Section 2

Turbine Inlet Cooling

Reference Charts

Gas Turbine Inlet Cooling

Scope, cost and performance for new and retrofit power plant projects

Turbine inlet cooling has always been prized for its ability to increase power output and improve the efficiency of simple cycle and combined cycle gas turbines in hot day operation.

Increasingly, operators have also come to see cooling as a low cost alternative for providing up to 25% more zero-emissions plant capacity without the environmental hassle, delay and cost of building a new plant. More specifically:

■ **Capacity.** Nominal increase in kW output on a 90F day can range from 5% to 25% of gas turbine nameplate rating depending on the inlet cooling technology, gas turbine design and ambient air conditions.

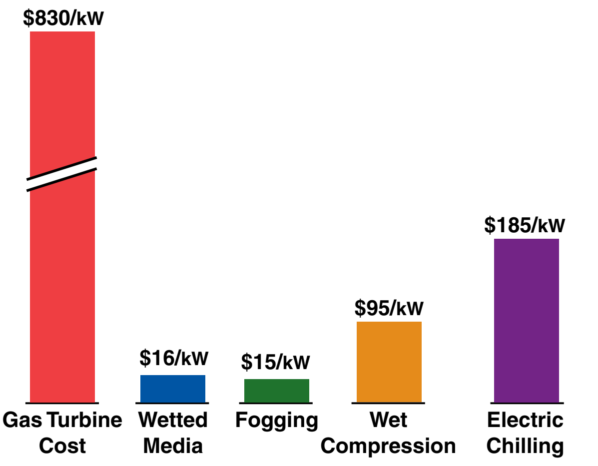
■ **CO_2 emissions.** The added capacity is accompanied by a decrease in site or regional CO2 and other fuel-related emissions directly proportional to the increase in kW output, a reduction in plant heat rate (Btu/kWh), and associated suppression of generating with less efficient machines in order to meet system demands.

■ **Capital cost.** Installed costs can range from $15 per kW for evap/fog water spray inlet cooling to $185 per kW for refrigerated chilling, as referenced to the gas turbine plant's standard ISO base load rating.

Aside from the considerable spread in capital cost of different cooling technologies *(see Fig. 1)* there is wide variation in their ability to enhance gas turbine performance during hot, cool or humid operating conditions.

Ultimately, the optimum choice of technologies is largely determined by site weather conditions, but it also depends on what you want to accomplish and how much you have to spend. Basic choices include:

Fig. 1. Ballpark estimates of TIC system costs for an F-Class combined cycle plant



Source: TICA White Paper, November 2009

Relative capital cost of turbine inlet cooling system installations referenced to the $/kW cost of a new F-Class combined cycle power plant prior to the addition of gas turbine inlet cooling.

Wetted media. Turbine inlet air flowing through a continuously wetted honeycomb type fiber material (normally cellulose) evaporates water off surrounding surfaces of the wet medium thereby cooling itself. Wetted media can cool the inlet to within 85% to 95% of the difference between ambient dry bulb and wet bulb temperature. In low humidity areas, the evaporative cooling can boost power output by up to 15%, while in high humidity areas the increase is more likely to be under 10%, approaching zero at the point of saturation (100% relative humidity).

Fogging. Very fine droplets of water are sprayed into the warm inlet air stream where the droplets evaporate to cool the air (similar to wetted media systems). In this case, the fogging can be controlled to produce droplets of various sizes, depending on desired evaporation and inlet residence time under prevailing ambient air temperature and humidity conditions. Fogging can cool inlet air by 95% to 99% of the difference between ambient dry bulb and wet bulb temperatures which makes it a bit more effective than wetted media.

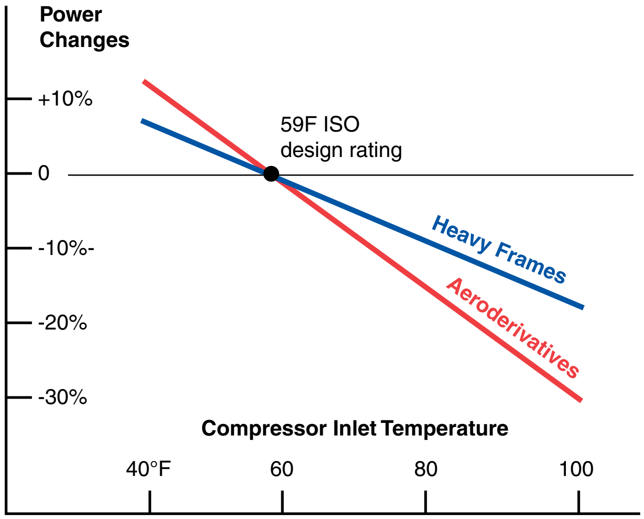
Wet compression. More finely atomized water than needed for inlet cooling alone is sprayed into the intake as micro-sized droplets. Typically 3x to 4x more fogging is added than can be evaporated in the inlet (sometimes referred to as high fogging or overspray). The air stream carries over the excess water fog into the compressor section of the gas turbine where it further evaporates for compressor inter-cooling and mass flow enhancement. Combination of inlet and compressor cooling can boost power output by upwards of 25% independent of ambient temperature conditions.

Chilling. Refrigeration based system where the ambient intake air is cooled by chilled heat transfer fluid circulating through cooling coils placed inside the inlet ductwork. Electrically driven mechanical chillers or absorption chillers (steam or hot water) may be used to cool the heat transfer fluid. Chilling is not limited by humidity so it is possible to cool ambient air below its wet bulb temperature, typically down to around 45F to 55F, for upwards of a 25% increase in power output.

Gas turbine sensitivity

The power output of any gas turbine is very sensitive to ambient temperature. Maximum power typically drops by about 0.3% to 0.5% for each degree Fahrenheit increase in ambient

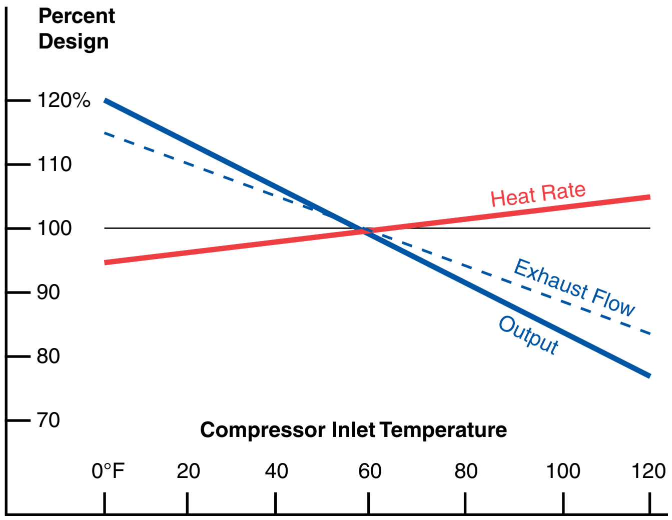
Fig. 2. Generic response of gas turbine power to changes in ambient air temperature



Source: GE Energy Oil & Gas

All gas turbines lose power as ambient air temperature increases, with higher pressure ratio aeroderivative designs losing almost twice as much per degree rise in temperature than do lower pressure ratio heavy frame units.

Fig. 3. Impact of temperature on MS7001 power output, exhaust flow and heat rate



Source: GE Energy Oil & Gas

Each gas turbine model has its own temperature-effect curve determined by cycle parameters (such as pressure ratio) and component efficiencies as well as air mass flow.

temperature (0.5% to 0.9% for each degree Celsius rise).

Heavy frame machines are less sensitive than aeroderivative units. Typically, they operate at lower pressure ratios than aero units but with much higher mass flow, so that temperature changes have proportionately less impact.

For example, on a 95F day, the power output of an old heavy frame unit operating at a pressure ratio of around 10 to 1 will decline by 7 or 8% (off its standard 59F nameplate rating) as compared to a 15% drop for a new aeroderivative gas turbine operating at a 30 to 1 pressure ratio *(see Fig.2)*.

The chart shows the generic sensitivity of heavy frame and aero gas turbine output to changes in ambient temperature. In real life, each gas turbine model has a unique temperature-effect curve specific to its design parameters and component efficiencies with respect to change in power output, heat rate and exhaust flow *(see Fig.3)*.

How inlet cooling helps

High ambient temperatures usually coincide with peak demand periods and are especially detrimental during hot summer days when the reduction in power output is greatest.

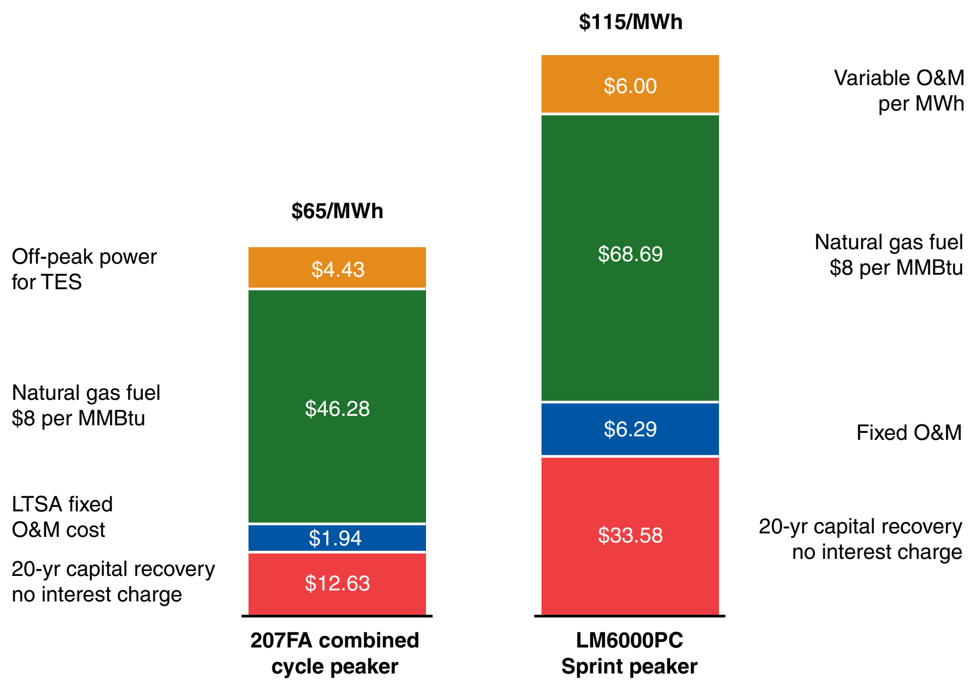
Inlet cooling offers a low cost solution to offset power loss at high ambient temperatures. Cooling the inlet air below 59F allows gas turbines to exceed their rated output.

In addition, inlet cooling and particularly wet compression helps minimize the degradation in heat rate with increases in ambient temperature. Since gas turbine heat rate is inversely proportional to fuel efficiency, any increase in heat rate means higher fuel consumption – along with fuel related CO_2 emissions and other pollutants.

Inlet cooling also has a positive effect on steam production and power output of combined cycle plants. Increased gas turbine mass flow entering the heat recovery boiler produces more steam which, in turn, helps increase steam turbine kW output.

Retrofitting a high efficiency combined cycle plant with inlet cooling is also an effective way of increasing peak power output and reducing the cost of electricity (COE) compared to an advanced simple cycle peaker (*see Fig. 4*).

Fig. 4. Chilling improves comparative COE of combined cycles ($65 vs. $116/MWh)



Source: TICA White Paper, November 2009

Annualized $65/MWh cost of electricity for a 2x1 combined cycle 207F peaking plant with chilling added is over 40% less than the $115/MWh COE for a simple cycle LM6000PC Sprint peaker with hot selective catalytic reduction and inlet cooling.

Combined cycle cost includes an annual fixed long term service fee of $20 per ton ($110,000) for the chiller plus an off-peak power cost of $40 per MWh (amortized over peak hours) to recharge thermal energy storage tanks.

COE for simple cycle LM6000PC includes a fixed cost of $250,000 per year for scheduled overhaul and maintenance, $6 per MWh variable O&M cost, plus additional fuel cost.

Dispatch factors

The preferred order of dispatch for providing electric power from a combined cycle peaking plant incorporating turbine inlet cooling and duct firing is to bring the most efficient combination of technologies online first (*see Fig. 5*).

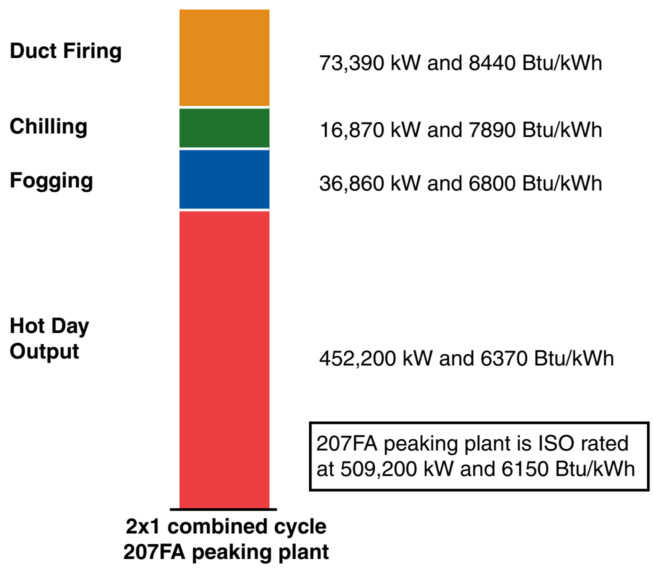
This chart is based on a 2x1 Fr 207FA combined cycle peaking plant ISO rated at 509,200 kW and 6150 Btu/kWh heat rate (55.5% efficiency) equipped with evap/fogging and inlet chilling plus supplementary duct firing to increase HRSG steam output.

Calculations show that plant performance falls off to around 452,200 kW output and 6370 Btu/kWh heat rate (53.6% efficiency) at 95F dry bulb and 78F wet bulb inlet air temperature conditions.

Cooling the inlet air flow by fogging to its dew point will add 36,860 kW and increase net plant output to 489,060 kW at 6800

Cost of incremental energy ($/MWh) for a chilled 207FA combined cycle peaking plant is significantly lower than for a simple cycle LM6000PC Sprint peaker with inlet cooling.

Fig. 5. Turbine inlet cooling has priority over duct firing for max dispatch efficiency



Source: TICA White Paper, November 2009

Power output of a 2x1 207FA combined cycle can be raised to almost 580 MW from 452 MW on a 95F DB and 78F WB day by fogging to dew point for a 36.9 MW gain, chilling to 50F for another 16.9 MW, and supplementary duct firing for a 73.4 MW boost in steam turbine output.

Btu/kWh heat rate (50.2% efficiency). Chilling to further cool the air to 50F will add another 16,870 kW for a net plant increase to 505,930 kW and 7895 Btu/kWh heat rate (43.2% efficiency).

Supplementary duct firing could boost steam turbine generation by 73,900 kW and increase total combined cycle plant output to 579,830 kW at 8440 Btu/kWh heat rate (40.4% efficiency).

CO_2 reduction

One major environmental benefit of inlet cooling technology is that it enables simple cycle and combined cycle gas turbine plants to operate at higher than rated power output and efficiency, despite hot and humid air conditions.

The increase in capacity helps defer (and sometimes eliminate) the need to bring older and less efficient power plants online to meet grid demand, particularly for peaking power. Higher efficiency reduces fuel consumption and production of collateral CO_2 emissions and other fuel-related pollutants.

Turbine inlet cooling for already efficient combined cycle plants allows them to operate at significantly lower CO_2 emissions per kWh of generation in comparison to highly efficient simple cycle gas turbines equipped with inlet cooling (see Fig. 6).

The 1x1 F-Class combined cycle plant shown in the chart is rated at 260MW and 57% to 58% efficiency. Under 95F dry bulb and 78F wet bulb temperature conditions, with inlet air cooling, the combined cycle plant will generate about 700 lb of CO_2 per MWh of generation compared to 980 lb for the same plant without cooling.

That is less than the 1100 lb of CO_2 per MWh for a simple cycle LM6000 Sprint peaking plant equipped with inlet cooling – and significantly lower than the 1900 lb of CO_2 produced by a natural gas-fired steam plant.

Regulated criteria pollutants

Additional benefits of gas turbine inlet cooling include a decrease in emissions of all kinds that accompany improvements in heat rate.

The reduction in regulated criteria pollutants, notably hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxide (NOx), is similar to that of carbon dioxide emissions for inlet cooled simple cycle and combined cycle plants.

Compare a 2x1 207FA combined cycle plant with those of a simple cycle LM6000PC Sprint peaking plant, for example, both plants operating with selective catalytic reduction (SCR) to limit NOx emissions to 3 ppm and both equipped with turbine inlet cooling *(see Fig. 7)*.

As shown in the bar chart, the combined cycle plant produces 0.19 lb of regulated criteria pollutants per MWh of generation versus 0.42 lb for the simple cycle plant – better than 50% lower in all categories.

TIC project benefits

Operational and economic benefits of turbine inlet cooling apply to new gas turbine projects, both simple cycle and combined cycle plants, and to existing plants on a retrofit basis.

For new projects, the economic benefit of inlet cooling is that the $/kW cost for the increase in capacity is usually well below the $/kW capital cost of the plant on its own.

When retrofitted to existing plant installations, especially combined cycles, the added capacity can be enough to eliminate the need for new generating capacity.

The relative potential of various cooling technologies to increase capacity (without burning more fuel) depends on ambient air conditions. Take for instance a 2x1 501FD combined cycle plant ISO rated at 500 MW *(Fig. 8)*.

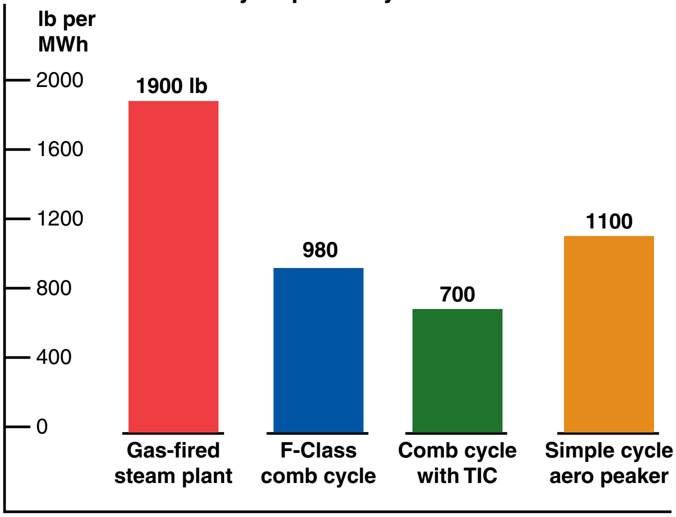
As shown, wetted media and fog cooling are more effective adding capacity when the relative humidity of the ambient air is lower; chilling and wet compression are both much less dependent on humidity.

It is worth noting that many comparative charts (including those in this reference section of the GTW Handbook) are based on reasonable assumptions for each technology based on experience and in-depth design study of equipment capabilities and performance.

They are intended to provide a generic grasp of commonly applied cooling technologies and should be treated accordingly rather than be accepted as gospel or case history.

For preliminary planning purposes or questions about performance, the major TIC system suppliers are always the best source for information directly related to your project interests.

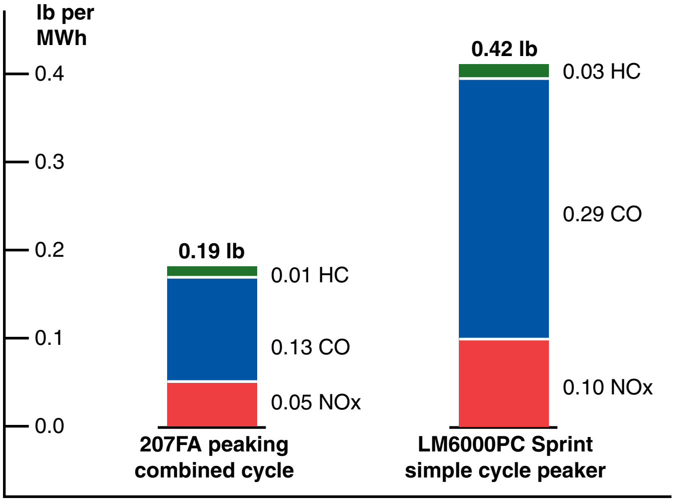
Fig. 6. Inlet cooling can also reduce CO2 of combined cycle plants by 30%



Source: TICA White Paper, November 2009

Adding inlet cooling to a typical F-Class combined cycle plant can reduce CO_2 to 700 lb/MWh at 95F DB and 78 WB conditions, far less than the CO_2 emissions produced by simple cycle aero peaking and gas-fired steam plants.

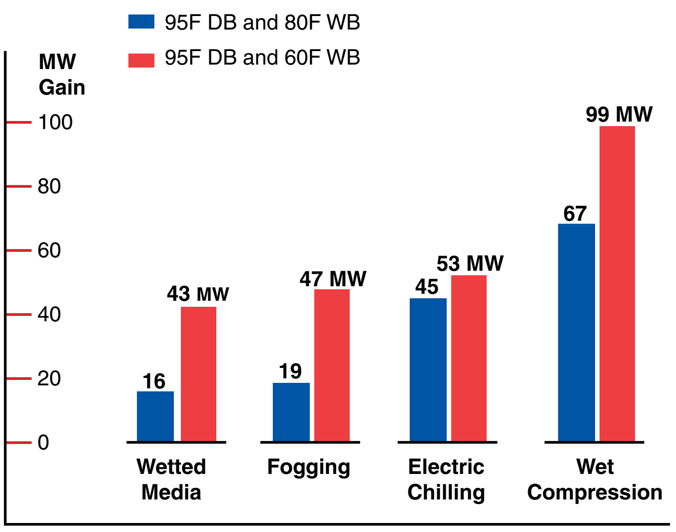
Fig. 7. Inlet cooling reduces total emissions of regulated criteria pollutants



Source: TICA White Paper, November 2009

Nominal 530 MW 207FA combined cycle peaking plant, with inlet cooling, will produce less than half the regulated criteria pollutants (0.19 lb/MWh) of an inlet cooled simple cycle LM6000PC Sprint peaking plant (0.42 lb/MWh).

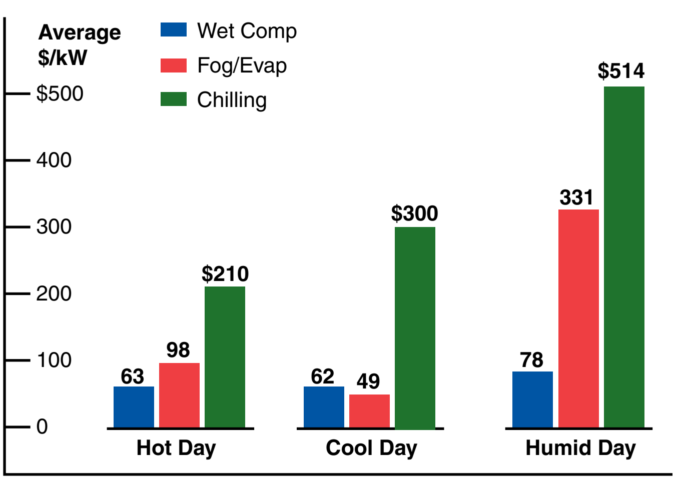
Fig. 8 Impact of humidity on hot day power gain of turbine inlet cooling technologies



Source: Caldwell Energy, January 2010

Chilling and wet compression are much more effective than evap/fogging at both high and low humidity levels, as shown here for a retrofitted 500 MW 2x1 W501FD1 combined cycle plant on a 95F day.

Fig. 9. Cost per kW of power augmentation for a 24-hour period



Source: Caldwell Energy, January 2010

Calculating the $/kW cost of inlet cooling based on the kW gain under hot, cool and humid conditions is a better indicator of true costs than a plant's $/kW capital cost.

Evaluation factors

The power capacity enhancement potential of different turbine inlet cooling technologies for a specific project application depend largely on geographic location of the plant (climate and weather) and gas turbine design performance characteristics.

The economic choice of technologies depends largely on the projected return on investment with respect to expected hours of operation during the year under comparable temperature and humidity conditions, amount and value of the incremental increase in power produced, and competitive cost of outside purchased power.

The same historical weather data that utility planners work with to analyze peak load demand during different seasons and hours of the day can also be used to evaluate and estimate the annual gas turbine inlet cooling load and frequency of hot, cool and humid days of operation *(see Fig. 9)*.

For purposes of this chart, a hot day is defined as 90F dry bulb and 60F wet bulb temperatures at 15% relative humidity; cool day as 67F DB and 50F WB at 27% relative humidity; and humid day as 72F DB and 64F WB at 65% relative humidity.

Hourly costs ($/kW) are averaged over the entire day that a system is used to approximate the relative cost of cooling technology options operating at hot day, cool day and humid day ambient air conditions.

For hot day operation, as the chart shows, the wet compression average cost is $63/kW; fog/evap cooling is $98/kW; and chilling $210/kW. The significant difference between these technologies, say cooling project engineers, is due to the varying spread between dry and wet bulb temperature throughout the day.

Similarly, energy gains (MWh) differ for each technology (see Fig. 10). For hot day operation, wet compression shows a gain of 854 MWh; fog/evap cooling 235 MWh; and chilling 301 MWh.

The cooling technology gains for hot day, cool day and humid day operation represent the increase in saleable energy over a 24-hour period.

Built-in cooling

Gas turbine builders also incorporate compressor intercooling to augment power output. GE Energy Aero, for one, has been increasing the power output of its LM6000 series by at least15% to 20% with its Sprint (spray intercooling) design upgrades.

The latest LM6000PF model is ISO rated at around 43 MW and 8220 Btu/kWh heat rate (41.5% simple cycle efficiency). The LM6000F Sprint version, with water intercooling, is rated at 48 MW.

Last year, Rolls-Royce introduced its new Trent 60 gas turbine design with an inlet spray intercooling (ISI) option that integrates inlet and compressor fogging to significantly enhance performance.

For instance, the Trent 60 DLE design is nominally rated at around 52 MW base load output and 8100 Btu/kWh heat rate (42% simple cycle efficiency) at 59F ISO conditions. The same machine can be uprated by inlet spray intercooling to around 58 MW and 7965 Btu/kWh heat rate (42.8% efficiency).

Results are even more dramatic for hot day operation where the Trent 60 DLE design is rated at 42 MW and 8580 Btu/kWh heat rate (39.8% efficiency).

With ISI enhancement, the same machine can be uprated to 53 MW and 8200 Btu/kWh heat rate (41.6% efficiency) at an ambient air temperature of 90F *(see Fig. 11)*.

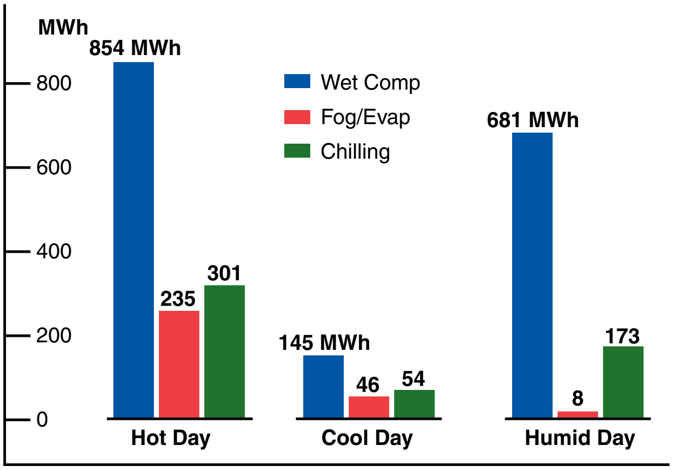
GE Energy's LMS100 gas turbine design incorporates off-engine intercooling (heat exchanger) to give it a nominal rating of 100 MW and 7580 Btu/kWh heat rate (45% simple cycle efficiency).

Several LMS100 power plant peaking and base load installations have been equipped with evaporative inlet cooling systems for hot day performance enhancement. ■

Reference material

We want to thank the industry suppliers and cooling system project engineers who contributed to this reference piece. For more information about the impact of power augmentation on reducing carbon footprint, we refer you to a White Paper published by the Turbine Inlet Cooling Association entitled *Turbine Inlet Cooling: An Energy Solution That's Better for the Environment, Ratepayers and Plant Owners,* dated November 24, 2009 You can reach the TIC Association online at www.turbineinletcooling.org.

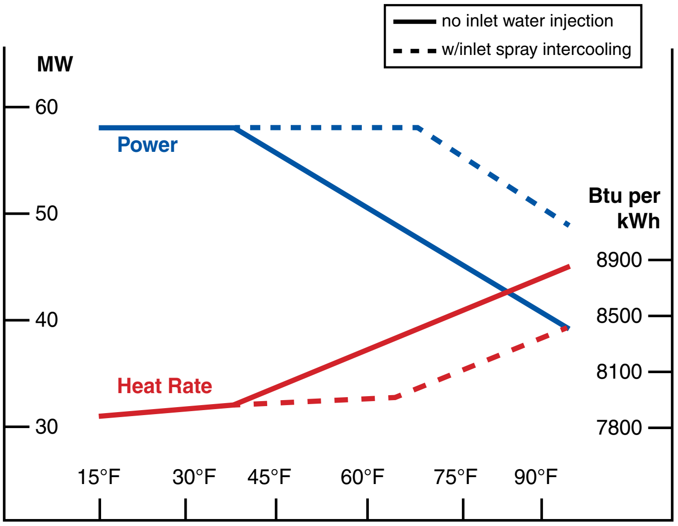
Fig.10. Increased daily energy from inlet cooling power augmentation



Source: Caldwell Energy, January 2010

Increased output of two 120 MW class gas turbines in combined cycle operation with turbine inlet cooling under hot, cool and humid day conditions represents the increase in saleable energy per MWh for a 24-hour period.

Fig. 11. Inlet water spray injection enhances Trent 60 DLE performance



Source: Gas Turbine World, Nov.-Dec. 2008

With water spray intercooling, power output can be increased from its 52 MW ISO design rating to a maximum 58 MW winter output from below zero to around 70F.