MASTER

Studies of Hybrid Repowering of Utility Electric-Power Plants

(INTERIM REPORT)

THE AEROSPACE CORPORATION
El Segundo, California

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STUDIES OF SOLAR HYBRID REPOWERING OF
UTILITY ELECTRIC-POWER PLANTS
(INTERIM REPORT)

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The Department of Energy
Solar Energy Division, DOE/SAN

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FOREWORD

This report summarizes the interim results of systems engineering studies of some of the issues of solar repowering. The Aerospace Corporation is providing systems engineering studies, technical monitoring, and project support to The Department of Energy, Solar Energy Division (DOE/SAN) on various advanced systems and applications projects of the Solar Central Receiver Program. Results reported in this document represent a portion of the effort under the systems engineering studies subtask in support of the Repowering Project.

The work is being conducted under DOE Contract No. EY-76-C-03-1101(PA #14) under the overall cognizance of Mr. R. Hughey, Director of Solar Energy Division, and under the general direction of Mr. L. Prince and Dr. S.D. Elliott, Program Managers, DOE/SAN.

This report was prepared by Dr. Prem Mathur of the Energy Projects Group of the Energy and Resources Division of The Aerospace Corporation. Mr. S.D. Huffman is the General Manager and Mr. H. Bernstein is the Acting Principal Director of the group. Dr. P. Mathur is the Principal Investigator and Mr. P. DeRienzo is the Project Engineer on this contract. This report is the result of notable contributions of several supporting members of the technical staff of The Aerospace Corporation: Dr. J. Albert and Dr. R. Janz, systems and utility simulation analyses; Mr. M. Masaki, heat balance and performance/cost studies; and Dr. N. Stockwell and Dr. L.D. Schelhorse, special economic studies.

1. SYNOPSIS AND MAJOR FINDINGS

The potential benefits and issues of solar repowering of utility electric power plants have been examined from the utility and programmatic points of view. Repowering offers an opportunity for an early introduction of central receiver technology in a redundant mode with existing fossil plants. This hybrid operation can minimize utility concerns for technical risks and loss of capacity in the event of solar equipment failures or adverse weather conditions. Repowering also offers a cost-effective vehicle for the demonstration of alternate solar technologies required for the commercialization of eventual solar systems such as hybrid and solar stand-alone systems. An important limitation of most repowering options is that repowering only renews the existing capacity of a plant scheduled for retirement, but does not provide additional capacity. The exception is the Brayton topping concept discussed in the text in Section 5.

Reductions in the unit cost of heliostats must be achieved to establish economic viability of solar plants. Repowering and other applications offer the possibility of establishing a manufacturing base leading to high production rates needed to reduce unit cost. A potential of 10 GW_e solar repowering market (1.6×10^6 heliostats) has been identified. Considerations of site-specific scheduling and economic constraints will reduce this market size significantly. However, a number of constraints utilized in the assessment of this market can be relaxed to increase the market size as reported in Section 6. Approximately 80 percent of the estimated solar capacity is in the repowering of reheat plants, which also have a relatively longer life expectation desired. Nearly 50 percent of the total estimated market is represented by the Texas-Oklahoma region. In this region the insolation deficiencies may dictate the need for solar storage in repowering. A review of the retirement schedule for candidate plants indicates opportunities in the period from 1985-2000 to accomplish repowering of most of the non-reheat plants and a large fraction of the reheat plants. The repowering project must therefore continue at an accelerated pace to accomplish the project aims and to begin commercialization during this period so as to avoid retirement of some of these units.

A review of the available solar central receiver system technologies and of the technology match with the candidate plants indicates that a variety of technologies would be required to meet the differing needs of the market and to accommodate utility preferences. Repowering with water-steam systems offers a high confidence option for non-reheat plants, in applications where storage is not required. Advanced Central Receiver (ACR), Brayton, salt or sodium technology is suitable for both non-reheat plants and reheat plants. Repowering designs with these technologies can provide inherent storage buffer against cloud and other system transients along with high performance cycles and efficient storage. Probably the most attractive repowering option involves the use of a fossil-augmented solar Brayton topping cycle, in which the air exhaust

SYNOPSIS AND MAJOR FINDINGS (Continued)

of the Brayton engine produces steam through a heat-recovery generator. Technical risks using ACR technologies are somewhat higher due primarily to uncertainties in the long-term behavior of materials and limited industrial experience with these technologies at high temperatures.

To assess the economic impact of repowering, cost/benefit studies were made using an Aerospace simulation model to determine the impact of the complex interaction of system parameters associated with solar plant design, utility system characteristics (such as load demand, site insolation, and conventional generation mix), and various economic factors. Maximum use has also been made of data developed in other DOE studies.

The results indicate that if heliostat cost goals can be achieved, the cost/benefit ratio of a solar-repowered plant integrated into various representative utility systems would be within the regime of economic acceptability. The cost/benefit ratio varies from utility to utility influenced by the various economic factors as well as by the characteristics of the utility system in which it is to operate. The most sensitive parameters affecting the cost/benefit ratios are heliostat costs, fuel escalation rates, and plant operating and maintenance costs. Significant improvements in cost/benefit ratios can occur if fuel costs increase over the assumed levels and if buffer storage and improved dispatch techniques are used.

Further investigations are needed to examine the role of storage in solar repowering for efficient hybrid operation, particularly in situations where little or no oil would be saved by repowering and where increased solar fraction, capacity credit, and fuel oil savings are required for technical or economic reasons. Techniques for improving the performance and economics of repowering such as steam sharing from adjacent units, and alternate dispatch strategies need further investigation. To assess the cost effectiveness of solar repowering for market penetration, economics of alternate non-solar options (such as repowering with a coal boiler or with fossil Brayton topping cycle, or by replacing oil boilers and/or turbines with high efficiency components) must also be investigated.

2. INTRODUCTION

Aerospace interim studies of repowering of utility electric plants have addressed several key issues of repowering to provide some insight into complex problems, to identify solution approaches, and to develop information in support of DOE Repowering/Retrofit project activities. Potential benefits of repowering from the programmatic, utility, and national points of view have been summarized.

The concept of a solar-fossil hybrid electric plant combines the use of a solar heat source with a fossil heat source (e.g., boiler) to operate a common turbine-generator unit. Two types of concepts, namely, new solar-fossil hybrid systems and repowering of existing oil/gas fired steam plants, have been investigated by DOE in previous studies. (1,2)* The current DOE Repowering/Retrofit project, aimed at early implementation of central receiver technologies, is investigating several site-specific repowering plant designs through multiple industry studies. The overall scope of the repowering project, however, also includes new hybrids and solar retrofit of industrial process heat plants.

The Aerospace interim studies reported in this document have been aimed at investigating several key issues of repowering of utility electric plants, and at providing background for and insight into complex problems in support of DOE Repowering/Retrofit project activities. In conducting these studies, maximum use has been made of the results of various DOE studies on related subjects to supplement Aerospace analyses and assessments.

Section 1 presents a brief synopsis of the interim results and conclusions of this study. Section 3 defines a baseline repowering configuration used as a reference in this study, outlines the potential benefits of repowering from the programmatic, utility (users), and national points of views, and presents a brief discussion of repowering issues. Sections 4 through 6 discuss these issues in further detail. Section 4 reviews the market size for solar repowering with the split by plants and their requirements imposed on solar technology and plant design. Section 5 discusses various solar technology implementation options.

The Aerospace repowering study emphasis has been on the investigation of economics and integration of repowered plants into various utility systems to gain insight into the complex interactions and the effects of major plant design, economic and utility systems parameters on the overall utility economics. Section 6 presents highlights of the key results of these studies. Section 7 presents our interim conclusions and recommendations.

* The numbers in parentheses refer to the list of references in Section 8.

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3. REPOWERING OVERVIEW

- 3.1 Baseline System Concept**
- 3.2 Potential Benefits of Repowering**
- 3.3 Repowering Issues**

BASELINE SYSTEM CONCEPT

- FOSSIL PLANT CHARACTERISTICS
 - EXISTING OIL FIRED UNIT
 - PLANT CAPACITY = 50 MW_e
 - NON-REHEAT STEAM TURBINE
 - EQUIPMENT REBUILT FOR 30 YEAR LIFE
 - INTERMEDIATE LOAD OPERATION
- RETROFITTED SOLAR EQUIPMENT
 - BARSTOW PLANT TYPE COLLECTORS, RECEIVER/TOWER AND MASTER CONTROL SYSTEM (MCS)
 - STEAM CONDITIONS MATCHED WITH THOSE OF FOSSIL PLANT
 - SOLAR CAPACITY = 50 MW_e (i. e., Solar to Fossil Fraction = 1.0)
 - NO STORAGE
- SOLAR-FOSSIL INTEGRATION
 - SOLAR BOILER IN PARALLEL WITH FOSSIL BOILER
 - MCS INTEGRATED WITH PLANT CONTROL
 - FEEDWATER, WATER TREATMENT EQUIPMENT MODIFIED TO ACCOMMODATE SOLAR RECEIVER

3. REPOWERING OVERVIEW

3.1 BASELINE SYSTEM CONCEPT

A baseline concept for a repowered utility electrical plant utilizing first generation water-steam solar technology is defined in Chart 3-1 and described below. This concept is used as a reference in the various studies reported in this document.

Several system configurations for repowering are possible depending upon the type of solar technology utilized, the type of existing fossil-fired plant to be repowered (e.g., reheat or non-reheat plant), and the location and the manner in which solar heat is introduced into the plant electric power generation cycle. The baseline configuration depicted in the figure in Chart 3-1 is used as a reference in this study. This configuration utilizes first generation water-steam solar technology to provide steam to a non-reheat turbine in parallel with the existing fossil boiler of an oil-fired plant.

Other plant characteristics of this system are outlined in Chart 3-1. The primary solar retrofit equipment for this system includes collector field, receiver and tower, master control, water-steam lines, and other associated equipment. Storage is not included in the baseline configuration. However, storage may be required in various situations where transient operations, such as those under cloud transients, place excessive demands (high ramp rates and thermal cycling loads) on the existing boiler/turbine equipment.

Repowered plant integration involves hookup of the extended receiver water-steam piping into the existing Electric Power Generating System (EPGS) loop, modification of master control and the plant control, and modifications of the feedwater and water treatment systems to match the flow rates and quality of cycle water for reliable receiver operation.

The plant operational mode includes the use of solar steam during normal insolation with the fossil boiler in a standby mode to respond to cloud transients, use of both solar and fossil steam during partial insolation, and fossil operation during evenings, if required.

POTENTIAL BENEFITS OF REPOWERING

HYBRID NATURE OF REPOWERING OFFERS SEVERAL FEATURES APPEALING TO UTILITIES

- ENHANCED PLANT RELIABILITY
 - Plant can operate at full capacity in event of insolation/solar equipment outages
 - Plant can operate on solar in event of fossil boiler outages
- OPERATIONAL FLEXIBILITY AND CAPACITY OF FOSSIL PLANTS
 - Fossil portion ensures delivery of power when needed (flexible dispatch capability)
 - Solar stand-alone plants limited in dispatch capability, require additional backup fossil plants
 - Repowered plant reduces that additional backup, i. e. , effectively has larger plant capacity value
- BEST VEHICLE FOR OBTAINING EARLY UTILITY ACCEPTANCE
 - Utilities traditionally reluctant to accept new technology; solar introduces additional insolation uncertainties
 - Those concerns minimized by introducing solar technology redundantly into an already operational and familiar plant
 - Problems of fossil fuel availability facing the utilities are reduced
- EXTENDED LIFE FOR OIL/GAS PLANTS FACING RETIREMENT
 - Makes use of existing equipment, site and transmission facilities
 - Reduces siting and other problems of installing new fossil plant equipment (e. g. , coal repowering equipment)

3. REPOWERING OVERVIEW

3.2 POTENTIAL BENEFITS OF REPOWERING

The solar repowering initiative offers several benefits from the utility, programmatic, and national points of views, as outlined in the following charts and discussed below. These benefits, as noted in Chart 3-2, include enhancing reliability, providing flexibility of operation comparable to fossil plants, providing a vehicle for a cost-effective demonstration of alternate systems technologies, and extending the life of retiring plants. Repowering provides other features noted in Chart 3-3.

In addition to economic considerations, utilities (users) place a premium on the reliability and availability of their power generation equipment to ensure that utility system hourly load demand is met with high reliability (i.e., with a very low loss-of-load probability (LOLP), a few hours of loss of load in a 10-20 year period). Risks associated with new solar technology and concern for the unreliability of insolation due to weather make solar less attractive to users than the other alternatives. These concerns are reduced in a repowered plant due to the redundant nature of the hybrid plant operation, as noted in Chart 3-2.

The ability of a plant to produce and dispatch power when needed (e.g., during peak demands) is another factor of major importance to utilities in terms of capacity displacement value and the dollar savings by displacement of more expensive fuels. The capacity displacement of a solar plant can be viewed as megawatts of conventional power generation plants that need not be installed due to solar. A stand-alone solar plant of, say, 100 MW_e rating displaces less than 100 MW_e of conventional generation since additional backup fossil plants must be installed to handle solar outages.^e The hybrid nature of repowering eliminates this additional backup by providing operation comparable to a fossil plant.

POTENTIAL BENEFITS OF REPOWERING

REPOWERING OFFERS

- VEHICLE FOR COST EFFECTIVE DEMONSTRATION OF ALTERNATE TECHNOLOGIES
 - Utility acceptance of promising technologies (salt, sodium) would require pilot demonstrations
 - Technology demonstrated on initial cost-shared repowered plants eliminates the need for additional pilot plants
 - Early involvement of utilities in partnership with the government
- EARLY COMMERCIALIZATION OF SOLAR THERMAL SYSTEMS TECHNOLOGY
 - Repowering of retiring plants can be and must be initiated in 1985
 - 25 - 60 MW_e solar repowering is next logical level of scale-up from 10 MW_e Barstow plant
 - Represents critical path to larger (150 - 500 MW_e) hybrid and stand-alone plant installations
- MORE FAVORABLE ECONOMICS THAN SOLAR STAND-ALONE
 - Use of existing plant facilities saves capital investment
 - Less collector area/cost than stand-alone
- OPPORTUNITY TO CREATE HELIOSTAT PRODUCTION BASE
 - Large manufacturing base to reduce solar costs
 - Market pull initiated by repowering, extended by new hybrids, provides approach to develop production capability
- INITIATIVE FAVORABLE FROM NATIONAL AND OTHER POINTS OF VIEW
 - Offers early cutbacks in consumption/imports of oil - NEA objective
 - Increased employment associated with larger but cost-effective capital investment than for alternate fossil options (e.g. coal repowering)
- Interest by Congress and utilities indicated

3. REPOWERING OVERVIEW

3.2 POTENTIAL BENEFITS OF REPOWERING

Industry must have confidence in solar technology and its operational characteristics (reliability, safety, hardware performance, and maintenance) before it will accept the risk of building solar plants. Repowering appears to be the most cost-effective way to provide this acceptance through early involvement of utilities in demonstrations. Alternate technologies utilizing molten salt and liquid sodium fluids, currently under development by DOE, show economic promise for repowering applications as well as for subsequent commercialization of new hybrid and stand-alone plants. These technologies, in conjunction with the 10 MW_e pilot plant project, can be demonstrated in a cost-effective manner through repowering of two or three oil plants, thereby eliminating the need for additional alternate technology pilot plant projects. This view is supported by the comments of some of the utilities suggesting the need for a next level of scale-up (from 10 MW_e solar at Barstow to 25-60 MW_e solar) for repowering. This level of scale-up is required to assess realistically the impact of operation of the solar plants on a utility electric grid before installation of larger scale (100-500 MW_e) commercial solar plants can begin. Thus repowering represents a critical path to the commercialization of solar electric hybrid and stand-alone plants.

Reductions in the unit cost of heliostats are required to establish the economic viability of solar plants. Large cost reductions are possible through research and development, currently under way at Sandia Laboratories, and through high production rates. A credible near term and future market must exist before manufacturers/suppliers will commit investment in heliostat production at the required rates. Repowering and new hybrids, respectively, offer potential for this near term and future market.

REPOWERING ISSUES

- POTENTIAL OF SOLAR MARKET SIZE (MW_e)
 - Market size an indication of national benefits and justification for federal expenditures
 - Market size identified in PSNM and MITRE surveys
 - Results from two surveys differ
 - Market size expected to reduce with more detailed surveys due to site-specific factors
 - Market size can be increased if certain constraints relaxed
 - Process heat retrofit applications add to this market
 - Hybrid systems offer a substantial additional new market
- MARKET TECHNICAL FACTORS AND REQUIREMENTS
 - Market split by plant type (e.g., reheat and non-reheat), size, and operating conditions, retirement schedule
 - Impact of market on solar retrofit designs
 - Repowering opportunities and economic window, technology availability
 - Utility site and electric grid system characteristics and their impact on solar plant design and economics
- REPOWERING OPTIONS
 - Matching of solar technology with existing fossil plants
 - Types of solar heat input in fossil plant cycles (e.g., feedwater heating, evaporation, superheat)
 - Repowering techniques offering new capacity addition
 - Role of storage
 - Role of new hybrid system options
 - Alternate fossil repowering options

3. REPOWERING OVERVIEW

3.3 REPOWERING ISSUES

Aerospace interim studies of repowering have attempted to address several key issues relating market factors and their technical implications, solar technology applications and repowering configurations, and utility systems integration and economics. These issues are briefly noted in this section and discussed in detail in Sections 4, 5, and 6.

1. Market Factors

The size of the market for solar repowering and hybrid systems is indicative of the potential benefits of a repowering/retrofit initiative on a national scale. It also indicates the potential for developing a manufacturing base for heliostat production required to reduce solar plant costs. Market estimates and factors affecting these estimates, noted in Chart 3-4, are discussed in Section 4.

An assessment of the various technical aspects of the repowering market, identified in the market surveys (3,4), is required to develop guidelines for the repowering project that will lead to maximum solar penetration. Some of these factors, noted in Chart 3-4, are reviewed in Section 4.

2. Repowering Options

To develop appropriate repowering plant options, solar technology must be matched with fossil plant characteristics to develop cost-effective designs from the standpoint of market penetration, utility appeal, and system economics. Various factors related to this issue are noted in Chart 3-4. In addition, benefits and limitations of conventional fossil repowering options must be examined and compared with solar repowering options. A review of possible repowering configurations is presented in Section 5.

REPOWERING ISSUES

- ECONOMICS OF INTEGRATION OF REPOWERED PLANTS INTO UTILITY SYSTEMS
 - Economic criteria, integration and assessment methodology
 - System parameters and uncertainties associated with
 - plant design, costs
 - utility system parameters (e. g. , power plant mix in the grid)
 - economic parameters
 - Interrelations of design, utility characteristics, and economics
 - Validity of approaches to make repowering more attractive in terms of design economics and market potential
- OTHER ISSUES
 - Repowering renews but does not add capacity
 - Temporary loss of capacity during retrofit
 - Thermal cycling of boiler and turbine
 - Site-specific factors
 - Fuel savings

3. REPOWERING OVERVIEW

3.3 REPOWERING ISSUES

A major emphasis of the Aerospace effort on interim repowering studies has been on investigating the economics of integrating repowered plants into various utility systems as discussed below. Chart 3-5 outlines some of the areas addressed in this study.

The economics of a repowering plant, when integrated into a utility system, involves a large number of parameters associated with the solar retrofit plant (e.g., collector size, performance, cost), and utility system (e.g., site, power generation mix, hourly load demand of the grid, and other utility characteristics). Thus a cost-effective plant design cannot proceed independently of the considerations of characteristics of a utility system into which it will be integrated. For example, for a given size of solar plant (MW_e) a particular size of collector field will offer the best economics in a given utility.

Because of the complexity of the problem and large uncertainties in the input data, Aerospace has utilized simplified models in the analyses of various issues noted in Chart 3-5. These models, although simplified, represent the basic mechanics of plant integration into a utility system and its economics. Extensive use of data generated by Westinghouse (3), using more precise tools, has been made to supplement Aerospace analyses. The thrust of our efforts has been to examine the sensitivity of major parameters in the economics of utility systems to gain insight into the various problems and utilize this understanding to develop possible solution approaches. The results of these studies are summarized in Section 6.

Chart 3-5 outlines other issues of repowering of interest to the utility. For example, repowering, in general, only extends the life of an existing plant and its capacity value to the utility, but does not provide any additional capacity needed to meet growing electric demand. Consequently, the capital to invest in repowering is difficult to acquire. Another issue of concern relates to fuel savings. Very little or no fuel oil is saved with certain repowering configurations; see discussion in Section 6.

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4. SOLAR REPOWERING MARKET POTENTIAL AND TECHNICAL REQUIREMENTS

- 4.1 Solar Repowering Market Potential**
- 4.2 Market Split by Plant Type - Reheat and
Non-Reheat Plants**
- 4.3 Repowering Time Windows**
- 4.4 Design and Operational Characteristics of
Candidate Plants**
- 4.5 Plant Repowering Characteristics - Solar
Fractions**

SOLAR REPOWERING MARKET POTENTIAL

Item	PSNM		MITRE	
	Number of Units	Solar Capacity (MW _e)	Number of Units	Solar Capacity (MW _e)
A. Units Rated Below 200 MW _e				
1. Identified repowering candidates	272	19,749	275*	12,900*
2. Repowering criteria:-				
a. land availability,	272	11,171	Unreported	Unreported
b. and land within specified distance,	205	7,248	Unreported	Unreported
c. and unit solar repowered fraction exceeds specified minimum,	82	5,189	Unreported	Unreported
d. and utility interest.	82**	5,189	Unreported	Unreported
B. Units Rated Above 200 MW _e				
1. Identified repowering candidates	51	25,594	257	62,301 -- 65,579
2. Repowering criteria:-				
a. land availability,	51	15,073	Unreported	Unreported
b. and land within specified distance,	37	6,294	Unreported	Unreported
c. and unit solar repowered fraction exceeds specified minimum,	17	5,728	Unreported	Unreported
d. and utility interest	17	5,728	Unreported	Unreported
Total estimated repowering potential	99**	10,917**	Unreported	18,047 ± 7,000 (2σ)

* Estimate includes unidentified number of units eliminated by MITRE totaling 38 MW_e rated capacity in 2 utilities.

** Includes 6 combustion turbines with total capacity of 138 MW_e.

4. SOLAR REPOWERING MARKET POTENTIAL AND TECHNICAL REQUIREMENTS

4.1 SOLAR REPOWERING MARKET POTENTIAL

Estimates of the number of plants to be repowered and the potential for solar capacity have been identified, but the estimates vary depending upon the various assumptions used. The solar repowering units represent 60 to 90 GW solar capacity and a savings of 20 to 40 million bbl/year of oil. These estimates would substantially increase when contribution of process heat and new hybrid system applications are included.

Studies conducted by the Public Service Company of New Mexico (PSNM) and MITRE (2,3) have surveyed the potential market for solar repowering represented by electrical generating stations in the Southwestern United States. The data from these studies are reviewed together with the sampling of data on steam reheat plants found in the Aerospace literature survey. Pertinent results of these studies are presented in Chart 4-1 and in Sections 4.2 and 4.3. Further details are included in the Appendix.

Chart 4-1 presents estimates of required solar capacity based upon availability of adequate land for the solar collector field. In the study, additional constraints were applied, as shown, which further reduced the solar capacity shown. A total of approximately 10,000 MW_e of solar market is indicated for both the reheat and non-reheat plants (number of units and capacities circled in Chart 4-1). These estimates are expected to be reduced when more detailed surveys are made and other constraints such as boiler cycling capabilities are included. On the other hand, relaxation of constraints, such as the distance of the solar tower from the fossil unit at some performance penalty, can increase the solar market significantly (see Section 6.2). The solar capacity potential for the 1985-2000 time frame would be substantially increased when contributions of process heat and new hybrid plants to the solar market are included. (Consideration of these factors is outside the scope of this interim report.)

MARKET SPLIT BY PLANT TYPE - REHEAT AND NON-REHEAT PLANTS (DATA, REFS. 2 AND 3)

- AVAILABLE LAND ONLY CONSTRAINT
- 100% SOLAR FRACTION
- NO LIMIT ON DISTANCE FROM UNIT TO COLLECTOR FIELD

- APPROXIMATELY 46% OF UNITS OF ALL SIZES USE REHEAT CYCLE
- APPROXIMATELY 80% OF TOTAL SOLAR CAPACITY POTENTIAL IS IN THE REPOWERING OF REHEAT PLANTS

4. SOLAR REPOWERING MARKET POTENTIAL AND TECHNICAL REQUIREMENTS

4.2 MARKET SPLIT BY PLANT TYPE - REHEAT AND NON-REHEAT PLANTS

Approximately 50 percent of candidate units in all rating categories use reheat cycles and represent 80 percent of the total solar repowering capacity potential.

The market split in terms of reheat and non-reheat units and associated potential solar capacity is shown in Chart 4-2. Figure a shows that approximately 46 percent of the total candidate steam plants utilize reheat cycle. Approximately 40 percent of all plants with a rating $\leq 200 \text{ MW}_e$ and 100 percent of plants with a rating $>200 \text{ MW}_e$ are reheat units. The solar repowering capacity (MW_e) represented by the reheat plants, however, is approximately 80 percent of the total capacity represented by all candidate plants, as shown in Figure b.

Thus, the plants with reheat cycle represent a significant portion of the solar market. Section 5 examines the compatibility of the solar technology with the reheat plants and identifies a number of possible repowering configurations (4).

REPOWERING TIME WINDOWS (DATA, REF. 2)

- AVAILABLE LAND ONLY CONSTRAINT
- $\leq 200 \text{ MW}_e$ CAPACITY PLANT DATA BASE

4. SOLAR REPOWERING MARKET POTENTIAL AND TECHNICAL REQUIREMENTS

4.3 REPOWERING TIME WINDOWS

The retirement schedule for candidate steam plants indicates a 1985 to 2000 period time window in which repowering of most non-reheat plants must be accomplished (Chart 4-3). A similar opportunity exists for repowering of reheat plants, for which the time window is shifted 10 years downstream. Approximately 140 non-reheat units are scheduled to be retired during the 1985-1990 period. This schedule and the economic considerations discussed below suggest that the repowering initiative must proceed at an accelerated pace to accomplish both technology demonstration and user acceptance by the mid-1980s.

Chart 4-3 shows the scheduled retirement periods for the candidate repowering units, in the size category ≤ 200 MW_e, based upon land constraint only. During the 1950s, the economics of reheat plants and advances in material technology encouraged utilities to install reheat units simultaneously with the non-reheat units. Most of these units are currently reported to be in good condition. The life of these plants appears to be longer than 30 years.

The retirement schedule (2) of the candidate plants shown in the figure indicates that a large portion of the non-reheat plants (approximately 140 units) is scheduled to be retired during the 1985-1990 period. This fact suggests that repowering of these units must be initiated by 1985 and completed within the time window of 1985-2000. The reheat units are relatively newer plants, and the repowering time window is simply shifted downstream by approximately 10 years. The retirement schedule does not take into account the possible impact of the National Energy Act that encourages cutbacks in the consumption of oil and gas in the utility and industrial sectors. The intent of this act and uncertainties in the availability of oil or gas may force early retirement of oil and gas plants. These uncertainties suggest that the repowering initiative must proceed at an accelerated pace so that the technology demonstration and user acceptance are accomplished by the mid-1980s. Recent studies of repowering by the Solar Energy Research Institute (SERI) also show the existence of an economic window in the 1985-1995 time period during which repowering appears most cost effective. These trends have been observed in Aerospace studies in which the value of a repowered plant decreases significantly when the ratio of coal/oil generation mix becomes large (an indication of anticipated increased use of coal); see Section 6.2.

DESIGN AND OPERATING CHARACTERISTICS OF REPOWERING PLANTS (DATA REF. 2)

• AVAILABLE LAND ONLY CONSTRAINT

□ NON-REHEAT PLANTS

▨ REHEAT PLANTS

OIL/GAS PLANTS $\leq 200 \text{ MW}_e$

OIL/GAS PLANTS $> 200 \text{ MW}_e$

4. SOLAR REPOWERING MARKET POTENTIAL AND TECHNICAL REQUIREMENTS

4.4 DESIGN AND OPERATIONAL CHARACTERISTICS OF REPOWERING PLANTS

Chart 4-4 characterizes candidate non-reheat and reheat plants by typical operating conditions (steam temperature/pressure). Of the 152 non-reheat units, approximately 60 percent have throttle steam temperatures of 900°F-950°F at pressures below 1500 psi. These steam conditions are compatible with the Barstow-type first generation solar steam technology.

The reheat plants of all sizes use much higher steam conditions than the first generation solar steam technology. A typical reheat plant utilizes 1000°F steam at the throttle inlet and 1000°F reheat after expansion from the high pressure turbine. The design steam pressures at the throttle vary from plant to plant within the range of 1800-3000 psi (2400 psi typical). The distribution of the candidate plants as a function of plant size (MW_e) for reheat and non-reheat units is illustrated in the lower diagrams of Chart 4-4.

PLANT REPOWERING CHARACTERISTICS - SOLAR FRACTIONS

- AVAILABLE LAND ONLY CONSTRAINT 50% SOLAR FRACTION
- SOLAR FRACTION = SOLAR SIZE
(MW_e)/Fossil Plant Size (MW_e) 50% SOLAR FRACTION

4. SOLAR REPOWERING MARKET POTENTIAL AND TECHNICAL REQUIREMENTS

4.5 PLANT REPOWERING CHARACTERISTICS - SOLAR FRACTIONS

Repowering market estimates discussed above are based upon the selection of plants that permit ≤ 50 percent solar fraction (ratio of the solar to fossil capacity). The larger plants with small allowable solar fractions would also be of interest since repowering techniques such as solar feedwater heating (providing 15 to 20 percent solar fraction) may be ideally suited to capture this market.

Repowering fraction is an important system parameter that determines solar penetration, boiler operating logic, fuel savings, and control philosophy. Repowering with low solar fraction and an inefficient boiler operation can result in little or no savings in critical fuels (Section 6.2).

Chart 4-5 shows the distribution of allowable repowering fractions for the candidate plants in various size ranges. For the small size plants, the distribution of units is distinctly in the regions of high solar fraction and very low solar fraction. For very small plants, low solar fractions might not be of interest from the standpoint of penetration. However, the large plants with a smaller solar fraction would be of interest. For example, a 500 MW_e fossil plant with a 20 percent solar fraction represents 100 MW_e of solar penetration. The repowering techniques, such as solar feedwater heating, accomplish 10 to 15 percent of solar fraction and may be ideally suited to capture this neglected market.

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5. SOLAR TECHNOLOGY AND REPOWERING OPTIONS

- 5.1 Repowering Technology and System Option Matrix
- 5.2 Review of Solar Central Receiver Technologies for Repowering Applications
- 5.3 Characteristics of Candidate Non-Reheat and Reheat Cycle Plants
- 5.4 Options for Solar Heat Utilization in Repowering
- 5.5 Solar Technology Match for Repowering of Non-Reheat Plants
- 5.6 Solar Technology Match for Repowering of Reheat Plants
- 5.7 Role of Storage in Hybrid Repowering
- 5.8 Alternate Repowering Options

REPOWERING TECHNOLOGY AND SYSTEM OPTION MATRIX

RETROFIT TECHNOLOGY OPTIONS	TYPE OF STEAM PLANT	TYPE OF HEAT INPUT	REMARKS
CURRENT TECHNOLOGY SOLAR STEAM	NON-REHEAT	<ul style="list-style-type: none"> • SOLAR BOILER • SOLAR FWH 	<ul style="list-style-type: none"> • STORAGE, IF NEEDED, IS NOT COMPATIBLE WITH EXISTING TURBINES • SOLAR FWH PROVIDES LOW SOLAR FRACTION. APPLICABLE TO REHEAT PLANTS ALSO
ADVANCED TECHNOLOGY SOLAR STEAM (a) BOILER + REHEAT RECEIVER (b) BOILER AND NEW FOSSIL REHEATER	REHEAT	SOLAR BOILER, SOLAR OR FOSSIL REHEAT	<ul style="list-style-type: none"> • REQUIRES DEVELOPMENT OF RECEIVER WITH HIGHER STEAM CONDITIONS • OPTION (a) REQUIRES DEVELOPMENT OF RECEIVER WITH REHEAT PANELS • STORAGE IS NOT COMPATIBLE WITH EXISTING HIGH TEMPERATURE TURBINES
ACR TECHNOLOGY (a) LIQUID SODIUM (b) MOLTEN SALT (c) BRAYTON	<u>REHEAT OR NON-REHEAT</u>	SOLAR HEAT FOR BOILER AND REHEAT	<ul style="list-style-type: none"> • ACR DESIGNS CAN BUFFER AGAINST INSOLATION TRANSIENTS • <u>STORAGE IS COMPATIBLE WITH TURBINES</u> • SALT SYSTEM NEEDS REDESIGN FROM 950°F TO 1,000°F STEAM
CONVENTIONAL TECHNOLOGY (a) COAL BOILER (b) BRAYTON TOPPING (c) NEW EPGS AND/OR BOILER	REHEAT OR NON-REHEAT	FOSSIL STEAM	<ul style="list-style-type: none"> • ENVIRONMENTAL AND INSTITUTIONAL PROBLEMS • OPTIONS APPEAR ECONOMICALLY UNATTRACTIVE

5. SOLAR TECHNOLOGY AND REPOWERING OPTIONS

5.1 REPOWERING SYSTEM OPTION MATRIX

Many repowering configuration options are possible depending upon the type of solar or fossil retrofit technology used, the type of fossil plant to be repowered, and the type and manner in which solar heat is added into the plant cycle (Chart 5-1). The following section discusses the various configurations in further detail.

Chart 5-1 presents a matrix of possible solar and non-solar repowering options for utility steam electric plants. The matrix represents a large number of repowering options based on combinations of the solar and non-solar repowering technology, the type of steam plants to be repowered, and the type and manner in which the retrofit heat is incorporated into the plant cycle. Another important variable that may be added to this matrix relates to storage. Storage may be required in various situations where transient operations, such as those during the passage of clouds, impose excessive cycling loads on boiler or turbine or cause excessive expenditure of oil or gas. Selection of a particular option will depend upon the matching of solar technology with the plant design and operational characteristics, economics, and other factors, including the preference for specific technology by the user. General comments on various repowering options are noted in the last column of the chart. The sections following discuss the features and limitations of the various options in further detail.

REVIEW OF SOLAR CENTRAL RECEIVER TECHNOLOGIES

	WATER-STEAM (WS)	LIQUID SODIUM (LS)	MOLTEN SALT (MS)	BRAYTON CLOSED CYCLE	SANDERS OPEN CYCLE	DYNATHERM/ BECHTEL	BLACK & VEATCH
<u>RECEIVER</u>	METAL TUBE	METAL TUBE	METAL TUBE	METAL TUBE	SILICON CARBIDE (SiC) MATRIX	METAL HEAT PIPE	SILICON CARBIDE (SiC) TUBE
FLUID TEMP (°F) PRESSURE (psi)	WS 960 1460	LS 1100 500	MS 1050 500	AIR 1500 500	AIR 2000 15	AIR 1500 120	AIR 2000 120
<u>STORAGE TYPE</u>	OIL ROCK OIL-ROCK	LS STAND-ALONE & HYBRID 1100 15 (coal heater)	MS STAND-ALONE & HYBRID 1050 15 (oil heater)	MGO BRICK CHECKER STOVE	MGO BRICK	MGO BRICK	FOSSIL COMBUSTION
TEMP (°F) PRESSURE (psi)	550 450			2000 500	2000 120	1500 120	
<u>TURBINE TYPE</u>	DUAL ADMISSION	WS, REHEAT	WS, REHEAT	GAS TURBINE CLOSED CYCLE AIR	GAS TURBINE OPEN AIR REGENERATING CYCLE	OPEN AIR COMBINED CYCLE	OPEN AIR REGENERATIVE CYCLE
TEMP (°F) PRESSURE (psi) EFFICIENCY (%)	950 1450 36	1000 / 1000 2400 43	950-950 2400 43	1500 500 43	2000 120	2000 120	2000 120
<u>ADVANTAGES</u>	UTILITY FAMILIARITY	EFFICIENCY, BUFFER CAPABILITY, HEAT TRANSFER	LOWEST COST STORAGE, EFFICIENCY, BUFFER	FULL / PART LOAD PERFORMANCE	PERFORMANCE, FAST RESPONSE	FOSSIL BOOST	HIGH TEMPERATURE
<u>LIMITATIONS</u>	ADMISSION TURBINE STORAGE TEMPERATURE, EFFICIENCY	LIMITED HIGH TEMPERATURE EXPERIENCE	LONG-TERM EFFECTS ON MATERIALS UNKNOWN	RECEIVER COST SEE TEXT DISCUSSION	LOW RECEIVER AIR PRESSURE SiC TECHNOLOGY	EXPERIMENTAL VALIDATION REQUIRED	NEAR-TERM TECHNICAL RISKS WITH SiC TECHNOLOGY

5. SOLAR TECHNOLOGY AND REPOWERING OPTIONS

5.2 REVIEW OF SOLAR CENTRAL RECEIVER SYSTEM TECHNOLOGIES FOR REPOWERING APPLICATIONS

Chart 5-2 presents a summary of the various solar central receiver systems technologies under development by DOE that could be matched and utilized for various repowering applications. Some of the main advantages and limitations of these systems and technologies are also highlighted in the table and below.

Of the various concepts investigated by Aerospace, the solar Brayton topping cycle added to existing steam plants is the most attractive from the standpoint of versatility and other utility* considerations discussed in Section 5.5. There is also a substantial market for solar Brayton in process heat and cogeneration. A basic limitation appears to be the availability of a cost-effective technology. Certain technology developments are desirable from the point of view of these applications:

1. Open cycle incolog metal tube cavity receiver design in the lower pressure regime (50-120 psi) and maximum allowable air temperatures (1600^oF-1800^oF) based on the development work on a closed cycle receiver.
2. Refinements in cavity receiver design to enhance flux concentration, reduce direct radiation losses, and reduce receiver cost.
3. Investigation of fossil boost techniques to boost temperatures to 2000^oF for utility applications and higher for process heat applications.

*NOTE: The word "repowering" originated from the fossil Brayton topping retrofit of existing oil plants in utility industry.

CHARACTERISTICS OF CANDIDATE PLANTS

NON-REHEAT PLANTS

- 200 MW_e CAPACITY
- T_2 : 700-950°F
- P_2 : 1200-1800 psi

Figure (a)

REHEAT PLANTS

- 50-1000 MW_e CAPACITY
- $T_2 = T_4$: 1000-1050°F
- P_2 : 1500-2400 psi

Figure (b)

5. SOLAR TECHNOLOGY AND REPOWERING OPTIONS

5.3 CHARACTERISTICS OF CANDIDATE NON-REHEAT AND REHEAT CYCLE PLANTS

The size of the solar retrofit equipment and its associated costs for a given solar capacity (MW_e) will be relatively smaller for the higher efficiency reheat plant than for the non-reheat plant. Cost effectiveness of the repowering, however, will depend upon the solar technology utilized and the manner in which it is implemented.

Chart 5-3 presents simplified power conversion cycles and representative steam conditions for the candidate non-reheat and single stage reheat plants. In the reheat cycle, steam is partially expanded through the high pressure turbine (see Figure b, stage 2-3) and reheated in the boiler (stage 3-4) prior to expansion through the intermediate pressure turbine. The reheat stage adds heat to the cycle more efficiently at elevated temperature. This fact and the increased steam temperature contribute significantly to increased cycle efficiency. The performance advantages of the reheat process are sufficient to warrant the added cost of reheat piping for conventional steam plants. This reheat process can be repeated to have two or more stages of reheat (not shown). Relatively newer and larger steam plants utilize reheat cycles.

For solar repowering, the size of the collector field and associated receiver, tower, and storage equipment were significantly influenced by the power conversion cycle. Thus, the cost of solar retrofit will be smaller for reheat cycle than for non-reheat cycle. Consequently, the cost of the solar retrofit equipment to provide the same solar capacity (MW_e) is less. Solar repowering of these plants may involve addition of solar heat in series or in parallel at various stages of the cycle as shown on Chart 5-4.

OPTIONS FOR HEAT UTILIZATION IN REPOWERING

DESIGN CONSIDERATIONS	FWH	EV	SH	RH	EV+SH ⁽¹⁾	EV+SH ⁽²⁾	EV+SH ⁽²⁾ +RH
• SOLAR FRACTION-RATIO OF SOLAR CAPACITY/ FOSSIL CAPACITY	10-15	50-65	25-35	10-20	85-90	70-80	85-90
• RELATIVE RETROFIT INTEGRATION COMPLEXITY AND DOWNTIME	LOW	HIGH	HIGH	HIGH	MODERATE	HIGH	MODERATE
• RELATIVE OPERATIONAL AND CONTROL DIFFICULTY	LOW	HIGH	HIGH	HIGH	MODERATE	HIGH	MODERATE
• HEAT ADDITION MODE (Series or Parallel)	P, S	P	P	P	P	P	P

(1) Non-reheat cycle boiler functions

(2) Reheat cycle boiler functions

5. SOLAR TECHNOLOGY AND REPOWERING OPTIONS

5.4 OPTIONS FOR SOLAR HEAT UTILIZATION IN REPOWERING

Solar heat can be utilized in the fossil plant cycle at various stages of the cycle, e.g., feedwater heating (FWH), evaporation (EV), superheating (SH), reheating (RH), or combinations thereof. Heat could be added in series or in parallel (displacement) modes. Chart 5-4 presents some of the design considerations of solar heat addition in parallel for various options. On the basis of these considerations, the two preferred methods of solar heat utilization are FWH and boiler heat addition in parallel with fossil heat. The solar fraction or energy displacement potential is, however, lowest for FWH and highest for adding heat in parallel with the fossil boiler. On the other hand, integration of solar equipment and operational control are relatively simpler for feedwater applications.

REPOWERING CONSIDERATIONS FOR NON-REHEAT PLANTS - BOILER DISPLACEMENT MODE

• WATER-STEAM TECHNOLOGY
REPOWERING

- $\leq 950^{\circ}\text{F} / 1460 \text{ psi}$
- STORAGE AT $550^{\circ}\text{F} / 450 \text{ psi}$

Figure (a)

• ACR TECHNOLOGY
REPOWERING

- $\leq 1000^{\circ}\text{F} / 2400 \text{ psi}$
- INHERENT BUFFER
- STORAGE AT $1000^{\circ}\text{F} / 2400 \text{ psi}$

Figure (b)

— EXISTING FOSSIL EQUIPMENT
 --- ADDED SOLAR RETROFIT
 EQUIPMENT

5. SOLAR TECHNOLOGY AND REPOWERING OPTIONS

5.5 SOLAR TECHNOLOGY MATCH FOR REPOWERING OF NON-REHEAT PLANTS

Repowering of candidate non-reheat plants with water-steam solar technology is well suited for applications in which solar storage is not required. The ACR technology is better suited for applications requiring storage, higher solar fractions, and associated oil savings. The inherent buffering provided by these systems significantly reduces the transient loads on the turbine and duty cycles of the boiler important for extended life of these components.

1. BOILER DISPLACEMENT MODE

Various solar technologies can be utilized to provide solar evaporation/superheat steam to the turbine in parallel with the fossil boiler as shown in Chart 5-5. The steam design conditions for the candidate non-reheat plants are generally compatible with those of water-steam technology (950°F/1450 psi). This configuration is the same as the reference configuration defined in Section 3, Chart 3-1.

This configuration is useful for applications in which solar storage is not required. Solar storage for this technology is limited to low temperature steam which is not compatible with the operating temperatures and the designs of the candidate plants. In a number of applications, situations are likely to occur in which the weather transients, persistent cloudy weather, and/or utility load demand characteristics can impose severe loads on the turbine, and standby and cycling requirements on the boiler. Inefficient operation of the boiler can result in large consumption of fuels by the fossil boiler that can negate the savings in oil due to solar energy (2).

Figure b illustrates an alternate configuration utilizing advanced central receiver (ACR) liquid sodium (or molten salt) technology. This configuration provides an inherent buffer against short-term receiver transients resulting from weather or solar equipment failures. Storage steam conditions are compatible with the candidate fossil plant designs. Improved storage design permits an efficient use of solar energy to accomplish higher solar fractions and larger fuel displacements. Operation of the fossil boiler can thus be limited to extended periods of solar outages. The receiver fluid and steam temperatures can be reduced to match those of candidate plants thus significantly reducing the possible technology risks associated with high temperature operation of the receiver.

ALTERNATE CONCEPTS - NON-REHEAT FLANTS

SOLAR FEEDWATER HEAT

- 150-550°F
- 10-15% SOLAR FRACTION

SOLAR BRAYTON TOPPING CYCLE

- OPEN CYCLE BRAYTON, 1500°F
- FOSSIL BOOSTED, 2000°F
- TURBINE, 2000°F

5. SOLAR TECHNOLOGY AND REPOWERING OPTIONS

5.5 SOLAR TECHNOLOGY MATCH FOR REPOWERING OF NON-REHEAT PLANTS

The solar Brayton topping concept of repowering renews as well as adds capacity to the candidate repowering plants. The resulting combined cycle plant offers increased performance.

2. FEEDWATER SOLAR HEATER

While the solar fraction and full displacement potential of solar feedwater retrofit configuration (Figure a, Chart 5-6) are small, it offers a simpler integration and control. The small solar fractions (10-15 percent) required by this configuration offer a match with those plants rejected due to small fractions (0-25 percent), thereby increasing the solar market potential. The water-steam solar technology at reduced steam conditions can be applied to this configuration.

3. SOLAR BRAYTON TOPPING CYCLE

The configurations described above can renew the capacity of the retiring fossil plants but do not increase the existing capacity to the utility grid--a factor of importance to utilities in securing financing for new plant initiative. The solar Brayton retrofit configuration shown in Figure b can provide both a renewal of the fossil plant capacity and an increase in the capacity of the plant. This configuration utilizes an open cycle solar Brayton topping engine to produce electricity. The turbine exhaust is utilized to generate steam through a heat recovery steam generator to operate the steam plant. The repowered plant operates like a high performance combined cycle plant. To ensure reliability and performance a fossil combustor is used in the Brayton cycle, to augment heat during little or no solar insolation and to boost air temperature to values compatible with the high performance (2000°F air) Brayton unit(s). Several other fossil augmentation techniques, such as fossil augmentation of heat recovery steam generator, used for conventional power plants can also be incorporated in the design.

This concept represents the most attractive repowering option. Its primary limitation is the availability of cost-effective Brayton technology as discussed in Chart 5-2.

SOLAR REPOWERING OF REHEAT PLANTS - ACR TECHNOLOGY CONCEPT

ACR STEAM CONDITIONS

- $T_2 = T_4 = 1000^\circ\text{F}$
- $P_2 = 1800\text{--}2400 \text{ psi}$

BENEFITS OF ACRS

- SINGLE PHASE HEAT TRANSFER AVOIDS FLOW INSTABILITIES
- INCREASED CYCLE EFFICIENCY, REDUCED COLLECTOR, TOWER, STORAGE SIZE/COSTS
- IMPROVED STORAGE PERFORMANCE
- COMPATIBILITY WITH REHEAT AND NON-REHEAT PLANTS
- STORAGE FEASIBLE IN REPOWERING, ADDS TO CAPACITY, SOLAR FRACTION AND FUEL DISPLACEMENT
- INHERENT BUFFER AGAINST CLOUD AND CONTROL TRANSIENTS REDUCES IMPACT ON BOILER/TURBINE OPERATION AND LIFE
- INCREASED FLEXIBILITY OF OPERATION - DELIVERY OF SOLAR AND FOSSIL ENERGY AT RATED CAPACITY WHEN NEEDED

AREAS OF CONCERN

- LONG TERM MATERIAL RESPONSE AND FATIGUE LIFE
- LIMITED OPERATING EXPERIENCE AT HIGH TEMPERATURES

5. SOLAR TECHNOLOGY AND REPOWERING OPTIONS

5.6 SOLAR TECHNOLOGY MATCH FOR REPOWERING OF REHEAT CYCLE PLANTS - ACR TECHNOLOGY CONCEPT

The repowering configuration which presents the best match of solar technology with candidate reheat plants is illustrated in Chart 5-7. Benefits and concerns of this application are also outlined. Several other possible solar repowering configurations for reheat plants are discussed Charts 5-8 and 5-9.

A. REPOWERING WITH ADVANCED CENTRAL RECEIVER (ACR) TECHNOLOGY

The advanced central receiver (ACR) molten salt or liquid sodium system designs utilize reheat cycle turbines. Thus the ACR system technology and designs, shown in Chart 5-7, provide a direct solar technology match with the candidate reheat fossil plants. The steam temperature and pressure characteristics are comparable to those of candidate reheat plants. Major benefits and concerns of this configuration are also listed in Chart 5-7.

REPOWERING OF REHEAT PLANTS - WATER-STEAM TECHNOLOGY

CONCEPT-B

SOLAR BOILER/REHEATER RECEIVER

- REHEATER PLANTS ADDED TO RECEIVER
- STEAM CONDITIONS INCREASED TO MATCH THOSE OF CANDIDATE REHEAT PLANTS
- REHEAT STEAM LINES CONNECTING RECEIVER AND TURBINES ADDED

CONCEPT-B

CONCEPT-C

SOLAR BOILER RECEIVER- FOSSIL REHEATER

- NON-REHEAT SOLAR RECEIVER
- FOSSIL REHEATER IN PROXIMITY OF FOSSIL BOILER ADDED

CONCEPT-C

5. SOLAR TECHNOLOGY AND REPOWERING OPTIONS

5.6 SOLAR TECHNOLOGY MATCH FOR REPOWERING OF REHEAT CYCLE PLANTS - WATER-STEAM TECHNOLOGY CONCEPT

Chart 5-8 illustrates two concepts of solar repowering of reheat plants using water-steam technology as discussed below.

B. SOLAR BOILER/REHEATER RECEIVER

Repowering Concept B, shown in Chart 5-8, is a modification of the reference configuration (Charts 3-1, 5-5) utilizing water-steam technology. This concept requires significant modifications to the existing technology water-steam system to match the steam and design conditions of candidate reheat plants. If the reheat is to be supplied by solar retrofit, it would be necessary to redesign the receiver to add reheat panels and to modify associated solar retrofit equipment, including the installation of additional steam pipes between the turbine and the receiver/tower for the reheat loop. The design conditions of the solar equipment must be increased to 1000°F/1000°F and 1500-2000 psi steam at the turbine from those of the referenced water-steam design shown in Chart 3-1. This concept is also limited to only those repowering applications requiring no solar storage as discussed in Section 5.5.

C. SOLAR BOILER RECEIVER FOSSIL REHEATER

Concept C utilizes a non-reheat solar receiver (EV + SH) with higher temperature/pressure steam and adds a fossil-fired reheater to provide matched reheat steam to the intermediate pressure turbine during solar operation. The fossil reheat heater, in this concept, reduces the solar fraction by approximately 15 percent from that of Concepts A and B. This concept also suffers from the limitations of storage steam technology.

REPOWERING OF REHEAT PLANTS - ALTERNATE SOLAR OPTIONS

CONCEPT-D

SOLAR BOILER-STEAM/STEAM
REHEAT EXCHANGER

- NON-REHEAT TYPE (EV + SH)
SOLAR RECEIVER
- RECEIVER OVERSIZED TO
PROVIDE ENERGY FOR
REHEAT DESIGNED TO MATCH
HIGHER STEAM CONDITIONS
OF CANDIDATE REHEAT PLANTS
- SOLAR REHEAT EXCHANGER
(RH-X), SOLAR FEEDWATER
HEATER (SFWH) ADDED

CONCEPT-D

5. SOLAR TECHNOLOGY AND REPOWERING OPTIONS

5.6 SOLAR TECHNOLOGY MATCH FOR REPOWERING OF REHEAT CYCLE PLANTS - ALTERNATE SOLAR CONCEPTS

D. SOLAR BOILER-STEAM/STEAM REHEAT EXCHANGER

Another method of supplying solar reheat would be to utilize receiver steam heat for reheat steam through a heat exchanger (RHX) as illustrated by Concept D, Chart 5-9. This concept utilizes a non-reheat water-steam receiver, similar to that for Concept C. The receiver is oversized to provide reheat thermal energy. This technique is attractive but results in reheat steam at a temperature considerably lower than that of the receiver and will show attendant loss in performance and possible moisture problems in the low pressure turbine.

E. FEEDWATER SOLAR HEATER

This concept is similar to that described above (Chart 5-6) for non-reheat plants and may have potential application match with the reheat plants. These plants typically are large in capacity and a number of them have been rejected on the basis of land constraint or solar fraction constraint (i.e., >50 percent solar fraction). For example, a 500 MW_e plant having a solar fraction of 20 percent will have sufficient land for 100 MW_e solar field. Solar size (MW_e) required for solar FWH retrofit of this plant is approximately 75 MW_e, i.e., adequate for the available land.

F. SOLAR BRAYTON TOPPING CYCLE

This concept is also similar to that described above for non-reheated plants (Chart 5-6).

ROLE OF STORAGE IN HYBRID REPOWERING

- BENEFITS OF STORAGE
 - BUFFER AGAINST SHOCK LOADS ON TURBINE DUE TO WEATHER AND SYSTEM TRANSIENTS
 - REDUCED CYCLING AND STANDBY REQUIREMENTS FOR FOSSIL BOILER OPERATION
 - REDUCED FUEL EXPENDITURE DUE TO SELECTIVE USE OF STORAGE AND BOILER
 - INCREASED SOLAR FRACTION PLANT CAPACITY FACTOR AND FUEL SAVINGS
 - INCREASED OPERATIONAL FLEXIBILITY TO STORE SOLAR ENERGY
AND DISPATCH SOLAR OR FOSSIL ENERGY WHEN MOST NEEDED
 - INCREASED CAPACITY AND VALUE TO UTILITIES
 - REDUCED ENERGY COSTS WITH EFFICIENT DESIGN OF STORAGE
- STORAGE ISSUES AND LIMITATIONS
 - COMPATIBILITY OF STEAM STORAGE WITH REPOWERED PLANTS
 - COST OF STEAM STORAGE
 - VALUE OF STORAGE - NOT COST EFFECTIVE IN ALL APPLICATIONS
 - SIZE OF COST-EFFECTIVE STORAGE IN REPOWERING

5. SOLAR TECHNOLOGY AND REPOWERING OPTIONS

5.7 ROLE OF STORAGE AND HYBRID REPOWERING

Considerations of the frequency of insolation transients and associated impact on equipment life, operational requirements for fossil boiler, and economics of hybrid operation suggest the need of a small amount of storage buffer in the hybrid design. The need for additional storage to optimize fossil boiler operation, however, will be dictated by individual situations depending upon the characteristics of hybrid plant (including storage costs), site insolation, and other utility system characteristics.

In the previous investigations of repowering and hybrid systems (2,7) the storage function was assumed to be replaced by the fossil energy sources. Further considerations of insolation, design, operation, and economic factors of these concepts indicate that a small amount of storage buffer is essential for hybrid operation as noted in Chart 5-10.

Storage may be required in certain situations where increased solar fractions and oil savings are desired, particularly for the cases where little or no fuel oil is saved by a utility with a repowered plant (2). Various benefits of buffering and storage are noted in Chart 5-9. Some of the associated limitations discussed in Section 5 are also noted.

The need for additional storage required to optimize the fossil boiler operation and maximize oil savings will be dictated by the individual situations and will depend upon the characteristics of the hybrid plant (including storage cost), site insolation, and other utility system characteristics. Aerospace has initiated a study to address these issues in further detail. Initial results are presented in Section 6.4

SOLAR REPOWERING vs FOSSIL REPOWERING

- SOLAR REPOWERING OPTION
 - CURRENT TECHNOLOGY SOLAR
 - 50 MW_e CAPACITY
 - NO STORAGE
 - EXISTING BOILER AND EPGS
- FOSSIL REPOWERING OPTION
 - INSTALL NEW EPGS
 - CYCLE EFFICIENCY = 0.38
 - CAPITAL COST = 150 \$/kW_e
 - INSTALL NEW BOILER
 - PEAK EFFICIENCY = 0.87
 - CAPITAL COST = 110 \$/kW_e
- EXISTING FOSSIL PLANTS
 - PLANT TYPE
 - 50 MW_e CAPACITY
 - OIL FIRED, NON-REHEAT CYCLE
 - PLANT PERFORMANCE (varied)
 - CYCLE EFFICIENCY, η_{0c}
 - BOILER EFFICIENCY, η_{0b}
 - PLANT EFFICIENCY, $\eta_{0p} = \eta_{0c} \eta_{0b}$

5. SOLAR TECHNOLOGY AND REPOWERING OPTIONS

5.8 ALTERNATE REPOWERING OPTION

The discussions above addressed the issues of repowering with the solar technologies. To establish the cost effectiveness of these approaches, it is also essential to examine non-solar alternatives that might also be available to utilities. These might include repowering with a coal boiler, repowering with fossil Brayton topping cycle (similar to the solar-fossil Brayton topping cycle discussed in Section 5.6, Chart 5-6, and replacing inefficient boilers and/or turbines with similar but more efficient units. These options are currently under investigation.

Chart 5-11 presents a sample case in which solar repowering is compared with an alternate fossil option, installing a new and more efficient boiler and turbine to effect saving fuel by a more efficient fossil operation. The figure in the chart presents the cost/benefit ratio (i.e., ratio of the cost of retrofit to the benefits or savings in fuel costs) for the solar and stated fossil options for a spectrum of candidate steam plants (represented by their plant efficiency values, η_{Op}). These results indicate that this type of fossil repowering option is not as cost effective as the specific case of solar for candidate plants with efficiencies greater than 25 percent.

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6. ECONOMICS OF INTEGRATION OF SOLAR REPOWERED PLANTS INTO UTILITY SYSTEMS

- 6.1 Assessment Methodology**
- 6.2 Repowering Economics Summary**
- 6.3 Sensitivity Analyses**
- 6.4 Weather Analysis for Storage and
Boiler Requirements**

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6.1 ASSESSMENT METHODOLOGY

- 1. Economic Criteria**
- 2. Utility System Simulation Model**
- 3. Comparison of Simulation Results**
- 4. Utility System Analysis - Example**
- 5. Major Parameters of Utility System Analyses**
- 6. Reference Case Assumptions**

ECONOMIC CRITERIA

- MEASURES CURRENTLY IN USE
 - COST/BENEFIT RATIO
 - NET VALUE
 - BREAKEVEN COST
 - LEVELIZED BUSBAR ENERGY COST
- COST/BENEFIT RATIO
 - COSTS: CAPITAL, OPERATING AND MAINTENANCE
 - BENEFITS: $\text{NET FUEL SAVINGS} = \text{TOTAL FUEL SAVINGS} - \text{FUEL COST, VARIABLE O \& M SAVINGS, CAPACITY CREDIT}$
- COST/BENEFIT RATIO BREAKDOWN
 - COSTS: CAPITAL, O & M, FUEL
 - BENEFITS: CAPACITY CREDIT, O & M SAVINGS, FUEL SAVINGS
- BREAKEVEN COLLECTOR COST
 - $\text{COLLECTOR COST YIELDING COST/BENEFIT RATIO} = 1.0$

6.1 ASSESSMENT METHODOLOGY

1. Economic Criteria

The cost/benefit ratio (C/B) is used as a criterion for the economic merit of repowering. It represents the ratio of the cost of solar retrofit equipment to the savings (benefit) to the utility as a result of repowering. An alternate criterion, namely the heliostat breakeven cost, is also used. It is the allowable heliostat unit cost that will yield a $C/B = 1.0$.

Several economic indices are currently used to evaluate the relative economic merits of candidate power plants, including cost/benefit ratio, net present value, system or subsystem breakeven costs, and levelized busbar energy costs (Chart 6-1). In this study no attempt is made to evaluate all these different criteria, but we are attempting to evaluate solar repowered plants from the point of view of a utility and to compare them with the existing data which has been generated in DOE studies (2) using one of these measures, the cost/benefit ratio. With this criterion, all the costs incurred to the utility as a result of solar retrofit (i.e., capital costs and associated operation and maintenance (O&M) costs) are allocated as cost. The savings incurred to the utility as a result of operation of the repowered plant into the utility grid over the life of the plant are allocated as benefit. These do not include the various benefits derived by solar applications on a national basis (e.g., curtailment of consumption of oil leading to reduced imports and trade balances, reduced environmental pollution, increased employment, etc.).

Benefit or saving is defined here as the dollar value of solar to a utility (independent of the cost of solar) in terms of conventional power equipment not required, net savings in the system fuels (oil, coal fuel, etc.), and associated savings of O&M due to the contribution of the repowered plant. These savings are presented by a single discounted dollar value of a stream of savings that occur yearly over the operating life of the plant.

Some of the results are also presented in terms of an alternate criterion, namely the breakeven heliostat unit cost, which is the maximum allowable collector unit cost ($\$/m^2$) yielding a cost/benefit ratio of 1.0.

UTILITY SYSTEM SIMULATION MODEL

- MEASURES ACTUAL ENERGY DISPLACED FOR EACH TYPE OF FUEL IN THE SYSTEM
- USES LOAD DURATION CURVES TO COMPUTE DISPLACED ENERGY AND SYSTEM-WIDE FUEL SAVING
- ACCOUNTS FOR POWER PLANT MIX AND DIFFERENT FUEL TYPES, ESCALATION RATES
- EXAMINES REPOWERING OF A GIVEN PLANT WITHOUT OTHERWISE CHANGING THE SYSTEM MIX

6.1 ASSESSMENT METHODOLOGY

2. Utility System Simulation Model

A simplified utility system model (Chart 6-2) is utilized to determine the amounts and costs of all types of system fuel displaced as a result of solar repowering. Using the appropriate fuel cost and escalation rate for each type of fuel, the model then determines the present value of displaced fuel required in the calculation of cost to benefit ratio. Fuel expenditure due to fossil boiler operation is determined by the use of a hybrid simulation model.

The model analyzes the effect of solar repowering on a utility system by computing load duration curves associated with the total power generated from fossil fuel in the utility with and without solar repowering. Since in the static analysis assumption the plant mix does not change with time, the areas between the two load duration curves for each plant type in the utility are proportional to fuel displacement for those plant types.

The fuel expenditure of the repowered plant is estimated by a hybrid simulation model. The boiler operating losses associated with starting, shutdown, cycling, and standby operations are accounted for by reducing the energy displaced by a practical factor. The schematic drawing of the two load duration curves shows that solar repowering results in savings of gas, oil, and coal fuels even though the repowered unit is an oil-fired plant.

COMPARISON OF SIMULATION METHODS

COLLECTOR AREA
(m^2/kW_e)

UTILITY
SITE

PSNM
ALBUQUERQUE

COLLECTOR AREA
= 4.66 m^2/kW_e

EPRI-E
MIDLAND

6.1 ASSESSMENT METHODOLOGY

3. Comparison of Simulation Results

The Aerospace utility system simulation model has been verified by comparing its results against the corresponding data of Reference 2. A general agreement was found as shown in Chart 6-3.

Aerospace simulated many of the cases investigated in the PSNM study (2), using a utility system simulation model. This model is an approximate simulation of a utility in the sense that plants are grouped by fuel type and an annual average is used for plant availabilities and heat rates.

The basic system effects and mechanics of obtaining value in a utility system are represented in this model. Although Aerospace results are slightly more optimistic, there is a general good agreement between this model and the detailed simulations of Reference 2 as seen in Chart 6-3. In the chart at the right, the shaded region for Reference 2 data represents the variation between cold and warm boiler standby modes. In the Aerospace simulation data, the shaded region represents the variation in the penalty factor applied to account for startup, standby, shutdown and cycling losses.

In the figure on the left we also see similar effects, i.e., there is an optimum collector sizing in both cases.

UTILITY SYSTEM ANALYSIS

PLANT AND SETTING

- 50 MW_e INTERMEDIATE OIL PLANT, REPOWERED 50 MW_e SOLAR
- SOLAR: ALBUQUERQUE INSOLATION, COLLECTOR AREA 310,000 M², RUN-OF-THE-SUN OPERATION, NO STORAGE, 100% AVAILABILITY
- DEMAND: PSNM 1985 ESTIMATE (yearly peak 1545 MW_e)
- ECONOMICS: 1985 DOLLARS, PRESENT WORTH OVER 30 YEARS, COST OF CAPITAL 8.6%

SYSTEM MIX

	NUCLEAR	COAL	OIL STEAM	COMB TURBINE
CAPACITY (MW _e)	250	1300	350	100
FUEL COST (\$/Mbtu)	1.25	2.0	5.0	5.5
HEAT RATE (Btu / kWh)	10,050	10,000	9,600	14,000
FUEL ESCALATION RATE (%)	10	10	12	12
AVAILABILITY (%)	80	80	80	90

IMPACT OF SOLAR

SOLAR ENERGY (GWh / yr)	0	116.2	50.0	0
FUEL SAVINGS (M\$)	0	85.6	108.4	0

6.1 ASSESSMENT METHODOLOGY

4. Utility System Analysis - Example

The example data from the simulation model (Chart 6-4) illustrate the plant and utility system generation mix input assumptions and the results showing the impact of solar repowering on the utility system in terms of energy displaced and an associated present discounted dollar value of fuels saved by fuel types (i.e., coal and oil).

The utility system generation mix in this example is coal dominated; hence solar displaces larger amounts of coal (roughly 65 percent). This effect is masked somewhat in the dollar savings shown due to the significantly lower unit cost of coal than of oil fuels.

MAJOR PARAMETERS IN VALUE ANALYSIS METHODOLOGY

● ECONOMICS

- GENERAL: INFLATION AND ESCALATION RATES, TAXES
- UTILITY FINANCING: BONDS, STOCKS, DEPRECIATION, PLANT LIFE, TAX CREDITS AND INCENTIVES, INSURANCE
- PRESENT WORTH PARAMETERS: DISCOUNT RATE, CAPITAL RECOVERY FACTOR, FIXED CHARGE RATE, PRESENT WORTH ESCALATION FUNCTION

● SYSTEM DESCRIPTION

- TYPES OF PLANTS: i.e., NUCLEAR, COAL, OIL
- PLANT DATA: CAPACITIES, AVERAGE AVAILABILITIES AND HEAT RATES
- FUEL DATA: TYPES, AVERAGE COSTS, ESCALATION RATES
- CAPITAL, FIXED AND VARIABLE O & M COST FOR EACH TYPE

● UTILITY DEMAND DATA

- HOURLY PROJECTIONS FROM AEROSPACE DATA BASE
- CONVERSION TO LOAD DURATION CURVES WITH AND WITHOUT SOLAR

● REPOWERED PLANT DESCRIPTION AND OUTPUT

- PLANT DATA: CAPACITY, COLLECTOR AREA
- HOURLY SOLAR POWER PROFILE: USED TO OBTAIN RESIDUAL LOAD DURATION CURVE FOR COMPUTING ENERGY DISPLACEMENT BY TYPE OF FUEL
- PERFORMANCE OF FOSSIL PORTION OF PLANT: USED TO COMPUTE FUEL COST
- CAPITAL AND O & M COST

6.1 ASSESSMENT METHODOLOGY

5. Major Parameters of Utility System Analyses

The major inputs to the utility system simulation model are described. The economic conditions, the system characteristics of a particular utility being modeled, and the performance and cost data for the repowered plant.

Chart 6-5 shows a breakdown of the parameters involved in the utility system simulation model. Data on the performance of the repowered plant are generated by another Aerospace model simulating a hybrid solar/fossil plant operation. Data on the utility system are of three types: economic and financing, types of utility system generation mix (including plant characteristics and costs), and the utility grid load demand data. The model incorporates these data to determine energy displacements by type of fuel, system costs, and savings as well as several other value parameters.

REFERENCE CASE ASSUMPTIONS

- PLANT TO BE REPOWERED
 - 50 MW_e INTERMEDIATE OIL PLANT
 - SITE: MIDLAND, TEXAS: AEROSPACE INSOLATION DATA
 - UTILITY: EPRI-E: AEROSPACE DEMAND DATA
- SOLAR PORTION
 - COLLECTOR AREA: 233,000 m²
 - RUN-OF-THE-SUN OPERATION: 100% AVAILABILITY
 - NO STORAGE
- ECONOMIC SCENARIO
 - DISCOUNT RATE: 11%
 - FIXED CHARGE RATE: 18%
 - COLLECTOR COST: 65\$/m²
 - INDIRECT COSTS: 44%
 - O&M COST vs CAPITAL INVESTMENT: 3%
 - O&M ESCALATION RATE: 8%
 - 1985 \$
- SYSTEM DATA

TYPE OF FUEL	NUCLEAR	COAL	OIL STEAM	COMB TURBINE
CAPACITY (MW _e)	1600	2600	5600	500
AVAILABILITY (%)	80	80	80	90
FUEL COST (\$/MBtu)	1.25	2.0	5.0	5.5
HEAT RATE (Btu/kWh)	10,050	10,000	9,500	12,000
FUEL ESCALATION RATE (%)	10	10	12	12

6.1 ASSESSMENT METHODOLOGY

6. Reference Case Assumptions

A baseline case was chosen to correspond closely to one of the many cases investigated in the PSNM study (2). A 50 MW_e intermediate oil steam plant in a synthetic EPRI-E utility is assumed to be repowered with a solar collector size of 233,000 m². The plant is located in Midland, Texas, and Aerospace insolation tapes for that location are used. An Aerospace demand forecast for 1985 developed from EPRI data is used for the demand profile and load duration curves. The basic economic and system data shown in Chart 6-6 are taken from Reference 2 and the 1978 EPRI Technical Assessment Guide. For the reference case, a cost/benefit ratio of 0.83 is obtained, somewhat lower than the 0.94-1.02 estimated in Reference 2, primarily because 100 percent availability was assumed for the repowered plant in the Aerospace analysis.

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6.2 REPOWERING ECONOMICS SUMMARY

6.2.1 REPOWERING ECONOMICS OVERVIEW

1. Economics of a Solar Plant in Various Utility Systems
2. Effect of Increasing Fuel Costs
3. Effect of Increasing Fuel Escalation Rates
4. Breakeven Heliostat Unit Cost and its Sensitivity to O&M Costs

6.2.2 ENERGY AND FUEL DISPLACEMENT

1. Effect of Site and Utility System Characteristics on Fuel Savings
2. Effect of Fuel Mix on Utility Economics
3. A Repowering Design/Dispatch Concept

6.2.3 OTHER IMPROVEMENT TECHNIQUES

1. Longer Solar Heat Transport Pipes
2. Impact of Financial Incentives on Repowering Economics

ECONOMICS OF A SOLAR PLANT IN VARIOUS UTILITY SYSTEMS

ASSUMPTIONS

- 1985 START OF OPERATION
- 30 YEAR LIFE
- 70 \$/m², O&M 3% AND 1% OF CAP COSTS
- 50 MW_e SOLAR-WATER STEAM, NO STORAGE
- 50 MW_e FOSSIL
- SITE-SPECIFIC FACTORS NOT CONSIDERED

6.2.1 REPOWERING ECONOMICS OVERVIEW

1. Economics of a Solar Plant in Various Utility Systems

Estimates of cost/benefit ratios for a repowered plant integrated into various utility systems show that those ratios are approaching the regimes of economic acceptability. Repowering in EPRI-E type synthetic utilities (representative of utilities in the Texas-Oklahoma region with 50 percent of solar capacity market) and new alternate technology hybrid systems look the most attractive economically for the reasons discussed below.

Chart 6-7 shows the relative economics of integrating a water-steam solar technology repowered plant into various utility systems. The cost/benefit ratios are based on analyses of Reference 2 utilizing assumptions noted in this chart and those defined in Section 6.1.6. The O&M cost estimates have been varied from those of Reference 2 to lower values indicated in other contractor studies. For comparison, estimates of a new solar hybrid plant (which is also an option of the repowering project) utilizing molten salt technology (1) integrated into the Arizona Public Service (APS) power grid are also included. For a commercial plant utilizing first generation water-steam solar technology with the assumptions noted, the cost/benefit ratios are approaching the regimes of economic acceptability. The C/B values will increase somewhat when site-specific factors are accounted for in the solar plant costs. It should be noted that the EPRI-E case shows the lowest cost/benefit ratio due to the oil-dominated generation mix representative of the Texas-Oklahoma region at the Midland, Texas, site. This region represents approximately half of the solar repowering capacity potential (3). These results are very sensitive to a number of important parameters such as O&M costs, collector costs, fuel costs, and escalation rates. Sensitivity of these factors to the economics is highlighted in the following charts and discussed in Section 6.3.

The new hybrid plant looks relatively more cost effective due to higher performance central receiver technology, low cost storage, and storage buffer against cloud transients that significantly reduce the inefficient boiler firing requirements. Economics of this hybrid plant with storage are expected to be even better in the EPRI-E and PSNM type utilities which incur a relatively large expenditure of fossil boiler fuel.

The figure on the right in Chart 6-7 illustrates the fact that, for a given solar plant capacity (50 MW), there is a specific collector design to suit a particular utility system that will give the minimum cost/benefit ratio, i.e., an efficient plant design must take into account site-specific characteristics of a utility system. Similarly the role and size of storage in a plant will be dictated by the characteristics of the particular utility in which the solar plant is to be integrated. These and other utility integration considerations were highlighted in a DOE/SCE study (5) several years ago but only recently are being recognized by a small segment of the solar community.

EFFECT OF INCREASING FUEL COSTS

ASSUMPTIONS

- 1985 START OF OPERATION
- 30 YEAR LIFE
- 70 \$/m², O&M 3% AND 1% OF CAP COSTS (shaded area)
- 50 MW_e SOLAR-WATER STEAM, NO STORAGE
- 50 MW_e FOSSIL
- SITE-SPECIFIC FACTORS NOT CONSIDERED

OIL AND COAL FUEL COST
INCREASED BY 25% FROM
REFERENCE CASE
(Chart 6-7)

ECONOMICS

6.2.1 REPOWERING ECONOMICS OVERVIEW

2. Effect of Increasing Fuel Costs

The availability of oil and costs of oil and coal fuels and their escalation rates in the 1985-2010 period are areas of major uncertainties facing the utilities in their planning activity. These factors are also a major driver in the assessment of value of the solar repowered plants.

For the cases shown in Chart 6-7, the unit costs of the oil and coal fuels were arbitrarily increased by 25 percent both for the fuel displaced by solar energy and the fuel expended by the repowered plant boiler to meet the load demand. Chart 6-8 shows the result of that increase in fuel costs on the C/B values. The C/B values for the various utilities decreased by 16 to 20 percent. The opposite effect of a reduction in the fuel price will show a proportional increase in the C/B values over the cases shown in Chart 6-7, due to the linearity of the economics.

EFFECT OF INCREASING FUEL ESCALATION RATES

ASSUMPTIONS

- 1985 START OF OPERATION
- 30 YEAR LIFE
- 70 \$/m², O&M 3% AND 1% OF CAP COSTS (shaded area)
- 50 MW_e SOLAR-WATER STEAM, NO STORAGE
- 50 MW_e FOSSIL
- SITE-SPECIFIC FACTORS NOT CONSIDERED

OIL AND COAL FUEL COST
ESCALATION RATE INCREASED
BY 25% FROM REFERENCE CASE
(Chart 6-7)

ECONOMICS

6.2.1 REPOWERING ECONOMICS OVERVIEW

3. Effect of Increasing Fuel Escalation Rates

Chart 6-9 shows the effect of increasing the rates of fuel escalation over the reference case, Chart 6-7. The fuel escalation rates for the #2 oil fuel for the combustion turbines and combined cycle plants, #6 oil for steam plants, and the coal plants were increased as shown below for the 1985-2010 period. The unit fuel costs were kept static as for the cases shown in Chart 6-7.

<u>Fuel</u>	<u>Reference Escalation Rate</u>	<u>Increased Escalation Rate</u>
#2 Oil	12%	15%
#6 Oil	12%	15%
Coal	10%	12.5%

These increments in the fuel escalation rates typically result in a 40 percent reduction in the C/B values, indicating that the fuel escalation rate is the most sensitive system parameter.

BREAKEVEN HELIOSTAT UNIT COSTS

6.2.1 REPOWERING ECONOMICS OVERVIEW

4. Breakeven Heliostat Unit Cost and Its Sensitivity to O&M Costs

Chart 6-10 presents the same economic data of Chart 6-7 in terms of breakeven unit heliostat costs. These are the allowable heliostat costs for various utility systems to attain a cost/benefit ratio of 1.0. The upper dotted portion of the bars represents the range of variation due to plant O&M cost estimates (1-3 percent of the plant capital costs).

It should be noted that while the O&M costs are only a small fraction of the plant capital costs, they are a sensitive parameter. They represent a distributed stream of revenue requirements over the 30 year life of the plant, and the present value of this stream becomes a significant cost element. Special emphasis must therefore be placed on the heliostat and other system development efforts to investigate O&M characteristics and to reduce O&M costs.

EFFECT OF SITE AND UTILITY SYSTEM CHARACTERISTICS ON FUEL SAVINGS

6.2.2 ENERGY AND FUEL DISPLACEMENT

1. Effects of Site and Utility System Characteristics on Fuel Savings

Operation of a solar plant in a utility system results in displacement (savings) of energy from a spectrum of conventional plants varying from peaking to baseload units. The reduced output of these plants results in savings in system fuels typically consisting of #2 and #6 oil and coal fuels. The relative amounts of oil and coal saved depends upon the utility generation mix (or relative amount of fuels used in the utility) as well as the daily and seasonal load demand characteristics of the particular utility.

In the case of hybrid repowering, the net savings in oil consists of oil displaced by solar energy minus the expenditure of oil by the fossil boiler. Chart 6-11 illustrates the split in the coal and oil saved in various utility systems along with the estimates of oil expenditures due to fossil boiler operation.

It should be noted that while the EPRI-E reference case shows the most attractive economics due to large savings in oil, it also incurs a significant amount of oil expenditures by the boiler operation. Thus, the C/B value for this case can be further reduced by minimizing the fuel expenditures. Several solution approaches are possible for these situations including:

- (1) Use of sodium or salt receiver technology to provide storage and storage buffer against solar outages.
- (2) Steam sharing from adjacent units - approximately 89 percent of candidate units surveyed are located at sites with multiple units (2).

EFFECT OF FUEL MIX ON UTILITY ECONOMICS

- EPRI-E MODIFIED.
- 15% NUCLEAR REPLACED BY COAL
- 5% COMBUSTION TURBINES REPLACED BY OIL STEAM PLANTS
- STATIC MIX

6.2.2 ENERGY AND FUEL DISPLACEMENT

2. Effect of Fuel Mix on Utility Economics

The repowering cost/benefit ratio (C/B) increases with increasing coal capacity in a utility system. However a significant increase in C/B occurs only when the utility becomes heavily coal dominated. These conclusions should also be valid for other solar thermal plants, such as new hybrids and stand-alone plants.

The generation mix (or fuel mix) of a utility system is another sensitive parameter that dominates its economics. A sensitivity study was conducted in which a relative mix of oil- and coal-fired generation was varied parametrically. The EPRI-E reference case, discussed above, was utilized with some modifications in the generation mix. The utility generation mix was assumed to consist of only #6 oil- and coal-fired plants for a repowered plant integrated in this system.

Results are shown in Chart 6-12. C/B values increase with the increasing fraction of coal generation capacity in the utility as expected because solar is displacing more coal, a lower cost fuel. This means less savings or benefits in dollars or a higher C/B. However, the C/B increases only slightly as the coal generation capacity is increased to 40 percent of the total generation capacity. Increases in the coal capacity beyond 40 percent result in a rapid increase in the C/B. The C/B value may be reduced in such situations by using an alternate design/dispatch strategy discussed in Chart 6-13.

A REPOWERING DESIGN/DISPATCH CONCEPT

PREVIOUS REPOWERING STUDIES

- WATER-STEAM SOLAR TECHNOLOGY
- NO STORAGE
- SOLAR DISPATCHED FIRST
- NO CONTROL ON OIL AND COAL DISPLACEMENTS
- IN SOME SITUATIONS, OIL SAVINGS DUE TO SOLAR NEGATED BY OIL CONSUMPTION BY BOILER—NO OIL SAVING, HIGH C/B

ALTERNATE REPOWERING APPROACH

- STORAGE/TURBINE SUBSYSTEMS DESIGNED TO MEET DISPATCH REQUIREMENTS
- SOLAR DISPATCHED MOSTLY WHEN OIL IS BEING DISPLACED, STORED WHEN IT BEGINS TO DISPLACE COAL
- SOLAR STORAGE USED TO MINIMIZE INEFFICIENT BOILER OPERATION
- NET SAVINGS IN OIL INCREASED, C/B DECREASED

6.2.2 ENERGY AND FUEL DISPLACEMENT

3. A Repowering Design/Dispatch Concept

A possible repowering design and dispatch concept is proposed which may enhance the economic and oil displacement potentials of repowering, particularly in situations discussed below, where little or no oil was saved by repowering. It is not clear whether such an approach is economically and operationally feasible or, if feasible, whether it has wider application. This concept, however, appears to have sufficient merit to warrant further investigation.

Chart 6-13 describes a possible dispatch strategy which may maximize oil displacement by solar and decrease the C/B. In previous studies (2) the application of water-steam technology precluded the use of storage in repowering as discussed in Section 5. Thus, solar was dispatched first in a run-of-the-sun dispatch mode with no control on the displacement of more expensive peaking and intermediate generation fuel oils. In the repowered hybrid mode, fuel oil is also expended to maintain the boiler in standby condition to respond to the insolation variations. The associated cost of fuel is high and it subtracts directly from the economic benefits and oil savings derived from fuel displaced by solar energy. Under certain situations (2) there is very little or no net savings in the critical fuel oils.

The proposed approach makes use of an alternate systems technology, such as the salt system to provide low cost storage and a storage buffer against weather transients. The solar plant design is determined by the requirements of the dispatch strategy that maximizes displacement of oil. The dispatch strategy might involve delivering solar energy when oil is being displaced and storing it (even for delivery the following day) when solar energy begins to displace coal. To accomplish this, the storage and turbine may be oversized and/or additional turbines may be required.

It is not clear at this point whether such an approach is economically and operationally feasible, and if feasible, whether it has a wider application.

Ideally such an approach can be effective in situations where moderate amounts of oil and coal are consumed throughout the year. This approach may not be as effective in certain utility situations (e.g., summer peaking utilities) where only small amounts of oil are consumed during the winter season.

LONGER SOLAR HEAT TRANSPORT PIPES

DESIGN FACTORS FOR TRANSPORT PIPES

- PIPE LENGTH $L \leq 2500$ ft
- STEAM LINES, FOR WATER-STEAM TECHNOLOGY
- STEAM OR SALT (or Sodium) LINES, FOR ACR TECHNOLOGY

EFFECTS OF INCREASED PIPE LENGTH
($L \geq 5,000$ ft)

- INCREASED SOLAR MARKET POTENTIAL, REDUCED LAND CONSTRAINTS IN DESIGN
- INCREASED THERMAL LOSSES

RESULTS USING LONGER PIPES
($L \geq 5,000$ ft)

- FEWER CONSTRAINTS ON COLLECTOR FIELD DESIGN
- THERMAL LOSSES SMALL ($< 1\%$ OF DAILY ENERGY) PRODUCED (for $L = 5,000$ ft)
- LONGER WARM UP TIME FOR STEAM PIPE (much less for salt pipe) REQUIRED AFTER OVERNIGHT COOLDOWN
- INCREMENTAL COST VERY SMALL COMPARED TO PLANT CAPITAL COSTS
- SOLAR MARKET SIZE INCREASED BY 50% OR MORE

6.2.3 OTHER IMPROVEMENT TECHNIQUES

1. Longer Solar Heat Transport Pipes

The potential solar capacity market estimates presented in Section 4 can be increased substantially (by 50 percent or more) if the constraint on the distance, L , from the tower to the fossil plant (see Chart 6-14) is relaxed from 2500 ft or less to 5000 ft or more. The impact on performance, operational characteristics of the plant, and system costs is small.

Market data of Reference 2 indicate that the potential solar capacity market for repowering can be substantially increased if the constraint on the distance, L , from the tower to steam plant (see sketch in Chart 6-14) is relaxed.

A distance constraint of $L \leq 2500$ ft was initially placed for the market survey (2) based upon preliminary considerations of the loss of performance and added cost due to longer steam transport lines. Repowering with alternate technologies, such as salt system technology, permits the option of transporting solar heat either through salt pipes or through steam pipes (see Chart 5-2 of Section 5 for further clarification).

Longer pipes will incur increased steady state heat losses during daily operation and transient heat losses during overnight shutdown. Analyses of these losses, operational factors, and incremental costs were made as a function of pipe length. Typical results for a 5000 ft long pipe are summarized in Chart 6-14.

IMPACT OF FINANCIAL INCENTIVES ON REPOWERING ECONOMICS

INCENTIVES

- A. INVESTMENT TAX CREDIT
- B. REAL INTEREST LOANS
- C. ACCELERATED DEPRECIATION
- D. PROPERTY TAX CREDIT

IMPACT OF INCENTIVES

- PRESENT VALUE OF SOLAR EQUIPMENT CAPITAL COSTS REDUCED
- NO IMPACT ON O&M COSTS
- IMPACT OF INCENTIVES ON INDIRECT COSTS AND PLANT VALUE NEGLECTED

6.2.3 OTHER IMPROVEMENT TECHNIQUES

2. Impact of Financial Incentives on Repowering Economics

Repowering economics can be made substantially attractive to the utilities through government financial incentives as shown in the opposite chart for the EPRI-E reference case.

A brief incentive study was conducted and four financial incentives were identified for solar applications as noted in Chart 6-15. For incentive A, the tax credit is increased from 10 to 20 percent. For incentive B, the government pays interest on the secured portion of the construction loan. Incentive C requires an accelerated depreciation rate. Incentive D requires that solar installations be excluded from property tax. The effects of these incentives on the C/B ratio, individually and collectively, are shown in Chart 6-15.

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6.3 SENSITIVITY ANALYSES

1. Major Repowering System Parameters
2. Key Parameters Varied
3. Collector Area and Collector Cost Variations
4. Indirect and O&M Cost Variations
5. Variations in the Fuel Costs and Escalation Rates
6. Effect of Fuel Mix on Utility Economics
7. Utility/Site Variation
8. Sensitivity Comparison
9. Parameter Ranges Yielding Favorable Cost-Benefit Ratio

MAJOR REPOWERING SYSTEM PARAMETERS (UTILITY PLANTS)

UTILITY

- LOAD DEMAND PROFILE
- GENERATION AND FUEL MIX
- SITE INSOLATION
- FUEL-MIX CHANGE WITH TIME
- PERCENT PENETRATION
- FUEL COSTS, ESCALATION RATES
- CAPACITY CREDIT

PLANT DESIGN

- SOLAR FRACTION (MW_e SOLAR/ MW_e FOSSIL)
- EPGS CYCLE
- COLLECTOR SIZE
- PLANT PERFORMANCE
- BOILER OPERATING LOGIC
- STORAGE
- O & M COSTS

6.3 SENSITIVITY ANALYSES

1. Major Repowering System Parameters

Some of the significant system parameters of interest in the sensitivity studies are listed in Chart 6-16.

The utility system simulation model is capable of quickly handling many variations of the system parameters involved in solar plant value analysis. It is important to understand how these variations affect the economic index used for two reasons: (1) it helps detect the potential for error in a given set of data and (2) it aids in predicting trends and setting goals. Sensitivity studies have been performed by Aerospace for a number of potential repowering scenarios. Some of these data are presented in the following pages.

KEY PARAMETERS VARIED

● PLANT AND ECONOMIC PARAMETERS

VARIABLEVALUES*

COLLECTOR AREA (m^2 / kW_e)
 COLLECTOR COST ($\$/\text{m}^2$)
 INDIRECT COST FRACTION (%)
 O & M COST vs. CAPITAL INVESTMENT (%)
 O & M ESCALATION RATE (%)
 UTILITY/SITE

2, 3, 26, 4.66, 6.2, 8
65.16, 100, 150, 200, 250
15, 30, 43.75
 1, 2, 3
 5, 8
EPRI-E/MIDLAND, PSNM/ALBUQUERQUE

● SYSTEM PARAMETERS

VARIABLEVALUES*

FUEL COST
 FUEL ESCALATION RATE (%)

REFERENCE, OIL + 25%, COAL + 25%
 OIL = 10, 12, 15, 17, COAL = 10, 12, 15

* REFERENCE VALUE UNDERLINED

6.3 SENSITIVITY ANALYSES

2. Key Parameters Varied

The parameters varied in this study are indicated in Chart 6-17, with the values for the EPRI-E reference case underlined. Some parameters to be added in future studies are also listed.

In the sensitivity analysis described in this section, six parameters were varied: collector cost, solar plant indirect cost fraction, operations and maintenance escalation rate, fuel costs, and fuel escalation rates. The values chosen for this analysis are shown in Chart 6-17; those values used in the reference case are underlined. The effects on the cost/benefit ratio of varying these parameters are illustrated in the next two charts (6-18 and 6-19).

The indirect cost fraction is the ratio of indirect to direct plant capital costs. Operating and maintenance costs are treated parametrically by taking a percentage of capital costs. The effects of increased fossil boiler cycling, thermal storage, and capacity credit are currently under investigation and will be reported on at a later date.

COLLECTOR AREA AND COLLECTOR COST VARIATIONS

6.3 SENSITIVITY ANALYSES

3. Collector Area and Collector Cost Variations

The effects of changing collector area and collector unit cost are examined in Chart 6-18. The existence of an optimum collector area is seen and the large sensitivity of cost/benefit ratio to collector unit cost is illustrated.

The graphs in Chart 6-18 illustrate the variation in cost/benefit ratio for the EPRI-E reference case described above. It can be seen that an optimum collector sizing occurs at slightly over $6\text{m}^2/\text{kW}_e$. This optimum always occurs but varies with the utility and site, as illustrated. Optimizing the collector area in this example yields the most favorable cost/benefit ratio. The graph at the right shows one method of illustrating the sensitivity to collector cost. Collector cost is one of the most sensitive parameters involved. The bottom graph illustrates the use of breakeven collector cost. This figure is useful in evaluating this major component of cost and in correlating with both goals and present day realities.

INDIRECT AND O&M COST VARIATIONS

6.3 SENSITIVITY ANALYSES

4. Indirect and O&M Cost Variations

Chart 6-19 illustrates the sensitivity of the cost/benefit ratio to various plant cost parameters. There is some sensitivity but not as much as for collector cost. In this and succeeding charts, the cost/benefit ratio is normalized to the EPRI-E reference case.

VARIATIONS IN FUEL COST AND ESCALATION RATES

6.3 SENSITIVITY ANALYSES

5. Variations in Fuel Costs and Escalation Rates

Chart 6-20 illustrates the sensitivity of the cost/benefit ratio to fuel costs. It is immediately clear that this variable is a major driver and that continuing increases in fuel costs will make repowering more and more attractive.

The effects of changes in the fuel costs and/or escalation rates of coal and oil are depicted in Chart 6-20. In this example, for the utility in question, there is no variation when coal prices are changed because this utility is oil dominated and the solar energy displaces oil almost exclusively. The change in response to variations in oil cost or escalation rate, on the other hand, is dramatic. It is typical of the influence the fuel prices have on the cost/benefit ratio. In a utility with less oil (or more coal) in the system, such as a PSNM utility, the effects of oil prices would be less and the effects of coal prices will be significant.

EFFECT OF FUEL MIX ON UTILITY ECONOMICS

- EPRI-E MODIFIED
- 15% NUCLEAR REPLACED BY COAL
- 5% COMBUSTION TURBINES REPLACED BY OIL STEAM PLANTS
- STATIC MIX

6.3 SENSITIVITY ANALYSES

6. Effect of Fuel Mix on Utility Economics

The effect of changing the fuel mix in the system is illustrated by looking at utilities comprised of coal and oil only but having the same demand characteristics as for EPRI-E. As expected, the cost/benefit ratio is best with larger percentages of oil fuel.

The sensitivity of the cost/benefit ratio to fuel mix is illustrated in Chart 6-21. Although the case presented is a hypothetical one, it does illustrate how repowering will fare in utilities with different fuel mixes. For example, the PSNM 1988 utility fuel mix (2), has approximately 70 percent nuclear and coal and a cost/benefit ratio in the 1.4 to 1.6 range, and this chart indicates a cost/benefit ratio of 1.3 with 70 percent coal. Thus, cost/benefit ratio is not as sensitive to the exact demand characteristics of the utility as it is to the mix the utility has chosen to meet the demand characteristics. The chart also indicates very little change in cost/benefit ratio below 40 percent coal, primarily because the energy displacement from the repowered plant does not penetrate this far into the baseload region. The mix here is considered static over the 30 year life of the repowered plant. It is expected that utilities will move toward increasing amounts of coal in their mix over the time frame under consideration. If the data on Chart 6-21 are examined on the basis of a 30 year average coal penetration, there is a trend towards an increasing cost/benefit ratio as found by SERI using a dynamic mix analysis.

UTILITY/SITE VARIATION

6.3 SENSITIVITY ANALYSES

7. Utility/Site Variation

Two effects are seen by varying the utility and the site. The magnitude of the cost/benefit ratio changes and the collector area yielding an optimum cost/benefit ratio also changes.

Chart 6-22 illustrates the variation of cost/benefit ratio with collector area for two different sites. Although the minimum occurs at about $5\text{m}^2/\text{kW}$ for the PSNM utility with Albuquerque insolation, it is around $6\text{m}^2/\text{kW}$ for the EPRI-E utility with Midland insolation. One also sees a much more favorable cost/benefit ratio for all collector areas for EPRI-E, primarily because of the higher percentage of oil displaced in the utility.

SENSITIVITY COMPARISON

6.3 SENSITIVITY ANALYSES

8. Sensitivity Comparison

A method for comparing sensitivity to different parameters is presented, along with an example. The cost/benefit ratio is shown to be more sensitive to changes in fuel escalation rates than to collector cost.

The sensitivity of an economic measure to changes in the input parameters can be examined by looking at the percentage change in the economic measure vs. the percentage change in the input parameter. Constant percentage changes in either collector cost, indirect cost fraction, fixed O&M cost fraction, O&M escalation rate, fuel cost, or fuel escalation rate result in a wide variation in percentage change of the cost/benefit ratio. As indicated in Chart 6-23, a 50 percent increase in collector cost (relative to the reference value of 65 \$/m²) results in less than a 30 percent increase in the cost/benefit ratio. However, a 50 percent increase in fuel escalation, relative to the reference value of 7 percent, results in a 50 percent decrease in the cost/benefit ratio. In the chart, the magnitude of percentage change is graphed to facilitate comparison of parameters with opposite effects.

PARAMETER RANGES YIELDING FAVORABLE COST/BENEFIT RATIOS

6.3 SENSITIVITY ANALYSES

9. Parameter Ranges Yielding Favorable Cost/Benefit Ratios

Chart 6-24 shows how one can examine combinations of two parameters to bring the cost/benefit ratio below 1.0. The collector cost and fuel (oil) escalation rate are chosen here because they are the most sensitive parameters.

One of the problems one wants to solve is to determine under what conditions the cost/benefit ratio will be favorable. In this method, the most sensitive parameters are traded off against each other to yield a region where the cost/benefit ratio is less than 1.0. For example, if the DOE heliostat goal of 70 \$/m² is reached, the oil escalation rate would need to be 11 percent or higher to yield a favorable ratio. One can also examine trends in these parameters by varying some of the less sensitive parameters and obtaining a family of curves analogous to the one depicted in the chart.

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6.4 WEATHER ANALYSIS FOR OPTIMUM STORAGE AND BOILER REQUIREMENTS ₀

1. Characterization of Weather Losses
2. Energy Deficiency Distribution
3. Formula for Capacity Factor for Storage

CHARACTERIZATION OF WEATHER LOSSES FOR 50 MW_e PLANT LOCATED AT MIDLAND, TEXAS

Figure (a) June 21 Insolation Every Day
Observed Solar Azimuth and Elevation

Figure (b) Observed Insolation, Solar
Azimuth and Elevation

Figure (c) Difference Between (a) and (b)

6.4 WEATHER ANALYSIS FOR OPTIMUM STORAGE AND BOILER REQUIREMENTS

1. Characterization of Weather Losses

The hypothetical hourly solar power that would be generated by the reference 50 MW solar plant with "ideal weather" at Midland, Texas, is illustrated schematically in Figure a of Chart 6-25^e. In this analysis ideal weather consists of hourly values of normal incident radiation each day equal to those observed on the summer solstice. The solar power generated will vary from day to day even under these ideal conditions due to variations in the solar azimuth and elevation.

The hourly solar power that would be generated by the above plant accounting for the losses due to observed weather is illustrated in Figure b.

The difference between the solar power displayed in Figures a and b is defined to be the "hourly energy deficiency" (Figure c). This difference represents the loss in solar power due to weather effects. The "daily energy deficiency" is simply equal to the sum of the hourly deficiencies for a given day.

ENERGY DEFICIENCY DISTRIBUTION FOR 500 MW_e SOLAR PLANT LOCATED AT MIDLAND, TEXAS

6.4 WEATHER ANALYSIS FOR STORAGE AND BOILER REQUIREMENTS

2. Energy Deficiency Distribution

The distribution of daily energy deficiencies at Midland, Texas, for a 50 MW_e plant is illustrated in Chart 6-26. The interpretation of this distribution should be clear from the following example. There are 92 days for which the daily deficiency is greater than 20,000 kW_e H, but less than or equal to 40,000 kW_e H. This range amounts to between 4 and 8 percent of the energy which is generated on the summer solstice (490,000 kW_e H). Therefore, even though weather losses during 92 days are involved, the aggregate deficiency is relatively low.

Several other observations can be made directly from a graph of this type. First, some insolation is available every day of the year. Second, the maximum daily deficiency originating from less than ideal weather is between 65 and 70 percent of the energy generated on the summer solstice. This maximum loss in energy occurred on a single day. Third, for half the days during the year, the daily energy deficiency is less than 12 percent of the energy generated on the summer solstice.

FORMULA FOR CAPACITY FACTORS WITH STORAGE

CAPACITY FACTOR FOR PLANT WITH $20,000 * n kW_e h$ OF STORAGE $\approx$

CAPACITY FACTOR WITHOUT STORAGE

$$+ \frac{20,000 * (\text{INCREMENTAL COLLECTOR AREA})_w}{8760 * 50,000} \cdot \sum_{i=1}^{\# \text{ Bins}} \frac{(\text{NUMBER DAYS})_i * (i - 1/2)}{(\text{INCREMENTAL COLLECTOR AREA})_i}$$

WHERE,

$$(\text{INCREMENTAL COLLECTOR AREA})_r \approx \max_K \frac{(\text{DAILY ENERGY DEFICIENCY})_K * AC}{(\text{DAILY ENERGY PRODUCED})_K}$$

K = INDEX CORRESPONDING TO THOSE DAYS FOR WHICH THE
DAILY ENERGY DEFICIENCY IS LESS THAN OR EQUAL TO
 $20,000 * n kW_e h$

AC = ZERO STORAGE COLLECTOR AREA CORRESPONDING TO
 $(\text{DAILY ENERGY PRODUCED})_K$

6.4 WEATHER ANALYSIS FOR STORAGE AND BOILER REQUIREMENTS

3. Formula for Capacity Factor

A formula was developed (Chart 6-27) for estimating the required capacity factor of a solar plant with storage, given the capacity factor without storage, and the energy deficiency data described previously. This formula is based on the rationale that the daily energy deficiency can be eliminated with a storage capacity in $\text{kW}_e \text{H}$ equal to the deficiency, and an increase in collector area (relative to the zero storage collector area) that is large enough to fill storage on that day. This incremental area will, of course, depend on the available insolation on that day, or the electrical energy produced from this insolation on that day. In accepting this rationale, it follows that a storage capacity and incremental collector area which is capable of eliminating the energy deficiency on a given day will also be capable of eliminating smaller deficiencies on other days. In addition, since the storage and collector will be "oversized" for these other days, the total amount of energy produced on a day with a lower deficiency will be equal to the ratio of the incremental area on the given day to the incremental area required to eliminate the deficiency on the other day multiplied by the deficiency on the latter day.

A natural consequence of this reasoning is the formula that is shown for the capacity factor. The "# Bins," the bin width ($20,000 \text{ kW}_e \text{H}$), and the "(Number Days)," for the i th bin are obtained from the energy deficiency distribution shown earlier. The quantities 8760 and 50,000 refer to the number of hours in a year and the plant capacity (kW_e), respectively.

In order to use this formula, it is necessary to simulate the hourly operation of a solar/fossil hybrid plant with zero storage using the Aerospace Hybrid Simulation Program. (The program was modified to store the quantities required by the formula.) The hourly demand used in the simulation should correspond to the ideal weather "demand" described earlier, or some other demand of interest. That is, even though the formula was developed to analyze weather losses, it is general. The energy deficiencies in the more general sense correspond to the inability of a zero storage solar plant to satisfy a prescribed demand.

ENERGY GENERATED BY 50 MW_e SOLAR PLANT LOCATED AT MIDLAND, TEXAS

6.4 WEATHER ANALYSIS FOR STORAGE AND BOILER REQUIREMENTS

4. Preliminary Validation of Formula for Capacity Factors

The variation between the capacity factor and storage capacity/incremental collector area predicted by the formula is shown in the graph of Chart 6-28. Also shown are the capacity factors predicted by the Aerospace Solar Thermal Simulation Program with storage capacity of 2 and 4 hr at rated capacity, and the corresponding collector areas. The collector areas actually used in these two simulations were equal to the sum of the collector area with zero storage (233,000 m²) and the incremental areas shown. The agreement between the formula and detailed simulation results illustrated in the graph provides preliminary validation of the proposed formula.

The scale to the right of the graph denotes the correspondence between capacity factor and annual energy deficiency due to weather variations. This scale should be interpreted in the following way. With slightly over 2 hr of storage, the capacity factor will be approximately 0.35. If the energy produced by the solar plant equivalent to this capacity factor is produced at those times when the energy deficiencies occur, this amount of storage and an increase in collector area of 78,000 m² would be sufficient to eliminate all deficiencies for the year. However, the energy will, in general, not be produced at those times, since the availability of stored energy at any given time depends on the complex relationship between insolation and demand up to that time. Therefore, a solar plant with this capacity factor is producing as much energy as a plant with zero storage and ideal weather, but the energy is being produced at different times during the day.

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7. MAJOR FINDINGS AND INTERIM CONCLUSIONS

Potential benefits of repowering from the utility and programmatic points of view are summarized, and some of the important issues of repowering are examined in varying detail. The repowering issues addressed included market size for solar repowering and the technical requirements imposed by it on solar technology and on the DOE program, capabilities of solar central receiver technology and its match with the candidate fossil plants for promising repowering approaches, and the economics of repowering from the point of view of the utilities -- the ultimate users.

The studies of utility economics, involving investigations of solar design, utility, and economic factors, have highlighted the strong interrelationship that exists among these factors and pointed out the need to design a repowered plant specifically tailored to the utility system in which it will operate. Economic considerations have also pointed to the need for a buffer storage and judicious use of fossil boiler/storage to maximize savings in oil fuel and oil costs. We believe that the insight provided into such problems by these studies and the information developed as a result of our overall repowering studies will be helpful in guiding the ongoing and the follow-on contractor efforts on site/utility specific repowering designs and developments. Other major findings, interim conclusions, and recommendations are outlined below. Further details are given in the sections as noted.

BENEFITS AND LIMITATIONS

Repowering offers several potential benefits from the utility, programmatic, and national points of view (Section 3.2). Principal among them are:

- Repowering offers an opportunity to introduce central receiver system technology earlier than expected and in a redundant mode with an already operating fossil plant. With this approach, utility concerns for technical risks associated with a new technology and other concerns with solar technology (e.g., availability of insolation, reliability of solar equipment) are minimized. The hybrid repowered plant can operate at full capacity in the event of solar equipment failures or adverse weather conditions.
- Operational flexibility of a repowered plant approaches that of a conventional plant, i.e., the plant provides discretionary control in the generation and dispatch of power when needed.

- Repowering offers the best vehicle for demonstrating alternate solar technologies for hybrid systems and solar stand-alone systems (the ultimate solar market) in a cost-effective manner (i.e., simultaneous demonstration of repowering and solar technologies, elimination of the need for additional pilot plant projects for ACR technologies, and utilization of already paid for turbine, boiler, balance of plant, and transmission equipment and facilities). Repowering plants represent a logical step-up in plant size or a bridge between the 10 MW_e pilot plant operation and 100-500 MW_e plants.
- An important limitation of most of the repowering options (except the solar Brayton topping option, Section 5.5) is that repowering only renews the existing capacity of the plant scheduled for retirement but does not provide additional capacity to the grid that would be obtained by adding a solar stand-alone or a new hybrid plant. This consideration is important to utilities in meeting the increasing energy demand and in obtaining financing for new construction.

In order to maximize the benefits and effectiveness of a repowering program, information on technical, operational, and economic factors, concerns, and preferences of utilities for solar technology/applications must be acquired and evaluated and must be reflected in the designs and DOE program planning on a continuous basis. Some useful information had been acquired through limited interfaces with the interested utility representatives during various contractor design reviews. This interface should be encouraged and a mechanism found to expand it.

MARKET SIZE FOR REPOWERING AND TECHNICAL REQUIREMENTS

The market size for solar repowering is an important indicator of the initial market demand for mass-produced heliostats, for potential savings in fuel oil, and for other national benefits and hence a justification for the government expenditure for the repowering initiative. A review of the solar repowering market potential indicates that:

- Approximately 10 GW_e (20×10^6 heliostats) of solar potential exists for repowering (Section 4.1).
- These estimates will be reduced when more detailed surveys are conducted and site-specific factors (e.g., poor condition of boiler, poor local insolation, land geometry around the plant) are accounted for.
- Relaxation of initial constraints, such as the 2500 ft limitation on the distance between the tower and the fossil plant and limits on solar fraction, can substantially increase the above market size

potential. Relaxing the distance limit alone would result in an increase in the solar market size by 50 percent without a significant penalty on the solar retrofit design (see Section 6.2.3-1).

- The process heat applications and new solar-fossil hybrids applications can substantially increase the solar market further for the time period 1990-2000. This market area should be investigated.

A review of the characteristics of the candidate oil/gas fired steam plants (Section 4.1) shows that:

- Almost 80 percent of the estimated solar capacity is in the repowering of reheat plants. These plants have relatively longer remaining life and are desirable for a successful repowering operation for the next 30 years.
- The Texas-Oklahoma region represents approximately 50 percent of the total estimated market. Insolation deficiencies in the southeastern portions of this region may dictate the need for solar storage in repowering.

A review of the retirement schedule for the candidate plants indicates that opportunities exist in the time period 1985-2000 to accomplish most of the repowering of non-reheat plants and of a large fraction of reheat plants (Section 4.3). The repowering project must continue at an accelerated pace to demonstrate and start commercialization during the 1985-1990 period so as to avoid retirement of some of these units.

SOLAR TECHNOLOGY MATCH AND REPOWERING OPTIONS

A review of the available solar central receiver system technology and an investigation of the technology match with the candidate fossil plants to identify possible repowering configurations indicate that:

- A variety of technologies currently under investigation would be needed to meet the differing technical requirements of the market and to accommodate the preferences of the utilities for different technologies.
- The repowering with water-steam system technology in general offers a higher confidence option. This technology will be better suited for repowering of non-reheat plants in applications for which storage is not required for either technical or economic reasons (Section 5).

- The ACR system salt (or sodium) technology is suitable for both the non-reheat and the reheat plants (Sections 5.5 and 5.6) and provides an inherent storage buffer against cloud and other system transients. The ACR technology provides high temperature/high pressure steam suitable for high performance cycles and an efficient storage suitable for repowering. Technical risks for ACR technologies are somewhat higher primarily due to the uncertainties in the long-term behavior of the high temperature materials and limited industrial experience with these technologies.
- Technical risks of the ACR technologies are considerably reduced for non-reheat plant applications (lower temperature applications as shown in Chart 5-3 of Section 5.3).
- Probably the most attractive repowering option involves the use of a fossil-augmented solar Brayton topping cycle (Section 5.5). In this concept, the air exhaust of the Brayton engine is used to produce solar steam for the non-reheat or reheat repowered plant through the use of a heat recovery steam generator (Section 5.5). The repowered plant operates at an increased efficiency (efficiency of a combined cycle plant), and capacity is added to the plant and the grid by the amount of power output of the Brayton engine (see Chart 5.6, Section 5.5). It should be noted that the term "repowering" originated from this kind of repowering by a fossil-fired Brayton topping cycle already in use in the utility industry.
- Considerations of insolation characteristics, boiler firing requirements, and associated economics indicate that a small amount of buffer storage is essential for an efficient hybrid operation. The need for larger amounts of storage will depend upon the individual applications. Storage may be required in situations where little or no oil is saved by repowering (i.e., oil portion of the fuel saved by the solar energy is negated by the expenditure of oil by the fossil boiler), and where increased solar fraction, capacity credit, and fuel oil savings are required for technical or economic reasons. This area needs further examination to determine the role of storage, and optimum boiler/storage operation for situations where storage is required (Sections 5.7, 6.4).
- To establish cost effectiveness of solar repowering, it is essential to investigate also the relative merits of alternate non-solar repowering options. Such options might involve repowering with a coal boiler, with fossil Brayton topping cycle as discussed above, or by replacing oil boiler and/or turbine with high efficiency components to save fuel. Limited analyses have been conducted for one of these options (Section 5.8). Further work is needed.

ECONOMICS OF INTEGRATION OF SOLAR PLANTS INTO UTILITY SYSTEMS

In order to assess the economic attractiveness of repowering, studies have been conducted using one utility economic criterion, cost to benefit (or value) ratio. Assessment of this ratio involves a complex interaction of a large number of system parameters associated with solar plant design, utility system characteristics (such as load demand, site insolation, conventional generation mix) and various economic factors. To facilitate this analysis, a simplified Aerospace simulation model was developed and utilized. Maximum use was made of the data developed in economic analyses of repowering in other DOE studies to augment the results of Aerospace simulations and studies. Interim results of specific analyses are summarized in Section 6.2 and will not be repeated here. General conclusions and recommendations are noted below:

- The design of the solar portion of the repowered plant is influenced by various economic factors as well as by characteristics of the utility system in which it is to operate (Section 6.3).
- A solar plant operated in a utility will displace a spectrum of different fuels depending upon the types and fuel mix of the utility power plants (Section 6.2.2, Chart 6-13).
- The cost/benefit ratio of a plant integrated into various utility systems varies from utility to utility (Section 6.2.1).
- The cost/benefit ratios for a commercial solar repowering plant when integrated into various representative utility systems are within the regime of economic acceptability (see Section 6.2.1).
- Collector costs, fuel costs, fuel escalation rates, and plant O&M costs are the most sensitive parameters affecting the the cost/benefit ratios (Section 6.3.3, 6.3.4, 6.3.5).
- Solar repowering looks most favorable for utilities with a large percentage of oil. Increasing coal penetration with time will increase cost/benefit ratio (Section 6.2.2-2).
- Using various heliostat costs and present estimates for escalation rates, cost/benefit ratios in the 0.7-2.0 range can be expected for most Southwest utilities.
- Significant improvements in cost/benefit ratios will occur if fuel costs increase over the assumed predictions (Section 6.3.9) and if buffer storage and improved dispatch techniques are used (Section 6.2.2.3).

Further investigations are needed in the following areas:

- Effects of solar fraction and collector size on economics of repowering.
- Role of storage in repowering.
- Effects of site-specific weather and insolation transients on boiler/turbine equipment life, operation, and economics.
- Feasibility of dispatch strategies for increasing savings in oil and oil costs.
- Comparative evaluation of solar and alternate fossil repowering options.
- Techniques for improving the performance and economics of repowering (e.g., steam sharing from neighboring units).

8. REFERENCES

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APPENDIX - A4

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APPENDIX - A4

STATES COVERED IN SURVEY OF ELECTRIC UTILITY OPERATING COMPANIES (SOUTHWESTERN UNITED STATES)

Study State	PNM	MITRE
Arizona	Yes	Yes
California	Yes	Yes
Colorado	Yes	Yes
Kansas	No	Yes
Louisiana	Yes	No
New Mexico	Yes	Yes
Nevada	Yes	Yes
Oklahoma	Yes	Yes
Texas	Yes	Yes
Utah	Yes	Yes
Other *	Yes	No

* One utility with 2 units totaling 200 MW_e rated capacity located outside the nine-state area asked to be included in the survey.

STUDY METHODOLOGY
(SOUTHWESTERN UNITED STATES OIL- OR GAS-FIRED CENTRAL GENERATING STATIONS
— SOLAR REPOWERING POTENTIAL)

	PNM	MITRE
Data Base	<p>Power System Statement (FPC Form No. 12), Federal Power Commission, 1975 and 1976</p> <p>Inventory of Power Plants in the U. S., Department of Energy Report No. DOE/RA-001, December 1977.</p> <p>Federal Power Commission Regional Reliability Council Reports for the Southwest</p>	<p>Inventory of Power Plants in the U. S., Federal Energy Regulatory Commission, June 1977</p>
Repowering Criteria	<p>Land availability for collector field at 6 acres/MW_e</p> <p>Land within 2500 feet of turbine-generator.</p> <p>Not less than 50% of unit rating must be solar repowerable.</p>	<p>Land availability at 4.3 acres/MW_e</p> <p>Land within 15,000 feet of turbine-generator</p> <p>No specification on fraction of unit rating which must be solar repowerable</p>

SUMMARY OF OIL- OR GAS-FIRED CENTRAL GENERATING STATIONS
(SOUTHWESTERN UNITED STATES)

Item	PNM		MITRE	
	Literature Search	Utility Contact	Literature Search	Utility Contact [*]
Number of utilities	78	61	65	24
Number of sites	Unreported	Unreported	197	32
Number of units	884	455	624	115
Rated capacity (MW _e)	94,413	Incomplete	75,977 -- 79,255**	20,498
Identified solar repowering candidates:				
Number of units	Unreported	333	562 [†]	N/A
Rated capacity (MW _e)	Unreported	45,343	75,201 -- 78,479	N/A

* Limited random sample.

** Conflicting data throughout report.

[†] Estimate includes unidentified number of units eliminated by MITRE totaling 88 MW_e capacity in 2 utilities.

N/A = Not Applicable.