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ABSTRACT

The continued drop in energy prices and restructuring of the utility industry have reduced the likelihood that a follow-on commercial 100-MW$_e$ power tower project will be built immediately following the Solar Two demonstration project. Given this, it would be desirable to find a way to extend the life of the Solar Two project to allow the plant to operate as a showcase for future power tower projects. This paper looks at the possibility of converting Solar Two into a commercial Kokhala hybrid power tower plant at the end of its demonstration period in 1998. The study identifies two gas turbines that could be integrated into a Kokhala cycle at Solar Two and evaluates the design, expected performance, and economics of each of the systems. The study shows that a commercial Kokhala project at Solar Two could produce power at a cost of less than 7 ¢/kWhr.

INTRODUCTION

Solar Two is a 10-MW$_e$ nitrate salt solar power tower demonstration project located in Daggett, California. It is a key element of the industry plan to commercialize nitrate salt power tower technology. The primary goal of the Solar Two project is to reduce the perceived technical and economic risks associated with building the first commercial nitrate salt power tower plants. The initial plan called for the Solar Two project to operate for three years, one year for testing and two years for power production. At the end of this time it was thought that the technology would be tested sufficiently to allow the construction of the first commercial 100-MW$_e$ plants. The next step in the plan called for a number of southwestern U.S. utilities, which are participants in the Solar Two project, to build the first commercial 100-MW$_e$ plants. Unfortunately, due to the changing roll of utilities in the power generation market, the low cost of natural gas, and the glut of generating capacity in the Southwest, it seems unlikely that any of these utilities will be able to build the first plants. Given the high demand for new power in developing countries, the first power tower opportunities could be in international markets. Because there is likely to be a delay between the completion of the Solar Two demonstration and the construction of the first commercial plant, it would be desirable to extend the operation of Solar Two to allow it to be used as a showcase for power tower technology.

In recent years, there has been a significant focus on opportunities for hybridizing solar thermal electric technologies as a way of reducing initial costs and risks of projects. Some of the more innovative approaches include integration with gas turbines. One option is to use Solar Two to demonstrate one of the gas turbine hybrid options for power towers. This paper looks at the possibility of converting Solar Two into a commercial Kokhala hybrid power tower plant at the end of its current demonstration period.

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 hybrid power tower concept that integrates a power tower with a gas turbine combined-cycle plant and uses solar energy to preheat the gas turbine combustion inlet air. Figure 1 shows the Kokhala process flow diagram. The Kokhala solar plant is a conventional nitrate salt power tower plant except that it uses a salt-to-air heat exchanger (HX) in place of the salt/steam generation heat exchangers. The combined-cycle portion of the plant is conventional except that the gas turbine's high-pressure compressor discharge air is spooled off and routed through the salt-to-air heat exchanger and returned to the combustor inlet.

Kokhala power tower plants were first evaluated (Bohn et al, 1995) as a way to integrate today's nitrate salt power tower technology with modern high-efficiency combined-cycle power plants. Kokhala power plants offered an attractive way to reduce the risk of the new solar technology to investors, decrease the capital investment required to build the first commercial plant, and reduce the resulting cost of solar-generated electricity. Small Kokhala power tower plants were first studied (Price et al, 1996) as a way to

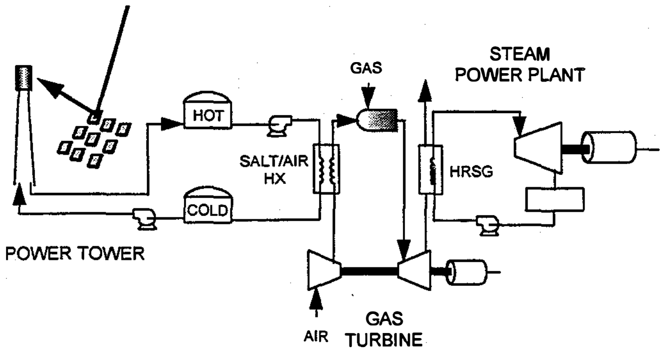

Figure 1 Kokhala Schematic Diagram

economically build small distributed solar power tower plants in the Sacramento Municipal Utility District (SMUD) service territory. The conversion of Solar Two to a commercial Kokhala plant was initially proposed by Kolb (1995b). Kolb looked at integrating a small intercooled recuperated gas turbine, the same gas turbine used in the SMUD study, with the Solar Two plant and operating it for 20 years. Based on the Southern California Edison (SCE) energy and capacity projections at the time, the project appeared to just pay for itself.

This analysis is an updated look at conversion of Solar Two to a Kokhala plant based on updated economic assumptions and more in-depth analysis of gas turbine options and solar plant performance.

SOLAR TWO KOKHALA ANALYSIS

This study looks at the selection of appropriate gas turbines for integration into a Kokhala cycle at Solar Two, the sizing of the salt-to-air heat exchanger, characterization of the performance of the combined-cycle plant in Barstow, California, modeling of the annual performance of the solar plant, calculation of the Kokhala plant annual net output, an estimation of the capital and operation and maintenance (O&M) costs, and an economic analysis of an independent power producer (IPP) type project. Finally, conclusions about the best gas turbine options and the potential economic viability of the project are presented.

Gas Turbine Selection

A number of criteria were used to identify the best gas turbine options for integration at Solar Two. The gas turbine needs to be appropriately sized such that the amount of solar energy delivered by Solar Two is a good match to preheat the gas turbine combustor inlet air. The gas turbine should be sized so that the existing Solar Two steam turbine can be used for the gas turbine's bottoming cycle. The gas turbine should be able to be adapted into a recuperative type configuration so that the high-pressure air can be spooled off to the solar heat exchanger and returned to the combustor. To minimize the impact on the Solar Two nitrate salt system, the air temperature entering the salt-to-air heat exchanger must be low enough to allow the cold salt to operate near its 288°C design point. The GateCycle program (Enter Software, 1995), a sophisticated program used to evaluate gas turbine and combined cycle plants, was used to evaluate the combined-cycle efficiencies and other operating parameters for 13 gas turbines representing all major gas turbine vendors. Table 1 lists the gas turbines that were considered for use at Solar Two. Two gas turbines were identified to be well suited for application in a Kokhala configuration at Solar Two: the Northrop Grumman/Rolls Royce WR21 and the General Electric (GE) PG5261.

WR21. The WR21 is an intercooled recuperated gas turbine that is currently being developed for Department of Defense marine

Table 1 Gas Turbine/Combined-Cycle Options[1]

	Power Output						Gas			Gas
Turbine	Gas Turbine MW$_e$	Steam Turbine MW$_e$	Combined Cycle MW$_e$	Combined Cycle Effic. %	Gas Turbine Pres. Ratio	Compressor Outlet Temp. °C	Turbine Inlet Temp. °C	Solar Heat Exchanger MW$_t$[2]	Solar Fraction %[2]	Turbine Outlet Temp. °C
GE PG5261	**16.8**	**12.2**	**29.0**	**41**	**8**	**277**	**926**	**28**	**39**	**522**
RR Avon	14.0	6.5	20.5	39	9	306	882	20	39	446
WH 251G	21.4	13.7	35.1	38	9	317	954	30	33	465
Allison 501-KB5S	4.1	1.7	5.8	41	10	321	1093	4	27	552
GE PG5371	25.8	13.8	39.6	42	11	328	986	29	31	493
Solar Jupiter	16.5	9.7	21.2	40	12	353	893	17	33	379
ABB 35J	18.4	6.3	24.7	41	12	364	995	16	26	414
ABB GT10	23.8	10.5	34.3	48	14	388	1218	12	17	541
WR21[3]	**19.8**	**7.6**	**27.4**	**47**	**14**	**246**	**1221**	**18**	**28**	**538**
GE LM2500	22.2	8.6	30.8	49	19	449	1264	6	10	531
UTC FT8	24.6	7.3	31.9	48	20	466	1247	6	9	450
RR RB211	26.2	10.2	36.4	48	21	453	1264	8	11	494
GE LM2500+	26.9	9.7	36.6	49	23	501	1309	3	4	510

[1] Data at standard air conditions: 15°C and 101 kPa.

[2] Assumes Solar HX Outlet Air Temperature of 538°C.

[3] Intercooled.

mechanical drive applications. Northrop Grumman recently purchased the division at Westinghouse that developed this engine jointly with Rolls Royce and is currently considering whether to develop a commercial version of this engine for power generation applications (Anson, 1996). The commercial version would be repackaged for industrial applications, it would require some blade material changes to increase the time between service, and the combustor would need to be modified for natural gas and low NOx burners.

The WR21 is intercooled and recuperated, which makes it a good choice for a Kokhala plant. In a Kokhala configuration the WR21's recuperator would be replaced with the nitrate salt-to-air heat exchanger and the gas turbine exhaust would be piped to a heat recovery steam generator. The WR21 was the gas turbine used in the SMUD Kokhala study. In the SMUD study the Solar Two solar plant was found to be near the optimum size for use with this gas turbine; however, the thermal storage volume at Solar Two is only half as large as the volume identified by the study that would be needed to avoid dumping solar energy. This is because the solar energy delivered to the gas turbine is less than the thermal input required by the current Solar Two steam turbine.

GE PG5261. The PG5261 is an older GE frame-5 gas turbine with a lower pressure ratio than the current PG5371 frame-5. Many of these units have been installed as gensets and as mechanical drives for gas pipeline compressor stations. The 2-shaft MS5000 mechanical drive variant on the PG5261 can be configured in a recuperative cycle and connected to a generator. The PG5261 is not currently available directly from GE but is still marketed by other licensed GE original equipment manufacturers. Due to the large number of units sold around the world it is possible that a used gas turbine could be purchased and then be rebuilt and modified to a recuperative configuration. The GE gas turbine offers a potentially cheaper alternative to the WR21 but with an impact on efficiency. The newer PG5371 frame-5 is a less desirable match for the operating temperatures at Solar Two.

Temperature and Elevation Correction

Gas turbine and combined-cycle performance is adversely affected at higher elevation and higher ambient temperatures. During the summer, air temperatures in Daggett, California, are significantly higher than the gas turbine rating temperature of 15°C. Figure 2, found on the last page, shows a GateCycle analysis of the power output and efficiency of a GE PG5261 combined-cycle plant operating at standard conditions and over a range of ambient temperatures for a plant located in Daggett. Figure 2 also shows power output and efficiency for a gas turbine combined-cycle plant with inlet air evaporative cooling. For the conventional plant, power output and efficiency both drop significantly at the higher temperatures that the plant would be operating at during the summer in Daggett. The system with evaporative cooling shows decreased sensitivity of power output and heat rate to air temperature. For purposes of this analysis, the Solar Two Kokhala plant is assumed to use evaporative inlet cooling on the gas turbine, and the gas turbine power and efficiencies were corrected to an elevation of 610 m (air pressure of 94 kPa) and an ambient temperature of 27°C. The corrected output and efficiency for each gas turbine is shown in Table 2.

Table 2 Solar Two Kokhala Design and Performance

	General Electric PG5261	Northrop Grumman WR21
Gas Turbine Characteristics[1]		
Gas Turbine Net Output (MW$_e$)	15.3	18.7
Steam Turbine Output (MW$_e$)	11.2	7.2
Total Combined Cycle Output (MW$_e$)	**26.5**	**25.9**
Combined Cycle Efficiency (%)	39.8	44.9
Solar HX Input (MW$_t$)	25.8	16.8
Solar Fraction (%)	38.8	29.2
Salt-to-Air Heat Exchanger Design		
Heat Exchanger Area (m^2)	2700	2700
Cold Air Temperature (°C)	277	246
Hot Air Temperature (°C)	536	546
Hot Salt Temperature (°C)	566	566
Cold Salt Temperature (°C)	305	291
Air Side Pressure Drop (kPa)	76	29
Solar Plant Thermal Performance		
Annual Direct Normal Insolation (kWhr/m^2)	2707	2707
Solar Input (MWhr$_t$)	220,351	220,351
Solar Heat to HX (MWhr$_t$)	80,277	69,326
Solar Thermal Efficiency (%)	36.4	31.5
Annual Electric Performance		
Solar Electric Generation (MWhr)	30,838	30,419
Fossil Electric Generation (MWhr)	86,466	99,347
Total Electric Generation (MWhr)	**117,304**	**129,766**
Annual Capacity Factor (%)	50.5	57.2
Annual Solar Fraction (%)	26.3	23.4
Solar to Electric Efficiency (%)	14.0	13.8

[1] Corrected for Daggett site elevation (610 m) and average summer air temperature (27°C).

Salt-to-Air Heat Exchanger Sizing

An ABB Lummus APEX (Advanced Plate Exchanger) heat exchanger design was assumed for the salt-to-air heat exchanger. The APEX heat exchanger is a fully welded stainless steel plate-type heat exchanger core installed inside a conventional carbon steel heat exchanger shell. A heat exchanger sizing program was developed to evaluate the effect of the heat exchanger area on gas turbine and solar plant performance. The heat exchanger area was adjusted to obtain a cold nitrate salt temperature near 288°C, the maximum hot air temperature leaving the heat exchanger, and the minimum air side pressure drop. The results are shown in Table 2. The WR21, with its lower cold air temperature, integrates better with the nitrate salt system at Solar Two. Use of the GE gas turbine would result in a slight increase in the cold salt operating temperature due to the higher compressor air discharge temperature and the higher solar thermal duty requirements. However, the Solar Two design should be able to accommodate the increased cold salt operating temperature (Kelly, 1996).

Calculation of Plant Annual Performance

The SOLERGY performance code (Stoddard et al, 1987) was used to model the Solar Two solar plant and thermal storage system (Kolb, 1995a). SOLERGY was configured to maximize solar output and not to dispatch power for peaking. Table 2 shows the annual solar input to the plant and the solar thermal energy transferred to the gas turbine salt-to-air heat exchanger. The energy delivered to the gas turbine varies significantly between the two gas turbine cases because the existing nitrate salt thermal storage system is undersized for the WR21. The WR21 Kokhala plant collects approximately 12% less solar energy on an annual basis because the gas turbine cannot use the solar energy fast enough to keep up with the solar plant thermal collection. As a result, the solar plant is shut down about 12% of the time because the thermal storage system is full due to the size of the existing storage tanks.

A separate model is used to calculate the electric output and to evaluate the project economics. This model imports 15 minute output data from SOLERGY to determine when solar energy is delivered to the gas turbine. Gas use is filled in to support the solar operation and then to support the desired gas operation strategy. A more detailed discussion of the operating strategy is presented in the next section. Table 2 shows the annual solar and gas net electric output of each gas turbine system. Although the WR21 has a slightly lower net electric capacity, its annual electric output is greater due to increased power generation during summer and winter off-peak periods. Interestingly, the annual solar-to-electric efficiencies are almost the same even though there is a large difference between the solar-to-thermal efficiencies.

Economic Analysis

For purposes of this study, it was assumed that the Solar Two extension project would be structured as an IPP. The project would be funded with private debt (mortgage) and equity (ownership) and guarantee market rates of return to investors. Table 3 lists the primary economic assumptions used.

Table 3 Economic Assumptions

Project Lifetime	5-20 years
First Year of Operation	1999
Effective Discount Rate	13.4%
Fuel Escalation Rate	3.5%
Capital and O&M Cost Escalation Rate	3.0%
Effective Federal & State Income Tax Rate	38%
Property Tax & Insurance	1%
Solar Investment Tax Credits	0%

Energy Pricing The power produced is assumed to be sold to Southern California Edison (SCE), the local utility. Given the current restructuring of power utilities, there is a large uncertainty as to what prices will be paid to generators in the future. For this analysis, the energy pricing is based on the current 1996 SCE avoided cost energy and as-available capacity pricing. Future SCE avoided cost energy price projections were calculated assuming the 1996 gas price of $2.20 per MMBtu higher heat value (HHV) with 3.5% inflation and constant SCE system heat rates. The as-available capacity prices were assumed to remain constant at the 1996 levels. Based on these assumptions, the average price paid for power over the life of the project is expected to be between 2.6 and 2.8 ¢/kWhr in 1996 dollars.

Solar and Gas Operation Strategy. In general an IPP power plant is operated whenever its marginal cost of generating electricity is lower than the price paid for the electricity. The marginal cost to operate includes variable O&M costs and fuel costs. In the case of a Kokhala plant the marginal cost to operate is different depending on whether solar energy is available or not. Table 4 shows the marginal cost to operate the Kokhala plants with and without solar during the first year of operation. The difference is due to the reduced gas consumption when solar is available. Table 4 also shows the prices

Table 4 First Year of Operation Electric Rates and Marginal Operating Costs

		General Electric PG5261		**Northrop Grumman WR21**	
		Gas Only	**With Solar**	**Gas Only**	**With Solar**
Marginal Cost to Operate (¢/kWhr)		2.49	1.68	2.26	1.71
Projected Utility Time-of-Use Energy & Capacity Rates	**Price Paid ¢/kWhr**	**Operate Plant**	**Operate Plant**	**Operate Plant**	**Operate Plant**
Summer On-peak	4.66	Yes	Yes	Yes	Yes
Summer Mid-peak	2.66	Yes	Yes	Yes	Yes
Summer Off-peak	2.13	No	Yes	No	Yes
Winter Mid-peak	3.01	Yes	Yes	Yes	Yes
Winter Off-peak	2.39	No	Yes	Yes	Yes
Winter Super Off-peak	1.97	No	Yes	No	Yes

the utility is expected to pay for avoided cost energy and as-available capacity during each time-of-use period. Based on these rates the plants can be economically operated in gas mode during summer on-peak and summer and winter mid-peak time-of-use periods. Also, due to the higher efficiency of the WR21 it can be operated at a profit in gas mode during winter off-peak time-of-use periods.

The solar plant should be operated to collect thermal energy whenever the sun is available. Because the marginal cost of operation with solar is always lower that the price paid for power, the combined-cycle plant should be operated whenever necessary to make sure that the solar plant does not have to dump energy when the solar thermal storage system is full. To maximize the net revenues generated by the plant, the use of solar thermal energy should always be prioritized for use first during the higher rate periods where the use of gas is economic. Only when solar energy cannot be saved for use during the higher rate periods should it be used during the lower priced rate periods. Using this strategy, the plants would be operated at an annual capacity factor of between 50 and 60% as shown in Table 2.

Capital Cost. The capital cost estimate is intended to be a first order of magnitude estimate of the cost required to retrofit the Solar Two project into a commercial Kokhala project. The cost estimate includes: upgrades to the heliostat field and receiver; purchase and installation of the salt-to-air heat exchanger, piping, gas turbine, heat recovery steam generator (HRSG), natural gas pipeline, and the switch yard interconnection; and engineering and procurement costs. The Solar Two heliostat field is approximately 15 years old, so some upgrades to the existing field are necessary to assure the high reliability of the field for the duration of the project. The Solar Two nitrate salt receiver has only a 5-year design lifetime. The project includes the cost to upgrade the Solar Two receiver to the next generation receiver. The salt-to-air heat exchanger cost assumptions are based on an ABB Lummus design for their APEX plate heat exchanger. The gas turbine costs are based on greenfield turnkey costs. The GE gas turbine cost is based on the manufacturer's quote. The WR21 gas turbine assumes the manufacturer's estimated price for the tenth unit built. Other cases were also considered in the study including a refurbished GE system and a WR21 system that included the full gas turbine development cost. A summary of capital costs is shown in Table 5.

O&M Costs. The O&M costs were developed by evaluating the solar and gas turbine O&M costs separately. The solar O&M costs were based on the utility central receiver studies, and the gas turbine O&M costs were based on IPP O&M cost data provided by SMUD. The O&M cost figures were factored up to account for the higher than normal expected costs for keeping Solar Two operational. The projected O&M cost for the Kokhala plant are approximately the same as the current operating costs of the Solar Two project.

RESULTS

The levelized energy costs (LECs) were calculated for the blended (average of the solar and gas) cost of power produced by the Kokhala plant. LECs were also calculated for the gas only power and solar only power. A breakdown of each of the LECs into its capital, O&M, and fuel components is shown in Table 5 for a project with a 20-year life expectancy. A Kokhala plant operated for 20 years at a 50% annual capacity factor would produce power at about 5.5 ¢/kWhr from gas and about 11 ¢/kWhr from solar resulting in a blended cost of power of about 7 ¢/kWhr. Figure 3, found on the last page, shows how the blended and solar LECs would vary for reduced project lifetime.

Table 5 Solar Two Kokhala Economic Analysis

	General Electric PG5261	Northrop Grumman WR21
Capital Cost (M$)		
Solar Equipment	8	8
Electric Power Generation System	10	15
Indirect	2	2
Total	**20**	**25**
Blended LEC ($/kWhr)		
Capital	0.027	0.031
Fuel	0.016	0.015
O&M	0.024	0.022
Total	**0.068**	**0.068**
Gas Only LEC ($/kWhr)		
Fuel	0.022	0.019
O&M	0.017	0.016
Total	**0.054**	**0.056**
Solar LEC ($/kWhr)		
Capital	0.060	0.065
Fuel	0.000	0.000
O&M	0.044	0.043
Total	**0.104**	**0.109**
Subsidy per kWhr ($/kWhr)		
Blended Power	0.040	0.041
Gas Power	0.027	0.029
Solar Power	0.077	0.082
Subsidy - Lump Sum (M$)		
One Time	38.5	45.4
Annual Payment	5.6	6.6

The levelized energy costs for either system are greater than the price received from the utility. Thus both projects require some form of subsidy to make a potential IPP project attractive. Table 5 shows the subsidy that would be required for each system. The subsidies are shown in several formats: a uniform $/kWhr for every blended kWhr produced, the same subsidy but split out by gas and solar power, a lump sum one-time value, and an annual lump sum subsidy. Note that even the gas only production requires a subsidy. This is primarily due to the small size of the Solar Two project, which results in a high O&M cost per kWhr of electricity produced and a relatively low gas-to-electric efficiency.

CONCLUSIONS

Two gas turbines, the GE PG5261 and the Northrop Grumman WR21, appear to be well suited for application in a Kokhala configuration at Solar Two. Based on either of these gas turbines, the Solar Two Kokhala project would have a net rating of about 26 MW$_e$, be operated to an annual capacity factor of about 50%, and have an annual solar contribution of about 25%. Although the intercooled

WR21 has a higher efficiency and is better matched for integration with the nitrate salt operating temperatures at Solar Two, the smaller thermal contribution by the salt-to-air heat exchanger results in dumping over 11% of the annual solar thermal input to the plant, resulting in a slightly higher annual solar electric output from the GE plant. It is clear that the development cost to convert the WR21 to an industrial machine cannot be economically borne by the project. The projected price for a WR21 in commercial production is competitive with a new GE PG5261 due to the higher efficiency of the WR21. However, a used GE PG5261 could probably be found for significantly less than a new unit and thus would provide the best economics.

The projected value of SCE's current avoided cost energy and as-available payments over the next 20 years is about 3 ¢/kWhr in 1996 dollars. Given a blended LEC of 7 ¢/kWhr for a Kokhala project, the revenues fall significantly short of providing the income necessary to make an attractive IPP project. A successful IPP project would need to be significantly subsidized.

The O&M costs are very high for both the solar and gas portions of the plant and significantly impact the resulting levelized energy cost. Some effort should focus on potential ways to reduce the O&M costs for a commercial Solar Two extension project. The heliostat field and receiver upgrade costs are very rough at this point; however, fine-tuning of these numbers should not significantly impact the conclusions of this study.

Studies have shown that hybridization of solar thermal power plants generally helps reduce the cost of solar-generated electricity. This is also true for Solar Two. However, in the current power market, the price of power generated by a Solar Two Kokhala IPP project would not be competitive. This is primarily due to high O&M costs and the need to pay off the capital investment. Other hybrid power tower configurations could also be considered, but it is unlikely that they would provide substantially better economics and result in a competitive IPP project. If only a few additional years of operation are desired at Solar Two, the least-cost option will most likely be to continue operating the plant in its current configuration.

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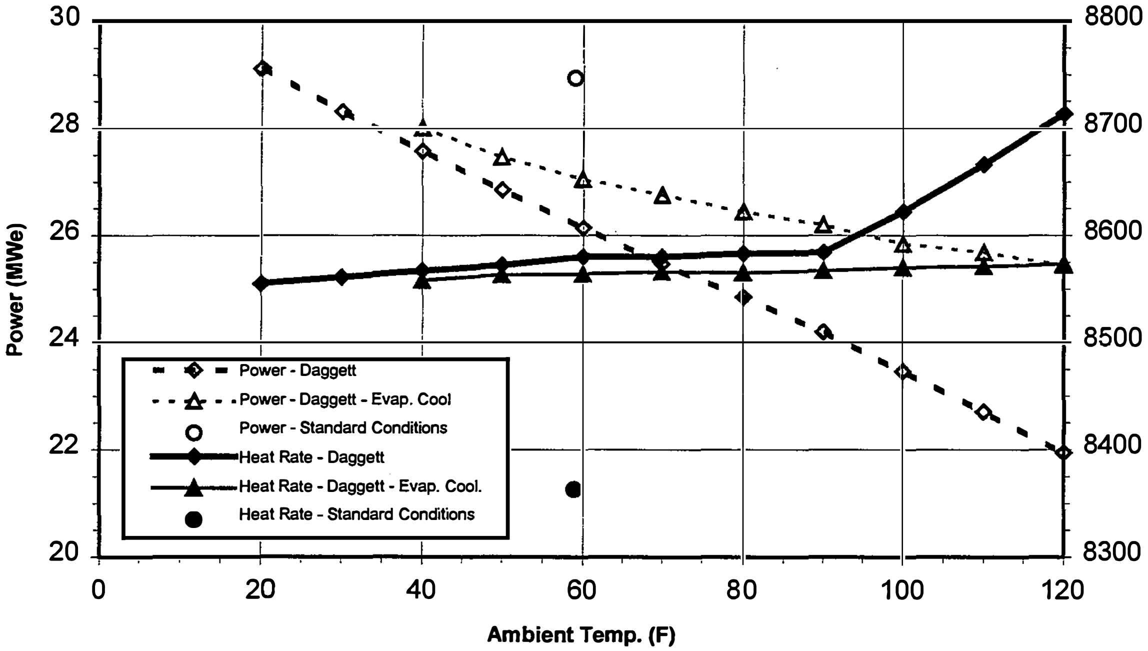

Figure 2 Effect of Temperature and Elevation on PG5261 Power and Heat Rate

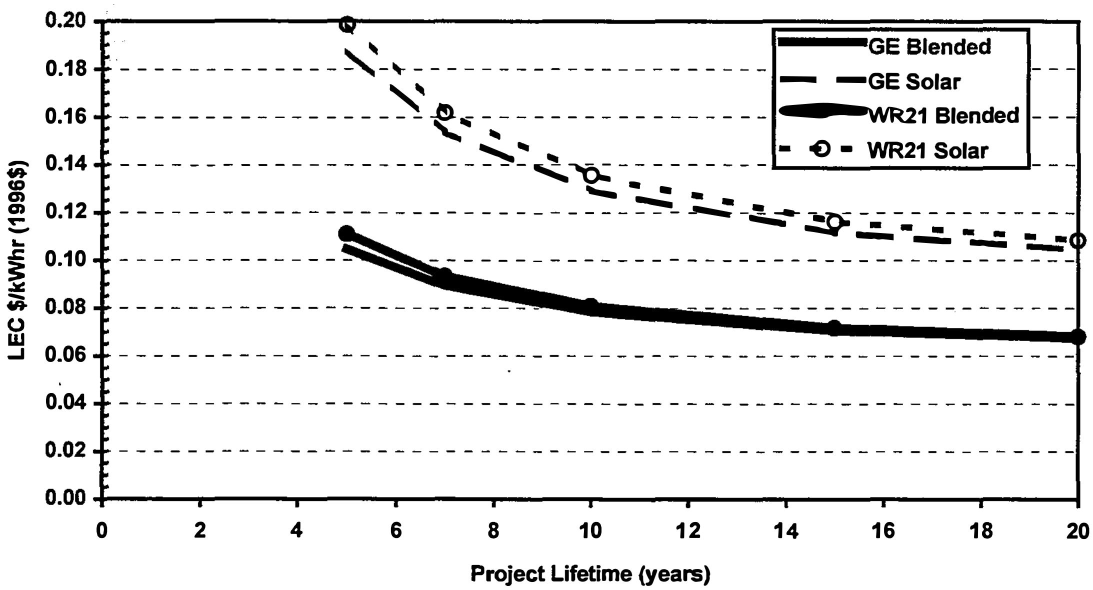

Figure 3 Solar and Blended Levelized Energy Costs