Central Solar Receivers — Applications for Utilities and Industry

Molten salt and forced air central receiver systems have been developed to the point of commercial demonstration. The projected costs are competitive, even for first generation plants

Paul Allen Curto
Gibbs & Hill Inc.
Washington, D.C.

George Stern
Consultant
Mamaroneck, N.Y.

Gibbs & Hill, Inc., a subsidiary of Dravo Corp., has recently completed two conceptual design studies relating to central receiver applications. The first deals with a "power tower" for repowering of the Saguaro Station of Arizona Public Service. The second deals with a solar cogeneration facility integrated with an industrial process in New Mexico to generate power and provide process heat. The two systems utilize the central receiver concept but effect solutions in fundamentally different ways; one uses a molten salt receiver with a heat exchanger for a steam cycle to efficiently generate electricity. The second utilizes a Brayton air cycle which produces electricity and provides total recovery of waste heat in the form of air at 980°F (526.6°C) for direct use in the industrial process.

For the past several years, G&H has performed numerous studies of the potential, design, and feasibility of central receivers for use in utility and industrial applications. These studies have been conducted with industrial teams, including Martin Marietta Aerospace, Boeing Engineering and Construction, Foster Wheeler, Arizona Public Service and Phelps Dodge Corporation. The latest study, entitled "Solar Central Receiver System Integrated with a Cogeneration Facility," was completed in August 1981. The findings of the work indicated good potential for central receiver applications in the primary metals industries, i.e., copper, lead, zinc, and nickel smelting, with further potential applications to steelmaking.

Concepts

In the molten salt system, molten salt is pumped from the cold storage tank to the receiver, where it is heated to about 600°C (1112°F). The salt is returned to the hot storage tank after heating. In a secondary loop, the hot salt passes through a steam generator, where water is heated, vaporized to steam which is then superheated and finally reheated in four heat exchanger blocks. The superheated primary steam is fed to steam turbines for power generation, returned to the salt-heated reheater, then recycled back to the low-pressure turbines to extract more energy for power generation. Bleed steam from the turbines is utilized for deaeration and feedwater heating prior to introduction to the salt/steam generator. Heat is rejected in water or air-cooled condensers from the steam to ambient. After the hot salt is cooled in the steam generator, it is returned to the cold storage tank. Recent studies conclude that the thermal storage capacity should be sufficient for four to 12 hours of steam generation at capacity (full rating) of the steam turbines. The overall peak efficiency, from sunlight to electricity, is approximately 23.2 percent using the molten salt concept. The level compares with 8- to 12-percent system efficiencies with photovoltaics, and 14 percent for the first generation water-to-steam central receiver plant at Barstow, Calif.

In the forced-air system, ambient air is inducted into

Reprinted from MECHANICAL ENGINEERING, *Vol. 104, No. 7, July 1982*

Combined cycle system performance

	Gas turbine exhaust temperature (°F)						
	700	750	800	850	900	950	1000
Optimum steam boiling pressure (psia)	350	380	420	465	520	580	640
Steam turbine inlet temperature (°F)	600	650	700	750	800	850	900
Air exhaust temperature from HX (°F)	400	400	400	400	400	400	400
Pinch point ΔT (°F)	29	33	35	37	40	44	52
Steam cycle heat rate (Btu/kWhe)	11,950	11,710	11,460	11,220	10,970	10,730	10,580
Peak net steam turbine power (MWe)	79	89	100	111	123	136	150
Peak gas turbine power (MWe)	526	493	460	427	397	371	350
Annual heat cycle efficiency (percent)	37.4	37.0	36.6	36.2	35.9	35.7	35.6
Plant factor (percent)	32.1	33.0	34.0	34.9	35.8	36.6	37.0

speed-controlled gas turbines and forced through an Inconel 617 metal tube receiver, where it is heated to between 600 and 816°C (1112 to 1500°F). The receiver discharge air is expanded in the compressor-turbine (which drives the compressor) and further expanded in the power turbine (which drives the synchronous generator). Depending on the downstream application (for further steam raising for power generation in steam turbines and/or for direct use in some industrial process), the exhaust temperature and pressure are tightly controlled by variation of compressor rotational speed and power turbine guide vane positioning. The exhaust air from the gas turbines is ducted to the thermal energy storage (TES) plenum, where it is further gated to either the TES or to the downstream process (depending on generation and load demand). The TES is discharged using compressors to force air up through the packed bed, until the air reaches required temperature and flow rate to accommodate the downstream process conditions.

In the table, the use of this exhaust air in steam generation systems is explored. As the turbine exhaust temperature is lowered, the steam power generation is reduced while the gas turbine generation is increased. The overall cycle efficiencies range from 35.6 to 37.4 percent (from heat to electricity) with these combined cycle configurations. Coupled with annual average (sunlight-to-heat) collection efficiency of 54 percent in the air receiver (peaking at 62 percent), overall annual system efficiency ranges from 19.2 to 20.2 percent, with peak efficiency as high as 23.2 percent. Of course, the turbine/exhaust air might also be used in an industrial process, such as copper smelting. The findings in the industrial cogeneration study (with Phelps Dodge and Boeing) predicted 90-percent smelting throughput improvement utilizing process air solar-preheated to 527°C (980°F). The greater oxidation potential and sensible heat content of the air more effectively burns the sulfur and iron in the smelting concentrates. In this system, 650 GWh of heat is collected annually by the solar system, while 231 GWh of fuel energy is used to produce 384 GWh mech/elec recovered by the cogeneration systems in the plant. The premodified plant burns 886 GWh of oil and recovers only 200 GWh mech/elec in its cogeneration system.

The plant capacity is nearly doubled, increasing from 106,000 metric tons of anode copper per year to 200,000, while sulfuric acid production increases from 630,000 metric tons to 1,200,000. The integrated solar facility virtually halves the required total primary fuel needed to produce a unit of anode copper, while greatly improving plant profitability and productivity. Three primary innovations make possible the use of gas turbine/combined cycle-cogeneration systems. These include:

(1) Thermal storage using copper slag;
(2) Multi-power port gas turbines;
(3) Integrated, intrinsically redundant master control and communications systems.

The slag storage concept is a breakthrough which enables heat storage at elevated temperature (up to 816°C) for several days rather than merely hours. Its cost (about $30 to $40 per cubic meter) results in thermal storage capacity costs on the order of pennies per thermal kilowatt-hour, or about 10 cents per electrical kilowatt-hour, once the heat is converted in heat engines. Multi-power port gas turbines provide speed control through electrical means, which tightly control receiver power extraction, air temperatures, pressures and flow rates without the use of auxiliary fuel or combustors, turbine valving, or complex interconnecting bypass ducting. The new Gibbs & Hill master control system concept makes possible continuous, distributed, fully automated power generation without resorting to complex, yet-to-be-developed computer hardware. Its projected reliability in the smelter application exceeds 0.9999.

Other Potential Applications

It is clear that the primary emphasis on central receiver development has recently switched to molten salt for utility power generation. However, the air systems can match or exceed the salt system potential economics for power, while adding the greater flexibility for far greater storage capacity and direct uses of high-quality exhaust air in industrial processes. For example, nickel smelting embodies technology that is virtually identical to that for copper. Zinc and lead are also produced from exothermic reactions of ore concentrates which could use pure, heated air more effectively. Steelmaking process efficiencies could be enhanced using preheated pure air, along with coke-produced CO and air blasting to improve furnace productivity rates. Use of pure gases other than air, such as helium, CO_2, O_2, synthesis gas (CO and H_2), and hydrocarbons (such as CH_4, C_2H_5, etc.) could be utilized in Brayton-type systems for chemicals and petroleum industry applications. Processes would be made cleaner, more productive, more economic, and manufacture chemical products of exceptional stability and purity.

Economics

Central receiver economics have historically been driven by the cost of heliostats, receivers, and thermal storage. In the case of utility applications, only the heliostat price, which is governed by production quantities

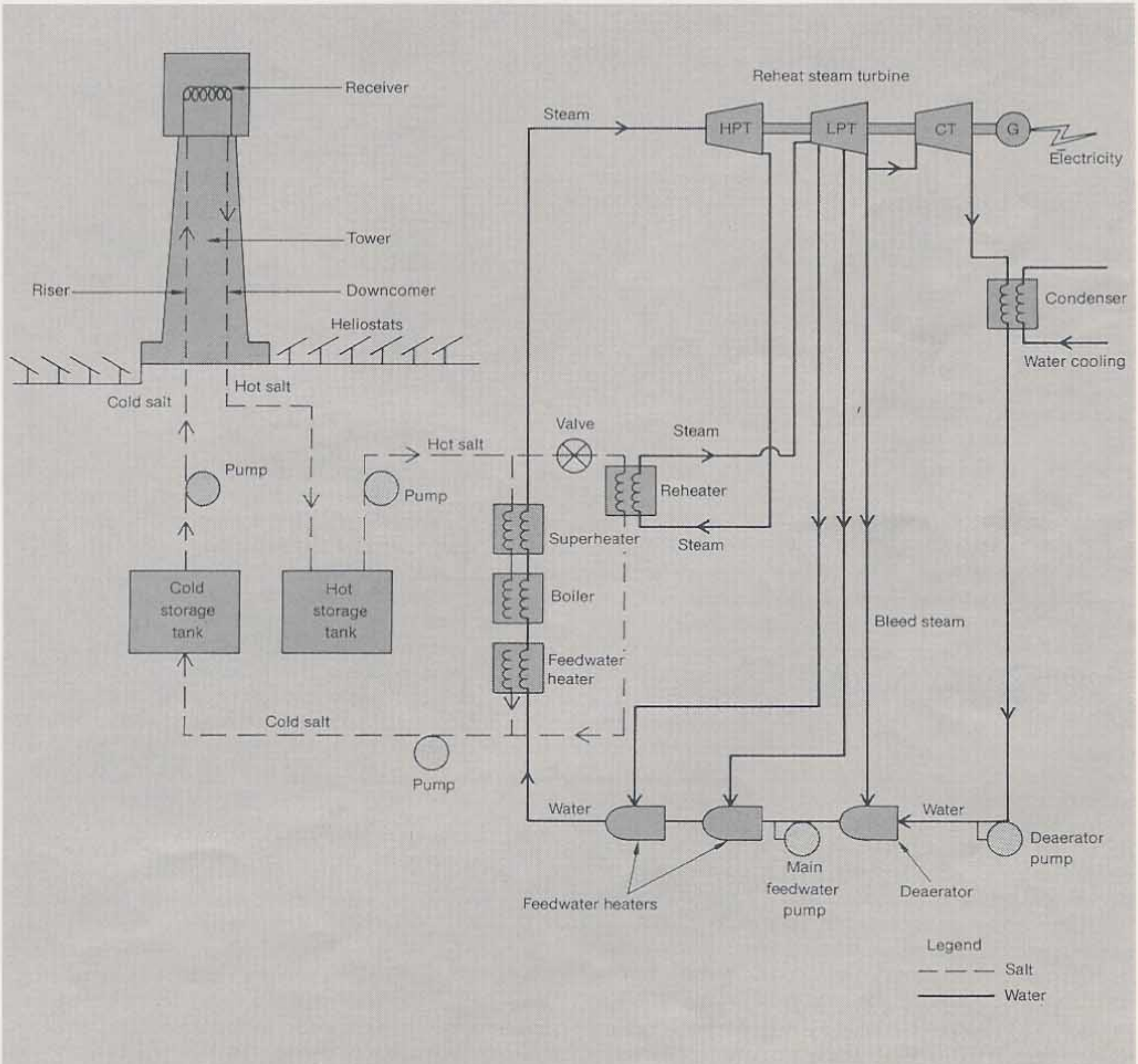

Fig. 1 Molten salt system for power generation.

and delivery schedules, becomes critical. The last Barstow heliostat cost over $250 per square meter. The 100,000th unit of a production line for commercial heliostats will likely be in the $90 to $130 price range, installed at a site within 1500 km of the heliostat plant.

We contend that the economy of scale for central receivers requires that production rates must exceed 50,000 heliostat units per year for the cost of thermal energy produced in a sunny region (insolation greater than 2000 $kWh_T/m^2/yr$) to be competitive for power generation. Some integrated processes in the industrial sector could tolerate high heliostat prices, perhaps as high as $200 per square meter installed. In the smelter application, a 50-percent discounted cash flow rate-of-return to equity is exhibited with a heliostat price in this range, but this is primarily due to the marked improvement in overall plant productivity.

A recent in-house Gibbs & Hill study concludes that a 500 MWe combined cycle plant (based on our concept) could be designed and built for about $750 million (1980 dollars) or $1.5 billion (1987 dollars) that would produce an average of 1600 GWhe per year. Power cost would be 16¢/kWhe in 1987 (8¢ in 1980), not rising in current dollars for about 10 years. This would compete favorably with small coal-fired systems, integrated coal gasifier/combined cycle systems, windmills, nuclear power, and most certainly with oil- or gas-fired combined cycle units. Such units could be installed throughout the Southwest, but also in areas as far north as eastern Oregon and Washington, Idaho, Montana, Wyoming, Nevada, and Utah. Power costs would vary about 20 percent over this entire area from those projected for the southern desert sites.

Molten salt and forced air central receiver systems have been developed to the point of commercial demonstration. The new generation of these plants have broad applications in new and retrofit utility and industrial facilities. The projected costs are competitive, even for first generation plants.

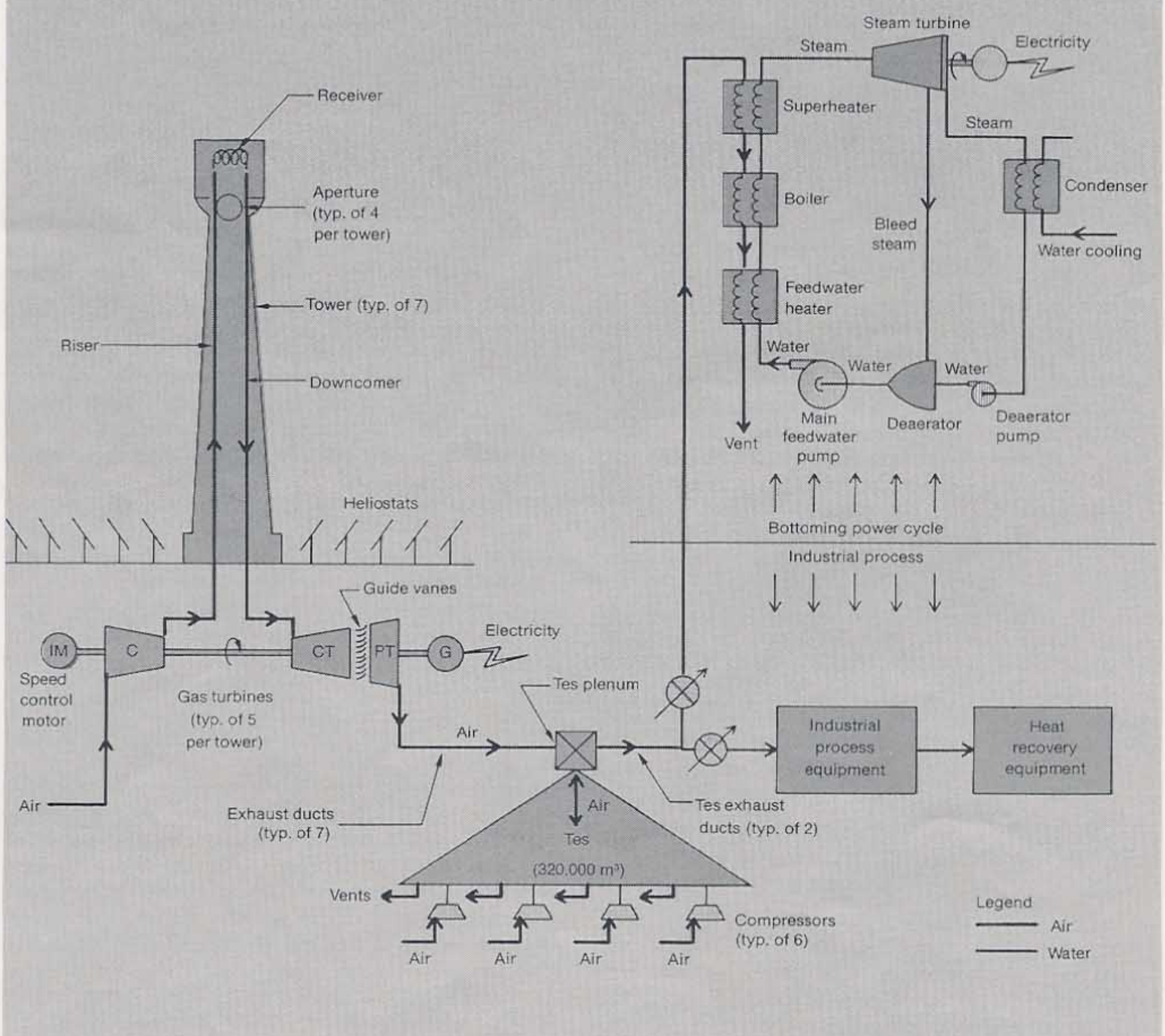

Fig. 2 Forced air system for combined cycle power generation and/or industrial process applications.

EXCERPT FROM SOLAR ENGINEERING & CONTRACTING ISSUE DATED NOVEMBER, 1982

The new 'generation' of solar power

by Timothy A. Fausch

Many announcements have been made recently concerning the development of large-scale solar power generating facilities. These projects utilize the technologies of central receiver power towers (CRPT), photovoltaics (PV), and solar thermal. Because of the large number of participants involved and the proximity of the projects, SE&C has contacted key personnel for updates on project developments. The table below is the result of this research.

The importance of these projects to the solar industry should not be underestimated. Successful completion of the facilities would improve immensely the image of solar as a major power source for the immediate future. Failure of the projects certainly would blemish the industry and provide ammunition for those who say that solar doesn't work.

After years of research and development, as well as the successful completion of "Solar One" (see table), these large-scale facilities no longer can be viewed as demonstration projects. Also, enormous cost overruns and multi-year delays in many nuclear generating projects have opened the door for solar to enter into large-scale electrical power generation.

DOE awards nearly $6 million

Because of the enormity of many of these projects, large companies, utilities, and government agencies are pooling their resources. Especially important are contracts for design and engineering of these facilities recently awarded by the Department of Energy (DOE), and also the financial involvement of utility companies, such as Southern California Edison Co. (SCE) and Sacramento Municipal Utility District (SMUD).

DOE contracts totaling $5.95 million were awarded for preliminary design studies of four solar CRPT facilities. Construction of the generating plants will be based on economic feasibility as concluded by the studies.

Design-package terms require the financial involvement of the sponsoring company and its subcontractors. Design packages and their awards from DOE include the following four companies:

Amfac Energy, Inc.'s design will cost $815,000, with DOE contributing $675,000. **Arizona Public Service Co.'s** (APS's) design will cost $2,367,000, with DOE's share being $2,103,000. The **El Paso Electric Co.** (EPE) design will cost $2,325,000, with DOE providing $1,831,000. **Rockwell International's** design will cost $2,068,000, with DOE contributing $1,341,000.

Other abbreviations used in the table are: B&R — Brown and Root, Inc.; B&V — Black and Veatch Consulting Engineers; B&W — Babcock and Wilcox; CAE — Consortium of Alternate Energies; CEC — California Energy Commission; F-W — Foster Wheeler; G&H — Gibbs and Hill, Inc.; Hels. — heliostats; M-D — McDonnell Douglas Co.; M-M — Martin Marietta Corp.; MWp — peak megawatt; N.A. — not available; PG&E — Pacific Gas and Electric Co.; S-R — Stearns-Roger; and S&W — Stone and Webster. ■

SOLAR POWER PLANT UPDATE

MWp	site	project known as	est. cost (mill. $)	major parties	technology	current stage	est. date 'on-line'
560	Ridgecrest, CA	Ridgecrest Solar Power Plant	1,700*	CAE, B&R, G&H, SCE	CRPT — 70,000 hels., 7 fields	prelim. design complete, pursuing contracts	1987-1990
100	Daggett, CA	Solar 100	400-600	SCE, M-D, M-M, S-R, Rockwell, ARCO, B&V	CRPT — 15,000 hels., 2 fields	prelim. design complete, obtaining bids	1986-1988
1-100	Sacramento County, CA	SMUD Solar Power Plant	270	SMUD, DOE, CEC, Acurex	PV — flatplate tracking panels	completing final detail design (by Dec. 1982)	1984-1994**
66†	Red Rock (Tucson), AZ	Saguaro Solar Repowering	215*	APS, DOE, M-M	CRPT — 5,740 hels., 1 field	concept design complete, enter prelim. design	1987
41†	El Paso, TX	Newman Station Solar Repowering	136*	EPE, DOE, B&W, S&W, Westinghouse	CRPT — 1,800 hels., 1 field	feasibility study done, enter prelim. engineering	1987
31.8†	Lahaina, Maui, HI	Amfac Solar Power Project	65.7*	Amfac, DOE, Bechtel, F-W	Cogeneration — CRPT & oil	concept design complete, enter prelim. engineering	1987
30†	Carrizzo Plain, CA	Carrizzo Plain Solar Power	152*	Rockwell, PG&E, DOE, ARCO	CRPT — 1,900 hels., 1 field	concept design complete, enter prelim. engineering	1985
15	Daggett, CA	Solar Trough Power Project	100+	Luz, SCE, Israel govt.	Solar thermal, linear troughs	prelim. design begun, construction begins 1983	1983-1985††
12	Daggett, CA	Acurex Solar Power Plant	75	Acurex, SCE	Solar thermal, 5,300 troughs	engineering complete, halted at construction	halted indef.
10	Barstow, CA	Solar One	141	SCE, DOE, M-D	CRPT — 1,800 hels., 1 field	constructed, producing electricity in tests	1987‡
1	Hesperia, CA	ARCO PV Power Project	N.A.	ARCO, SCE	PV — 100 tracking panels	engineering complete, under construction	Dec. 1982

*Estimated cost projected in 1986 dollar equivalents.

**SMUD design calls for 1 MW in 1984; 1 MW — 1985; 2 MW — 1986; 5 MW — 1987; 6 MW — 1988; 7 MW — 1989; 10 MW — 1990; 13 MW — 1991; 20 MW — 1992; 35 MW — 1993-94. Total: 100 MWp.

†Projects received DOE grants on Sept. 30, 1982.

††Luz project calls for 3 MW in 1983; 6 MW — 1984; 6 MW — 1985. Total: 15 MWp.

‡Solar One project will be used as a demonstration plant until 1987.