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# SMUD Kokhala Power Tower Study



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# SMUD KOKHALA POWER TOWER STUDY

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## ABSTRACT

Kokhala is the name of a new hybridized power tower design which integrates a nitrate-salt solar power tower with a gas turbine combined-cycle power plant. This integration achieves high value energy, low costs, and lower investor risk than a conventional solar-only power tower plant. One of the primary advantages of this system is that it makes small power tower plants much more economically competitive with conventional power generation technologies. This paper is an overview of a study that performed a conceptual evaluation of a small (30 MWe) commercial plant suitable for the Sacramento Municipal Utility District's (SMUD) Rancho Seco power plant site near Sacramento, California. This paper discusses the motivation for using a small hybrid solar plant and provides an overview of the analysis methodology used in the study. The results indicate that a power tower integrated with an advanced gas turbine, combined with Sacramento's summer solar resource, could produce a low-risk, economically viable power generation project in the near future.

## INTRODUCTION

Solar thermal electric (STE) technologies currently face a difficult commercialization path given today's power generation market. Until recently it was thought that large 100-200 MWe solar-only power towers would be able to provide power at competitive prices. However, the significant drop in natural gas prices over the last 10 years, the current trend toward deregulation of the electric power utilities, the focus on least direct cost power, and the current excess of generation capacity in the Southwest have created an environment that makes it increasingly difficult for solar technologies to compete. For these reasons, we need to take new approaches to commercialize STE technologies.

One approach is to design hybrid STE power plants which use both solar and fossil energy as input to the power cycle. The Luz developed Solar Electric Generating Systems (SEGS) parabolic trough plants are an example of a hybrid solar thermal electric plant. The SEGS plants can be classified as dual-fueled Rankine steam power plants. Dual-fueled means that they can operate using heat from solar energy, fossil energy, or a combination of the two. Unfortunately these plants suffer from a relatively low fossil-to-electric conversion efficiency compared to modern gas turbine combined-cycle power plants.

Newer, more innovative hybrid designs that integrate solar technologies with fossil fired combined-cycle power plants hold much promise for the future. The Integrated Solar Combined-Cycle System (ISCCS) design uses heat from a parabolic trough solar plant to augment steam generation in the bottoming cycle of a combined-cycle power plant (Kearney, 1995). Kokhala, a new hybrid power tower design, uses solar heat from a nitrate-salt power tower to preheat the combustion inlet air on a gas turbine, thus reducing the amount of natural gas required to fire the gas turbine (Bohn, 1995). A recent variation (Bechtel, 1995) is a combination of Kokhala and the ISCCS which uses a power tower to preheat the gas turbine combustion air and to augment steam generation in the bottoming cycle.

This paper is an overview of a conceptual evaluation of a small (30 MWe) commercial Kokhala type plant suitable for the Sacramento Municipal Utility District's (SMUD) Rancho Seco power plant site near Sacramento, California.

### Kokhala

Kokhala is a Native American Hopi word that means "heat from fire and sun," symbolically describing the synergy of hybridized fossil / solar power plants. Kokhala is the name given to the combined-cycle power tower concept. The primary difference between Kokhala and a conventional solar-only power tower plant is that Kokhala uses a combined-cycle power plant in place of the Rankine steam cycle used in the solar-only plant. Figure 1 shows the Kokhala process flow diagram. The Kokhala solar plant represents a

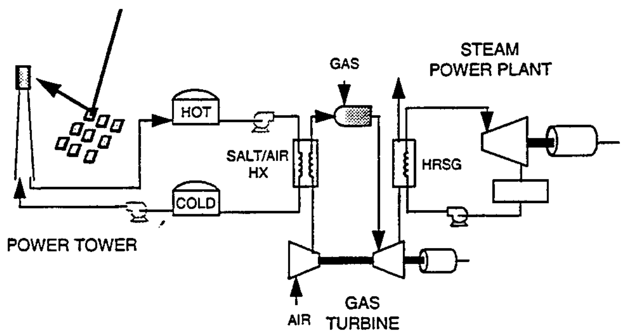


**Figure 1 Kokhala Schematic Diagram**

conventional nitrate-salt power tower plant similar to the Solar Two demonstration project in Daggett, California (SCE, 1992). The primary difference in the solar plant is that Kokhala uses a salt-to-air heat exchanger in place of Solar Two's salt/steam generation heat exchangers. The combined-cycle portion of the plant is conventional except that the high pressure (HP) compressor discharge air is spooled-off and routed through the salt/air heat exchanger and returned to the combuster inlet.

The study by Bohn (1995) evaluated 30 to 300 MWe size Kokhala plants and compared them with a 100 MWe, solar-only power tower plant. The study showed that Kokhala plants have a number of potential advantages over solar-only plants that could help the commercialize power towers. These advantages include improved operational flexibility, reduced risk, improved economics, and alternative commercialization pathways. One of the key findings of the study was that the economics of Kokhala plants were significantly better than similar sized solar-only plants. As a result, a much lower cost penalty was associated with building small Kokhala plants.

## SMUD

Until 1990, SMUD operated much like the classic integrated utility. However, a significant institutional restructuring and the closing of the Rancho Seco nuclear generating station, which provided more than half its generating capacity, forced SMUD to develop a new approach to providing their customer/owners with economical power generation and energy independence (Whitney, 1994). To solve their generation shortfall, SMUD issued a request for power. Based on the responses, SMUD decided to expand its existing demand-side management program (DSM) and to develop three blocks of new generation resources: independent power producer (IPP) operated gas turbine combined-cycle/cogeneration plants, economical transmission access to out-of-the-area resources, and advanced and renewable generation capabilities.

As part of the third block, advanced generation, SMUD has taken a lead role in the Collaborative Advanced Gas Turbine Project (CAGT), which is developing a cost-effective and high-efficiency intercooled aeroderivative gas turbine for utility power generation applications. To ensure that renewable sources of electrical generation are available, SMUD is actively supporting development of advanced technologies that show promise of economic viability in the next decade, including solar, wind, and biomass technologies.

In the process of developing these new generation resources, SMUD has moved away from the traditional centralized power generation stations to a more distributed mix of generation resources located throughout their service territory. SMUD believes this approach has provided significant benefits to both the utility and the community. For example, new cogeneration facilities provide an economic source of steam to industrial customers and reduce air emissions below those of the boilers previously used to supply steam. SMUD is firmly committed to the distributed power concept, but most large cogeneration (>100 MWe) steam-host customers in the Sacramento area have already been exhausted, and an excess of generation capacity is currently available on the Western grid. Thus, SMUD plans to focus on smaller cogeneration plants (25 MWe) which can supply the needs of smaller steam hosts.

Using small distributed generation plants requires a focus on minimizing the operation and maintenance (O&M) costs and the initial capital cost of the plants. O&M cost reductions are achieved through good plant design and by developing the plants to run with minimal on-site man-power or as an unattended plant. Capital cost savings can be achieved by building a standardized power plant design package that uses off-the-shelf parts, does not need to be optimized (re-engineered) for each site, and requires a minimum of on-site construction. The ultimate goal would be a standardized skid mounted package. This approach would also have the added advantage of potentially minimizing project development and permitting costs.

## SMUD Power Tower

As part of SMUD's development of renewable generation resources, it participates in the Solar Two project. In addition, SMUD has funded studies to evaluate a 100 MWe solar power tower sited in the Sacramento area (Bergquam, 1994). Given SMUD's focus on small distributed power plants and its interest in solar power towers, a small Kokhala plant is a potentially attractive option. To further investigate this option, a joint study between the National Renewable Energy Laboratory (NREL) and SMUD evaluated a small-scale commercial Kokhala plant.

## KOKHALA STUDY ANALYSIS

The main focus of this study was to investigate alternative design options for a small, 30 MWe scale Kokhala project located in the SMUD service area. The plant is assumed to operate at a 90% annual capacity factor. SMUD's energy pricing was used to evaluate the economic benefits of the plant. In keeping with SMUD's goal of developing standardized distributed power stations, efforts were made to develop modular plant designs and designs that are assumed to minimize O&M costs.

The general approach taken in this study was to select a specific gas turbine/combined-cycle power plant and to evaluate the trade-offs that solar field size and thermal storage would have on the economic attractiveness of the plant. In addition, to understand the potential performance impact of siting a plant in Sacramento, the analysis looked at plant sites in both Sacramento and Daggett, California. The study was broken into the following general steps: selecting and characterizing the combined-cycle power plant, developing optimized power tower solar plant designs, evaluating the solar plant thermal

**Table 1 Combined-Cycle Power Plants**

| | CC Power MWe | CC Pres. Ratio | Comp Out F | Turb In F | CC Eff. % | Solar Fract. % |
|---|---|---|---|---|---|---|
| GE PG5261 | 29 | 8 | 531 | 1698 | 41 | 39 |
| RR Avon | 20 | 9 | 583 | 1620 | 39 | 39 |
| WH 251G | 35 | 9 | 602 | 1750 | 38 | 33 |
| GE PG5371 | 39 | 11 | 623 | 1806 | 42 | 31 |
| Solar Jupiter | 21 | 12 | 667 | 1640 | 40 | 33 |
| ABB 35J | 24 | 12 | 688 | 1823 | 41 | 26 |
| ABB GT10 | 34 | 14 | 731 | 2224 | 48 | 17 |
| WH WR21* | 30 | 16 | 452 | 2370 | 46 | 27 |
| GE LM2500 | 30 | 19 | 840 | 2308 | 49 | 10 |
| UTC FT8 | 31 | 20 | 871 | 2276 | 47 | 9 |
| RR RB211 | 32 | 21 | 847 | 2135 | 46 | 11 |
| GE LM2500+ | 36 | 23 | 934 | 2388 | 49 | 4 |

* Intercooled

performance, evaluating the Kokhala plant electric performance, and performing an economic analysis. Each step is discussed in more detail in the following sections.

## Power Cycle Design

The Kokhala power plant is basically a standard combined-cycle power plant with a heat-recovery steam generator using the waste heat from the gas turbine exhaust to power a Rankine steam turbine bottoming cycle. The primary difference between Kokhala and a standard combined-cycle power plant is that solar heat is used to preheat the HP air at the inlet to the gas turbine combustor. Integrating solar in this way has the advantage of allowing the plant to operate at full load and full efficiency with or without the solar energy. Solar acts as a fuel saver in this cycle.

A limited number of gas turbines can be used in the Kokhala design because of the need to split off the high pressure air downstream of the HP compressor, route it through the salt/air heat exchanger, and return it to the gas turbine combustor. The design point solar fraction is the portion of the total energy added to the gas turbine by the solar/salt air heat exchanger. The maximum solar fraction is determined by the compressor air outlet temperature and the gas turbine inlet air temperature. Thus, raising the salt delivery temperature, lowering compressor outlet air temperature, lowering the turbine inlet air temperature, and minimizing the salt-to-air heat exchanger approach temperature will increase the solar contribution to the gas turbine cycle. Unfortunately, gas turbine cycles generally require both high compression and high turbine inlet temperature to achieve high efficiency. Higher compression results in higher compressor air discharge temperatures. Thus higher efficiency gas turbines with high pressure ratios and high turbine inlet temperatures will tend to have a lower possible solar contribution.

Table 1 presents a selection of gas turbine combined-cycle plants which are approximately 30 MWe in size and theoretically could be used for a Kokhala plant. This table is intended for comparative purposes only, and not all of the turbines listed could be adapted for the Kokhala cycle. The numbers in Table I are approximate and are based on a single pressure steam turbine bottoming cycle. Table 1 shows the size of the combined-cycle plant, the gas turbine pressure ratio, the compressor outlet air temperature, the turbine inlet air temperature, the net electric efficiency of the cycle, and the design point solar contribution for a Kokhala configuration. The table is ranked in order of increasing pressure ratios. In general it can be seen that the turbines with the lower pressure ratios have lower cycle efficiencies but larger solar contributions possible.

One practical way to increase the cycle solar contribution is to decrease HP compressor outlet temperature by providing Intercooling between low and high pressure compressor stages. The Westinghouse WR21 is the one gas turbine in table 1 which takes which takes this approach. The WR21 has a high pressure ratio and cycle efficiency, and has a high solar fraction. For these reasons the WR21 was the gas turbine selected to be used in this study.

The WR21 is currently being developed for military naval propulsion applications, but could be available for pre-commercial application by early 1998. Because the WR21 is an intercooled and recuperated gas turbine, it is an excellent candidate for a Kokhala plant. Intercooling significantly reduces the HP compressor discharge temperature and because it is recuperated it is already plumbed for the solar heat exchanger. In the absence of design data, the GateCycle program (Enter Software, 1995) was used to develop the combined-cycle design configuration for the WR21. The WR21 Kokhala combined-cycle plant generates 30.5 MWe net with a design point solar contribution of 18 $MW_t$, or approximately 27% of the total thermal input to the gas turbine.

## Solar Plant Design

Eight solar plants ranging from 10 to 70 $MW_t$, were designed to be integrated with the WR21 gas turbine combined-cycle plant described above. All solar plant designs were assumed to use a Solar-Two-type nitrate-salt external receiver with a surround solar field and round focusing 50 $m^2$ heliostats with a glass mirror reflective surface. The DELSOL3 computer code (Kistler, 1986) was used to optimize the receiver diameter and height, the tower height, and the number of heliostats for each of the eight solar plant designs. The design point optimization used a direct normal insolation of 950 $W/m^2$. Although this value allows the same design to be used in Daggett and Sacramento, the plants were designed to operate in Daggett and would be less optimal for a lower insolation environment like Sacramento. However, using this insolation value helps achieve the objective of using a single standardized design for multiple projects. Table 2 shows the solar plant design characteristics as optimized by DELSOL3. The plants have a heliostat areas ranging between 20,100 and 132,900 $m^2$.

## Solar Plant Performance

The annual thermal performance of the nitrate-salt power tower solar plants were modeled using SOLERGY (Stoddard, 1987). SOLERGY is usually used to calculate the annual electric output from a power tower plant, however, in this case it was only used to determine the thermal delivery of the nitrate-salt solar plant to the combined-cycle power plant. Input assumptions were based largely on the Sandia and DLR Second Generation Central Receiver

**Table 2 DELSOL Plant Design Characteristics**

| Plant Size | $MW_t$ | 10 | 15 | 20 | 30 | 40 | Solar Two 42.2 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|---|---|---|
| Receiver Diameter | m | 2.7 | 3.5 | 3.7 | 4.8 | 5.2 | 5.1 | 5.8 | 6.3 | 7.1 |
| Receiver Height | m | 3.2 | 3.8 | 4.4 | 5.3 | 6.2 | 6.2 | 7.0 | 7.6 | 7.8 |
| Tower Height | m | 28 | 34 | 40 | 47 | 53 | 64 | 59 | 64 | 69 |
| Heliostats | # | 421 | 599 | 789 | 1176 | 1587 | 1926 | 1984 | 2390 | 2781 |
| Heliostat Area | $m^2$ | 20,100 | 28,600 | 37,700 | 56,200 | 75,800 | 81,400 | 94,800 | 114,200 | 132,900 |
| Land Area | $km^2$ | .39 | .47 | .54 | .74 | .95 | .53 | 1.12 | 1.32 | 1.50 |

Technology Study (Becker, 1993), and the Sandia SOLERGY inputs for the Solar Two project (Kolb, 1995).

The annual performance of each of the eight solar plant designs was evaluated for plants located in Sacramento and Daggett, CA. Both locations were included because Daggett is the location of the Solar Two project and is generally considered one of the best solar sites in the US. The solar radiation data was taken from the National Solar Radiation Data Base (NREL,1992). For the Sacramento location, cases with and without thermal storage were evaluated. Only plants with thermal storage were evaluated for Daggett.

For the cases with thermal storage, the amount of storage was chosen to eliminate the necessity of defocusing heliostats due to fully charged storage, with an upper limit of 24 hours of equivalent full-load salt/air heat exchanger operation (423 $MWhr_t$). Thermal storage ranged between 0 and 423 $MWhr_t$, depending on the size of the solar plant.

## Kokhala Plant Electric Performance

The next step in the analysis is to determine the electric performance of a Kokhala plant given the thermal input from each solar plant. A spreadsheet model was developed to evaluate the performance and economics of the Kokhala plant. The model imports 15-minute solar-plant thermal values from SOLERGY and calculates the annual electric production level supported by solar. Natural gas is allocated to support this level of operation and then added to achieve the 90% annual capacity target.

With hybrid solar/natural gas plants, it is useful to know the fraction of energy provided from solar. Typically this can be evaluated at the design point and on an annual basis. The Kokhala cycle studied here has a maximum design solar fraction of 27% (i.e., 27% of the energy to the power cycle comes from solar energy). The annual solar fraction, the amount of energy that comes from solar energy on an annual basis, varies with the solar field size, amount of thermal storage, and the location of the plant. The annual solar fractions for the Sacramento plants with storage range from 3% and 18% depending on the size of the solar field. The Barstow cases achieved annual solar fractions as high as 24%. The Sacramento cases without thermal storage only achieved annual solar fractions of up to 8%.

## Economic Analysis

The final step of the Kokhala analysis is to perform an economic analysis for each plant configuration. The economic analysis includes developing capital and O&M costs for each plant, determining the value of the electric production, and calculating the appropriate figures of merit.

The capital and O&M costs of the solar plants were based on the Utility Central Receiver Studies (APS & PG&E, 1997) and the Sandia/DLR Second Generation Study (Becker, 1993). Since a large uncertainty exists as to the cost of heliostats for a relatively small build, assumptions between $120/m$^2$ and $250/m$^2$ were evaluated. The capital and O&M costs for the conventional combined-cycle plant equipment were based on SMUD estimates. The capital cost of a Kokhala plant with a 40 MWt solar plant, roughly the size of Solar Two, was about $77 million (assuming heliostat cost of $250/m$^2$), with an annual O&M cost of $2.3 million. The solar equipment represents approximately 50% of the plant capital cost and 25% of the O&M cost.

The value of the power produced was calculated using SMUD's June 1994 Marginal Cost Study (SMUD, 1994). SMUD's energy tariff structure is set up to pay a more for electricity generated from renewable energy technologies to account for the environmental benefits (e.g., reduced air pollution emissions). Two tiers currently exist, a low renewable-energy rate for wind power, and a high renewable-energy rate for PV power. This study evaluated benefits using the high renewable-energy rates for the solar portion of the electricity generated. SMUD has also developed its capacity payments to help account for distributed power generation benefits. A 30 MWe Kokhala plant is assumed to benefit from the first level of transmission capacity benefits. A detailed description of all capital, O&M, and economic assumptions are presented in the final report of the SMUD Kokhala Power Tower Study (Price, 1996).

In this study, three economic figures of merit were evaluated: the levelized energy cost (LEC), the solar levelized energy cost (SLEC), and a benefit-cost (BC) ratio. The LEC represents the average cost of electricity produced from the Kokhala plant in 1995 dollars. Because the low cost of fossil energy tends to dilute the LEC of hybrid plants with relatively small solar contributions, it is often desirable to look at the LEC for the solar-generated electricity or SLEC. The SLEC is calculated by including the cost of the solar equipment, solar O&M, and a pro-rated share of the conventional plant capital and O&M costs. For example, if 20% of the annual energy input to the plant comes from solar energy, then the SLEC includes 20% of the conventional plant capital and O&M cost, plus all of the solar related capital and O&M costs. The BC ratio is the primary financial figure of merit used by SMUD to evaluate new projects. The BC ratio compares the benefits, the present value of all the energy and capacity payments of the power produced during the project lifetime, to the costs. The costs are the present value of all costs over the project life. A BC ratio of 1.0 would mean the project meets the minimum economic criteria required by SMUD. The higher the BC ratio, the more attractive the project.

**Table 3 SMUD Kokhala Study Results**

| | Case 0 Gas Only | Case 1 Sacto. with Stor. | Case 2 Sacto. no Stor. | Case 3 Daggett with Stor. |
|---|---|---|---|---|
| Solar Plant Size ($MW_t$) | 0 | 50 | 20 | 50 |
| Thermal Storage ($MWhr_t$) | | 388 | 5 | 423 |
| Annual Efficiencies | | | | |
| Heliostat Field | | 0.571 | 0.565 | 0.562 |
| Receiver | | 0.776 | 0.787 | 0.791 |
| Storage | | 0.978 | 0.985 | 0.983 |
| Salt HX | | 0.999 | 0.995 | 0.999 |
| **Total Solar** | | **0.433** | **0.436** | **0.437** |
| Gross Solar to Electric | | 0.201 | 0.202 | 0.203 |
| Net Solar to Electric | | 0.193 | 0.191 | 0.196 |
| Annual Solar Fraction (%) | 0 | 15 | 6 | 21 |
| Economics | | | | |
| LEC (¢/kWhr) | 4.3 | 4.9 | 4.6 | 4.8 |
| SLEC (¢/kWhr) | | 8.6 | 10.1 | 6.8 |
| Benefit/Cost Ratio | 1.00 | 0.97 | 0.97 | 1.03 |

## RESULTS

The stacked bar chart in figure 2 shows the LEC for plants in Sacramento with thermal storage. Each bar is split to show the relative contribution to the LEC from the capital and O&M costs of the conventional power plant, the fossil fuel cost, and the capital and O&M costs of the solar plant. The first bar on the left represents a gas-only combined-cycle plant with an LEC of 4.3¢/kWhr. The remaining bars represent the LEC for each of the eight Kokhala plants evaluated. A reduction in the cost of fuel can be observed as the solar field size increases. Likewise, an increase in solar field capital and O&M costs can also be observed. Unfortunately the increase in solar field costs are greater than the reduced fuel cost. Thus the LEC increases with increasing solar field size. Figure 3 shows the LEC (the same as figure 2) and the SLEC for each plant. The SLEC reaches a minimum with solar plant sizes of 50 to 60 MWt.

Figure 4 shows the SLECs for each of the cases evaluated in this study: Sacramento with storage (the same as figure 3), Sacramento without storage, and Daggett with storage. The Sacramento case without storage has a minimum SLEC for a solar plant size of about 20 MWt. This corresponds to the 18 MWt heat input required by the gas turbine. Without storage, a significant amount of heat is dumped for solar fields larger than 20 MWt. It is interesting to note that Sacramento plants with storage were able to achieve a lower SLEC than plants with no storage. Also the Daggett case shows a fairly significant reduction in SLEC over both of the Sacramento cases due greater incident solar radiation.

Figure 5 shows the BC ratios for each of the three cases. In each case, the BC ratios reach their maximum at approximately the same point the SLECs were at a minimum. The Sacramento plants with storage resulted in a slightly higher BC ratio than the Sacramento plants without storage. Unfortunately only the Barstow case resulted in BC ratios above 1.0. However, figure 6 shows that a BC ratio of 1.0 can be achieved in Sacramento when heliostat costs drop below $\$180/m^2$.

Table 3 summarizes optimum solar field size for each of the three cases analyzed. The plant size is the one which had the maximum BC ratio. Table 3 shows the solar plant size, the amount of thermal storage, a breakout of the annual system efficiencies, the annual solar fraction, and the economic figures of merit. The optimum solar field size was 20 $MW_t$ for the Sacramento case with no storage and 50 $MW_t$ for the cases with thermal storage. The Kokhala plants have an annual solar to net electric efficiency of about 19% with annual solar fractions between 6% and 21%, and solar LECs of about 7-10 ¢/kWhr depending on configuration and location. The most significant result of the study is that the BC ratios that SMUD uses to evaluate new projects were very near or even greater than 1.0 for each of the cases analyzed.

## CONCLUSION

This study was a first attempt to evaluate a 30-$MW_e$ Kokhala hybrid power tower plant for Sacramento, California. Based on the analysis presented here, it is possible that a Kokhala plant could be built economically in Sacramento. Given SMUD's expected request for renewables in 1996, a real opportunity may exist to build a commercial Kokhala hybrid power tower plant in the near future

The analysis presented here is based on a number of assumed and potentially aggressive capital and O&M cost assumptions for both the solar and conventional portions of the Kokhala power plant. Further analysis is required to fine tune these numbers. It might also be desirable to perform a more detailed analysis of the concept, including some corrections in the parasitic loads and optimization of the amount of thermal storage and the size of the heliostats. However, these impacts are probably small compared with the potential error inherent in the capital and O&M cost assumptions.

For a small Kokhala project to have any chance of success, a significant effort must focus on designing a solar plant that minimizes O&M costs and developing a source of low-cost, reliable heliostats.

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**Figure 2 LEC for Sacramento Plants with Storage**

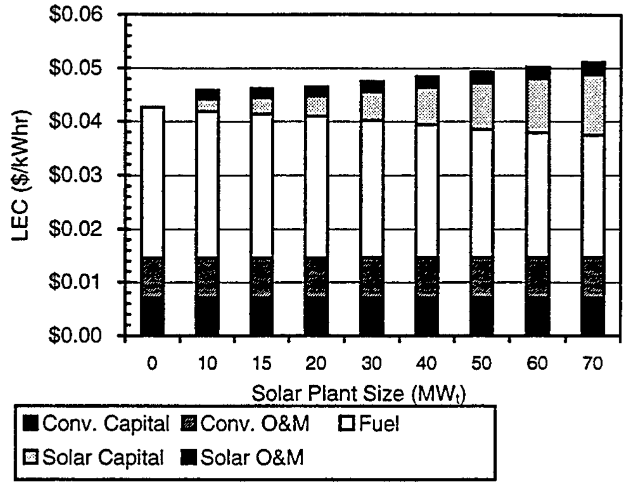



**Figure 3 LEC and Solar LEC for Sacramento Plants with Storage**

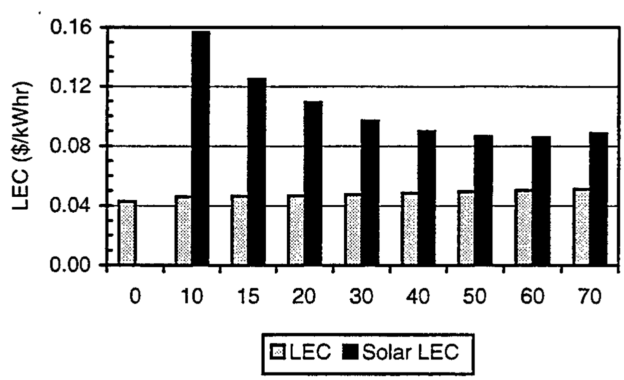


Figure 4 Solar LEC for Each Case

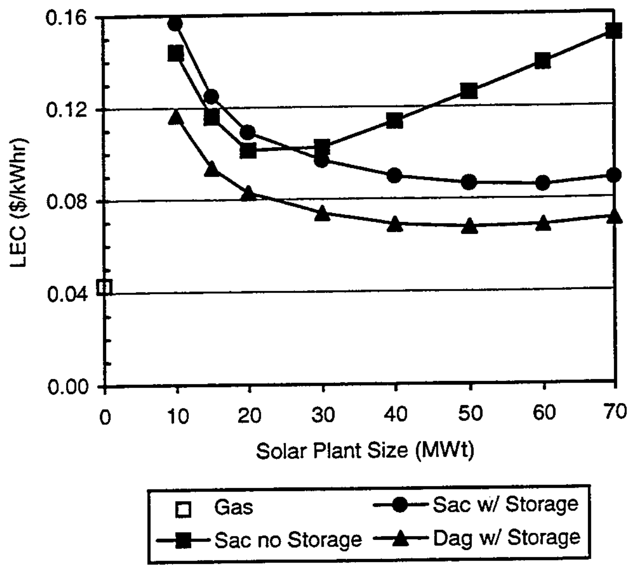



Figure 6 SMUD Benefit Cost Ratio

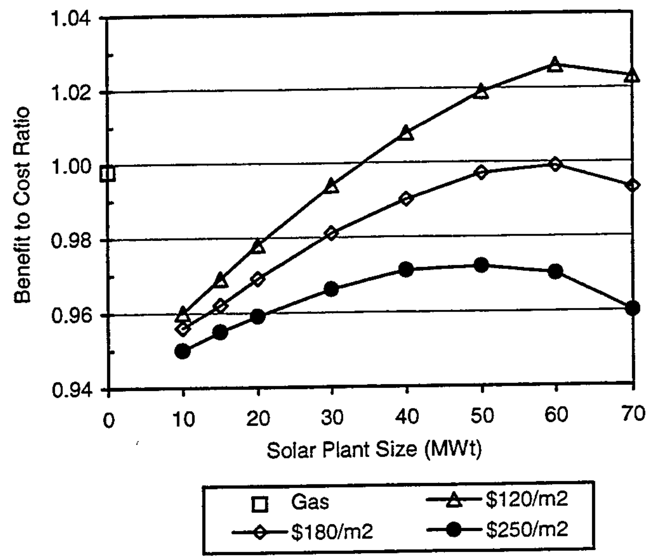
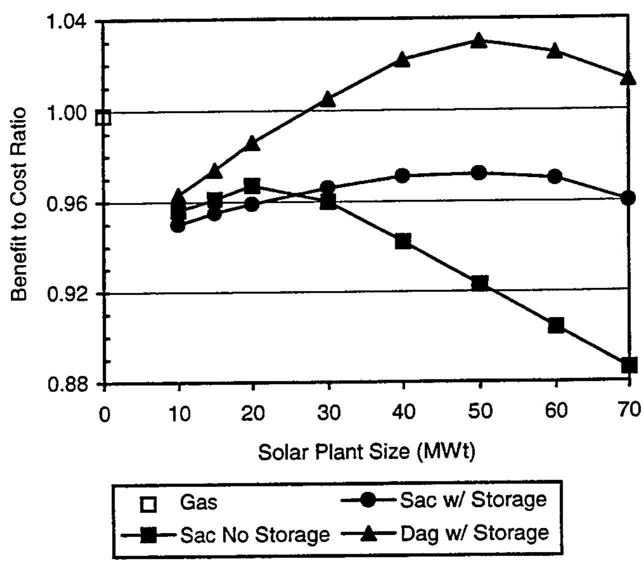



Figure 5 SMUD Benefit Cost Ratio



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