Solar Technology Assessment Project

State of the art

VOLUME IX

Heliostat Systems: Technical and Economic Assessment

A.F. Hildebrandt and C.L. Laurence,
Energy Laboratory,
University of Houston,
Houston, Texas

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Florida Solar Energy Center
300 State Road 401
Cape Canaveral, Florida

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David L. Block, Director
Florida Solar Energy Center

NOTICE

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PREFACE

The purpose of the Solar Technology Assessment Project is to present an assessment of the state of solar energy technology for individuals involved in energy research, industry, legislation and policy, and to others interested in a better understanding of the nation's energy future.

This project was organized and coordinated by the Florida Solar Energy Center under sponsorship of the Office of Policy, Planning and Evaluation; Office of Conservation and Renewable Energy; U.S. Department of Energy; Cooperative Agreement DE-FC02-79CS30278-A001.

For this project, nine solar technologies--four solar thermal, four solar electric, and one other--were evaluated as follows:

- Passive Heating
- Active Space Heating and Hot Water
- Cooling: Passive, Hybrid and Active
- Industrial Process Heat
- Photovoltaics
- Ocean Thermal Energy Conversion (OTEC)
- Wind Energy
- Heliostat Systems
- Biomass

Finally, to complete the picture, two other assessments were done, one on the current status and prospects of the solar industry and the other on state and community solar commercialization issues.

The Solar Technology Assessment Project selected 11 recognized solar experts, each to assess and write a paper on the particular solar technology or area of his expertise. Summaries of the assessment papers by the group were presented at the Solar Technology Assessment Conference in Orlando, Florida, on January 29 and 30, 1981.

After the January conference, each of the authors wrote a final assessment paper. These papers are presented as 12 volumes, one for each assessment area and one overall review by the project director. The authors are listed on the next page.

As a final comment, it is hoped that these assessments will provide the information and possibly supply the guidance that is needed by the decision makers in order to bring the utilization of solar energy to the level where its positive impact will be felt by all.

David L. Block
Project Director
Solar Technology Assessment Project
and
Director
Florida Solar Energy Center

SOLAR TECHNOLOGY ASSESSMENT PROJECT

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VOLUME IX

HELIOSTAT SYSTEMS: TECHNICAL AND ECONOMIC ASSEMENT

by
Alvin F. Hildebrandt & Clifford L. Laurence
Energy Laboratory
University of Houston
Houston, Texas

Dr. Hildebrandt has since 1975 been professor of physics and director of the University of Houston's Energy Laboratory. From 1975 to 1980, he was president of the Energy Foundation of Texas. Among Dr. Hildebrandt's more recent publications are two articles on power towers written in partnership with a colleague--they are, "Power From Solar: The Power Tower Concept," which appeared in the Houston Engineer, and "Survey of Power Tower Technology," carried in the Journal of Solar Energy Engineering. Dr. Hildebrandt also holds three patents on superconducting magnetic flux pumps and one for production of ultra pure HE^4 by superfluid flow. He earned the B.S. in physics at the University of Houston, and a doctorate in physics at Texas A & M University.

Dr. Laurence has, since joining the Energy Laboratory at the University of Houston, participated in a number of central receiver design studies including the JPL, MDAC Small Power System Experiment (a portion of which work was recently published in the ASME Journal of Solar Energy Engineering), the collector field optimization of the 10 MW Pilot Plant, and four of the repowering studies. He recently published, in partnership with Dr. Fred Lipps, a Users Manual for the University of Houston collector field optimization and design computer code. Dr. Laurence developed strong interest in solar technology during the five years he spent with Aerospace Corporation, where he did a comparative performance analysis of the Phase I central receiver design studies. He received a B.S. in physics from MIT and his doctorate in electrical engineering from Rice University.

HELIOSTAT SYSTEMS: TECHNICAL AND ECONOMIC ASSESSMENT

A.F. Hildebrandt and C. L. Laurence

Energy Laboratory

University of Houston

1.0 INTRODUCTION

1.1 Purpose of Study

This is a technical and economic readiness assessment of heliostat systems for industrial process heat and electric power production. Included will be published data from university, government and industry studies with a new small system study by the University of Houston and the Rockwell International, Energy Systems Group.

This report provides an extensive review of the literature on heliostat systems including subsystem design and research experiments, full scale system designs, assessments, evaluations, rankings, application and marketing studies, and heliostat manufacturing studies. This report reviews and assesses the current status of heliostat system development, examines recent design reports, reports expected economic and performance improvements, makes recommendations for the role that government can play in heliostat systems development, and recommends state and federal policies for development of solar commercialization and the formation of heating utilities.

The introduction of any new energy source generally faces opposition from in-place energy suppliers. On the other hand, there is a prevailing public belief that solar can and will supply a significant portion of our long term energy needs. An important task in this paper is delineating what is practical now and for the long term. Some consideration is also given to general philosophical implications of our energy dilemma. Limited solutions are available for an ever growing population in a finite resource and space limited earth. Each birth above replacement tends to make us all a bit poorer. Our real goal should be a better world civilization for our grandchildren and generations beyond. We now consider the technical and economic aspects of solar thermal systems that offer a renewable energy option. These systems can stabilize our predictable energy needs and long-range requirements.

1.2 Description of heliostat systems

Many of us are acquainted with the ability of a small lens magnifier to focus the sun's image onto and burn a leaf. This can also be accomplished with a concave parabolic shaving mirror. It is possible to collect solar energy from a large area with a large number of parabolic mirrors focusing the energy to a multitude of small focal regions. The heat can then be collected from the large number of parabolas, shaped like and often called dishes, by means of a labyrinth of piping collecting a heat transfer fluid to a common point. This is called a distributed system.

A heliostat system approximates a single huge parabola laid out on a flat area of terrain with a single focal point. A heliostat is shown figure 1.1. It is a simple large nominally flat mirror that may have a number of segments. It tracks on two axes and is computer controlled. Tracking enables the individual heliostat to reflect and project a beam of light continuously onto a distant boiler. In figure 1.2 is a drawing of the Solar One pilot plant under construction at Barstow, California. The surrounding field of heliostats focuses the sun's rays onto the boiler atop the tower near the center of the field, consequently the name central receiver. Water is pumped up to the boiler and the resulting steam is piped down to a conventional utility turbo-electric generator at the base of the tower. This configuration approximates a point focus parabola with an aperture area of about .33 km^2 (85 acres) and a focal distance to the boiler of about 75.4 meters. The generating capacity is 10,000 kilowatts of electricity which can supply a city of 6,000-10,000 people. A brief history of the concept can be reviewed in references 1-3.

The field of heliostats steer the solar beam energy onto the boiler and permit a single collection point. This can be contrasted to a parabolic dish with focal axis always pointing toward the sun. Although the geometric mirror collection efficiency of a heliostat field is slightly less than that of an array of parabolic apertures, the power tower field exhibits superior performance through optical collection of a large amount of energy to a common point. These systems always perform better optically than a fixed flat plate. The projection of the sun's beams onto a flat plate obeys a cosine law and in summer the sun can set behind the flat plate. Also, the flux density at the surface of the earth is inadequate to produce high quality steam directly. In contrast the sun never sets behind a heliostat since its surface normal bisects the angle between the sun and the central receiver. The performance of a central receiver heliostat system can have an annual average cosine of 85 percent that of a parabola aperture with normal incidence. However, because parabolas have mirror surface areas in excess of aperture area due to

FIGURE 1.1 McDonnell Douglas Advanced Design Heliostat

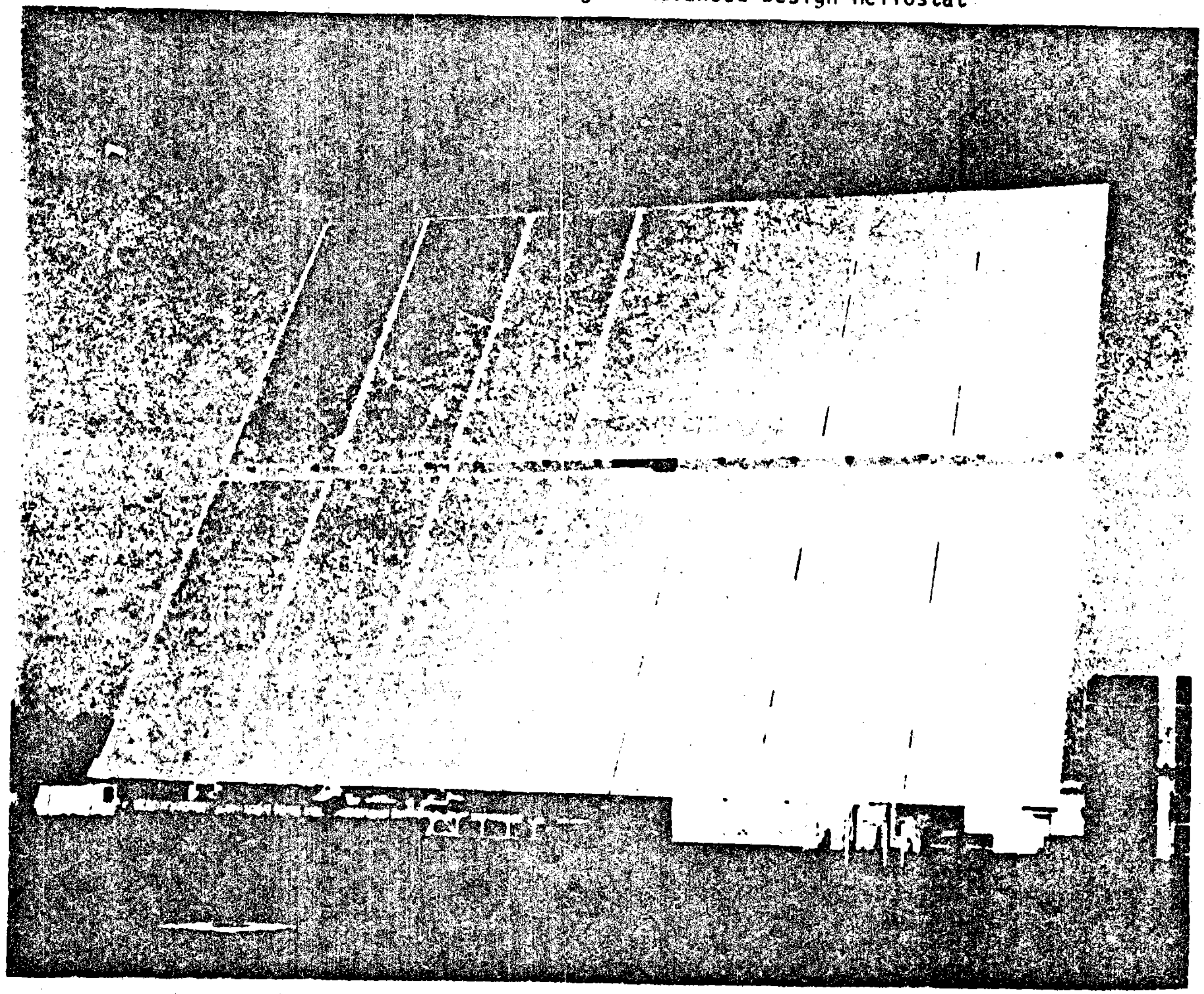
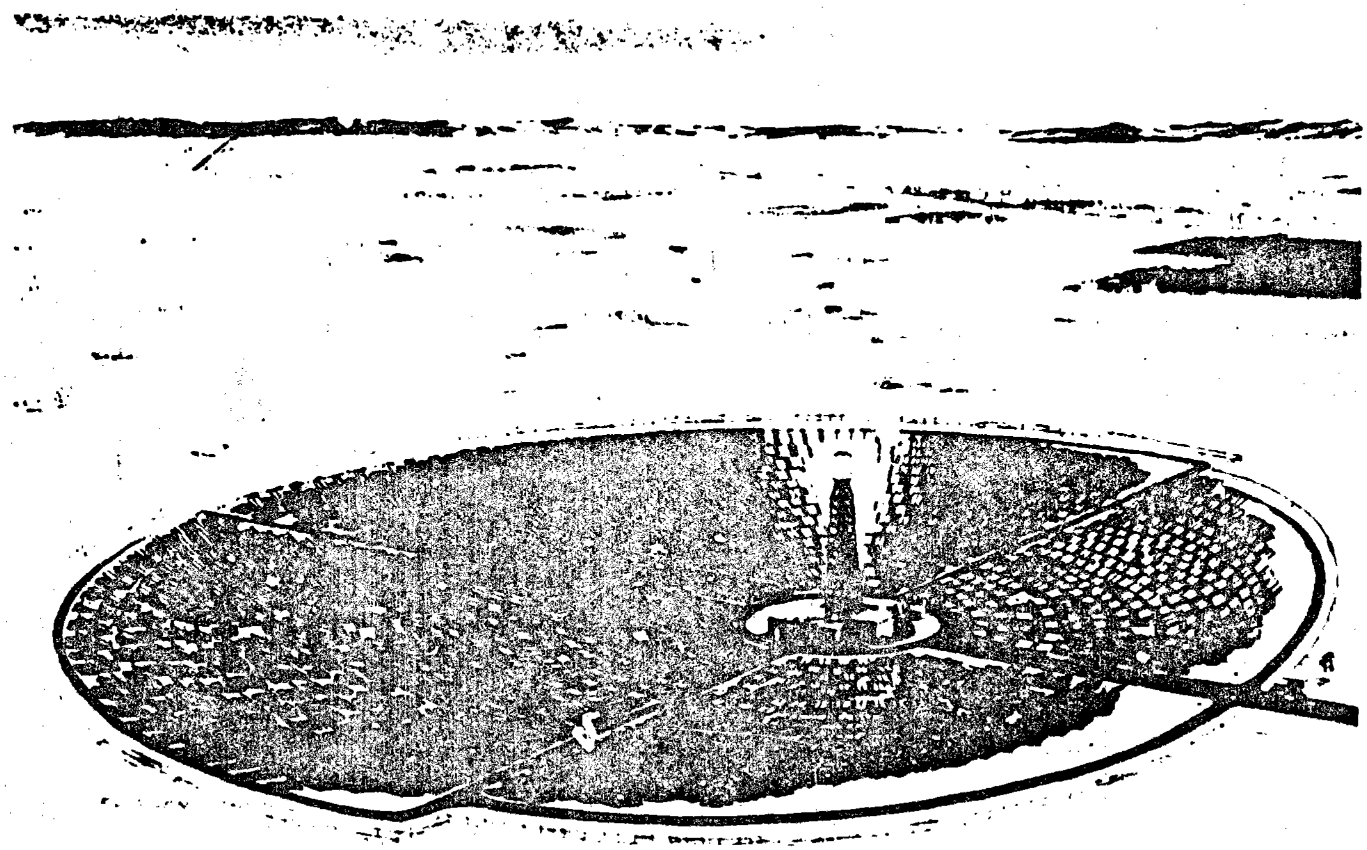


FIGURE 1.2



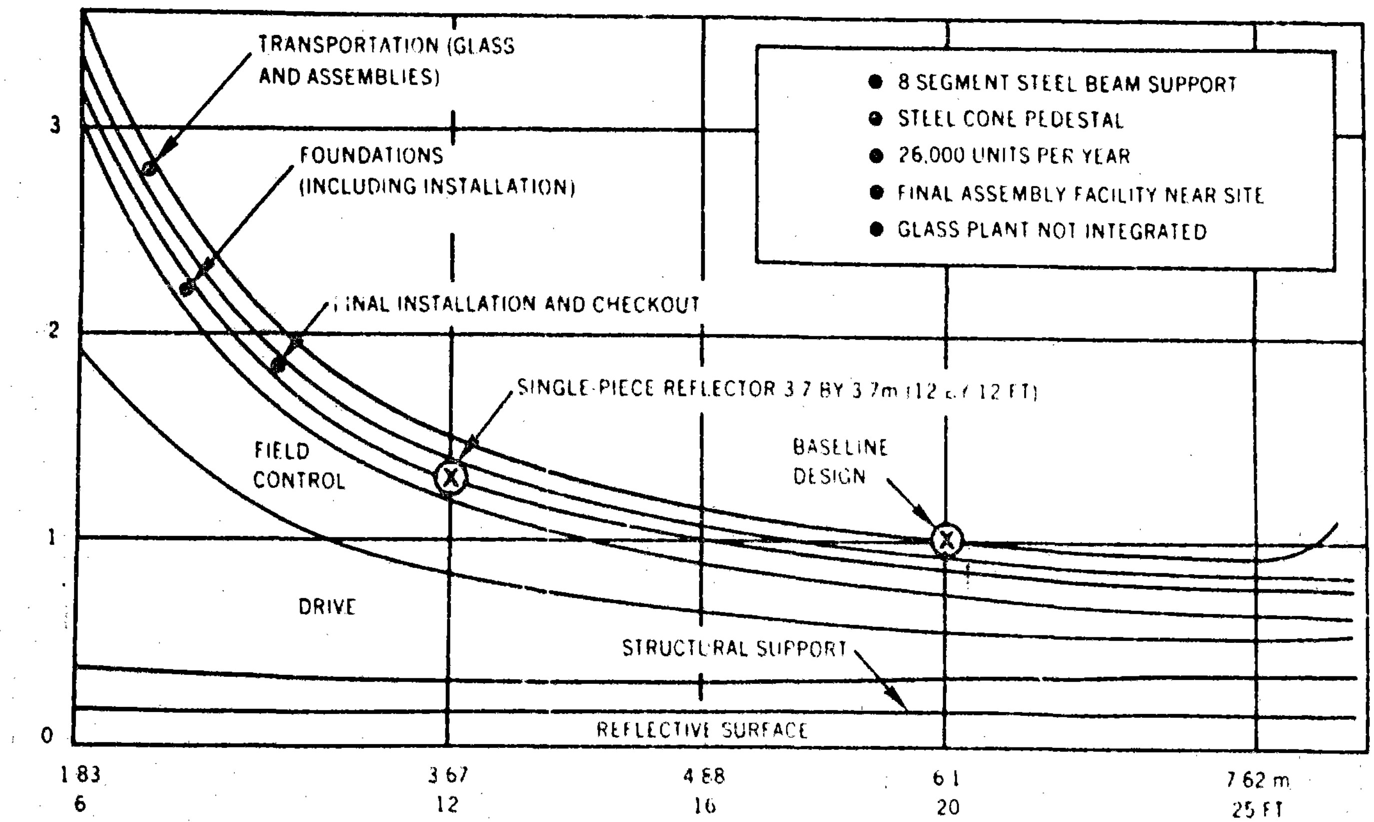
SOLAR POWER PLANT DESIGN CONCEPT

MCDONNELL DOUGLAS

SOUTHERN CALIFORNIA EDISON FACILITY, BARSTOW, CALIFORNIA surface curvature, in general they will cost more than heliostats.

The major advantages of heliostat systems over other systems lie (1) in the ability to transport the energy optically at low loss to a common point, with high concentration and (2) the ability to mass produce large essentially flat identical mirrors more economically than curved surface mirrors. Much of the hardware for heliostats or parabolas has common features, so improvements in one will be reflected in the other. There is, however, a scaling law in heliostat systems that is often poorly understood and involves the required concentration factor and resulting size of plant. First, flat optical surfaces can be mass produced cheaply with a broad minimum in the cost versus size. This cost latitude arises because every unit has a handling cost, number of parts cost, installation and gravity load factor to be considered. For a system to be operable the aiming distortion due to either wind or gravity loading must be small and, in fact, these two effects should be comparable in the limiting case. Nominal design of heliostats is for operation in winds of 12 m/s(27 mi/h) and survival in stow for 40 m/s(90 mi/h) winds. These factors, coupled with weight and strength of materials used, have generally dictated the larger size heliostats. Figure 1.3 shows relative cost versus dimension for the McDonnell Douglas type heliostat(4). A similar figure in reference 2 involves more recent data. In general, this will, dictate a scale factor. As an example, if you consider a flat 6 m wide heliostat and a field diameter of four tower heights coupled with a receiver size of just twice the minimum size to accept the solar subtense angle of 9.3 milliradians from the farthest heliostat, a tower height of about 270 meters is required. This in turn would dictate a minimum size plant of about 300 MW electric. This scaling may result in a power density at the receiver higher than that manageable with steam alone but it gives the basis of scaling requirements. The scaling law can be broken by a reduction in concentration ratio and reduction of operating temperature for smaller systems or by partial focusing of the individual heliostats, maintaining the concentration ratio and operating temperature. Focusing can be accomplished by curving or canting the segments of the heliostats. While this will reduce the image at the boiler nearer to that theoretically possible, it will create added heliostat costs due to manufacturing modifications of the heliostats and aberrations. Since the heliostat normal bisects the angle between the sun and the receiver, the focusing results in off axis aberrations in the morning and afternoon. These factors, along with flux density considerations at the receiver, led to development of the 10 MWe Solar One pilot plant as a design of maximum interest to utilities and representative of problems to be encountered in a later full scale 100 MWe plant. Design of efficient thermal systems as small as 250 kilowatts will be discussed later as well as larger systems. Again, it should be noted that a heliostat system approximates a single parabola; the smaller the power level, the lower the required operating temperature for efficient collection of optical energy and conversion to thermal energy. Stated simply,

FIGURE 1.3 Heliostat Diameter Versus Relative Cost



MDAC

eleven large flat heliostat images can be overlaid to give a usuable power density for certain low operating temperature requirements.

The highest operating temperature requires a larger number of heliostats, higher concentation ratios, and higher precision surfaces and aiming tolerances. High temperature systems can be used in electric power production with steam Rankine cycles as well as open Brayton gas cycles, Stirling cycles, and advanced concepts. Higher temperature systems are suited for supplying energy to chemical reactors for production of chemicals and fuels. Some chemical reactions are well suited for energy transmission by heating utilities. These and other potential applications of solar towers will be discussed after a more complete technical assessment.

Consider the relative thermal performance of various collectors versus temperature, i.e., flat plate, linear trough and point focus including central receiver.

The Stefan-Boltzmann Law of Radiation

$$P = \epsilon \sigma T^4$$

tells us that as the absolute temperatue of the receiver (in degrees Kelvin) is raised, it will reradiate to the surroundings. The emissivity ϵ can vary between zero and one, and the Stefan-Boltzmann constant is equal to 5.67×10^{-8} W/m^2K^4. For 1 kW/m^2 incident on a totally absorbing plate with $\epsilon = 1$ the radiation equilibrium temperature (all power reradiated with no useful power) is 365°K, or 91.6°C. Above this temperature of 365°K no net energy can be collected. The emmissivity can be reduced by covering the flat plate with a glass cover plate and introducing the greenhouse effect. For a linear trough, the sun's image is linear with a concentration typically of 30 being practical. A perfectly formed parabola could result in a geometric concentration of the sun of approximately 75,000; however, typical values for mass produced competitive parabolas are about 1500-2500. The limitation to the concentration ratio is due to finite solar image size. Astronomical telescopes have a wave length limit, whereas for solar energy collection a much lower concentration of about 2,000 or less is actually dictated because of fluid heat transfer limitations. A concentration of 1500 to 2000 is readily attained by a heliostat field of 20,000, which is roughly that required for a 100 MWe plant.

Parabolic dishes can produce very high temperatures and can effectively produce small amounts of on-site electricity in remote areas and be competitive today with photovoltaic systems and with oil and gas. Industrial process heat applications of flat plate, linear systems and dishes will be considered separately in another portion of this solar technology assessment project. Because of the uniqueness of heliostat systems to supply primary thermal energy, the industrial process heat application of heliostat systems will be considered further in this report.

To realize the best first penetration of central receiver technology, we need to discuss several of the pertinent technical parameters that will determine the economics. These will be the factors directly influencing the cost per kilowatt hour. One factor is location. It is an advantage to place concentrators in the highest direct beam areas of the Southwest. Figure 1.4 shows direct beam radiation contours for the U.S. This indicates that first choice areas are in the Southwest. However, it should be noted that relief from foreign oil imports in the Southwest can have a strong effect on the Northeast.

Towers have three major immediate areas of potential impact. These are as follows:

(1) Repowering of electric utilities in the Southwest. This consists of adding a heliostat system to an existing generating station to supply the heat for steam generation. There are 6-10 gigawatts of existing capacity that can benefit from this technology,

(2) Industrial retrofit, i.e., the addition of solar tower systems to supply industrial process heat to existing industrial plants. Examples are gypsum drying, enhanced oil recovery, and ammonia fertilizer production,

(3) The construction of new solar stand-alone or solar-fossil hybrids for the Southwest where there are requirements for additional generating capacity.

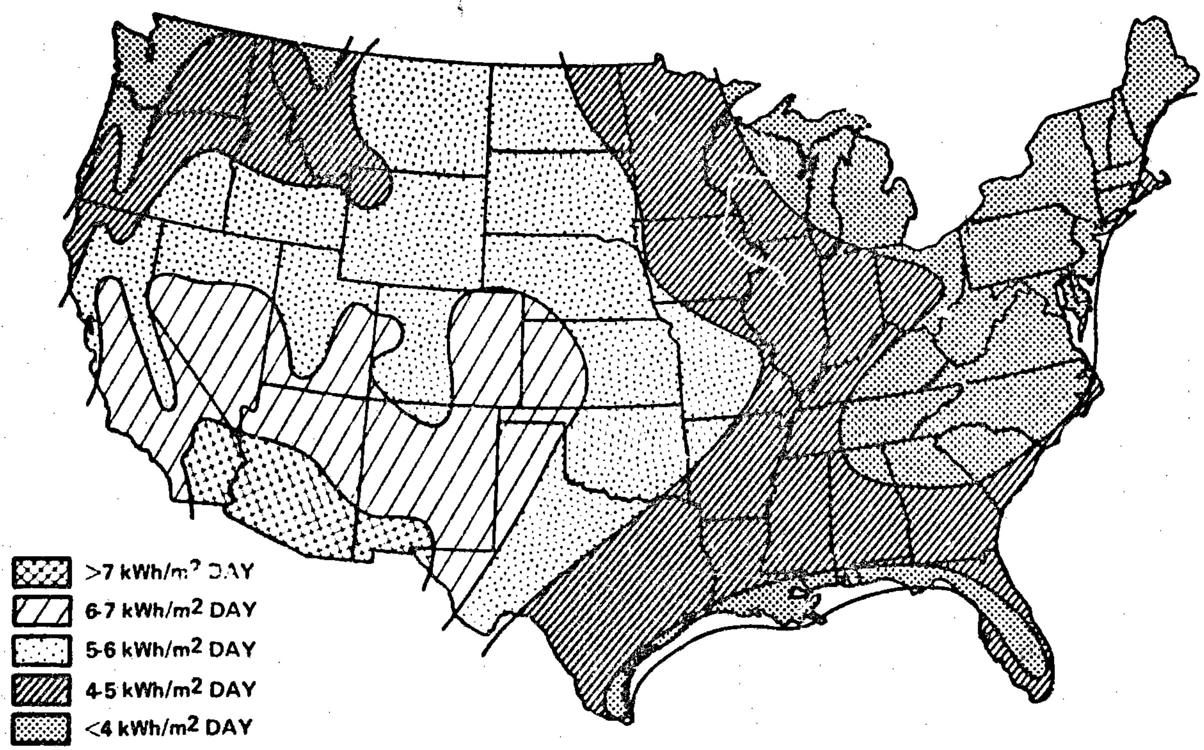
Additional first order performance parameters control the economics of solar plants. Among these are: weight and cost of materials in heliostat construction, reflectivity of mirrors, absorptivity of receiver surface and lifetime of plant. Also, the total energy output over the useful life of the plant must obviously be much greater than the capital energy required to create the plant (manufacturing, construction, transportation, etc.). Otherwise, solar towers cannot solve energy problems. The net energy factor (lifetime energy produced divided by the energy required to create) for power towers is 60 on a basis of fuel saved and 20 on a basis electric energy produced. See section 2.3.5 and reference 1, table II-5. Another factor is the cost of land. Although it is obviously more economic to site plants on remote desert land many existing power plant sites near cities in the Southwest can be used.

The cost of solar thermal energy with heliostats is largely determined by heliostat costs. This fact is shown in section 2.0. Generally, about half of first plant costs lie in the installed heliostat component. Through a well understood learning process, mass produced items experience rapid cost reduction. The learning

FIGURE 1.4

U.S. SOLAR INSOLATION REGIONS

(DIRECT NORMAL INSOLATION IN kWh/m² DAY)



SOURCE: DOE/JPL-1060-17, MARCH 1979,
WATT ENGINEERING, LTD.

Rockwell International
Energy Systems Group

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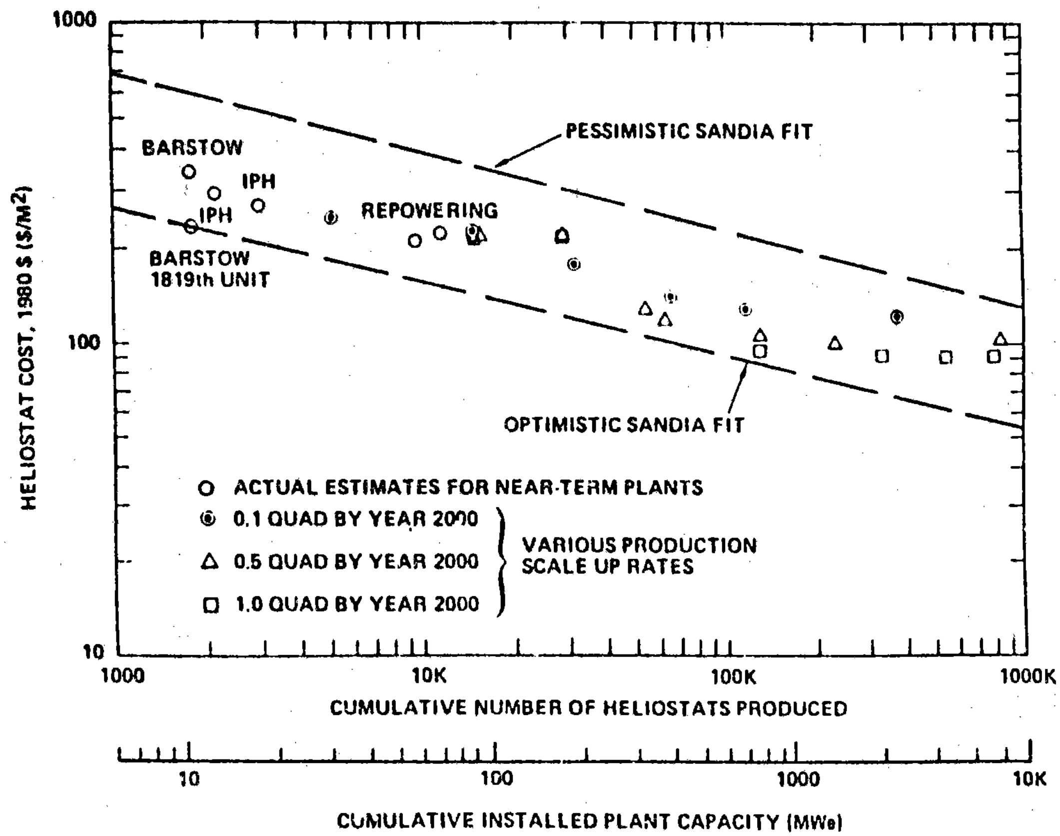
curve aspect of any mass produced item is now utilized quantitively by all manufacturing companies. To illustrate, Henry Ford found that the first 1,000 Model T's built in 1909 could be produced at about $4,000 each and for about $850 each in 1927 at which time 14 million units had been built. These are in constant 1958 dollars. There was, however, no incentive to proceed with the same model because people wanted newer more stylish versions. The same thing happened to the VW "Beetle." This would not happen for heliostat production where stylishness is unimportant. The reason for this cost reduction lies in more efficient use of mechanization rather than labor. One typically can expect about 10 percent reduction in cost for each doubling of automobile production and heliostat production, flat plate, linear trough and parabolic dish production. Because of costs associated with the additional problems of handling curved surfaces we expect flat plates and heliostats to have more significant cost reductions with design and production experience than troughs and dishes.

Learning curve experience and prediction for heliostat production are shown in figure 1.5. This data was developed by ESG, Rockwell Inc. The abscissa is in 1980 dollars per square meter, and the ordinate is in terms of cumulative number of units produced. Shown on the figure is the cost in 1980 dollars of the heliostats for the Barstow 10 MWe pilot plant presently under construction. Upper and lower boundaries are estimated cost trends. Several issues are important here. These long term costs of about $\$85/m^2$ in 1980 dollars are consistent with heliostat cost estimates of about one dollar per pound of total weight (MDAC design) exclusive of sand and gravel in pedestal mounts (5). The MDAC inverted stow, second generation design heliostat has 49 m^2 of glass area and weighs 4041 pounds. This compares favorably with American pickup trucks costs. A heliostat has far less parts than a pickup truck and should be cheaper per pound in mass production. If one achieves expected cost reductions here, there should be beneficial effects for dish and trough collectors. The notion has been expressed that smaller systems are more economical than larger systems per unit of energy production because of rapid learning in building many more small units. It is difficult to accept this view since the starting point is higher for parabolas and curved surfaces and cost improvements with mass production are expected to be slower. Building a house with double the floor area of a small house is generally not as expensive as building two small houses. The maintenance costs are generally higher for two small units compared to one larger unit of equal area.

The learning curve in figure 1.5 can have a very strong positive effect on our energy prices and national security. As more units are built, the cost decreases. Thus as heliostats go into production, solar will effectively provide a lid on energy prices. This can have a significant stabilizing effect on the economy. There is some concern that increased domestic oil production will undermine heliostat system production, and solar energy development will not be pursued. This reasoning cannot be justified. First, energy prices

FIGURE 1.5

HELIOSTAT COSTS VS CUMULATIVE NUMBER PRODUCED



Rockwell International
Energy Systems Group

are escalating over normal inflation, we are dealing with a depleting resource and the drilling of deeper wells increases recovery costs. Second, the learning improvement for oil well drilling will be small, and it will require a longer time to again double production if that is even possible, whereas this is not true for heliostat production. In contrast, heliostat production has just begun and is already in the general competitive economic range. Doubling the energy production by this means can result in a ten percent reduction in energy costs. This economic savings does not hold true for the balance of plant. Because some parts such as towers, generators, and turbines have had extensive production, rapid improvement is not expected. Receivers and storage systems are another matter; their evolution has just begun. Thus solar tower energy cost is expected to decrease in constant dollars for some time to come.

The size of thermal plants can be in the range of 250 kilowatts thermal up to possibly 1,600 megawatts thermal. Electric plants can under special conditions, be economic as small as 1,000 kWe but are preferred in the range of 10-200 MWe. These latter sizes are smaller than baseloaded nuclear and coal plants and thus can be added to many systems gradually as needed. The effect of size on economics will be considered later. Also of great importance is the expected short construction time for heliostat power plants of three to four years. This is anticipated to be a significant advantage of solar plants over coal and nuclear installations.

1.3 Program Status. U.S. and International

Within the U.S. there is a 220 heliostat, 5 megawatt thermal central receiver test facility (CRTF) for testing components at Sandia Laboratories in Albuquerque as shown in figure 1.6. This has been in operation since 1978. This facility has provided considerable experience in operation and accumulation of performance data on heliostat systems. A history of experience with heliostat operation is shown in figure 1.7. Total heliostat operating hours to December, 1980 are 294,000, an average of approximately 1,200 hours per heliostat. Only a minimum of operating experience and repair experience was necessary before the percent of non-operational heliostats decreased significantly and the frequency of repair dropped off rapidly. There are also test facilities at White Sands, New Mexico, Georgia Tech, and the Jet Propulsion Laboratory as well as a number of parabolic dishes at universities and SERI. There are test facilities at Marseille and O'Deillo. Table 1.1 is a summary of some of the test facilities and their capabilities, courtesy of the Solar Thermal Test Facility Users Association.

The first pilot plant in the U.S. to produce power into an electrical grid is being constructed at Barstow, California as a joint DOE-Utility venture and will be rated at 10,000 KWe. Two utilities are involved, Southern California Edison and Los Angeles Power and Water. Dedication of construction occurred February 21, 1980, and

FIGURE 1.6 Central Receiver Test Facility (CRTF)
Albuquerque, New Mexico

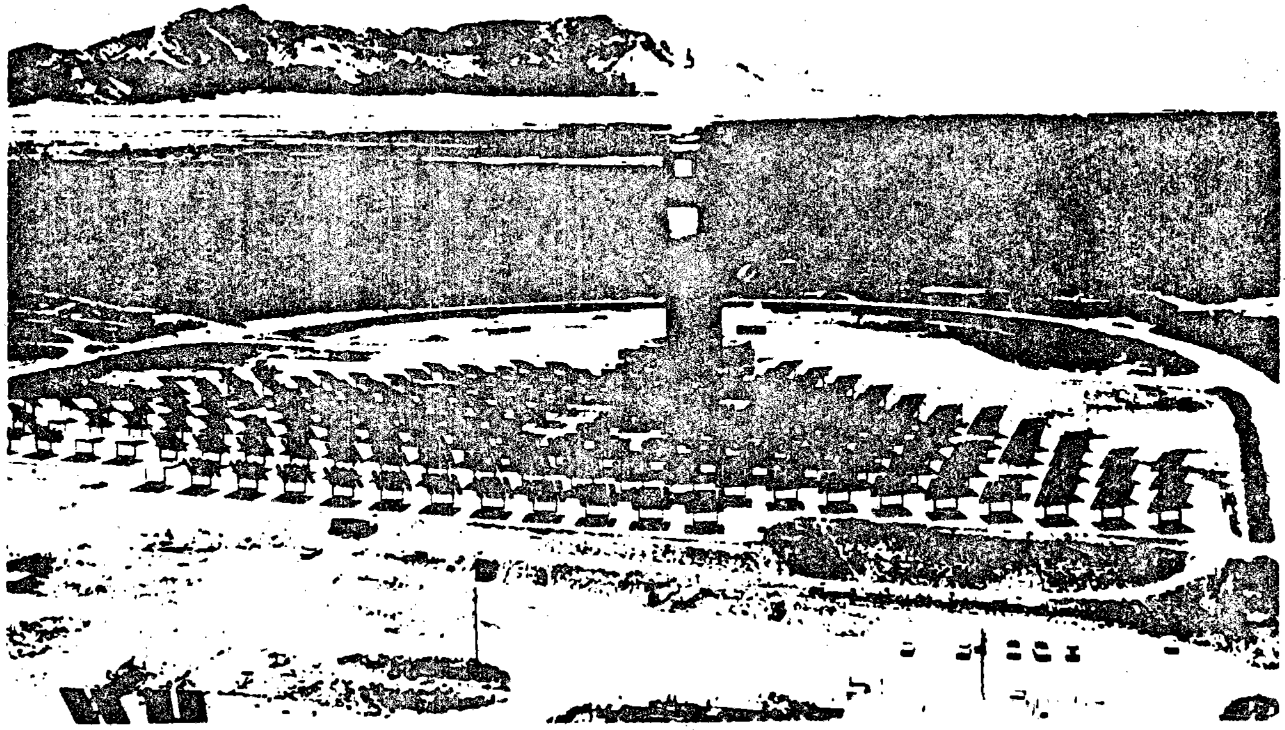
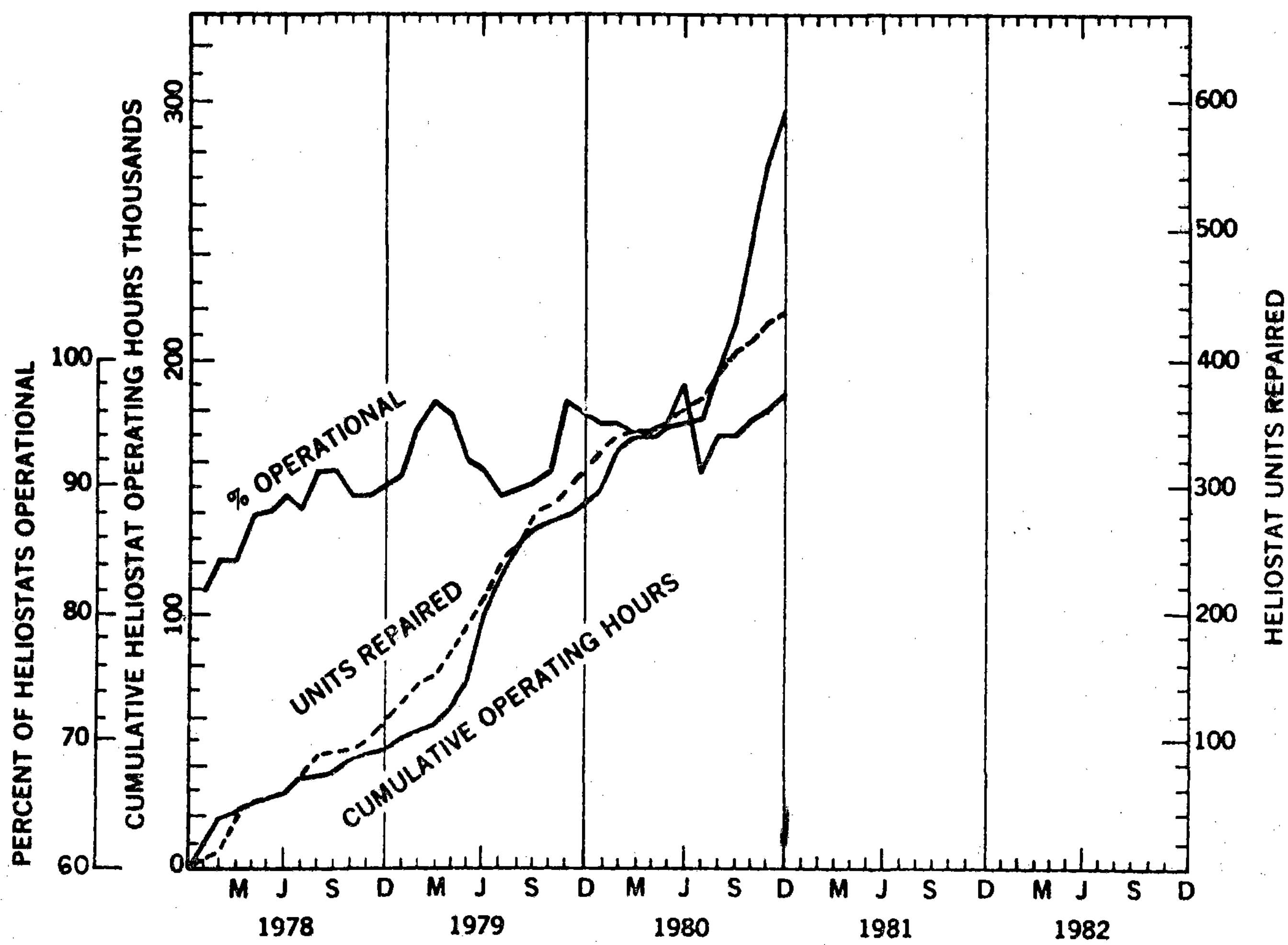


FIGURE 1.7



HELIOSTAT OPERATIONAL HISTORY

TABLE 1.1

APPROXIMATE SPECIFICATIONS FOR STTFs AND SOLAR FURNACES

Facilities	SANDIA	GEORGIA TECH	WHITE SANDS	ODEILLO
Total Thermal Energy, kW	5000	400	30	1000
No. of Heliostats	222	550	1	63
Heliostat Size, m	6 x 6	1.1D	11 x 12	6.0 x 7.5
Total Heliostat Area, m^2	8257	532	132	2835
Test Area Diameter, * m	2 - 3	0.5 - 1.0	0.08-0.15	0.25 - 1.0
Peak Flux, ** W/cm^2	250	200	400	1600
Maximum Calculated Equilibrium Temperature, ** K	2600	2500	2900	4100

* The first number is area receiving approximately one-half of total energy ; second number is area capturing 95% of total energy.

** Small area at center of beam.

the first turbine roll is planned for December 1981. This plant is depicted in figure 1.2 and has 1818 heliostats. The tower is 75 meters high with a boiler 7.0 meters diameter at the top. The cycle is a steam cycle operating at 510°C(950°F) with a 2-4 hour thermal storage in oil and rock. This first-of-a-kind plant is designed to demonstrate real operational requirements and reliability appropriate for a 100 MWe plant and to permit utilities to fully evaluate operational modes and requirements for solar integration into utility grids. This step is also the first step in the repowering and retrofit program. Studies under this DOE program will be examined in section 2.0. Several of these are expected to be taken to construction and operation through a cost sharing program involving utilities and industries with DOE. This program is required by utilities, especially since local public utility commissions are virtually mandated to allow only mature technologies in the rate base.

International efforts underway are tabulated in table 1.2. These have been reported in Financial Times (World Solar Markets) (6). Two Russian projects are in early design stages but are not included in the table. Considerable activity is planned worldwide and probably there are additional projects not yet reported.

1.4 Energy Demand

The demand for energy is obviously growing and the developing pressure on oil from the third world is ever growing. Clearly, solar technology should be fostered by the developed countries. If this is not accomplished, it will be virtually impossible for the third world countries to develop and use solar thermal. The U.S. goal of 3 quads solar thermal and solar electricity by 2000 is certainly possible and probably conservative. At least 0.5 quad for electric production by heliostat systems is a reasonable goal. The most significant first demand lies in the utility sectors of the Southwest where some 20-25 percent of the energy requirements are solar beam related and solar thermal would be an excellent choice since demand could be met with intermediate type plants. If one can hybridize with fossil fuels, one can get a deeper penetration with some baseload applications. Also, if high voltage direct current (HVDC) is utilized for transmission from the Southwest, significant penetration into additional markets can be made. Solar plants coupled with hydroelectric facilities can greatly enhance hydro capabilities. Transmission of heat via chemical heat pipes and heat transmission systems could have the largest penetration of all. Once a reliable heat utility is developed, additional sectors can be opened. The Germans are developing the chemical heat pipe, EVA-ADAM system (discussed in more detail in section 4 of this report) for their High Temperature Gas Reactors (HTGR) and this can be developed for direct application to solar towers(7).

The highest demand sector is in chemical fuels. Our most significant

TABLE 1.2

SOLAR HELIOSTAT PROJECTS AROUND THE WORLD

Country	Project	Cost (M$)	Operator Client	Main Contractors	Rated Output	Power Source/ Process	Date of Commissioning	Status
Australia	Solar thermal power plant	16.0 (Aust$)	Northern Territory Government	McDonnell Douglas Sabrimo & Transfield	1-2MW	220 heliostats $57m^2$ each	1983	Under review
Corsica	Solar electric plant (Ajaccio)		COMES	SOFRETES	300kW	$1,200m^2$ Ceta heliostats segmented-mirror	1982	Under construction
France	Solar Plant (Targassone)		COMES	Cethel	2MW	200 heliostats $53m^2$ each	Nov.'81	Under construction
Italy	Solar Plant Eurelios (Adrano)	14.3	Italian State Electricity Co (ENEL)	Ansaldo Cethel MBB	1MW	70 heliostats $52m^2$ each 112 heliostats $23m^2$ each	end-'80	Nearing completion
Spain	Solar plant CESA 1 (Almeria)		IEA	SEBER CASA	1MW	60m-high tower 300 heliostats	early '82	Under construction
	Solar thermal GAST (Badajoz)	280.9	West German Ministry for Development (DFVLR)	Interatom MAN MBB	20MW	3,000 heliostats, $40m^2$ each		Conceptual design Components being tested
Japan	Pilot Plant Nio in Kagawa Prefecture Shikoku		Sunshine Projects	Electric Power Development Co. Mitsubishi Ltd.	1MW	72m tower 807 heliostats $16m^2$ each	1981	Under Construction
					10MW	770 heliostats $36m^2$ each		Planned

energy shortage at present in this country lies in liquid fuels. Ultimately battery powered cars may impact liquid fuel use but this will require long term development. Solar towers can be used in enhanced oil recovery, oil shale production, and conversion of biomass to fuels. Conversion of biomass can be through pyrolysis and providing a heat source for alcohol production. Here one has a storage system both before distillation and after distillation in the final alcohol product.

A final requirement is the need of energy by the Federal government in day to day use, by various agencies and the Department of Defense. A most significant case could be in the MX missile program. Solar towers could be used as well as hybridized dish systems. The military is well versed in gas turbines and operation of communications parabolas.

The obvious need of energy sources within our continential boundaries has broad implications for national security and U. S. relationships with foreign nations. The better we can manage our long term energy problems within our boundaries, the less we will be subject to the turbulance of the world arena.

2.0 TECHNICAL AND ECONOMIC ASSESSMENT

2.1 Assessment/Review Basis

Technical and economic data presented in this report is drawn from recent system design studies, advanced subsystem studies, cost/production analyses, comparative rankings, and economic assessments. The scope of this report is to present pertinent data direct from these reports for analysis and to use a minimum of scaling to bring the performance and cost data to a reasonably common basis. Though scaling is not sufficient to permit close comparisons or rankings, it is intended to point out consistencies or inconsistencies, to look for trends, and to form some guidelines to project capital costs for energy production scenarios.

The assessment/review basis consists of:

a. Thirteen repowering and retrofit studies completed in 1980 (references 8 to 20).

b. Two hybrid system studies completed in 1979 (references 21 and 22).

c. Seven design studies completed in 1979 and 1980 (references 23 to 29).

d. Eleven assessments/evaluations completed in 1979 and 1980 (references 5 and 30 to 39).

e. Eight application and marketing stuies completed in 1979 and 1980 (references 38 and 40 to 46).

f. Two subsystems studies and test reports, completed in 1980 (references 47 and 48).

g. Two reports on the cost of heliostat production, completed in 1979 (references 49 and 50).

2.2 Cost/Thermal Performance Assessment Summary

A series of twenty-two system design studies have been selected from the review basis to represent the most definitive currently available data on the cost and performance of heliostat systems. They were selected on the basis of the following criteria:

a. Representative of the widest possible range of system sizes

b. Widest variety of independent design analysis

c. Results formulated to allow accurate extraction of the capital cost of the solar-thermal portion of the system

d. Availability of thermal performance analysis.

In part c, solar-thermal refers to the capital cost of only that portion of a system required to deliver solar generated thermal energy.

Two parameters have been selected to form a basis of comparison for the selected design studies: (1) the annual thermal energy delivered to the process and (2) the capital cost of the solar portion of the system delivering the thermal energy. For most larger systems the ultimate objective is the delivery of electrical energy. However, the additional complexities of electrical power generation subsystem performance efficiencies and capital cost variations are not reevaluated here and only reported estimates of BBEC are given. Considering the wide variety of sizes chosen, the only common denominator is thermal performance. Thermal performance can be scaled to a common annual insolation level with reasonable accuracy to form a basis for comparison. For economic parameters the prime factors for cost comparison in this report are simple capital cost and annual thermal energy production, although bus-bar energy costs given by the various studies are included. In this report, capital costs are scaled to a common set of heliostat costs.

Twenty-two design studies selected for review are listed in table 2.1. Pertinent data extracted from these studies are listed in table 2.2. The studies consist of thirteen for repowering and retrofit, four for hybrid, one for advanced systems, one for site latitude and

TABLE 2.1

Selected Design Studies

Identification Number(Id.No.)	Contractor Study Title	Reference Number
1	University of Houston, Energy Systems Group (RI), "Small IPH Heliostat Systems" (unpublished)	--
2	McDonnell Douglas Astronautics Corp., "Phase I of the First Small Power System Experiment, Final Technical Report"	29
3	Northrup, Inc., ARCO Oil and Gas Co., "Solar Industrial Retrofit System--North Coles Levee Natural Gas Processing Plant--Final Report"	8
4	U.S. Gypsum Co., Boeing Engineering and Construction, "U.S. Gypsum Plant Solar Retorfit Program, Final Report"	9
5	McDonnell Douglas Corp., "Solar Repowering Industrial Retrofit Systems Study, Gulf Mt. Taylor Uranium Mill Solar Retrofit, Final Report"	10
6	Martin Marietta Corporation, "Solar Repowering/Industrial Retrofit Systems, Solar Thermal - Enhanced Oil Recovery System, Final Report"	11
7	PFR Engineering Systems, Inc., "Solar Central Receiver Reformer System For Ammonia Plants, Final Report"	12
8	Foster Wheeler Development Corporation, "Solar Industrial Retrofit System for the Provident Energy Company Refinery, Final Report"	13
9	Jet Propulsion Laboratory, "Site Latitude Study of Central Receiver Systems" (to be published)	28

10	Black and Veatch, Consulting Engineers, Public Servie Co. of Oklahoma, "Solar Repowering for Electric Generation, Northeastern Station Unit 1, Fi 1 Report"	14
11	El Paso Electric Company, "Newman Unit I Solar Repowering, Final Report"	15
12	General Electirc Company, "Southwestern Public Service Company Solar Repowering Program, Final Report"	16
13	Rockwell International(ESG), "Solar Repowering System for Texas Electric Service Company Permian Basin Stream Electric Station Unit #5 Final Report"	17
14	Rockwell International (ESG), "Conceptual Design of the Solar Repowering System for West Texas Utilities Company Paint Creek Power Station Unit No. 4, Final Report"	18
15	Rockwell International (ESG), "Solar Central Receiver Hybrid Power Systems Sodium Cooled Receiver Concept, Final Report"	21
16	McDonnell Douglas Astronautics Corp.,"Sierra Pacific Utility Repowering Final Technical Report"	19
17	Arizona Public Service Company, "Saguaro Power Plant Solar Repowering Project"	20
18	Same as study 15	21
19	McDonnell Douglas Astronautics Corp., "Central Receiver Solar Thermal Power System Phase I, Commercial Plant Cost and Performance"	24

20	Martin Marietta Corporation, "Solar Central Receiver Hybrid Power System, Phase I"	22
21	Rockwell International (ESG), Conceptual Design of Advanced Central Receiver Power Systems Sodium-Cooled Receiver Concept"	26
22	Same as Study 15	21

TABLE 2.2

Assessment Design Studies

Id.No.	Rated Power Thermal/ Electric (MWt/MWe)	Solar Capacity Factor/ Solar Multiple	Total Reflective Surface (m^2)/ No. Heliostats	Design Annual Energy (MWht)$ Annual Insolation (MWh/m^2)	Capital Cost 1 Based On $230/$m^2$ (M$1980)[b]	Annual O&M Cost[a] (M$)	Solar Only Levelized BBEC[a] (mills/ kWh) e-ele, t-therm	Id.No.
1 UH	0.44	.32	621/11	1,346/3.263	0.310-			1
2 MDAC	4.72/1.0	.40	6,524/133	10,050/2.609	2.582	.085		2
3* NI	9.52	.27	16,832/320	22,555/2.193	6.448-		20.7 t	3
4* BEC	11.85	.25	19,963/407	26,450/2.296	8.819-			4
5* MDAC	13.90	.26	21,601/383	31,800/2.495	12.00-	.163(1.45)		5
6* MM	29.3	.22	40,123/818	55,870/2.260	14.033-		23.9 t	6
7* PFR	34.5	.27	58,677/1040	82,500/2.782	24.872-	.542		7
8* FWDC	43.2	.28	66,214/1174	105,000/2.772	23.460-			8
9 JPL	45.8	.24	68,684/1217	95,812/2.327	24.530			9
10* BY	73.3/30	.19	110,608/2255	120,000/1.924	51.767-	.248		10
11* EPE	130.0/41	.18	211,000/2776	206,800/2.652	93.100-			11
12* GE	158.0/60	.23	235,881/4809	290,527/2.374	112.49-	.675		12
13* ESG	124.0/50	.49/1.23	267,544/4742	355,500/2.520	116.00-	1.16	187.0 e	13
14* ESG	226.0/72	.38/1.56	336,636/7882	482,500/2.346	145.00-		125.0 e	14
15# ESG	229.0/100	.24/0.8	416,729/8496	540,289/2.609	131.37		145.0 e	15
16* MDAC	322.0/77	.27	474,549/8411	759,000/2.630	198.85-	2.0		16
17* MM	305.0/120	.27	515,025/10500	719,730/2.519	209.69-			17
18# ESG	364.0/100	.39/1.4	663,205/13251	898,328/2.609	209.84	3.3	122.0 e	18
19 MDAC	500.0/100		942,907/16713	1,293,388/2.591	325.90-			19
20# MM	740.0/100	.75	1,224,680/24968	1,682,633/2.683	514.74	3.8(3.2)	101.0(71.4)e	20
21 ESG	1084.0/281	.46/1.50	1,994,373/40660	2,599,650/2.609	614.25	5.4(3.2)	(64.3) e	21
22# ESG	1600.0/430	.42/1.44	2,976,000/60676	3,910,000/2.609	900.10		109.0 e	22

$ Megawatt hours thermal, solar only.
* Repowering Study
\# Hybrid Study

a 1st plant costs (Figures in parentheses are for nth plant costs)
b M$ = $10^6$$
-Indicates nearest cost to the design basis

two for small systems. In the remainder of this report design studies will be referred to by the identification number as given in the left column of tables 2.1, 2.2, 2.3, 2.5, and 2.10.

In table 2.2 the second column from the left margin is the rated thermal and electrical power of the system. These are taken from design point performance data. The ratio of the thermal to electrical values does not necessarily indicate the thermal-electrical cycle efficiency, since for high capacity factors a portion of the thermal energy is going to storage. The third column is the capacity factor(CF) and solar multiple(SM), if stated. Unless otherwise stated in the design study such as in 13, 18, 20, 21, and 22, the CF is computed from the annual thermal energy and rated thermal power. The fourth column is the total heliostat reflective surface and number of heliostats. Systems are listed and numbered in terms of total reflective surface; therefore, the position in the tables is an indication of overall system size. The annual thermal energy delivered by the system is given in the fifth column. This is the annual energy delivered to the process and is representative of collector, receiver, and piping subsystem efficiencies. The annual insolation level that forms the basis for the annual thermal energy delivered is site dependent and is given in the same column.

The first capital cost (other capital costs will be given in subsequent tables) reported in column 6 is based on a heliostat cost of $230/m^2$.* This is the heliostat cost basis for the repowering studies and is representative of first plant costs. In cases where capital costs were not reported based on this value, capital costs have been altered by a linear scaling of the collector field cost to the $230/m^2$ value. The annual operations and maintenance costs and levelized bus-bar energy costs are given, as available from the contractors in columns seven and eight. The O&M and BBEC are unaltered except by conversion to 1980 dollars where necessary.

2.3 Performance Parameter Comparison And Analysis

2.3.1 Collector Field Efficiencies

The annual average collector field performance efficiencies as reported by the designers, are listed in table 2.3. In contrast to some other assessment papers the interception fraction is included as a collector field efficiency factor.

The larger systems with surround fields accept lower cosine efficiencies in order to preserve the interception efficiency. Surround fields have heliostats south of the tower. These heliostats

*All dollar values are reported in 1980 dollars unless otherwise noted. Dollar values taken from the studies are multiplied by 1.21 if given as 1978 dollars and 1.10 if given as 1979 dollars.

TABLE 2.3

Annual Average Collector Field Performance Efficiencies

Id. No. Field Type*	Cosine	Reflectivity and Dust	Shading and Blocking	Field Geom & Heliostat Availability	Atmospheric Attenuation	Interception (Spillage)	Net Collector Efficiency	Id. No.
1 N UH		.912		1.000	1.000	.987	.749	1
2 N MDAC	.867	.880	.936	.950	1.000	.981	.666	2
3 N NI	.829	.870	.995	1.000	.969	.991	.689	3
4 N BEC		.930		1.000	.980	.952	.670	4
5 N MDAC	.834	.912	.967	.963	.987	.974	.684	5
6 N MM	.862	.900	.932	1.000	.971	.983	.684	6
7 N PFR	.859	.912	.922	.968	.975	.912	.622	7
8 N FWDC	.838	.912	.907(.937)	.968	.978	.964	.633	8
9 N JPL		.912	.959	.960	.984	.958	.683	9
10 N BV	.840	.900	.958	1.000	.962	.985	.686	10
11 N EPE		.900		1.000	.930	.950	.640	11
12 S GE		.914		1.000	.959	.986	.607	12
13 S ESG	.767(.799)	.912	.938	.968	.969	.986	.627	13
14 S ESG	.811	.904	.951	.960	.957	.971	.622	14
15 S ESG	.751(.767)	.912	.932	.980	.964	.954	.587	15
16 N MDAC	.856	.912	.943	.970	.958	.970	.669	16
17 S MM	.815	.900	.942	1.000	.940	.976	.631	17
18 S ESG	.724(.749)	.912	.966	.980	.959	.967	.592	18
19 S MDAC	.749	.912	.956	.963	.953	.961	.576	19
20 S MM	.766	.900	.945	1.000	.940	.980	.597	20
21 S ESG	.763	.912	.934	.967	.940	.954	.583	21
22 S ESG	.752(.763)	.912	.932	.980	.927	.962	.570	22

* S-surround
N-north

have lower annual average cosine efficiencies than heliostats north of the tower. For larger systems surround fields become necessary, since an equivalent north field would have heliostats too far away from the tower to maintain acceptable interception. Surround fields in larger size plants become more cost effective. Cosine values given for studies 13, 15, 18, and 22 have adjusted values provided by authors of this report. The values given by the contractors were believed to include errors in interpretation of computer printouts. These errors do not imply an error in the annual thermal energy in table 2.2, since energy is computed and reported independent of the values given for cosine efficiency in table 2.3.

To indicate system performance properly, annual cosines are computed by insolation weighting. Poor cosine values occurring early and late in the day do not properly represent system efficiency since lower levels of direct normal insolation are available at those times. Some variation in cosine values is to be expected due to the various shapes of the collector field layouts.

Data given in the second column of table 2.3 indicate the contractors' allowance for heliostat intrinsic reflectivity and average annual degradation due to dust. All studies examined here used second surface silvered glass mirrors. The frequent occurrence of the figure 0.912 is due to the use of 0.940 for intrinsic reflectivity and 0.970 allowance for dust by the University of Houston Energy Laboratory. With the exception of studies 3 and 4, the balance of the estimates fall in the range of 0.90 to 0.91.

Measurements of the intrinsic reflectivity of various second surface silvered glass mirrors are summarized in table 2.4 (48).

TABLE 2.4

Second Surface Silvered Glass Reflectivities

Type	Reflectivity
Early, High Iron, CRTF	0.83
Barstow Prototype Low Iron Float	0.90
Thin, Low Iron Float	0.90-0.91
Boeing, Thin Fusion	0.94

Since the reflectivity of the silver alone is 0.96, the 0.94 figure for thin fusion glass is about the best that can be expected without a significant change in heliostat mirror technology. The use of 0.94 for intrinsic reflectivity in system design analysis is, therefore, realistic and at worst, only slightly optimistic.

Measurements of specular reflectivity variation with exposure to dust and weather conditions in Albuquerque, N.M., have been made by Sandia Laboratories(51). Mirrors were exposed with and without cleaning and to a variety of cleaning schedules. Reflectivity degradation of from 2 to 12 percent, and at worst 20 percent was observed. The degradations are highly dependent on site weather conditions, winds, frequency of rain, snow, etc. Proper stowage during rain and melting snow can significantly restore reflectivity. These observations, combined with more recent measurements(48), indicate that by taking advantage of rain and snow, combined with reasonable cleaning schedules, the average yearly reflectivity degradations can be kept to within 3 or 4 percent. Thus, the system design allowance of 0.97 for dust alone is the maximum realistic value. The combined reflectivity and dust figure of 0.93 for study 4 is the only overly optimistic figure in the twenty two studies.

In an effort to significantly decrease the cost of heliostat systems, the development of an enclosed heliostat (plastic or bubble heliostat) has been undertaken (52,53). This heliostat consists of a silver coated mylar reflector protected by an inflated mylar or kynar dome. The net reflective efficiency of the enclosed heliostat is considerably less than a glass mirror heliostat, but the materials are much lighter and lower in cost. In an advanced CR systems study, GE with UH designed fields with both glass and enclosed heliostats for a 100 MWe system(27).

The reflective efficiencies of the heliostats were taken at 0.574 for the enclosed heliostat (0.86 enclosure transmission, 0.88 reflectivity, 0.99 enclosure blockage, and 0.89 degradation) and 0.90 for the glass heliostat. The enclosed heliostat reflective efficiency is 64 percent as efficient as the glass heliostat. The costs of the heliostats were taken as 25 $\$/m^2$ for the enclosed heliostat and 65 $\$/m^2$ for the glass heliostat (these are goal or nth plant costs). The collector field designs gave a figure of merit (FM) for the enclosed heliostat field of 74 \$/MWht and 82 \$/MWht for the glass heliostat field. Consequently, the designers chose to pursue the enclosed heliostat field. Notice that the enclosed heliostat cost used for the study is 39 percent the cost of the glass heliostat. It is interesting to ask what enclosed heliostat cost would have produced the same figure of merit as the glass heliostat. For an assumed lifetime of 30 years for both, the answer is 32 $\$/m^2$, which is 49 percent of the glass heliostat cost. Recalling that the enclosed heliostat is 64 percent as efficient as the glass heliostat, for this case(64) it must be less than 49 percent the cost of the glass heliostat to justify its use. This is due to the fact that not only more heliostats must be used but they must be spread over a larger land area resulting in heliostat fields that are, on the average, even less efficient than their reflective efficiency indicates.

Additional problems were revealed after extended life tests(54). The enclosure lost 6 percent in transmissivity of which, 1 to 2 percent was permanent, and the specular reflectance loss was 16 percent, of which 12 percent was permanent. The enclosure also experienced seam damage. However, more recent developments in use of materials and design techniques make the enclosed heliostat look more promising. The use of Kynar enclosures may improve lifetime thus reducing potential costs. The newer design enclosed heliostats have yet to be built and tested. Concerns about lifetime were the primary reason enclosed heliostats were not pursued in second generation efforts. If indeed the newer design for enclosed heliostats can achieve the necessary lifetime, they hold the potential for reducing energy costs for heliostat systems below that predicted for attainable goal costs with glass heliostats.

The annual shading and blocking (S&B) efficiencies shown in table 2.3 result from the collector field design process. Most of the collector fields were designed by a process which minimizes the capital cost of the plant (a function of heliostat cost and placement) divided by the annual thermal energy produced (55-58). Therefore, for freely optimized fields (no artificial restrictions such as land boundaries) the annual S&B efficiency varies as a function of heliostat cost. With expensive heliostats a lower heliostat density is cost/performance optimal and there is less shading and blocking. With lower cost heliostats, a high density is optimal resulting in more shading and blocking.

The design effort for the twenty two studies reported here was not carried out for the same heliostat costs. This affects the optimization. The small systems study (1), the repowering studies (3-8, 10-14, 16, 17), and a commercial plant study (19) were done for $230/m^2$, while the small systems study (2), the latitude study (9), and the hybrid and advanced system studies (15, 18, 20-22) were done for lower costs, typically $80/m^2$ ($72/m^2$ in 1979$). The values of annual S&B are also affected by restrictions placed on the optimization. For example, if there are restrictions on the amount of land available or the location of boundaries, it may be necessary to increase the density of heliostats, taking larger S&B losses than is cost/performance optimal. Therefore, the differences in S&B performance listed in table 2.3 are not unexpected. On the whole, they appear to be reasonable with the following exceptions. For high cost heliostats the 0.995 for study 3 is higher than expected, the .922 and .907 for studies 7 and 8 are lower than expected, and the .966 for low cost heliostats in study 18 is higher than expected. More reasonable figures are: study 3, 0.96; study 8, 0.94; and study 18, 0.94. A reasonable range of values for annual shading and blocking is 0.93 to 0.97.

In this report capital costs are scaled to various heliostat cost values. This is done by subtracting collector field cost from total cost to get balance of plant cost, scaling the collector field cost linearly with heliostat cost and adding the result to the balance of plant cost. This has been done without regard to changes in performance which would result if the system were re-optimized to the new heliostat costs. This second order error is probably a few percent in performance. Time would not permit such a re-analysis, nor is it necessary for the purposes of this report.

The field geometry and heliostat availability figures given in table 2.3 allow for additional losses expected to occur when actual heliostat locations are determined and for the average annual fraction of heliostats not available during system operation. Studies 15, 18, 22 did not formally include a number for these effects in their reports, nevertheless an allowance of 0.98 was actually used in their analyses. For other studies not reporting a specific number for these effects, a value of 1.000 has been entered in the table

The allowance for field geometry is due to the additional shading and blocking losses that can occur when actual heliostat locations are determined in relation to the original field optimization. Such analysis must sample the field (divide it into discrete cells) and ignore discontinuities at cell boundaries, as well as roads and obscurations within the field. Analyses derived by the University of Houston reported in many of the studies examined here are based on efficiencies as determined by the cellwise method and include an allowance of 0.97 for field geometry (heliostat layout). Other studies may have included this effect in other efficiency factors or may have failed to allow for it. The additional 3 percent for field geometry came from experience in laying out the collector field for the Solar One pilot plant(57). This is expected to be a reasonable allowance for design purposes but could vary depending on the size of the field and number of constraints on the position of heliostats (roads, powerlines, etc.).

The average fraction of heliostats not in operation is difficult to assess. In practice, the number could vary considerably, and, of course, the impact of the loss of a few heliostats will be much greater on a small plant. The loss of heliostats can be kept to a minimum by well planned maintenance, particularly if preventative maintenance and mirror washing are done at night. MDAC and ESG have established an average design allowance efficiency for non-operational heliostats of 0.99.

Atmospheric attenuation is estimated from attenuation coefficients derived through atmospheric modeling(59). The average attenuation for a field depends on assumed annual average atmospheric conditions (visibility) and the average slant range from heliostats to receiver. If assumed atmospheric conditions at the varous sites do not vary appreciably, a trend toward greater atmospheric attenuation in larger fields should be observed. This is evident in table 2.3. The models used by the University of Houston to compute atmospheric attenuation of reflected beams from heliostats to receiver have recently been revised. The revised models are predicting greater levels of attenuation. Initial work with the new model for a 100 MWe plant (20,000 heliostats) indicates an increased annual average loss for the plant of 4 percent over the previous model. The optimized design process will tend to compensate for the increased atmospheric attenuation by increasing the density of heliostats. The net effect on the figure of merit (capital cost divided by the annual thermal energy produced) for a 100 MWe plant is approximately a 3.5 percent increase. In view of this development, the values given in table 2.3 for atmospheric attenuation in studies done by UH, ESG, and MDAC are overly optimistic.

The interception efficiency is the average annual ratio of energy incident on the receiver working surface (aperture, absorbing surface) divided by the energy redirected from the field, not including atmospheric absorption. Interception losses are sometimes referred to as spillage losses. They are dependent on heliostat surface shape, heliostat tracking, overall field size and receiver size. Interception efficiencies less than unity are acceptable to systems designers to reduce receiver size, thus minimizing receiver cost and thermal losses.

The formulation of computed interception efficiency depends on analytic formation of images from heliostats(60-63). The effects of surface waviness and tracking errors are usually included by convolution of the images with Gaussian distributed error functions, or, in the case of ray tracing, by perturbations to ray vectors. Experience has shown that interception efficiency shows almost insignificant variation during the year. Interception efficiency tends to drop off early and late in the day when heliostat image aberrations become significant. Just as with cosine efficiency, the systems receive much less insolation at these times. Thus, the effect on net power production is minimal. Present day design techniques assume interception efficiency to be constant during the year. Thus, the values reported in table 2.3 are usually for the design point and are thus not necessarily annual averages. It is presently assumed that insolation weighted annual average interception fractions can be represented by the design point. This is very likely the case for cylindrical receivers; however, the effect of aberrations on flat panel and cavity receivers may be more pronounced. Plans are underway at the University of Houston to examine interception efficiency variations in more detail and to form more accurate annualized interception fractions.

For larger size systems with increased slant range the interception efficiency would be expected to decrease due to the spread of heliostat images. This has been shown to be the case and limits the maximum size plant that can be built with the minimal cost/performance ratio expected for central receiver systems. Several studies have shown that this limit occurs near the 300 to 500 MWe system size(22,64). Study 22 was chosen to represent the maximum practical size system.

No trend as a function of size is obvious in the interception data of table 2.3. The geometry of the heliostats and receivers has been chosen to keep interception efficiency within a reasonable range of value. Note that study 7 has a relatively low interception efficiency. The receiver for this system is a high temperature cavity and therefore would need to be of minimal size to limit thermal losses. Studies 3 and 6 are for lower temperature cavities than 7, but nevertheless appear to be higher than necessary in interception, possibly indicating oversized apertures. The .950 given for interception on study 11 appears to be somewhat low compared to the other studies. This may be due to the fact that it is a partial cylinder with a north field of heliostats subtending 160°. The .980 figure given in study 20 may be one or two percent high for a field of that size.

Reasonable interception efficiencies for heliostat systems are from .95 to .99, lower values being more a result of optimizing for high temperature operation than for large field size.

Considering the large variety of design requirements and analytic techniques, net collector efficiencies are remarkably consistent. Some fields are fully optimized (2, 9, 15, 16-22); others, such as many of the repowering studies were subject to land constraints. The net collector efficiency of study 7 is low due to a high temperature process that limits interception. For study 8 it is low, due perhaps, to an error in reported shading and blocking; study 16 has a relatively high collector efficiency since it is a north field. Reasonable values for net collector efficiencies vary from 0.57 to 0.69 over a very wide range of system types and field sizes. It is necessary also to look at receiver efficiency and system costs since these trade with interception and S&B respectively.

2.3.2 Receiver Efficiencies

The design studies consistently quote absorptivities of 0.95 for open receivers (flat and cylinders) and 0.98 for cavity receivers. A summary of receiver efficiencies and net thermal system efficiencies is given in table 2.5. Three receivers using advanced heat transfer media are shown in figure 2.1. Sufficient test experience with these receivers and with high temperature absorption coatings renders these estimates of performance reliable. Some advanced receiver designs attempt to take advantage of cavity characteristics in an open receiver. This is achieved, for example, by screening super heat tubes with preheat tubes(13). Study 10 reports a two percent improvement in receiver absorptivity. Hopefully, these improvements will prove correct, but at present there is very little experimental evidence to back up these claims.

The situation is also fairly well defined for expected radiation losses. For given receiver geometry and operating temperatures a comprehensive basis exists for estimating radiation losses. Unfortunately, the same is not true for convection losses. In many

TABLE 2.5

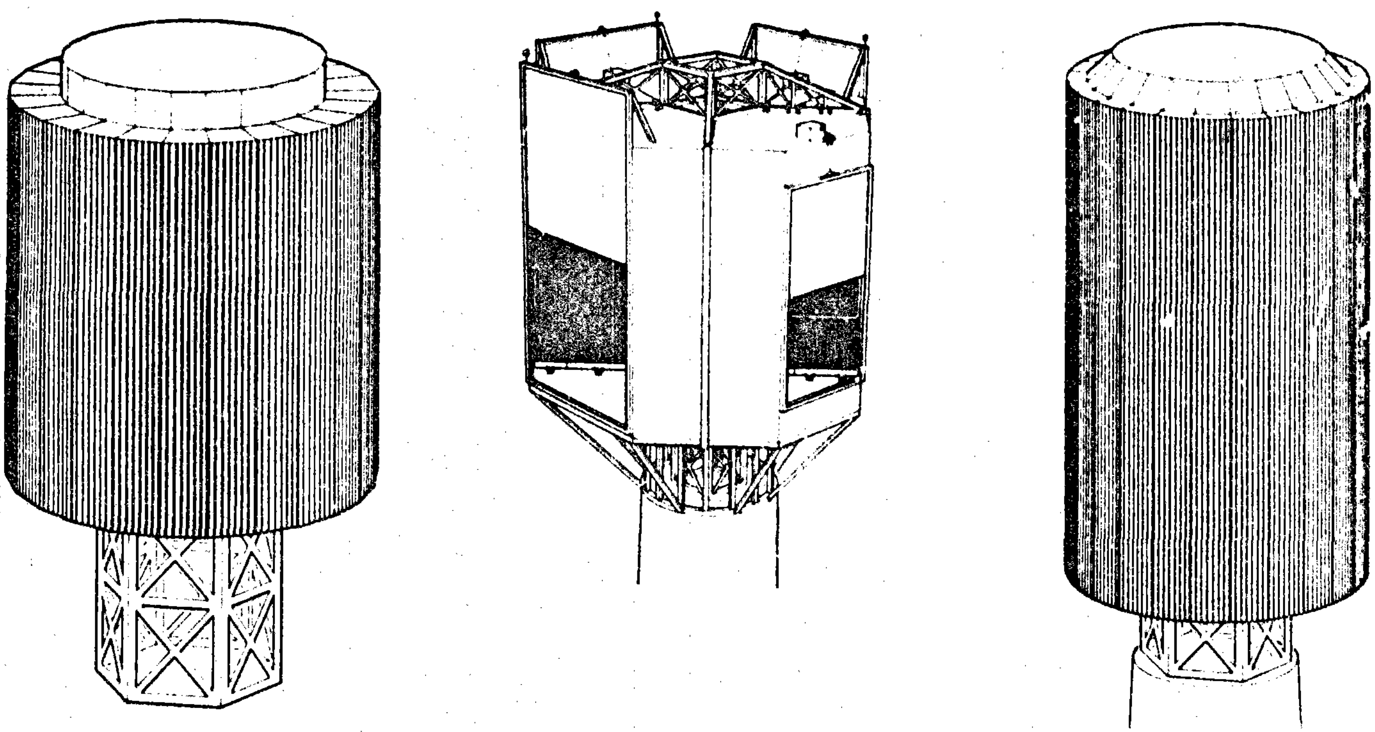
Annual Average Receiver Performance Efficiencies and Net Thermal Efficiency

Id. No.	Receiver Type (working media)	Receiver Outlet Temp. (°C/°F)	Receiver Absorptivity	Radiation Convection	Net Receiver Efficiency	Additional Factors*	Net Thermal Efficiency (collector, receiver, piping)	Thermal-Electric Gross Cycle Efficiency	Id. No.
1 UH	flat(H_2O)	121/150	.950	.933	.887	.999	.664		1
2 MDAC	flat(salt)	566/1050	.946	.916	.867	.992	.555	.388	2
3 NI	cav(oil)	301/575	.983	.928	.900	.971	.623		3
4 BEC	cav(air)	724/1335			.857	1.000	.577		4
5 MDAC	flat(H_2O)	204/399	.950	.953	.905	.994	.612		5
6 MM	cav(H_2O)	285/545	.980	.918	.900	.990	.615		6
7 PFR	cav(chem)	790/1454	.962	.866	.833	.976	.506		7
8 FWDC	flat	271/520	.950	.959	.911	1.000	.577		8
9 JPL	flat(H_2O)		.950	.959	.911	.990	.594		9
10 BV	cyln(H_2O)	544/1012	.970	.879	.853	.967	.567	.427	10
11 EPE	cyln(H_2O)	549/1020	.950	.830	.789	1.000	.509	.410	11
12 GE	cyln(Na)	593/1100	.964	.955	.870	1.000	.516	.420	12
13 ESG	cyln(Na)	593/1100	.950	.915	.869	1.000	.528	.400	13
14 ESG	cyln(Na)	593/1100	.950	.915	.869	1.000	.523	.413	14
15 ESG	cyln(Na)	593/1100	.950	.937	.890	1.000	.522	.435	15
16 MDAC	cav(salt)	566/1050	.980	.953	.934	.994	.616	.426	16
17 MM	cav(salt)	566/1050	.981	.904	.887	1.000	.558	.394	17
18 ESG	cyln(Na)	566/1050	.950	.936	.890	1.000	.526	.435	18
19 MDAC	cyln(H_2O)	516/960	.950	.917	.871	.999	.521	.350(.250)#	19
20 MM	cav(salt)	566/1050	.980	.902	.884	.998	.512	.424	20
21 ESG	cyln(Na)	593/1100	.950	.958	.910	1.000	.515	.432	21
22 ESG	cyln(Na)	593/1100	.950	.916	.870	1.000	.496	.437	22

* Piping, Receiver Warm-up, Tower Shadow, Parasitics, etc.

Operation from storage (derated steam)

FIGURE 2.1 Liquid Sodium/Molten Salt Receivers



non-solar energy systems, convection losses can be minimized by design, such as for enclosed fossil fired boilers where detailed analyses of these losses have not been necessary. This is not the case for most solar systems. The interface with solar radiation presently necessitates the use of an open absorber surface or cavity aperture. A more complete and reliable basis for examining convective losses is required.

A number of programs are currently being sponsored by the U.S. Department of Energy(DOE) to advance both the analytical and experimental basis for determining receiver convective losses(65). Nevertheless, reasonable estimates for design purposes can be made, even though they may tend to be optimistic, depending on actual operating conditions at a given site. Therefore, very little comment is warranted on the absolute validity of the radiation and convection related efficiencies in table 2.5, except to look for trends in the data. The 0.830 efficiency figure given for study 11 is low, apparently because of the presence of a reheat receiver which will provide for a superior thermal-electic cycle conversion efficiency for the water/steam system. Some representative cycle efficiencies are also given in the right column of table 2.5. The radiation and convection efficiencies for studies 4 and 7 are low because of the high temperature requirements (working fluid outlet temperatures are given in table 2.5). For the five flat receivers the estimates of radiation and convection loss are consistent at approximately 0.96. The estimates for cylindrical receivers vary from 0.83 to 0.96. These receivers vary in size but are all designed to operate at nearly the same temperature. Estimates for cylindrical receivers with a sodium working fluid vary from 0.92 to 0.96. With the exception of study 16, radiation and convection efficiencies given for cavity receivers are fairly consistent and are generally lower than those given for external receivers. Even though the effective absorptivities of the cavities are higher, there are additional radiation and convection losses to contend with. The receiver for study 16 is a quasi-cavity, a concave semi-cylinder, taking advantage of some of the properties of both cavities and open receivers. If the estimate of its thermal performance proves to be experimentally accurate, it will have a superior net receiver efficiency.

Net receiver efficiencies are reported in table 2.5 and are the product of absorption efficiency and radiation and convection efficiencies. The net reported receiver efficiencies vary from 0.79 to 0.93, with most falling around 0.90. The lowest value is from study 11, for a water/steam cylindrical receiver with reheat. Study 11 is consistently more pessimistic about performance efficiencies. The highest efficiency is from study 16 for the quasi-cavity molten salt receiver.

2.3.3 Net Thermal Efficiencies

Table 2.5 reports the net thermal efficiency of the twenty-two studies. The net thermal efficiency is annual thermal energy delivered to the process (to storage, to a turbine, to a chemical process, etc.) divided by the annual solar energy available to the collector field. The annual solar energy available is the annual direct normal solar insolation multiplied by the total reflective mirror surface of the collector field. Values given are taken directly from contractor reports where available. The values for net thermal efficiency are the product of the efficiency factors given in tables 2.3 and table 2.5. Not all studies report the same set of performance efficiencies. In some studies additional efficiency factors reported, such as piping losses, tower shading, receiver warm up, and parasitics, are listed in table 2.5 and are included in the net thermal efficiency. Net thermal efficiencies range from 0.52 to 0.75. Although study 1 supports the trend of improving collector efficiencies for small low temperature systems, it is not complete in scope and has not been previously reported. It was compiled especially for this report to form a more complete set of system sizes and to indicate a trend in performance and cost for small, lower temperature IPH heliostat systems.

There is a noticeable but only gradual dependence of net thermal efficiency on system size. Smaller systems are kept more efficient because of selection of a lower operating temperature. Studies 2 and 9 through 22 are designed for electric energy production and therefore trade net thermal efficiency against the thermal-electric cycle efficiency. If the larger systems were designed strictly for thermal energy production at lower temperatures, net thermal efficiencies could be improved over those shown. It seems likely that 65 to 70 percent efficiencies can be achieved for thermal energy production, and it varies little with system size, improving some for smaller systems operating at lower temperatures.

2.3.4 Heat Transfer Media, Storage and Cycle Efficiencies

The heat transfer media currently being considered for use in the receivers of heliostat systems are listed in table 2.6. Unless there are advantages for a specific application, (see reference 6) trade-off studies seldom show any cost/performance advantage for oils over an appropriate choice of one of the other media. An example of such a trade study is given in reference 29, the MDAC First Small Power System Experiment.

Hot air system designs with Brayton cycle receivers have been developed by a number of contractors, among them Boeing, Bechtel, Sanders, Dynatherm, and Black and Veatch(66-68). They range in size up to 260 MWt (Bechtel) and a 1 MWt receiver has been built and successfully tested at the CRTF (Boeing). The Electric Power Research Institute has assisted in the development of Brayton cycle receivers, by sponsoring a number of design studies and experimental tests. Four of the Brayton cycle receivers are shown in figure 2.2.

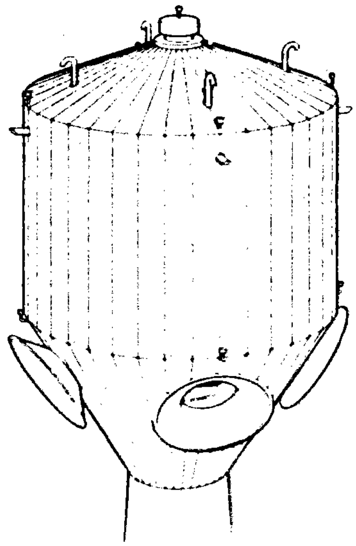
TABLE 2.6

Receiver Heat Transfer Media

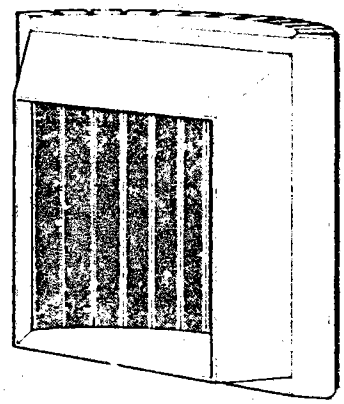
Type	Outlet Temp. (°C)	Advantages	Disadvantages
air	500-1100	low cost high temperature high cycle eff.	low density low heat capacity high thermal losses poor heat transfer no storage require regeneration
water/ steam	100-500	low cost established technology minimal pumping requirements	phase change high pressure alternate storage medium required
oils	200-500	low cost storage non corrosive low pressure	low temperature deterioration
salt	566	high heat capacity low cost storage good heat transfer low pressure high cycle eff. single phase	pump technology moderate cost deterioration corrosiveness
sodium	593	high flux density high heat transfer low pressure high cycle eff. single phase experience with nuclear	high cost confinement high reactivity

FIGURE 2.2 Brayton Cycle Receivers

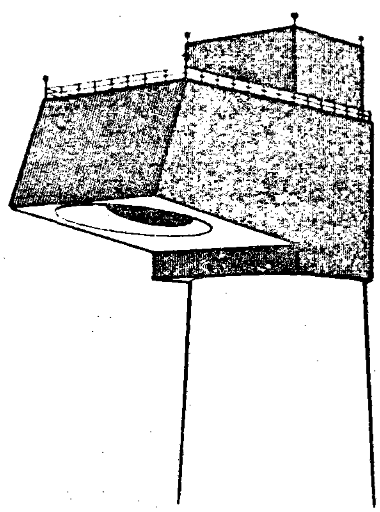
HOT AIR RECEIVER BOEING
ENGINEERING AND CONSTRUCTION



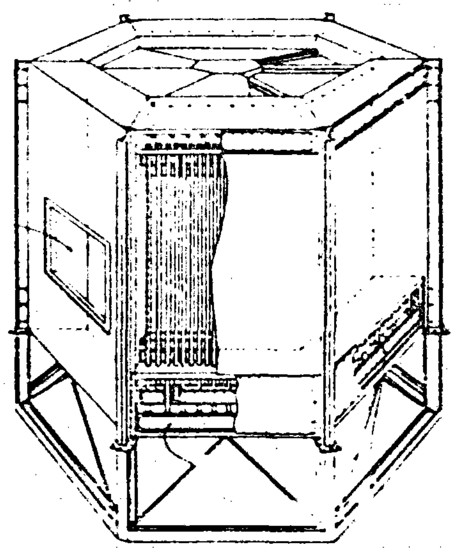
HOT AIR RECEIVER
DYNATHERM CORPORATION



HOT AIR RECEIVER
SANDERS ASSOCIATES INC.



Black and Veatch



The first U.S. operational central receiver system (Solar One, the Barstow Pilot Plant) will operate with an open cyclindrical receiver employing a single pass to super heat water/steam system. The receiver is coupled to a dual admission Rankine turbine that will operate at a nominal cycle efficiency of 34 percent. Operation from storage is at an efficiency of approximately 25 percent. Solar One is rated at 10 MWe and is designed as a one-tenth scale pilot plant for a 100 MWe commercial plant. Primary design advantages of the Solar One receiver are small size and low weight (lower cost of the rceiver and its support tower). More recent research into advanced water/steam systems has shown that higher operating pressures and an added reheat capability should boost the cycle efficiency to 42 percent. A study of receiver technology by Sandia National Laboratories Livermore(SNLL) indicates that recirculating solar boilers will improve the cost/performance of water/steam systems by permitting the use of less expensive receiver materials(33). This study also indicates that reheat is only cost effective in systems with capacity factors greater than 35 percent. (All the systems in the SNLL study are scaled to 100 MWe). Only in these higher capacity factor systems will the increased cycle efficiency pay for the reheat equipment.

Salt and sodium heat transfer fluids have been proposed in several advanced central receiver systems studies (21, 22, 26, 27, 69). Salt refers to a mixture of molten eutectic nitrate salts and sodium refers to liquid sodium metal. These media have higher densities and heat capacities than water/steam leading to higher heat transfer rates. They can be used for thermal storage, not requiring additional heat exchangers for storage in another media. They can operate without phase change (though they must be kept above the melting point) allowing for low pressure operation. They both can withstand higher solar flux densities than any of the other mentioned materials, sodium being able to withstand an even greater flux density than salt. The primary reason for introducing salt and sodium is that they can generate gross steam cycle efficiencies of from 40 to possibly 44 percent.

Some of the disadvantages of salt and sodium are rather obvious. Sodium oxidizes violently with exposure to air or water and must therefore be carefully contained. Sodium is also high in cost. Salt deteriorates through molecular decomposition and is corrosive. It must be replaced periodically. In addition, there are doubts concerning the development of pumps for salt commensurate with receiver tower heights. Cycle efficiencies for some of the systems intended for electric generation are given in table 2.5.

The study by SNLL(33) is the most recent effort to compare receiver technologies and working media on a systems level basis. Engineering and performance data from eleven design programs by ESG, GE, BEC, MM, BECH, CE, and BW were brought to a common basis by Sandia. Cost estimates were brought to a common basis by Kaiser Engineers. Systems were scaled to 100 MWe and 72$/m^2 (1979$) heliostat costs.

Bus-bar energy costs were determined as a function of capacity factor which was varied from 0.25 to 0.65. The results were grouped according to working media.

At a capacity factor of 0.40 salt systems had the lowest bus-bar costs, followed by sodium and advanced water/steam, with water/steam only slightly higher than sodium and with air systems at significantly higher cost. Additional data reported by the study at capacity factors greater than 0.4 showed salt systems decreasing further in energy cost with increasing capacity factor while sodium systems increased in energy cost with increasing capacity factor, widening the gap between salt and sodium at higher capacity factors. This latter result is highly questionable. There may have been a misinterpretation of contractor data. In view of numerous other analyses that have been done (some are addressed at other points in this paper), it is highly unlikely that energy costs for sodium systems would increase at higher capacity factors. They are expected to decrease.

The SNLL study recommends continued development of salt technology for large scale electric generation, but this evidence is not sufficient to warrant only salt being pursued aggressively. Salt, sodium, and advanced water/steam certainly appear to be the most cost effective for large systems, but there is no single superior system for all applications at this time. Research and development in all three technologies should continue until such time as a more definitive comparison can be made. We anticipate that with additional development salt and sodium working media for large systems will be the most cost effective choices for electric utilities. Water/steam will probably be first choice for many IPH applications.

2.3.5 Net Energy Analysis

Net energy analysis refers to a comparison of the net energy produced during the design lifetime of a plant to the total energy consumed to build and operate the plant. Meyers and Vant-Hull(70) have done a net energy analysis on a 100 MWe commercial central receiver plant with six hours of storage for electric generation. Data presented in study 19 are for a plant similar to this size. The net energy analysis (including electrical systems) concluded that the plant would produce electrical energy in its lifetime 20 times the energy required to create the plant. In addition, if the materials are recycled or perhaps the heliostats are rebuilt for use in subsequent plants, then up to 42 percent of the original energy investment is recaptured. This would increase the 20 factor to 35. The thermal energy produced by the plant (without recycling) is 60 times that required to create it(1). Even though the energy required to build a plant is rather high, the plants can be extremely energy efficient.

2.3.6 Available Analytic Computer Programs

Table 2.7 summarizes some of the computer programs most commonly used for design and analysis of heliostat systems. The development of most of these programs was sponsored by the U.S. Department of Energy, and they are available, upon request from their originating organization. A great many other computer programs are being used by organizations involved in the development of heliostat systems: government, national laboratories, and private industry. Many of the programs used by private industry other than those listed in table 2.7 are proprietary; therefore, no attempt has been made to list them here.

Potential users of these computer programs should consult the references given here and the originating organizations concerning the types of analyses, capabilities, methods, computer requirements, and limitations of each program.

2.4 Expected Performance Improvements

2.4.1 Collector Fields

At the present time, only second surface silvered glass mirrors have the necessary durability to meet reasonably long lifetime requirements. Within the framework of this technology we might expect improvements in heliostat intrinsic reflectivity of perhaps several percent. The most important requirements for maximizing net reflective efficiency will be maintaining effective cleaning schedules while taking advantage of rain and snow when possible.

Cosine efficiency and shading and blocking efficiency are a result of the collector field layout process usually involving cost/performance optimization. There is no reason to assume that these factors should change significantly.

Interception efficiency trades with receiver losses. With advances in receiver technology, e.g., control of the radiative and convective losses, it may be possible to improve the interception efficiency by designing larger receiver apertures. Improvements in interception efficiency may be, at most, one percent or less. The cost of significant improvements in heliostat tracking accuracy and focusing capability for the purposes of increasing interception are not likely to be worthwhile.

In summary, we believe cost effective improvements in net collector efficiency will probably be limited to less than a few percent over the values given in this report. Let us keep in mind, however that significantly lower heliostat costs will result in the desirability of less efficient physical performance (more shading and blocking, larger fields, more south heliostats) when the design is

TABLE 2.7

Analytic Computer Programs

Name	Originating Organization	Application	References
RCELL	UH	Collector Field Optimized Design	58,71
NS	UH	Cellwise Optical Systems Analysis	72
IH	UH	Optical Systems Analysis by Individual Heliostats	73
CREAM	UH	Cavity Radiation Exchange Analysis	74
HELIOS	SNLA	Optical Analysis of Solar Concentrators (Cone Optics)	75
MIRVAL	SNLL	Optical Analysis of Central Receivers (Ray Tracing)	63
DELSOL	SNLA	Systems Design of Central Receivers	76
STEAC	SNLL	Systems Analysis for Electric Energy Production	77
SOLSTEP	PNL	Solar Plant System Simulations	78
BUCKS	SNLL	Solar Electric Plants Economic Analysis	79
STMPPS	AC	Pilot Plant Dynamic Simulation	80

cost/performance optimized.

2.4.2 Receivers

For applications involving receiver surface temperatures less than 400°C selective absorbers are available which can increase absorptivity and decrease radiation losses. At present, there are no selective absorbers that can operate at the high temperatures of most central receiver systems. Even with a technical breakthrough in the development of high temperature selective absorbers, the net receiver efficiencies of most systems could increase by only a few percent.

At the present time, the use of cavity receivers looks more promising. The increase in effective absorptivity is considerable and radiation losses decrease. The use of cavity receivers will require minimization of convection losses. There is considerable research under way at the present time, both analytical and experimental, devoted to convective thermal losses from receivers(65). With continued effort in this area we expect technical improvements that could enhance receiver net thermal efficiencies by perhaps as much as 3 to 5 percent. Two drawbacks to the use of cavity receivers are the desirability of lower absorptivity materials to achieve more uniform flux distributions and the heliostat field restrictions of a single cavity. Usually multiple cavities will be required.

One method to control receiver losses may be the use of a window in the cavity aperature. This concept was considered early in receiver development but has been largely abandoned in current design work due to materials problems. The most promising materials have been quartz and sapphire. Sapphire has obvious high cost problems. All materials have the problem of reduced optical efficiency for the optical radiation entering the aperture. Broad band antireflection coatings will not stand up to the operating temperatures. Windows must be kept clean. Any particulate contamination on a window during operation will create hot spots that can damage the window. There is, nevertheless, considerable potential for development in this area of receiver windows that could significantly increase receiver thermal efficiencies.

2.4.3 Thermal - Electric Conversion

The most promising near-term prospects for more efficient thermal to electric conversion are with the advanced water/steam, salt, and sodium systems being developed at the present time. As shown in table 2.5 gross cycle efficiencies of up to 44 percent are expected. High cycle efficiencies are also being developed with Stirling cycle heat engines powered by hot air cavities. These are expected to develop up to 48 percent engine efficiency and 40 percent combined receiver and engine efficiency(81). They are primarily being developed for small systems (small central receivers and parabolic dishes). Since the heat engine and cavity receiver are integral, they are not likely to be used in larger central receivers due to increased weight of the receiver and consequent increased tower costs. Additional performance improvements beyond these predictions are not likely without significant new breakthroughs in an already well developed technology.

Any improvement in performance represents a corresponding improvement in the cost of energy produced. A one percent improvement in performance means that one percent fewer heliostats can generate the same energy. This represents a cost savings of $6.5 million in a large first plant with 50,000 heliostats.

2.5 Economic Assessment

2.5.1 Heliostat Costs

The most dominant single cost item in central receiver systems is heliostat cost. First plant heliostat costs ($\$230/m^2$) can represent from 45 to 70 percent of the total solar plant cost, depending upon system size. Nth plant heliostat costs ($\$80/m^2$ to $\$120/m^2$) represent from 20 to 35 percent of the total solar plant cost. Considerable effort has been expended in recent years to design the low cost heliostats. Typically, they have been designed to performance requirements similar to those listed in table 2.8 which have been taken from reference 26. The most definitive and most recent cost and production studies for heliostats have been done by PNL(49) and GM(50).

TABLE 2.8

Typical Heliostat Design Requirements(26)

Slew Rate	15 deg/min
Reflector Pointing Error	1.5 mr
Beam Quality Error	2.2 mr
Operating Temperatures	-30 to 50°C
Operating Sustained Wind Speed	12.0 m/s (26.8 mph)
Survival Gusting Wind Speed	
In Stow Position	40 m/s (90 mph)
In any position	25 m/s (50 mph)
Stow Position	Inverted

Each of these studies involved a detailed piece-by-piece examination of the cost of producing the MDAC invertable, second generation heliostat. This heliostat is shown in figure 2.3. Results of the PNL and GM studies are shown in table 2.9. The 1979 dollar column contains the original results and the 1980 dollar column is computed assuming a 10 percent general inflation rate. The guideline heliostat cost ($230/m^2) set by SNLL is from the low production rate, PNL study.

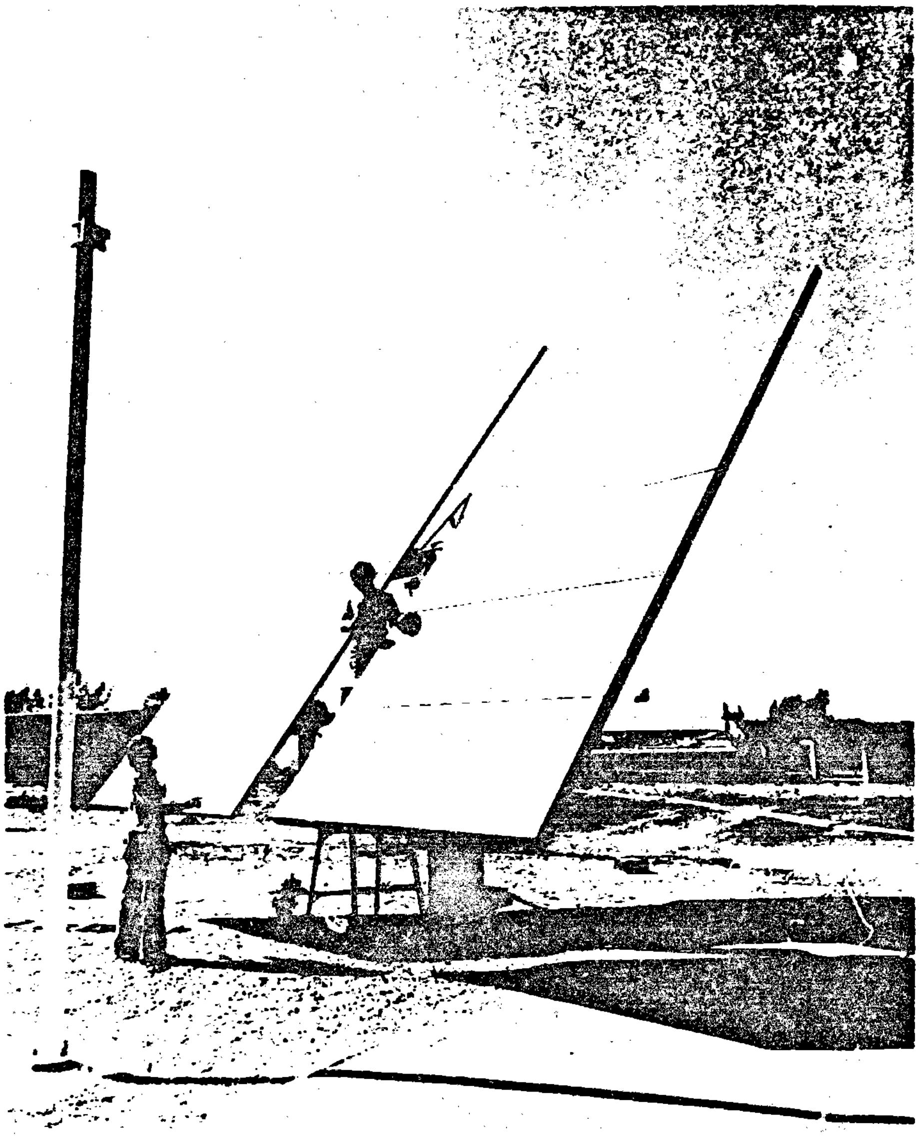
TABLE 2.9

Heliostat Cost Analysis Results

Production Rate (/yr)	Cost($1979/m^2)	Cost($1980/m^2)
2,500 (PNL)	187-215	205-237
25,000 (GM)	122	134
250,000 (GM)	89	98

The $134/m^2 figure represents a realistic near term (5 year) prospect for heliostat costs, and the $98/m^2 figure represents a realistic long term (15 to 20 year) prospect. In the next section, the capital cost estimates of the twenty-two design studies presented in section

FIGURE 2.3 McDonnell Douglas Second Generation Invertable Heliostat



2.2. will be scaled to the latter two heliostat costs and combined with scaled performance data to develop a set of cost/performance figures of merit.

Additional heliostat cost data is presented in figure 2.4. This graph was prepared by ESG and includes production cost estimates by Martin Marietta, as well as, Battelle Pacific Northwest Laboratories, and General Motors Transportation Systems Center. The information content of figure 2.4 is similar to that presented in figure 1.5, but represents a refinement in terms of production rates based on numbers of commercial electric plants built per year. The scales used in figure 2.4 bring out the asymptotic behavior of the cost data. These data indicate that the $\$134/m^2$ cost figure can be achieved by building less than the equivalent of one commercial plant and the heliostat costs will level out at approximately $\$98/m^2$. Since these cost production studies were completed, additional design analysis has been done to lower heliostat costs still further. An example is the heliostat shown in figure 1.1 where, the inverted stow requirement has been eliminated. It is expected that further cost reductions can be realized by the use of design concepts especially adaptable to mass production and by a relaxation of some of the design specifications. Design specifications are discussed in more detail in section 2.5.4.

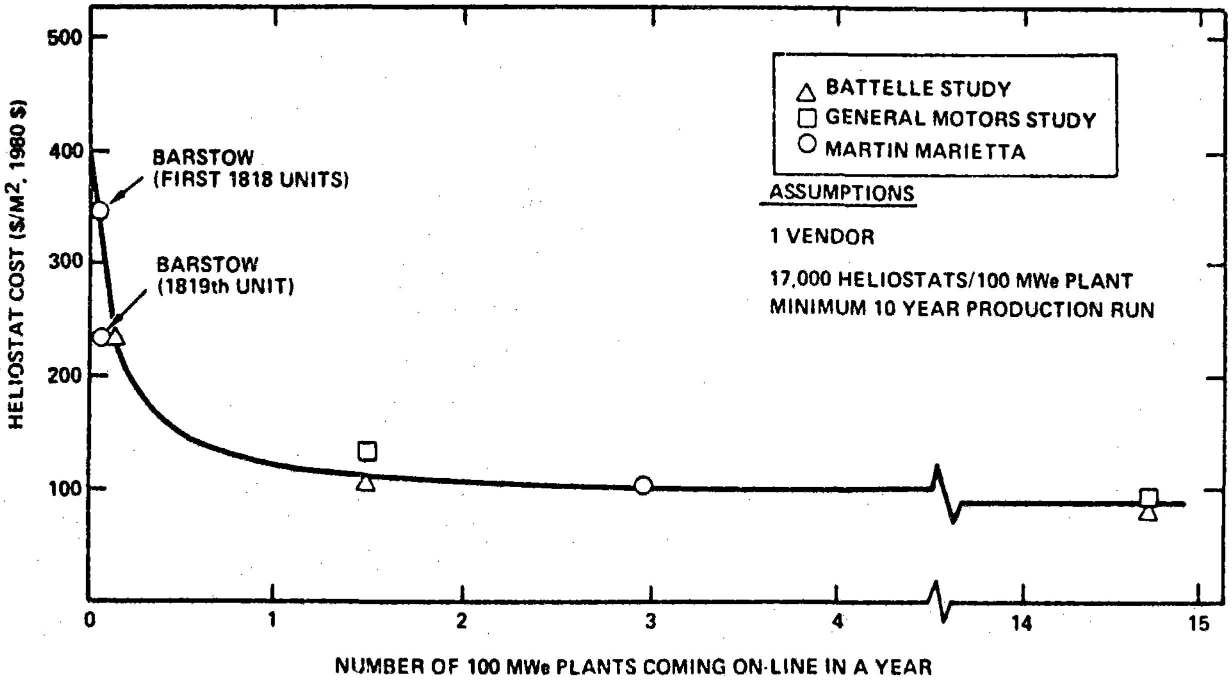
Large scale mass production will provide the primary expected economic improvement in heliostat costs. The GM study(50) estimates that a \$96 million (\$87.3 million in 1979\$) investment is required to establish a 25,000 heliostat per year manufacturing facility and that a \$432 million (\$392.8 million in 1979\$) is required to establish a 250,000 heliostat per year facility. We see the establishment of the 25,000 per year facility as the most realistic economic scenario for the near term. As the market permits, this manufacturing facility can be expanded to increase its production rate, requiring only a reasonable additional capital investment. This would be followed by the construction of additional plants in response to an unfolding market, each with production rates perhaps greater than 25,000 per year.

2.5.2 System Costs and Scaled Cost/Performance

The thermal performance and capital cost data from the twenty-two design studies presented in table 2.2 have been scaled, and the results are listed in table 2.10. The annual thermal energy of each study is scaled to a representative value for annual direct normal insolation. Capital costs based on $\$230/m^2$ heliostats are scaled to $\$134/m^2$ and $\$98/m^2$ heliostats. Scaling by these parameters is not totally sufficient to bring the cost/performance data of the studies to a common basis. However, this level of scaling is felt to be the minimum required to make any reasonable examination or comparisons. No attempt has been made to do any scaling of system sizes. It is

FIGURE 2.4

EFFECT OF MARKET ON HELIOSTAT COSTS



Rockwell International
Energy Systems Group

80-D16-109-9

TABLE 2.10

Design Studies Cost/Performance Comparison (1980$)

Id. No.	Annual Energy Scaled to 2.5 MWh/m^2 (MWh)	Capital Cost 2 Scaled to 134 $/$m^2$ (M$1980)	Capital Cost 3 Scaled to 98 $/$m^2$ (M$1980)	Annual FM ($/MWht)[1]	Lifetime[2] FM 1 ($230/$m^2$) (mills/kWht)	Lifetime[3] FM 2 ($134/$m^2$) (mills/kWht)	Lifetime[4] FM 3 ($97/$m^2$) (mills/kWht)	Id.No.
1 UH	909.4	0.250	0.227	340.9	11.363	9.164	8.321	1
2 MDAC	9,594.	1.956	1.715-	269.1	8.971	6.796	5.959	2
3 NI	25,715.	4.832	4.209	250.7	8.358	6.264	5.456	3
4 BEC	28,800.	6.840	6.077	306.2	10.207	7.917	7.034	4
5 MDAC	31,864.	9.797	8.997	376.6	12.553	10.248	9.412	5
6 MM	62,300.	10.181	8.697	225.2	7.508	5.447	4.653	6
7 PFR	72,879.	19.239	17.068	341.3	11.376	8.800	7.807	7
8 FWDC	94,246.	17.103	14.654	248.9	8.297	6.048	5.182	8
9 JPL	103,198.	17.933	15.392-	237.7	7.923	5.792	4.972	9
10 BY	160,285.	41.149	37.056	323.0	10.766	8.557	7.706	10
11 EPE	194,947.	72.844	65.037	477.6	15.919	12.455	11.120	11
12 GE	306,477.	89.845	81.118	367.0	12.235	9.772	8.823	12
13 ESG	352,679.	80.316	70.417	328.9	10.964	7.591	6.655	13
14 ESG	501,282.	107.88	93.580	289.3	9.642	7.174	6.223	14
15 ESG	517,717.	91.422	76.026-	253.7	8.458	5.886	4.895	15
16 MDAC	721,483.	153.29	135.73	275.6	9.187	7.082	6.271	16
17 MM	714,143.	160.25	141.19	293.6	9.787	7.480	6.590	17
18 ESG	860,797.	146.34	121.86-	243.8	8.126	5.667	4.719	18
19 MDAC	1,247,962.	235.38	200.49	261.1	8.705	6.287	5.355	19
20 MM	1,567,856.	249.91	204.59-	328.3	10.944	5.313	4.350	20
21 ESG	2,491,041.	422.79	348.99-	246.6	8.219	5.657	4.670	21
22 ESG	3,747,000.	614.40	504.29-	240.2	8.007	5.466	4.486	22

1. Capital Cost 1 divided by the Scaled Annual Energy
2. Capital Cost 1 divided by the Scaled Lifetime Energy (Design life multiplied by annual energy)
3. Capital Cost 2 divided by the Scaled Lifetime Energy
4. Capital Cost 3 divided by the Scaled lifetime Energy

\- Indicates nearest cost to the design basis not the purpose of this report to make direct comparisons or to rank the sytems in any precise order of economic desirability. There are a wide variety of underlying assumptions, differences in analytical design techniques, and differences in costing methods among the various contractors that are beyond the scope of this paper. For these reasons and due to the large number of economic parameters involved, we make no attempt to independently generate bus-bar energy costs. The intent behind table 2.10 is to present a minimal number of fundamental system design parameters and to apply simple linear scaling to eliminate those factors that cause the most significant differences in reported design data. It is assumed that this will allow us to look for consistencies in the data, as well as general trends and develop some guideline cost/performance parameters.

The scaled annual thermal energy produced by each of the twenty-two representative systems is given in the first column of table 2.10. It has been formed from the design annual energy and annual insolation given in table 2.2. For scaling purposes it was necessary to adopt a representative value for annual insolation. The value 2.5 MWh/m^2 (annual direct normal) was chosen. There is no special significance to this particular value other than it is an approximate average for the southwestern U.S., and is representative of many sites with favorable insolation. Areas in southern California, Arizona and New Mexico can exceed this value, but it is typical for California, southern Nevada, northern Arizona, central and northern New Mexico, and west Texas. In studies where receiver thermal losses were reported as a percentage of incident energy it was necessary to scale the design annual energy linearly, multiplying by the ratio of 2.5 MWh/m^2 to the design annual insolation. In cases where absolute annual thermal losses are reported or could be easily computed, receiver losses are added to the annual energy to form the annual incident energy, which is linearly scaled, and the losses subtracted from the result to form the scaled annual energy.

The next two columns in table 2.10 are formed from the capital cost 1 given in Table 2.2 with the collector field portion of the costs scaled to $\$134/m^2$ for capital cost 2 and $\$98/m^2$ for capital cost 3. Collector field costs are subtracted from the total capital cost forming the balance of plant cost. The collector field cost is scaled by the factors 134/230 or 98/230 and the balance of plant cost added on. In cases where the design work and cost estimates were originally done at costs nearer the $98 value, capital costs 2 and 3 are formed from the original cost estimates and capital cost 1 represents scaled up collector field costs for these plants. In tables 2.2 and 2.10 the "-" after the capital cost indicates the cost nearest to that cost used for the field design. In all cases 1978 and 1979 dollars were converted to 1980 dollars by multiplying by 1.21 and 1.10, respectively, before any scaling was done.

The annual figure of merit reported in table 2.10 is formed from the capital cost 1 divided by the scaled annual energy. The lifetime energy for each plant is formed from the scaled annual energy multiplied by the design life of the plant. Most of the studies reported here specify a 30 year life. Since the same heliostat costs are used for all the studies, and there has been no concerted effort in any of these studies to produce significantly lower costs based on shorter design lives, it has been assumed the design life for all systems is 30 years. Without further information it would be an arbitrary penalty to any of these systems to do otherwise. A set of three lifetime figures of merit is given in table 2.10. These are formed from capital cost 1, 2 and 3, divided by the lifetime thermal energy produced. The lifetime figure of merit (LFM) 1 is representative of first plant costs and LFM3 is representative of nth plant costs.

The lifetime figure of merit No. 3 (LFM3), given in the right column of table 2.10, shows no significant trend as a function of system size, with the possible exception that the LFM's for studies 13 to 22 fall more consistently into a narrower range of values. The mean LFM3 of all twenty-two studies is 6.3 with a standard deviation of 1.8; the mean LFM3 of studies 13 to 22 is 5.4 with a standard deviation of 0.9; and the mean of studies 1 to 12 is 7.0 with a standard deviation of 2.1. Using these figures as crude guidelines we may isolate studies 5, 11 and 12 that appear to be somewhat pessimistic compared to the norm and studies 6 and 20 that are fairly optimistic compared to the norm.

The LFM3 of study 11 is relatively high because of both low performance efficiency estimates and high cost estimates. Among the net thermal efficiencies given in table 2.5, study 11 has the lowest value of all the studies except for the high temperature cavity system of study 7. Let us compare the capital cost no 1's and the overall system sizes for studies 10, 11, and 12 given in table 2.2. For system size, use the number of heliostats as an indicator. System 11 is not much larger than system 10 but the capital cost is closer to that of system 12. Allowing, of course, that there may have been special requirements for this particular study, the cost estimate is significantly higher compared to the norm.

The LFM3 of study 5 is relatively high. This is apparently due to a high cost estimate and the fact that the fraction of these costs in the collector field is low, since there is less benefit in scaling to the lower heliostat costs. Comparing studies 5 and 6, the number of heliostats more than doubled in study 6, but the capital cost no. 1 increases by only 14 percent. The results from studies 1 to 12 indicate that not only is the cost of 5 high but the cost of system 6 is low.

In a comparison of the capital costs of studies 12 and 13, the fraction of capital cost represented by the collector field is lower for 12 than 13, resulting in less of a cost reduction in scaling to lower heliostat costs, and this results in a relatively high LFM3 for study 12.

The LFM3's of studies 6 and 20 are slightly optimistic compared to the rest of the studies. Performance parameters for these studies show no significant variations to produce this result. The value of LFM1 for study 20 is high compared to the other large systems. The differences in LFM1 and LFM3 for studies 19, 20 and 21 indicate that study 20 has a high fraction of the capital cost in the collector field. The LFM's of study 6 are consistently lower than other small system studies. Cost estimates, therefore, for studies 6 and 20 appear to be somewhat optimistic compared to the balance of the studies.

In view of the number of independent design efforts represented by the twenty-two studies* and the generally high level of sophistication that has been developed for performance and economic analysis of heliostat systems, we feel extremely confident that heliostat systems can produce solar thermal energy in the southwestern United States with a capital cost (interest and O&M costs are not included) of 4.5 to 7.0 mills/kWht (1980$) for a 30 year lifetime. Note that this figure is not the usual mills/kWh to utility customers but the capital investment divided by lifetime thermal energy produced.

2.5.3 Review of Other Economic Assessments

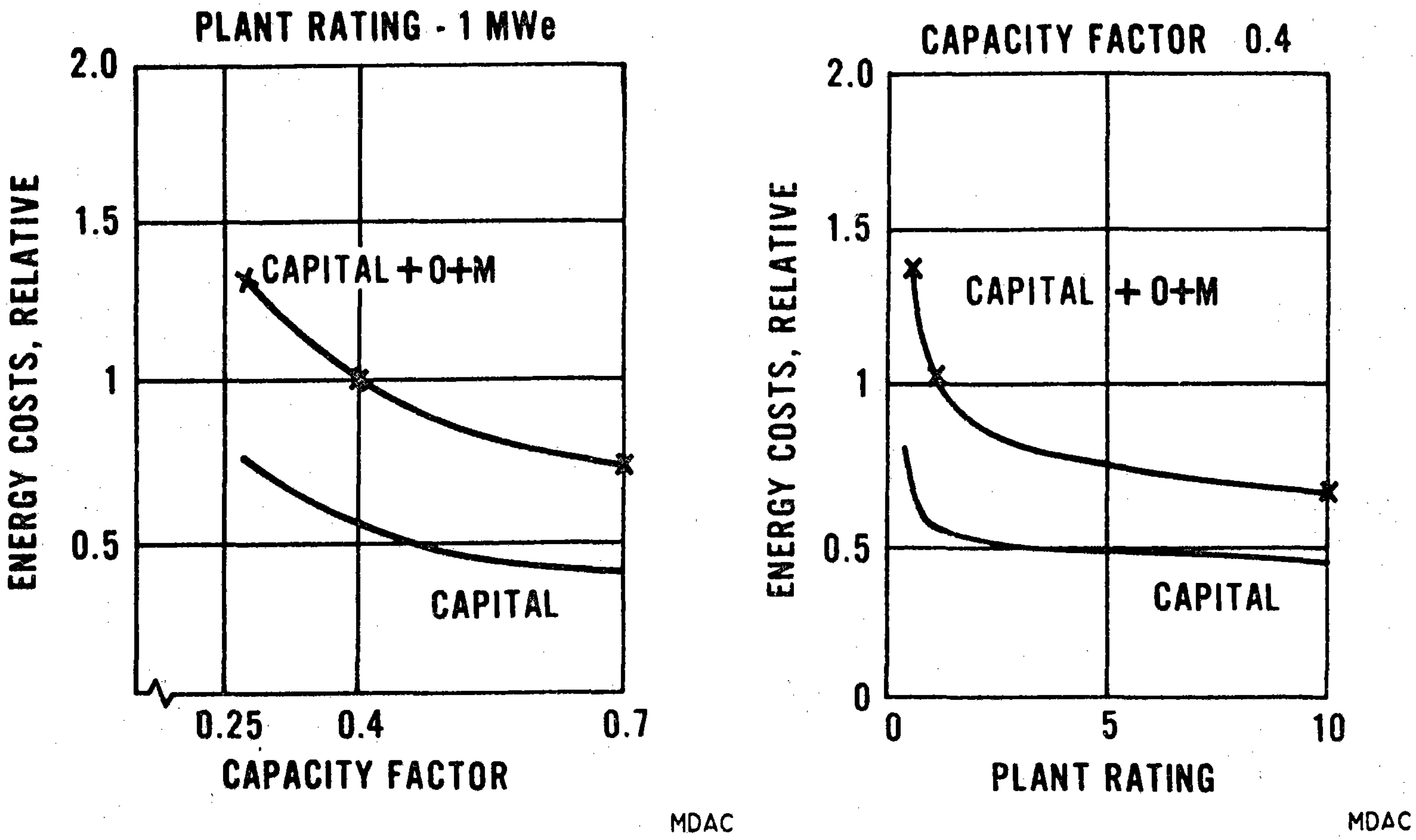
There are many recently published economic assessments that reveal information on the potential of heliostat systems to achieve economic viability and displace fossil fuel use. We have selected studies by MDAC, MM, ESG, AND SERI for comment. The comments are to highlight important findings and note potentially misleading information.

The first economic assessment considered is that of MDAC. Starting in 1973-74 in the early stages of the funded studies, they were pioneers in putting forth cost estimates and methodology that have stood the test of time. The capital costs for some MDAC studies are given in tables 2.2 and 2.10.

They have also put forth sensitivity results in a study for the 0.5-10 megawatt range(29). These results are shown in figure 2.5. The two lower curves are for relative capital costs. Please note that cycle efficiencies assuming the use of radial out-flow turbines for 0.5 MWe and 10 MWe are taken as 0.365 and 0.394 respectively or only about a 10 percent change from the large to the small. The smaller systems, aside of constant capacity factors, are more capital

*If organized into independent groups, there are eleven independent cost analyses and seven independent performance analyses.

FIGURE 2.5 Results of a Sensitivity Analysis by McDonnell
Douglas Astronautics Corp.



intensive and have a higher operating and maintenance cost. For a 0.5 MWe plant production rate of 10,000 plants per year and 10 MWe plant production rate of 500 per year or for about equal total power production, the capital cost per unit power for the smaller 0.5 MWe units is really only about 10 percent larger than the 10MWe units. This can largely be explained in terms of cycle efficiency. However, there are real added costs of installing a small system. You must buy a site plan, obtain permits, and operate each site. The O&M costs for these plants are about three times larger for the smaller than for the larger unit resulting in double the BBEC for the small units. This added maintenance cost is attributed to the need of 5-10 specialists required fractionally at each site.

Let us compare the O&M costs for a 0.1 MWe plant with a 100 MWe plant. A 100 MWe plant requires an estimated 45 man years per year for O&M and thus, assuming a linear relationship, a 0.1 MWe plant could be allocated about 12 man days per year(24). This means that small plants must utilize part-time, perhaps non-resident staffs at an increased cost. This added O&M cost makes the totally stand-alone small systems like flat plates and photovoltaics more attractive than small plants requiring maintenance. A minimal size cost effective solar thermal system would require at least two full time maintenance personnel. This would result in a plant size of about 4 MWe to keep maintenance costs equal to that of a full 100 MWe plant. It is also at this plant size that current comparisons of solar-thermal electric systems show point focus central receiver systems ranked higher than all other types of systems (33,34,82).

The results of a Martin Marietta study(11) of levelized costs of energy in 1980 dollars focuses on IPH costs. Shown in figure 2.6 are the baseline thermal energy costs for oil in $ per MBTU, along with solar thermal energy costs vs. heliostat costs. At the present cost of heliostats, solar towers can compete with present oil prices, and mass production of heliostats will improve this situation.

The Rockwell International(ESG) data on a range of systems are shown in figure 2.7 in 1978 dollars(41). These results are in levelized BBEC versus capacity factor. For curves in the figure heliostat costs are goal costs at $\$65/m^2$ ($\$79/m^2$ in 1980$). The economic assumptions are given in table 2.11. Absolute numbers are not as important as the relative numbers. These are results of a single study with economic parameters and capacity factors applied uniformly to all systems. The major short term goal of the solar tower program is to penetrate the intermediate market and not baseload. There is a large requirement for intermediate or non-baseload electricity in the Southwest; i.e., when there is sunshine you need electricity. Baseload coal and nuclear plants to date have produced cheaper electricity than we expect from first generation solar plants; however, they would not work effectively or be competitive in the intermediate mode. This is explained by the lack of full time use of capital and the wear and tear on cycling a baseload plant. Nuclear

FIGURE 2.6 Effect of Heliostat Cost on Energy Cost - Martin Marietta

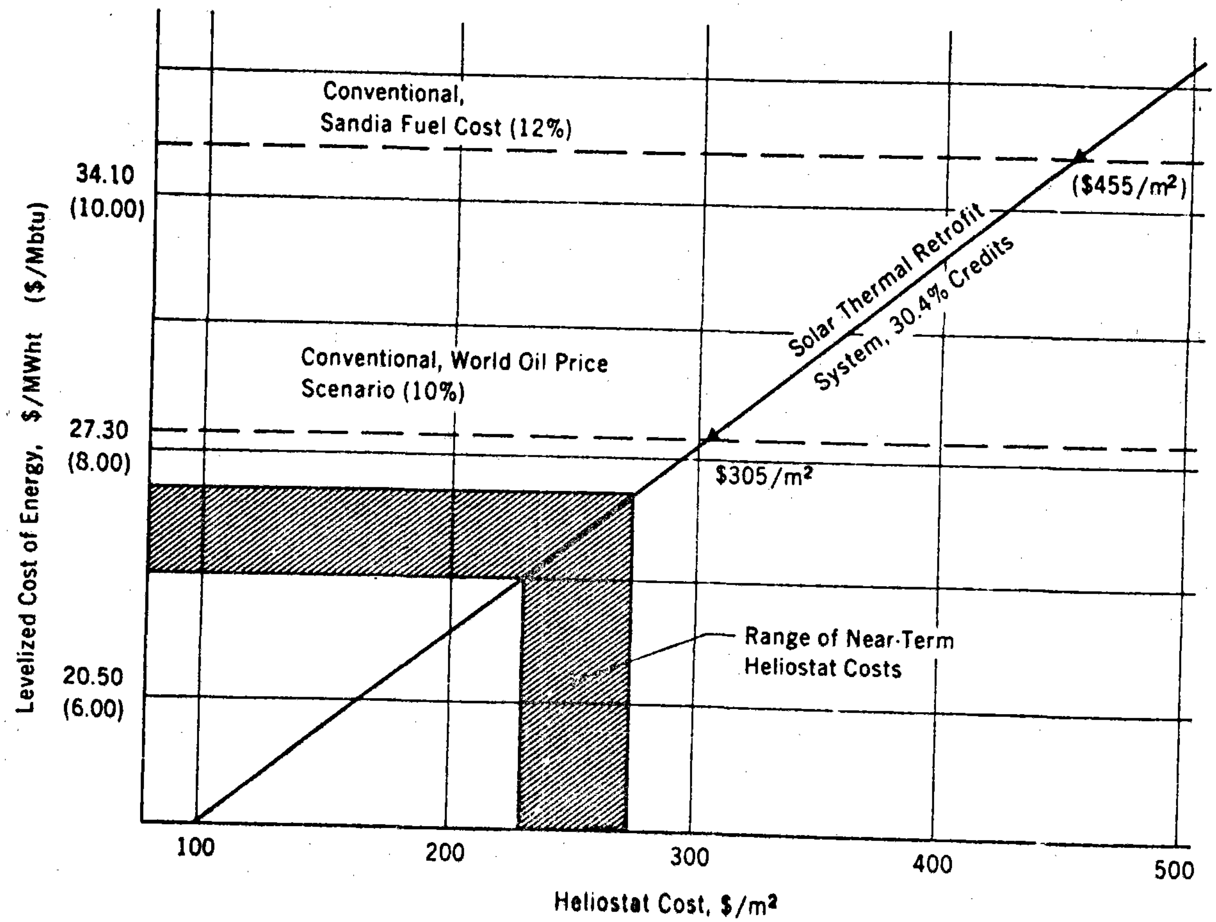


FIGURE 2.7

BUSBAR ENERGY COSTS - - -SOLAR 'STANDALONE' PLANTS

SODIUM CONCEPT SOLAR CENTRAL RECEIVER

(1990 START OF OPERATION)
ESG BASIC ECONOMIC MODEL

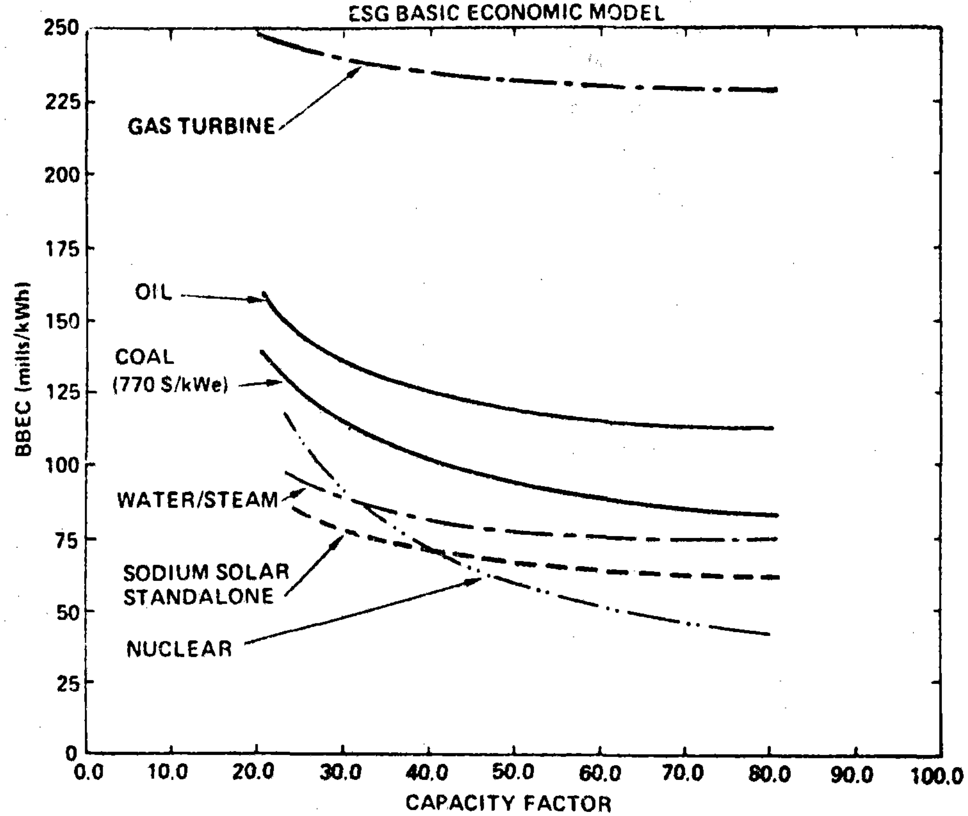


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TABLE 2.11

ECONOMIC ASSUMPTIONS FOR SOLAR PLANT STUDIES

	BASIC (ACR)	REQUIREMENTS DEFINITION DOCUMENT (HYBRID)
• COST OF CAPITAL (WEIGHTED AVERAGE AFTER TAX)	8%	10%
• ESCALATION RATES		
▪ CAPITAL INVESTMENT	6%/YEAR	10%
▪ OPERATIONS AND MAINTENANCE	8%/YEAR	8%
▪ FUEL (GAS, OIL, OR COAL)	8%/YEAR	10%
▪ GENERAL INFLATION	6%/YEAR	10%
• PLANT LIFE AND AMORTIZATION PERIOD	30 YEARS	30
• START OF OPERATIONS	1985 AND 1990	1990
• CAPITAL INVESTMENT CASH FLOWS	ONE YEAR BEFORE INITAL OPERATIONS	AFDC (20%)
• ANNUAL INSURANCE	0.0025 OF CAPITAL	SAME
• ANNUAL PROPERTY TAXES	0.02 OF CAPITAL	SAME
▪ OPERATIONS AND MAINTENANCE – FIXED	1%	1%
– VARIABLE	% OF FUEL COST*	SAME
▪ FUEL – OIL	2.55 $/MBtu	2.00
– COAL	1.45 $/MBtu	1.00

*10% FOR OIL, 20% FOR COAL PLANTS; FOR FGD ADD 10%

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80-J29-1-27

and baseload coal plants are not designed to go up and down every day. If nuclear is to provide intermediate electricity in the future, additional storage or load management costs will have to be included. The solar stand-alone component in a southwest grid could constitute at least 20 percent grid penetration. Hybridization, i.e., introduction of plants using both gas or oil and solar, could greatly increase penetration. We believe solar plants will have a distinct advantage over coal and nuclear due to an estimated short term construction period of approximately three years. Also, solar plants could be used in the desert Southwest with dry cooling towers. Dry cooling would reduce efficiency and increase cost by a few percent; however, dry air cooling towers are a proven technology. This technology is not suitable with nuclear water reactors because of the low temperature thermodynamic cycle.

SERI has studied the viability of solar thermal heat. Provided heliostat cost goals are met, solar produced process heat is clearly viewed as competitive(42). A recent study of the distribution of U.S. industrial process heat (IPH) usage by SNLL sheds important light on numbers of facilities and their energy use(82). Currently, 48,282 facilities ranging from 0 to 1000 MWt in size, consume 10.65 quad per year. Many small facilities (isolatable processes within industries requiring a specific temperature) tend to require lower temperatures. In terms of numbers, 60 percent of the facilities are less than 3 MWt and operate at less than 230°C(450°F). However, most of the energy consumed is in the larger size facilities, and they tend to require higher temperatures. Facilities greater than 3 MWt consumed 94 percent of the energy with 70 percent of energy use in facilities ranging in size from 30 MWt to 300 MWt. Less than 15 percent of that energy is required at 230°C or less. Thus, the greatest impact on U.S. IPH energy consumption must come from large systems. This finding is parallel to findings for electric generation.

A good comparative study by SERI involving electric power production in the range of 0.1 - 10 MWe has nevertheless added a degree of confusion(34). This study and later associated reports do not clearly indicate the basis of smaller designs and performance data. From the study one may conclude that smaller systems cost less per kilowatt, producing energy more cheaply than larger systems. Clearly very small central receivers cannot operate at high temperatures and thus lose second law thermodynamic efficiency. However, heliostat systems can collect first law energy very efficiently at lower temperatures and still possess the advantage of a common collector area with single receiver. The parabolic dish system, however, has second law advantage for [redacted]all sizes. The parabolic systems have a large potential market, but energy costs produced with small units will be inherently higher. In terms of first law efficiency, heliostat system cost projections have repeatedly been found to be better than dishes and tracking troughs where curved surfaces are required. For heliostat fields with less than ten units receiver costs begin to dominate and reduce the advantage of a single receiver.

The uncertainties that still arise in the various comparisons largely stem from not giving appropriate parameters related to the first and second laws of thermodynamics. The first law parameter should be capital dollars per kilowatt hour-thermal-lifetime, and the second parameter should be the operating temperature. At least two parameters are always required. If the cost per kilowatt thermal or electric is given, the capacity factor must always be given. When the cost of energy delivered is given, such as levelized BBEC, the economic model and O&M costs must also be given. The adoption of a standard set of economic parameters is essential. Comparisons to previous work should also be made. All of solar needs to be more quantitative.

2.5.4. Expected Economic Improvements

A number of possibilities are available for reducing heliostat costs beyond those costs indicated in table 2.9. The heliostat shown in figure 1.1 is a further refinement over the heliostat shown in figure 2.3 for which costs were derived in the PNL and GM reports. Lower cost figures are expected if this heliostat is subjected to the same detailed cost scrutiny. Additional improvements are expected with later, more cost effective heliostats specially designed for mass production.

There are potentially several other ways to reduce heliostat costs, some of which involve re-assessing the design specifications(38). One is to eliminate the inverted stowage requirement. This has already been done in the heliostat of figure 1.1. A second lowers the wind load requirements. This may be done, for example, by surrounding the collector field with berms to reduce the wind and lower stess on the more vulnerable perimeter heliostats. This would allow reductions in drive component sizes or permit more area of glass on each heliostat. An additional possibility may be elimination of communications wiring through the use of FM or laser communications.

Cost benefits are also expected from improvements in construction techniques and in limited mass production numbers for receivers and storage systems. Prospects for solar utilization have stimulated new interest in low cost thermal and electric energy storage and in efficient low loss transmission of thermal energy. Developments in these areas will synergistically boost the cost effectiveness of all types of solar systems.

No large improvements in turbine and generator costs are expected since these are already mature technologies.

Government support is required before the first heliostat manufacturing plant can be built. The technology and the market are not fully demonstrated as required by utilities and their customers. Once the initial inroads are established, such as two or three fully operational energy plants and one heliostat manufacturing facility, the support can give way to tax incentives, and the technology will soon carry itself in the market place.

3.0 INSTITUTIONAL FACTORS

3.1 Solar Technology - User Interface

The ultimate large scale utilization of solar energy lies largely in the private sectors. This requires the involvement of the user in the early phases of the program, and answering the problems of the user as early as possible. Working together at all levels - from R&D to full implementation - is required for new technical developments. Cost sharing with the final user at an early stage has many merits. The government risks are reduced because officials find themselves dealing with talented, interested, and capable professionals. This is true for utilities and much of industry; they have the talent and capital to evaluate worthwhile projects and put them in place.

The first users must receive some incentive, presumably on some serious cost shared basis. The early high risk efforts, of minimal value to the user but of great value to the nation, will require cost sharing by the government. Later, as acceptable commercialization is accomplished, federal cost sharing decreases. Energy use in this country has been shown to be proportional to previous subsidy, and solar will be no exception. The solar community will never mature if it naively accepts the challenge from the in-place energy producers that the first solar plant must be competitive before it will be used. Solar needs research funds and initial commercialization incentives resembling those granted the oil and gas industries. One way is through tax incentives.

The first most likely users for the central receiver are the electric utilities followed by industrial process heat suppliers and heating utilities. The major requirement of a utility is to provide a reliable product at lowest cost. Because of strong profit regulation of utilities, reliability is often more important than cost, i.e., fuel cost escalations are passed on to the user. On the other hand, a public or private utility is forced to keep rates as low as possible because of public utility commissions and general public pressure. This pressure, often too intense, results in foregoing research to improve costs in future years because of emphasis on restricted budgets in the current year. Research always has some element of risk, yet in restricted budgets the first to be cut is anything involving uncertainty. Also, solar is commonly perceived to involve elementary technologies and it is difficult to develop patents for marketing advantages to protect initial investment. Lack of research is a general problem of business, the tendency to sacrifice future improvements for short term profits. This attitude makes acceptance of new capital intensive solar more difficult even with zero fuel costs.

The Electric Power Research Institute (EPRI) is a major research effort by the utilities. They have been authorized since 1973 to levy a surcharge against the utility customer for developement of research dollars; however, the total funds available are relatively modest compared to the problems that need to be solved. There needs to be some cost sharing with the Federal Government since all utility customers will benefit from many advances made by EPRI even though some are not under the EPRI umbrella. Also the pressures on EPRI come from many directions, not just alternative energy development, but rather improvement in present fossil systems, solving nuclear waste and safety problems, transmission line development and others.

Special attention should be given to unique problems faced by utilities in alternative energy development. It is not sufficient for the government to develop a product to within a factor of 2 of competitiveness and expect commercialization to be passed off smoothly to the utility. The government can ill afford many large scale projects, yet we believe it is necessary for government involvement and cost sharing with the end user (utility or IPH) in the first four to ten significant projects. The government cost sharing should decline with each project. The utility or end user in each case should be given authority and responsibility to move the contract to rapid completion. If each of these projects were developed with different utilities and different vendors, the competition requirement of the public could be met. This would promote the best projects and move them rapidly from research to implementation.

Solar will ultimately become competitive, but under present world conditions this could be much too late. Government can play vital roles in solar thermal growth.

3.2 Role of Government in Technology Development

The U.S. Government through the Department of Energy has conducted a highly commendable program to stimulate the development of solar energy in this country. The introduction and support of a new technology, although initially uneconomic, is certainly a proper role of government for the long term benefit of the country. As a result of this effort we have advanced significantly toward implementation of energy production by solar systems. With the current situation of dependence on foreign oil and the concerns within the nuclear industry with regard to safety and waste management, we must develop every possible, reasonable source of energy. If we wait until the demand for energy is so high and the supply of oil is so low that solar has "become economic," it will be too late to develop this industry. The government could clearly assist in research and early implementation with rapid phase out as commercial feasiblity is established.

Diversity in the methods of applying solar to energy production has resulted in considerable misunderstanding. In an effort to eliminate development of uneconomic systems, considerable funds have been spent for systems studies, evaluations, and rankings. The primary failure has been a lack of response to the findings of these studies and the diversion of funds and efforts into the most economic concepts. Because of pressures from many groups to support yet another new system, it has been difficult to move ahead rapidly on the more viable concepts.

One of the most important findings of the past few years has been that the increased quality in energy production from tracking collectors far outweighs the additional cost of tracking mechanisms required. For applications above 200°C (392°F) three primary systems emerge; the central receiver, the parabolic dish, and the parabolic trough. Of these, the central receiver has been repeatedly evaluated as the most cost effective system for significant impact on energy production. Also, the cost of energy for first systems is now within a factor two to three of cost competitiveness with fossil fuels. The sheer magnitude of these projects does not assure commercialization. There is a parallel consideration from nuclear or synthetic fuels. There is no single Fortune 500 company that can handle the whole project and our antitrust laws may prevent them from working together.

A major problem for any government agency involved in R&D, such as the DOE, is obtaining reliable reviews of new proposals by objective non-profit oriented referees without the review group becoming interested in researching the problem themselves. There is a great possibility for the government review process to promote its own growth. There is a tendency for the bureaucracy to expand to handle the new problem in-house with the result that little funding remains available for outside research. Funding cuts are, in effect, absorbed by industries and universities even if there is little money to be managed by the governmental groups. What we need is energy and what we want is competition in energy. To achieve both we need the involvement of the free enterprise system and universities. Yet government forces are required to assure competition.

3.3 Incentives, Barriers and Impediments

Oil and gas and nuclear use in the U.S. have been shown to be proportional to subsidy(83). The oil and gas industry have had an enormous subsidy in the form of a depletion allowance. Nuclear energy has had enormous support both from present fuel production subsidy as well as long term support for the reactor program. Excess profits are better handled by plow-back provisions, fostering more competition rather than less. We need government investment in energy and support of technology development to a point where industry will apply private funds and realize a profit.

Energy and natural resources play a peculiar role in a free-marketplace system in comparison to other goods and services. Many goods and services can either be in short supply or oversupply and the economy responds through the law of supply and demand. However, in the case of energy there is a more serious aspect. Energy shortages affect almost every aspect of American life. When rapid escalation of energy costs is experienced, other product supply and demand behavior can become nonlinear. There is no historical precedent for catastrophic energy shortages, where we may be immediately faced with irrational reaction, chaos, and nuclear war. The need for a sound energy policy is as strong as the need for national defense.

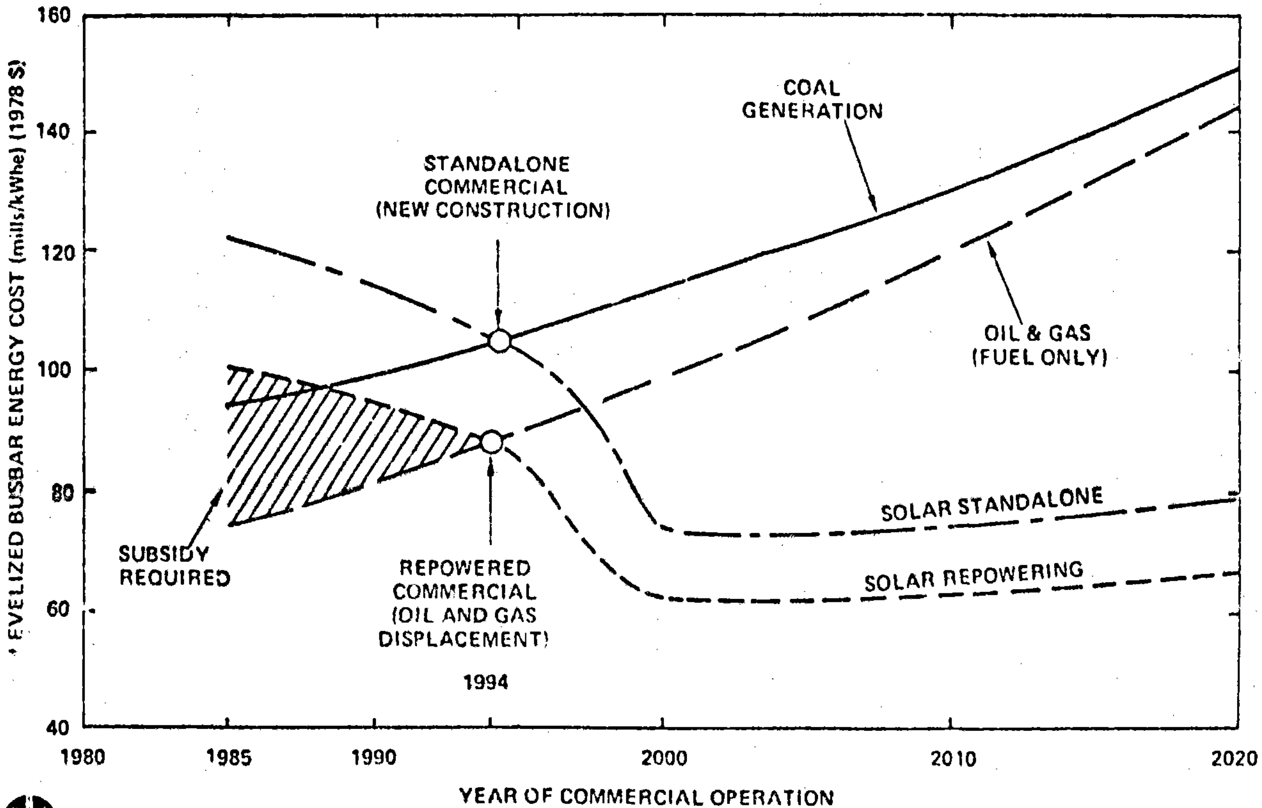
A major requisite for the implementation of heliostat systems is the development of initial plants and the availability of hardware. Heliostat production in sufficient quantities for solar to be cost competitive with conventional sources depends on the existence of an active market, i.e., the commitment to build several plants. The commitment to build several plants, however, will rely heavily on assumptions about heliostat costs in mass production and the availability of those heliostats. Only with government stimulation can we solve this "chicken and egg" type problem. A detailed example of a scenario for government support is given in section 4.3.

Sufficient tax incentives or write-offs to encourage several manufacturers to build component manufacturing facilities will solve the problems of component cost, such as heliostats. Also, the user or utility could be given a tax credit or write off for purchasing first heliostats that do not provide the normal economic return. To take advantage of these incentives, utility investors will have to receive consideration from the local PUC's or obtain an acceptable arrangement with a third party. The third party arrangement would consist of a new entity that can benefit from tax credits where the utility investor cannot. The third party constructs a solar plant, possibly with a guaranteed loan, and sells steam to a utility at an acceptable price. Such tax incentives help identify the market for the manufacturers of equipment and the users of the energy such that manufacturers and the utilities can arrive at an agreement.

There is also a need for additional risk reduction by demonstration of hardware beyond the Solar One plant to convince the utility-industry complex to undertake full scale implementation. Rockwell International has estimated the economic barrier to implementation of solar thermal electric between now and the year 2000(84). Figure 3.1

FIGURE 3.1

"TYPICAL" ENERGY COSTS
CONSERVATIVE PROGRAM (NO.1)



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shows the differential in projected cost of energy for repowering and stand-alone plants as a function of the year of the start of operation of the plant. The cost of heliostats starts at $\$250/m^2$. This chart is based upon certain assumed factors relating to the rate at which the plants are built and the cumulative number of heliostats produced in time.

This particular scenario assumes that one 30 MWe repowering plant goes on line in 1985, that a 60 MWe repowering plant goes on line in 1989, and that two 100 MWe plants with six hours of storage go on line simultaneously in 1995. Since the cumulative number of heliostats manufactured increases with each plant, the cost of energy continues to decrease until about the year 1998. At the same time, however, the cost of oil and gas continue to rise (assumed to be 2 percent over general inflation). Where the two BBEC curves intersect is an approximate measure of the year of commercialization. If one compares the solar repowering energy cost with the fuel-only energy cost, the crossover is about 1994. The cross-hatched area between the two curves is a measure of the portion of the plant cost that requires support or incentive (see figure 3.11). The cross-hatched area relates only to the needed cost sharing of the required plant and does not reflect the fact that industry will invest millions of dollars in capital equipment to produce the components that go into the plant. At least part of this investment would also need to be subsidized until there is reasonable assurance that enough plants will be built to get the central receiver concept at least near its commercialized (economic) point. We emphasize this situation because it relates to the amount of subsidy required to stimulate the market so that the ultimate central receiver cost goals can be met expeditiously. The scenario that forms the basis for this chart results in the achievement of only about 0.1 quad by the year 2000. More aggressive scenarios must be implemented requiring a minimum of two to four vendors simultaneously designing and constructing repowering demonstration units.

To meet an ambitious national goal of solar implementation, a number of key factors must be present in order for utilities to buy solar electric plants at the required rate: (1) technology readiness must be demonstrated, (2) competitive economics must be demonstrated to satisy utility management, (3) an adequate industrial base must be present, and (4) a favorable regulatory climate must exist.

Technology readiness is really only achieved by demonstration of large size plants operated in a utility environment. According to a utility advisory committee, a one to two year demonstration would probably be the minimum required to bring technical risks down to a level acceptable by the utilities.

Competitive economics will occur when the proven cost of solar plants, as evaluated by a utility, is less than the oil, gas, or coal costs which it is displacing. A utility must compare a large initial capital investment versus yearly fuel costs which are expected to inflate over the life of the plant. Like any other large system, the solar-thermal-electric system is expected to have higher costs associated with early lead units. Solar plants carry the benefit of fixing the cost of the energy they produce during their lifetime (usually 30 years). The only costs that can escalate are O&M costs.

Subsequent cost reduction is contemplated as learning takes place with investment in automated, high-volume production. At the current first-of-a-kind solar costs, our studies indicate that solar thermal would not be competitive until gas and oil prices escalate substantially. Left totally to free market forces, solar thermal would not be competitive until after the year 2000. Without government market stimulation, the national stated goal of 0.4 quads, requiring some ninety 100 MWe plants, cannot be realized.

The government can assume two prime tasks in encouraging commercial acceptance: (1) cost-sharing large scale demonstration plants to reduce technical risks to acceptable commercial levels, and (2) providing direct subsidies to utilities to offset the first-of-a-kind portion of the cost and the unusual risks associated with building early plants.

In return for this government investment, government objectives are achieved in reduced oil imports, reduced natural gas consumption by the utility sector, reduced environmental risks due to the use of coal and in the implementation of national solar goals.

Discussions with utilities and their management indicate their willingness to share a portion of the early plants to the level of competitive value. Although definitive numbers must wait until repowering conceptual studies are complete, preliminary estimates indicate that utilities could provide up to an average of 25 percent of the early plant cost.

Considering the time involved in demonstrating the technology to utility satisfaction, the earliest this cost-sharing could occur is about 1987. This leaves only 13 years to build up the industrial base necessary to manufacture the 90 plants required to meet national solar goals. Industry will need to invest several hundred million dollars in order to build the manufacturing capabilities necessary to supply the heliostats and balance-of-plant components. Substantial investments will be required by industry before a self-sustaining competitive market is etablished without the need for government market subsidies. We expect that industry will be reluctant to make large investments until government policies appear stable and new ventures appear manageable and profitable. A change in administration policy or political climate could jeapordize capital investments.

The proposed DOE solar repowering concept is an ideal vehicle by which to introduce solar into the utility environment, since it makes use of already existing utility equipment. It therefore minimizes government support while directly reducing oil and gas consumption in those plants. The equivalent of about 635,000 barrels of oil per year can be saved by each 100 MWe repowered plant with six hours of storage. We feel, therefore, the repowering program should be a government high priority effort for Fiscal Year 1981. It is a natural extension of the central receiver concept presently being tested at Barstow. Rockwell International(ESG) commercialization studies show that a minimum of three parallel large repowering programs using several different technologies need to be started now to demonstrate the technology, provide utility acceptance, and establish the necessary competitive industrial base to meet the national solar goals. In order to do this, three parallel design studies should be initiated in FY 1981. It is estimated that this would be at a government cost of $50 million in FY 1981. In this connection, NSF, ERDA, and now DOE management have fostered widespread participation of new industry teams.

We endorse an aggressive repowering program to include the design of a minimum of three parallel repowering plants to start in FY 1981. The government role should envision three major contributions to the repowering program: (1) a direct market subsidy in terms of grants to the utilities, (2) cost-sharing of the necessary capital required by industry, and (3) covering the "open end" or risk associated with early plants. Utilities should be expected to contribute only the portion of the plant of economic value. Multiple vendors of differing technologies are necessary to minimize risk and ensure that industrial capacity is available when the large number of plants need to be supplied. Sodium and salt technologies are recommended for demonstration of electric utility projects, whereas steam and air may be preferred for industrial process heat demonstrations.

Finally, we would like to say that repowered solar plants and hybrid-solar plants could competitively displace significant quantities of oil and gas before the year 2000. We believe considerably more than 0.4 quads can be displaced provided we move very aggressively along a directed program.

Capital requirement for cost sharing of first plants that would be viewed as risks by the PUC's and the rate payer can be met partially by the utility, possibly with participation of state governments. Repayment of funds can be made by the participating utility upon plant start-up.

Funds for implementation of solar thermal commercialization could be secured with modifications of the Synfuels Program as proposed by Senator Matsunaga of Hawaii. He proposes that 2 billion dollars be taken out of the Synfuels Program to be used by solar. He argues that the 2 billion dollars would produce more results from solar than from synfuels.

The declaration of a national solar goal is very helpful to set the attitude of industry and utilities. It remains to be seen where the new administration's area of emphasis on solar will be. If national goals neglect solar to 2050 and beyond, this technology will not have a foreseeable impact on our energy problems. If it is given a significant place in our energy spectrum for 2000, we will benefit from it each and every year. A reaffirmation of goals and a planned program are needed for solar to maintain momentum.

3.4 Social and Political Barriers

Few perceived social barriers prevent implementation of solar programs. Most people believe solar should have a long term place in our energy picture and are ready to encourage implementation now. There are, however, some who are mixing solar technology development with political ideology. Their attitude largely centers on a perceived failure of our cities and large institutions as well as our energy supplies in the big oil companies and utilities. Despite the fact we have a very high standard of living in this country, some self-appointed political leaders essentially decide on a blanket restructuring of everything they perceive as faulty. First, it must be said that everything in the oil and utility area is not faulty and, second, the "blanket fix" is often worse than the problem.

Inefficiencies of technology seldom dictate the return to a divided system even though there are strong pressures for that today. Two power systems are generally more expensive to operate than one system twice the size. Statements have been made that because a gigawatt nuclear plant requires a back-up unit, three, 300 megawatt units would be better. This does not indicate smaller systems are more desirable but rather that backup is needed regardless of size. It is a question of statistics not size. Multiple systems have a lower probability of failing at the same time. We all know that any system can fail and that we need one, two or maybe ten backup systems to absorb the failures. The need for hundreds or thousands is absurd. There will always be economy of scale demanding relatively large units with the constraint of statistics mandating a required minimum number. A gain in statistical reliability for any total system must be weighed against losses due to the lack of economy of scale. Those who favor small systems would have you believe that each small community, and even individual homeowners, should produce their own energy. There are no real technical or economic data to support the argument. Small communities can often benefit greatly from use of local energy plants, but this in no way implies that smaller systems produce energy cheaper than large systems. The small user often pays more because he will not benefit from economy of scale.

Proponents of small systems have led opposition to solar thermal central receivers because the equipment appears to fit into a scheme of large centralized systems. In fact, the principles of central receiver concepts can be applied with economy to a great variety of sizes, thus appropriately matching a greater variety of applications. As opposed to the very small solar systems serving individual residences or buildings, we envision the emergence of new concepts in utilities, serving small communities, isolated communities, industrial complexes, remote industries, rural communities and other specialized customers. These utilities will meet the need for reliable electric and heat generation at costs not subject to excessive escalation. These applications are large enough to take advantage of economy of scale; yet they are small enough to meet the special needs of isolated sectors within the country. Heliostat systems with energy storage and a conventional fuel back-up can meet size and reliability requirements and help to limit the cost of energy.

Of paramount importance in the face of energy limitations is population control. Every child born above replacement level limits our freedom of action especially as our space and resources become more limited. There are no real quality of life improvements possible if the population growth continues. Hopefully our new found methods of communication during the last century will permit us to understand the economics of population before it is too late. Our tendency as a civilization however is to only do those things we absolutely have to after it is too late.

The problems of energy are not only matters of economic supply and demand but also of national security. If we cannot make our system work at home, we can hardly hope to live in harmony with the many new players abroad defending their own interests. If the U.S. cannot solve its energy problems within continential boundaries with all our available technology, how much more difficult will be the task for the Third World countries. We need to lead in population control and energy developement for all of civilization.

4.0 RECOMMENDATIONS

4.1 Federal and State Policy

4.1.1 Federal Policy

Assistance to utilities through cost-sharing, tax forgiveness, and grants or guaranteed loans is essential to demonstrate and build the first 3 to 5 solar thermal plants including Solar One. This should be acceptable to the public as a whole since utilities simply cannot alone do the job of developing renewable resources. Local utilities do not have the charter to conduct research and development at the expense of their local rate payers. If there is no support or definition of market, solar will be kept out of the market by the in-place energy companies, and utilities will have to pass on all fuel escalation costs to their customers. This may be in the short range interest of the local rate payer but not in his long term interest and certainly not in the national interest. Acceptance of delayed profits should be encouraged by giving write off consideration to solar implementation. Tax credits should be given over a period of time for solar implementation.

As in the development of the synthetic rubber industry in World War II, loans and abbreviated tax write offs should be used to encourage construction of a number of component manufacturing facilities. This would stimulate the availability of low cost components and foster competition essential to any solution of our energy problems.

Encouragement of third party involvement is needed in developing and selling solar produced energy to utilities. This is necessary at present where utility regulations are largely designed for low to modest capital investment and generous fuel-pass-through clauses for power production. Solar power is different. For solar, you essentially must pay for the fuel supply for thirty years at start-up through the capital investment. Many utilities are ready to buy acceptable new energy sources, provided they can somehow get it into the rate base. Unless intelligent decisions are made to include solar in our energy mix, it is not clear that the solar transition will ever occur in a timely manner. Only through mass production can we reduce heliostat cost and only through market identification can we increase demand. Synthetic rubber production in World War II was not fostered by supply and demand market forces and probably would not have occurred in time. New energy production is even more crucial now, since energy shortages could lead to World War III. We are very concerned about giving excess profits to industry, but utilities are now regulated sufficiently to prevent excess profits. We as a nation are the benefactors of an energy policy that stimulates the development of solar energy as a viable non-depleting energy source. In summary, the recommendation for the federal sector is to move ahead by working with the in-place utility structure and other industries to develop competition in renewable energy.

4.1.2 State Policy

Many states can benefit from state support of solar programs. A Federal-State cost sharing approach should help in getting the first few heliostat power plants in place and in reducing heliostat costs to goal level and below. Through Federal-State cost sharing a national program can be put in place. The most important aspect of state policy would be to encourage utility involvement. A more flexible regulatory environment is needed to allow the utilities to develop alternate energy sources. State support of in-state solar projects will improve local economies (use of local labor, local manufacturing) and promote the national image of the state. We need to assist utilities in producing cheap solar electricity and not try to regulate cheap solar electricity. Regulation will not work in countries contending to have a free market.

In a similar manner to the Federal level, states should, where possible, give fast write-offs and tax breaks for equipment manufacturing plants. They should give tax considerations for purchase of solar equipment. They should encourage cost sharing between utilities and rate payers to develop new sources and encourage delayed profit sharing. The states should be willing to cost share with the Federal Government on utility projects that are profit controlled. The states should support the development of HVDC transmission, ~~heat~~ transmission (such as EVA-ADAM) and heating utilities.

4.2 Utility Development

4.2.1 Electric Utility Development

The development of solar energy for utility grids should be strongly encouraged and supported. The large number of rural utilities can be expanded and assisted in supplying our energy needs. We need to continue development of statistically reliable low cost of electrical energy systems. This is not possible with insistence on a number of small single stand-alone units. Utilities should not bear the brunt of our population problems alone. Clearly, electric energy transmission is a socially equitable means of energy distribution and is of prime importance to the country. Our technology and social structure have in part taken their form based on its existence. We believe there are no comparable, acceptable systems with the exception of other utilities such as gas utilities. Electric utilities can be improved by guaranteeing a sufficient number of operating units to ensure uninterrupted service and utilizing sufficiently large units to provide ever present economies of scale. With the advent of silicon controlled rectifiers it is now possible to stably interconnect systems by means of high voltage direct current(HVDC) lines. HVDC permits long distance ties through more economic transmission and less adverse environmental impacts.

Every indication is that electric generation will have significant impact on our liquid fuel needs in the not so distant future, especially in the transportation sector. Individual electric vehicles can readily meet our short distance, daily transportation needs, and electric mass transit can meet the needs of our cities as well as provide for high speed long distance travel. The conversion to electric based transportation may appear to skeptics to be a large, untenable perturbation to the structure of society, but we believe the structure is much more flexible than it may appear and significant changes can take place in one or two decades. The benefits of a conversion to electric transportation are enormous and needed by our society. First, we can generate electricity from many sources such as coal, oil, nuclear, solar-thermal, photovoltaic, ocean thermal, and biomass, whereas combustion engines require high quality liquid fuels. Second, electric vehicles generate little or no pollution. It is much easier and cheaper to clean up emissions from our electric generation facilities than it is to clean up emissions from each individual automobile. Third, the use of fuels to generate electricity for transportation can be more efficient than direct combustion transportation. Fourth, with anticipated breakthroughs in battery technology the vehicles themselves may be less expensive than combustion vehicles.

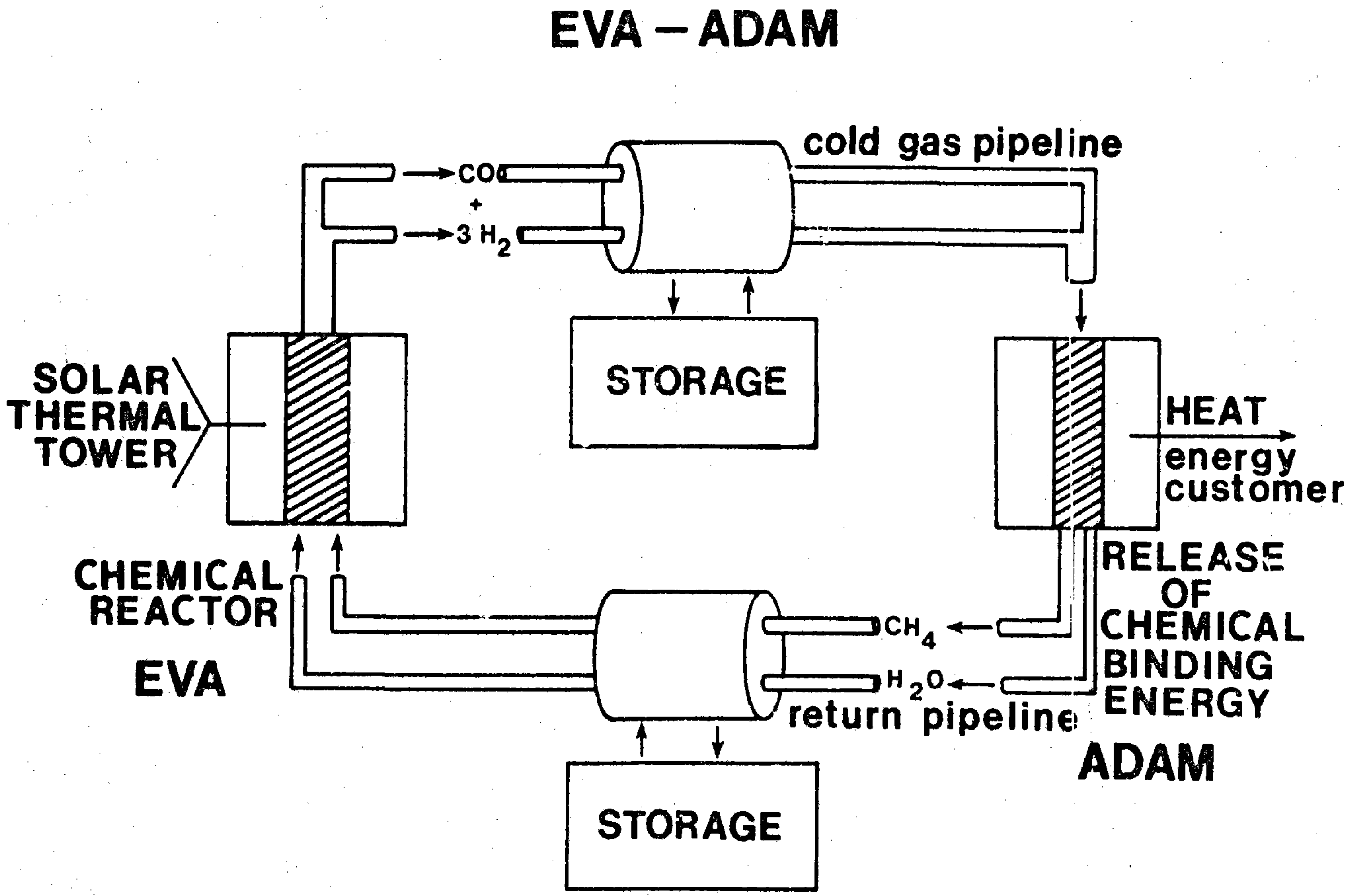
4.2.2 Heating Utilities

Transmission of thermal energy via direct heat or chemicals will soon be possible over distances of 10 to 50km and with low loss. The Germans are developing a methane-water decomposition-recombination cycle called EVA-ADAM for distributing high temperature gas reactor (HTGR) heat for distances of 50 to 100km. Their requirement is more for process heat than electrical energy. Chemical heat pipes or chemical closed transmission cycles offer efficient means of transmitting solar heat, HTGR heat and heat from large coal furnaces. These cycles have a higher efficiency in transmitting heat than electric transmission preceded by a thermodynamic cycle. The schematic for a closed cycle system appropriate for solar applications is shown in figure 4.1. The products are not consumed but used to transmit energy chemically much in the same way freon is used in air conditioning circuits. Here the chemical binding energy of the water gas reaction is used instead of the heat of vaporization in freon. The reaction for the EVA-ADAM system is

$$CH_4+H_2O+Heat=CO+3H_2$$

Heat is used to disassociate methane and water into carbon monoxide and hydrogen. The user some distance away recombines the carbon monoxide and hydrogen into methane and water over a catalyst resulting in the extraction of the binding energy heat. This "chemical heat pipe" approach avoids the delivery problem faced with conventional nuclear reactors intended for delivery of steam. Steam lines of 10km and longer are now prohibitive, and this limitation adversely affects use of reactors for process heat delivery. Additional problems are the adverse impact on real estate near a reactor and the reluctance of an industry to accept a single reactor as a source of supply. Solar tower parks, HTGR's, coal furnaces and even fusion systems, should they develop, could supply and deliver energy over reasonable distances and not adversely affect real estate values. Heat could also be delivered via salts or oils over shorter distances, but further modeling studies are needed for these applications.

FIGURE 4.1 Chemical Heat Pipe Concept



A very sizable solar IPH market is available through utility development. Development of IPH on an industrial, case by case basis, is commendable, but many industries do not have the capital or manpower to develop and maintain the required heat source. They would much rather buy a service from a heating utility or third party. The product delivered could be process steam at a standard temperature and pressure. The heating utility aspect for solar and other energy alternatives will require some new policy and legislative considerations on both the Federal and State levels.

In conclusion, it is hopeful that the status and outlook of the program is well enough understood to carry solar thermal developement into commercialization. This was the goal set by the original NASA/NSF Study Group in 1972, which we still believe was a timely effort leading to laudable decision.

4.3 Commercialization

Heliostats are in a state of technical readiness to permit application to repowering and commercialization by 1991. From estimates recently supplied by Rockwell, a most probable path to commercialization requires $745 million support from the government with $1.93 billion investment by industry and utilities by 1991, the point of commercialization. With no further expenditures by the government, the utilities would be expected to invest an additional amount of $24 billion by 2000. This is the amount required for attaining the 1.0 quad goal in the solar thermal sector by 2000. The cost of intermediate solar electricity in 1991 in constant 1980 dollars would be 82 mills/kWhe and declining. In table 4.1 is shown the government incentives required to obtain 0.1 and 1.0 quad of energy from heliostat systems according to two scenarios proposed by Rockwell International(ESG). The figures for 1.0 quad development are based on an accelerated pattern of development. Notice how nearly equal the total incentives are for the two programs. The 1.0 quad program is of even greater value since solar systems will operate in the free market five years sooner than in the other scenario. Table 4.2 shows the cash flow schedule given by ESG to implement commercialization by 1991. Table 4.3 shows the accumulated capacity, natural gas savings, and cost of energy under such a program. The implementation of the 1.0 quad program would be largely in the Southwest. A survey by ESG reports the distribution of potential electric and IPH users on a state by state basis (Table 4.4).

TABLE 4.1

GOVERNMENT INCENTIVES FOR TWO SCENARIOS#

	CASE 1	CASE 2
ENERGY LEVEL BY YEAR 2000	0.1 QUADS	1.0 QUADS
YEAR OF COMMERCIAL VIABILITY	1996	1991
PLANT COSTS UNALLOWED BY PUC	$408 M	$332 M
HELIOSTAT MANUFACTURING INVESTMENT	$253 M	$330 M
BALANCE-OF-PLANT MANUFACTURING INVESTMENT	$55 M	$161 M
TOTAL GOVERNMENT INCENTIVES*	$564 M	$735 M

*THIS TOTAL REPRESENTS THE UTILITY/GOVERNMENT COOPERATIVE USING SHORT-TERM AMORTIZATION OF MANUFACTURING FACILITIES BEFORE THE YEAR OF COMMERCIAL VIABILITY

#COURTESY OF ROCKWELL INTERNATIONAL (ESG)

ASSUMPTIONS

GENERAL INFLATION RATE AT 8%
GAS ESCALATION RATE AT 10%
COST OF GAS = $2.50/MMBTU

TABLE 4.2

REPOWERING CASH FLOW SCHEDULE*
(MILLIONS OF DOLLARS)
(SHORT-TERM AMORTIZATION)

	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	TOTAL
	← DEMONSTRATION PHASE →						← EARLY COMMERCIALIZATION →					← COMMERCIAL →		
FEDERAL SHARE	4	6	48	48	48	0	10	13	88	219	261	0	0	745
	4	6	1	1	1	0	10	13	2	2	2			
	TITLE I	TITLE II	TITLE III				TITLE 1	TITLE II	TITLE III					
NONFEDERAL SHARE	0	0	64	64	64	0	0	0	96	588	1051	1789	1788	5505
TOTAL	4	6	112	112	112	0	10	13	184	807	1312	1789	1788	6250

*COURTESY OF ROCKWELL INTERNATIONAL (ESG)

TABLE 4.3

SOLAR CENTRAL RECEIVER FUEL SAVINGS & ENERGY COST#

	YEAR							
	1993	1994	1995	1996	1997	1998	1999	2000
MWe (CUM)*	1020	1620	2820	4010	5970	7920	10,620	13,220
CUM* GAS SAVINGS (10^9 FT^3)	90.4	158.2	276.3	444.6	694.5	1,026	1,471	2,028
BBEC (mills/kWhe)	82	82	82	81	81	81	81	81

*AS OF BEGINNING OF YEAR
#0.5 QUADS IN 2000
COURTESY ROCKWELL INTERNATIONAL (ESG)

TABLE 4.4

ELECTRIC UTILITY AND IPH
CENTRAL RECEIVER USERS#

POTENTIAL LOCATIONS BY YEAR 2000
(1.0 QUAD TOTAL)

STATES	NO. OF EXPECTED 100 MWe PLANT BY YEAR 2000	NO. OF PLANTS WITH AVERAGE SIZE OF 225 MMBtu/h (66 MWt)
ALABAMA	--	44
ARKANSAS	2	--
ARIZONA	9	22
CALIFORNIA	40	133*
COLORADO	5	16
FLORIDA	--	22
GEORGIA	--	44
KANSAS	2	22
LOUSIANA	3	133*
MISSISSIPPI	--	2
MISSOURI	2	--
NEBRASKA	1	--
NEVADA	3	4
NEW MEXICO	2	11
NORTH CAROLINA	--	2
OKLAHOMA	8	44
OREGON	1	--
SOUTH CAROLINA	--	2
TEXAS	50	555*
UTAH	3	11
WASHINGTON	1	--
WYOMING	--	9
TOTALS	132	1,076

*NO. OF PLANTS IS PROBABLY LESS DUE TO A FEW LARGE PLANTS
#COURTESY OF ROCKWELL INTERNATIONAL (ESG)

The breakdown of the details of the federal implementation requires considerable consultation; however, there are several essential items involved. These are:

(1) cost-sharing on two to four electrical repowering or industrial retrofit plants after Solar One;

(2) tax incentives for manufacturers and users of hardware for early plants, including tax credits, fast write-offs, and tax forgiveness for utilities;

(3) continued research support for universities and industry; and

(4) development of a heating utility.

Large solar systems in the hands of utilities, industries, and small communities will be properly maintained and operated preserving their potential for maximum fossil fuel displacement. We believe that 1.0 quad or more by the year 2000 is definitely achievable and, once attained, solar power is an environmentally appropriate unlimited resource. Solar tower plants are flexible. They can be added to the system as needed. They are non-polluting. The program to develop solar tower technology is well advanced and on schedule at this time.

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LIST OF ABBREVIATIONS

AC	Aerospace Corp.
APS	Arizona Public Service
ARCO	Atlantic Richfield Oil Company
BBEC	Levelized Bus-Bar Energy Cost
BE	Badger Energy, Inc.
BEC	Boeing Engineering and Construction Co.
BECH	Bechtel, Inc.
BV	Black and Veatch Consulting Engineers
BW	Babcock & Wilcox Co.
cav	Single or multiple cavity receiver
CE	Combustion Engineering
CF	Capacity Factor, Annual energy produced divided by the rated power times 8760 hours/yr.
chem	Chemical process working fluid
CR	Central receiver
CRTF	Central Receiver Test Facility
cyln	Cylindrical open receiver
DOE	U.S. Department of Energy
EPE	ElPaso Electric Co.
EPRI	Electric Power Research Institute
ESG	Energy Systems Group - Rockewell Int.
EXXON	Exxon Research and Engineering Advanced Energy Systems Laboratory
flat	Flat panel open receiver
FM	Figure of Merit (cost/performance ratio)
FWDC	Foster Wheeler Developmemt Corp.
GE	General Electric
GH	Gibbs and Hill, Inc.
GM	General Motors Transportation Systems Center
GULF	Gulf Research and Development Co.
IPH	Industrial Process Heat
JPL	Jet Propulsion Laboratories
KE	Kaiser Engineering, Inc.
MDAC	McDonnell Douglas Astronautics Corp.
MM	Martin Marietta Aerospace Denver
N	North collector field, heliostats are located north of an east-west line through the tower.
NI	Northrop, Inc.
O&M	Operations and Maintenance
PFR	PFR Engineering Systems, Inc.
PNL	Pacific Northwest Laboratories (Battelle)
PSCO	Public Service Co. of Oklahoma

S	Surround Collector Field, heliostats located both north and south of the tower
S&B	Shading and Blocking
SL	Sargent & Lundy Engineers
SM	Solar Multiple, Maximum thermal energy collected divided by the thermal energy required to achieve rated output.
SNLA	Sandia National Laboratories Albuquerque
SNLL	Sandia National Laboratories Livermore
SRI	SRI International
SRS	Stearns-Roger Services, Inc.
SW	Stone and Webster Engineering Corp.
SWPSC	Southwestern Public Service Co.
TESC	Texas Electric Service Co.
UH	University of Houston
USGC	United States Gypsum Co.
WEC	Westinghouse Electric Corp.
WTU	West Texas Utility Co.

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