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A SOLAR-DRIVEN COMBINED CYCLE POWER PLANT

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Abstract—The main results of a feasibility study of a combined cycle electricity generation plant, driven by highly concentrated solar energy and high-temperature central receiver technology, are presented. New developments in solar tower optics, high-performance air receivers and solar-to-gas turbine interface, were incorporated into a new solar power plant concept. The new design features 100% solar operation at design point, and hybrid (solar and fuel) operation for maximum dispatchability. Software tools were developed to simulate the new system configuration, evaluate its performance and cost, and optimize its design. System evaluation and optimization were carried out for two power levels. The results show that the new system design has cost and performance advantages over other solar thermal concepts, and can be competitive against conventional fuel power plants in certain markets even without government subsidies. © 1998 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

Combined cycles (CC), comprising a Brayton cycle gas turbine with a Rankine-cycle steam turbine, are an attractive option for the power generation industry. The high efficiency of CCs, and their use of relatively inexpensive fuel, contribute to their increasing popularity (Barker, 1995). The operating temperature of gas turbines is today in the range of 1000–1350°C, and newer models operating at even higher temperatures are expected soon. Solar energy could effectively serve as the high-temperature heat source driving a CC, since the increased efficiency offsets the high initial investment required in solar applications, producing a more effective solar electricity generation system. The leading system concepts proposed and developed in recent years for large-scale solar thermal electricity generation plants, however, provide only lower temperature solar technologies, which are suitable for driving steam Rankine cycles but not CCs. Examples are the Luz SEGS plants (operating at 300–400°C), PHOEBUS and Solar Two (500–600°C steam).

Several schemes were suggested for integration of solar technologies that supply low temperature energy into CC plants (Fig. 1). Supplemental solar heat to the bottoming Rankine cycle (Rheinländer *et al.*, 1994), option (I) in Fig. 1, improves that part of the CC, but conversion of solar-derived heat is at the low efficiency of the Rankine cycle, and solar contribution is low. Modifications to this solar-augmented CC scheme were proposed, in order to better accommodate the solar component, such as significant oversizing of the bottoming cycle, or shutting off the topping cycle during non-solar hours. Such modifications diminish the

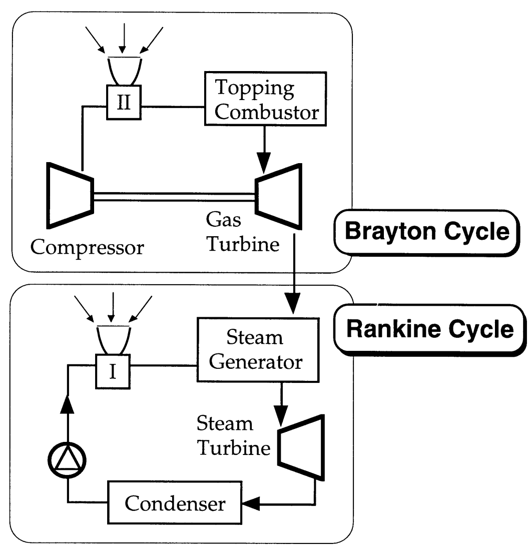

Fig. 1. Options for integration of solar energy into combined cycle plants. Option (I): steam supplement to the Rankine cycle. Option (II): heating or preheating at the Brayton cycle.

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plant's performance, and are not likely to appear attractive to plant owners and operators. Bohn *et al.* (1995) propose solar preheating at the topping Brayton cycle, option (II) in Fig. 1. This scheme offers high conversion efficiency, but limited solar contribution to the overall plant's electricity production. A new scheme is proposed here, that would fully exploit the potential of the solar/CC combination, based on the following principles:

(1) supply solar heat to the topping Brayton cycle (option II), to achieve the highest possible conversion efficiency;
(2) supply solar heat at the highest temperature of the topping cycle, to achieve the highest possible solar contribution (100% solar at design conditions);
(3) hybrid (solar and fossil fuel) operation, to provide dispatchable full capacity at all times, without solar-specific restrictions on the plant's operation.

A detailed feasibility study was conducted by a team consisting of McDonnell–Douglas Aerospace, El-Op Electro-Optics Industries, Ormat Industries, Rotem Industries and The Weizmann Institute of Science (McDonnell–Douglas *et al.*, 1995). Its goal was to evaluate the technical feasibility, performance and cost of a novel solar power generation system concept. This concept combines innovations in collection technology (high-concentration large-scale optics) and radiation-to-thermal conversion (high-temperature receivers), integrated with CC thermal-to-electricity conversion. Modeling and optimization tools were developed to analyze the optical and thermal performance of the proposed system. To optimize the plant design, we used in this study a modified version of DELSOL3 (Kistler, 1986), expanded and enhanced with the new optics model and additional options for receivers, storage, hybrid operation and power generation. The new optics model has been validated against corresponding ray-tracing calculations. To distinguish between the original and enhanced versions, we designated this new version as WELSOL. Preliminary designs for two plant configurations were developed and optimized as part of this study: a 600 kW_e system and a 34 MW_e system. These represent a typical range of plant scaling achieved using the new plant concept. A schematic view of the 34 MW_e solar plant is shown in Fig. 2.

This paper presents highlights of the feasibility study. The new system concept and components are outlined, models and analytical tools developed for the study are described, and the main performance and cost results are presented. Also presented is a comparison to other solar central receiver plant options. The results are very promising in terms of efficiency, installed cost and levelized energy cost (LEC), and merit further development and demonstration of the new plant design.

2. SYSTEM CONCEPT

2.1. Collection optics

Traditional solar central receiver plant design consists of large receivers installed on top of a central tower. The optics and receiver designs proposed and tested to date accept solar radiation at intermediate concentration (about 300–1000 suns), and supply heat at intermediate temperature (up to 600°C) to a steam Rankine power cycle. Solar One/Two (Kelly and Singh, 1995) and PHOEBUS (Fichtner, 1990; PHOEBUS-TSA, 1994) are typical examples.

The Solar Concentration Off-Tower (SCOT), also called Reflective Tower or Beam-Down, optical configuration was first proposed by Rabl (1976). A hyperboloid reflector is installed at the tower top, redirecting the concentrated solar radiation towards a lower focal region near ground level (Fig. 2). This is similar to the common Cassegrain telescope design. It offers several advantages for central solar receiver systems:

2.1.1. Better collection optics. The Cassegrain arrangement produces a relatively low concentration at its lower focus. However, it also produces a narrow view angle and a large effective focal length (due to magnification by the hyperboloidal mirror). This reduces optical aberrations, and allows a higher overall maximum concentration by non-imaging terminal concentrators installed at the lower focus (Fig. 3). The effect is especially significant for large fields, where the field radius is typically three to four times the tower height.

2.1.2. Stable flux distribution. The heliostat field has a single aim point, producing a single "spot" at the lower focal region. This spot is divided among several CPC secondary concentrators, each accepting radiation from the entire field, and therefore the fraction of power allocated to each CPC varies little with time. Thermal balancing and heliostat field control issues are therefore greatly reduced, unlike tower-mounted CPC's.

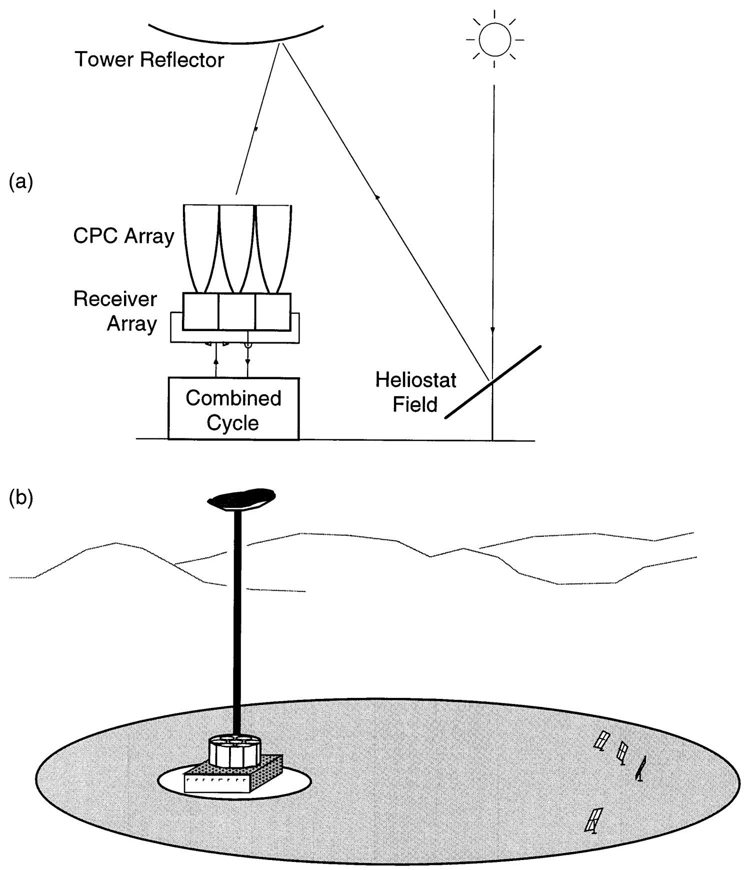

Fig. 2. The new concept of a solar-driven CC plant. (a) plant schematic; (b) artist's view, approximately to scale, of the 34 MW_e plant.

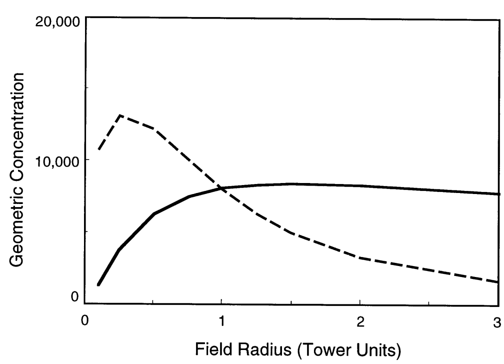

Fig. 3. Geometric concentration ratio vs field radius for a solar central receiver plant with a symmetric surround field and CPC terminal concentration, assuming: dense heliostats (no spaces); 5 mrad "pillbox" sun; reflector errors of 2 mrad and 1 mrad for heliostats and TR. Solid line: SCOT system with TR at 0.8 of field focus height; dashed line: tower-top system.

2.1.3. Ground-level plant. The major hardware (CPC, receiver, storage, power block, etc.) is located near ground level. This eliminates a massive and expensive tower, long piping, and the need for frequent personnel access to the tower top. The tower is light and inexpensive, supporting only a passive reflector component.

Previous work on SCOT optics for solar towers has concluded that this configuration is not effective, because of the losses in the extra reflections, and the low concentration obtained at the low focal region (Vant-Hull, 1991). However, a combination of SCOT with modern high-reflectivity surface technology, high concentration using non-imaging (CPC) terminal concentrators and high-temperature, high efficiency power conversion, mitigate these objections and make the SCOT optics an effective option for large-scale solar power plants. The technical feasibility and estimated cost of the Tower Reflector subsystem were verified in a parallel study (Epstein *et al.*, 1996).

2.2. Receiver

The high temperature and pressure required for CC operation are achieved using the Directly Irradiated Annular Pressurized Receiver (DIAPR; Karni *et al.*, 1997). This receiver incorporates the *Porcupine* volumetric absorber,

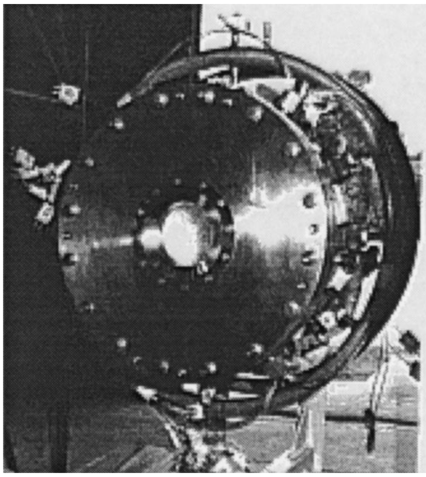

Fig. 4. The high-temperature volumetric receiver (DIAPR) developed at the Weizmann Institute.

and the Frustum-Like High-Pressure (FLHiP) window technologies. A 50 kW (thermal) DIAPR has been under test at the Weizmann Institute for the last two years (Fig. 4). It operates at aperture flux of up to 10 MW m^{-2}, using secondary concentration. It is capable of supplying hot gas at a pressure of 10–30 bar and exit temperature of up to 1300°C, which are compatible with the requirements of modern, high-performance gas turbines. The DIAPR can be upscaled to 1 MW_{th} using current manufacturing capabilities, and to larger sizes with some investment in manufacturing facilities.

A SCOT plant may contain one or more DIAPRs, depending on its rating, providing a degree of modular design flexibility. For efficient use of the available flux distribution, heating is performed in two or three stages connected in series, where the lower temperature stages may be either DIAPR-design or simpler structures (Ries *et al.*, 1995; Doron and Kribus, 1996).

The DIAPR can also supply power to a stand-alone Brayton cycle, in a tower or dish plant; the operating conditions in such a plant are usually less demanding than in a CC. Such a plant offers lower efficiency than a CC, but also lower specific cost and minimal startup time for supplying peak demand periods.

2.3. *Electric power generation*

The electric power generation system (EPGS) includes a high-temperature Brayton cycle (gas turbine), and a bottoming Rankine cycle. The solar receiver is connected between the compressor and the gas turbine inlet, as seen in option II of Fig. 1. The power block also includes a fossil fired combustor which guarantees dispatchability of electricity at any time. During normal daylight operation, fuel is used only in a "topping" mode, to compensate for insolation fluctuations. The plant may also include various storage options to provide solar-derived electricity after daylight hours, if the additional costs are justified by the local consumption and price patterns. Short-term thermal storage may be provided, for example, using sensible-heat ceramic bed vessels. Longer term storage can be envisioned using solar chemical processes such as closed-loop methane reforming, or metal oxide reduction cycles, currently under development. The analysis presented here does not include thermal storage.

3. SIMULATION AND ANALYSIS

The code DELSOL3 (Kistler, 1986) contains a general framework for the sizing and parametric study of central receiver plants, including a set of physical, cost and economic models. This code, however, was written with a molten salt and steam system (Solar Two) in mind. We have used DELSOL3 as a starting point, and extended it with a SCOT optics model and additional options for receivers, hybrid operation and power generation. To distinguish between the original and enhanced versions, we designate this new version of the code as WELSOL.

The original DELSOL calculates the power incident within the aperture of a tower-mounted receiver. WELSOL extends the intercept efficiency calculation of the optics model to treat also a ground-level (SCOT) aperture. Definition of the Tower Reflector boundary, calculation of losses due to the additional optical elements, models for performance of high-temperature air receivers, and a selection of gas turbines and combined cycle performance models, were added. Cost models for new components (additional reflectors, receivers, etc.) were added, and existing cost models were updated to 1995 conditions.

The original DELSOL uses a parametric search algorithm that allows variation of three geometric system parameters within a specified range. For each combination of parameters, the code constructs a system design, including selection of heliostat field zones that are most effective; calculates annual performance, installed cost and LEC; and saves the system configuration that yields lowest LEC. WELSOL extends this parametric search with three new parameters that are relevant to a SCOT system.

A system optimization code necessarily sacrifices accuracy for computation speed, since the optimization procedure requires many evaluations of the objective (e.g. cost of electricity) at different values of various system parameters. The physical models used in the code are therefore simplified to allow this fast repetitive evaluation. Tools for a more detailed and accurate performance simulation were therefore also developed. The performance simulation process contains two parts. The optics are simulated using a statistical ray-tracing code (Segal, 1996), which is based on MIRVAL (Leary and Hankins, 1979), with additional utilities for field layout and secondary optics. The output of the optics calculation was fed into the thermal analysis code ANN (Kribus, 1995), which simulates the performance of receivers, storage and power conversion subsystems, and handles annual integration. The results of the more detailed simulation were used to validate the performance predictions of WELSOL-recommended system configurations.

4. SYSTEM DESIGN AND PERFORMANCE

4.1. *Example plant designs*

Two specific SCOT/CC plant designs are presented, optimized for low LEC and practical design (e.g. when two designs produced similar LEC, the one with shorter tower and/or smaller Tower Reflector was selected). The 34 MW_e plant uses the Pratt & Whitney FT8 gas turbine, combined with a bottoming steam Rankine cycle. The small-size 600 kW_e plant uses an Allison 250-C30 gas turbine coupled with an Ormat Turbines organic Rankine bottoming cycle. Table 1 summarizes the main design features and performance of these plants. Figure 5 shows the heliostat field layout for the two plants.

4.2. *Efficiency of example plants*

We used the site data for Barstow, California, for the assessment of the plants' energy balance. Table 2 shows the two example plants' annual solar-to-electricity efficiency, based on hybrid operation with fossil fuel topping when necessary, with solar capacity factor of 0.24. Also shown for reference is the efficiency for the two other solar thermal designs: salt-in-tube/steam (SIT/steam; Solar Two design) and air/steam (PHOEBUS design), taken from Becker and Klimas (1993), denoted below as B&K, and also assumed to operate in hybrid mode. The annual efficiency of the 34 MW_e plant is high, mainly due to a high efficiency power conversion unit (CC). Receiver efficiency is reasonable, in spite of the high temperature, which is made possible by the high flux concentration. The annual efficiency of the 600 kW_e system is lower than the larger CC plant, but remarkably it is still at the same level as the larger 30 MW_e reference solar plants.

Table 1. Main design and performance features of the 34 MW_e and 600 kW_e SCOT/CC example plants

Plant rating	34 MW_e	600 kW_e
Heliostats	1323	48
Glass area	126000 m^2	2736 m^2
Tower height	163 m	49 m
Aim point height	180 m	60 m
Tower Reflector area	3270 m^2	190 m^2
CPC concentration	20:1	25:1
High-temp. receiver inlet flux	8400 kW m^{-2}	6300 kW m^{-2}
Turbine inlet temp.	1200°C	1000°C
Net annual electricity from solar	72.1 GW h	1.16 GW h
Annual efficiency	0.213	0.161
Solar capacity factor	0.242	0.220

5. COST ANALYSIS

Cost estimates were based on manufacturer/vendor quotes, with no allowance for government subsidies, large volume production or other cost-reduction measures that are not currently available. O&M data were based on utility data and on experience with the Solar One facility at Barstow. Conditions appropriate to the U.S. market were assumed.

5.1. *Capital costs*

The cost breakdown of the two example plants is given in Table 3. The major contributors to the plant costs are the heliostats and the EPGS. The heliostat cost used for all plants was \$248 per m^2, based on recent manufacturer cost quotes for a 50 MW_{th} plant (Epstein *et al.*, 1996), which does not assume any future cost cuts or government subsidies. Contingency is included in each component's cost.

Also presented in Table 3 are the costs of the two SIT/steam and air/steam plant designs. These figures were adjusted as follows, to provide common grounds for comparison to the current study:

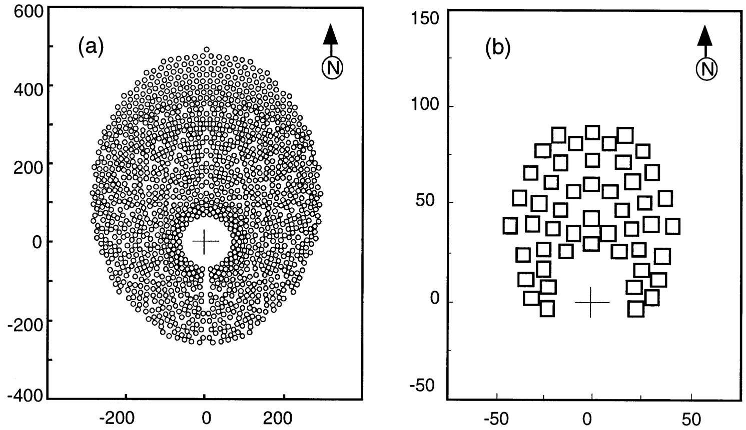

Fig. 5. Heliostat field layout for the two example SCOT/CC plants: (a) 34 MW_e; (b) 600 kW_e. Coordinate grid is in meters. Heliostats are 95 m^2 in (a) and 57 m^2 in (b); see Table 1 for details.

Table 2. Annual efficiency of the SCOT/CC example plants, compared to 30 MW_e SIT/steam and air/steam designs; efficiency for the tower-top systems was adjusted for higher heliostat reflectivity

Plant type size	Air/steam 30 MW_e	SIT/steam 30 MW_e	SCOT/CC 34 MW_e	600 kW_e
Optics (heliostats, TR, spillage)	0.604	0.648	0.575	0.574
Receiver (incl. CPC)	0.793	0.778	0.829	0.827
Piping (incl. steam gen.)	0.983	0.978	0.989	0.995
Power conversion (gross)	0.399	0.389	0.470	0.356
Parasitic loss efficiency	0.864	0.864	0.962	0.958
Total solar-to-electricity	0.162	0.166	0.213	0.161

Table 3. Cost breakdown (M$) and specific costs ($/kW_e) of example SCOT/CC plants and other solar thermal plant designs; the data for the tower-top systems was adjusted for consistent comparison with the present study (see text)

Plant rating (MW_e)	SIT/steam 30	Air/steam 30	SCOT/CC 34	0.6
Heliostats	34.4	38.0	35.5	0.678
Tower	3.0	5.1	3.6	0.046
TR and CPC	–	–	5.3	0.276
Receiver	8.6	10.0	7.7	0.240
Thermal storage	3.3	0.0	–	–
EPGS and steam generation	37.5	34.8	23.1	0.726
Fixed	4.0	4.2	3.9	0.122
Indirect	11.2	11.2	8.9	0.278
Total capital cost	102.0	103.3	88.0	2.366
Specific cost $/kW	3400	3443	2588	3943

(1) Inflation from 1990 to 1995 was added to all costs.
(2) Reflective area was reduced according to the higher reflectivity assumed (0.93).
(3) Cost of heliostats was set to \$248 m^{-2}.
(4) The fossil-hybrid option was selected.
(5) The effect of storage was removed, by scaling down the solar components using the appropriate Solar Multiple. Storage was either scaled down (SIT/steam system, where a minimum salt holding capacity must be retained) or eliminated (air/steam system).
(6) The percentage of indirect costs was set equal to the SCOT/CC estimate.

Obviously, the scaling to remove the effect of storage is not accurate, and a complete redesign of the plants for $SM=1$ may yield somewhat lower costs. On the other hand, B&K assume a 10% cost reduction due to competitive bidding, which was not assumed in the present study. The opposite influence of these two factors should then provide a fair comparison.

The new SCOT/CC design has an installed cost that is lower by about 25% than the other plants at $SM = 1$. The small 600 kW_e system shows higher specific cost than the 34 MW_e plant, but still a very reasonable one. The small system is suitable for a different market niche, where power prices are usually higher anyway. This degree of scalability to small size at reasonable cost is not possible with the competing solar plant designs.

Figure 6 presents a sensitivity analysis, demonstrating the effect on installed cost of two changes that are feasible and can be expected in the near future: heliostat cost reduction and improvement in gas turbine efficiency (Barker, 1996). A combination of these two factors can reduce the installed cost well below 2000 $/$kW_e$.

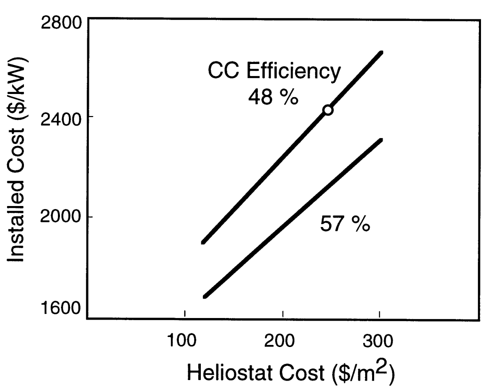

Fig. 6. Effect of heliostat cost and power conversion efficiency on installed cost of the 34 MW_e SCOT/CC plant. Circle: design point for the present study.

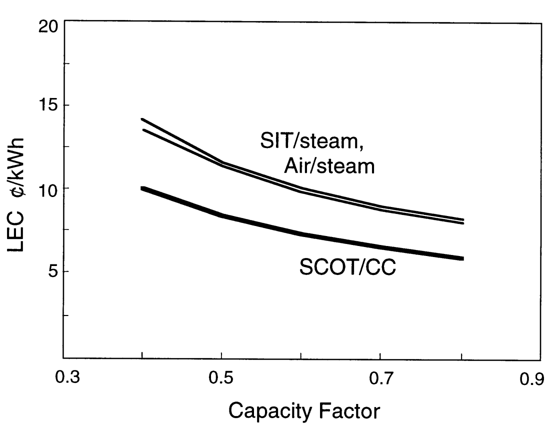

Fig. 7. Levelized energy cost of the 34 MW_e SCOT/CC, and 30 MW_e SIT/steam and air/steam plants, as a function of capacity factor in hybrid solar/fossil mode.

5.2. Levelized energy cost

LEC for the 34 MW plant is shown in Fig. 7, assuming a typical U.S. gas price of $2.5/MBTU and 14% FCR financing (this is higher than the value used in the B&K study). Operation above 60% capacity factor is the usual range of CC plants. The LEC is lower for higher plant capacity factor, not only due to the contribution of low gas price, but also due to the distribution of plant costs over longer operation hours. Also shown in Fig. 7 are the corresponding LEC values for the SIT/steam and air/steam plants. The LEC of the SCOT/CC plant is about 25% lower than that of the other plants. A LEC of 6–7 ¢/kW h, achievable in the new plant design without any subsidy or future improvements (e.g. heliostat cost reduction), is considered viable for solar energy in the U.S. market today. In other markets where generation costs are higher, the solar plant could be already competitive against conventional power plants.

Figure 8 shows the separate LEC of the solar and fuel contributions for the SCOT/CC plant, computed by separate accounting of the solar costs, and assigning a part of the shared costs and O&M to each contribution, by proportion to the amount of electricity produced. The same breakdown is also presented in Fig. 8 for the SIT/steam plant. An advantage of the SCOT/CC plant over SIT/steam is seen in each category, even for fuel-derived electricity (due to the higher conversion efficiency in the CC). In spite of this advantage, it is clear that under the defined conditions, the solar component of a SCOT/CC plant is still not competitive against fossil fuel on its own.

In markets where fuel prices are higher, the competition against fuel discussed above is different. An appropriate criterion for evaluation of the competitiveness of a solar plant is the cost parity point, i.e. the cost of fuel that would render the LEC of solar-derived and fossil-derived electricity equal. Figure 9 shows that for a SCOT/CC plant, cost parity occurs at a fuel price of $13/MBTU, which may be appropriate for remote areas or countries where fuel supply is scarce. Also shown in Fig. 9 are the cost parity points for the SIT/steam and air/steam plants, showing higher LEC at their respective parity points. The lower LEC of the SCOT/CC plant, even under the same fuel price, is due to the higher efficiency of the CC relative to steam cycle power conversion in the other plants.

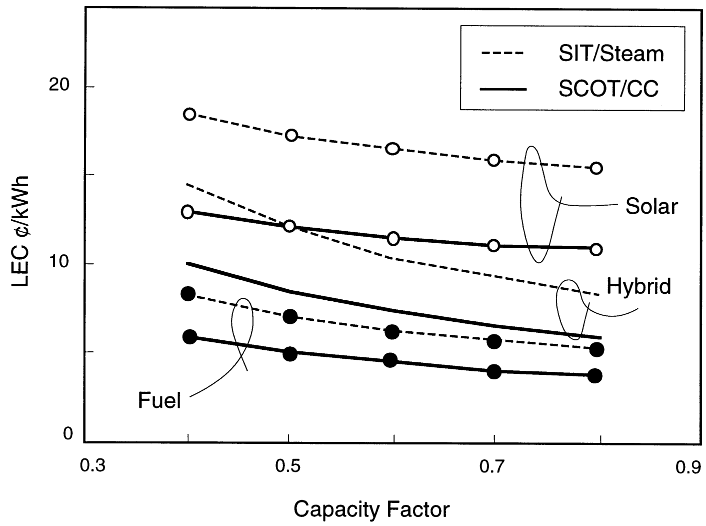

Fig. 8. Levelized energy cost of the solar-derived (open circles), fuel-derived (solid circles) and overall electricity, as a function of plant capacity factor. Solid lines: 34 MW_e SCOT/CC plant; dashed lines: SIT/steam plant. Fuel price of 2.5 $/MBTU and FCR of 14% were assumed.

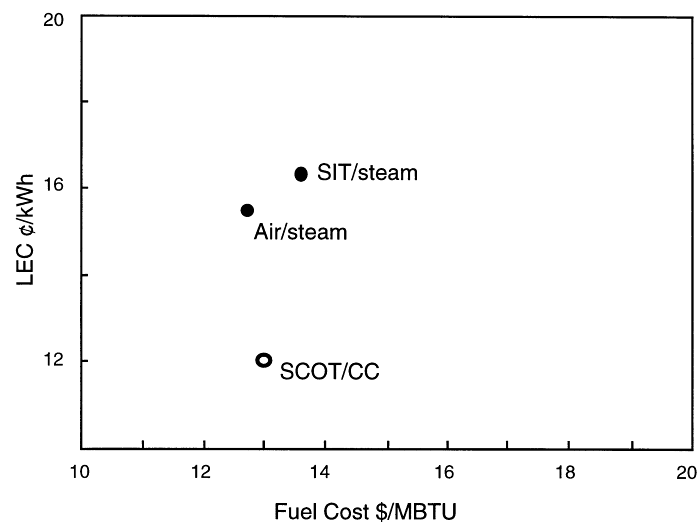

Fig. 9. Solar vs fuel LEC parity points at capacity factor of 0.6, for SCOT/CC, SIT/steam and air/steam plants.

LEC results for the small 600 kW_e plant are presented in Fig. 10. When operating in hybrid mode at a high capacity factor, this plant can achieve LEC of about 10 ¢/kW h. This is similar to the range achieved with the 30 MW_e SIT/steam and air/steam plants mentioned above, but at a much smaller scale. For solar-only operation in remote and off-grid applications, the system can be coupled with sensible-heat thermal storage, to provide installed cost of 6000–7000 $/kW, and LEC in the range of 26–32 ¢/kW h (depending on the cost of storage), at solar capacity factor of 0.4. This is very competitive against other solar-only solutions, and even against conventional solutions in the off-grid market (Moszkowicz, 1995).

6. CONCLUSIONS

The feasibility study results show that the new SCOT/CC hybrid plant technology offers the potential for high performance and low installed cost and LEC. High receiver and electrical generating efficiency provide the advantage in solar-to-electric conversion efficiency, leading to lower cost of electricity. Even at very small size, the new solar plant concept provides very attractive performance and costs,

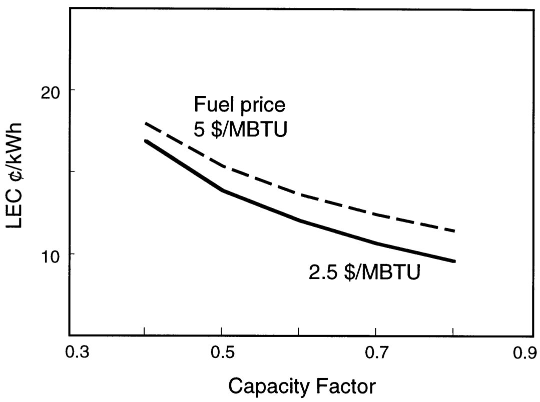

Fig. 10. Levelized energy cost for the 600 kW_e SCOT/CC plant as a function of capacity factor and fuel price.

making it suitable for distributed, remote and off-grid applications. In terms of both installed cost and levelized energy cost, the new concept may be already competitive against conventional power plants in several market niches. This holds even without any government subsidy or other cost-reduction schemes. The new SCOT/CC system concept has built-in growth capability due to its inherent scalability and modularity. This provides a unique low risk growth path from very small systems to the larger systems and expanded markets. SCOT/CC systems also offer growth following the development of modern higher efficiency gas turbines, providing compatibility with market trends and leading to a further reduction in costs.

The question of the optimal SCOT plant size was not addressed in this study. We may speculate that the optimum should be found at a plant size smaller than the 100–200 MW_e range that was identified, for example, for the SIT system. On the other hand, the high efficiency of the CC system is already available at much smaller sizes; a large SCOT power plant may then be constructed from a number of 30–50 MW_e modules without loss in performance or cost effectiveness. The optimal size issue should be considered in future studies.

Based on the promising results of this study, a joint development program has been launched led by U.S. and Israeli industry, and supported by the U.S. and Israeli governments. The goal of this program is upscaling the technologies to commercial size and constructing a SCOT/CC demonstration plant. This program is scheduled to begin in April 1997, aiming to complete the demonstration within three to four years.

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