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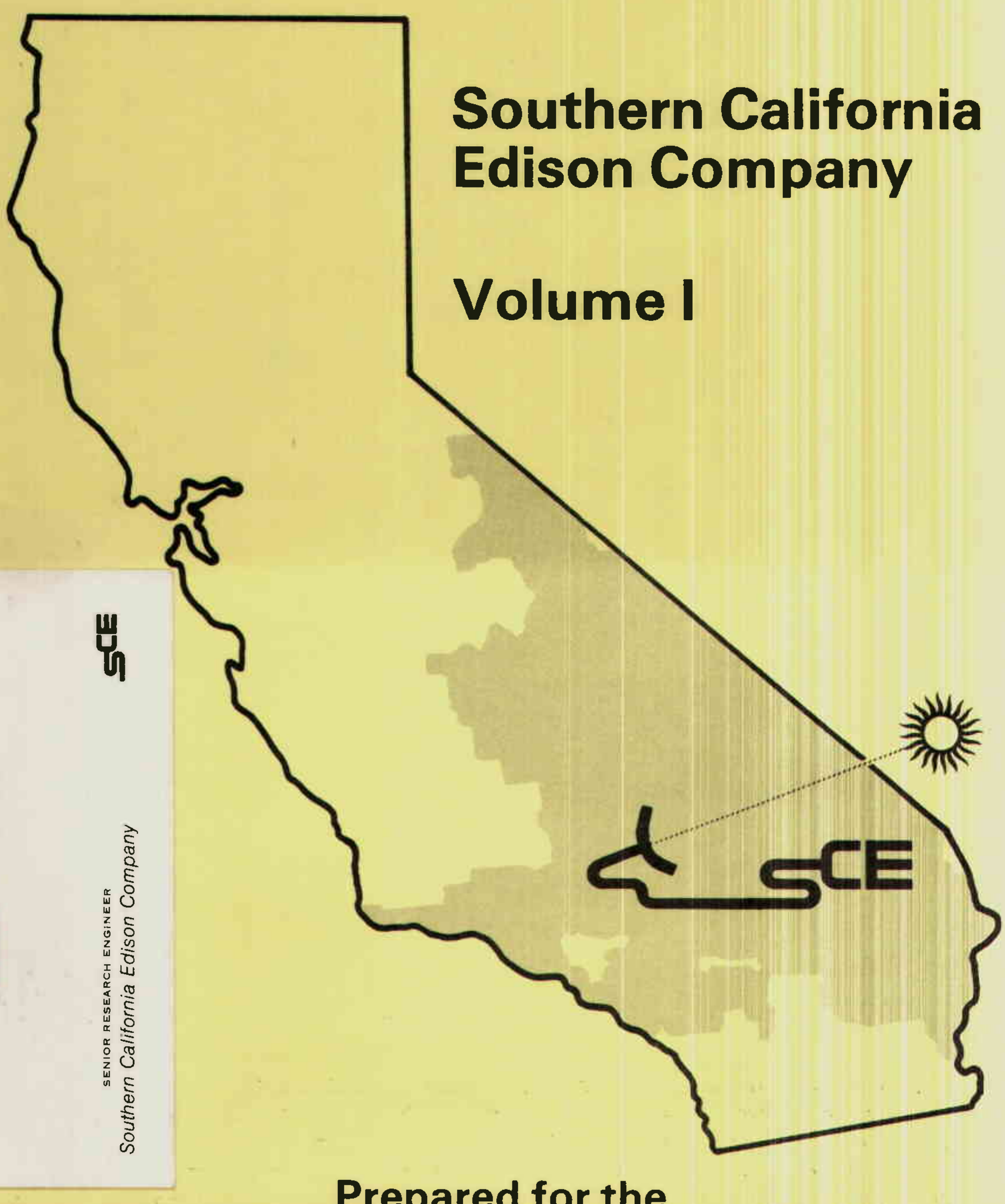
INTEGRATION OF Solar Thermal Power Plants INTO Electric Utility Systems

Southern California Edison Company

Volume I



(213) 572-1888

P. O. BOX 800
2244 WALNUT GROVE AVENUE
ROSEMEAD, CALIF. 91770

JIM GRISWOLD
~~GERALD W. BRAUN~~

SENIOR RESEARCH ENGINEER
Southern California Edison Company

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INTEGRATION OF SOLAR THERMAL POWER PLANTS INTO ELECTRIC UTILITY SYSTEMS

VOLUME I. SUMMARY REPORT

Edited by:

G.W. Braun and J.W. Ballance

Study team:

J.W. Ballance, G.W. Braun, J.W. Griswold,

D.A. Schuil, R.L. Shedden, D.P. Steinberg, M.J. Ziol

SOUTHERN CALIFORNIA EDISON COMPANY

2244 Walnut Grove Avenue

P. O. Box 800

Rosemead, California 91770

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Principal Investigator: Ira Thierer

PREFACE

Southern California Edison is pleased to present herein the results of a major effort to study the integration of solar thermal power plants into electric utility systems of the future. Calculations are described which were used to compute the economic value of solar power plants to an electric utility under assumptions that are valid today, based on SCE experience. The results of these calculations clearly establish that solar thermal power plants would have significant economic value to an electric utility.

This report makes no attempt to supply definitive projections regarding the future economic viability of solar power. Economic viability is subject to both the success of efforts to achieve cost goals and the way in which these goals may be affected by changing conditions and unforeseen constraints. The sensitivity of calculated solar breakeven costs to financial and other assumptions is explored in Volume II of this report.

There is a substantial gap between the estimate of economic value and estimated cost of a solar power plant that could be built today without further development. Nevertheless, patient efforts to reduce the cost of this technology and enhance its value have reasonable prospects of success.

It is in recognition of these prospects that Edison has made a proposal of partnership with ERDA to design, construct, and operate the nation's first experimental solar bulk power generating facility. If goals for future commercialization of solar power generation technology are to be met, the experience gained through such pilot projects and the insight gained in studies building upon this report, must be effectively combined.

INTRODUCTION

This report summarizes the findings of a study designed to fill the need for an electric utility to evaluate solar thermal power plants as they would be evaluated if they were commercially available and could be put to immediate use. The study was motivated by a mutual recognition of this need by the Energy Research and Development Administration and the Southern California Edison Company.

The value of a solar thermal power plant to an electric utility will depend upon its effect on the investment and operating cost of the entire electric system. Solar generation is dependent upon sunlight for its input energy. Because the solar input energy varies both hourly and seasonally, reaching a peak level for only a few hours in each year, solar generation is unique relative to conventional generation currently in use by most electric utilities. These special characteristics necessitated an analysis of the effects of integration of solar generation into an electric utility system.

This report consists of two volumes: Volume I is a summary report which provides an overview of the study. Volume II is a complete technical report, which includes detailed discussions of data, models, assumptions and results.

STUDY OBJECTIVES

The principal objective of the integration study was to define the nature of the economic interaction between system generation requirements and solar generation characteristics and thus identify the economic value of solar generation to an electric utility. Specifically, this involved defining how the electric system resource mix and operation would be modified to accommodate and make best use of varying amounts of solar generating capacity and associated

Study Objectives Cont'd.

storage capability. Note that the effect of solar energy systems installed on individual buildings (e.g. for heating and cooling) was not a consideration in this study.

MAJOR VARIABLES

The value of solar thermal power plants to a utility system is comprised of two components: energy and capacity. The energy produced is valuable because it reduces the net fuel consumption of conventional power plants in the generation mix. In addition, the ability of the solar plants to serve part of the demand has value (i.e. "capacity value") to the utility.

The value of solar generation integrated into a large electric system depends on:

1) The coincidence between the solar generation pattern (sunfall pattern) and the electric system load shape.

2) The percentage of the electric system capacity that is solar, i.e. the "solar penetration" (5, 10, and 20 percent penetrations were assumed.)

3) The mix of conventional (non-solar) resources in the system.

4) The energy storage capability associated with the solar units measured in megawatt-hours (MWh) of energy stored per megawatt (MW) of peak unit output (0,1,2 and 6 MWh/MW capabilities were assumed.)

5) The way in which the solar units are dispatched, i.e. the way thermal energy storage is used to modify the output profile of the solar unit.

SUBSTUDIES

The study was organized around two major substudies dealing with

Substudies Cont'd.

reliability and economics. These substudies were parallel and interactive and based on the same idealized solar unit and electric system characteristics.

The reliability substudy addressed the effect of solar generating capacity on generating system reliability. This analysis involved optimizing the operation of the solar units as a part of the total generating system in order to minimize the total system installed capacity requirements.

The economics substudy dealt with the question of how much solar generating capacity is worth. The economic evaluation minimized the total cost of generating electricity by optimizing the mix of conventional resources.

In addition, four other substudies interfaced with the reliability and economics substudies and addressed the following corollary questions.

Operation - What would be the impact of operational considerations that were not modeled?

Design - What are the utility concerns regarding the design of "real" solar units?

Cost - What are likely to be the critical cost engineering concerns with "real" solar units?

Alternatives - What would be the impact on the cost and value of solar units if they had design features other than those assumed in the models?

Volume II contains separate sections discussing each of the six substudies.

RELIABILITY EVALUATION

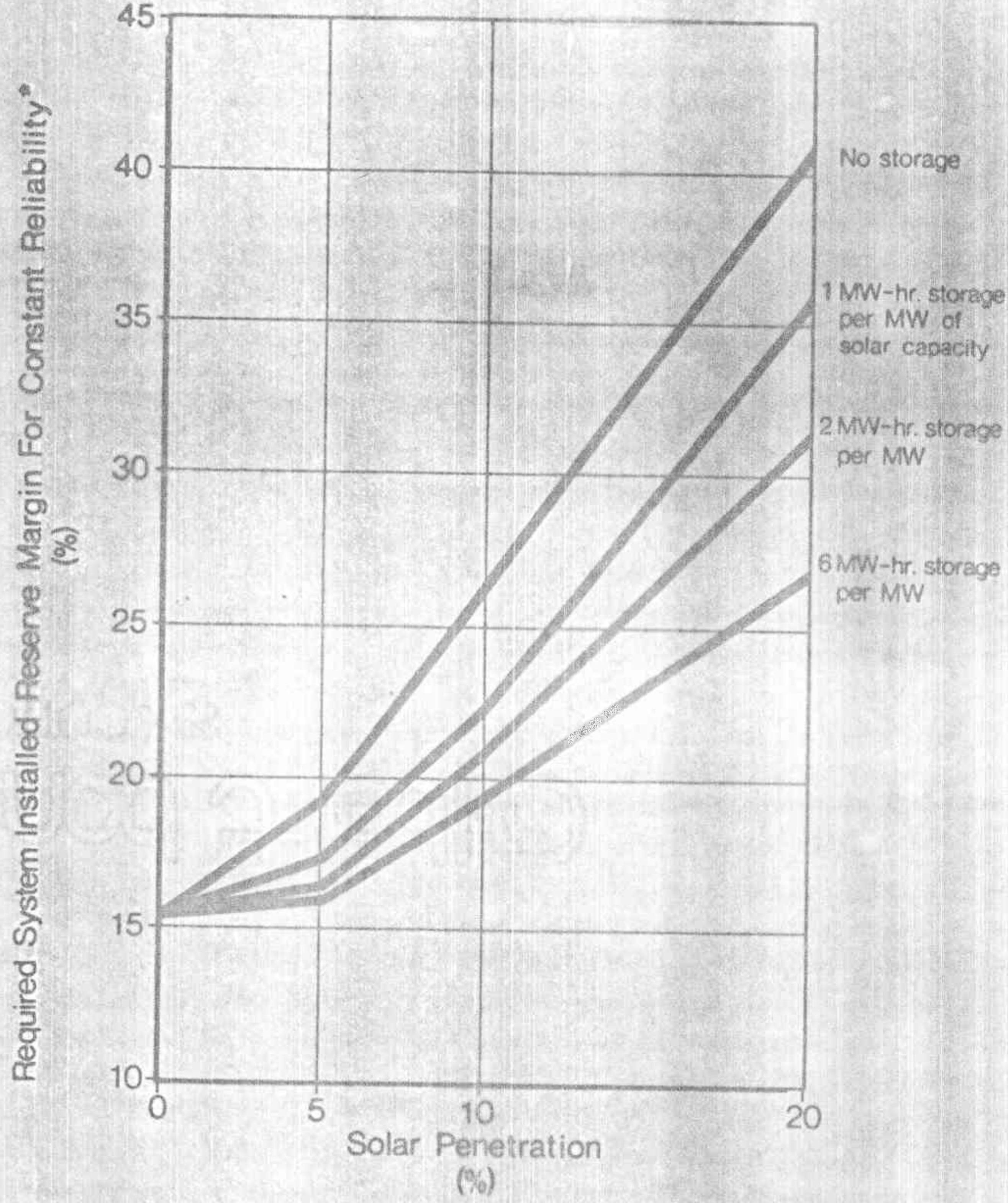
Both the amount of solar generation included in the electric utility's aggregate resources, and the amount of thermal energy storage associated with solar generating units have significant effects on the value of solar generating units to a utility. The results of reliability studies, which evaluated the effect of varying both of these parameters on the total system installed reserve margin requirements, are summarized in Table 1. The relative collector size and electric system installed capacity for the various levels of storage and solar generation are indicated, along with electric system installed reserve margins required in each of the cases considered. The effective load carrying capability of the solar units, which is a probabilistic measure of the amount of load the units could carry at the specified reliability, is also presented.

Figure 1 illustrates the variation in system installed reserve margin requirements as a function of solar penetration in the system. As illustrated in Figure 1, at any fixed amount of storage, system installed reserve margin requirements increase as the level of solar generation is increased. Figure 1 also indicates that for a given level of solar penetration, margin requirements are reduced by an increase in the amount of thermal energy storage and the attendant increase in collector capability. Figure 2 shows that the effective load carrying capability of the solar generation is reduced as the solar penetration increases.

From Figure 2, it is apparent that the solar units can have significant load carrying capability under certain conditions, but in all cases it is less than that of the average conventional unit. With modest amounts of storage, solar units have significant capacity

Figure 1

REQUIRED INSTALLED RESERVE MARGIN vs. SOLAR PENETRATION



*Loss Of Load Probability Held Constant At 1 Hour Of Outage (Total) In 20 Years

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Southern Calif. Edison, Sept. '76

value at low solar percentages, and with substantial amounts of storage the same is true at higher percentages. This suggests that the first solar units may require relatively little extended operation capability to achieve close to their full potential usefulness in a generating system.

ECONOMIC EVALUATION

The results of the economic evaluation of solar generation are summarized in Table 2. The 1986 present worth total of the lifetime capital-related, fuel and operating costs of various systems (excluding costs for solar generation) for all combinations of assumptions on storage and penetration are presented. Calculations were based on operation over the 1986-2015 period. The equivalent value of solar generation (capital equivalent of total lifetime capital and O&M costs) to the utility, expressed in 1986 investment dollars, is presented in Table 2 and plotted (in 1986 dollars) in Figure 3. To convert 1986 values in Figure 3 to 1976 dollars, divide by 2.16. Referring to Figure 3, the value of solar generation is shown ranging from $530/kw to $1470/kw in 1986 dollars. These values were developed by deducting the total lifecycle cost of the conventional resources in each solar resource plan from the total cost of a totally conventional base plan. These values represent the "breakeven" cost, or that cost below which solar units would certainly be economically attractive to a utility. For example, the amount that a utility would be willing to pay for solar units having 6 MWh of storage per MW of capacity and making up 10% of its system installed capacity would be $1370/KW, expressed in 1986 dollars.

The combined economic value of solar capacity and energy is

Economic Evaluation Cont'd.

seen to decrease as the solar percentage increases, but not as sharply as the capacity value decreases, since the energy value of solar is relatively unaffected by penetration. The value of solar generation is increased by providing storage, but it appears, as might be expected, that beyond a certain point, each additional increment of storage and associated collector becomes less valuable. In a system containing relatively little solar generation, small amounts of storage, allowing one or two extra hours of operation, will suffice to achieve most of the solar units' maximum potential economic value.

The economic evaluation was performed on hypothetical "optimum" resource plans containing a maximum desirable amount of nuclear generation and therefore differing significantly from the predominantly oil based systems of present-day southwestern electric utilities. The value of solar generation in a non-optimum electric system may exceed these "breakeven" levels. To indicate roughly how great a difference this might make, two resource plans were studied in which the conventional resources were entirely comprised of oil fired generating units. As indicated in Figure 3, the value of a 10% penetration of solar with 6 MWh/MW storage in such a system would be approximately $1470 kW, expressed in 1986 dollars, which is 7% higher than in the "optimum" resource plan.

It should be noted that, because the economic value of the solar units was derived parametrically as the cost difference between two resource plans (one with solar, one without), the values are very sensitive to the input parameters. Because of this and a similar sensitivity to a number of cost and modeling assumptions, they should not be considered exact.

STORAGE

Based on the discussion in the preceding paragraphs, a key finding of the study is that thermal energy storage has a major impact on the value of solar power plants in an utility electric system. Storage increases the capacity value of solar units by allowing them to be operated during the evening peak load periods. The additional collector area associated with storage increases the annual energy production capability of solar units.

In the analysis, an "ideal" storage system was assumed. The amount of storage was characterized as the ratio of the number of MWh of electrical energy which could be stored, to the turbine generator rated output, expressed in MW. As discussed in Volume II, in order to provide "reserve energy" with which to heat the turbine plant in preparation for operation after an overnight or cloud-related interruption in solar input, it may be necessary to provide an additional one or two MWh/MW of storage capability, and to maintain "heatup" energy in storage. This additional storage was not accounted for parametrically in the reliability and economic evaluations.

RESOURCE MIX

The addition of solar generation would be accompanied by adjustments in the mix of conventional generation resources to both optimize economics and maintain acceptable levels of service reliability. As indicated by study results, solar generation will not directly replace any single resource type.

In most present electric systems, solar would reduce the need for intermediate generation additions. As the system resource mix approaches optimum levels, the addition of solar begins to displace small amounts of base load generation. However, additional peaking capacity is required to maintain acceptable levels of system reliability as the level of solar generation is increased.

Figure 4 illustrates the variation in an optimum resource mix due to the addition of solar. As illustrated, the amount of peaking required to maintain acceptable reliability when solar is added can be significantly reduced by adding thermal energy storage to the solar units.

SYSTEM OPERATION CONSIDERATIONS

Solar units having storage are likely to be subjected to spinning reserve performance standards now applied to energy limited hydroelectric units. Such standards require that in order for a unit to be considered as on-line operating capacity during any hour, it must have at least two hours of energy production capability in storage. The dispatch of the solar units, as modeled in this study, is likely to be modified to reflect this standard. The introduction of solar generation into electric utility systems will affect several aspects of electric system operation. Implementing a peak shaving dispatch strategy using solar complicates daily capacity planning and suggests that increased use of weather forecasts and telemetered sunfall data may be required. Similarly, computer programs to optimize combined solar and thermal generation may be necessary to assist operating personnel in optimizing the use of solar generation.

More complicated automatic generation control algorithms than are presently used by utilities will be required to handle solar unit output variations that cannot be buffered effectively with storage. Optimal maintenance strategies for large solar penetrations will

System operation Considerations Cont'd.

require a departure from present practice, and solar unit designs will need to reflect a desire to defer outages until non-critical hours. In summary, as the amount of solar generation in an electric system increases, additional sophistication in system operation will be essential to fully benefit from its capabilities. In most cases, system operation computer programs and algorithms currently available or in effect can be adjusted and/or expanded to properly effect the integration of solar.

COST AND DESIGN CONSIDERATIONS

The cost to build a solar unit today, without the benefit of further technological development, would be well above the breakeven costs indicated in Table 2 and Figure 3. Reducing the cost of concentrating mirrors (e.g. heliostats in the central receiver concept) and their support structure and aiming gear to an absolute minimum is the key to economic feasibility. It appears that these costs must be reduced to no more than one half of the overall plant cost.

Accordingly, there are incentives to reduce the cost of the storage subsystem and the balance of plant to allow higher mirror costs, and to increase the efficiency of the storage and balance of plant to require fewer mirrors. These competing objectives will require cost trade-offs based on integration study results. Another important area of optimization is to balance the value of the cycling capabilities that are needed to fully utilize the varying solar input against the associated costs. Demonstration of the features of resulting cost optimum designs should be a major objective for pilot scale units.

It is essential to recognize that the breakeven costs discussed

Cost & Design Considerations Cont'd.

in this report are breakeven lifecycle costs. The major development thrust should thus be toward components, e.g. heliostats, that can be cheaply maintained as well as cheaply fabricated and installed in the field.

Volume II of this report identifies critical cost and design issues and contains quantitative discussions of the economics of thermal energy storage and of certain solar/fossil hybrid concepts. Recommendations are offered concerning the design of commercial as well as pilot scale solar thermal power plants.

METHOD OF ANALYSIS

Analytical Tools

The key to our ability to deal with the reliability and economic questions raised above was that the questions posed regarding solar generation were similar to those which must be answered in the process of utility generation resource planning. Thus, the overall study strategy was to use the analytical tools of this process to evaluate solar.

The study used production costing and installed generation reliability programs developed by SCE for use in its future generation resource planning process. Both programs were modified to appropriately model the solar generation.

The reliability program was used to evaluate the likelihood of successfully serving the forecast load for each hour of the year without requiring emergency interconnection support from other utilities. The production costing program simulates the daily operation of the electric system, and was used to evaluate annual system fuel requirements, total operating costs, plant capacity factors, etc. Detailed descriptions of the programs and the models used are presented in Volume II of this report.

Strategy

To assess the value of solar generation integrated into a utility system, generation resource plans were developed for each assumed level of solar penetration and storage. The total amount of installed capacity, and the relative mix of each of the various non-solar resource types were adjusted so that each plan would meet the SCE generation system reliability criterion while serving the same SCE forecast load pattern, at the lowest possible total present worth cost (including capital related, fuel, and operating costs). Each of the resulting plans represented the ideal mix of resources to achieve the lowest total cost at the specified level of solar penetration and storage. Each of these plans was then compared to an optimum base plan which contained no solar generation.

To reduce the complexity of the evaluation, all the resource plans were developed using three basic types of conventional generating capacity (nuclear, combined cycle, and combustion turbine) as well as a fixed amount of hydroelectric generation. Standard unit sizes and reliability characteristics were assumed for each resource type. These standard units were a 1000 MW nuclear unit assuming 50% SCE ownership (base), a 250 MW combined cycle unit (intermediate) and a 100 MW combustion turbine (peaking). Unit reliability and maintenance assumptions for these conventional resource types and for the solar units are summarized in Volume II, as are the cost characteristics for each conventional resource type.

To simplify the economic analysis, it was assumed that the opti-

Strategy Cont'd.

mum mix of resources would remain constant throughout each year of the studies. Furthermore, because the load pattern, carrying charge rates, and escalation rates were assumed to be long term averages which would remain constant throughout the 1986-2015 study period, it was necessary to determine the total capital and operating costs for one year only.

Solar Unit Assumptions

The central receiver concept was used as the baseline design, because it is receiving more attention in the ERDA program than other concepts. The central receiver concept involves a large number of individually steerable flat mirrors (heliostats) directing concentrated solar radiation to a tower-mounted heat exchanger.

A 100 MW solar unit size was assumed, with the 100 MW rating defined as the output capability of the unit at noon on the summer solstice (6/21). The 100 MW solar unit was assumed to include a thermal energy storage system and a single turbine which could accept steam from the receiver, from storage, or from both in parallel. This reflects the specified capabilities of ERDA central receiver designs. It was further assumed that the turbine could produce 70 MW when operating solely from storage, with no loss in conversion efficiency relative to operation using heat directly from the receiver. The size of the collector field was assumed to be matched to the storage capability being modeled, such that sufficient collector was provided to both operate the unit at full output during all sunlight hours, and totally charge the storage unit on the summer solstice without losing any energy due to the storage system being fully charged and unable to absorb excess collector production.

Solar Unit Assumptions Cont'd.

The assumed derate to 70% capacity when operating from storage permits an evaluation of the capacity value of the ERDA specified single turbine central receiver designs. Although neglecting the efficiency losses when operating from storage causes a small over-optimism regarding the economic value of solar, it permits an unambiguous definition of storage capacity and yields results that can easily be adjusted to reflect the efficiency of specific storage configurations.

Solar Input/Output Assumptions

The available output of the solar unit was assumed to be proportional to the heat absorbed by the receiver. This parameter was established for each hour of a typical day in 13 four week seasons, using curves developed by the University of Houston based on predicted levels of solar radiation.

Solar unit output was normalized to 100 MW at the hour of peak solar input. Corrections were made to reflect measured sunfall in areas of interest. Five years worth of solar data was averaged to provide a basis for assumptions on sunfall-related total and partial forced outages. For example, the number of days of total sunfall outage was defined to be equal to the number of days having less than 50% of the possible solar input.

A complete description of the solar unit input data and modeling assumptions is included in Volume II of this report.

ADDITIONAL STUDY

The integration study discussed in this report was intended to fit into a design optimization process that, it is hoped, will culminate in a technically successful, economically feasible solar thermal power generation technology. The process has just begun, and

Additional Study Cont'd.

this report is but a first step.

Additional study is needed in several areas, particularly as the designs for solar power plants become firmed up, field tested and verified. One key area is the modeling and optimization of solar unit design with respect to the value and cost of storage and cycling requirements associated with preferred dispatch strategies. Once this has been done, additional integration studies should evaluate the effect of making different assumptions than for the present study. Different solar unit sites, electric systems, solar unit configurations, subsystem efficiencies, dispatch strategies, and fossil fuel cost and availability scenarios should be considered in order to refine the basic results which have been achieved in this first study.

References

Integration of Solar Thermal Power Plants into Electric Utility Systems, Volume II, Southern California Edison Company

TABLE 1

SUMMARY OF RELIABILITY RESULTS
(For Constant Loss of Load Probability Index
Of Approximately One Hour Of Outage In 20 Years)

Case Identification	Solar Penetration (%)	Storage MW-Hr/MW of Solar Capacity	Solar Collector Size (Per Unit Of Solar Electrical Capacity)	Total Installed Capacity MW	Installed Reserve Margin (%)	System Effective Load Carrying Capability	Solar Generation Effective Load Carrying Capability
00/0	0	-	-	20608	15.4	86.6	-
05/0	5.16	0	1.0	21338	19.3	83.8	32.3
05/1	5.23	1	1.18	20938	17.1	85.4	63.7
05/2	5.28	2	1.29	20838	16.5	85.8	71.5
05/6	5.30	6	1.71	20738	16.0	86.2	79.4
10/0	9.76	0	1.0	22538	26.1	79.3	12.1
10/1	10.03	1	1.18	21938	22.7	81.5	35.8
10/2	10.17	2	1.29	21638	21.0	82.6	47.6
10/6	10.31	6	1.71	21338	19.3	83.8	59.4
20/0	19.81	0	1.0	25238	41.2	70.8	7.1
20/1	19.80	1	1.18	24238	35.6	73.8	21.8
20/2	19.63	2	1.29	23438	31.1	76.3	34.1
20/6	19.35	6	1.71	22738	27.2	78.6	45.2

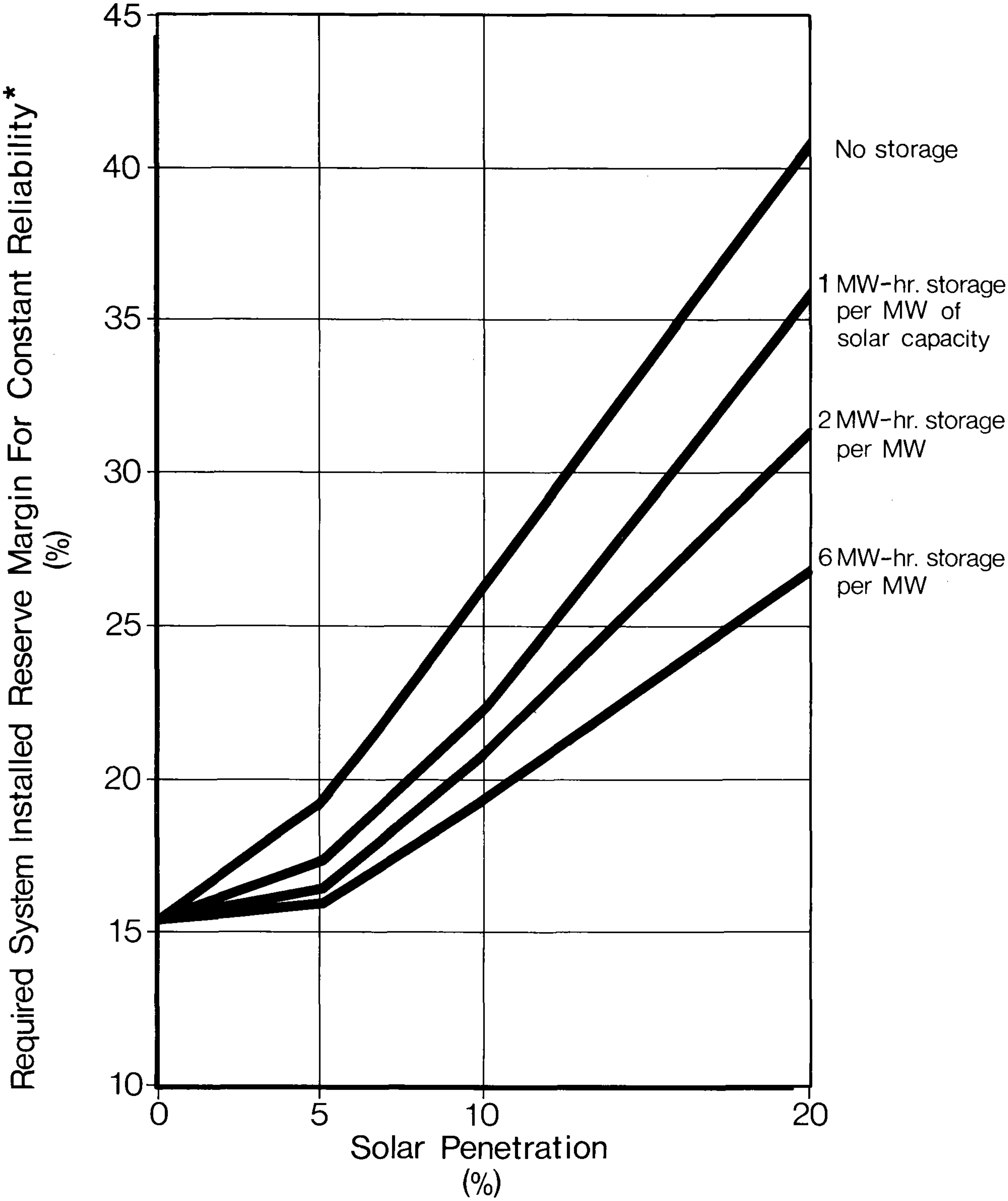
TABLE 2

SUMMARY OF ECONOMIC COMPARISONS

1	2	3	4	5	6	7	8	9	10
				1986 Present Worth Costs-Billions of Dollars			Value Of Solar Capacity		
Solar Penetration (%)	(MW)	Storage (MWh/MW)	Total Installed Capacity (MW)	Capital & O&M	Fuel	Total	1986 Differential Present Worth (Nonsolar Minus Solar) Billions Of Dollars	Equivalent 1986 Investment $/kW	Equivalent 1976 Investment $/kW
0	BASE		20638	36.92	10.82	47.74	BASE		
5	1100	0	21338	34.55	11.93	46.48	1.26	753	349
5	1100	1	20938	34.36	11.55	45.91	1.83	1093	506
5	1100	2	20838	34.23	11.60	45.83	1.91	1141	528
5	1100	6	20738	34.17	11.13	45.30	2.44	1457	675
10	2200	0	22538	34.62	10.92	45.54	2.20	657	304
10	2200	1	21938	34.23	10.18	44.41	3.33	995	401
10	2200	2	21638	34.04	10.18	44.22	3.52	1051	487
10	2200	6	21338	32.93	10.23	43.16	4.58	1370	634
20	5000	0	25238	30.91	12.78	43.69	4.05	533	247
20	4800	1	24238	30.27	11.66	41.93	5.81	795	368
20	4600	2	23438	29.75	12.11	41.86	5.88	840	389
20	4400	6	22788	29.69	10.44	40.13	7.61	1136	526
All Combined Cycle Base System									
0	BASE		20138	22.02	34.69	56.71	BASE		
10	2000	6	20638	20.25	31.98	52.23	4.48	1470	681

Figure 1

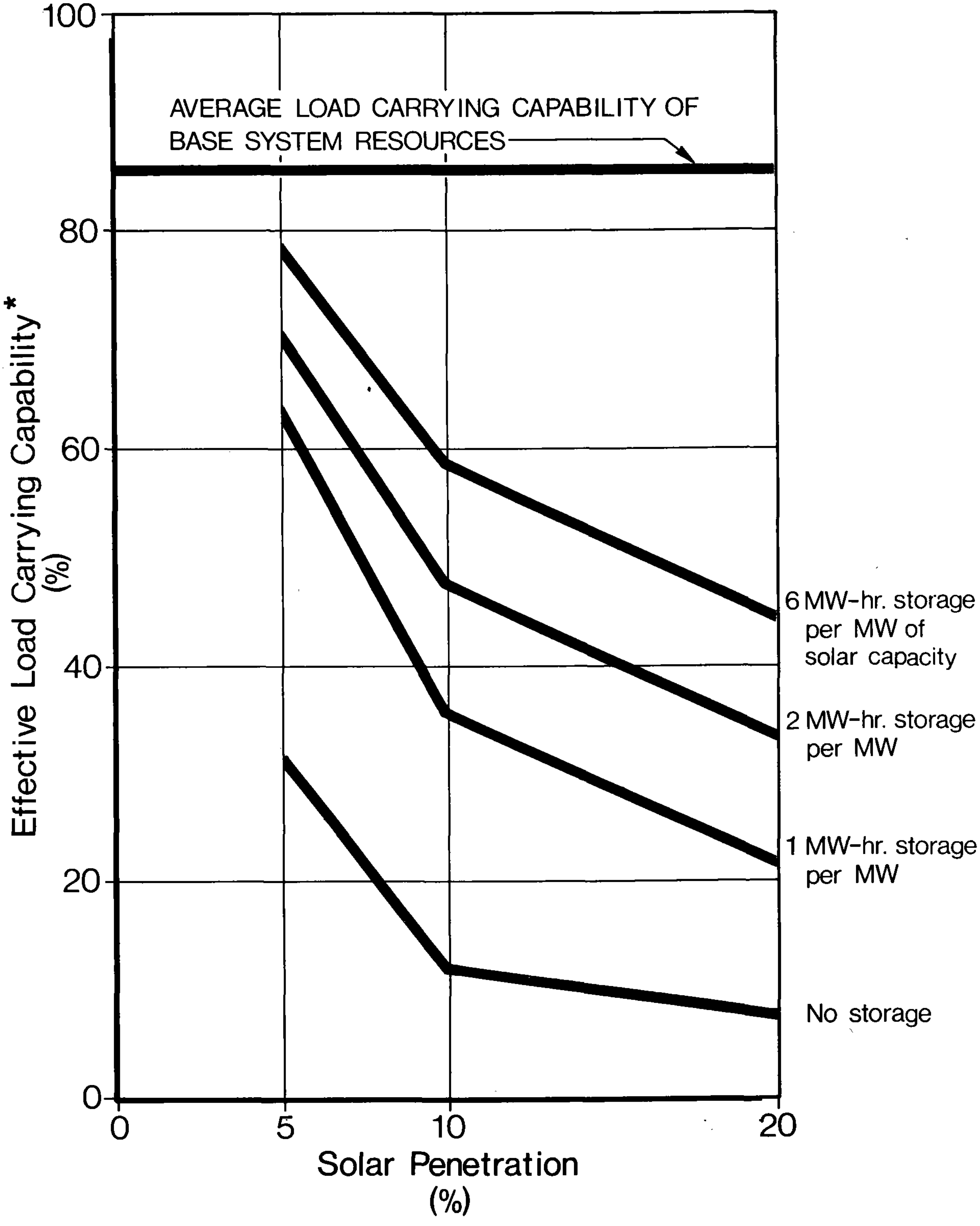
REQUIRED INSTALLED RESERVE MARGIN vs. SOLAR PENETRATION



*Loss Of Load Probability Held Constant At 1 Hour Of Outage (Total) In 20 Years

Figure 2

EFFECTIVE LOAD CARRYING CAPABILITY OF SOLAR GENERATION vs. SOLAR PENETRATION

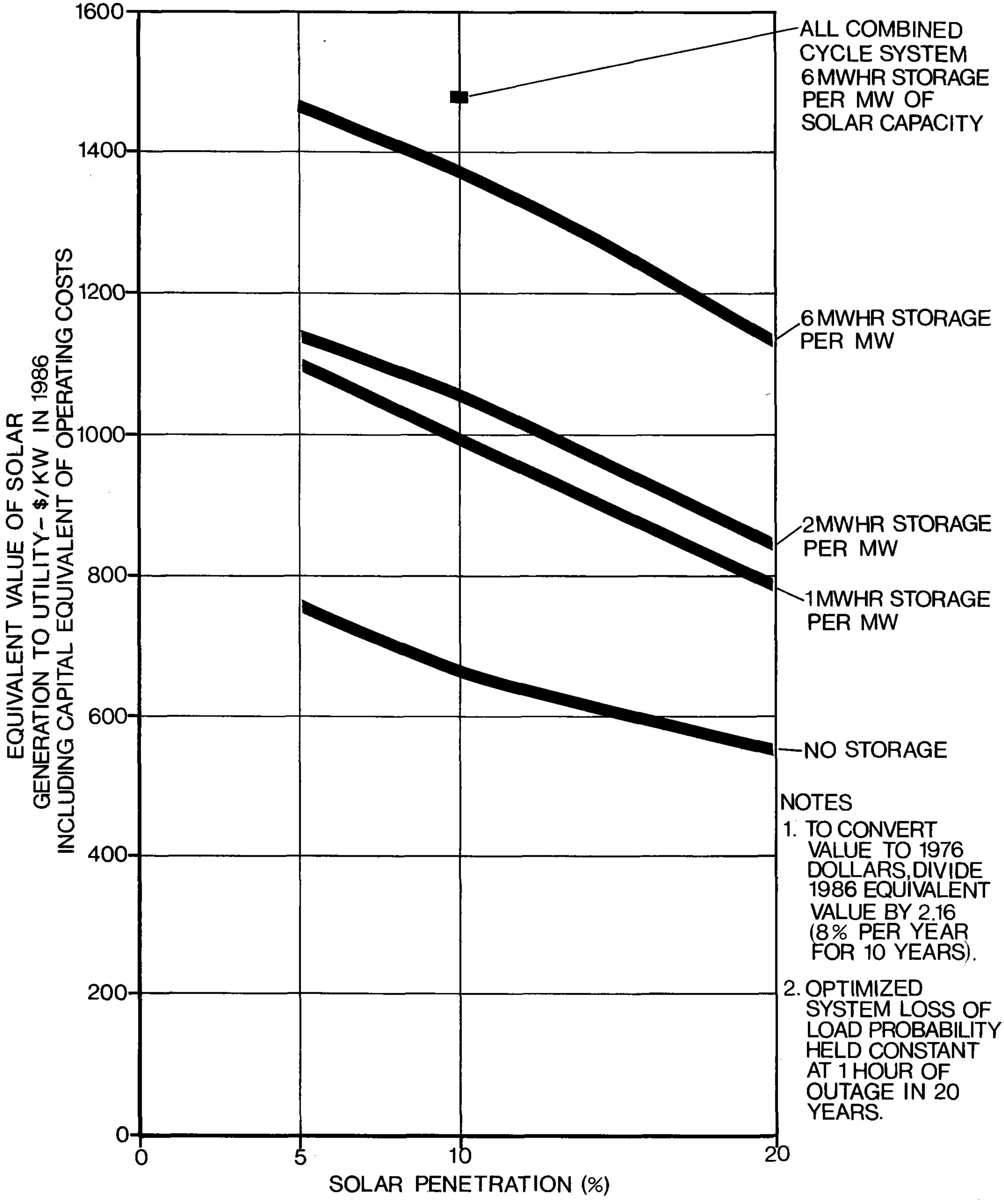


*Loss Of Load Probability Held Constant At 1 Hour Of Outage (Total) In 20 Years

Figure 3

SOLAR BREAKEVEN COSTS

(EQUIVALENT VALUE OF SOLAR GENERATION TO UTILITY)



EFFECT OF SOLAR GENERATION ON MIX OF NON-SOLAR RESOURCES

Figure 4