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 importance weight means.

significantly different from all other attributes. Thus, for both the utilities and DOE, levelized energy cost and capacity factor are clearly the most important attributes.

Significant differences were found 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). U.S. Department of Energy representatives assigned significantly lower importance weights to ENV than did the utility industry because the range of impacts was narrow and rather benign. The utility industry representatives stated they know, through experience, that regardless of the level of environmental impacts, major costs can arise from the environmental impact statement and hearing process. Fixed

costs were significantly more important to the utility sample than to the DOE sample. Finally, R&D was clearly the least important attribute to the utility sample and, as expected, significantly more important to the DOE than to the utility sample.

The utility and DOE subjects were also asked questions that revealed the relative importance of changes in the level of each attribute, holding the level of all other attributes constant. An analysis of these data showed there were significant similarities between the utility and DOE samples. What differences existed were, for the most part, related to the differences in importance weights assigned by the two groups.

The major conclusion from analyzing decision maker preferences was that the overall relative importance the utility sample placed on the seven attributes was not significantly different from the overall relative importance expressed by the DOE sample. Thus, there would be no major differences in concept rankings using preference data from each group.

4.2.2 Concept Rankings

The decision maker preference data were combined with output from the systems analysis to yield the concept rankings. As hypothesized, there were no statistically significant differences in concept rankings between the DOE and utility samples. Therefore, only the rankings for the utility sample are presented.

For each concept, only three attributes had variable levels. These were LEC, CF, and FIX. Attributes FLEX, FO, ENV, and R&D were invariant with respect to the concept. For example, for any given concept there may be 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, initial indications from utility representatives suggested that LEC and CF were considerably more important than the other attributes. Second, limited data were available for estimating the level of FLEX, FO, ENV, and R&D. Therefore, two sets of rankings were calculated. One set considered only LEC, CF, and FIX; the other set considered all seven attributes.

Both sets of rankings are presented because some differences exist, suggesting that the combined effect of FLEX, FO, ENV, and R&D is important. Because the ranking methodology was designed around seven attributes, this is the appropriate set for decision making. However, the level of technical information differs significantly between LEC, CF, FIX, and the four other attributes.

4.2.2.1 Rankings Using Attributes LEC, CF, FIX

Figure 4.7 shows the rankings at a capacity factor of 0.4 and at the optimal capacity factor (that which produced the highest score for each concept). The solid horizontal lines represent statistically significant differences between the concepts above and below the line. Concepts falling within the cross-hatched areas were not significantly different from adjacent concepts. 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. Also, the rankings 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.

4.2.2.2 Rankings Using Seven Attributes

As with the three-attribute case, the general trend of higher rankings with higher capacity factors was present. This trend is indicated on Figure 4.8. 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 systems relative to the central receivers. The Point Focus Central Receiver Brayton system was ranked lower than with the three-attribute case because of relatively high R&D costs. The line focus and

FIGURE 4.7. Rankings by Concept Score of 5-MWe Concepts--
Three-Attribute Case (LEC, CF, FIX)

FIGURE 4.8. Rankings by Concept Score of 5-MWe Concepts-- Seven-Attribute Case

nontracking concepts showed significant improvement relative to the three-attribute case. This is due to the relatively low R&D costs associated with these two concepts.

4.3 COMMENTS AND CONCLUSIONS

Several conclusions from this study are highlighted in this subsection. They relate primarily to the ranking results. In the process of formulating concepts, developing their costs, determining levelized energy costs, and performing sensitivity studies, many comparative characteristics of small power systems were noted by the PNL study team. Comments on the more important observations are included here.

4.3.1 Comments

Supporting details for the following comments are included in the other volumes of this report.

- Distributed generation concepts (PFDR/S,B) scale down to 1 MWe with less economic penalty than central generation concepts. All concepts, however, experienced a significant increase in operating cost at 1 MWe. Shared operating personnel and/or more automation should be considered by designers of small plants.
- For the production rates analyzed, the free piston Stirling engine has cost and lifetime advantages over the kinematic engine that more than compensate for a small performance reduction.
- Central receiver concepts in the 1- to 10-MWe range should use cavity receivers.
- If a capacity factor greater than 0.5 is desired, the thermal storage and energy conversion subsystems should be designed to allow rated plant operation from storage.
- Concepts that have extensive piping networks, and use molten salt for a transport fluid, have lowest energy cost if operated at a temperature low enough to allow the use of carbon steel piping.

- Providing a thermal buffer storage for distributed generation concepts appears prohibitively expensive. Alternative methods of controlling short transients should be considered.
- Sensible heat storage subsystems have much greater throughput efficiencies than do electric storage systems. Further, because of generally lower variable costs, the thermal storage provides for a reduction in LEC with capacity factor. Except for very small plants, concepts employing electric storage have the lowest LEC at no storage.

4.3.2 Conclusions

- When only the three more traditionally compared attributes of levelized energy cost, capacity factor, and fixed costs were considered, concepts using central receiver subsystems ranked above those with distributed receivers; concepts with thermal storage ranked above those with electric storage at higher capacity factors (>0.4); and two-axis tracking concepts ranked above one-axis tracking concepts which, in turn, ranked above the nontracking concept.
- When all seven attributes were used for ranking, the central receiver concepts dropped to a significantly lower group, primarily because of higher forced outage rate. In addition, the central receiver Brayton concept was penalized for higher R&D costs. Distributed line focus and nontracking concepts moved up in ranking, particularly at high capacity factors, due primarily to relatively low R&D costs.
- Utility decision makers indicate that plant flexibility, forced outage rate, environmental and safety effects, and R&D requirements affect the commercialization potential of solar concepts. Therefore, research, development, and demonstration programs should include provisions for establishing these plant characteristics.

- The Point Focus Central Receiver with Rankine power conversion and the Point Focus Distributed Receiver with Brayton or Stirling power conversion consistently ranked high.
- The Line Focus Distributed Receiver with a tracking receiver and the Line Focus Central Receiver consistently ranked low.

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