Repowering with

Solar Energy

DO NOT MICROFILM
THIS PAGE.

The MITRE Corporation

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DOE/CS/35147--T1

DE83 016950

Repowering with

Solar Energy

AC01-78CS35147

Paul Curto

MP 79W00004

March 1979

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

The MITRE Corporation
Metrek Division
1820 Dolley Madison Boulevard
McLean, Virginia 22102

MASTER

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ABSTRACT

During the transition phase between today's fossil fuel-based energy markets in the U.S. and the ultimate condition of widespread use of renewable resources, solar energy utilization will become commercialized. One of the more-efficient means to use solar energy is based on direct solar thermal conversion. Since sunlight is a diffuse energy source, the more efficiently it is converted to useful form, the less hardware is needed. Since sunlight is inherently intermittent in nature, providing a useful output that is predictable and steady requires the use of some form of storage--thermal, electric, mechanical, chemical, magnetic or in stored fuel. Further, since there exists a large number of fossil-fuel burning installations and a well-established fuel-distribution system to supply them, the initial use of solar energy will likely be in a "repowering" mode--retrofit hybrids as fuel savers. This is the fundamental basis for solar-thermal repowering.

TABLE OF CONTENTS

	<u>Page</u>
LIST OF ILLUSTRATIONS	vi
LIST OF TABLES	vi
OBJECTIVE	1
APPROACH	1
MARKET FACTORS	2
GEOGRAPHIC FACTORS	3
REQUIREMENTS ANALYSIS	3
The Goal	4
Heliostat Production Requirements	4
Annual and Cumulative Capital Requirements	4
Labor and Materials Requirements	4
Net Energy Analysis	7
Delayed Goals	7
ENGINEERING COSTS	10
GENERIC DEVELOPMENT PLAN	13
IMPLEMENTATION PROGRAM	13
MARKET SIMULATIONS	16
CENTRAL RECEIVER SYSTEM DESCRIPTION	21
CONCLUSIONS	26
REFERENCES	29

LIST OF ILLUSTRATIONS

<u>FIGURE NUMBER</u>		<u>PAGE</u>
1	Generic Development Plan Timeline	15
2	Timeline for Implementation of 0.1 Quad/Year Scenario	17
3	Energy Savings for Central Receiver Technology	20
4	Scenario II: Energy Saving Due to Different Technologies	22
5	Solar Thermal Repowering Plant Configuration	23

LIST OF TABLES

<u>TABLE NUMBER</u>		<u>PAGE</u>
I	Annual and Cumulative Capital Requirements for 0.1 Quad/Year Goal by 1985	5
II	Material Requirements for Solar Thermal Repowering	6
III	Direct Labor Requirements for 0.1 Quad/Year Repowering by 1985	8
IV	Net Energy Analysis for Solar Thermal Repowering	9
V	Engineering Cost vs. Capacity for Central Receiver Repowering Plants	11
VI	Experience Curve Parameters for Solar Thermal Central Receiver	12
VII	Generic Development Plan Activity Schedule	14
VIII	Results of Market Simulations	19
IX	Plant Auxilliary Power Requirements and Loss Inventory	25

OBJECTIVE

MITRE was tasked by the U.S. Department of Energy to study the options related to solar thermal repowering and to provide an assessment of its ultimate potential given the stimulus of federal incentives. The task involves the identification of appropriate federal actions, timing of such actions and resource allocations to accelerate commercialization, market assessment using attitudinal and physical suitability surveys, market projections, and predictions of both relative economics and logistics for users and producers of the hardware.

APPROACH

The study began with an assessment of the necessary actions for utilities, industry and government to achieve energy savings at four different levels by 1985: 0.03, 0.1, 0.3 and 1.0 quads per year through repowering. It was quickly established that only the first two scenarios could be achieved given the lag times and inertia in the system. Highlights of this requirements analysis approach were:

- (1) definition of plant configuration and performance
- (2) estimation of probable market splits by plant type
- (3) likely geographic distribution of sites
- (4) determination of the developmental sequence for each plant
- (5) assessment of the required production within supporting industries
- (6) laying out the deployment of plants over time
- (7) timing of the deployment of construction facilities
- (8) estimating total system capital costs
- (9) calculating capital requirements
- (10) calculating busbar or energy costs
- (11) estimating net benefits (lifetime savings)
- (12) projecting materials requirements
- (13) projecting labor requirements
- (14) performing a net energy analysis
- (15) recommendation of a set of realizable federal actions to stimulate such growth.

It is important to note that this approach--determining what is required to establish a program, is fundamentally different from a projection or a venture analysis. A projection is based on what may happen given a set of well-defined conditions within a free marketplace. A venture analysis would use both techniques (requirements analysis and projections) to assess the relative merit of the investment--its costs, risks and potential payoff.

MITRE then proceeded to perform a utility site survey in the Southwest and an attitudinal survey of both industrial and utility executives to determine the character of the market. A sample of utility sites for the survey was pre-selected from Federal Energy Regulatory Commission (FERC) records from which an extrapolation was made for each state in the sunbelt. Similarly, a sample of key industries (petroleum refining and industrial chemicals) provided the basis for extrapolation of industrial process heat markets.

Next, using the investment decision criteria, site suitability limitations, relative economics data for both solar and conventional generation, and a proven market penetration model known as SPURR*, a set of projections were made.

Finally, a set of reports were generated which essentially perform a venture analysis for solar thermal repowering [1, 2]. From these reports, one can assess the relative merits of fundamentally different approaches within the purview of federal policy to stimulate the commercialization of solar energy utilization within this market.

MARKET FACTORS

One of the key programmatic attributes of solar thermal repowering is that there is a substantial real market that is readily identifiable and could provide an early opportunity to develop commercial solar thermal central receiver systems. In the Southwest, in areas of high direct insolation, there is a capacity of over 76,000 MWe of oil- and gas-fired steam plants. About 65 percent of the fuel burned is natural gas and 35 percent is oil. This capacity exists at 197 sites where 624 boilers and turbogenerators are currently in place. The plants are owned by 65 utilities. The MITRE survey indicates that sufficient land is available on or near these sites to repower approximately 18,000 MWe of capacity and displace 0.5 quads per year of fuels.** The estimated error for the survey sample is $\pm 3,440$ MWe at the 67 percent confidence level and $\pm 6,900$ MWe at the 95 percent confidence level. Thus, at least 11,000 MWe of capacity is a reasonably confident estimate of the solar repowering market potential. A more conservative estimate of about 5000 MWe market potential was made by Public Service of New Mexico, [3] based on more restrictive conditions for suitability: less than a 2500-foot pipe run from the tower to the existing plant; no allowance for reheat turbines; a maximum fossil plant size of 200 MW; and at least 50 percent of the plant capacity to be repowered. By comparison, MITRE's criteria allow for a 15,000-foot pipe run (which only results in 3 percent losses), reheat turbines, a minimum fossil plant size of 25 MW, and no lower limit on the percentage of repowering when more than 150 acres (equivalent to about 25 MWe of repowering capacity) are available.

*System for Projecting Utilization of Renewable Resources

**One quad = 10^{15} Btus.

Another potential market, primarily concentrated in Texas, Louisiana and Oklahoma, is the petrochemical industry. Land restrictions, rate of return on investment, internally produced fuels, process compatibility and other factors will impact this sector. No firm figures are yet available for the size of this repowering market (using the solar thermal central receiver as a process steam source), but preliminary calculations indicate that this market could be as large as that for the utility sector--on the order of 0.3 quads per year repowerable. This industrial market is distributed over the Southwest in a manner quite similar to the utility market.

GEOGRAPHIC FACTORS

In the Southwest, there are 10 contiguous states that might be considered for repowering:

• Texas	• Wyoming
• Oklahoma	• Arizona
• Kansas	• Nevada
• New Mexico	• Utah
• Colorado	• California

According to the MITRE survey, Texas has by far the greatest market potential (about 12 of 18 GWe) for repowering. California is second at 2 GWe, while the balance (4 GWe) is distributed among Oklahoma, Kansas, New Mexico, Arizona and Nevada. It was found that no site is suitable in Colorado, Utah or Wyoming. The Texas sites are generally larger than the others both in land area and capacity per site and in general have newer equipment. Furthermore, substantial new generating capacity has to be added to satisfy the growing use of electric energy in the future. According to a recent study by the National Energy Reliability Council [4], the generating capability of Southwest utilities will be increased by 62 percent in the near future (1978-1986). If planned expansion through 1985 for new combined-cycle, oil-burning facilities at new sites is included, California and Texas appear to be very large markets--1.1 GW in Texas and 4.1 GW in California. This market may expand the market potential of solar thermal repowering beyond the assumed level of 18 GW.

REQUIREMENTS ANALYSIS

To summarize the results of the requirements analysis, it is clear that immediate federal action is needed to achieve early market penetration and commercialization.

The Goal

The goal of about 0.1 quad of fuel savings per year by 1985 requires that about 3350 MWe of solar thermal repowering capacity be constructed--or sixty-seven 50 MWe power plants. The aggressive schedule described later in this section could bring the first plant on line by 1982. If four additional plants could be constructed during the following 18 months (by the end of 1983), then 13 plants (650 MW) may be added in 1984 and 50 more in 1985.

Heliostat Production Requirements

The heliostat production rate required to meet this goal is 4399 units in 1982; 30,000 units in 1983; 97,500 units in 1984 and 375,000 units in 1985. This will require one production facility at 8.8 percent capacity the first year, 60 percent capacity the second year, and 100 percent thereafter. The second facility would run at 95 percent capacity in 1984 and 100 percent in 1985. Six new facilities would be required in 1985 and would operate at an average of 92 percent of capacity in that year. Each production facility would support about 300 to 350 MW per year of new repowering capacity, or 200 to 250 MW per year of storage-coupled system capacity.

Annual and Cumulative Capital Requirements

The capital requirements for utilities and manufacturers would be very large to support the goal of 0.1 quads per year by 1985. In Table I, the requirements are estimated for both annual and cumulative expenditures by government, industry and utilities. These figures include a 45 percent contingency for the first plant, 40 percent for the second two plants, 30 percent for the next two plants, and 15 percent for all subsequent plants. Annual capital requirements in 1985 reach nearly \$3 billion with a cumulative level of just over \$5 billion. The distribution in 1985 of cumulative expenditures is 79 percent utility, 17 percent industry and 4 percent Federal.

It should also be noted that no additional capital spending was assumed for production facilities other than for heliostats.

Labor and Materials Requirements

The materials used to construct a generic solar thermal repowered plant are steel, concrete, aluminum, glass, insulation, chrome, molybdenum, silver and miscellaneous plastics, wood, block, etc. In Table II, these requirements are estimated and put in the context of U.S. production levels in 1974. The right-hand column indicates the added capacity at which one percent of U.S. production in 1974 would be used to support such a growth rate. The 1985 growth rate of 2500 MW (50 plants) would consume 0.25 percent of the

TABLE I

ANNUAL AND CUMULATIVE CAPITAL REQUIREMENTS FOR
 0.1 QUAD/YEAR GOAL BY 1985
 (1978 Constant Dollars, Billions)

	1981	1982	1983	1984	1985
ANNUAL CAPITAL REQUIREMENTS (10 ⁹ Dollars)	<u>0.180</u>	<u>0.191</u>	<u>0.273</u>	<u>1.501</u>	<u>2.863</u>
GOVERNMENT	0.122	0.055	0.023	0	0
INDUSTRY	0.038	0	0.114	0.684	0
UTILITIES	0.020	0.136	0.136	0.817	2.863
CUMULATIVE CAPITAL REQUIREMENTS (10 ⁹ Dollars)	<u>0.180</u>	<u>0.371</u>	<u>0.644</u>	<u>2.145</u>	<u>5.008</u>
GOVERNMENT	0.122	0.177	0.200	0.200	0.200
INDUSTRY	0.038	0.038	0.152	0.836	0.836
UTILITIES	0.020	0.156	0.292	1.109	3.972

TABLE II
MATERIAL REQUIREMENTS FOR SOLAR THERMAL REPOWERING

MATERIAL	REQUIREMENT (Short Tons/Megawatt)	U.S. PRODUCTION (10 ⁶ Tons/Yr)	MEGAWATTS/YR GROWTH AT 1% OF U.S. PRODUCTION
STEEL	150	150	10,000
CONCRETE	1000	250	2,500
ALUMINUM	10	5	5,000
GLASS	80	4	500
INSULATION	5	0.5	1,000
CHROME/MOLY	0.6	0.5	8,300
SILVER	0.014	0.0014	1,000
MISCELLANEOUS	10	LARGE	N/A

steel, 1.0 percent of the concrete, 0.5 percent of the aluminum, 5.0 percent of the glass, 2.5 percent of the insulation, 0.30 percent of the chrome/molybdenum, 2.5 percent of the silver, and a negligible percentage of other materials used in 1974. Therefore, glass, insulation and silver are the critical limiting material factors that may pose a problem after commercialization.

In Table III, direct labor requirements are presented in terms of a normalized requirement in man-years per megawatt and in terms of the projected annual labor force. Since the experience curves reflect a reduction in the normalized labor requirement, this reduces significantly during the 1981 to 1985 timeframe. Note that this requirement is only one-third to one-fourth the total impact since it reflects only direct labor. A multiplier effect for indirect support labor can increase the impact dramatically. This impact can be interpreted as a benefit rather than a cost for the program, since these are domestic jobs.

Net Energy Analysis

The net energy production rate for solar thermal repowering is estimated from the expected energy production rate, the energy required to mine, mill, fabricate, assemble, ship and construct all the materials and equipment for the plant and the energy consumed by the labor force during these activities. The expected energy payback period is about 1.3 years according to the calculation shown in Table IV. As a result, the net energy production rate between 1981 and 1985 is always negative--in fact, in 1985 the net output is negative 0.1 quad/year while the gross output is a positive 0.1 quad/year. This analysis points out one of the serious problems the nation faces during the transition to renewable resources--we must make an investment of fossil fuels in order to construct the new facilities. The longer we wait, the more difficult such a transition becomes.

Delayed Goals

A requirements scenario could also be postulated to achieve a goal of 0.1 quads per year of central receiver capacity by 1990. While this scenario goal is more plausible and more easily achieved, special government incentives would still more than likely be required. Starting by 1983 with a 25 MW repowering plant and doubling the capacity on line each year would reach 3200 MW by 1990, or about 0.1 quads per year. The growth rate in 1990 would be 1600 MW per year. The labor force would approach 30,000 direct jobs in that year. About five heliostat production facilities would be in operation at near full capacity. The same amount of capital would have been expended as in the earlier scenario, but spread out over an eight-year rather than a four-year period. Yearly material requirements would average about 40 percent less than the 1935 scenario. Net energy production would be roughly minus 30 percent of the installed capacity each

TABLE III

DIRECT LABOR REQUIREMENTS FOR 0.1 QUAD/YEAR REPOWERING BY 1985

REQUIREMENT	1981	1982	1983	1984	1985
NORMALIZED LABOR (Man-Years/MW)	76	49	38	29	24
TOTAL LABOR WORK FORCE (Thousands of Jobs)	0.5	3.4	12	32	45

TABLE IV

NET ENERGY ANALYSIS FOR SOLAR THERMAL REPOWERING

MATERIAL	MMBtu/SHORT TON	MMBtu/MW
STEEL	42	6,300
CONCRETE	13	13,000
ALUMINUM	200	2,000
GLASS	39	3,100
INSULATION	40	200
CHROME/MOLY	160	100
SILVER	100	--
MISCELLANEOUS	20	200
Total Material		25,000

LABOR	MMBtu/MAN-YEAR	MMBtu/MW ¹
DIRECT ONLY	500	Total Labor 15,000
TOTAL INPUT ENERGY		~40,000

¹At 30 MY/MW

$$\text{ENERGY OUTPUT: } 0.35 \times 8760 \times 10^3 \times 10^4 \times 10^{-6} = 30,600 \frac{\text{MMBtu}}{\text{MW-YR}}$$

Energy Output =

$$\text{Capacity Factor} \times \text{Hours per year} \times \frac{\text{kW}}{\text{MW}} \times \frac{\text{Btu}}{\text{kWh}} (\text{Heat Rate}) \times \frac{\text{MMBtu}}{\text{Btu}}$$

$$\text{ENERGY PAYBACK RATE: } \frac{40,000}{30,600} = 1.3 \text{ Years}$$

year (-0.03 quads per year in 1990). This scenario goal is not only delayed in its capacity on line at a given date, but also in the rate of new additions.

Although of significantly higher risk, it would appear to be both technically and economically possible to achieve the goal of 0.1 quads of energy savings by 1985 if an aggressive Federal and utility/industry program is initiated. The risks, however, are great to both government and industry. A major technical failure could result from lack of time to fully prove out each system concept. This could lead to a disenchantment with the concept and ultimately longer market acceptance time.

ENGINEERING COSTS

Engineering cost estimates for the central receiver have been made by JPL, MITRE, Sandia, Martin Marietta, McDonnell-Douglas, Honeywell, Boeing, and several supporting contractors including Bechtel, Black and Veatch, Sterns-Rogers, Rocketdyne, Sheldahl, and Westinghouse. Estimates made by MITRE [5] in 1976 attempted to place all known previous estimates on a common basis for labor and materials costs, markups and fees. In addition, MITRE prepared estimates for the experience curve (cost reduction as a function of learning gained with system production) effects that can be expected for the system. These are based on a parametric study [6] that analyzed the experience curves for various materials (concrete, reinforcing bars, structural and stainless steel, float glass, insulation), components (pumps, generators, compressors), electrical and electronic equipment, and construction labor. These constitute the principal elements of solar thermal central receiver systems. The estimates of engineering costs are presented in Tables V and VI in 1978 dollars, reflecting the inflation since 1976 (16.64 percent). Further adjustments were made to remove the cost of the turbogenerator and cooling system (already in place in the re-powering concept) and to add the cost of plant modifications, which are expected to be minor. Note that the ultimate engineering cost is about \$900/kW at about 10 GWe of cumulative capacity. This figure is not the capital cost, but an "overnight construction cost," which does not include escalation, interest during construction, or special fees and contingencies over and above that normally considered appropriate (about 15 percent).

The operations and maintenance (O&M) costs have also been estimated at \$9.33/kW/year for the operation of the solar unit alone. Maintenance and fuel costs for the existing facility are not treated, although these may be substantial if the plant is base loaded.

It has been further estimated that 25 percent of the engineering cost is expended in the first year and 75 percent in the second year of the generic development plan cycle. Extension of the cycle to three years results in an

TABLE V
ENGINEERING COSTS VS. CAPACITY FOR
CENTRAL RECEIVER REPOWERING PLANTS
(1978 Dollars)

NUMBER OF PLANTS BUILT	ENGINEERING COST (\$/kW)	CAPACITY (MWe)
1	2974	25
2	1602	75
3	1449	125
4	1312	175
5	1257	225
10	1100	475
20	1010	975
50	946	2,475
100	922	4,975
200	898	9,975
360	878	17,975

TABLE VI

EXPERIENCE CURVE PARAMETERS FOR SOLAR THERMAL
CENTRAL RECEIVER (1978 DOLLARS)

MODULE	NO. REQ'D PER 50 MW PLANT	CUMULATIVE PRODUCTION (MODULES)	RATE (% SLOPE)	COST PER UNIT (\$/MODULE)
HELIOSTAT	7,500	1,125	85	11,020
		100,000	97	3,850
		22,500,000	100	3,030
RECEIVER AND TOWER	1	1	85	23,650,000
		45	97	9,690,000
		10,000	100	7,640,000
CONTROLS	300	45	85	45,030
		4,050	97	15,680
		900,000	100	12,360
BALANCE OF PLANT	1	1	100	6,010,000

estimated distribution of 9 percent, 49 percent and 42 percent for the capital outlays in each year, respectively.

GENERIC DEVELOPMENT PLAN

Once solar thermal repowering is fully commercialized, the development cycle for plant construction should be extremely short because the system is highly modular and compatible with mass production techniques. Since the boiler, turbogenerator, electrical plant equipment and the site are already available, repowering with solar will not require the long lead times usually associated with steam plants. A generic environmental impact statement for repowering would be required to keep the development and construction cycle on schedule. There are roughly 15 activities, most of which can be conducted in parallel, that may take only two years from inception to completion. In Table VII, these activities are listed along with the participants, time required for each activity, and number of months prior to plant start-up that the activity must be begun.

In Figure 1 these activities are shown on a timeline which outlines the parallel sequence of events. First generation facilities may take up to four years to complete the schedule due to delays in design, equipment availability, and financial negotiations. However, after about five years from the first plant's inception, the two-year plan may be in effect. Compared to conventional power plants, this estimated development cycle is very short. Construction periods for gas turbine systems are comparable, but new steam systems take up to 10 years for the entire development cycle.

IMPLEMENTATION PROGRAM

In order to achieve the utilization goal of 0.1 quad per year by 1985, the following actions must be executed in the near term:

- (1) A generic environmental impact statement for solar thermal repowering must be prepared and filed. This should begin immediately and be completed within 15 months.
- (2) Alternative heliostat designs must be built and thoroughly tested for performance, reliability, and expected life. They must be evaluated by production engineers for mass-reproducibility. A decision based on the above criteria must be made and the design frozen by May of 1979.
- (3) A site bank of facilities in the Southwest U.S., rank-ordering the sites on the basis of available land area, system age and efficiency, insolation, terrain characteristics, and

TABLE VII
GENERIC DEVELOPMENT PLAN ACTIVITY SCHEDULE

ACTIVITY	PARTICIPANTS	TIME REQUIRED TC COMPLETION (Months)	TIME REQUIRED PRIOR TO START-UP (Months)
Planning Studies	Utility	3	24-21
Preliminary Design	Utility/A/E Firm	4	21-17
Permits/Licenses	Utility/Federal, State, Local Governments	3-4	21-17
Environmental Statement	Utility/Federal, State, Local Governments	6	21-15
Site Development Plan	Utility/A/E Firm	2-3	20-18
Final Design	Utility/A/E Firm	5	17-12
Financial Negotiations	Utility/Banks/Stockholders	3	17-14
Long Lead Orders	Utility/A/E Firm/Manufacturers	3	14-11
Site Preparation	Utility/A/E Firm/General Contractors	3	13-10
Heliostat Installation	A/E Firm/General Contractors	7	11-4
Tower Installation	A/E Firm/General Contractors	4	9-5
Receiver Installation	A/E Firm/General Contractors	4	7-3
Controls Installation	A/E Firm/General Contractors	4	7-3
Shakedown Tests	A/E Firm/Engineering Firm	3	3-0
Operations	Utility	-	0

FIGURE 1
GENERIC DEVELOPMENT PLAN TIMELINE

willingness of the involved utilities to repower with solar must be prepared. This should be completed by August 1978.

- (4) Federal cost-sharing funds must be provided for preparation of preliminary repowering system designs for the first seven repowering sites, and advanced planning must be conducted with the utilities involved. This should begin by October, 1978.
- (5) FY79 funds must be programmed to place large orders for heliostats (for the first three powerplants) by May of 1979, using the production design chosen in step (2); and a contractor must be selected from interested industrial entities.
- (6) Additional funds to accomplish the above actions and to partially share the cost of construction of the first three repowering facilities must be requested within the timeframe desired.

A timeline for these activities is shown in Figure 2.

MARKET SIMULATIONS

The MITRE/Metrek System for Projecting Utilization of Renewable Resources (SPURR) model was used to simulate the market penetration for solar thermal repowering in the utility market for two sensitivity scenarios. These include all conventional technologies and applicable solar technologies to this market sector. (intermediate electric utility). The conventional technologies include:

- Coal steam with flue-gas desulfurization plants
- Oil combined cycle plants.

The solar technologies are:

- Wood-burning steam plants
- Wind energy conversion system (WECS)
 - combined with hydroelectric facilities
 - with gas turbine backup
- Photovoltaics
 - thin film flat panel

FIGURE 2
TIMELINE FOR IMPLEMENTATION OF 0.1 QUAD/YEAR
SCENARIO

- concentrator (gallium arsenide)
- silicon flat panel
- Solar thermal central receiver
 - with oil combined cycle backup
 - fuel saver (no backup)
 - with three hour thermal storage
 - with six hour thermal storage
 - repowering.

The first sensitivity scenario included a 20 percent investment tax credit for all solar technologies, a \$3 billion demonstration program by 1985 for first generation plants (for each generic solar technology), and the earliest possible introduction date for each technology into the commercial marketplace (1981 for repowering). The second sensitivity scenario included a 30 percent investment tax credit coupled with parallel demonstrations and streamlined permit/license/EIS approval procedures for all solar technologies. A market simulation of the NEP program with a 20 percent investment tax credit and the planned demonstration program was also performed and the results of the market penetration analysis for all three scenarios are presented in Table VIII.

Note that the market simulation for Scenario II projects the central receiver capacity at 3300 MW (0.1 quads/year of saved energy) by 1985. The energy savings (quads/year) for solar central receiver technologies are compared for Scenario I, Scenario II and the NEP with a 20 percent investment tax credit in Figure 3. The early introduction of the solar central receiver technology through repowering in Scenarios I and II results in a rapid market penetration by the year 2000. For example, the energy which is saved with the Scenario II program is more than three times that achieved under the NEP with a 20 percent investment tax credit program (1.4 quads/year vs. 0.4 quads/year).

The curve in Figure 3 indicates a "knee" about the year 2000 and a tapering-off by 2010. The spurt in 2000 is due to the introduction of cost-effective solar thermal systems as compared to the best conventional alternative. The "S-curve" market penetration is characterized by a "bandwagon" effect roughly ten to twenty years after market entry. The curve ultimately saturates at some point, thus the tapering effect in 2010.

Furthermore, a significant amount of energy is saved before the turn of the century for Scenarios I and II. The same amount of energy (3 quads/year) is saved in the year 2005 for Scenario II and in the year 2015 for the NEP. This 10 years of lead time could play a very important role during the transition towards utilization of renewable energy resources.

TABLE VIII
RESULTS OF MARKET SIMULATIONS

SCENARIO	YEAR	CUMULATIVE CAPACITY/SAVED ENERGY BY TECHNOLOGY MW/Quads per Year					TOTAL
		Repowering CF ¹ =0.37	Combined Cycle CF ¹ =0.37	Fuel Saver CF ¹ =0.37	3 Hour Storage CF ¹ =0.35	6 Hour Storage CF ¹ =0.50	
NEP	1985	---	---	---	---	120/0.005	120/0.005
	1990	---	200/0.006	300/0.01	200/0.006	520/0.02	1220/0.04
	1995	---	1000/0.03	2500/0.08	1500/0.05	1720/0.07	6700/0.23
	2000	---	2000/0.06	5000/0.16	2600/0.08	3020/0.13	12600/0.43
	2005	---	4300/0.14	10300/0.33	5800/0.18	9820/0.43	30200/1.08
	2010	---	6800/0.22	19100/0.62	10600/0.32	21400/0.94	57900/2.10
	2015	---	7600/0.25	23400/0.76	16900/0.52	33500/1.47	89000/3.00
	2020	---	7900/0.26	31900/1.03	24100/0.74	49500/2.17	133000/4.20
Scenario I	1985	1850/0.06	300/0.01	---	---	600/0.03	2750/0.10
	1990	2900/0.10	1400/0.05	1800/0.06	1200/0.04	1500/0.06	8800/0.31
	1995	4400/0.14	2000/0.06	5400/0.17	2500/0.08	2700/0.12	17000/0.57
	2000	7250/0.23	2400/0.08	9400/0.30	3900/0.12	3900/0.17	26800/0.90
	2005	19250/0.62	2700/0.09	17700/0.57	10500/0.32	9800/0.43	59900/2.03
	2010	19250/0.62	3800/0.12	28700/0.93	21200/0.65	21000/0.92	93900/3.24
	2015	19250/0.62	4000/0.13	34200/1.11	30800/0.94	32000/1.40	120000/4.20
	2020	19250/0.62	4100/0.13	43200/1.40	42400/1.30	44800/1.96	153000/5.41
Scenario II	1985	2000/0.06	400/0.01	---	---	900/0.04	3300/0.11
	1990	4600/0.15	1400/0.04	2900/0.09	1500/0.05	2100/0.09	12500/0.42
	1995	9600/0.31	2100/0.07	6600/0.21	3600/0.11	3000/0.13	24900/0.83
	2000	16700/0.54	2400/0.08	10400/0.34	7400/0.23	3800/0.17	40700/1.36
	2005	19250/0.62	3300/0.11	24600/0.78	22900/0.70	18000/0.79	88000/3.00
	2010	19250/0.62	3400/0.11	40300/1.31	39600/1.21	34100/1.49	136000/4.74
	2015	19250/0.62	3600/0.12	47200/1.53	52000/1.59	47300/2.07	169000/5.93
	2020	19250/0.62	3800/0.12	61100/1.98	65600/2.01	59600/2.61	190000/7.34

¹Capacity Factor.

FIGURE 3
ENERGY SAVINGS FOR CENTRAL RECEIVER
TECHNOLOGY

Energy savings due to various solar central receiver technologies are shown in Figure 4. It may be readily observed that the repowering of existing electric utilities power plants has a near-term impact and represents 40 percent (0.5 quads/year) of the total energy saved by the year 2000. After this year the market for repowering becomes saturated and other solar thermal technologies (fuel saver, three-hour and six-hour storage systems) will become more important.

Solar thermal was the most competitive of all solar technologies in the simulation in the Pacific, Mountain, and West South Central census regions, with estimated busbar costs of 30 to 50 mills per kWh versus 50 to 80 mills per kWh for all competitors.

CENTRAL RECEIVER SYSTEM DESCRIPTION

A solar thermal central receiver repowering system consists of a field of heliostats or mirrors that are controlled to aim direct sunlight to a common receiver mounted atop a tower. In the receiver, water is evaporated to steam and then superheated. The water is fed by a riser to the receiver and exits via a downcomer as superheated steam. The steam is then tempered, i.e., buffered, using water injection to the required temperature and pressure conditions at the turbogenerator inlet. The turbine exhaust steam is condensed in a cooling system. The condensate is then deaerated and preheated by turbine exhaust feedwater heaters before being pumped back to the riser. When the sun is shining, the system operates on the solar loop; when it does not, the conventional plant operation is followed. The schematic shown in Figure 5 displays the plant layout for a repowering system.

There are several potential complications for repowering regarding system design. For example, if the maximum output from the solar portion is nearly equal to the plant rating, a highly variable output could be expected during periods of intermittent cloud cover, which may require a thermal storage buffer to increase the thermal inertia of the steam supply system. The storage may be inserted directly in-line with the primary steam line. Also, many conventional steam plants employ reheat which would require intermediary heat exchangers. In about 90 percent of the sites that have been identified, the solar contribution may be less than 30 percent of the rated plant capacity, in which case the solar unit may be a primary steam source only that requires little boiler adjustment for the conventional unit. The problem of matching the two sources of steam to the turbogenerator will require a unique set of control criteria in order to assure a reliable plant operation.

The solar repowering system works on the direct component of sunlight only. Beam radiation varies from zero to 90 percent of the total insolation available, depending on cloud cover, haze, pollution and particulates suspended

ENERGY SAVED
(QUADS/YEAR)

FIGURE 4
SCENARIO II: ENERGY SAVING DUE TO DIFFERENT
TECHNOLOGIES

FIGURE 5
SOLAR THERMAL REPOWERING PLANT
CONFIGURATION

in the atmosphere. The beam is reflected by the heliostat to the receiver. En route, the beam is refracted, partially absorbed and scattered by the atmosphere. Also, some of the radiation is absorbed in the reflective coating on the heliostat and the glass protective layer for the coating. At the receiver, the beam is absorbed in the working fluid, some is reflected, a portion is re-radiated, some of the absorbed heat is conducted away through the walls of the receiver and the remainder is convected by the air flows from the receiver tube surfaces. Some of the heat in the working fluid is lost during the piping to the power plant. The steam produced is then expanded in the turbine and produces shaft work which drives the generator. The steam is only partially condensed in the turbine. The bulk of the heat of vaporization in the steam is removed in the condenser. A pump increases the pressure of the condensate and drives the working fluid back to the receiver whereupon the cycle continues. There are other losses in the system and requirements for auxiliary power. These include: piping losses, valve losses, losses in the attemperator and deaerator, pump and fan requirements for the condenser, power to drive the heliostat tracking motors (about 5 watts per square meter) and general power requirements for the maintenance of the power plant. In Table IX, an estimate is made for the plant requirements and losses for a 50 MWe (200 MWth) solar repowering facility. For this system, the overall efficiency is 25 percent from sunlight to electricity at the busbar.

The yearly energy output depends strongly on the availability of sunlight and the plant operation schedule. For five different sites in the Southwest, an estimate is made of the insolation and net plant output assuming 10 percent downtime for forced and maintenance outages coupled with periods when the plant is not dispatched. These are shown below:

Location	Insolation ($\text{kWh}_{\text{th}}/\text{m}^2/\text{yr}$)	Net Plant Output ($\text{kWh}_{\text{e}}/\text{m}^2/\text{yr}$)	Rated Power ¹ (kWe/m^2)	Potential Capacity Factor (%)
Albuquerque, NM	2600	585	0.175	38.2
Fort Worth, TX	1700	383	0.175	25.0
El Paso, TX	2650	596	0.175	38.9
Ely, NV	2420	545	0.175	35.6
Inyokern, CA	3000	675	0.175	44.0

¹Based on $0.7 \text{ kW}/\text{m}^2$ mean insolation.

TABLE IX

PLANT AUXILIARY POWER REQUIREMENTS AND LOSS INVENTORY
(50 MWe SOLAR REPOWERING FACILITY)

MODE OF LOSS	INVENTORY (kW/METER ²)		
	Input	Loss	Output
Heliostat Reflection	1.000	0.079	0.921
Tower Shadow, Shading, Blocking	0.921	0.037	0.884
Atmosphere Transmission	0.884	0.053	0.831
Effective Field Cosine	0.831	0.047	0.784
Receiver Reradiation	0.784	0.011	0.773
Receiver Conduction	0.773	0.006	0.767
Receiver Convection	0.767	0.025	0.742
Piping Loss	0.742	0.019	0.723
Attemperator Loss	0.723	0.004	0.719
Turbine Inlet Loss	0.719	0.007	0.712
Heat Engine Efficiency	0.712	0.442	0.268
Cooling Fans	0.268	0.008	0.260
Pumps/Auxiliaries	0.260	0.005	0.255
Heliostat Motors	0.255	0.005	0.250

- Backsilvered Glass
- North Facing Field
- Cavity Receiver (196 m² aperture or 2110 ft²)
- Mean Beam Transmission Distance: 620 meters
- Mean Atmospheric Loss Coefficient: $1.0 \times 10^{-4} \text{ m}^{-1}$
- Wet Cooling Towers
- Steam Generated at 516°C and 101.9 kg/m² (960°F @ 1450 psia)
- Piping Distance: 1000 m (3281 ft.)
- Tower Height: 198 m (650 ft.)
- Height to Receiver Centerline: 213 m (700 ft.)

Insolation data, based on direct beam radiation only, have been estimated for 26 locations [7]. Once adjusted for the fact that a central receiver only operates once the sun is above 10° over the horizon, these data correspond to that in the table above for these five locations. About half of the potential repowering sites are in central Texas (near Fort Worth) which means that plant energy costs may be up to 60 percent higher than for the clearer areas in the Mountain states.

If storage is added to the system, the capacity factor may be increased substantially. However, the average plant efficiency also decreases while the plant rating reduces for the same array size. With three hours of storage at 70 percent of the nominal plant rating, the capacity factor may increase from 0.35 to 0.45. With six hours of storage, the capacity factor may increase to 0.52. However, the solar multiple (ratio of plant rating without storage to that with storage)¹ would increase from 1.0 to 1.4 with three hours and to 1.7 with six hours of storage.

After the construction is completed, there will be shakedown tests which may require the host power plant to be shutdown for a period of about three months.

CONCLUSIONS

Solar thermal repowering appears to be the solar thermal central receiver technology closest to commercialization. The repowering concept as well as the storage-coupled central receiver concept will be demonstrated with the 10 MW Barstow pilot plant which will serve as a vital source of technical information for all phases of the first repowering projects--design, construction and operations. If a solar thermal central receiver program with a major repowering element is successfully implemented during the next six years, a fast-growing and self-sustaining industry is likely to develop in support of this technology. From simulations of the future market based on a \$200 million government program and a 30 percent investment tax credit for solar technologies, it also appears that it may be possible to displace

¹For example, a heliostat field and tower may be rated at 200 MWth of insolation, and produce 50 MWe without storage with direct coupling to the turbogenerator. If storage is introduced at a 1.7 solar multiple, then the turbogenerator is derated to about 30 MWe (using 120 MWth of the direct steam generated) while 80 MWth goes to charging the storage unit. Since storage input/output efficiency is roughly 70 percent, the turbogenerator may produce about 21 MWe from the stored energy. On average, 41 percent of the steam charges storage to produce 33 percent of the plant net output while 59 percent of the steam is directly used to produce 67 percent of the plant output.

up to 0.1 quads per year of fossil fuels by 1985, about 1 quad in 2000, and more than 7 quads in 2020 with the solar thermal central receiver systems. Under such a growth pattern it is expected that all potential repowering sites may be exhausted by 2005 and new solar thermal central receiver systems built after that point will be either stand-alone with storage, hybrids or fuel savers.

Government cost-shared repowering as described herein also provides a rapidly developed new market resulting in immediate cost reductions for solar thermal systems, enabling the construction of heliostat mass production facilities. As a result, the other central receiver concepts are more likely to become competitive earlier.

Material requirements may be a problem after 1990, when growth rates may exceed 3000 MW per year. The critical areas include glass, silver and insulation.

The labor force required in the new industry may reach nearly 50,000 direct labor jobs by 1985, and as many as 150,000 jobs in supporting commercial sectors. By 2000, the industry may be 10 times larger.

Capital requirements for the industry are substantial. It is not clear at this time what the total relative capital needs are going to be for all electric generation alternatives. It is likely, however, that capital availability may be a problem by the turn of the century independent of the mix of energy technologies chosen.

At least \$200 million of federal "seed" money may be required over the next five years (in addition to RD&D expenditures currently planned) to support the birth of the industry.

Certain federal actions are needed in the near-term to begin the process of commercialization. These include:

- Reprogramming FY79 funds to initiate both heliostat production and repowering facilities
- Performing a heliostat design competition and making a production design choice by May of 1979
- Obtaining funding approval for a six-year repowering program (on the order of \$200 million)
- Completing a site bank for all southwestern utilities
- Cost sharing the first three repowering plants between FY79 and FY83, with an option for an additional four plants

- Preparing and filing a generic environmental impact statement (EIS) within 15 months
- Cost sharing the first heliostat production facility or placing a guaranteed order for approximately 25,000 heliostats.

If the above actions are completed on schedule, if all of the technical systems perform as planned, and if the costs are near to that projected, then the commercialization activities may proceed as projected.

REFERENCES

1. P. A. Curto and Z. D. Nikodem, "Solar Thermal Repowering," MTR-7861, The MITRE Corporation, Metrek Division, McLean, Va., May 1978. *62c*
2. N. Lord and P. A. Curto, "Solar Thermal Repowering: Utility/Industrial Market Potential in the Southwest," MTR-7919, The MITRE Corporation, Metrek Division, McLean, Va., Dec. 1978. *67c*
3. Public Service of New Mexico, unpublished briefing documents, delivered at DOE program review, Albuquerque, New Mexico, Feb. 1978.
4. National Electric Reliability Council, "Fossil and Nuclear Fuel for Electric Utility Generation Requirements and Constraints, 1977-1986," Princeton, New Jersey, Aug. 1977.
5. P. A. Curto, "Systems Descriptions and Engineering Costs for Solar-Related Technologies, Volume V, Solar Thermal Electric Systems," MTR-7485, Vol. V, The MITRE Corporation, Metrek Division, McLean, Va., June 1977.
6. N. Gadsby, "Systems Descriptions and Engineering Costs for Solar-Related Technologies, Appendix to Volume I, Experience Curves and Cost Trends: A Preliminary Consideration of Some Factors Likely to Influence Capital Costs in Selected Solar Energy Systems," MTR-7485, Appendix to Vol. I, The MITRE Corporation, Metrek Division, McLean, Va., June 1977.
7. E. C. Boes, et. al., "Availability of Direct Total and Diffuse Solar Radiation to Fixed and Tracking Collectors in the USA," SAND 77-0885, Sandia Laboratories, Albuquerque, New Mexico, Aug. 1977.