NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Electrical And Electronic Engineering

SOLAR POWER PLANTS

Graduation Project
EE-400

Student: Mahsun Erkar(981031)

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Lefkoşa-2003

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ABSTRACT

So many experimental demonstrations has been introduced the performance of SSPs is largery based.The followings must be considered :

-Almost all the SSPs were operated under different conditions;
-All the thermal SSP technologies are in general of different maturities ,each technology representing only the 1 st or 2 nd generation development status reached after 10 –15 years development efforts.

Performance in terms of energy produced and ultimately in terms of cost for productionof or revenue achieved are the bottom line criteria for a comparison of power plant economics.In the past peak power efficiencies of systems, subsystems and components were frequently employed for this purpose.With caution, the transfer function based on aggregate daily net energy output to daily solar direct irradiation input may be used for an efficiency-based performance comparision.Such transfer functions can make technology specific distinctions and relative performance differences apparent.

INTRODUCTION

In parallel with rising interest in solar power generation, several solar thermal facilities of different configuration and size were built, operated, and evaluated in the last decade and a half. Some of these facilities were of exploratory, first-of-a-kind or demonstration nature, in some cases designed merely as engineering experiments for the purpose of gaining performance and operating data at the subsystem and overall plant level. Most facilities were designed as modest-size experimental or prototype solar power plants (SPP) for producing electricity, in a few cases also for cogenerating thermal energy. Of all solar thermal technologies investigated, SPPs using parabolic trough concentrators were the first to reach sufficient maturity to be constructed on a commercial basis in a favorable regulatory environment.

In this chapter, selected examples of the major technology lines of thermal SPI's are presented; also, major experience and lessons learned from experimenting with and operating such systems will be excerpted. This experience base is still fragmentary and, in some cases, preliminary — a fact not surprising considering the different approaches attempted and the first-generation technologies frequently involved, However, the data base is broad enough to identify major system operating characteristics, and to allow, with reasonable confidt,nce, an extrapolation of future thermal SPP performance with mature technology under good solar resource conditions.

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INTRODUCTION

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In this chapter, selected examples of the major technology lines of thermal SPI's are presented; also, major experience and lessons learned from experimenting with and operating such systems will be excerpted. This experience base is still fragmentary and, in sôme cases, preliminary — a fact not surprising considering the different approaches attempted and the first-generation technologies frequently involved, However, the data base is broad enough to identify major system operating characteristics, and to allow, with reasonable confidt,nce, an extrapolation of future thermal SPP performance with mature technology under good solar resource conditions.

1. FARM SOLAR POWER PLANTS WITH LINE-FOCUSSING COLLECTORS

Using line-focussing parabolic troughs, a solar thermal power facility of about 35 kWmech capacity was demonstrated successfully as early as 1913 in Egypt . This facility had 1,233 m2 of collector aperture and was designed for pumping water for field irrigation. Disturbances by World War I and the advent of the 'oil economy' stymied any subsequent development efforts.

Development activities started again in the mid 197Os in response to the sudden oil price increase. R&D programs financed by industry and governments spawned a multitude of alternate designs of collectors and SPP system approaches.

Technological progress of line-focussing collector technology can be illustrated by three significant examples:

- the 150 kWe facility at Coolidge/AZ, USA (1979), the first solar thermal full experiment to demonstrate automated operation in an actual application environment;
- the 500 kWe experimental Small Solar Power System plant in Almeria, Spain (1981) designed, built and operated as a collaborative R&D project under the auspices of the International Energy Agency (IEA-SSPS); and
- the 30 MWe Solar Electricity Generating Systems (SEGS lI—VII; 1985—1989), developed commercially by a group of American, Israeli and German companies and marketed by Luz International Inc., Los Angeles/CA, USA.

1.1 PLANT CONFIGURATIONS

System diagrams of the early 500 kWe IEA-SSPS facility and of the SEGS VIII plant, lustrative of the most advanced commercial design, show the typical plant lay-out and evolution in the design (Figs. 7.3 and 7.4); some observations can be highlighted:

- Each collector field consists of parallel loops of individual parabolic trough collectors -series. Heat transfer medium (HTF) is thermo-oil (suitable up to 3OO C) or synthetic oil (stable up to

400 C; more expensive by a factor of 10). Water/steam as HTF is not yet used (advance development in progress).

The advantage of oil as primary HTF is a low vapor pressure, resulting in operating pressures<5 bar. The disadvantage of oil is the low viscosity at low temperatures, which is critical at start-up after the plant has cooled down. By temperature stratification, oil offers the advantage of one-tank thermal energy storage of small to medium capacity (thermocline principle), but application is constrained for cost reasons, and by the limited temperature range of thermo-/synthetic oils.

- Small collector fields need some amount of storage to allow operation of the power conversion unit (PCU) independent from changes in oil temperature as a conseqence of irradiation transients. The oil inventory of large collector fields, particularly if in hybrid combination with one or more fossil-fueled water/steam heaters, provides sufficient operational flexibility without buffer storage.
- For maximizing annual generation, yet minimizing size and cost of collector fields, thermodynamic conversion must be as efficient as possible for the solar-induced broad range of operating conditions. Taking advantage of off-the-shelf PCUs for cost reasons, early small-capacity cycle designs tended to be rather straight-forward and not well adopted to variable operating conditions. The large SEGS hybrid systems in use today incorporate highly sophisticated cycle configurations with (solar and/or fossil) superheating, and PCUs specifically adapted to solar operating conditions.

In this context, wet cooling is essential for best possible cycle efficiency. In sunny but arid regions, scarcity of water may necessitate that dry cooling be used for large thermal SPPs, affecting annual plant performance.

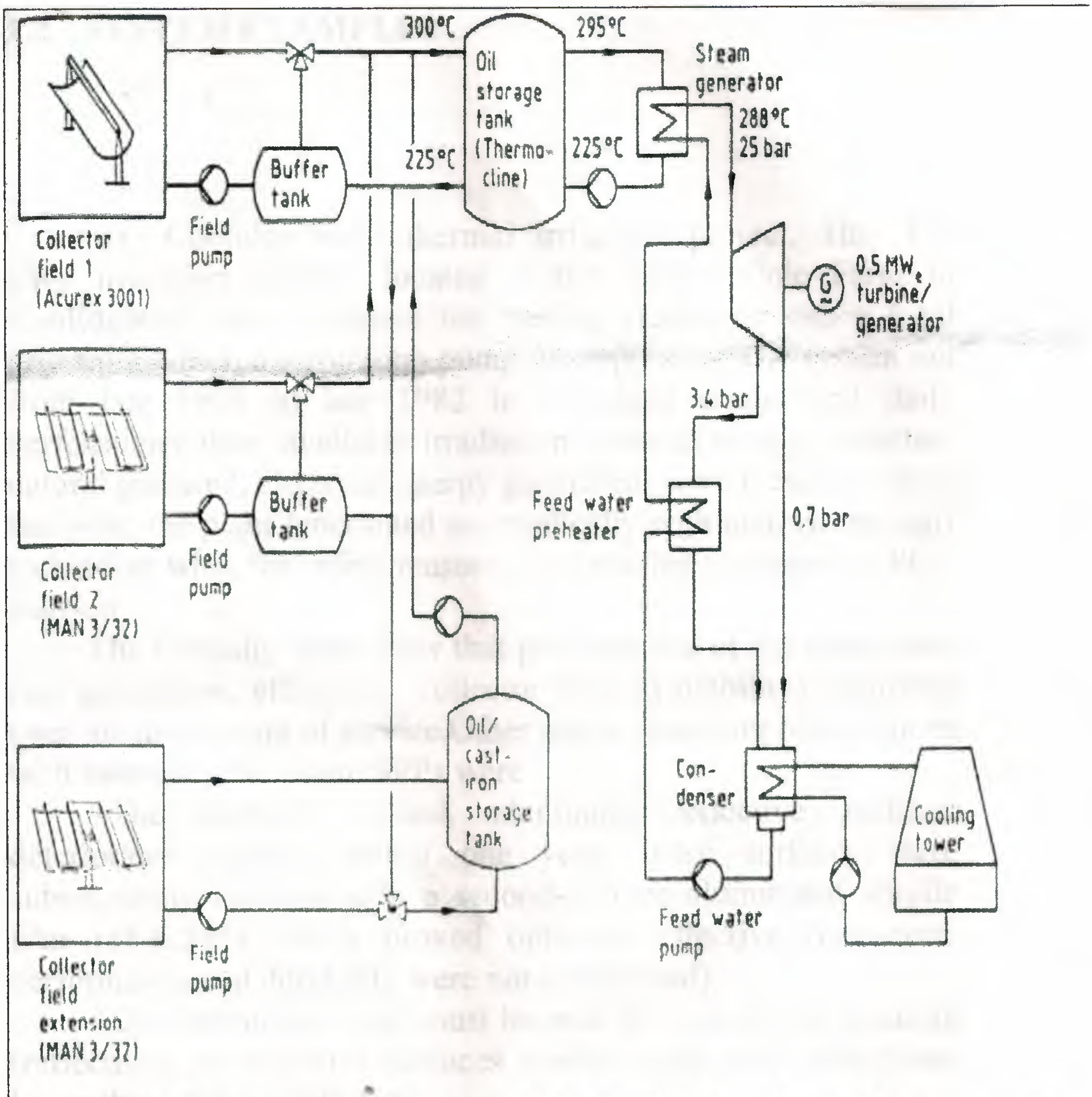


Fig. 7.3. Simplified system configuration of the IEA-SSPS 500 kW$_e$ thermal SPP in Almeria, Spain. The experimental facility uses 1- and 2-axes tracking collectors in three different collector fields, and two storage tanks. The 500 kW$_e$ turbine/generator is an off-the-shelf, non-solarized unit.

1.2 SYSTEM EXAMPLES

(a) Coolidge solar thermal irrigation project. This 150 kWe irrigation facility, located at the Dalton Cole Farm in Coolidge/AZ, was designed for feeding electricity into a local grid from which an irrigation pump was operated. The system ran from late 1979 to late 1982 in a hybrid mode, and daily performance data (available irradiation, thermal energy collected, natural gas used, electrical energy generated) were recorded. In its last year, the plant functioned automatically with merely one staff technician who, for safety reasons, was needed to supervise PCU start-up.

The Coolidge data show that performance of the solar plant (net generation, efficiency, collector field availability) improved over the three years of service.Other major operating observations with relevance for future SPPs were :

-The original Coilzak aluminum reflective surfaces deteriorated rapidly within one year; these surfaces were subsequently covered with a second-surface aluminized acrylic film (FEK.244) which proved optically effective (long-term performance and durability were not established).

-Demineralized water must be used for wet mirror cleaning (reflectivity of collector surfaces washed with hard water was lower than of those left dirty);

-Flexhose and pump seal leaks were found to be safety/reliability hazards, causing two fires;

-Mechanical motor drives have to be of adequate quality (many drive motors and pump seals failed).

(b) IEA-SSPS. The experimental parabolic trough IEA-SSPS farm plant was designed for 500 kW. net generation at 920 W/m2 irradiation at equinox noon (Fig. 7.3). For side-by-side performance comparison, two different collector types were installed in three collector fields. For the same reason, two thermocline storage vessels, one with dual media, were incorporated and provided storage capacity equivalent to 0.8/0.37

MWhe. A steam turbine generator was. selected in preference to an ORC-based power conversion subsystem. One collector field consisted of one-axis tracking collectors with < 1 mm thin glass second-surface (S/S) sili mirrors glued onto a flexible steel substrate. The other two fields were made up of two-axes tracking modules, each carrying four line-focussing troughs formed of sagged-glass S/S silvere mirrors. The sagged-glass concept was used later in the design of the Luz solar coflector assemblies (see below).

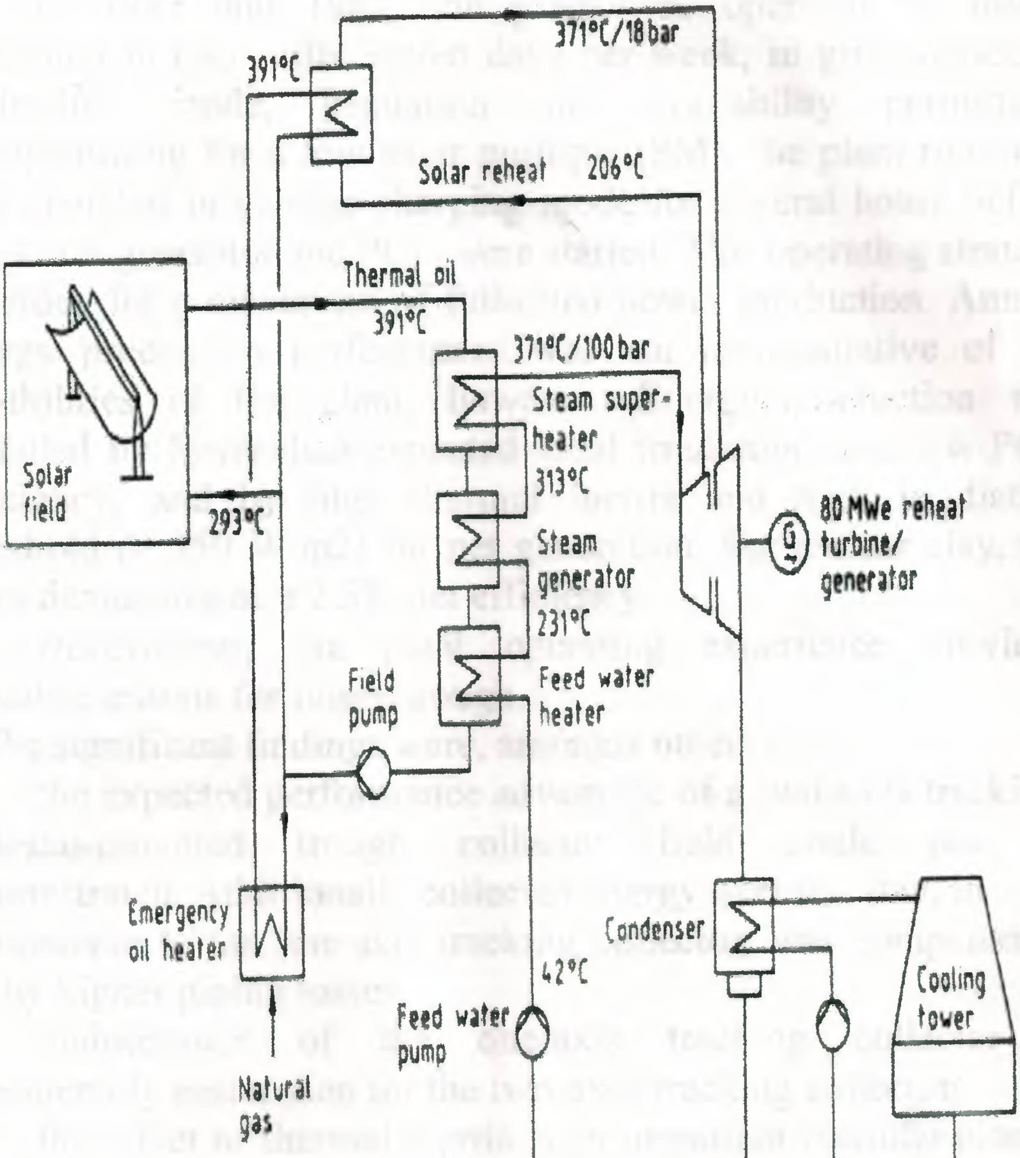


Fig. 7.4. Simplified system configuration of the 80 MW$_e$ solar electricity generating system (SEGS VIII), operational since 1989 at Harper Lake/CA, USA.

In 1982 and 1983, the plant was operated by utility personnel in two shifts, seven days per week, in grid-connected utility-like mode, insolation and availability permitting. Compensating for a low solar multiple (SM), the plant routinely was operated in storage charging mode for several hours before the steam generator and PCU were started. This operating strategy provided for a maximum of full-rated power production. Annual energy production performance was not representative of the capabilities of the plant, however. Energy production was curtailed by lower-than-expected local irradiation and low PCU efficiency, and by high thermal inertia and high irradiation threshold (> 350 W/m2) for net generation. For a clear clay, the plant demonstrated a 2.5% net efficiency.

Nonetheless, the plant operating experience provided valuable lessons for future trough
SPPs; significant findings were, amongst others :

• the expected performance advantage of a two-axes tracking, pedestal-mounted trough collector field could not be demonstrated. Additionally collected energy over one day, in comparison to the one-axis tracking collector, was compensated for by higher piping losses;

• maintenance of the one-axis tracking collector is considerably easier than for the two-axes tracking collector;

• the effect of thermal inertia is an important consideration to be included in plant sizing and performance analysis at the design stage;

• plant performance decreases sharply as compared to rated performance if irradiation is less than assumed for the design point;

• degradation of black-chrome absorptive coating on receiver tubes does not necessarily affect the output performance of collectors;

• flexhose, seal, joint and weld leaks leading to oil spills can be a significant maintenance factor (and environmental hazard).

c) 80 MWe Solar electricity generating systems (SEGS). Taking the advantage of Federal/State tax benefits and of purchase agreements made possible by the Public Utility Regulatory Policies Act (PURPA), a series of plants based on one-axis trough collectors has been placed in operation in the service area of Southern California Edison Co. (SCE)/CA, USA (Fig. 7.3).

Each plant is structured as a third-party financial venture so as to maximize the value of tax benefits and the cash flow from electricity sales under negotiated or standard purchase agreements with SCE. Plant annual performance is guaranteed by the manufacturer.

The solar collectors were developed by Luz Industries (Israel), building effectively on the experience accumulated in the U.S. and in Europe (e.g. IEA-SSPS) and forging them into a family of commercially marketable trough solar collector assemblies. These collectors progressed to ever larger trough apertures, higher concentration ratios and improved absorber emissivities. Routine hybrid operation of the SEGS plants renders it difficult to determine their performance in solar-only operating mode from output statistics. One approach is to estimate coarsely the energetic value of the solar contribution in the hybrid input energy by the prorating of output according to the heat supplied from the fossil boiler and the solar field without consideration of the supply temperature. The solar performance improvement achieved in the more recent plants is apparent.

Although SEGS development started from an advanced state of trough collector development, a number of operational problems were encountered (and were corrected) in the first two facilities. Staggered deployment of the series of SEGS plants carried out by one industrial supplier led to improved subsequent plants by applying the lessons learned, resulting in rapid and effective technology advance. Other key findings:

- leakage or failures of fiexhoses, welds and pump/valve seals were the cause of a signilicant number of major oil leaks and fires, leading to subsequent design and component refinements;
- significant efficiency gains are attributable not only to improved solar collector assemblies, but also to the adaptation of the cycle configuration and the turbine-generator power block to the operating conditions of the SEGS plants;

• quality assurance during manufacture and field installation, and usc of quality equipment, arc more important than low investment cost.

1.3 COLLECTOR SUBSYSTEM

Several of the trough collectors underwent testing and were investigated at several R&D institutions, e.g. at Sandia National Laboratories, Albuquerque/NM, or were employed in thermal SPPs or experiments.

The IEA-SSPS project in Almeria tested and evaluated in detail the relative performance of fields of 1- and 2-axes tracking collectors with the objectives to

• compare their long-term performance;
• compare behavior of steel-sheet-laminated thin-glass mirrors (0.6 mm) with second-surface-silvered sagged-glass mirror reflectors;
• gather system-related experience with trough collectors using black-chromium or black-cobalt-based selective receiver coating, swivel-joint or flexible-hose pipe interconnections, and open- versus closed-loop subsystem control.

Key results were, that

- a single 2-axes tracking collector unit, its aperture always oriented normal to incident irradiation, absorbs up to 30% more thermal energy than a 1-axis tracking, E-W oriented collector assembly (Fig. 7.5).
- when interconnected in a field set-up, the higher energy collection potential of two-axes tracking collectors shows up only at high irradiation levels; major reasons are. higher thermal losses due to longer/more complex field piping and a large number of piping supports (Fig. 7.6);

- in terms of optical performance and physical ruggedness, thin-glass-on-metal reflecting surfaces proved as effective and robust as thick sagged-glass mirrors.
- periodic removal of air-transported dust/grime deposits from mirror surfaces is essential for maintaining reflectivity and collector field performance, cleaning intervals being dependent on local air quality and/or seasonal sandstorm occurrences ,Fig. 7.7.

Polymer-based second-surface-silvered reflecting surfaces on steel substrates, which proved optically effective at Coolidge, are lightweight with the promise of lower cost; however, long-term performance and durability are not yet established.

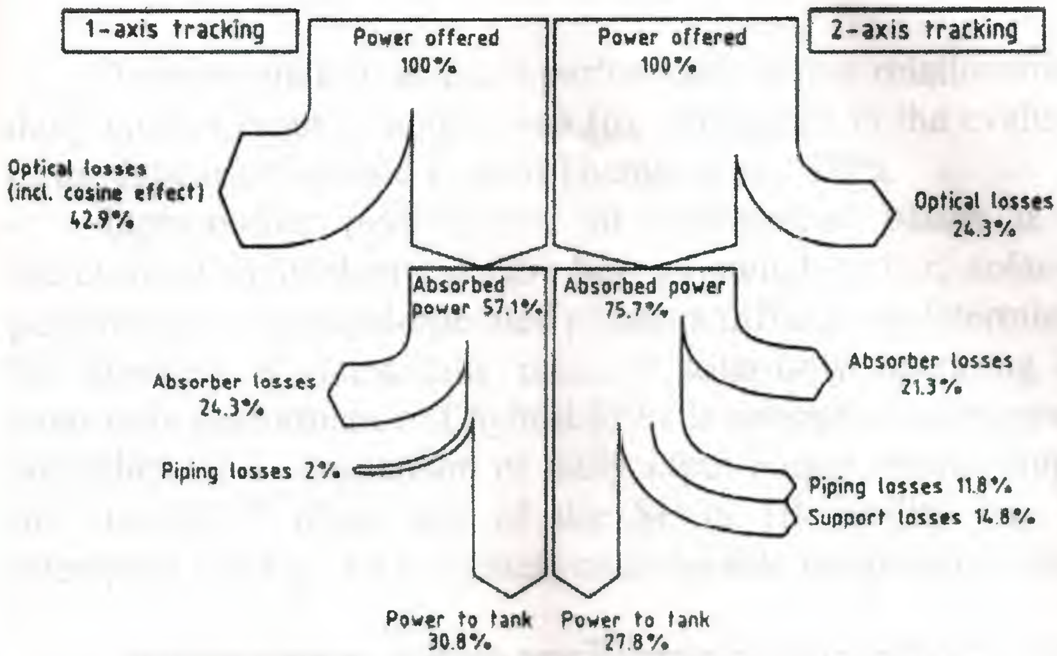


Fig. 7.5. 24-hour performance of 1-axis (Acurex 3001) and 2-axes (Helioman 3/32) tracking parabolic trough collectors over an arbitrary day with about 6 kWh/m²d of direct normal irradiation at Almería, Spain [30].

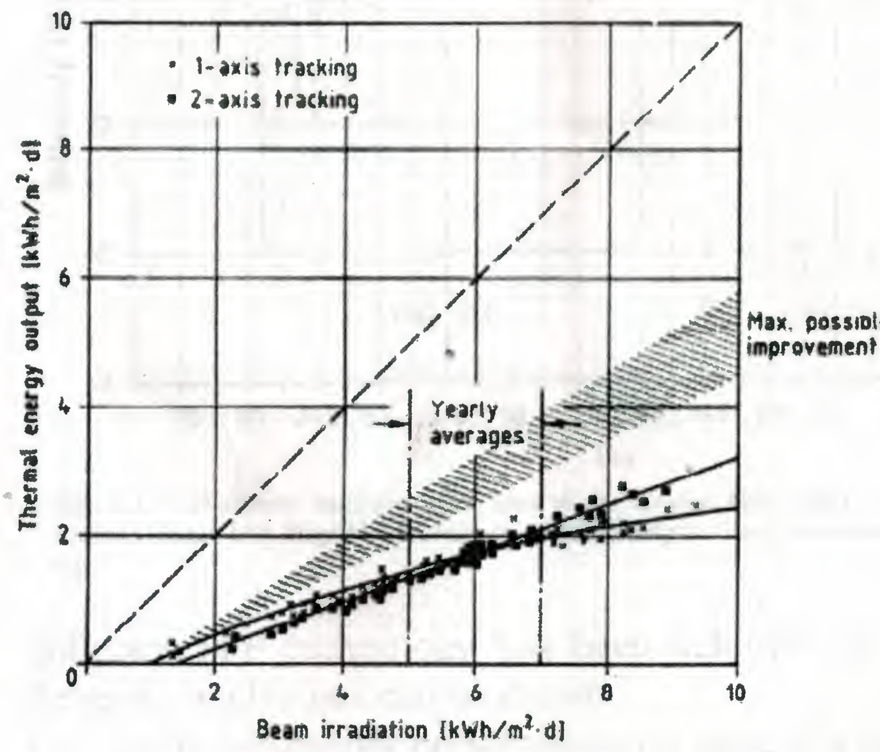


Fig. 7.6. Daily input-output performance of 1-axis (Acurex 3001) and 2-axes (Helioman 3/32) tracking parabolic trough collectors for different levels of total direct normal irradiation at Almería, Spain [30].

1.4 PLANT PERFORMANCE CHARACTERISTICS

A determination of plant performance using relationships of daily energy input to output was first attempted in the evaluation of the Japanese Nio and French Themis tower SPPs.

- Input-output performance of commercial plants is also increasingly published (SEGS) but, as stated earlier, solar-only performance of hybrid-operated plants is difficult to determine. In the absence of statistically relevant solar-only operating data, solar-only performance of hybrid SPPs is subject to interpretation. Nonetheless, a comparison of daily input-output relationships of the IEA-SSPS plant and of the SEGS III facility has been attempted ; as Fig. 7.8 indicates, considerable progress in trough

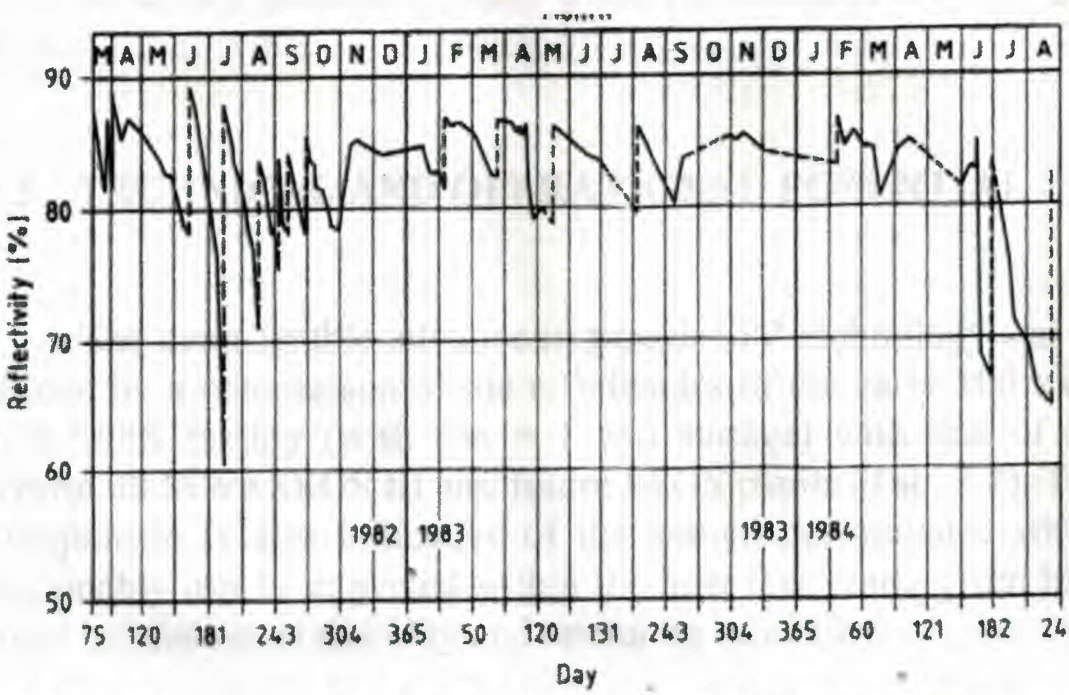


Fig. 7.7. Reflectivity variation with time of the Acurex Mod. 3001 parabolic trough mirror collectors at Almeria, Spain [30]. Rapid improvements of reflectivity indicate occurrence of precipitation or heliostat washing.

collector SPP technology has been achieved in the past years. Several conclusions can be drawn:

- daily net energy performance on system level was improved from 4-6% to about 12%, primarily by minimizing non-active pipe length, higher CR, reduced thermal losses of receivers (vacuum insulation), and high collector field availability (in the 97—99% range for SEGS Ill—V);

• minimum daily energy input needed before producing net output did not change significantly; it is argued that a threshold of 2.5—3.5 kWh/m2d of daily direct normal irradiation (at SM = 1.0) is a technology-specific constraint for trough SPPs irrespective of capacity.

Net output performance is improved (indicated by a steeper slope of the input-output curve) by yet higher efficiency of the thermodynamic cycle. Such refinement measures have in fact been undertaken for the SEGS plants. Starting with SEGS VI, a power conversion subsystem (power block) was installed which was specifically adapted to the SEGS operating conditions. As a consequence, the collector field size could be reduced by about 20% (affecting predicted yearly plant performance by only 1—2%).

1.5 TECHNICAL AND OPERATIONAL POTENTIAL

The considerable advance in trough SPP technology can be shown by a comparison of the efficiencies of the early 500 kW~ IEA-SSPS facility (with SM = 1 and storage) with that of the hybrid 30 MWe SEGS III and future SEGS plants (Tab. 7.7). This comparison is also indicative of the annual performance which reasonably can be expected within the next few years, given high local irradiation availability and operating reliability.

In summary, the following observations seem valid:

• early SPP facilities, lacking previous operating experience, were designed optimistically, actual performance falling short of expectations;

• collector and collector field performance improved significantly, from about 28% over a day with ‘good’ irradiation in the IEA-SSPS facility, to about 57% annually in the 30 MWe SEGS III plant; this improvement is attributable as much to refined operating strategies as to better design, reliability and operational availability of today's collectors and collector fields;

- thermodynamic cycle efficiency was increased by virtue of higher operating temperatures, by longer periods of steady-state cycle operation, and by adaption of off-the-shelf PCU equipment to solar-specific operating conditions;
- internal parasitic energy requirements in operation and stand-by are critical for perforinance and must be minimized.

Commercial opportunities created by federal and state legislation in the U.S. provided the impetus for the rapid succession of the SEGS family of solar plants — and continue to do so. While the first plants (SEGS I and II) had difficulties in meeting performance targets/projections in the early years of operation, all subsequent plants (SEGS III and beyond) met targets and even exceeded projections in the first year. Instrumental for this was the fossil-fueled heater which was originally introduced mainly for meeting contract performance guarantees independent of weather or time. The fossil heater, however, soon became a key element for improving plant performance (by superheating of solar-produced steam; by avoiding part-load operation in winter), and for maximizing annual revenues (45% of annual revenues but only 18% of annual energy are produced during summer on-peak periods). For this reason, all SEGS plants are tuned for peak performance during summer on-peak periods, typically exceeding rated performance (30 MWe) for most of the day from April to September (Fig. 7.10).

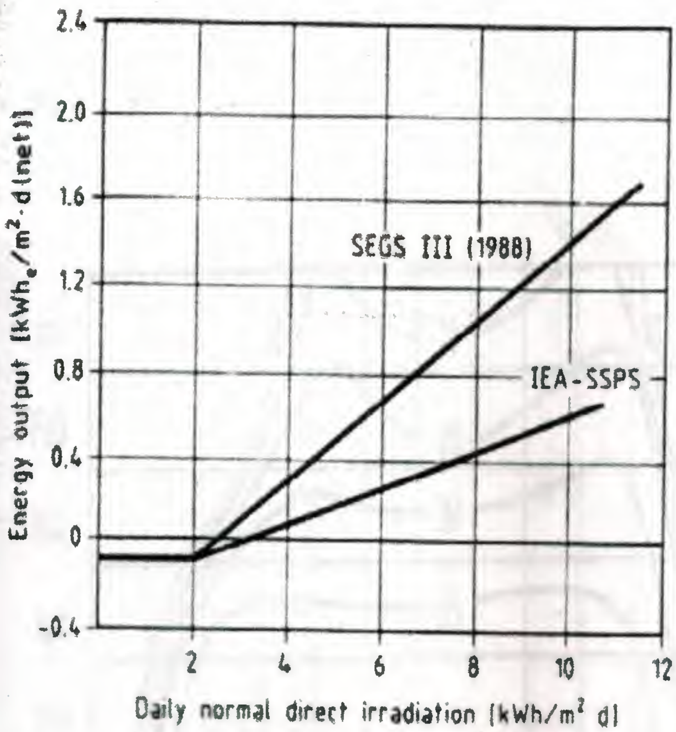


Fig. 7.8. Performance comparison of daily energy input to net output of the IEA-SSPS facility at Almeria, Spain and of the 30 MW$_e$ SEGS III plant at Kramer Junction/CA, USA in solar-only operating mode [29].

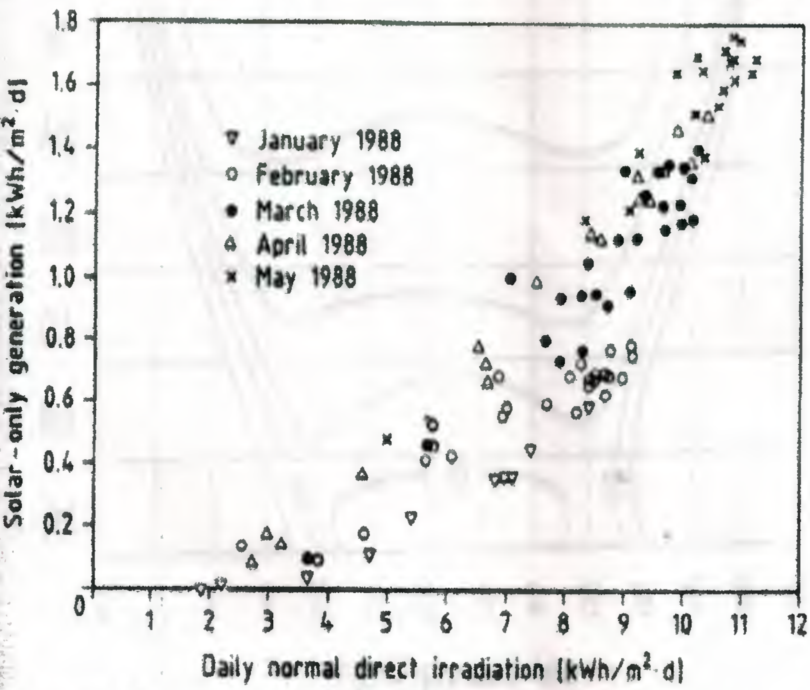


Fig. 7.9. Solar-only input/output data (Jan–May 1988) of the 30 MW$_e$ SEGS III plant at Kramer Junction/CA, USA [28]

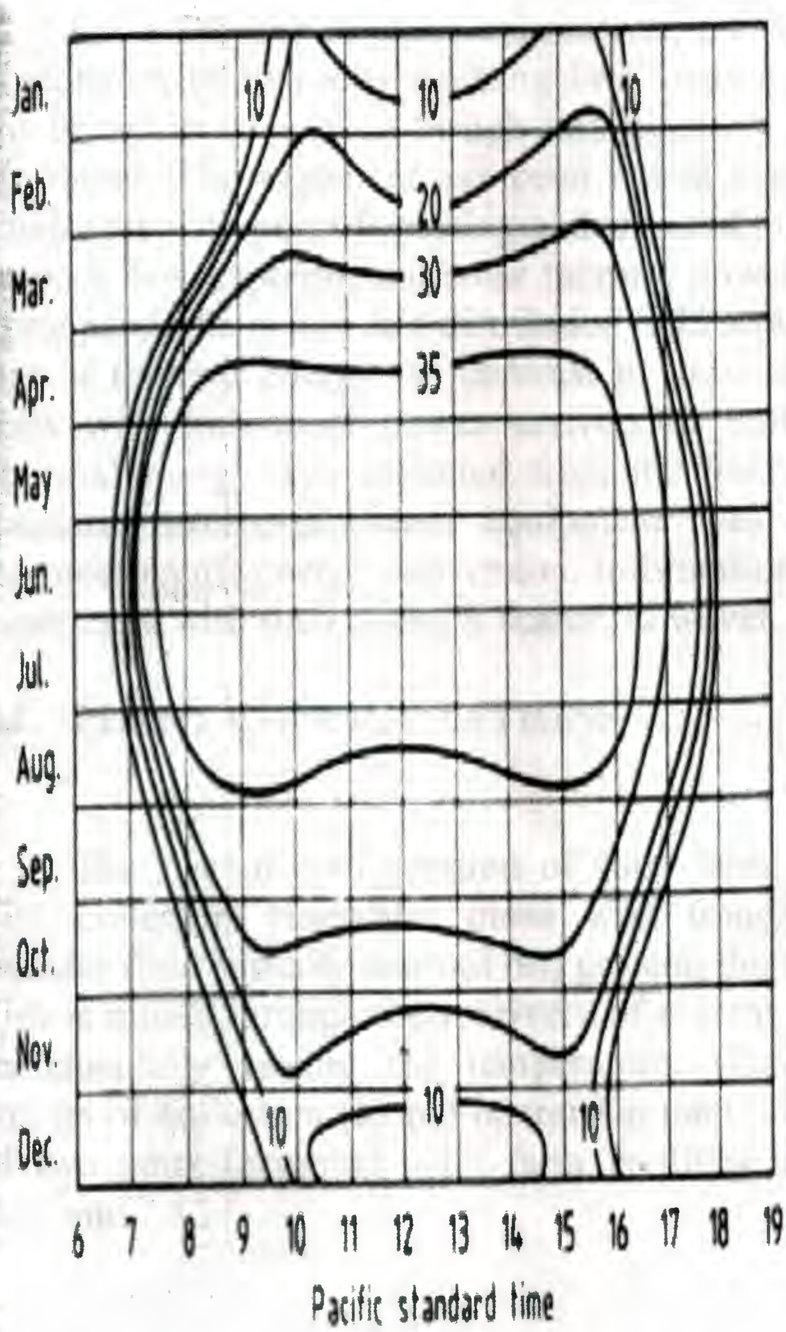


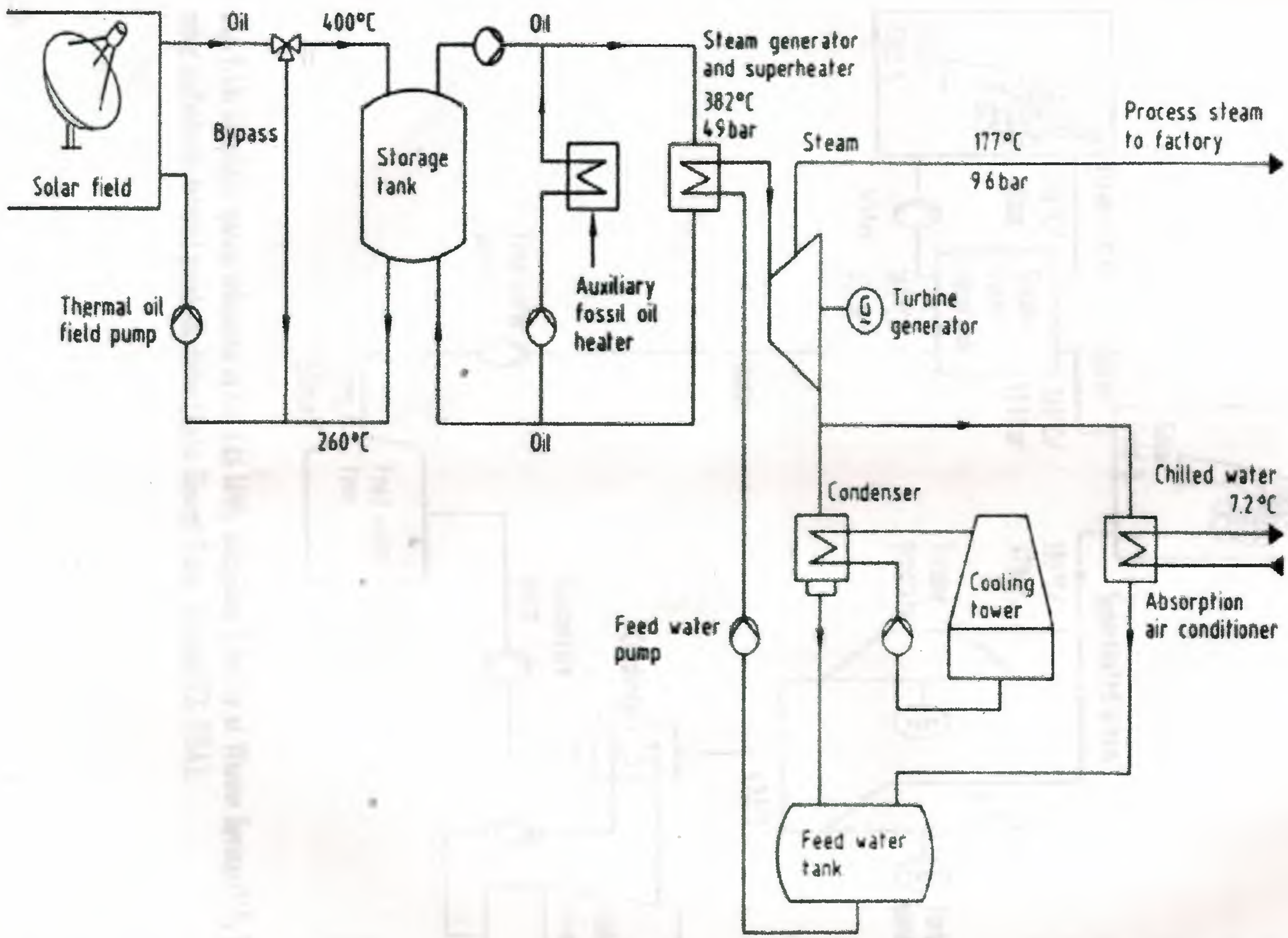
Fig. 7.10. Contour plot of gross solar-only electricity production of a typical 30 MW_e SEGS power plant under irradiation conditions of the Mojave Desert/CA, USA [40]. Parameter is peak plant output (in MW_e) which can be achieved under average irradiaton conditions.

2. FARM SOLAR POWER PLANTSWITH POINT-FOCUSSING COLLECTORS

For a number of technical reasons, the higher performance expectation of two-axes tracking line-focussing collectors could not be achieved with a trough configuration of moderate concentration. The argument has been raised that better results are obtainable with point-focussing collectors of higher concentration ratio. A few experimental solar thermal power plants were built using parabolic dishes in a distributed field arrangement as collectors of thermal energy (in contrast to individual parabolic dish units with individual power conversion units for each dish). Thermal energy was collected from the field of collectors, and standard turbine-generator equipment was used for central thermodynamic energy conversion. Information about operational experience with such plants is scarce, however.

2.1 PLANT CONFIGURATIONS

The system configuration of solar farm power plants with dish collectors resembles those with trough collectors. Heat transfer fluid (usually thermal oil) passing the receiver of the first dish is routed through the receivers of several subsequent dishes, incrementally raising the temperature. Usually, several such strings of collectors (loops) operate in parallel. System diagrams of two point-focussing solar farm facilities are shown in Figs. 7.11 and 7.12.



'ig. 7.11. Simplified system schematic of the cogenerating 400 kW_e/468 kW_t point-focus Solar Total Energy Project (STEP) at Shenandoah/GA, USA (built and perated in partnership between U.S. Department of Energy and Georgia Power Company).

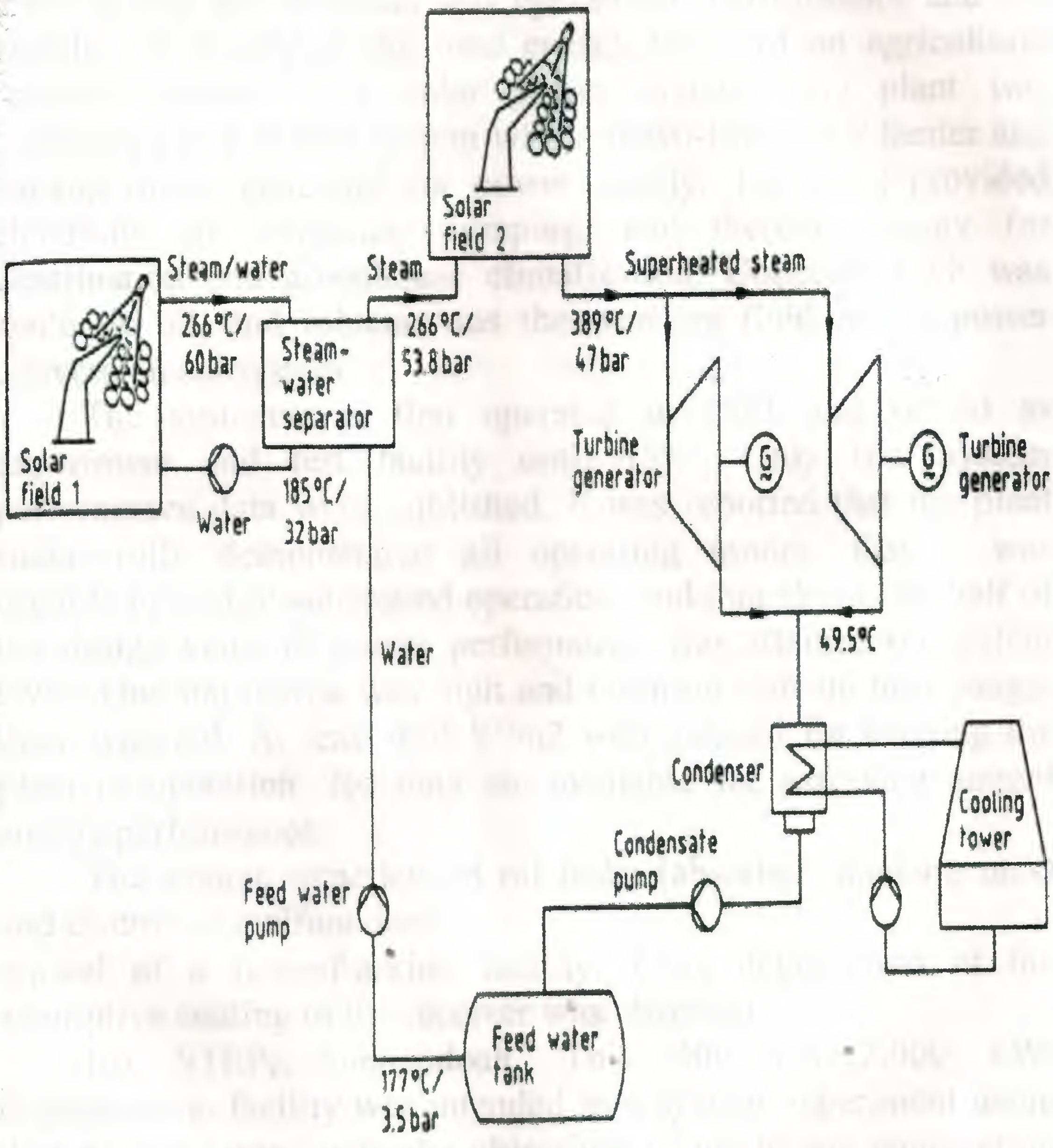


Fig. 7.12. Simplified system schematic of the 4.88 MW, Solarplant 1 facility at Warner Springs/CA, USA, using individually-facetted parabolic dishes (LaJet Energy Corp., Abilene/TX, USA).

2.2 SYSTEM EXAMPLES

(a) Sutaibyah, Kuwait. The 100 kWe/400 kWt Sulaibyah facility was designed and intended as an experiment for investigating the technical and operational performance and the viability of supplying the total energy needs of an agricultural research station by a solar power system. The plant was configured as a hybrid system with a fossil-fired HTF beater and backup diesel generator for power supply. The plant provided electricity for irrigation pumping, and thermal energy for desalination and greenhouse climatization. Collector HTF was synthetic oil, and toluene was the working fluid in the power conversion subsystem.

The system was first operated in 1981 and served as experiment and test facility until 1987. Only few system performance data were published. It was reported that the plant successfully demonstrated all operating modes, that it was capable of highly automated operation, and that about one half of the design value of power performance was attained on system level. Thermal inertia was high and morning start-up time longer than expected. At least 400 W/m2 were needed for keeping the plant in operation. No data are available for assessing annual energy performance.

The system experienced oil leaks (absorber, tracking unit) and electronic malfunctions
typical of a first-of-a-kind facility. Also, degradation of the absorptive coating of the receiver was observed.

(b) STEP, Shenandoah. This 400 kWe/2,000 kWt cogenerating. facility was intended as a system experiment using dish concentrators, with the objectives of producing engineering and development experience, and of determining the interaction of a total solar energy supply system in an industrial user environment (Fig. 7.11). The plant was started up in 1982. The solar energy collected was experimentally used to determine to what degree the electrical air conditioning and process steam requirements of an industrial host could be met.

Oil as HTF is used to collect and to transport the absorbed energy from the dish collectors. The thermal energy coming from the field is supplemented with thermal energy from the gas-fired HTF heater. Superheated steam, produced in a steam generator, drives a conventional turbine/generator set. Steam extracted from the turbine provides process steam, and the low pressure exhaust steam is used as input for an absorption chiller which produces chilled water.

The plant is routinely started using the gas-fired boiler, which provides all thermal energy needed initially. The heater also is used to warm up the HTF which is circulated through the collector field until operating temperature is reached. Output from the field and the heater are then combined for generating steam. The facility operates in a hybrid mode from this point on. For meeting thermal and electric load demands, the heater output is adjusted so as to cover any deficit in thermal energy in case the collector field provides less than required. The plant can also operate in a solar-only mode, but a capacity mismatch between the collector field and the power conversion subsystem results in continuous part-load operation and associated low performance of the entire system.

Although STEP performance was below expectations, the experiment provided experience and data of value:

- auxiliary heaters are more efficient when placed in the steam loop rather than the primary heat transfer circuit;
- part-load efficiency of the heater is also an important system design issue;
- all weather-exposed components of the system must be qualified for local conditions (for example rain soaked the thermal insulation of the small cavity receivers and led to corrosion and leaks of the carbon-steel receiver tubes.).
- depending on temperature control capabilities, adequate margins must exist between the nominal system operating temperature and upper temperature limit of the HTF (STEP operating temperatures had to be reduced because of local HTF overheating);
- delamination of reflective polymer films from aluminum substrates in a moist environment remains a serious issue;

- adequate reliability of all components of the plant system is an important requirement for achieving adequate SPP availability.

(c) Solarplant 1, Warner Springs. This nominally 4.88 MWe SPP (Fig. 7.12) was privately financed and built, and is operated within PURPA provisions. The plant uses 700 of the Lajet LEC-460 dish concentrators with cavity receivers. Water is used as primary HTF, being evaporated in a field segment of 600 collectors and superheated from 276 C to 371 C in the remainder of the field. Power conversion is split into two turbines with 3.68 MWe and 1.24 MWe rating; the smaller PCU is used during start-up and shut-down, during periods when irradiation is too low to operate the main PCU, and whenever peak/excess energy becomes available. Annual (design) performance is 12 GWhe/a.

The innovative LEC-460 dish collector is of lightweight construction and uses polymer-based stretched membrane reflector segments, with the provision to replace easily these membranes several times during the life of the plant.

Solarplant 1 went on line in 1985. It is claimed that the plant averaged 106% of projected output over a seven-day test period with all collectors on line, but performance data are not published. Significant equipment problems and operational probletns with the steam loop were reported, associated particularly with daily cycling and start-up. The start-up time is stated as 30—60 minutes for consecutive operating days, but up to half a day alter an extended shut-down period. The value of Diesel generators for assuring a mimimum level of supply was experimentally investigated for the first time for a thermal SPP, using the recovered exhaust heat to keep headers and turbine warmed-up.

2.3 PLANT PERFORMANCE CHARACTERISTICS

Of the farm-type dish solar systems, multi-day performance data were published only for the STEP system. However, as

STEP represents a very early stage of SPP development, the performance is merely illustrative, but by no means conclusive, of the potential of a mature system of similar type at locations more favored with direct irradiation than Shenandoah/GA.

STEP operated continuously over ten and thirty consecutive-day periods during the summer of 1985 to determine solar contribution, capacity factor (CF), operations and maintenance (O&M) costs, and standby losses when keeping the system operational over several days. During these test periods, the plant supplied the entire daily electrical and thermal energy needs of the industrial host, both from solar input (irradiation permitting) and from the gas heater. Despite 50% radiation-to-thermal conversion efficiency and > 95% operational availability of the collector field, significantly less solar energy than expected was collected and made available. This is attributed, mainly, to lower.than-average and highly transient irradiation during the test periods. Regression analysis of daily thermal energy input-output performance of the collector field (Fig. 7.15) suggests that about 2.5 kWht/m2d of direct normal irradiation must be accumulated before achieving net output from the collector field. This value exceeds by far the amount of thermal energy needed for heating up the plant from ambient temperature; hence, the remainder must be attributed to thermal losses and parasitics .

The experimental attempt to satisfy all energy needs of an industrial user by a hybrid thermal SPP demonstrated some key facts of fundamental significance. During the tests, much fossil energy was expended to keep the solar facility operational so that the energy demand of the user could be satisfied without delay. The amount of natural gas consumed for that purpose was significantly higher than the energy needed if the industrial demands were covered conventionally. Keeping the solar system warmed up by the auxiliary heater, irrespective of the contribution ability of the solar field, is ineffective (Fig. 7.16).

If no flexibility exists to adjust user energy needs to local solar irradiation conditions, advance analysis is mandatory to determine whether demand can indeed be totally satisfied from solar in terms of energy (and cost). The effects of parasitic loads, plant availability, solar availability and integrated system performance are key considerations in this context.

2.4 TECHNOLOGICAL AND OPERATIONAL POTENTIAL

Operating experience with dish farm SPPs provides little basis for extrapolating technical and operational potential of future mature systems. Assessment of physical arguments is the only means for an evaluation.

The advantage of dish collectors (i.e. high concentration and temperature) does not r ally pay off in a farm configuration, mainly because the physical potential of high operating temperature cannot be exploited due to the low upper temperature limits of thermo-oils As already shown with trough thermal SPPs, this deficit cannot be compensated for by th inherently higher energy yield with 2-axes tracking dishes when compared to 1-axis track lug trough collectors. This situation may have to be reassessed if the development efforts for using water/steam as a primary heat transfer medium prove successful (Solarplant 1) As water/steam is also considered as primary HTF in future trough collector SEGS plants,

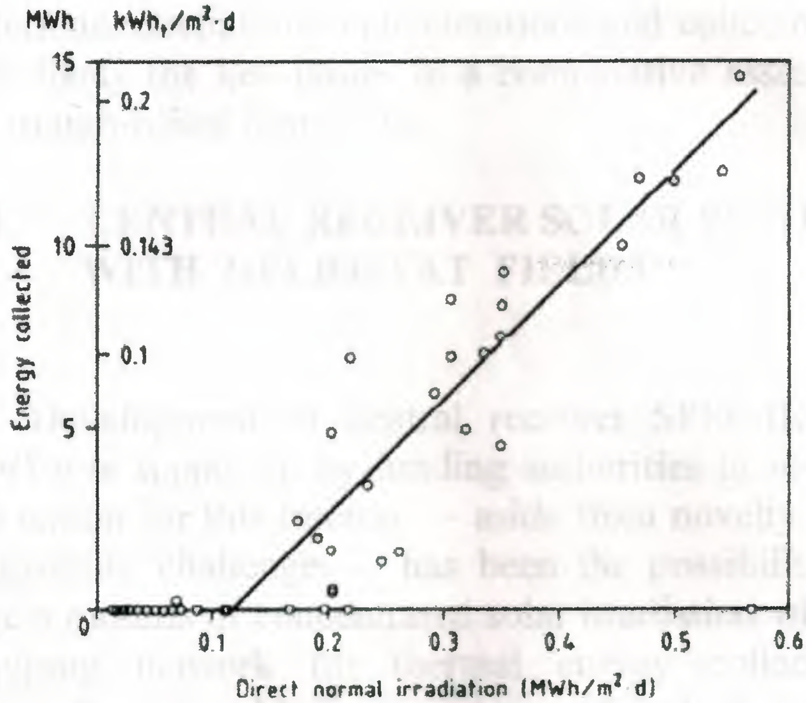


Fig. 7.15. Collector field input-output perfomance of the 400 kWe/483 kW_t parabolic dish (C = 235) Solar Total Energy Project (STEP), Shenandoah/GA, USA. [67]

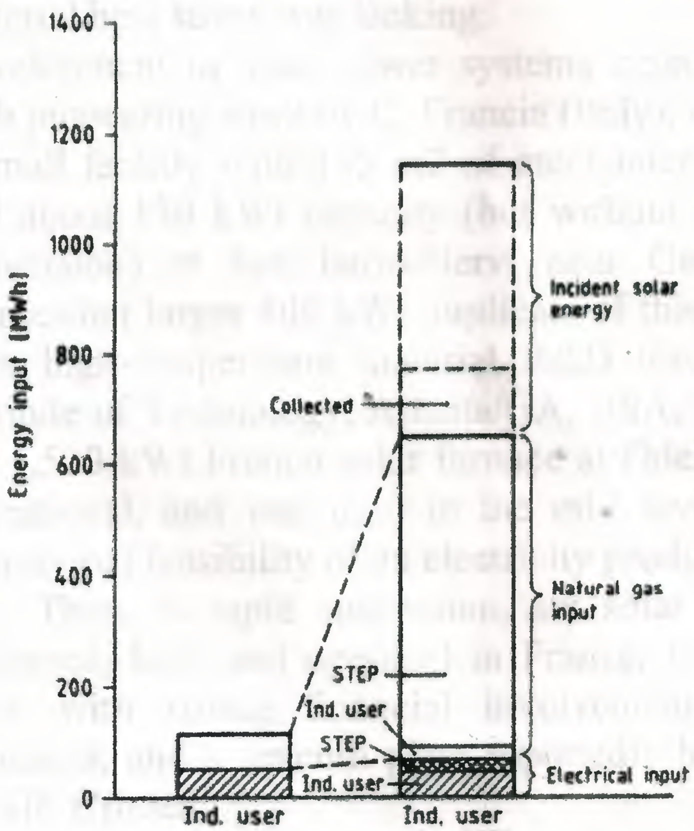


Fig. 7.16. Gas use when cogenerating electricity and thermal energy in response to supply needs of an industrial user; 400 kW_e/483 kW_t Solar Total Energy Project (STEP), Shenandoah/GA, USA [67].

performance/reliability considerations and collector field cost are most likely the key issues in a comparative assessment of dish- and trough-based farm SPPs.

3. CENTRAL RECEIVER SOLAR POWER PLANTS WITH HELIOSTAT FIELDS

Development of central receiver SPPs (tower SPPs for short) was supported by funding authorities in several countries. The reason for this interest — aside from novelty of concept and engineering challenge — has been the possibility of collecting large a.rnounts of concentrated solar irradiation without requiring a piping network for thermal energy collection, and the expectation of achieving economy-of-scale benefits in system sizes approaching those of utility power plants. The R&D interest evolved because the system design was complex, and prior experience with high irradiation flux conditions and associated material heat stress was lacking.
Development of solar tower systems began in the early sixties with pioneering work by C. Francia (Italy); until 1975 he operated a small facility with 135 m2 of mechanically controlled mirrors and about 130 kWt capacity (but without thermodynamic cycle conversion) at San llario-Nervi near Genoa, Italy. In 1978, asomewhat larger 400 kWt duplicate of this facility was installed as a high-temperature material R&D test bed at the Georgia Institute of Technology, Atlanta/GA, USA. In the early seventies, the 1,500 kWt French solar furnace at Odeillo, Pyrenees became operational, and was used in the mid seventies to demonstrate operational feasibility of an electricity producing cycle (64 kWe).

Then, in rapid succession, six solar tower facilities were projected, built and operated in France, Italy, Japan, Spain and USA with strong financial involvement of respective governments, and a seventh plant reportedly began operation in the USSR, Crimea .

3.1 PLANT CONFIGURATIONS

Approaching utility power plants in nominal rating, the 10 MW. Solar One configuration at Barstow/CA, USA was of single-loop design, employing water/superheated steam as the primary heat transfer medium and as working fluid in the power conversion cycle (Fig 7.19).

Water is preheated in two steps, evaporated and superheated in a once-through external receiver. A dual-medium (oil/rocks) thermal storage can be charged/discharged via steam/oil heat exchangers. Heat supply for the steam turbine can come from the receiver directly, or from storage via a steam generator (at degraded steam conditions), or both simultaneously.

Two experimental tower SPPs employed dual-loop heat transport concepts using a liquid as primary coolant. Primary HTF was eutectic salt in the 2.3 MWe Themis plant at Targasonne/France, and sodium in the IEA-SSPS 500 kWe tower plant in Almeria, Spain. Compared to single-loop and once-through water/steam configurations, the dual-loop concept allows higher receiver heat fluxes yet reduces cycle fatigue stress of the receiver material, i.e. subjecting it to lower internal pressure and avoiding quenching effects by oscillating water columns.

Being good thermal conductors, hot and cold molten salts/metals must be stored in separate vessels if used as a heat transfer and storage medium (as exemplified by the Themis
Being good thermal conductors, hot and cold molten salts/metals must be stored in separate vessels if used as a heat transfer and storage medium. Using molten salt/metals as primary lITF and a dual-tank arrangement for storage, intermediate heat exchangers and associated losses arc avoided, plant controllability is improved, and power-conversion is effectively decoupled from front-end solar energy input.

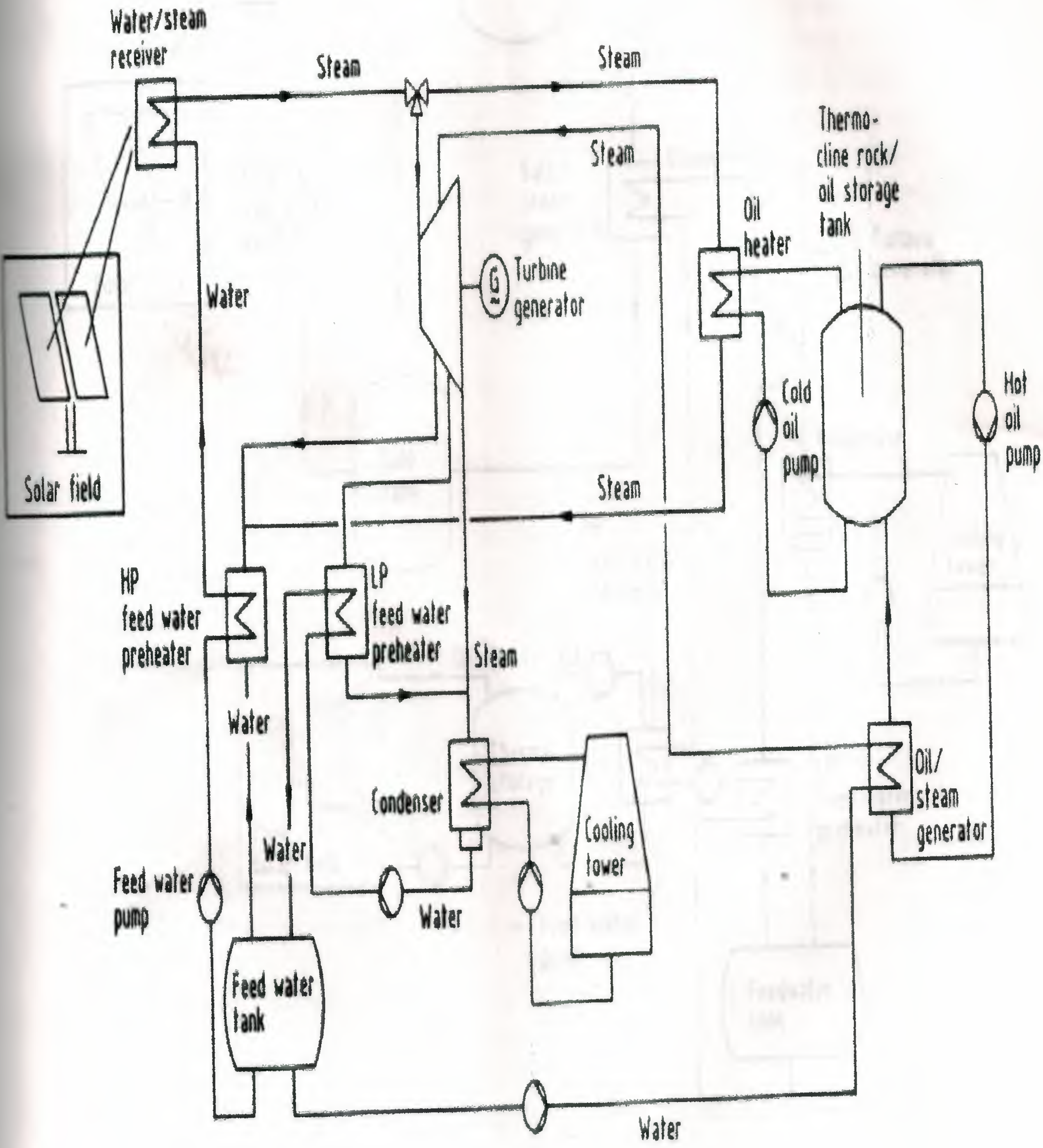
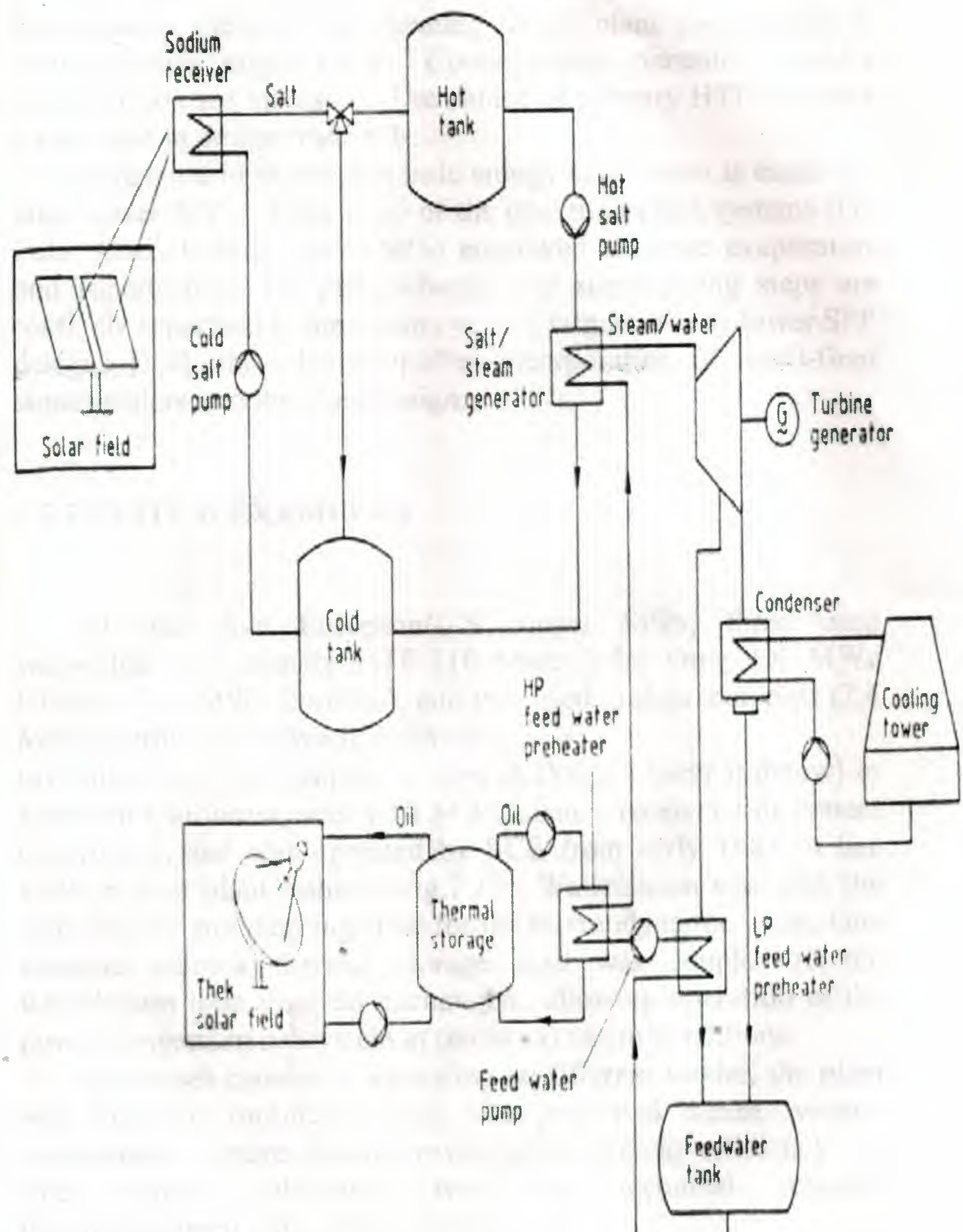


Fig. 7.19. System diagram of the Solar One 10 MW_e pilot tower SPP at Barstow/CA, USA.


Sodium
receiver
Salt
Hot
tank
Hot
salt
pump
Cold
salt
pump
Solar field
Salt/
steam
generator
Steam/water
Turbine
generator
Cold
tank
Condenser
Cooling
tower
HP
feed water
preheater
Oil
Oil
Thermal
storage
Thek
solar field
LP
feed water
preheater
Feed water
pump
Feedwater
tank

The drawback is that salts and metals solidify well above 100^0C, necessitating electric trace heating of all plant components in which liquids might freeze. Consequently, parasitic stand-by energy needs are increased. The choice of primary HTF becomes a key issue in design trade-oils.

Optimization of thermodynamic energy conversion is easier for large tower SPPs. While none of the operating plant systems (i.e. Solar One, Themis, IEA-SSPS) employed separate evaporators and superheaters, the phase-change and superheating steps are routinely separated in the steam cycle of large-capacity tower SPP designs [1,4]; this also simplifies incorporation of fossil-fired super-heaters into the plant design.

3.2 SYSTEM EXAMPLES

Of the five European/U.S. tower SPPs, three used water/steam as primary HTF (10 Mwe Solar One; 1.0 MWe CESA-1; 1.0 MWe Eurelios), and two used molten materials (2.4 MWeThemis; 0.5 MWe IEA-SSPS).

(a) Solar One. This project, located at Daggett (near Barstow) in Southern California, was a 10 MWe central receiver full system experiment, and was operated by SCE from early 1982 to late 1988 in pilot plant fashion (Fig.7.19). Water/steam was both the heat transfer and working fluid for the thermodynamic cycle. One separate oil/rock thermal storage tank was coupled to the water/steam loop via heat exchangers, allowing operation of the power conversion subsystem at (reduced) steam conditions.

Although capable of operating in different modes, the plant was operated routinely using solar-generated steam without intermediate storage, thus improving annual energy efficiency. The storage subsystem was, for technical reasons, decommissioned after a fire incident.

Although annual energy production never reached design predictions, Solar One was the most successful tower SPP project so far. The long-term operation of the plant provided extensive data which were analyzed and evaluated, and which are most useful today for designing and assessing the performance of future tower SPPs. The size of Solar One and its utility-like operation rendered its performance less vulnerable to losses and parasitics which overshadowed the performance of the other smaller-sized experimental demonstration tower SPPs.

The wealth of information, experience and lessons learned from this pilot plant experiment has been comprehensively published [20~59,60]. Modelling and calculation codes for the design of tower SPPs were modified as a consequence of these data, providing the basis for all design studies currently undertaken (for instance the University of houston Solar Central Receiver Code System, or the SOLERCY code developed by Sandia National Lal)oratories see Sect. 7.8).

(b) CESA-1. The 1.0 MWe CESA-l project was also it full system experiment, located near Almeria in Spain; it. was intended to demonstrate the feasibility of this type of plant, and to develop the specific technology and industrial base for tower SPP components. The plant started operation in early 1983 and was operated umntil the end of 1984. Water/stcam was used as primary and secondary IITF, and molten salt as the storage medium in a two-tank configuration.

Designed to operate in six modes (direct, charging, discharging, direct and charging, direct and discharging, and buffered operation), the plant was operated only 324 Ii in grid-connected mode, producing about 130 MWh . The short duration of operation provided useful information applicable mainly to the specific plant design .

(c) Eurelios. Eurelios was a 1.0 MWe full system experiment located in Adrano, Italy. Its objective was to demonstrate the grid-connected operation of a tower SPP, and to gain data for technical and economic evaluation. Eurelios was the first tower SPP ever to be operated, being connected to the grid in the Spring of 1981. Operation continued through 1984.

The plant design incorporated a once-through water/steam receiver and a short-time buffer storage, using molten salt and a water/steam accumulator for steam superheating. Two types of heliostats of different size were used and were arranged in an East and West sector of a North field. A minimum irradiation of 450

W/m2 of direct normal irradiation, a. cloud cover <25%, no haze, and > 75% heliostat availability were specified.

Due primarily to the extreme pipe length of the receiver, total start-up of the plant required typically about 2 hours. On the other hand, heliostats were moved into stand-by position three minutes after irradiation had dropped about 20% below nominal insolation. Also, local irradiation was more affected by cloud cover than expected. The total gross electricity production of the plant was only about 130 MWhe, while parasitic power needs were higher (as compared to 14.5% efficiency prediction).

(d) Themis. The Themis 2.4 MWe tower SPP, located at Targasonne in the French Pyrenees, was intended to conduct full system- and subsystem experiments, and to demonstrate the feasibility of this type of thermal SPP for deployment in sunbelt countries. The plant became operational in 1983 and was operated for 3 years. Themis used molten salt as primary HTF and as a storage medium in a two-tank configuration. A steam generator linked the secondary conversion cycle ioop to the primary salt loop. This decoupled solar energy input and storage charging from power output generation., rendering plant operation more flexible. Thus, temporary drops in the collection of solar energy in the primary circuit hardly affected operation of the PCU at nominal cycle conditions.

Nominal operating procedure called for energy accumulation in the storage tanks until enough salt at sufficiently high temperature was available to sustain a rated output generation for 2—3 hours. Only at this point was the secondary circuit conditioned, the turbine started and power generated. Typically, three hours elapsed before adequate conditions for power production were achieved; about 45 minutes later, rated output power was attained, to be continued in the evening until storage was depleted to preset levels.

Themis performance was below prediction. Gross energy production was about. 650 kWhe/a on average, and net output was negative, due primarily to large parasitic loads.

However, the Themis experience produced some significant findings and conclusions :

the concept. of separating solar thermal energy generation from power production by intermediate energy storage was successfully demonstrated;

- although heliostats were seriously damaged by the breaking of pedestals in two bad wind storms, 95% of heliostat availability was demonstrated; no corrosion was experienced with laminated glass mirrors;
- the design/layout of the primary (salt) loop can be simplified, trace heating concepts need to be improved, and parasitic loads in stand-by mode need to be drastically reduced to improve net power generation.

(e) IEA -SSPS. The 500 kWe IEA-SSPS tower plant was a full system experiment conducted in parallel with the IEA-SSPS parabolic trough project, both experiments under IEA auspices. The IEA-SSPS is the only tower SPP using sodium as a primary HTF and storage medium. The objective was to demonstrate the viability of this concept, to determine operational characteristics, and to compare performance of the two IEA-SSPS plants. The plant was operated from late 1981 until August 1986.

It was a two-tank storage configuration like Themis. A sodium steam generator decoupled the secondary water/steam loop from the primary sodium circuit. A steam motor was chosen as PCU.

The plant started operation after reaching levels> 300 W/m2 of direct normal irradiance. After circulating through the receiver and reaching 500 C, sodium was accumulated/stored for about 2—4 hours in the hot tank. With hot storage sufficiently charged, the steam generator, the power circuit and steam motor were conditioned and output produced about 30 minutes later. Power generation continued until the hot tank was depleted to a minimum level.

Equipment outages and operating complications limited the ability to accumulate longterm system-level performance data. A combination of factors contributed to this situation such as high thermal inertia, SM = 1.0 despite storage, high-quality steam requirements for steam motor operation, and substantial parasitics. This situation was extensively analyzed and ways for plant improvement were determined. Design deficiencies were identified which, if avoided, would improve start-up and performance. Total gross production of the plant amounted to about 80 MWhe. The project produced a number of important results and accomplishments:

- the technical feasibility and excellent component-level performance of a high-flux sodium receiver were demonstrated; predicted receiver performance were reached;
- the reliability of trace heating elements is not sufficient to support reliable SPP operation when using HTFs with a freezing temperature > 100 C; repair/replacement of trace heating elements is difficult and tedious;
- high standards of quality control and assurance are essential to avoid hazards and costly O&M associated with sodium equipment.

3.3 HELIOSTAT AND HELIOSTAT FIELD

Development history and outlook of heliostats (Fig. 7.21) indicate a trend from early rigid and heavy constructions with second-surface glass mirrors to lightweight low-cost constructions with front-surface-silvered polymer foil reflectors. Presently, two development lines are followed towards low-cost solutions, (a) the large-area glass-facctted configuration (150 m2) with correspondingly lower specific costs for support structures and drive tiaifl for a field of many heliostats, and (b) the so-called stressed membrane design (i.e. thin metal membranes stretched over front and rear of a circular supporting ring, the front surface being covered by reflective films or thin-glass mirror facets). Prototypes of such heliostats are currently being tested for performance at the CRTF and PSA test sites.

Via experimental tower SPPs, operational experience was gained with fields of glass-mirror heliostats, and with heliostats with as much as 65 m2 of reflective surface (about 3,ooo units in total with about 132,000 m2 surface). This experience represents about 50 Mio million of heliostat operation.

Operational availability of the Solar One heliostat field remained above 96% in the yearly average (up to 99.7% per month), and averaged above 90% in all other tower SPPs operated routinely for extended time periods. However, due to inadequate grounding control, the electronics of heliostat units, subfields or the entire field proved vulnerable to damage by lightning effects (IEA-SSPS; Themis; Solar One), causing plant outages of several days (up to 15 operating days at Solar One).

As high optical reflectivity is a key factor for optimum plant output performance, comprehensive reflectivity degradation measurements by soiling were carried out for the locations at Solar One (Barstow) and IEA-SSPS (Almeria). Experience shows that mirror cleaning is unavoidable. Frequent washing can keep average reflectivities at 95%, requiring about 2% of heliostat investment cost annually for such maintenance. Need and frequency for washing depends on local environmental conditions. Rain, if it occurs, effectively assists in rinsing off dust but is less effective in removing grime. Hence, cost-effective methods and procedures for the cleaning of reflective surfaces is an important issue when operating large tower SPPs.

Corrosion of the mirror reflective layer also was observed at Barstow and Almeria. The corrosion growth rates and underlying causes were attributed mainly to moisture entering through protective paint layers and imperfections in the mirror edge seals.

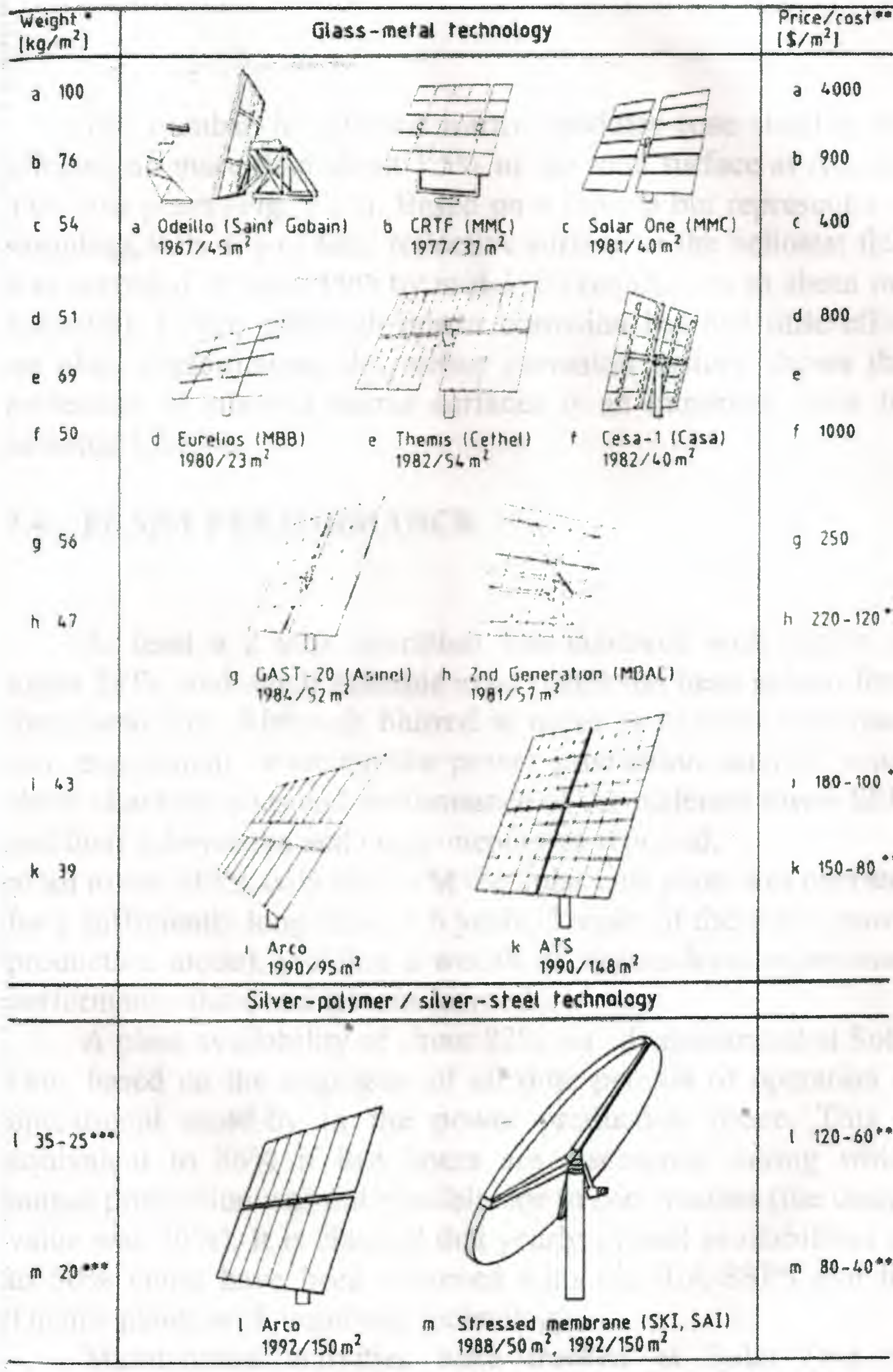


Fig. 7.21. Status and trends in heliostat development (1988 status): configuration, technologies, specific weights and specific costs.

The number of affected mirror modules rose steadily but affected no more than about 1.5% of the total surface at Almeria alter five years (Fig. 7.22). Based on a limited but representative sampling, 0.06 1% of total reflective surface of the heliostat field was corroded at Solar One by mid-1986 (equivalent to about one heliostat). Hence, although mirror corrosion has had little effect on plant performance, the mirror corrosion history shows that protection of silvered mirror surfaces is an important issue for heliostat lifetime.

3.4 PLANT PERFORMANCE

At least a 2 year operation was achieved with nearly all tower SPPs, and much valuable expe rience has been gained from these activities. Although blurred at times as to what constitutei test, experiment or utility-like power production activity, much about characteristics and performance of the different tower SPPs and their subsystems and components was reported.

of all tower SPPs, only the 10 MWe Solar One plant was operated for a sufficiently long time (> 6 years, 3 years of these in a power production mode), yielding a wealth of system-level experience, performance data, and lessons learned.

A plant availability of about 82% was demonstrated at Solar One, based on the aggregate of all time periods of operation or operational stand-by in the power production phase. This is equivalent to 86% if lost hours are discounted during which output production was not possible due to bad weather (the design value was 90%). It is claimed that yearly overall availabilities up to 50% could have been achieved with the IEA-SSPS and the Themis plants with improved technology.

Maintenance activities were tracked at Solar One by computerized management systems used routinely by utilities. These records show that 60% of maintenance efforts was spent on preventive maintenance, and that 40% of maintenance costs was expended on solar-specific plant elements. By optimizing operation procedures, the original plant staff of 40 (for 7-day/3-shift operation) was pared down to about 20 at the end of the power production phase; of this number, 8 persons would be needed for maintenance.

All tower SPPs were designed without the benefit of precursors, based solely on available irradiation data and knowledge about component and subsystem characteristics put to use in conventional power plants. It is not surprising, therefore, that original design and performance predictions were met only to a degree.

Solar One was designed with a SM 1.0 using Barstow irradiation data for 1976 (8.0 kWh(DNI)/m2d average). Assuming 100% equipment availability, design production was 26 GWhe/a. Actual irradiation in the three years of power production not only was lower than in 1976 (by 16, 10 and 14%, respectively), but also remained lower than the 25-year irradiation average. Accounting for actual irradiation and plant availability, the performance goal was adjusted to 15 GWh/a; about 10 GWh/a of net generation (1985/1986) were obtained in 7 days/week, 24-hour operation, equivalent to about 6% average annual energy efficiency; highest monthly percentage of energy output to energy input was 9.8% (in August 1985).

Highest capacity factors achieved in Solar One were 24% per month (in August 1985) and about 12% annually, with little or no utilization of the thermal storage subsystem. Low and even negative capacity factors were observed in the low-irradiation months of December and January.

3.5 PLANT PERFORMANCE CHARACTERISTICS

Relationships of daily energy input to net energy output were determined for Themis (2.4 MWe), Solar One (10 MWe), and IEA-SSPS (500 kWe), based on observed performance as well as on performance estimates for improved plants (i.e. taking lessons learned from test and pilot plants into account). These input-output characteristics are contrasted with the design performance of a hypothetical future 100 MWe solar tower plant of mature technology , assuming California irradiation conditions (Fig. 7.23).

Considering that performance can be improved when introducing storage and SM > 1, or that it is reduced as a consequence of transient output operation, extended operational stand-by periods or inclement weather, some general observations can be made:

- Solar One and (improved) Themis appear to have similar performance characteristics in spite of differences in capacity and primary heat transfer fluid. This experience contradicts recent study results which indicate higher annual performance for large-capacity systems with liquefied metals/salts as primary HTF;
- daily energy input as high as 4 kWh(DNI)/m2d may be needed for net output generation using present technologies under SM = 1 conditions; energies collected below this level are consumed for covering (completely or in part) thermal losses and parasitics;
- with sufficiently large storage capacity, it is expected that as little as 2 kWh(DNI)/m2d may be needed as minimum input for large-capacity tower SPPs of advanced design, using molten-salt as primary heat transfer medium, SM = 1.6, and storage equivalent to 6 hour operation, provided cloud interference is not too high.

In essence, excellent direct irradiation conditions, and minimal thermal losses and parasitics both during operation and stand-by, are key design criteria for good net energy performance from solar input. Peak power performance, although of considerable technical interest, is an inadequate indicator for judging real system performance.

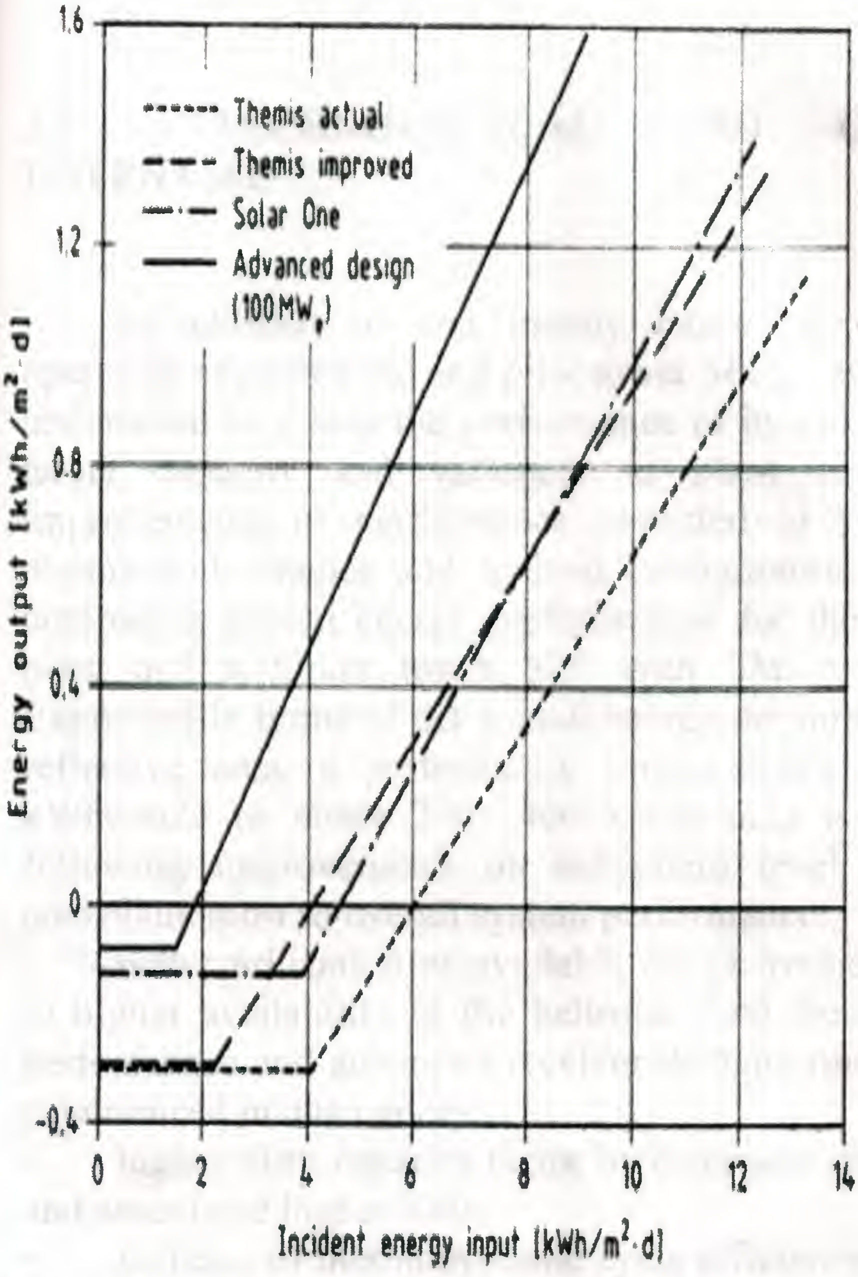


Fig. 7.23. Comparison of daily energy input-output characteristics for tower solar power plants (2.4 MW$_e$ Themis (actual and improved), 10 MW$_e$ Solar One (actual), 100 MW$_e$ advanced tower SPP design (SM = 1.6,

3.6 TECHNOLOGICAL AND OPERATIONAL POTENTIAL

In addition to and mainly based on experience from operating experimental and pilot tower SPPs, several studies were undertaken to assess the performance of hypothetical systems of larger capacity and variances in plant configuration. The improvements of performance expected to be achieved with mature technologies and optimal configuration is illustrated by comparing annual energy performances for the Solar One pilot plant and a future tower SPP with SM = 1.6 (Fig. 7.24). Expressed in terms of net annual energy per unit area of installed reflective area, a performance improvement from about 150 kWbe/m2a to about 270—400 kWh~/m2a is expected . The following improvements on subsystem level are expected to contribute most to overall system performance:

- better utilization of available direct irradiation, attributable to higher availability of the heliostat field, better heliostat field performance and advanced receiver de.ñgns (mature technology; experienced maintenance);
- higher plant capacity factor by incorporating thermal storage and associated higher SMs;
- increase of thermodynamic cycle efficiency through optimal cycle parameters, a high degree of steady-state output operation, and larger power converters;
- reduction of internal losses and parasitic consumption.

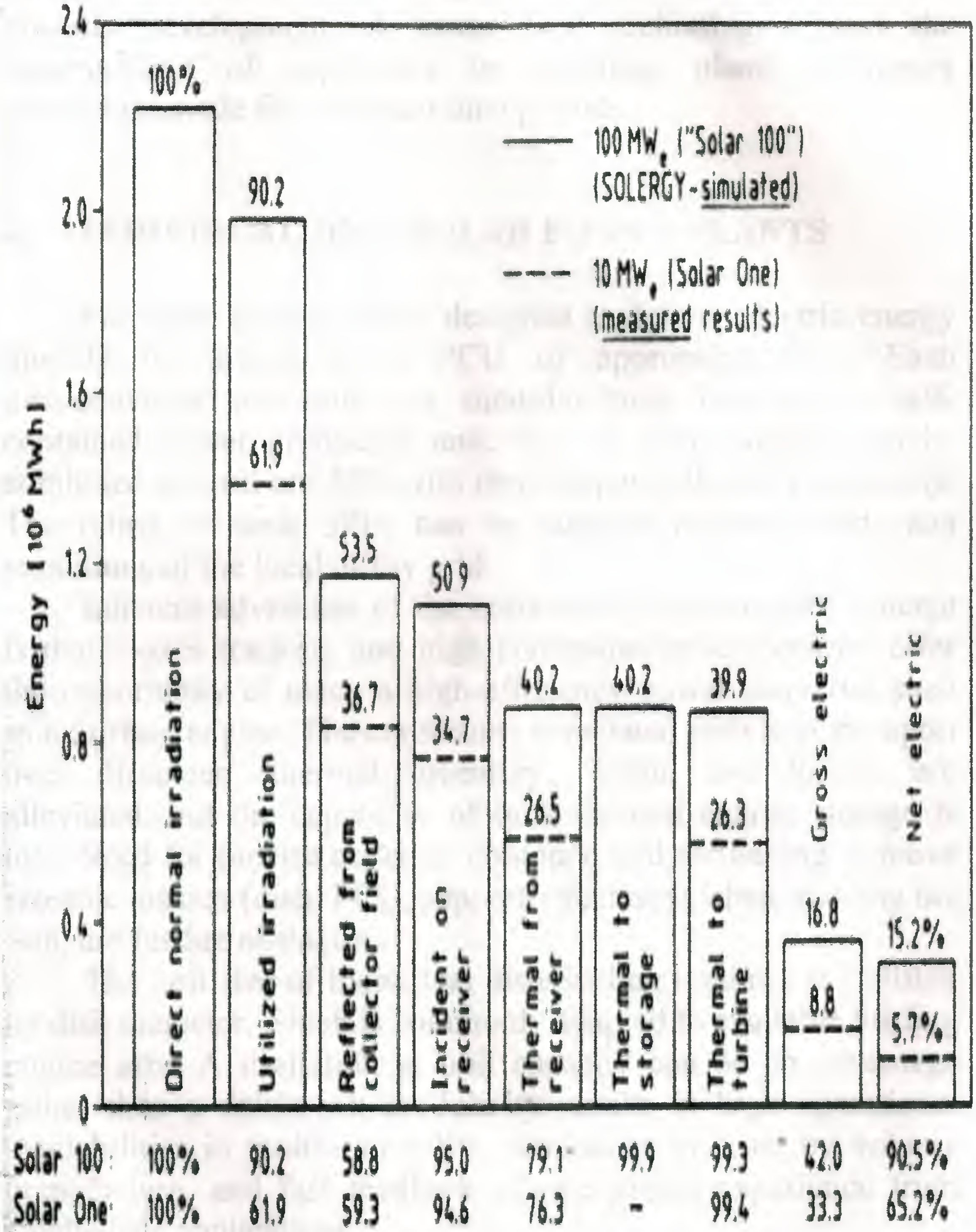


Fig. 7.24. Comparison of annual energy performance of the 10 MW$_e$ Solar One pilot plant and of a future 100 MW$_e$ tower plant with SM = 1.6 under the same irradiation condition (Solar-100) [29].

Such performance improvements require continued efforts towards development of tower SPP technologies, and the accumulation of experience in operating plants in power production mode for extended time periods.

4. INDIVIDUAL DISH SOLAR POWER PLANTS

Parabolic dishes can be designed to deliver electric energy directly by means of a PCU of appropriate size. Each dish/converter assembly (or module) thus becomes a self-contained power producing unit. Several dish modules can be combined to form one SPP with their output collected electrically. The rating of such SPPs can be adapted to load needs and conditions of the local utility grid.

Inherent advantage of the individual dish/converter concept is that 2-axes tracking and high concentration/temperature offer the opportunity of using a high-efficiency power converter such as a Stirling engine. The constraints associated with heat transport over distances (thermal inventory, inertia and losses) are alleviated, but the capability of bulk thermal energy storage is lost. Need for precise collector contours, and for having to move sizeable masses (dish, PCU, support structures) when tracking the Sun, are further obstacles.

The unit size of individual dish/Stirling modules is (leflfled by dish diameter, which is commonly adapted to available Stirling engine size. A limitation in unit capacity can be an advantage rather than a detriment: modularity results in high operational availabilities in multi-unit SPPs, economies of scale by volume manufacture, and fast feedback of operational experience from small-scale applications.

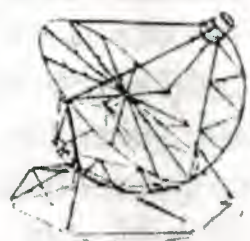
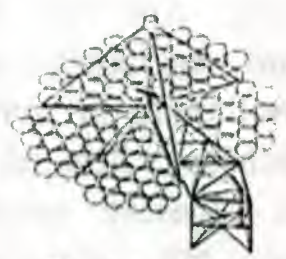
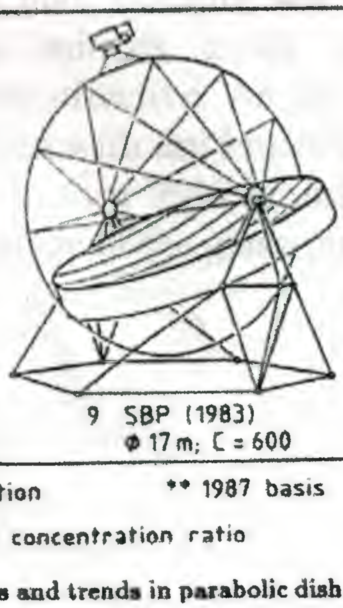
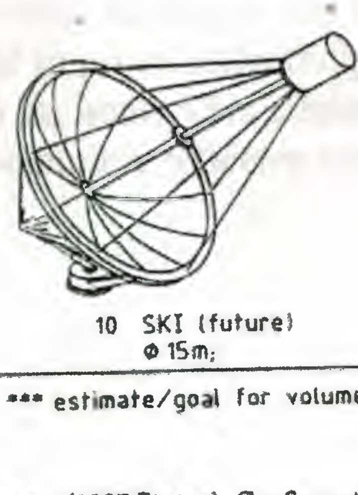
In any case, achieving optical precision with large, lightweight and non-rigid structures in dish/Stirling modules is a considerable engineering challenge and a requirement for cost reasons. This situation, together with the prototype Stirling engine development status, renders todays dish/Stirling modules still expensive in comparison to other solar thermal alternatives.

4.1 CONFIGURATION AND TECHNOLOGY

Key element is the paraboloidal concentrator which is formed either by individual reflector elements held by a support structure, or by a continuous (but possibly subdivided) surface. The concave surface is covered by second-surface glass mirrors or by front-surface reflective (silvered or aluminized) films, Fig. 7.25 illustrates the diversity of construction approaches and technologies pursued in the past decade or yet under development (1987 status).

Positioning accuracy requirements for the power conversion subsystem (consisting of the receiver integral with thermodynamic converter, generator, and heat rejection device) increase with concentration. This may require engineering efforts to compensate gravity bending moments or thermal expansion of structural parts, or to sustain wind forces. The design challenges regarding structural integrity (particularly for large dishes of lightweight construction and long focal length) may be exacerbated by engine vibrations.

On the other hand, very high concentration is not necessarily superior; it has been shown that dish/Stirling annual energy performance is not improved much beyond a concentration of about 1,500—2,000 (Fig. 7.28). Only a few Stirling engine designs exist and have been tested , of which only a few engines are suited to operate in tilted positions (for reasons of lubrication). Brayton and Ranking cycle converters in dish applications have been assessed as alternatives to Stirling engines but proved inferior in terms of performance .

Weight * [kg/m²]				Price/cost ** [\$/m²]
	Glass-metal technology			
1 162 2 118 3 73	 1 TBC (1977) Φ 11 m, C = 3000	 2 Vanguard (1980) Φ 11 m, C = 2800	 3 MDAC (1984) Φ 11 m; C = 2400	1 1300 2 650 3 300-200
	Aluminized film technology			
4 74 5 56 6 37	 4 SKI (1980) Φ 7 m, C = 250	 5 GE (future) Φ 12 m, C = 1000	 6 LaJet (1986) Φ 7.4 m; C = 800	4 ~1000 *** 5 ~300 *** 6 190-160
	Silver-polymer / silver-steel technology			
7 67 8 55	 7 Acurex (future) Φ 15 m; C = 1100	 8 LaJet (future) Φ 15 m; C = 700		7 ~127 *** 8 ~88
	Stretched-membrane technology			
9 52 10 30	 9 SBP (1983) Φ 17 m; C = 600	 10 SKI (future) Φ 15 m;		9 < 180 *** 10 < 140 ***

* w/o foundation ** 1987 basis *** estimate/goal for volume production

C = geometric concentration ratio

Fig. 7.25. Status and trends in parabolic dish development (1987 Status). Configuration, technologies, specific weights and specific costs

4.2 DISH/STIRLING EXAMPLES

Vanguard 1. This 25 kWe prototype dish/Stirling module was operated at Rancho Mirage/CA in the Mojave desert in power production mode for an 18-month period (Feb 1984— Jul 1985, Fig. 7.26). The results of operational testing were analyzed and reported . The 86.7 m2 dish with a 25 kWe Stirling/generator unit was designed for 20 kWe at 850 W(DNI)/m2, 25 kWe at 1,000 kWe(DNI)/m2, and 200 W(DNI)/m2 operating threshold. With over 30% peak power efficiency, this module achieved the best performance ever measured for any solar thermal power system. MDAC 25. This 91.5 m2, 25 kWe dish/Stirling system was commercially developed. Several units were built and operated by utilities at different locations the U.S. In 1985, commercial development activities were terminated; operating experienCE was reported to a limited degree.

SBP 50. Two units with 227 m2 reflective stretched membranes with 50 kWe Stirling engines were built and operated near Riyad/Saudi Arabia and were in operation from 1986 to 1989. Peak net electric output to the grid exceeded 34 kWe under optimum conditions. The systems suffered from reliability problems but generally demonstrated the same operational characteristics as the other dish/Stirling systems. Total operating hours for both systems were over 4,000 hours. Cleaning of the thin-glass mirrors glued to the metal membranes proved particularly effective. As the collecting surface could be walked on, two men with dry brushes could improve reflectivity from the low 70% to over 90% in less than an hour. This demonstrated a key advantage of the glass-metal membrane reflector technique.

4.3 PLANT PERFORMANCE

The Vanguard 1 experiment provides well documented and representative operating experience for single dish/Stirling units; supporting performance data were also provided by the SBP 50 tests in Saudi Arabia. Following statements and conclusions are based mainly on this information.

• Excluding times for planned maintenance (luring daylight hours, Vanguard 1 achieved 64% operational system availability based on total operating hours during the 18-month operating perio(1 (72% if based on operating days with irradiation sufficiently high for Operation). To maintain this availability, continuous on-site presence of technical personnel was required. 38% of downtime was caused by Stirling engine malfunction, and 20% each by the need for dish, receiver and control system repairs.

• Almost immediate response (in the order of 1 minute) of electric output to thermal energy input was recorded, caused by the small thermal tintss which is characteristic of compact PCUs such as a 25/50 kWe, Stirling engine with a generator. As a consequence, rapid irradiation-following capability was verified in the Vanguard I experiment (Fig. 7.29). Stirling engine output is usually controlled by H2-ressure variations.However, thermal lag is evident after the gas temperature drops below the set level; in this case time is needed to reach the temperature set level again, after which pressure control can take over again.

• Decrease in mirror reflectivity by soiling immediately impacts on the output. This becomes evident by slope differences in gross electrical power output as a function of direct irradiation input (Vanguard 1; Fig. 7.30). Reflectivity values have been found to differ as a function of location on the dish, rendering it difficult to determine overall mirror reflectivity accurately. It has been suggested that the power slope method can serve not only as a detector for reflectivity changes but also as a tool for best characterizing the system performance, irradiation threshold for operation (x-intercept), and electrical power lost as a result of receiver, wind and mechanical losses (y-intercept).

- Both Vanguard 1 and SBP 50 provided information on the importance of structural strength and the interplay between optical accuracy and performance. Output of the SBP 50 module degraded under windy conditions (Fig. 7.31) due to flux spillage (observed) and increased receiver convection losses (not measured). Annual average wind speed at the SBP 50 test location was 3.9 m/s, leading to a calculated annual energy performance reduction of 15% as compared to calm conditions. For Vanguard 1 with specified beam accuracy of ±1.25 cm (C = 2,500), a worst case deflection of 1.0 cm, due to the weight of the Stirling PCU, was calculated for a dish movement from 10 to 75 of elevation, although the engine block was mounted on a stiff tripod and was decoupled from the dish structure.
- Image deflection and convective effects (varying with dish elevation) contributed to uneven performance of the cavity receiver of Vanguard 1. However, energy flow to the four pistons is a prerequisite for mechanically smooth operation and for optimal conversion efficiency. Temperature differences over 100 C were measured between the four receiver quadrants, equivalent to a 15% difference in upper cycle temperature between the four pistons of the Stirling engine (Fig. 7.32).

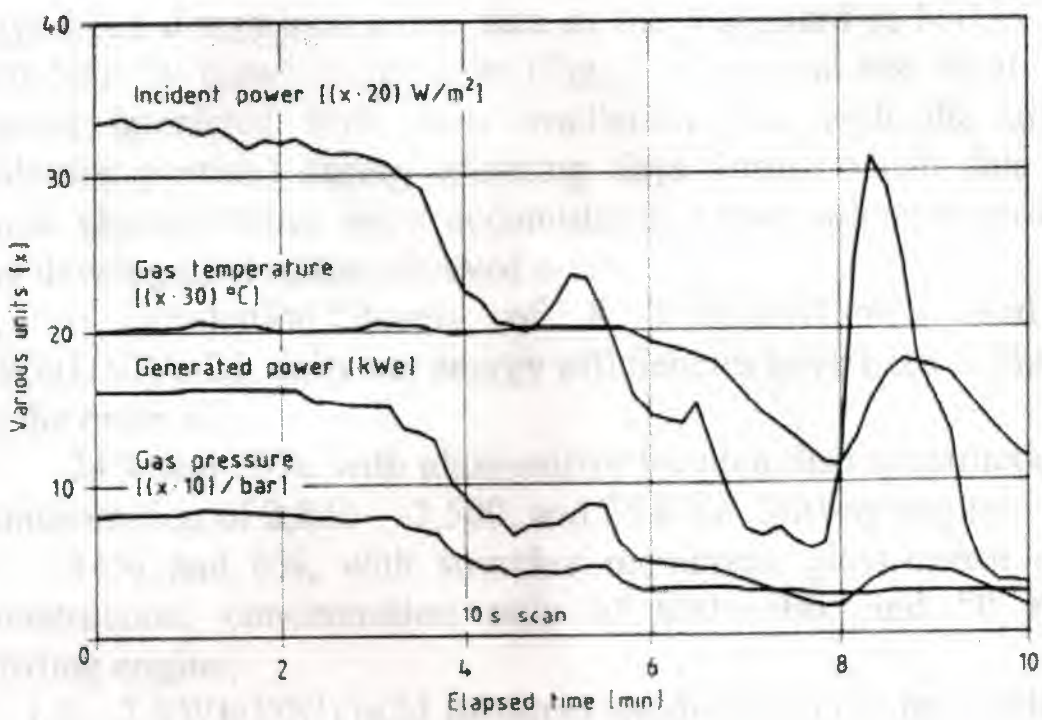


Fig. 7.29. Capability to respond to irradiation transients 25 kW, Stirling/generator power conversion block Vanguard 1 module (relative scales) [23].

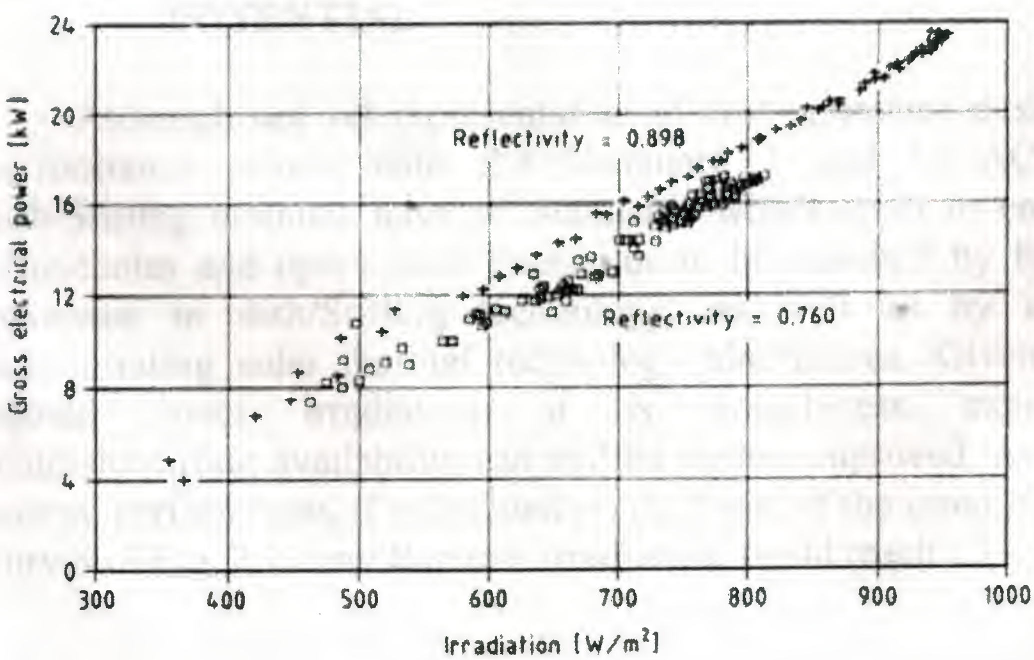


Fig. 7.30. Effect of dish reflectivity on electrical output as a function of direct irradiation, Vanguard module [23].

4.4 PLANT CHARACTERISTICS

Characteristics of daily energy input to net energy output have been determined using data of the Vanguard 1, MDAC 25 and SBP 50 dish/Stirling units (Fig. 7.33). At all test locations, clouds interfered little with irradiation (i.e. with the direct radiation portion) during operating days during which data for these characteristics were accumulated. Observations regarding the development status achieved are:

1. At irradiation levels of 8 kWh(DNI)/m2d and 4 kWh(DNI)/m2d, daily net energy efficiencies have been achieved in the order of

- 24% and 20%, with glass-mirror facetted dish constructions, concentration of 2,000— 2,500, and 25 kWe Stirling engine;
- 14% and 8%, with stretched-membrane glass-mirror dish construction, concentration ratio of 600—800, and 50 kWe Stirling engine;

2. 1.5—2 kWh(DNI)/m2d of direct irradiation must be available and must be collected daily before net electricity output can be attained with Stirling engines of 25—50 kWe rating.

4.5 TECHNOLOGICAL AND OPERATIONAL POTENTIAL

Although not yet representative of cost-optimized designs, performance results with the Vanguard 1 and MDAC 25 dish/Stirling modules have set standards with respect to energy efficiencies and operational thresholds to be matched by future advances in dish/Stirling technology, as well as by other concentrating solar thermal technology alternatives. Given adequate direct irradiation, it is nonetheless expected thatdish/Stirling availability can still be further improved. Annual energy performance, if calculated on the basis of the input-output curves of Fig. 7.33 and Barstow irradiation, could reach 23—27%

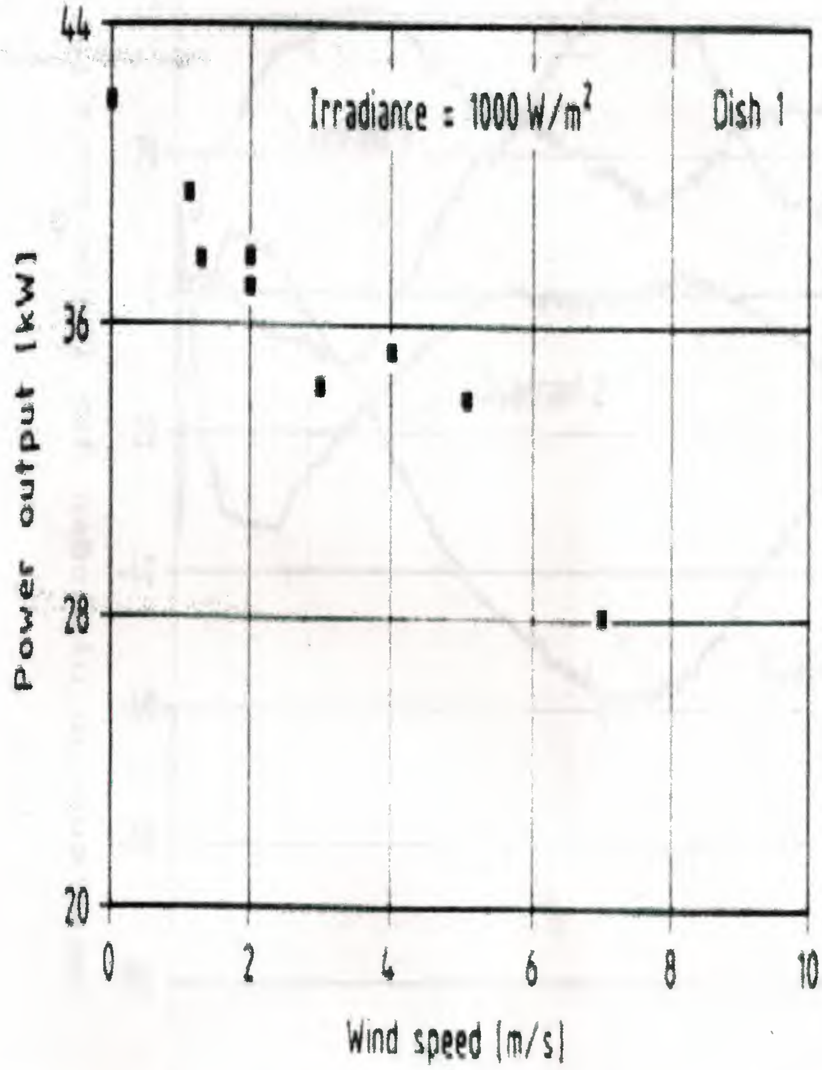


Fig. 7.31. Influence of wind speed on the performance of the SBP 50 kWe stretched-membrane dish/Stirling module [35].

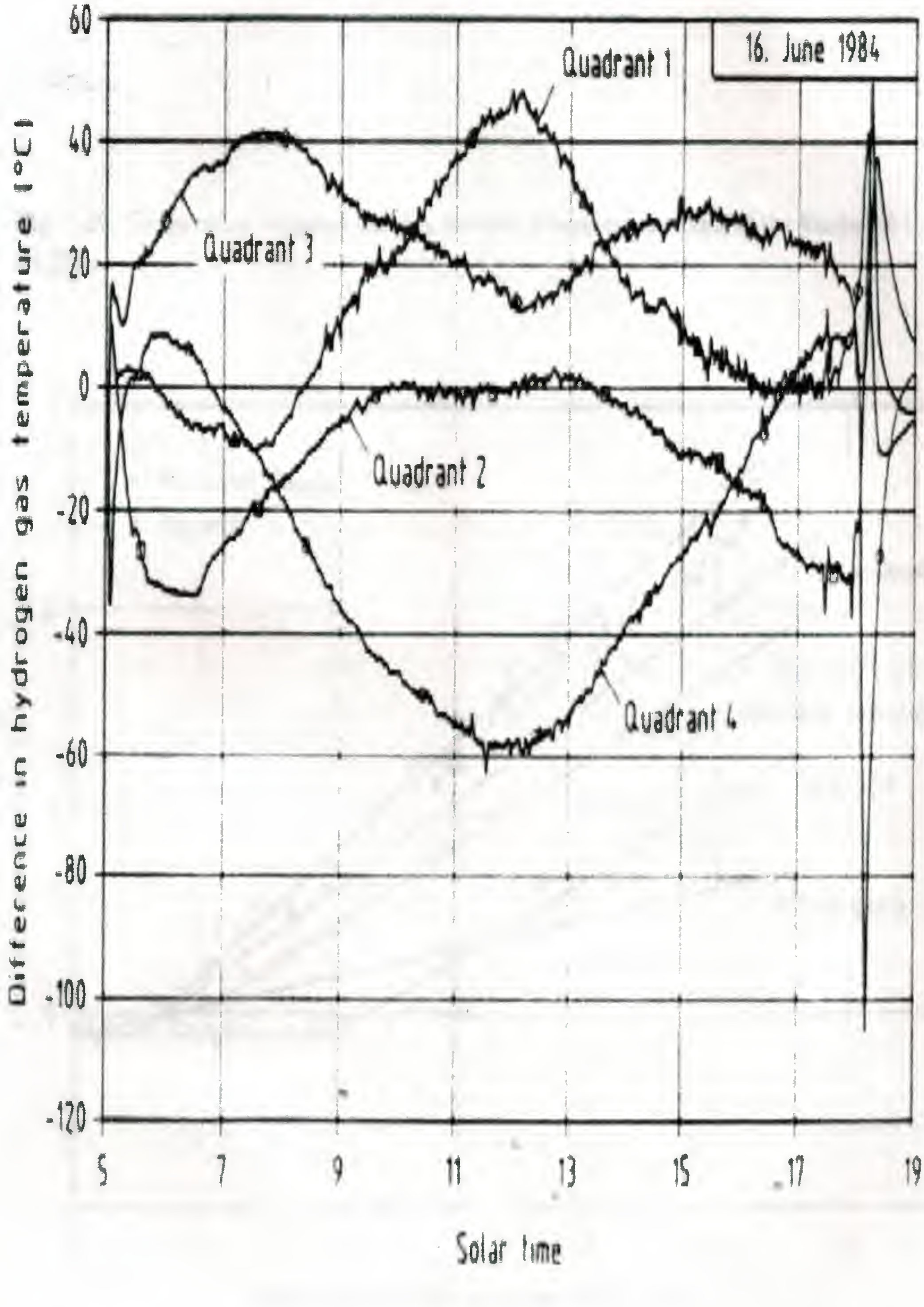


Fig. 7.32. Temperature variation between the cavity receiver quadrants of the Vanguard 1 dish/Stirling module [23].

Fig. 7.32. Temperature variation between the cavity receiver quadrants of the Vanguard 1 dish/Stirling module [23].

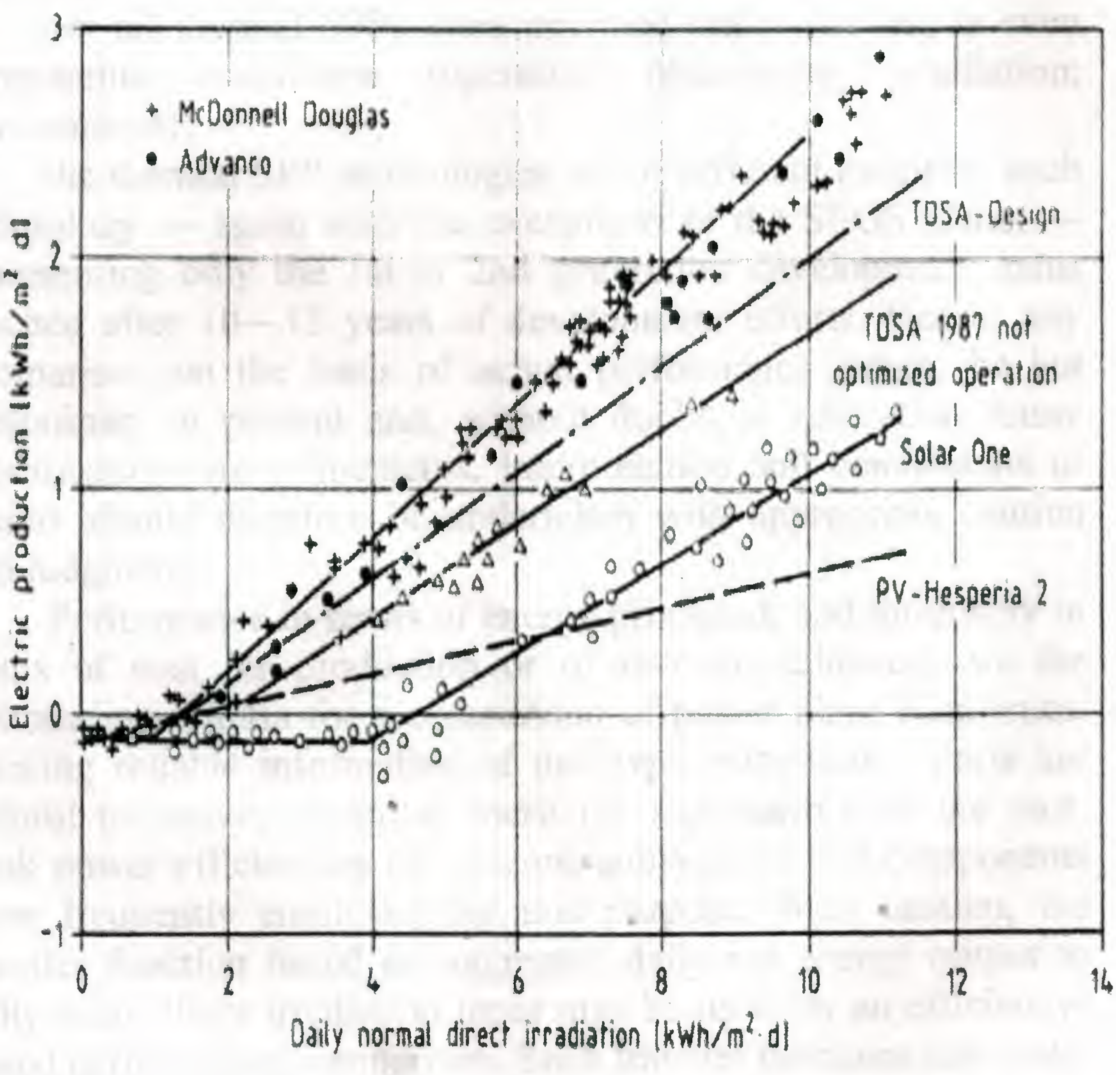


Fig. 7.33. Measured daily energy input-output performance of different dish/Stirling units [63].

CONCLUSION

Although an appreciable number of experimental, demonstration or even (emerging) commercial thermal SPPs has been installed, the performance assessment of SPPs is largely based- with the exception for the SEGS family of parabolic trough plants on information which yet carries little statistical significance. Hence the following conditions prevail under which any comparison must be carried out:

- not all thermal SPPs were operated under similar, or even comparable, conditions (operating philosophy; irradiation; environment);
- the thermal SPP technologies are of different maturity, each technology — again with the exceptions of the SEGS plants — representing only the 1st or 2nd generation development status reached after 10—15 years of development efforts. Hence, any comparison on the basis of actual performance cannot be but preliminary at present and, without doubt, is subject to future modification and refinements. Interpretation and conclusions of results should therefore be undertaken with appropriate caution and judgment.

Performance in terms of energy produced, and ultimately in terms of cost for production or of revenue achieved, are the bottom-line criteria for a comparison of power plant economics. Lacking reliable information of that type, substitute criteria are helpful to convey technical merit (or superiority). In the past, peak power efficiencies of systems, subsystems and components were frequently employed for this purpose. With caution, the transfer function based on aggregate daily net energy output to daily solar direct irradiation input may be used for an efficiency-based performance comparison. Such transfer functions can make technology-specific distinctions and relative performance differences apparent. Transfer functions do not convey a complete picture, however, as effects such as reliability, availability, durability, operating complexity, controllability, or O&M requirements of the technology involved, are not fully incorporated.

For a fair comparison, the contribution of natural gas to the output of the SEGS systems must be taken into account. On this basis, net annual performance of early trough and tower SPPs is comparable in terms of MWhe generated per kWe installed. Technical improvements are evident, looking at the performance of the more recent SEGS systems which took up operation only one or a couple of years after SEGS I. This fact demonstrates the significant influence of learning-curve effects in the rapid and continuous SEGS systems development. Other thermal SPP technologies so far did not benefit from such continuity. The maturity level of the thermal SPP technologies differs therefore at the present time.

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