

**Turbine Inlet Cooling:  
An Energy Solution That's Better for the  
Environment, Ratepayers and Plant Owners**

**A White Paper**

**TURBINE INLET COOLING**  
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**ABSTRACT**

Worldwide campaigns are underway for reducing the emissions of carbon dioxide – a major greenhouse gas. Various organizations, including electric power producers, are making efforts to reduce the carbon footprint of the electricity they generate. Many of the options for reducing the carbon footprint of power production come at a premium price to the plant owners and eventually, the ratepayers. However, turbine inlet cooling (TIC) is a commercially-proven option for reducing the carbon footprint of power production during hot weather while saving money for all stakeholders. It achieves this by maximizing the power output and improving the energy efficiency of the existing combustion turbine-based power plants during hot weather. It has been successfully applied to combined-cycle, simple-cycle and cogeneration (combined heat & power) systems. TIC also reduces the need for investment in and problems related to environmental issues for siting new power plants. This paper discusses the power augmentation potential of TIC and its impact on reducing the carbon footprint of the power grid system as well as reducing the fuel cost and incremental investment for the augmented capacity.

**INTRODUCTION**

Worldwide demand for electric power has been increasing and is expected to continue to increase. Most of the world experiences power shortages during the hot summer periods. There are two primary reasons for power shortages occurring during hot summer weather:

1. Increased cooling loads of air conditioners
2. Decreased output capacity of all combustion turbine systems

Figure 1 shows a typical hourly electric power load profile for a day in the state of California. It shows the various types of power demand loads that contribute to almost doubling of electric power demand from the early morning to the peak of the afternoon. It also shows that the air conditioning load is the largest “adder” to the power demand during the peak period. The hourly electric power load profiles for other parts of the U.S. and the world are expected to show similar trends.

Figure 2 shows typical hourly profiles for power generation by a combustion turbine (CT), ambient air temperature and power demand in the market. It shows that the power generation characteristics of the CT widen the gap between the generation capacity and the power demand as the ambient temperature rises. It is unfortunate that just as the grid demands more power, the CT power output capacity decreases. According to the database of the U.S. Department of Energy, shown in Table 1, the deleterious impact of ambient temperature on the output capacity of CT is responsible for over 29,000 MW of output capacity reduction during summer compared to that during winter.

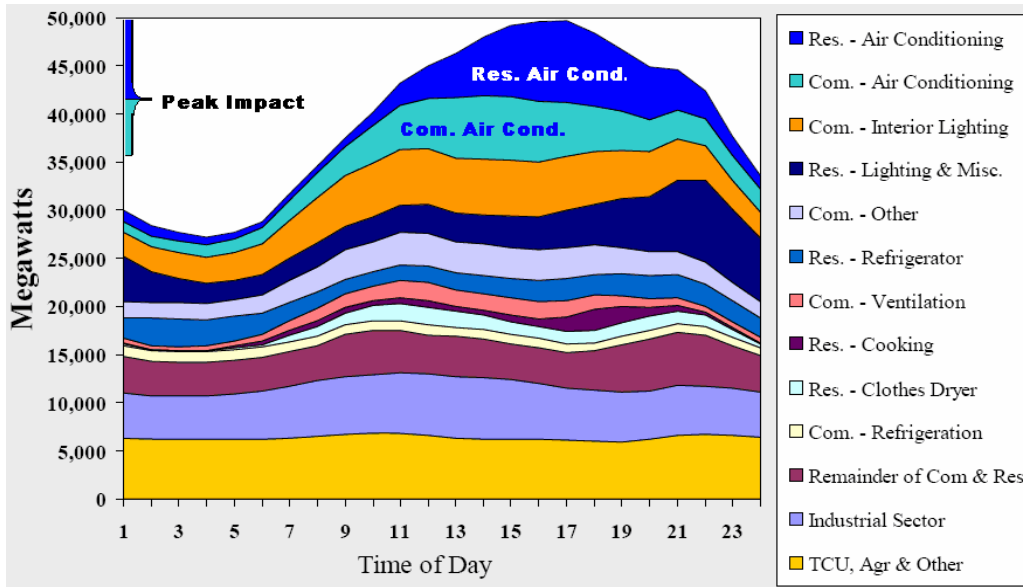


Figure 1. Typical Hourly Electric Power Load Profile for California (Duncan 2007)

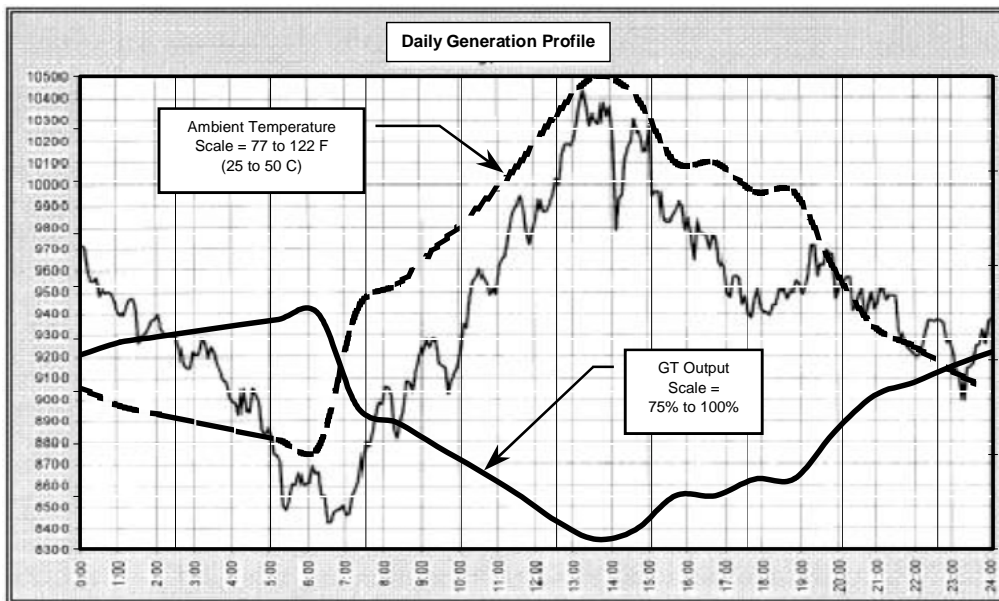


Figure 2. Typical Hourly Profiles for Power Generation by Combustion Turbines and Power Demand (Punwani 2005)

**CARBON FOOTPRINT FOR POWER GENERATION**

Most of the electric power in the U.S. is generated by using fossil fuels: coal, oil or natural gas. All fossil fuel based power plants emit carbon dioxide — a major green house gas (GHG). Carbon footprint for power generation is proportional to the pounds of carbon dioxide produced per unit of energy utilized. Therefore, the higher the energy

<b>Fuel</b>	<b>Winter Capacity, MW</b>	<b>Summer Capacity, MW</b>	<b>Lost Summer Capacity, % of Winter Capacity</b>
<b>Coal</b>	<b>315,556</b>	<b>313,380</b>	<b>1</b>
<b>Petroleum</b>	<b>61,171</b>	<b>58,548</b>	<b>9</b>
<b>Natural Gas</b>	<b>412,241</b>	<b>383,061</b>	<b>9</b>

Table 1. U.S. Power Generation Capacities during Winter and Summer (EIA 2005)

efficiency of a fossil fuel power plant, the smaller its carbon footprint and also lower its fuel cost per unit of energy utilized.

Electric power producers obviously prefer to bring their most energy efficient power plants online first. However, in order to meet the peak demand during summer even the most inefficient power generation systems have to be brought online as shown in Figure 3 for the State of California. In other states that do not have as much hydro option for power generation as in California, much more inefficient peaking power plants have to be brought online. All of the inefficient peaking power plants are fossil fuel plants that significantly increase the carbon footprint during the peak demand period as shown in Figure 4. It shows that even with the large contribution of hydro power plants to the generation option, the carbon footprint of electric energy generated more than doubles during the on-peak period compared to that during the off-peak period.

As is well known, fossil fuel based power plants are significant emitters of carbon dioxide and there two major types of these power plants:

1. Burn natural gas or oil directly in a combustion turbine that is connected to an electric generator
2. First burn natural gas, oil or coal in a boiler to produce steam that is used to operate a steam turbine connected to an electric generator

The power plants that use combustion turbines are designed for operation in simple cycle, combined cycle or cogeneration. In a simple-cycle system the exhaust gases of the CT are vented to the atmosphere. In a combined-cycle system the thermal energy in the turbine exhaust gases is recovered for producing steam that is used for operating steam turbines that produce additional electric energy. In a cogeneration system, also known as combined heat and power (CHP) system, some of the thermal energy in the CT exhaust gases is utilized directly as a source of heat at or near the site of the power plant. The energy efficiency is the highest for CHP systems, followed by combined-cycle systems, simple-cycle and steam turbine systems. Therefore, the carbon footprint for power generation is the lowest for CHP

systems and the highest for steam turbine systems. Table 2 shows some examples of emissions from these power plants.

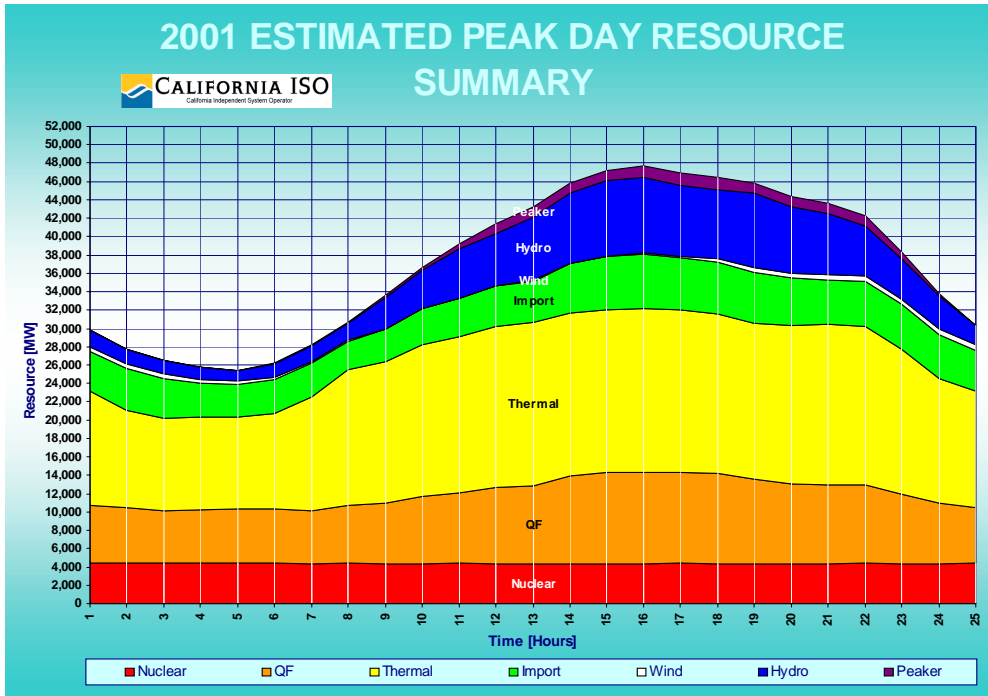


Figure 3. Contributions of Various Power Generation Technologies for Meeting Power Demand (Duncan 2007)

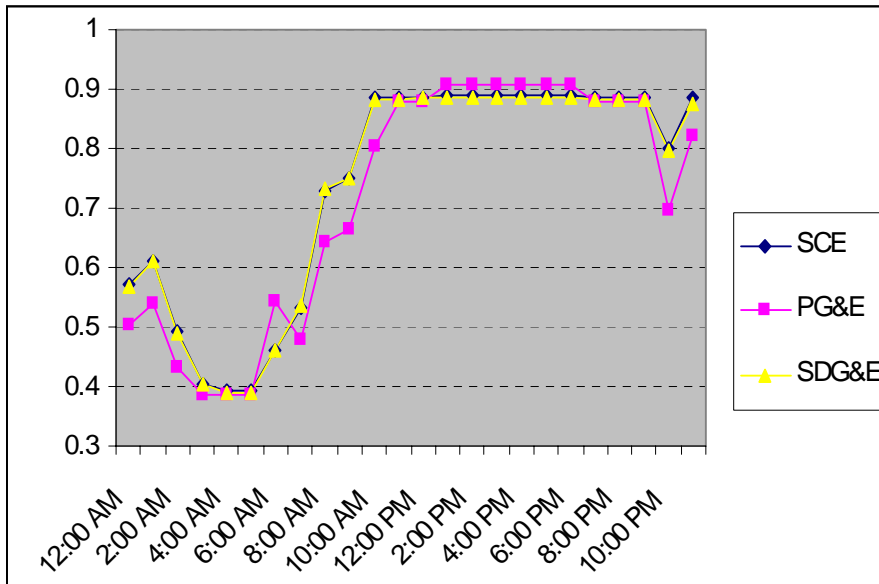


Figure 4. Carbon Dioxide Emissions for Electric Energy Generation during a Typical Summer Day (Duncan 2007) Note: Y-Axis Scale Shows lb of CO<sub>2</sub>/kWh

Energy efficiencies of the various power plants are typically in the ranges of 65% to 75% for CHP/Cogeneration, 48% to 52% (or heat rates of 6,500-7,000 Btu/kWh) for combined-cycle, 34% to 42% (or heat rates of 8,000 to 10,000 Btu/kWh) for simple-cycle, and 23% to 28% (or heat rates of 12,000 to 15,000 Btu/kWh) for steam-turbine power plants. An example of carbon emissions from these systems is shown in Table 2.

Unit Type	TIC Candidates			Existing Older Plants
	CHP/Cogeneration	Combined-Cycle CT	Simple-Cycle CT	Boiler + Steam Turbine (STG)
Prime Mover	Frame CT	Frame CT- STG	Frame CT	Condensing STG
Fuel	Natural Gas	Natural Gas	Natural Gas	Natural Gas
Plant Age (Yrs)	< 5	< 5	< 5	> 30
CT Heat Rate (Btu/kWh)	10,750	7,000	10,750	13,000
Generation Capacity (MW)	100	100	100	100
Hours of Operation	1	1	1	1
Thermal Energy Need, MMBtu	465	465	465	465
Fuel Use, MMBtu				
Power Generation	1,075	700	1,075	1,300
Thermal Use (1)	0	547	547	547
Total	1,075	1,247	1,622	1,847
Energy Efficiency, %				
Electric Power Generation	32	49	32	26
Overall Energy Efficiency, %	75	71	55	48
Carbon Emissions, Tons	17.0	19.8	25.7	29.3
Notes	1. CHP provides thermal energy from the CT Exhaust without using additional; Other systems use 85% efficiency boilers for providing thermal energy needs.			

Table 2. Typical Carbon Emissions for Various Power Plants

It shows that to minimize the emissions of carbon (or reducing the carbon footprint) and fuel cost, the preferred order of operating fossil fuel power plants is cogeneration (CHP), combined-cycle, simple-cycle and steam turbine systems. Therefore, in order to minimize the operation of the highest carbon-footprint system of steam turbines, it is important to prevent the loss of generation capacity of the CT-based systems during hot weather or hot climates by implementing TIC on these systems.

### IMPACTS OF AMBIENT TEMPERATURE

As discussed in the previous section, increase in ambient air temperature leads to increased environmental emissions during the on-peak period because of increased use of less energy efficient power plants. Increase in ambient temperature also results in increased cost of electric energy to the rate payers and adverse performance of CT systems as discussed below.

### Cost of Electric Energy to the Ratepayers

Typical hourly power demand and electric energy profiles are shown in Figure 5. It shows that as the power demand doubles from the off-peak period to the on-peak period, the electric energy price increases by a factor of four. This is an example of a day-ahead market pricing for energy payment only. For some deregulated generation markets, the balancing market, the portion of generation needed to meet unforeseen shortfalls in generation, can show even a larger variation between the off-peak and on-peak electric energy pricing. The high price for the balancing power is normally for a short period, but in ERCOT the price in 2008 exceeded \$4000/MWH.

### CT Performance

Since CT-based systems are the preferred choice among the fossil fuel power plants for minimizing environmental emissions and fuel cost, numerous installations of these systems

exist worldwide. All CT systems, however, have two major drawbacks when the ambient air temperatures increase: Power generation capacity decreases and efficiency is reduced.

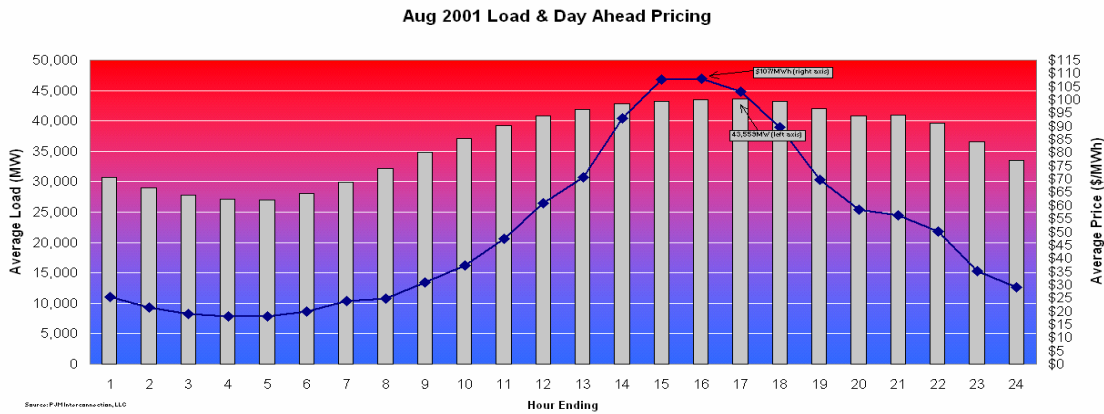


Figure 5. Typical Hourly Power Demand and Electric Energy Price Profile (Data Source: PJM Interconnection LLC)

Typical effects of ambient air temperature on the CT power generation capacity and heat rate are shown in Figures 6 and 7, respectively for two classes of turbines: aeroderivative and frame. It is very unfortunate that the CT output decreases just when the market demand for electric power increases with increase in ambient temperature.

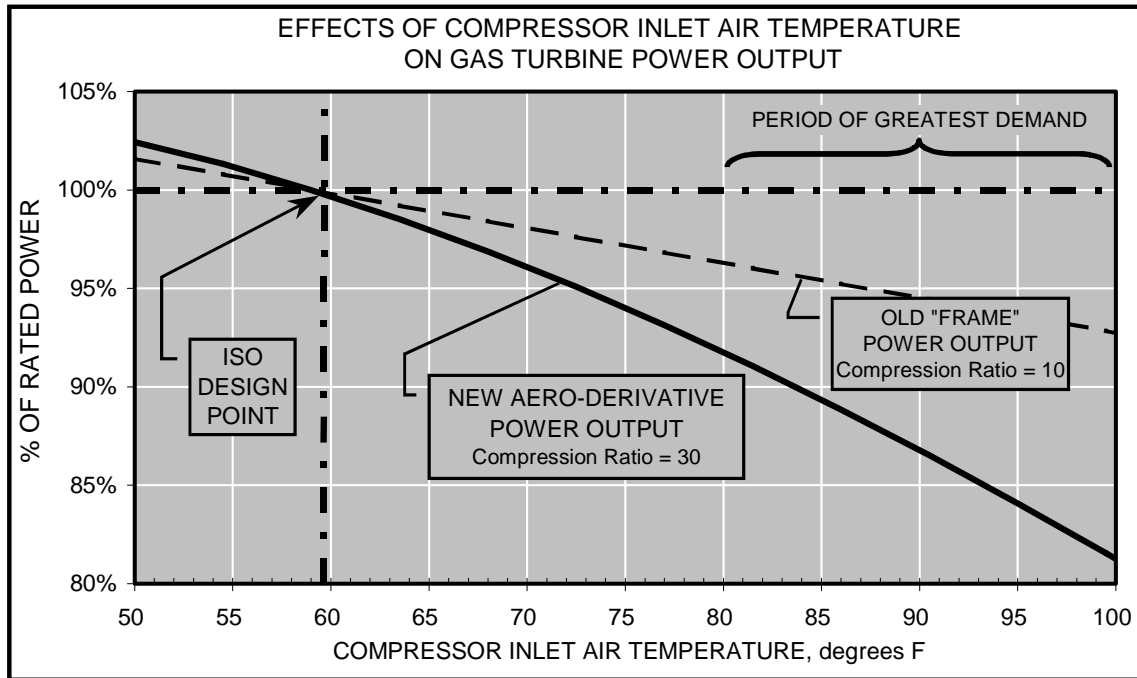


Figure 6. Effect of Ambient Air Temperature on CT Power Generation Capacity (Punwani 2005)

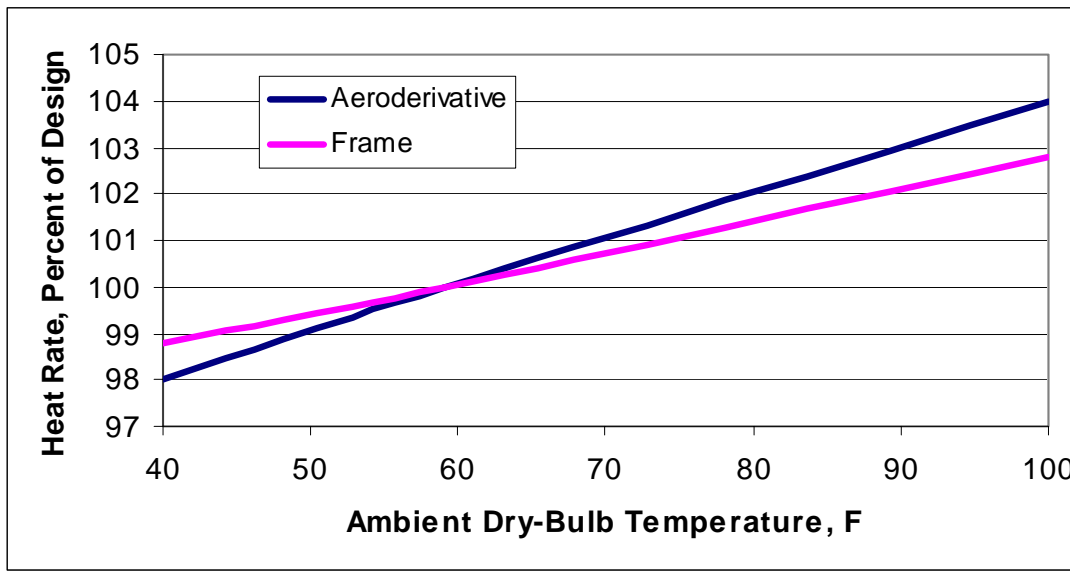


Figure 7. Effect of Ambient Air Temperature on CT Heat Rate

Each CT is designed to intake a fixed maximum volumetric flow rate of ambient air. However, the CT output depends on the mass flow rate of the inlet air to the system. The reason CT’s power generation capacity decreases with increase in ambient temperature because the later decreases the air density and thus, for the same volumetric intake of air, the mass flow rate decreases and hence the reduced output capacity.

Because power generation capacity and heat rate of a CT depend on ambient air temperature, the rated capacity of a CT is based on an ambient dry-bulb temperature of 59F at 60% relative humidity at sea level (because CT output is also adversely affected by altitude) and atmospheric pressure of 14.7 psia with zero pressure drops in the inlet and exhaust system of the CT. These rating conditions were selected by the International Standards Organization (ISO) and are well accepted worldwide.

**TURBINE INLET COOLING: SOLUTION TO THE HOT-WEATHER IMPACT ON CT PERFORMANCE**

The solution to the adverse effects of increase in ambient temperature on the CT performance is simple: cool the air before it enters in the CT. A typical effect of turbine inlet cooling (TIC) on the power generation capacity of a CT and its comparison with an un-cooled CT and rated capacities are shown in Figure 8. It shows that TIC significantly overcomes the derating of the CT output capacity.

**TIC Technologies**

The concept of turbine inlet cooling (TIC) is not only simple, a number of commercially-proven technology options are available too. All of these technologies are commercially well proven. There are three major categories of TIC technologies:

- Evaporative Cooling: Wetted-Media or Fogging
- Chillers: Mechanical/Electric or Absorption; without or with Thermal Energy Storage

- Liquefied Natural Gas (LNG) Vaporization (Applicable where LNG needs to be vaporized)
- Wet Compression

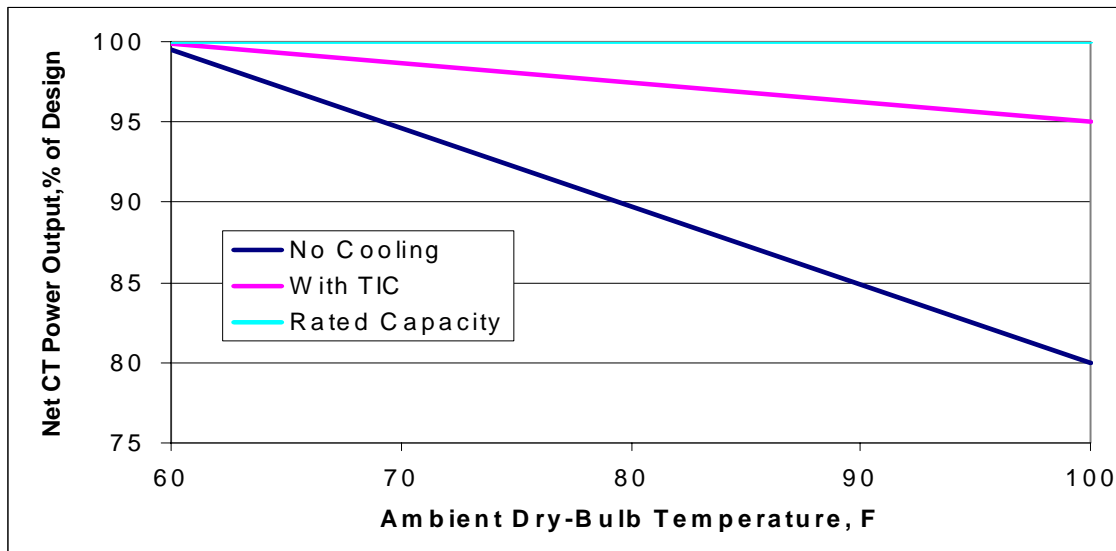


Figure 8. Effect of a TIC Technology on the CT Power Generation Capacity

TIC is a power augmentation option that could be used alone or in conjunction with other complimentary power augmentation technologies such as wet compression (Kraft 2006).

Descriptions of these technologies are available at the Website of the Turbine Inlet Cooling Association (<http://www.turbineinletcooling.org/technologies.html>) and in many publications (Andrepoint 2005, ASHRAE 2008, Cho 2003, Farmer 2007, Kraft 2004, Punwani 2008 and Stewart 1999). Each technology has its advantages and disadvantages. Selection of the best technology for a specific plant has to be evaluated on the basis of the plant characteristics, its location, fuel cost and market value of the electric energy.

**Power Capacity Enhancement and Economics**

A TIC system’s power capacity enhancement potential and economics depends on several parameters, including the following:

- CT design and characteristics, including the impacts of inlet air temperature
- TIC Parasitic load
- Pressure drop across the component inserted upstream of the compressor (insertion loss)
- Water usage
- Hourly weather data (dry-bulb and coincident wet-bulb temperatures) for the geographic location of the CT
- Selected ambient design conditions
- Selected cooled air temperature upstream of compressor
- Cost of fuel
- Cost of water
- Power demand profile
- Hourly market value of electric energy
- Hourly market value of plant capacity

Preliminary estimates of net capacity enhancement by evaporative cooling and chiller (without thermal energy storage) TIC options and the associated costs can be made by the ASHRAE calculation procedure (ASHRAE 2008), which is based on several rules of thumb. More accurate calculations can require sophisticated combustion turbine models and site-specific cost analyses. A few examples of the capacity enhancement potential of some of the TIC options are shown in Figure 9 for a typical 500 MW combined-cycle system. It shows that evaporative cooling produces more capacity enhancement when the relative humidity of the ambient air is lower. The results also show that a chiller provides the most capacity enhancement irrespective of the ambient air relative humidity.

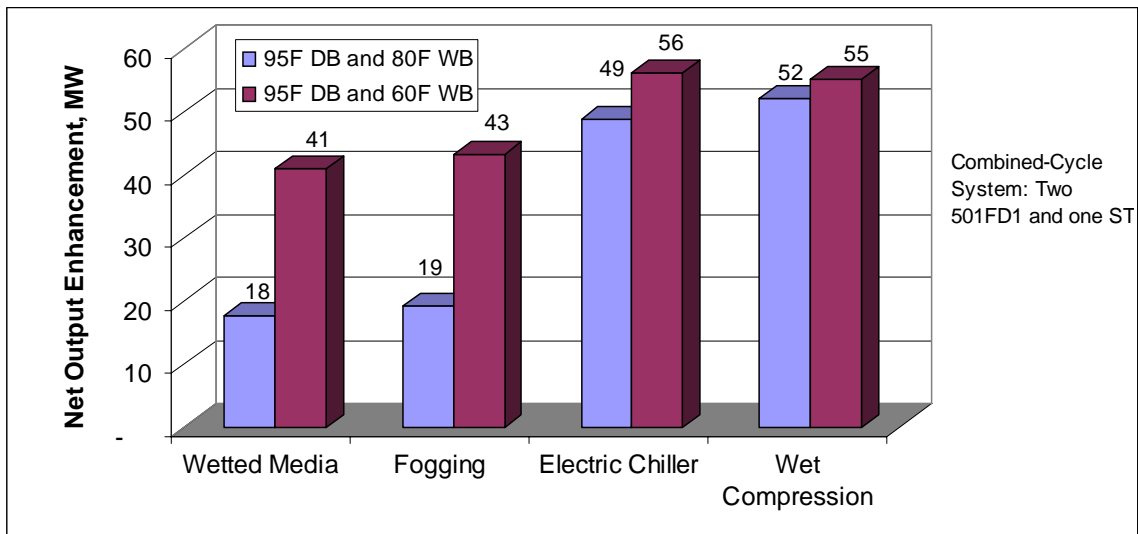


Figure 9. Examples of the Effect of TIC Technology on Capacity Enhancement Potential (Source for Wet Compression: Caldwell Energy Company; Source for all others: Punwani 2008)

A few examples of the economics of some of the TIC options are shown in Figure 10 for a 316 MW cogeneration plant in Pasadena, TX. It shows that the capital investment required per unit of incremental capacity is the lowest for the evaporative cooling technologies and the highest for the chillers systems and that the capital cost of all of these TIC technologies is only a small fraction of the cost of that for the un-cooled system.

Another example of the favorable economics of TIC is shown in Figure 11. It shows that the cost of incremental electric energy provided by TIC of a combined-cycle system is less than that for an un-cooled simple-cycle peaker. It shows that the major portion of the cost savings by TIC come from its reduced cost of fuel.

Figure 12 shows the preferred order of dispatching electric energy from a combined-cycle system that incorporates duct-firing and TIC. It shows that the use of TIC for supplying incremental electric energy saves fuel compared to that supplied by duct firing.

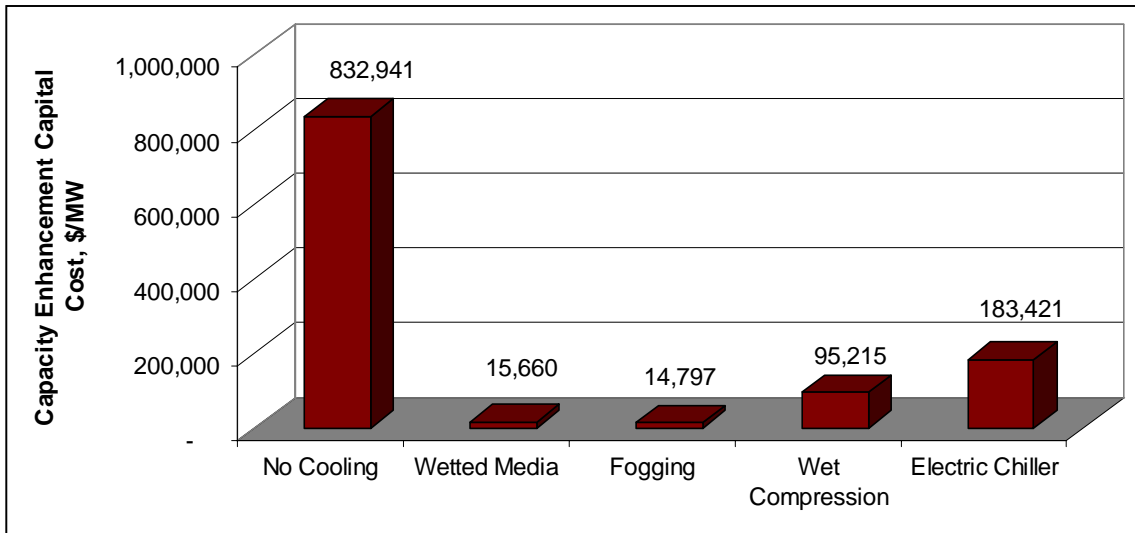


Figure 10. An Example of the Effect of TIC Technology on the Capital Cost of Capacity Enhancement (Source of Wet Compression: Caldwell Energy; Source for All Others: www.turbineinletcooling.org)

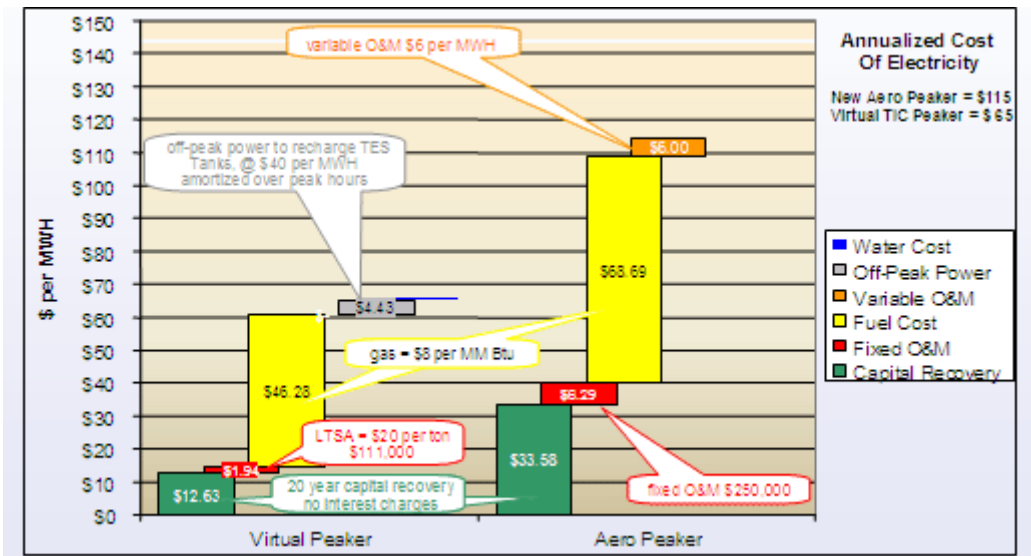


Figure 11. A Comparison of the Cost of Incremental Electric Energy Provided by TIC of a Combined-Cycle System with that Provided by a Simple-Cycle Peaker

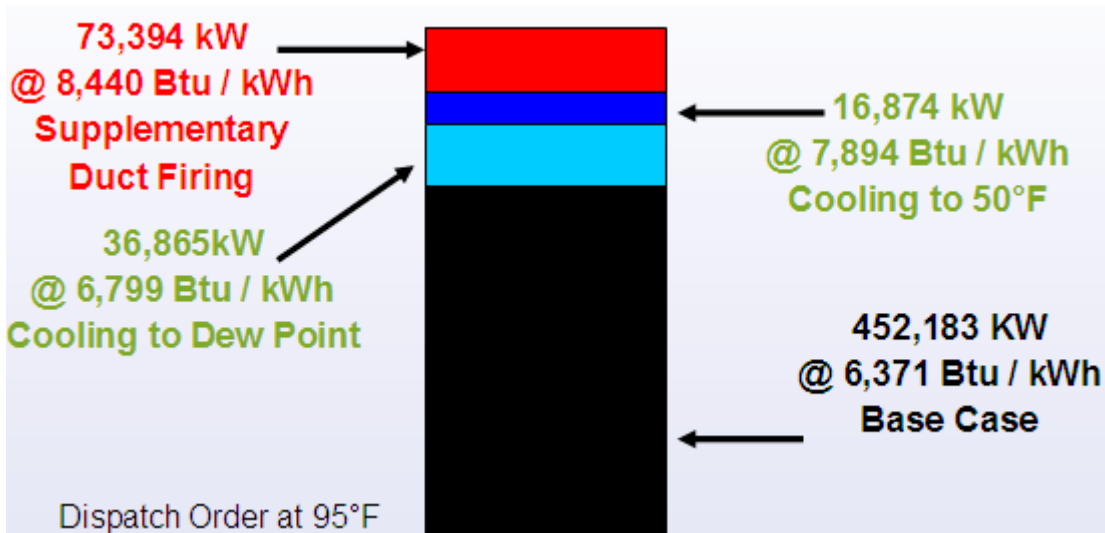


Figure 12. Preferred Order for Providing Electric Power from a Combined-Cycle System Incorporating TIC and Duct Firing

The estimates of simple payback period and/or internal rate of return require analyses based on the hourly weather data for the plant location and costs of fuel and water, and market value of the incremental electric energy. An example of the results of hourly analyses is shown in Figure 13 for a 316 MW cogeneration plant in Pasadena, TX. It shows the monthly incremental electric energy produced by some of the TIC technology options. It also shows that TIC provides maximum electric energy enhancement during the hot weather summer months.

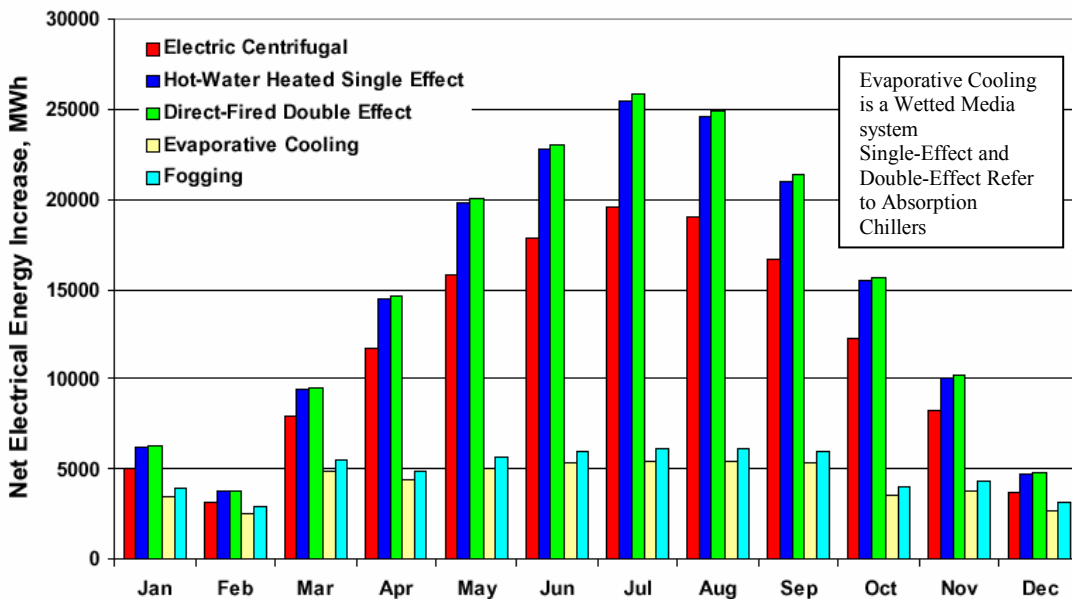


Figure 13. An Example of Monthly Incremental Electric Energy Provided by Various TIC Options for a 316-MW Cogeneration System in Pasadena, TX. (Punwani 2001)

**TIC BENEFITS**

TIC provides environmental and economic benefits as discussed below:

**Environmental Benefits**

There are two major environmental benefits of TIC:

- TIC allows minimum use of inefficient and higher-emission power plants by maximizing the output of the efficient and cleaner combustion turbine plants and thus, helps
  - a. Reduce emissions of carbon dioxide — a green house gas
  - b. Reduce emissions of regulated criteria pollutants (SO<sub>x</sub>, NO<sub>x</sub> and others)
- TIC Minimizes/eliminates siting of many new power plants

The use of TIC on the efficient combined-cycle plants allows these plants to produce more electric energy at their higher fuel efficiencies on hot days, as opposed to securing the same electric energy by dispatching an un-cooled simple-cycle aero-derivative CT “peaker.” When TIC is combined with thermal energy storage, which shifts some of the chiller’s electric load to the off-peak hours, additional electric energy is made available due to reduced TIC parasitic load during the on-peak period.

Figure 14 shows that the emissions of carbon dioxide per MWh unit of electric energy available from TIC of a typical combined-cycle plant is only about 700 lb, which is significantly less than over 1,100 lb and over 1,900 lb of carbon dioxide produced by securing the same electric energy from peaking simple-cycle and thermal power plants. Figure 15 shows a similar reduction in the emissions of the regulated criteria pollutants (SO<sub>x</sub>, NO<sub>x</sub> and others) by the use of TIC.

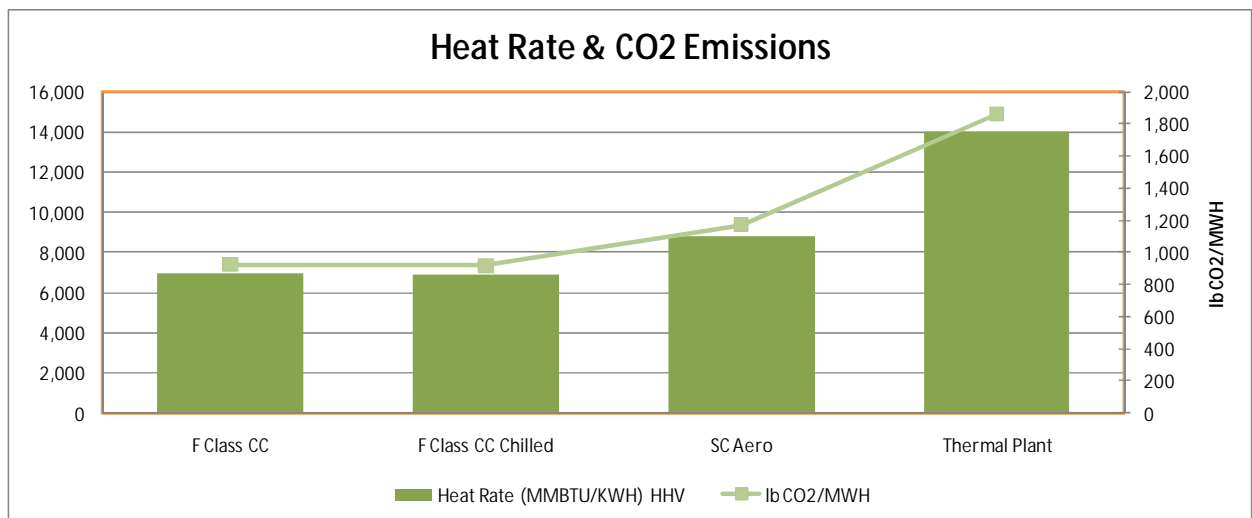


Figure 14. A Comparison of Heat Rate and Carbon Dioxide Emissions from Combined-Cycle, Simple-Cycle and Thermal Power Plants (Ambient Air at 95°F Dry-Bulb and 78°F Wet-Bulb Temperatures)

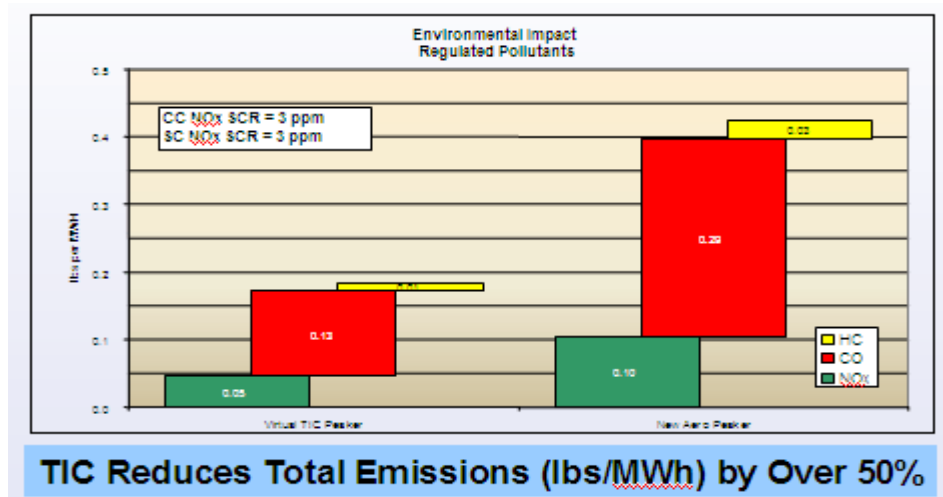


Figure 15. A Comparison of Regulated Pollutants Emission from the Incremental Electric Energy Produced by TIC Cooling of a Combined-Cycle System with that of a Single-Cycle Peaking Plant

As shown in Table 1, the power generation capacity during summer is about 29,000 MW less than that during winter. The primary reason for this reduction in generation capacity during summer is the derating of the CT-based plants. If TIC could be installed on all CTs, it would eliminate the need for siting and building 29,000 MW of new generation capacity.

### Economic Benefits

TIC also provides economic benefits:

- TIC Captures “hidden” capacity when most-needed and most-valuable
- TIC Enhances combustion turbine asset value via:
  - a. Lower capital cost per MW capacity gain produced (Also lower total blended capacity cost)
  - b. Improved heat rate (Lower fuel cost per kWh)
  - c. Faster capital cost payback (High Return on Investment)
  - d. Higher net present value
- Reduce ratepayer rates (Lower rates to electricity users)

Examples of the economic benefits of TIC have been illustrated in Figures 10 through 12 in the previous section. In addition, an independent analysis conducted for PJM Interconnection

LLC (PJM 2005) shows that the capital cost for the additional capacity provided by TIC is only \$216/kW — about 30% less than that of \$297/kW for an un-cooled CT.

## **SUMMARY**

In summary, TIC is a viable solution that is:

### **Better for the power producer**

Power producers benefit by having efficiently generated more power with reduced carbon footprint during high demand periods. TIC also reduces the capital investment and construction time required for increasing their power generation capacity.

### **Better for the ratepayer**

Because TIC helps minimize the need to operate less energy efficient peaking systems, ratepayers eventually pay less than they would have for the electric energy.

### **Better for the environment**

TIC helps reduce the carbon footprint for power production by minimizing the need to operate less energy efficient peaking plants. It also reduces the need for siting new power plants and the associated environmental impact.

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