

**A Hybrid System for Combustion Turbine Inlet Air Cooling at the Calpine Clear  
Lake Cogeneration Plant in Pasadena, Texas**

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### **Introduction**

Electric power deregulation is gaining popularity and independent power producers (IPPs) are becoming very aggressive. The IPPs plan to increase their share of the power generation market from 3% in 1994 to 29% in 2015<sup>1</sup>. The power generation capacity using gas turbines is expected to increase from 114 gigawatts in 1997 to 270 gigawatts in 2015.

Although gas turbines are great machines for producing electric power, they have one characteristic that is very unattractive for the power producers: Their power output decreases when ambient temperature increases. This means that power plant owners lose the opportunity to sell more electric energy just when the increase in ambient temperature increases demand for power for operating air conditioners. Since electric energy prices are high during on-peak hours, generally during the daytime when ambient temperatures are high, power plant owners are extremely interested in increasing their power generation capacity during the periods of high ambient temperature.

Cooling inlet air to the compressor of a gas turbine system is a low-cost option for preventing the loss of power output or even increasing turbine output in hot weather, compared to its rated capacity at the ISO conditions of 59°F, 60% relative humidity, and 14.7psia at sea level.

This paper discusses the results of some of the analyses performed for a 316.8MW cogeneration plant in Clear Lake, TX. The plant was retrofitted with a hybrid cooling system incorporating absorption chillers, an electric centrifugal chiller and a chilled water storage system. The turbine inlet cooling (TIC) system was started up in May 1999.

### **Calpine Clear Lake Cogeneration Plant**

The Calpine Clear Lake Cogeneration plant in Pasadena, TX is owned and operated by Calpine Corporation. The plant uses three Westinghouse 501D5 gas turbines, each with a rated capacity of 105.62MW. The plant produces steam as a co-product and sells it that is sold to the adjacent chemical plant. The plant was built in 1982 and a fogging system was added later for cooling inlet air to the turbine system.

In August 1998, management decided to use chillers to cool the inlet air to much lower temperatures than that possible with the fogging system, and also decided to evaluate various options for increasing the plant capacity for the sale of electric energy during on-peak periods. The preferred cooling technology for turbine inlet cooling (TIC) was

determined to a hybrid system consisting of absorption chillers, an electric chiller and chilled water storage.

### **Cooling Technologies Evaluated**

The following cooling technologies were evaluated for TIC for the plant:

- Evaporative cooling
- Fogging
- Electric Chillers
- Absorption Chillers
- Hybrid Systems

### **Power Capacity Enhancement**

Some of the performance characteristics of the 501D5 gas turbine are shown in Figure 1. It shows that increase in ambient temperature to 95°F decreases the turbine power output by nearly 14% below its rated capacity at 59°F. Cooling the inlet air to 50°F increases the power output by 4% above its rated capacity. Therefore, for this turbine, cooling the inlet air to 50°F from 95°F increases the turbine output from about 86% to 104% of the rated capacity. Thus, the turbine power output capacity at 50°F is nearly 21% higher than its capacity at 95°F.

Figure 2 shows the effect of cooling technology on the net power capacity enhancement of the Calpine plant when the inlet air is cooled from the 95°F ambient dry bulb temperature (and 80°F mean coincident wet bulb temperature) to 50°F by chillers, or to the temperatures achieved by evaporative cooling and fogging systems. The results show that the TIC systems with absorption chillers enhance power capacity up to about 49MW above that possible at 95°F ambient. This increase is about 33MW more than that using evaporative cooling, 31MW more than that using fogging, and 11MW more than that using electric chillers.

The TIC systems with chillers achieve greater power capacity enhancement than those using evaporative cooling and fogging because chillers can reduce the inlet temperature to 50°F while evaporative cooling and fogging can reduce the inlet air temperature to only 81.5°F (assuming 90% approach) and 80.3°F (assuming 95% approach), respectively.

As shown in Table 1, the parasitic power need of a direct-fired double-effect absorption chiller is the lowest while that for an electric chiller is the highest. Therefore, TIC systems that incorporate absorption chillers (using lithium bromide salt as the absorbent and water as the refrigerant) achieve higher net power capacity enhancement than that with electric centrifugal chillers. For similar reasons, TIC system that incorporate a DFDE achieves greater power capacity enhancement than that incorporating a hot-water single-effect (HWSE) chiller.

The results in Figure 2 assume pressure drops of 1.5-inch water column (WC) at the inlet coil for all chillers, 0.3-inch WC for the evaporative cooling, and 0.1-inch WC for fogging systems.

### **Steam Production Enhancement**

As shown in Figure 1, an increase in ambient temperature not only decreases power output of the turbine, but also decreases mass flow rate of exhaust gas from the turbine. Increasing ambient temperature to 95°F decreases mass flow rate of the turbine exhaust by about 7% below that at the ISO temperature of 59°F. Even though the exhaust temperature increases by about 3%, on an overall basis, steam production in the Capline plant decreases by about 5% with an increase in ambient temperature to 95°F. Cooling the inlet air to 50°F increases mass flow rate of the exhaust gas by about 2% and decreases the exhaust temperature by about 0.5%, and on an overall basis, increases steam production rate by about 1 percent. Therefore, on an overall basis, cooling the inlet air from 95°F to 50°F increases steam production by over 6 percent compared that at 95°F.

Figure 3 shows the effect of cooling technology on steam production rate enhancement when the inlet air is cooled from 95°F ambient dry bulb temperature (with 80°F mean coincident wet bulb temperature) to 50°F by TIC systems using chillers or to the temperatures achieved by evaporative cooling (81.5°F) and fogging (80.3°F). The results show that the TIC systems using chillers enhance steam production by more than over 15,000 lbs./hr compared to evaporative cooling and fogging systems. The TIC systems with chillers perform better than those with evaporative cooling and fogging for the same reason as that discussed earlier for the power capacity enhancement.

### **Turbine Efficiency Improvement**

When ambient temperature increases to 95°F, heat rate of the gas turbine increases by about 4 percent above its rated capacity as shown in Figure 1. This increase in heat rate results in corresponding decrease in fuel efficiency by about 4% below the rated efficiency. Cooling the inlet air to 50°F decreases heat rate and therefore, increases fuel efficiency by about 1% above the rating at ISO conditions of 59°F. Thus, cooling the turbine inlet air from 95°F ambient to 50°F decreases heat rate and increases turbine efficiency more 4 percent over that at 95°F.

Figure 4 shows the effect of cooling technology on reduction in heat rate of the gas turbine when the inlet air is cooled from 95°F ambient dry bulb temperature (with 80°F mean coincident wet bulb temperature) to 50°F by TIC systems using chillers or to those temperatures achieved by evaporative cooling or fogging. The results show that the TIC systems using chillers achieve the highest reduction (479Btu/kWh) in heat rate. In comparison, evaporative cooling and fogging achieve heat rate reductions of only 144 Btu/kWh and 152Btu/kWh, respectively. Therefore, the TIC systems with chillers reduce heat rate and improve fuel efficiency by over 4% compared to those at 95°F, when the heat rate is about 10,710 Btu/kWh. Thus, compared to the TIC systems using evaporative and fogging technologies, the systems with absorption chillers achieve about 3% better heat rate reduction.

### **Total Plant Capital Cost**

Figure 5 shows the effect of cooling technology on total plant (power generation plus TIC systems) cost per MW of net power capacity for the Calpine plant, when ambient dry bulb temperature is 95°F (with 80°F mean coincident wet bulb temperature), and when the TIC systems are adequate to cool the turbine inlet air to 50°F with chillers or to the temperatures discussed earlier for evaporative cooling and fogging technologies.

The estimates in Figure 5 are based on the installed costs for the six types of TIC systems shown in Table 2, and using a typical cogen plant cost (without TIC of any kind) of \$750,000/MW of the turbine capacity at ISO conditions. On this basis, total plant cost of the 316.8MW Calpine cogen plant (without TIC) is estimated to be \$237.6 million. The combined output of the three turbines at this plant decreases from about 317MW to 273MW, when the ambient temperature increases to 95°F. Therefore, at this ambient temperature, the same investment of \$237.6 million increases the effective capital cost per MW of the uncooled cogen plant from \$750,000 to about \$870,000. The results in Figure 5 also show that the total plant cost is lower for the systems incorporating TIC, and that the lowest total plant cost is achieved by using TIC with SHSE chiller.

The costs for the TIC systems in Table 2 are for the complete system with coils for cooling the turbine inlet air, chiller/cooler, all pumps, de-mister, cooling towers, and the heat recovery equipment, where applicable. Generally, the cost of TIC systems with electric centrifugal and steam-heated single effect chillers are within 15% of the cost of electric chillers. However, the cost of the TIC with HWSE chiller in Table 2 is much higher than that with electric chillers because of the following two factors:

1. Incorporates the cost of the heat recovery equipment for producing hot water, from the HRSG exhaust, for operating HWSE chillers
2. Accounts for the de-rating of WHSE chillers for operating on hot water, instead of steam.
3. De-rating of WHSE for producing chilled water at 40°F instead of the usual 43°F

### **Incremental Capacity Capital Cost**

In order to increase the power production capacity, power plant owners have two major options: Add another gas turbine without TIC or add TIC to the existing turbine system. Figure 6 shows the effect of cooling technology on capital cost for the incremental net power capacity enhancement for the Calpine plant without and with TIC, using various chillers under the same ambient conditions as discussed above. The results show that TIC systems with chillers achieve incremental capacity enhancement at nearly half the capital cost of installing an additional gas turbine without TIC. Figure 6 also shows that the lowest capital cost for incremental capacity enhancement for this plant is achieved with electric chillers.

### **Need for Annual Production and Net Revenue Analyses**

Figures 2 through 6 represent 'snapshot' results when the ambient dry bulb temperature is 95°F and the mean coincident wet bulb temperature is 80°F. Since the ambient

temperature in Houston, TX is not always at this condition, it is premature to conclude, from the results discussed so far, about the preferred TIC system for the Calpine plant. Further analyses must be conducted, using hourly weather data for 8760 hours of a year, for estimating the net annual production of electric energy and steam, and the net annual net revenues for each alternative.

### **Annual Net Electric Energy Production Enhancement**

Figure 7 shows the effect of cooling technology on the annual enhancement in the production of net electric energy (AEEE). The results in this figure are based on the typical hourly weather data for the city of Houston, TX. These estimates assume that the plant operates all 8760 hours the year and that turbine inlet air is cooled to 50°F any time the ambient dry bulb temperature is above 50°F. The results show that a TIC system using DFDE absorption chiller achieves the best results. This TIC system provides about 124,000MWh/yr more than a system with evaporative cooling and about 39,000MWh/yr more than a system with electric chillers.

Figure 8 shows the effect of cooling technology on net monthly increase in electric energy production. It shows that maximum effect of TIC on electric energy production enhancement occurs in the month of July. These results are based on typical monthly weather data for Houston, TX.

### **TIC Optimization and Economics**

Because of low electric energy rates during off-peak periods, the Calpine plant management decided that the TIC system would be used only during on-peak periods of about 10 hours per day.

On the basis of the typical annual hourly weather data for Houston, the maximum cooling load is 20830RT when the ambient dry bulb and wet bulb temperatures are 91.9°F and 82.6°F, respectively. However, this condition occurs only for one hour in July. In order to optimize the cooling capacity of the TIC, the effect of cooling capacity on AEEE was estimated as shown in Figure 9 when the TIC system is operated during the on-peak hours. The incremental effectiveness of cooling capacity on AEEE is shown in Figure 10. On the basis of these results, a cooling capacity of 18,000RT was selected for the Calpine plant as the maximum average load over the hottest 10hours/day period.

Hot water for the HWSE absorption chiller operation could be produced by cooling the HRSG (Heat Recovery Steam Generator used for recovering heat from gas turbine exhaust) exhaust gas from 340°F to 270°F. Also, in order to retrofit the inlet air cooling coil in the available space, chilled water must be produced at 38°F, instead of the usual 43°F. Since an absorption chiller cannot chill the water to below 43°F, a small electric chiller must be incorporated in the system. Since the Calpine plant did not plan to use TIC for about 14 hours of the day, a chilled water storage system was also considered as a desirable option to be evaluated. After considering the overall heat balance with the available exhaust heat for 24 hours balanced with the coil load over 10 hours, it was determined that 43°F was the optimum absorption design temperature with electric chiller chilling water from 43°F to 38°F.

The constraints and options discussed above, led to the evaluation of a hybrid system consisting of 9000RT HWH absorption chiller and a 1200RT electric centrifugal chiller with a 184,000 ton-hour chilled water storage system.

Figure 11 and Figure 12 show the effects of cooling technology on AEEE and additional annual steam production, respectively, when TIC is used only during the on-peak periods. The results show that the TIC systems with chillers produce about 190 million lbs./yr of more steam than evaporative cooling and that the TIC system with DFDE produces the most increase in AEEE.

The effect of using TIC system on the net annual increase in revenue depends on the following factors:

- Cost of natural gas
- Market price of electricity
- Market values of co-produced steam
- Other variable O&M costs

In order to make quantitative estimates of the effect of various TIC options with chillers, the following basis were used. For the above economic parameters:

- Average annual cost of gas: \$2.5/MMBtu
- Average on-peak market price of \$60/MWh
- Average market price of steam: \$3.25/1000lbs
- Average other variable O&M costs: \$3/MWh

The above costs and market prices are assumed to be only typical of such parameters and do not represent the actual cost or prices for the Calpine Clear Lake Cogeneration plant. Such information is highly confidential and is not available for presentation in this paper.

Using the hourly weather data for the on-peak periods and above parameter values, Figure 13 shows the effect of cooling technology on net annual revenue.

Installed capital costs for the complete TIC systems with various chiller options were estimated as follows:

Electric centrifugal chillers w/o chilled water storage	\$15.34 million
HWH absorption chillers w/o chilled water storage	\$22.8 million
DFDE absorption chillers w/o chilled water storage	\$26.4 million
Hybrid system (discussed above)	\$18.0 million

By treating the above capital costs as investments and the additional annual net revenues as return on those investments, Figure 14 shows that the TIC system with the hybrid cooling system produces the best return on the investment. It is generally more prudent to make decisions on the basis of net present value (NPV) or life-cycle cost of the project

over the useful life of the project. Figure 15 shows the NPV of the three chiller options. It also shows that the hybrid system is the preferred system for the Calpine plant.

**References**

1. "Electric Generation Sector Summary," a GRI Report #99/0010 prepared by Energy and Environmental Analysis, Inc., September 1999.

**Table 1. Parasitic Power Needs of Various Chillers**

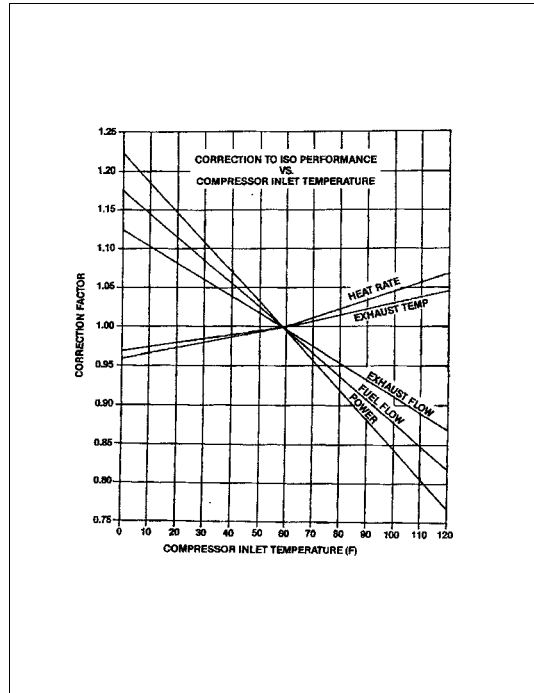
	<b>Electric Centrifugal</b>	<b>Single-Stage Steam-Heated Absorption</b>	<b>Direct-Fired Two-Stage Absorption</b>
	----- kW/RT -----		
<b>Chiller</b>	0.65	0.0217	0.0336
<b>Chiller Water Pump</b>	0.053	0.053	0.053
<b>Condenser Water Pump</b>	0.0618	0.1257	0.097
<b>Cooling Tower Fan</b>	0.0451	0.0818	0.0655
<b>Total</b>	<b>0.8099</b>	<b>0.2822</b>	<b>0.2491</b>

**Table 2. Capital Cost for TIC Systems with Various Cooling Technologies**

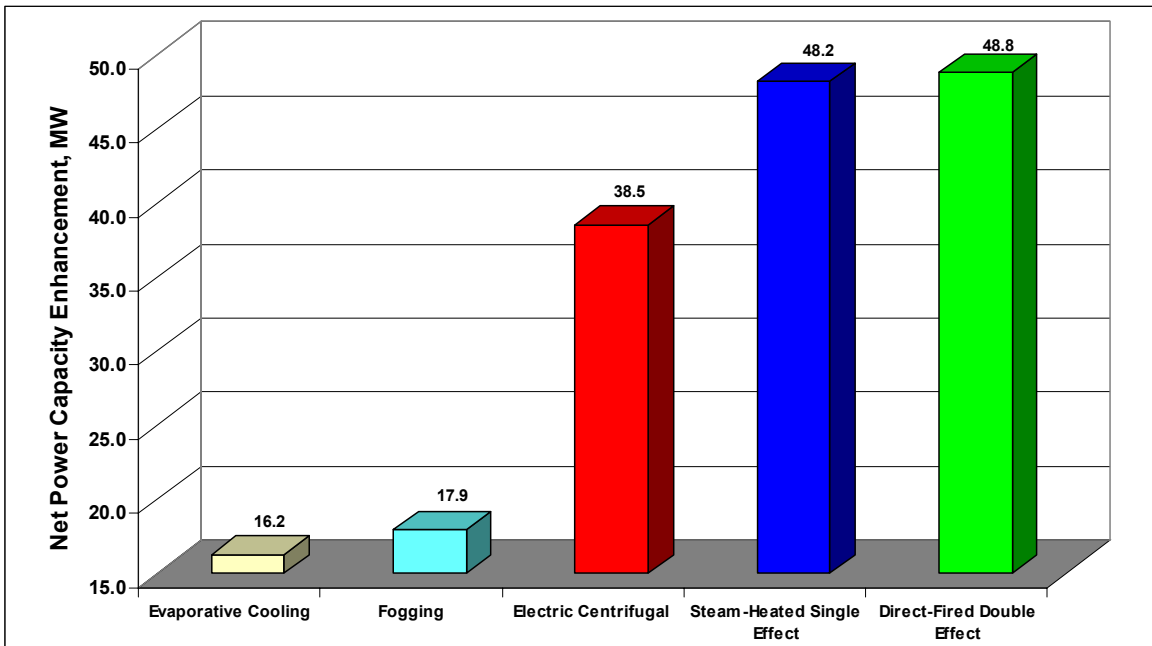
<b>Evaporative Cooling</b>	\$1894/MW
<b>Fogging</b>	\$1894/MW
<b>Electric Centrifugal</b>	\$834/RT
<b>Steam-Heated Single Effect</b>	\$1239/RT*
<b>Direct-Fired Double Effect</b>	\$1435/RT

\*Including cost of equipment for recovering heat from HRSG exhaust and de-rating for using hot water instead of steam and de-rating for producing chilled water at 40°F instead of the usual 43°F.

**Figure 1. Effect of Inlet Air Temperature on the Performance of W501D5**

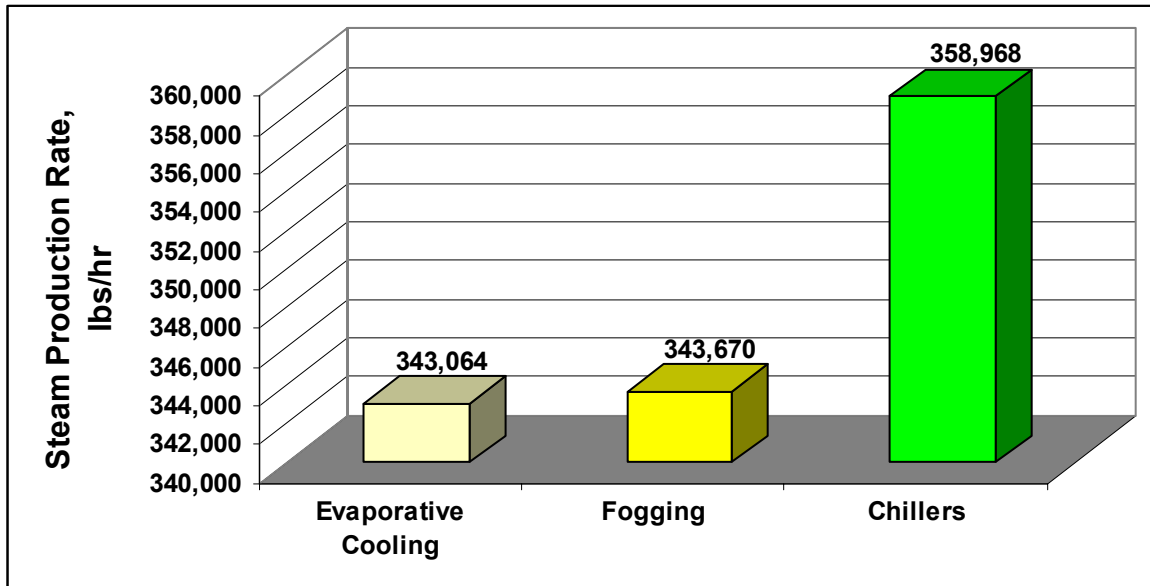


**Figure 2. Effect of Cooling Technology on Net Power Capacity Enhancement**  
 (95°F DB/80°F WB Ambient; Chillers Cool Inlet Air to 50°F; 90% and 98% Approach to Equilibrium with Evap and Fogging, respectively)



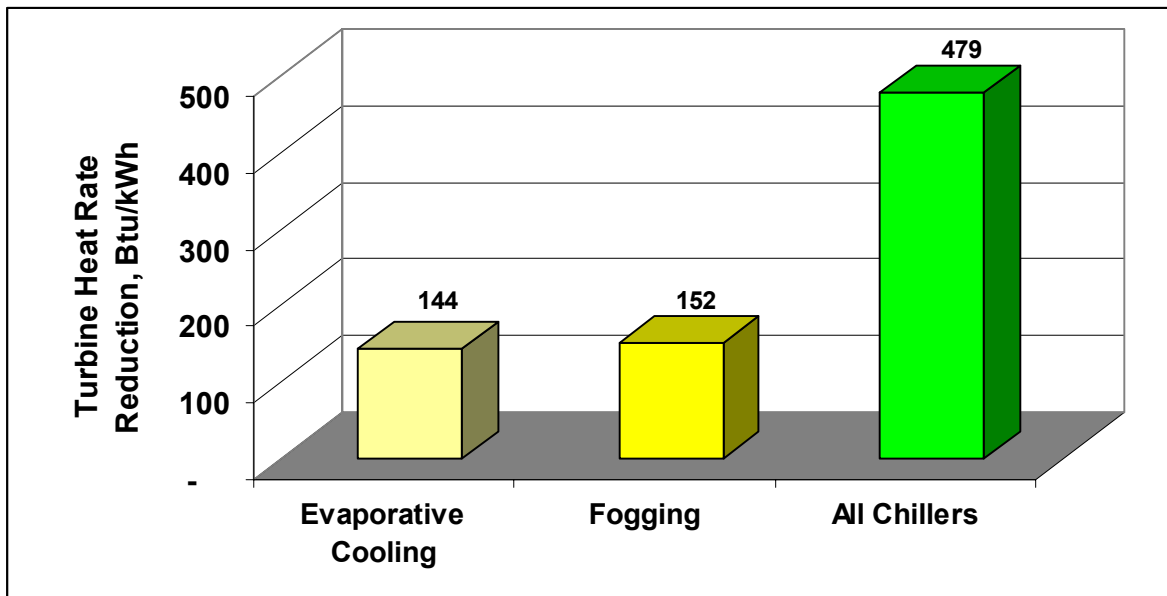
**Figure 3. Effect of Cooling Technology on Steam Production Rate**

(95°F DB/80°F WB Ambient; Chillers Cool Inlet Air to 50°F 90% and 98% Approach to Equilibrium with Evap and Fogging, respectively)



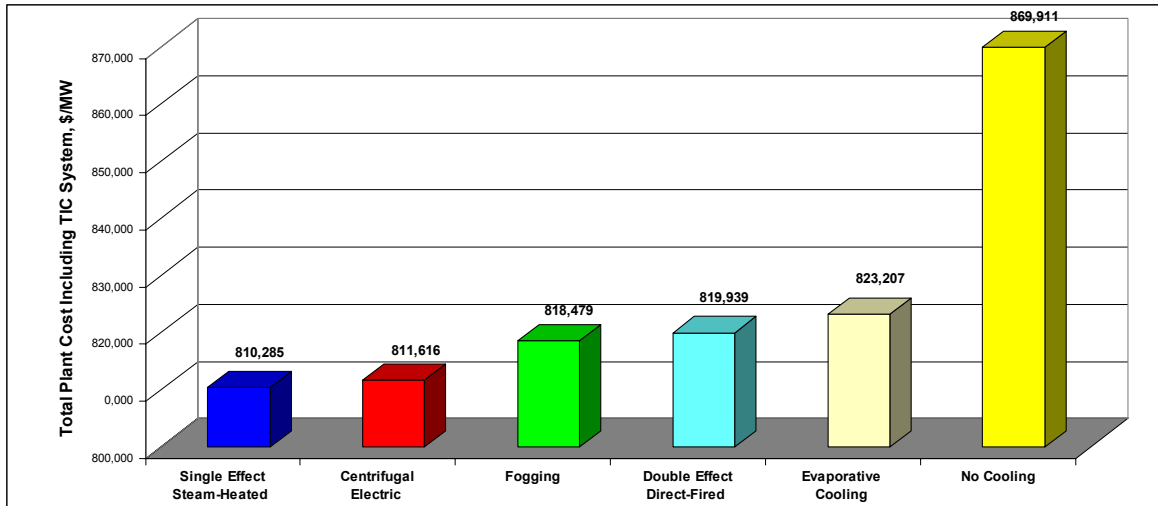
**Figure 4. Effect of Cooling Technology on Gas Turbine Heat Rate Reduction**

(95°F DB/80°F WB Ambient; Chillers Cool Inlet Air to 50°F; Approach to Equilibrium with Evap and Fogging is 90% and 98%, respectively)



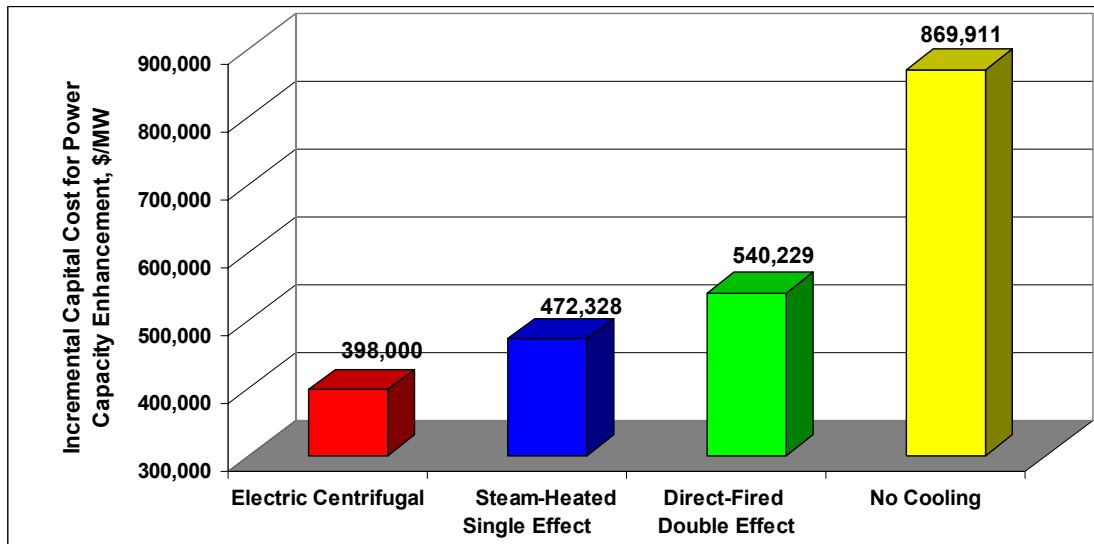
**Figure 5. Effect of Cooling Technology on Total Plant Cost Including TIC System**

(95°F DB/80°F WB Ambient; Chillers Cool Inlet Air to 50°F 90% and 98% Approach to Equilibrium with Evap and Fogging, respectively)



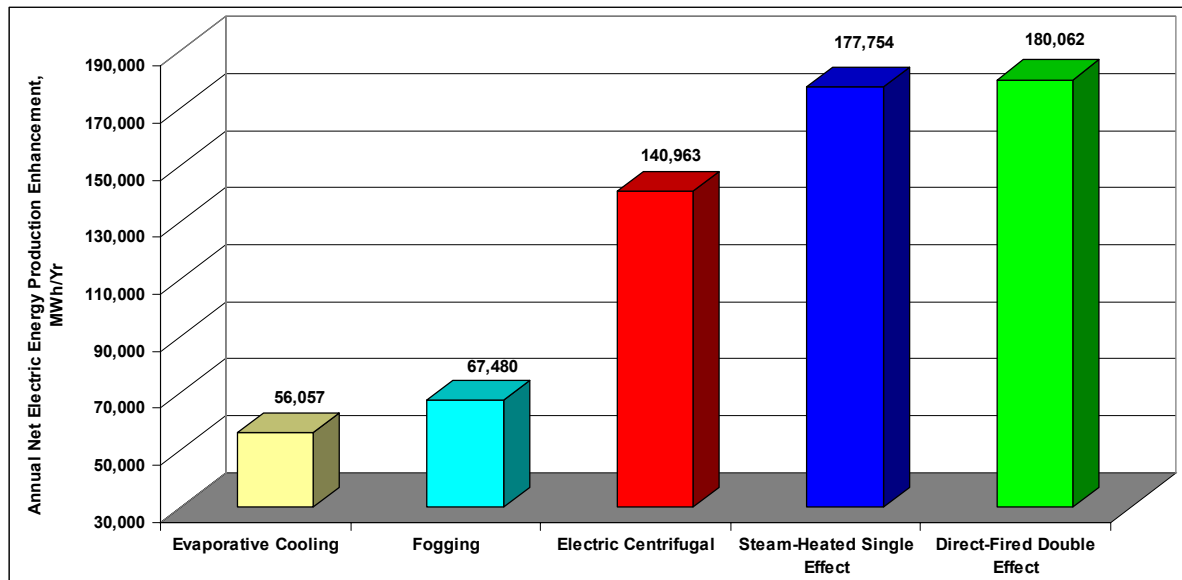
**Figure 6. Effect of Cooling Technology on Capital Cost for Additional Power Capacity**

(95°F DB/80°F WB Ambient; Chillers Cool Inlet Air to 50°F 90% and 98% Approach to Equilibrium with Evap and Fogging, respectively)



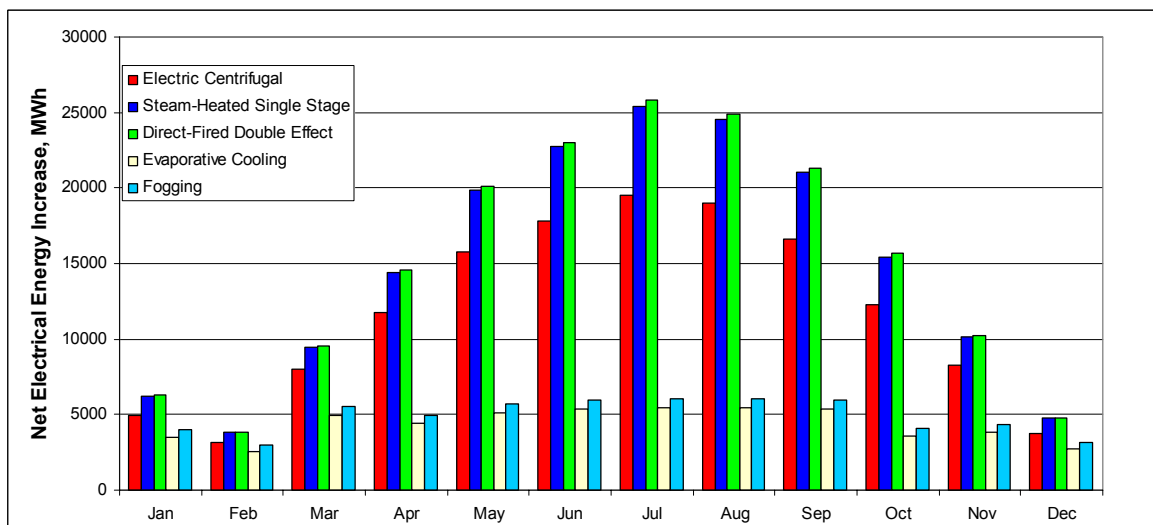
### Figure 7. Effect of Cooling Technology on Annual Net Electric Energy Production Enhancement

(Assuming 8760 hour annual operation; Chillers Cool Inlet Air to 50°F; 90% and 98% Approach to Equilibrium with Evap and Fogging, respectively)

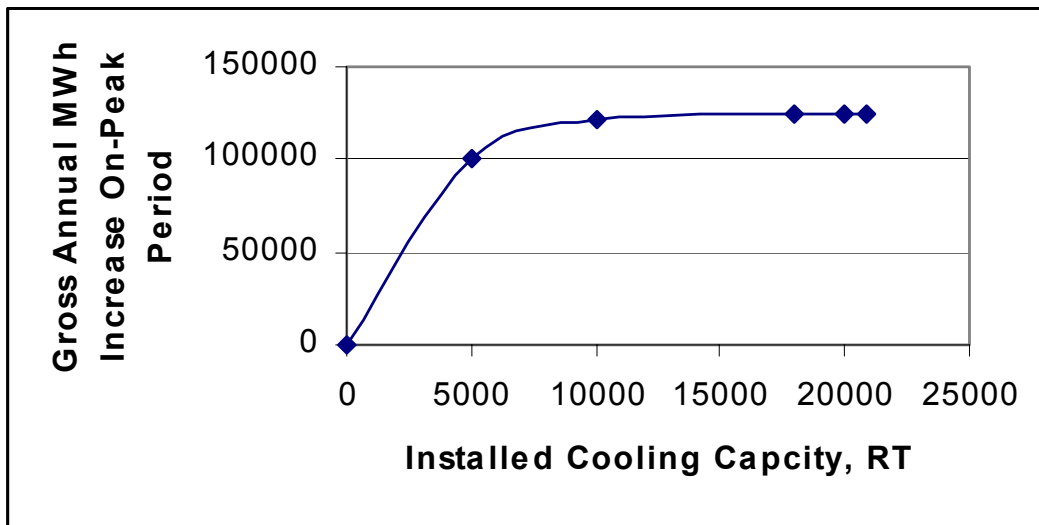


### Figure 8. Effect of Cooling Technology on Monthly Net Electric Energy Production

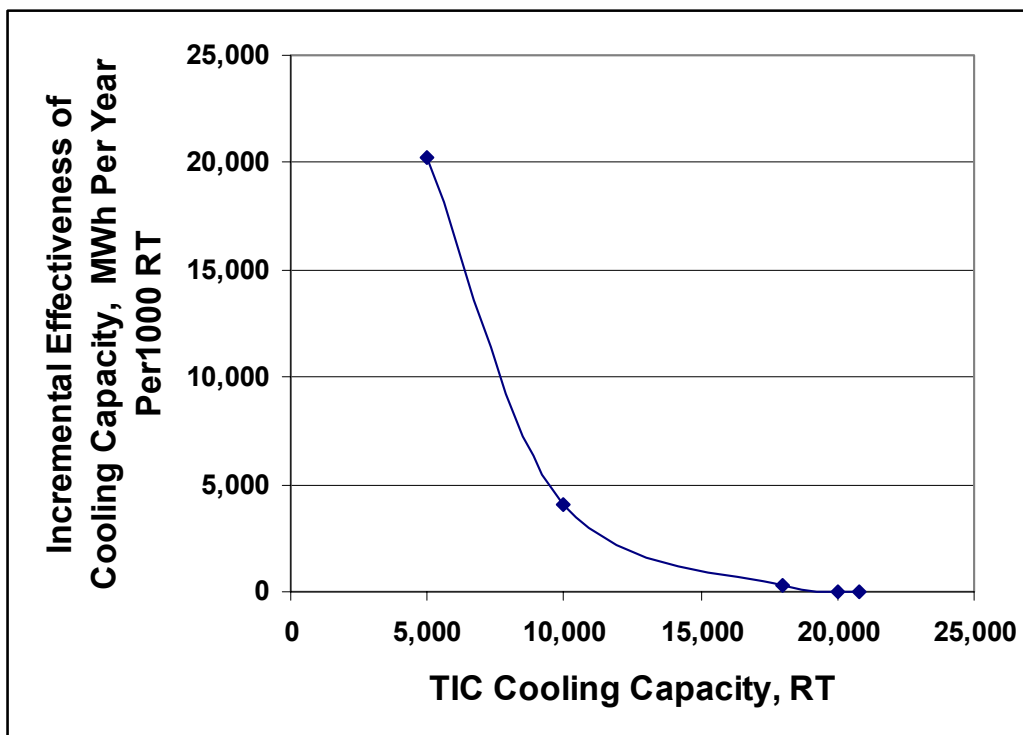
(Assuming 8760 hour annual operation; Chillers Cool Inlet Air to 50°F; 90% and 98% Approach to Equilibrium with Evap and Fogging, respectively)



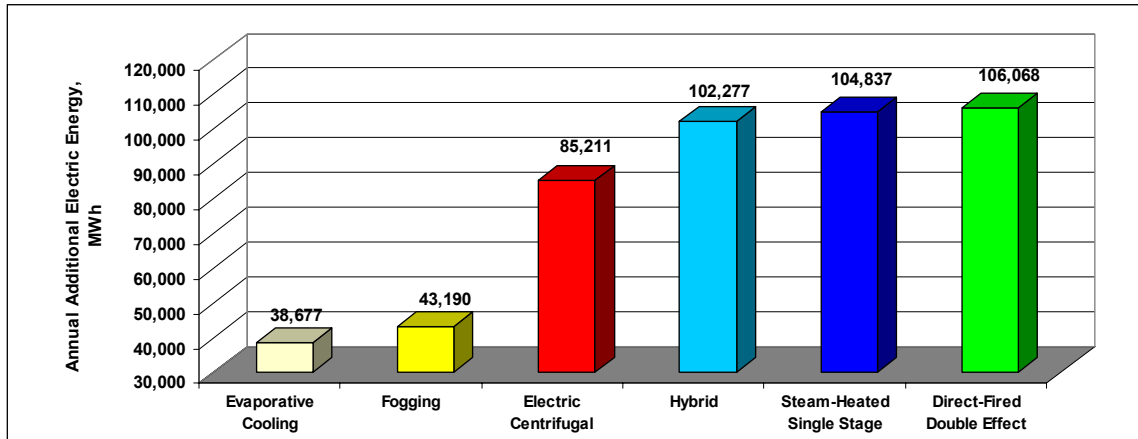
**Figure 9. Effect of TIC Cooling Capacity on Annual Increase in Electric Energy Production**



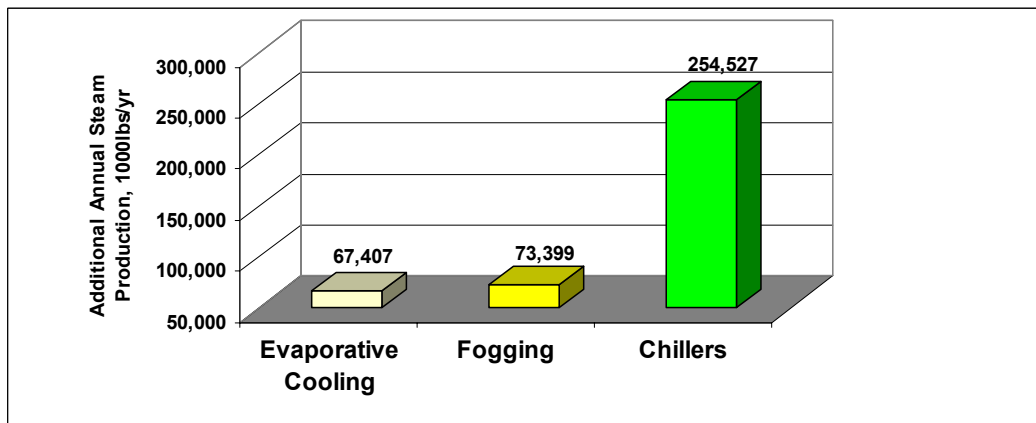
**Figure 10. Incremental Effectiveness of Cooling Capacity for Increasing Annual Electric Energy Production**



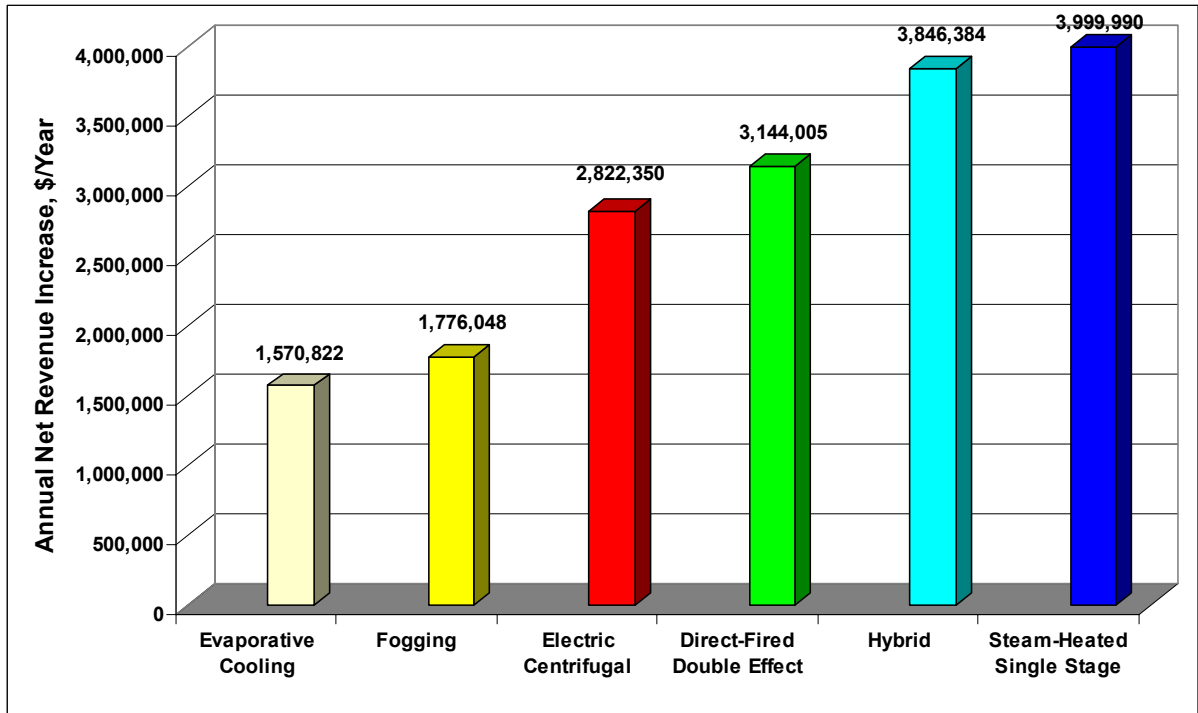
**Figure 11. Effect of Cooling Technology on Net Annual Electric Energy Production Using TIC for only During On-Peak Hours (10Hr/Day)**



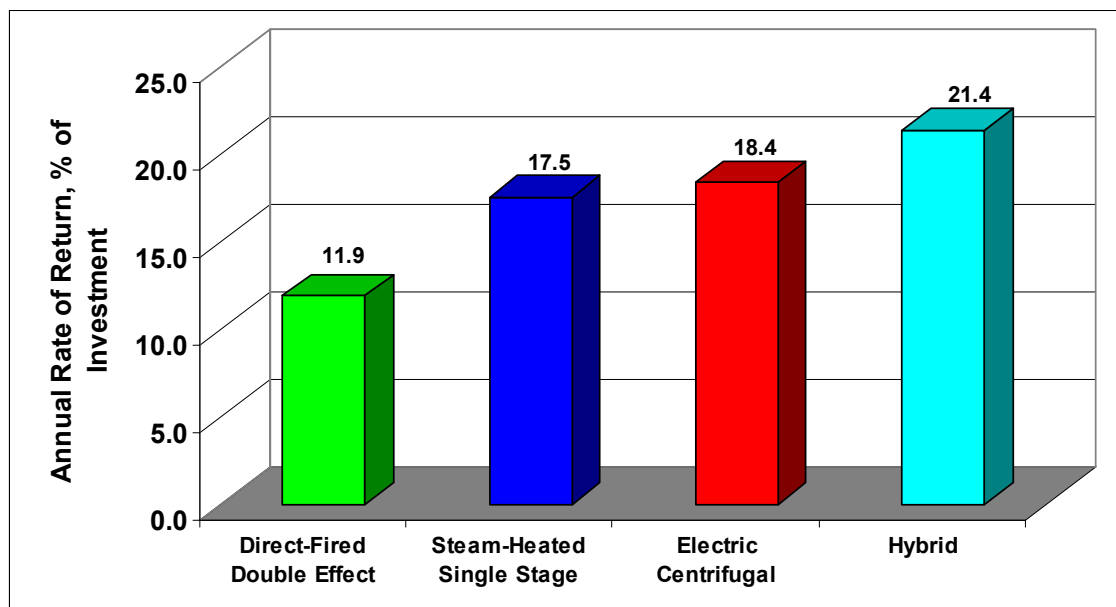
**Figure 12. Effect of Cooling Technology on Annual Additional Steam Production Using TIC for Only On-Peak Hours (10 Hours/day)**



**Figure 13. Effect of Cooling Technology on Annual Net Revenue Increase by TIC Only During On-Peak Periods (10Hours/Day)**



**Figure 14. Effect of Cooling Technology on Rate of Return on Investment Using TIC Only During On-Peak Periods (10 Hours/Day)**



**Figure 15. Effect of Cooling Capacity on Net Present Value of 20-Year project Life**

