TURBINE AIR SYSTEMS

ASSET OPTIMIZATION OF NEW POWER PROJECTS WITH GAS TURBINE INLET AIR COOLING

Winning Power Plant Projects in the GCC through a Simple and Proven Restructuring of Generation Technology

A guide for GT OEM's, IPP Developers, and Government Electricity Ministries

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INTRODUCTION

Gas Turbines (GT) are the current power generation method of choice for the majority of power needs. One major disadvantage of this generation technology is the degradation of capacity and heat rate during peak months on hot summer ambient days. Cooling the inlet air of the GT increases the mass flow rate and improves the GT performance.

Figure 1
"Packaged" chiller installation, approximate refrigeration capacity of 11,800 tons (41,000 kW_{th}).
This system was applied to a 633 MW F-Class combined cycle plant in 2002.

In recent years GT Turbine Inlet Air Cooling (TIC) has proven to be an economical solution for optimizing power generation assets. During the past four years standardization and packaging have lowered installed costs by 50% and shortened lead times from eighteen (18) to less than six (6) months. Coincident with the cost and time improvements, technology advances by the various OEM's have nearly doubled efficiencies.

Despite the proven technology success from TIC systems in operation globally for ten (10) to fifteen (15) years, applications in the Middle East region have been few. The purpose of this paper is to expose the myths and remove the barriers for installations into the region. What will be the TIC impact on the economics of simple and combined cycle plants operating in the extreme ambient temperature conditions? What is and when should thermal energy storage be considered? What are the expected operating and maintenance costs of a TIC system?

APPLICABILITY TO THE GCC

The region comprised of the Gulf Cooperation Council (GCC) (Bahrain, Iran, Kuwait, Oman, Qatar, Saudi Arabia, and UAE) is one of the most economically vibrant areas in the world. While the markets for power equipment in the Americas, Europe and Asia languish in 2003, there appears to be continued vitality for new power plant construction in the GCC. The concentration of economic opportunity in this one region makes every decision for equipment tendering strategies more important than ever for gas turbine manufacturers, and for the developers of large projects.

Power projects for the region are expected to continue to follow the four traditional major demand loads: summer peaking power, oil production loads, manufacturing and desalinization installations. Additionally, two new emerging trends will draw heavily on gas turbine technology: Liquefied Natural Gas (LNG) liquification facilities, and metal smelting.

Table 1

	LOAD	LOAD TYPE	DESCRIPTION
1	Summer Peaking	Commercial	Commercial and residential comfort cooling (air-conditioning and dehumidification)
2	Petro / chemical	Industrial	Electrical and steam loads derived from the oil production, refining, and petrochemical industries
3	Desalinization	Industrial	Base load power and intermediate pressure steam production for desalinization vessels
4	LNG	Industrial	Compression loads by mechanical compressors, usually driven by small GT's
5	Manufacturing	Industrial	Driven by low labor cost and strong infrastructure
6	Smelting	Industrial	Application of low cost electricity to create increased value by conversion of metal ores

In most of the GCC countries, the GT has been the predominant power generation method of choice. This trend is foreseen into the near future.

In each of the six markets described above, there should be little tolerance accepted for decreased power output from gas turbines due to the well-known effect on GT performance from increased ambient temperatures. For the four "industrial" loads of petrochemical, desalinization, LNG, and smelting, there should be minimal allowable impact on output due to seasonal variations in ambient conditions. In order to maintain reasonable industrial throughput during the summer, it will be necessary to install more GT's than might be required during more moderate winter temperatures. For the single "Commercial" load of summer peaking, there will continue to be increased demands by the comfort-cooling sector, with increased new building construction and global application of air-conditioning.

It is with particular interest that we highlight the increased peaking demands of the comfort cooling market. It is ironic that comfort cooling demand loads are going to be mitigated by the application of gas turbine power plants. In this regard, there is probably no worse choice for a power plant than gas turbines. The reasoning is quite simple: the hotter the ambient temperature becomes, the higher the electrical demand becomes, and the lower the gas turbine output will be. It is clearly a case where the demand curves and the supply curves are heading opposite to each other.

TYPICAL REGIONAL DEMAND

As shown in the above daily power demand graph for a local utility, the peak power demands of the day occur in the afternoon, when the ambient temperature is hottest. Another factor of note is that the true peak demand, estimated here as all the power above 9,600 MW, occurs only for approximately 6 hours per day. Unfortunately, it is the current practice to build enough generating capacity to meet the entire 10,400 MW load.

Of course, in order to achieve 10,400 MW of peak capacity, it is necessary to build approximately 13,000 nominal MW (ISO rated) of generating equipment, if no TIC technology is employed. We will show in this paper that instead of building 13,000 MW of capacity to meet this load, the utility could instead build only 10,000 MW of GT capacity and employ less-expensive TIC technology to maintain that power output in virtually any hot weather.

QUALITATIVE ARGUMENT FOR GAS TURBINE INLET AIR COOLING (TIC) IN THE GCC MARKET

The Gas Turbine is a wonderful machine. It is inexpensive to build, install, and operate; it is reasonably reliable. However, it has a weakness: Hot weather operation. The answer, to date, has been to simply apply more gas turbines to mask the problem. This causes a poor Capacity Factor in an Owner's fleet, as the result of many units being taken off-line for the spring, fall, and especially winter seasons.

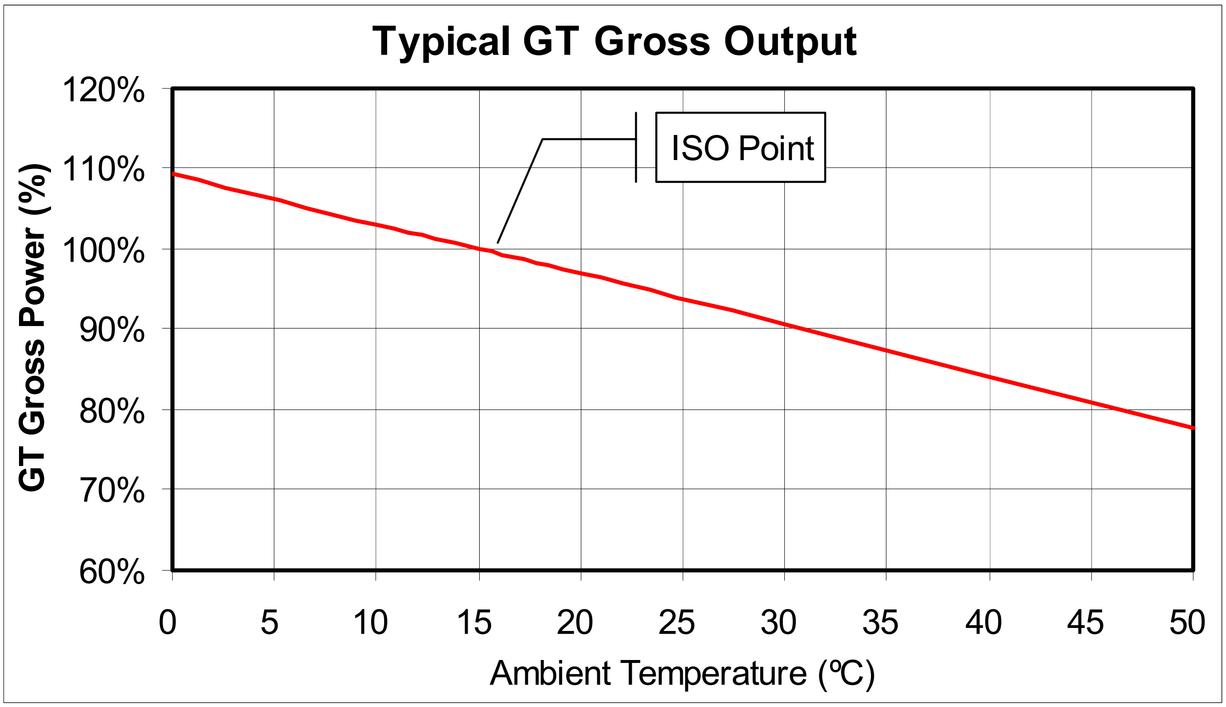

Figure 2

Typical heavy-duty "frame" gas turbine gross output, as a percentage of ISO rating, vs. ambient temperature.

It is this negative slope of the line, known as "lapse rate", that indicates the loss of power when ambient temperature increases.

It is our contention that by continuing to simply apply, almost exclusively, gas turbines to the GCC region, Owners are not getting the best economic mix of generating capability. We propose that all new GT installations should be provided with TIC technology as a primary tendering requirement.

We have heard some engineers and officials that believe that TIC applied to gas turbines makes economic sense only in the Western-style "Merchant" markets where there may be high hourly clearing prices during summer peaks. In fact, such high hourly rates did help pay for some TIC systems very quickly in the past few years. However, the fact remains that only in the Merchant markets was there an expectation that on the very highest peak hours there might be rolling blackouts when peak demand surpassed electrical supply. In fact, such rolling blackouts (and brownouts) have occurred in global markets in the past five years.

By contrast, in regulated markets (even in the newly liberalizing power markets that are developing in some GCC states) there will still remain an electrical ministry that may be against to knowingly allow rolling blackouts, particularly in such a harsh environment. Contrary to such needs to provide ample power capacity, utility pricing practices in the region have the potential to lead to extremely tight reserve margins. Observers in the region note that retail prices are subsidized by governments, and there are no time-of-use rates in effect. The result is that there is little economic incentive to limit peak electrical use; nor is there incentive for Demand Side Management programs such as Thermal Energy Storage (TES) for comfort cooling loads.

Therefore in a region where the electrical utility authority has the equivalent of an "obligation to serve", the fleet size of electrical generating capacity (supply) may be based solely on the forecasted peak load (demand), and not on economic considerations such as payback. Accordingly, we propose where peak electrical demand loads are being driven by high ambient temperature, and the supply of electricity is being met by gas turbines, then the gas turbines must be equipped with TIC. The reason for adding TIC capacity to the generation mix will be shown in this paper.

TIC equipment has historically been thought of as "power augmentation". This means that a basic primary decision is typically made as to the model and quantity of gas turbines to be installed. That first decision will be the "base". Then, the secondary decision is made to add TIC, so as to augment the base. For a given number of gas turbines, there would now be more power. This obviously helps in hot-weather power sales, but it also reduces the unit price of the power plant.

Alternatively, what if the amount of power is already prescribed before the model and number of gas turbines are chosen, such as in an equipment tender, or a IPP power tender? In such a case, if the "base" is already set to meet the minimum needs of the Tender, then there might be no economic value to the TIC augmentation equipment, or from the extra power that is produced. However, if the value of the TIC equipment is included in the up-front scoping of the project, then a very new and exciting dynamic will occur: a significant cost savings will be realized.

HOW "PULL" BECOMES "PUSH"

At present, in other regions of the world, particularly North and South America, the TIC market has been described as a "Pull". This means that many educated power plant customers have demanded the installation of TIC equipment from the Engineer-Procure-Construct (EPC) contractor and/or the GT manufacturer. No GT manufacturer has been actively "pushing" TIC technology on their customers. Nonetheless, most GT manufacturers offer at least some form of fog or evaporative cooling (a low-impact form of TIC) as an available option for their GTs; and at least one GT manufacturer offers standard filter houses that are "coil-ready" for chiller applications (one "aero-derivative" manufacturer takes the next step by selling a significant portion of their engines with the coils already installed in their filter houses).

This paper will demonstrate that it is now possible to meet the demands of an power plant Tender with fewer gas turbines than have historically been required. If the gas turbine plant is supplied with TIC, a decrease in one or more GTs is possible on a large plant, while still meeting the power output requirement of the Tender. By substituting low-cost TIC technology in place of a small portion of the GT capacity, the total cost of the plant will decrease, and the "unit price" evaluation criterion of "$ per kW" will decrease greatly. In addition, operating and maintenance (O&M) costs can be reduced by as much as 90% compared to the equivalent GT O&M annual cost on a cost per kW or kWHr comparison.

The potential of selling fewer GTs may be viewed negatively by most GT manufacturers. However, now that the customers in the power market are becoming more aware of the benefits of TIC, there may no longer be any other position for a manufacturer or an IPP developer. If, as we show in this paper, the real cost and the unit cost of the power project decreases for a specified power need. If, for example, a bidder chooses to not promote the TIC technology, then they are at adverse risk of bidding against another manufacturer (or IPP developer) that has included the TIC equipment. Accordingly, the non-TIC Tender will be significantly higher in first cost, in unit cost, and in long-term operating costs. As such, the non-TIC Tender will not offer the Owner the best value, and the Owners are now in a position to understand this.

We see an opportunity for GT manufacturers to take an aggressive position with a "Push" on TIC technology that could so significantly impact the project economics as to assure a "win" on a new power plant Tender. The benefit to such a forward-thinking manufacturer would be that the project is won with fewer GT's, instead of lost with more GTs.

The downside of not exploring the TIC option, at least as an alternate offering, would be to place their Tender efforts at risk of being noncompetitive in the arena where other players are openly (or secretly) pushing TIC technology.

EQUIPMENT SELECTION METHODOLOGY

The premise of this paper is to introduce the financial impacts of TIC. Most of the readers of this paper will surely have by now a basic technical understanding of several of the technologies used for TIC. However, we will provide much greater detail of plant performance impact, and cost impact, specifically described for the GCC region.

We propose to provide several calculations of typical power plant performance. We will use the gas turbines of two different GT manufacturers. These two turbine types will be taken as reasonably representative of the four major GT manufacturers. The performance data and costs of the installed plants will be taken, as much as possible, from published sources. There is no need to identify the manufacturers or model names, so we will reference them as Gas Turbines "X" and "Y". GT "X" is "smaller" than GT "Y", in part because GT "Y" has a higher compression ratio. Therefore, for a given power need, more of the GT "X" model will be required.

The gas turbine selections for Scenario A are shown graphically in Figure 3 and Figure 4. Note that the power of one GT is higher than the other GT. Nonetheless, each gas turbine exhibits the same downward sloping line when ambient temperature increases.

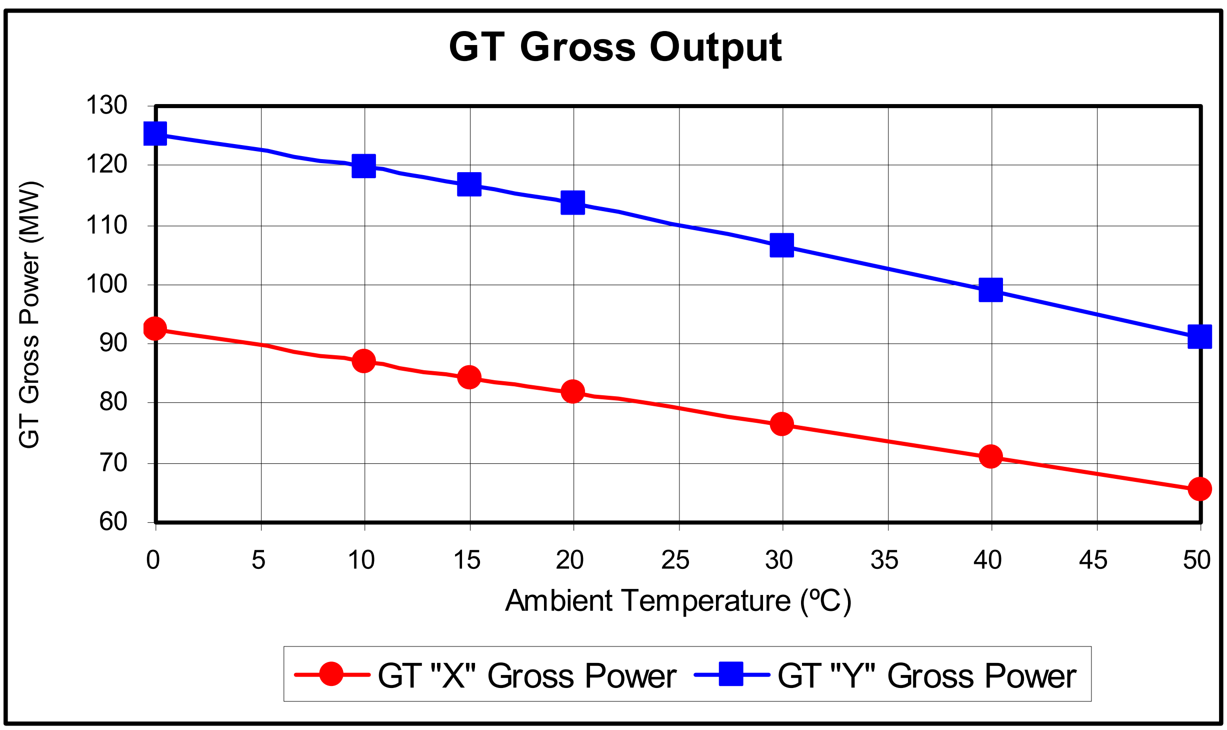

Figure 3
Gas turbine gross output vs. ambient dry bulb temperature.

The gas turbines shown are the 60-cycle variants of two popular GT families, both industrial "frame" engines that are already used extensively in the GCC region. These two GTs compete against each other regularly in new power projects. We used the 60-cycle variants of these two GTs for Scenario A, so as to replicate a competitive position that might be encountered in Saudi Arabia.

For further consideration, 50 Cycle variants of the same families are used in Scenario B, which although more powerful than their 60-cycle stable-mates, exhibit the same characteristic trend to lose power when ambient temperature increases.

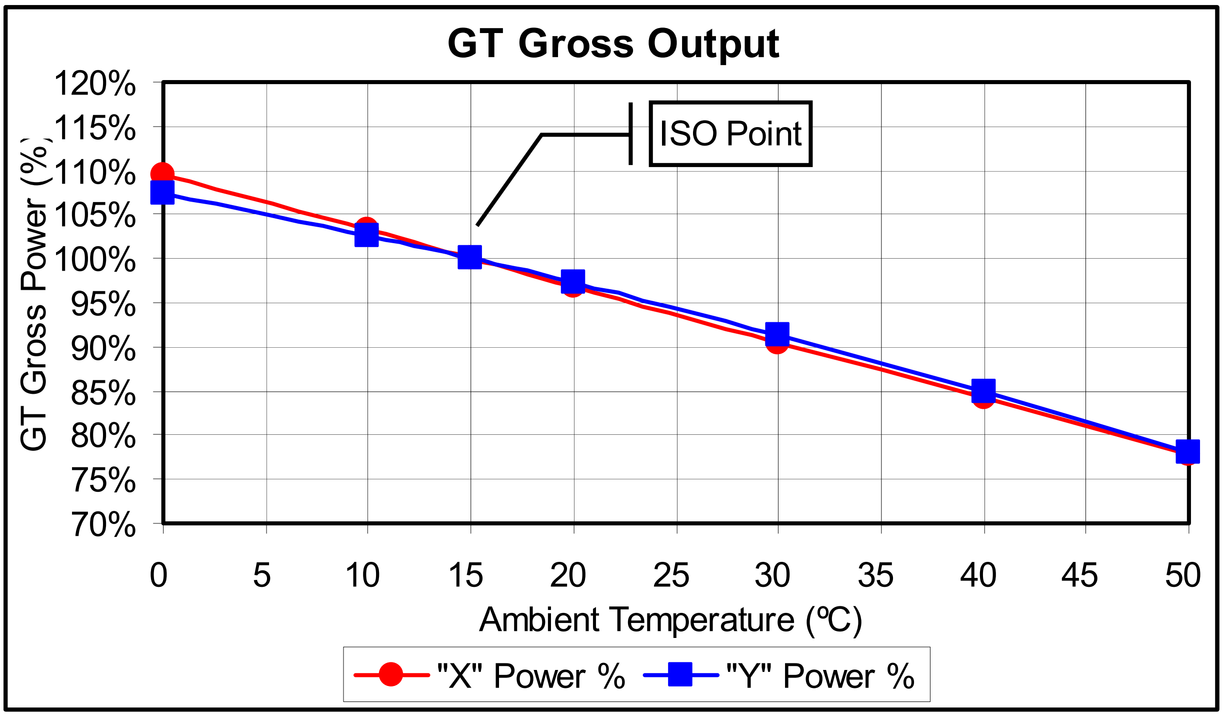

Figure 4

*Gas turbine gross output, as a **percentage** of ISO rating, vs. ambient dry bulb temperature. Note that despite the actual output difference shown in the previous figure, the relative power changes are very similar and nearly indistinguishable.*

By using a mix of scenarios that includes Peaking and Base-Loaded technology, air-cooled and water-cooled technology, equipment tender and IPP offering, and 50-cycle vs. 60-cycle equipment, we intend to show the universal nature of the results that consistently point to the successful use of chiller equipment as TIC in the GCC region.

ANALYSIS SCENARIOS

We want to explore the varied future needs of the GCC region, so we will look at both Simple Cycle and Combined Cycle applications. Accordingly, the calculations for this paper will be divided into two sections, Scenarios **A** and **B**:

A The first Scenario will describe a hot and dry location, such as Riyadh, KSA; or Al Ain, UAE. Here, the gas turbines will be chosen as Simple Cycle Peakers, with no water usage allowed for the inlet cooling technologies. The gas turbine selections will be from the two major manufacturer's large 60-cycle offerings. For a region generic example, assumptions are:

New installation
EPC bid for 800 MW
50°C (122°F) dry bulb temperature
20.7°C (69.3°F) wet bulb temperature
Sea-level elevation

This Example is based on an Engineer-Procure-Construct (EPC) Tender for a nominal 800 MW plant. More than 800 MW can be provided, but not less than 800 MW at the design point. No credit will be given for additional power above 800 MW. The basic bid evaluation criterion will be lowest first cost. No water usage is allowed, therefore no fogging or evaporative cooling will be considered; and the TIC system will be air-cooled.

In the air-cooled Scenario A calculations, an industrial air-cooled chiller system is used, such as a large screw-type ammonia refrigerant chiller, with air-cooled condensers.

B The second Example will describe a less-severe coastal location, where the ambient temperature will be slightly reduced, but the humidity will be much higher. Such a location would approximate the conditions of Dubai, Abu Dhabi, Dammam, Jeddah, or Doha. For these locations, assumptions are:

New installation
IPP bid for 1,000 MW
47°C (116.6°C) dry bulb temperature
30°C (86°F) wet bulb temperature (30% Relative Humidity)
Sea-level elevation

The power plant is selected as a water-cooled combined cycle, using wet cooling towers as the ultimate heat sink. The gas turbines will be selected from the same two GT manufacturers, but these gas turbines will be the larger 50-cycle variants, with matched Heat Recovery Steam Generators (HRSGs) and Steam Turbines. Of note, for many desalinization installations, there may not be a Steam Turbine; however, the premise is the same, and the steam turbine cost will act as a "proxy" for other loads and costs associated with a desalinization train.

In the water-cooled Scenario B calculations, an industrial water-cooled chiller system will be used, with dedicated cooling towers for refrigerant condensing.

It should be noted that although the dry bulb temperature is somewhat lower for the Scenario B calculations, as compared to Scenario A, the wet bulb temperature is much higher for Scenario B. It is the wet bulb temperature that has the predominant impact on the coil load for a TIC system. This is due to the condensation of water that occurs on the inlet coils. This is what is known as "latent" effect.

The assumptions will be that this new installation will be based on an Independent Power Producer (IPP) Tender for a nominal 1,000 MW plant. The Bid evaluation criteria for this project will be more liberal. The Bidder may provide more than 1,000 MW, within reason, but not less than 950 MW. The basic bid evaluation criterion will be the unit price parametric of "$ per kW". This will allow for a Bidder to meet the threshold of as near to 1,000 MW as reasonable achievable, without being unduly penalized for providing as much as + / –5% power deviation, due to the unique size of their GT's. Nonetheless, we will explore the "first cost" of each Tender, and some hourly operations costs as well, so that some proxy for life cycle costs can be evaluated.

For both Scenarios, we will perform up to five calculations per GT.

1. BASE CASE, otherwise known as the "Before" case. This will be standard measure against which the other cases are evaluated. It represents, for the most part, the current practice in the GCC. No TIC systems are applied in Case 1.

2. FOG CASE. In a location where makeup water is available, the application of Fog, or evaporative media, may be deemed beneficial and economical. For the "dry" simple cycle project described by Scenario A, fog will not be evaluated. However, fog will be evaluated for the combined cycle project of Scenario B, where makeup water is available.

   Both Fog and Evap Cooling are very good power augmentation methods. They require very little, nearly inconsequential, electrical parasitic load (driving power). The equipment costs of these technologies are very low. The increase in rated capacity of plants with these technologies is considered by many to be "almost free".

   Nonetheless, we will look at the real installation costs associated with these technologies. Evaporative cooling methods can provide a significant amount of low cost capacity to the plant, but not nearly as much as the three refrigeration systems described in the cases below.

3. TIC – "On-Line", or typical chiller-based system; that is, not employing any Thermal Energy Storage (TES) techniques. This involves the use of a water chiller, which provides cold water to a set of cooling coils inside the filter house that in turn cool the air.

The instantaneous peak demand of the TIC coils must be met by sufficient chiller installed capacity. This may be a unnecessarily expensive way to apply chilling in an environment that has high daily peaks, as compared to Case 4 and Case 5 TES technologies

In the air-cooled Scenario A calculations, an industrial air-cooled chiller system will be employed. This is a large screw-type ammonia-based chiller, with air-cooled condensers. In the water-cooled Scenario B calculations, an industrial water-cooled chiller system will be used, with dedicated cooling towers for refrigerant condensing.

The major benefit of On-Line chilling is that the "T2" temperature, that is the temperature of the cold air downstream of the chiller coils, can be dialed-in for the design rating, and held that rating for 24 hours per day, 7 days per week. This is the technology that would be required if a "flat-line" power output profile were required, as is the case where the electrical load is predominantly industrial in nature, with little or no "spike" in afternoon electrical demand.

"T2" design temperature can be set at whatever value will provide the best economic payback for the proposal. There has been much misconception about the ideal T2 temperature. There is no single "best" T2 temperature; each power project should be analyzed individually for the "sweet spot". T2 should never be *specified* by the Owner, or by the EPC contractor. Instead, the best T2 temperature should be solicited by requesting the TIC subcontractor to find the T2 temperature that best fits their equipment.

For lower boundary of T2 temperature, we typically start with 10°C (50°F) for first steps; but we will consider temperatures as low as 5°C (41°F). Although we typically don't recommend T2 temperatures in excess of 15°C (59°F), for exercises such as these, in which we are trying to "tune" an entire power project in a high ambient temperature environment, we would consider T2 temperatures as high as 20°C or 25°C (68°F to 77°F).

4. TIC – "Partial Storage". This is the first of the two TES methods. It is best described by removing approximately half of the installed chiller capacity as would be used in an "on-line" Example such as found in Case 3. In lieu of the chiller capacity, a large chilled water storage tank is added to the system. The chillers (known as the "primary" system) will operate nearly around the clock, but cold water will be pumped to the coils for only 12 to 16 hours per day, during the peak operating period. The pumping apparatus to the coils, and associated piping, is known as the "secondary" system.

   The amount of operating discharge time is known as Effective Full Load Hours (EFLH). By designing for 12 EFLHs, knowing full well that it would be virtually impossible to be at the peak ambient design conditions for 12 hours straight, the system will likely discharge for well in excess of 12 hours, and perhaps as much as 16 partially-loaded hours. This is a conservatism built into the model.

A minor benefit of a Partial Storage system as compared to "on-line" chilling is that approximately half of the cost of the chillers is eliminated. However, there is still a comparatively large fixed cost, associated with coils, piping, controls, engineering, etc, that remain constant over all three TIC refrigeration options.

For TES, the loss of chiller capacity must be mitigated by adding "tank capacity". In water-cooled chiller applications described in Scenario A, the cost of displaced chiller capacity versus the added tank capacity can be nearly equal. Therefore, there may be little economic impact on first cost for Case 4 as compared to Case 3. However, for the more expensive (and less efficient) air-cooled systems as we describe in Scenario B, the tank capacity will always be less costly than the displaced air-cooled chiller capacity. Therefore, in air-cooled environments, it would be recommend to always employ TES to improve first-cost economics.

The major benefit of Partial Storage is that the parasitic electrical loads are diminished by approximately half during the daytime peak period. These loads are not completely eliminated; they are instead deferred to nighttime operation. This arrangement allows for much improved daily capacity factor on the chillers, which would otherwise not see much nighttime operation. Furthermore, because the ambient dry bulb temperature is always less during the off-peak (night time) charging cycle, the total daily parasitic megawatt-hours will also be less, making this a more efficient system as well.

The number of chillers required for Case 4 is based on providing at least 12 hours of "Discharge" time per day, but not more than 16 hours. A Partial-storage TES system is ideal where the plant operates on a nearly base-load basis through the evening, but still is pressed for peak power for a significant portion of the afternoon.

For TES systems in Cases 4 and 5, where the chilled water is typically stored at approximately 4°C (39°F), it is undesirable to attempt to achieve too low a T2 temperature. 13°C to 15°C (54°F to 59°F) is considered a reasonable lower limit for T2, to allow for an economical amount of heat exchange "approach" for the air coils. In some cases, a T2 of 10°C (50°F) may be considered, although the secondary system costs will be much higher due to the low available approach. The two disadvantages in this situation are the high secondary flow rates (and large pipes and pumps associated with the flow rate) and the larger TES tank that comes from a low secondary "delta-T" (change in chilled water temperature). Nonetheless, we will use 10°C as the design point in some of the cases in order to achieve the lowest first cost, or overall unit price, for the project.

5. TIC – "Full Storage". This is the second of the two TES methods. It is best described by removing at least 50% and up to 75% of the installed chiller capacity as would be used in an "on-line" Example such as found in Case 3. In lieu of the chiller capacity, a larger chilled water storage tank is added to the system. By means of the secondary system, cold water will be pumped to the coils for only 6 to 8 hours per day. The chillers and primary system will operate only for the 16 to 18 hours per day of off-peak time, no

primary electrical load during the daytime peak demand. The design criteria will be to provide no less than 6 EFLH (hours) per day of discharge. Again, considering load diversity the system will likely dispatch nearly 8 hours.

Moreover, the chillers never run during the peak period in a Full-Storage scenario. This displaces ALL of the primary electrical load during the peak period, providing significantly more net electrical output from the plant. The only electrical load required is the relatively small pumping load from the secondary pumps. Because the chillers don't run during the peak demand period, nearly the entire net GT output is available; we call this operating mode "a full load shift".

By designing for 6 EFLHs, the system will likely produce nearly 8 partially-loaded hours.

The Full-Storage arrangement allows for the maximum load shifting of the chiller system. This system is best when summer peak loads are of short hourly duration such as when largely driven by comfort cooling demand. Full storage is ideal where the GT plant is not required to run at full load at night. By running the chillers only in the off-peak period, the station can artificially create off-peak demand, which could decrease the number of unit starts per year, or help minimize operations of GTs at inefficient part-load operations.

The Full Storage TES system also provides the lowest installed cost, both on a first-cost basis and a $ / kW basis, when the discharge period is kept to reasonably low times such as 4 to 8 hours per day. Full Storage is one of the most cost-effective ways to shift megawatt-hours from on-peak to off-peak periods.

Figure 5
Chilled water storage tank for (3) Westinghouse 501D5 GTs, installed in 1999.
Tank volume is approximately 23,000 cubic meters (6.5 million gallons).
The chiller system is water-cooled. The project was a retrofit to an existing facility.

PROJECT PRICING METHODOLOGY

The gas turbine equipment pricing is taken from the publication Gas Turbine World, 2001 – 2002 Handbook. While this may not be the exact price that a customer would expect to pay, it does provide a reasonable estimate of the equipment cost for the main GT driver.

Installation costs for the simple cycle cases are estimated at an additional 50% of the cost of the GT. Installation costs for the combined cycle cases are taken from GT World.

A 15% line item has been provided for 'other development and "All-In" costs', which is intended to cover land fees, engineering, permitting, and costs outside the fence such as gas pipeline and transmission line interconnects (interconnects only – no allowance made for long transmission lines). Readers of this paper are encouraged to develop a similar spreadsheet with their own estimated costs, for comparison purposes.

We will then add the cost of the TIC augmentation equipment. This cost represents the state-of-the art equipment, and realistic charges for installation. There have been other papers written which have either over-estimated or under-estimated the costs of TIC equipment and installation, depending on the bias of the writer. The estimates used in this paper are based on actual market conditions and should be quite accurate.

Costs are also included for line items that might not be borne directly by the TIC contractor, such as a significant increase in the cost of the OEM filter house, water treatment, and the cost of additional electrical infrastructure to support the large TIC systems. Such items might be contracted by either the GT OEM or the EPC contractor, not by the TIC subcontractor. Nonetheless, these costs are included here for conservatism, completeness and accuracy.

The TIC costs also include shipping to the GCC region from the USA, FOB job site, and 5% import duties on equipment (but not on installation labor). Finally, an additional 30% mark-up is added to the cost of the TIC system, to account for the overhead, engineering, and profit of the GT manufacturer, and/or the EPC contractor, who will install the TIC system. This additional markup represents a realistic cost to the Owner, who must pay for the pass-through expenses; such costs are not often quoted in economic analyses. As such, we are able to provide a realistic, yet conservative cost impact of the TIC technology.

The goal of the calculations will be to provide a realistic installed cost for each power plant configuration. From these costs, we can analyze how the incremental power and cost of the TIC system will impact the viability of the project offering. We will be able to look at real first costs, as well as derived $ / kW parametric figures.

(The primary TIC technology proposed in this paper is by means of mechanical refrigeration. However, it would be unfair to not include a fogging system for comparison, where applicable by virtue of available make-up water. For the Fog equipment in Case 2 for the water-cooled equipment calculation Scenario B, we include the cost of a fogging system: pump skid / electrical / controls, with stainless steel distribution piping / tubing, three arrays of fog nozzles, allowance for OEM stainless-steel for filter house and transition duct wetted parts, a dedicated demineralizer system, installation, engineering, project management, shipping, duties, and OEM mark-up).

Included in the cost build-up for refrigeration Cases 3, 4 and 5:

<table>
<tr><th colspan="3">Table 2</th></tr>
<tr><th>Category</th><th>Scenario A – Air-cooled</th><th>Scenario B – Water-cooled</th></tr>
<tr><td>Chillers</td><td>Ammonia refrigerant, screw chiller skids</td><td>R123 or R134a refrigerant, multi-compressor, “series” water chillers</td></tr>
<tr><td>Heat rejection</td><td>Air-cooled condensers, with supports and piping</td><td>Dedicated water cooling towers, with supports and piping</td></tr>
<tr><td>Inlet Coils</td><td colspan="2">12-row water coils, with drip pans, plumbing, and moisture eliminators</td></tr>
<tr><td>Filter House</td><td colspan="2">Allowance for OEM modifications for larger filter house, ready for coil installation</td></tr>
<tr><td>Water Treatment</td><td>Not Applicable</td><td>CT water treatment / blowdown system, with condensate collection pumps for chiller coils</td></tr>
<tr><td>Power Distribution Center (PDC)</td><td colspan="2">Step-down transformers and switchgear to convert high voltage feeder into necessary medium and low voltage lines</td></tr>
<tr><td>TES Tanks</td><td colspan="2">For Cases 4 and 5, TES tank, insulated, with internals and foundations, with instrumentation and appurtenances</td></tr>
<tr><td>Secondary Pump Skids</td><td colspan="2">For Cases 4 and 5, with variable frequency drive</td></tr>
<tr><td>Installation</td><td colspan="2">Clearing of land, concrete foundations, setting of chiller equipment and PDCs, run of piping from chillers to coils, coil installation and associated piping, makeup and blow-down piping (Section 2 only), all thermal insulation, all wiring, commissioning labor support</td></tr>
<tr><td>Commissioning</td><td colspan="2">Hydro, flush & fill, rotation checks, alignment, refrigerant and lubrication, etc.</td></tr>
<tr><td>Start-up</td><td colspan="2">Field tech support for controls, testing, training, etc.</td></tr>
<tr><td>Shipping</td><td colspan="2">Shipping from USA or Europe to GCC of pre-fabricated components (most commodities such as piping, wiring, structural steel would be locally sourced)</td></tr>
<tr><td>Duties</td><td colspan="2">5% import duties, CNF basis, on all shipped equipment, but not on locally-sourced equipment or on installation labor</td></tr>
<tr><td>GT OEM / EPC Mark-up</td><td colspan="2">30% for pass-through of TIC sub-contract, to cover engineering, project management, procurement overhead, and profit</td></tr>
</table>

SCENARIO A CALCULATIONS – AIR-COOLED SIMPLE CYCLE PEAKER

This scenario describes a hot and dry location, such as Riyadh, KSA; or Al Ain, UAE. Here, the gas turbines will be chosen as Simple Cycle Peakers, with no water usage allowed for the inlet cooling technologies.

The design ambient conditions for this location are chosen as 50°C (122°F) dry bulb temperature and 20.7°C (69.3°F) wet bulb temperature. Elevation is set at Mean Sea Level, for simplicity.

This scenario will be for an Engineer-Procure-Construct (EPC) Tender for a nominal 800 MW plant. The Bidder may provide more than 800 MW, within reason, but not less than 800 MW at the design point. However, no credit will be given for any additional power above 800 MW. The basic bid evaluation criterion will be lowest first cost. No additional credit is given for lowest unit cost ($ / kW), because with a fixed denominator of 800 MW, such a bid evaluation criterion would simply be redundant to the primary bid criterion of lowest first cost.

Table 3

Scenario A, Air-Cooled, Simple Cycle Peakers

	Case 1 "Uncooled"		Case 3 "Online Cooling"		Case 4 "Partial Storage"		Case 5 "Full Storage"	
	GT "X"	GT "Y"	GT "X"	GT "Y"	GT "X"	GT "Y"	GT "X"	GT "Y"
Design Basis								
T1 Dry Bulb Temperature	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
T1 Wet bulb Temperature	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7
T2 Temperature	50.0	50.0	11.0	7.0	16.0	9.0	20.0	15.0
Equipment								
GT quantity	13	9	10	7	10	7	10	7
chiller quantity			7	8	3	7	2	7
# hours of TES discharge					12.1	14.1	6.7	6.2
Power								
Net Plant MW	850	817	818	802	816	813	814	813
Evaluated Net MW	800	800	800	800	800	800	800	800
Economics at Design Point								
GT plant, US$, millions	$475	$374	$366	$291	$366	$291	$366	$291
Chiller subcontract impact, US$, millions	-	-	52	51	44	45	39	35
total project cost, US$, millions	$475	$374	$417	$342	$409	$336	$404	$326
project cost savings, US$, millions			$58	$32	$66	$39	$71	$48
project cost savings, %			12%	9%	14%	10%	15%	13%
US$ / kW (based on 800 MW)	$594	$468	$522	$428	$512	$419	$506	$407
incremental US$ per kW			($73)	($40)	($83)	($48)	($89)	($61)
			-12%	-9%	-14%	-10%	-15%	-13%

Moreover, although fuel efficiency has certain qualitative benefits, no quantitative evaluation points are given in the bid selection process for lowering the heat rate. This is despite the fact that adding TIC will in fact lower the heat rate of the station significantly.

Because the nature of this Bid process is to drive the first cost as low as possible, while attempting to procure as much equipment as possible, we will use the TIC system to "tune" the overall offer to as near 800 MW as possible. This means offering a quantity of GTs that, in an unaugmented condition, would not reach the required 800 MW. We will add a sufficient capacity of chiller system to reach, and slightly exceed, the 800 MW target.

By employing this strategy, it is possible to "displace" expensive GT capacity with less expensive chiller system capacity. Further leverage is gained by displacing moderately expensive air-cooled chillers with less expensive chilled water storage tank capacity through the TES technology.

Figure 6, immediately below, shows the quantity of Gas Turbines required to meet the design basis of Scenario A. As expected, it will require more units of the smaller GT "X" than the larger GT "Y" to meet the 800 MW threshold. In fact, as can be seen in Figure 7 and from Table 3, GT "X" is at a further disadvantage, because 12 GT's are not quite enough to meet the 800 MW mark, so much of the 13th unit (approximately 50 MW) is largely unaccounted for in the economic analysis.

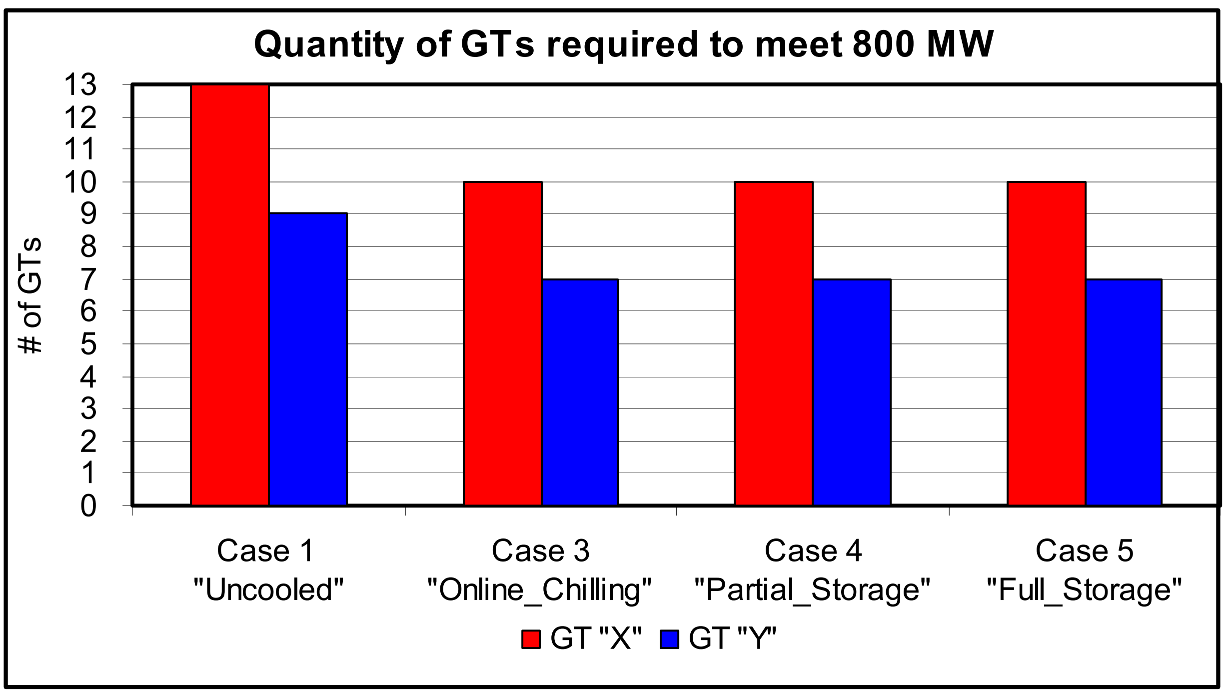

Figure 6

With TIC, the required quantity of GTs decreases by 3 for GT "X" and 2 for GT "Y".

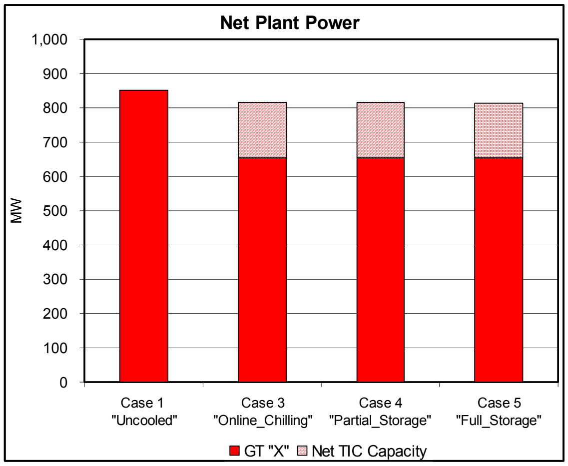

Figure 7
For GT "X", it is possible to displace 130 MW of GT capacity with TIC capacity, "tuning" the Proposal to just over 800 MW

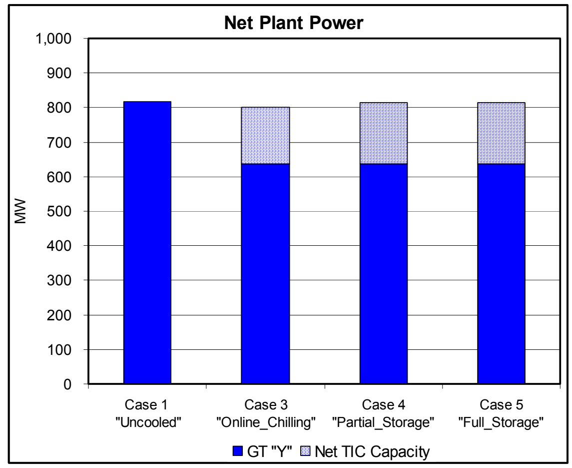

Figure 8
For GT "Y", it is possible to displace 180 MW of GT capacity

Economically, the project offering is improved by displacing a fraction of expensive GT capacity with less expensive TIC capacity. In Scenario A, the TIC systems are air-cooled, which are more expensive and less efficient than water-cooled chiller systems. Nonetheless, ALL TIC options are less expensive than the equivalent amount of GT capacity. Further, the TES Cases 4 and 5 are even less expensive, because we are displacing air-cooled chillers with less expensive TES tank capacity.

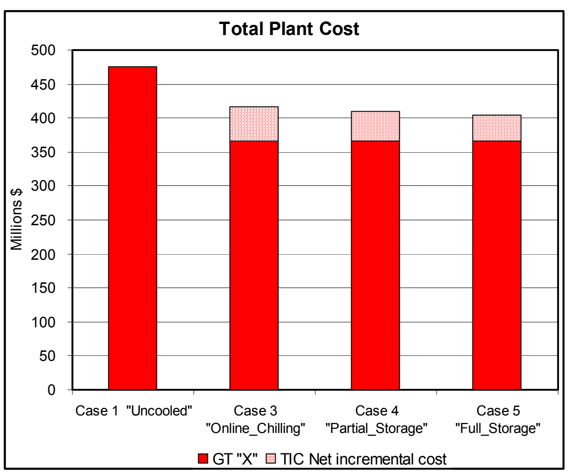

Figure 9
For GT "X", it is possible to produce a NET cost savings of between $58 and $71 million USD

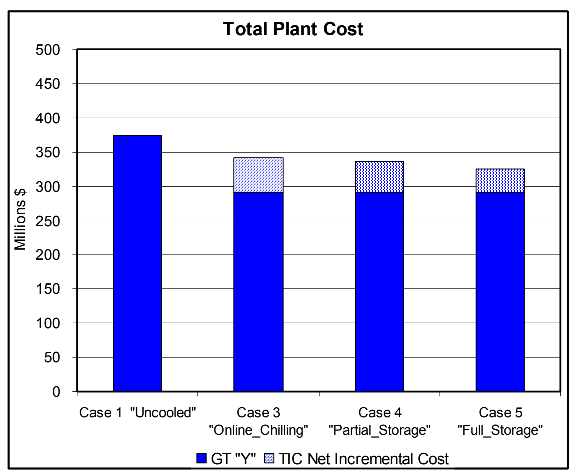

Figure 10
For GT "Y", it is possible to produce a NET cost savings of between $32 and $48 million USD

Although unit cost ($ per kW) is not a specified bid evaluation criterion, we can make a calculation based on the evaluated power output of 800 MW. This step may be redundant to the absolute costs shown in Figures 9 and 10; but it is helpful for the reader to visualize the project unit cost, as shown in Figure 11 below.

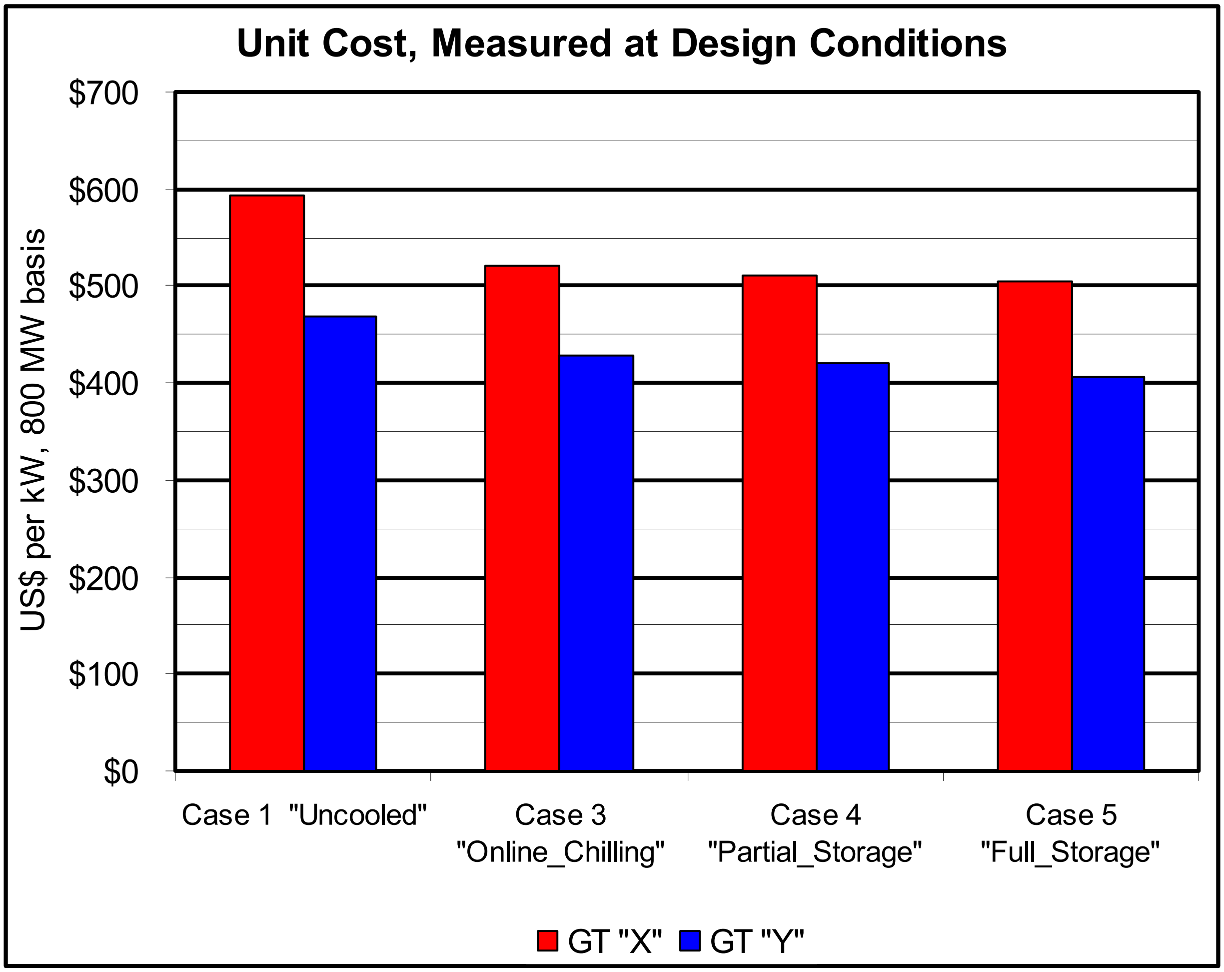

Figure 11

Unit cost of project, based on a levelized 800 MW evaluation criterion. Project cost savings of between 9% and 15% are possible.

SCENARIO B CALCULATIONS – WATER-COOLED COMBINED CYCLE

Figure 12

Water-cooled chiller system for (2) F-class GTs, installed in 2002.
"Packaged" chillers skids are at right side of picture.
System capacity is approximately 12,000 refrigeration tons.
Design "T2" temperature of 11°C, with ambient WB temperature of 25°C

This second Scenario describes a coastal location, such as Dammam, Jeddah, Doha, Dubai, or Abu Dhabi. Here, the gas turbine plant will be chosen as a Combined Cycle base loaded configuration, with make-up water usage allowed for the site cooling tower (sea-water condenser cooling is not considered in this paper) and the inlet cooling technologies.

The design ambient conditions for this location are chosen as 47°C (116°F) dry bulb temperature and 30°C (86°F) wet bulb temperature. Elevation is set at Mean Sea Level, for simplicity. This design condition has been taken from other projects specified in the area.

This scenario will be for an Independent Power Project (IPP) Tender for a nominal 1,000 MW plant. The Bidder may provide more than 1,000 MW, within reason, but not less than 950 MW at the ambient design point. The general guideline is to provide no more than +/- 5% deviance from the design point, although as will be shown below, it will be necessary to exceed the upper 5% guideline for some options, and we will consider this acceptable.

Credit will be allowed for any additional power above 1,000 MW because the basic bid evaluation criterion will be unit price, $ per kW. Unlike Scenario A, the evaluation will primarily be for project value, not for first cost, although some first cost considerations will have some secondary evaluation credit. As a tertiary bid criterion, fuel efficiency may be considered, even though the natural gas fuel prices for most regions, particularly in Qatar and Bahrain, may be very low.

Table 4

Scenario B, Water-Cooled, Combined Cycle IPP

	Case 1		Case 2		Case 3		Case 4		Case 5	
	GT "X"	GT "Y"	GT "X"	GT "Y"	GT "X"	GT "Y"	GT "X"	GT "Y"	GT "X"	GT "Y"
Design Basis										
T1 Dry Bulb Temperature	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0	47.0
T1 Wet bulb Temperature	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
T2 Temperature	47.0	47.0	32.6	32.6	14.6	12.5	12.0	12.5	10.0	10.0
Equipment										
GT quantity	6	5	6	5	5	4	5	4	5	4
chiller quantity					7	8	4	7	3	7
# hours of TES discharge							12.0	11.9	6.2	6.0
Power										
Net Plant MW	970	1,012	1,077	1,116	975	967	1,000	983	1,028	1,011
Economics at Design Point										
CC Plant, $, millions	$704	$726	$704	$726	$586	$581	$586	$581	$586	$581
Chiller subcontract impact, $, millions	-	-	5	7	47	50	46	44	42	40
total project cost, $, millions	$704	$726	$709	$733	$633	$631	$633	$625	$629	$621
project cost savings, $, millions			($5)	($7)	$70	$95	$71	$101	$75	$105
project cost savings, %			-1%	-1%	10%	13%	10%	14%	11%	14%
$ / kW	$726	$717	$658	$657	$650	$652	$633	$636	$612	$614
incremental $ per kW			($67)	($60)	($76)	($65)	($93)	($81)	($114)	($103)
			-9%	-8%	-10%	-9%	-13%	-11%	-16%	-14%

As in Scenario A, it will be possible to "tune" the overall offering, in this Scenario to as near to 1,000 as possible. However, in Scenario B, we will use the TIC system to primarily find the lowest overall unit price of the project. It just so happens that when doing so, we still are able to meet the +/- 5% power guideline.

By employing this strategy, it is possible to "displace" expensive CC capacity with less expensive chiller system capacity. Further leverage is gained in this Scenario in Cases 4 and 5 by displacing on-peak chiller parasitic electrical load with chilled water storage tank capacity through the TES technology.

"Duct-Firing" was not considered for this IPP project, due to the relatively high cost of make-up water, presumably from desalinization sources. For a seawater cooled application, duct firing would have some economic benefit, particularly as is most likely if the project was combined with a desalinization project. In desalinization projects, the steam demand is usually in excess of the steam output capabilities of a standard combined cycle plant, and heavy amounts of supplemental firing (and auxiliary boilers) are typically required.

Figure 13 shows the quantity of Gas Turbines (in combined cycle) required to meet the design basis of Scenario B. As expected, it will require more units of the smaller GT "X" than the larger GT "Y" to meet the 1,000 MW guideline.

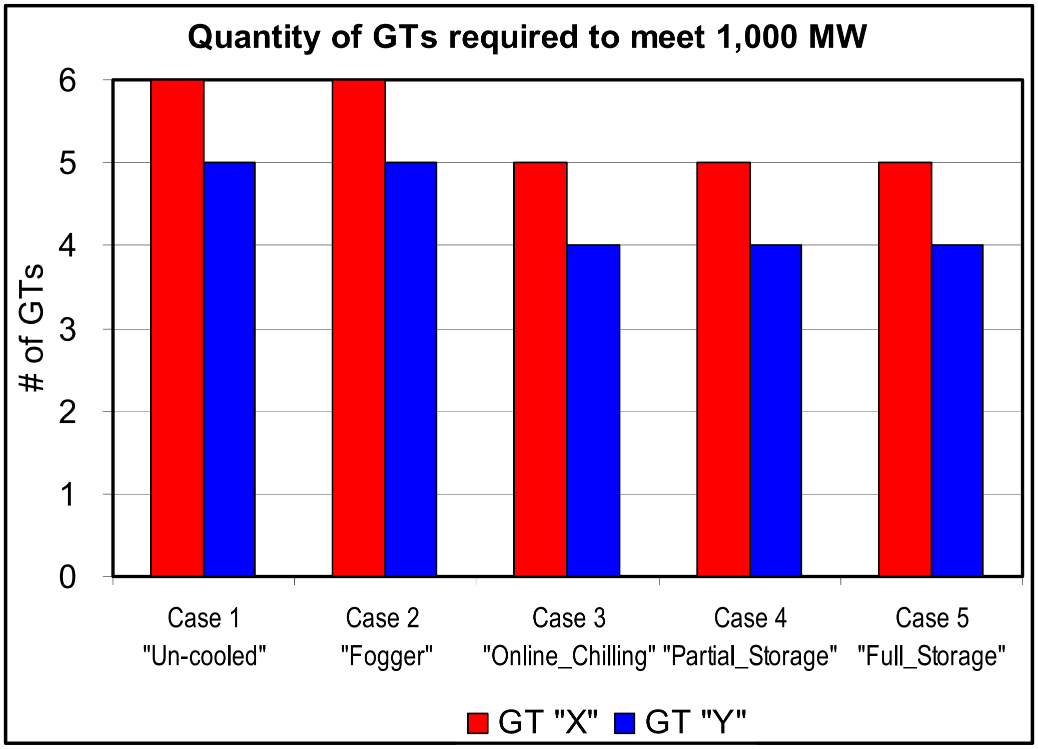

Figure 13
With TIC, the required quantity of GTs decreases by 1 each for both manufacturers.

For Case 2, we would expect that the number of gas turbines would decrease relative to the Base Case 1. In fact, in order to displace a single GT/CC train, the additional power expected from the fogging system in aggregate would need to exceed the power output of at least one GT (plus its associated steam turbine contribution). This did not happen. (The power output associated with fogging was only 77 MW for 6 of the GT "X", and only 104 MW for the GT "Y". A single GT (plus steam turbine output) is 162 MW for GT "X" and 202 MW for GT "Y" in the Base Case 1. Therefore, for Case 2, it would have been desirable for the very inexpensive fog technology to displace at least 1 GT worth of expensive CC capacity. This was not possible.)

The result is that the Case 2 fogger calculations turn out to be the most expensive project offerings on a first cost basis, even though the unit cost evaluations are attractive (but not as good as Cases 3, 4, and 5).

The popular knowledge is that fogging systems are "almost free" or "are so much less expensive than chillers", so that fogging should be used in lieu of chillers. Here is a realistic side-by-side comparison that shows the error of this common assumption.

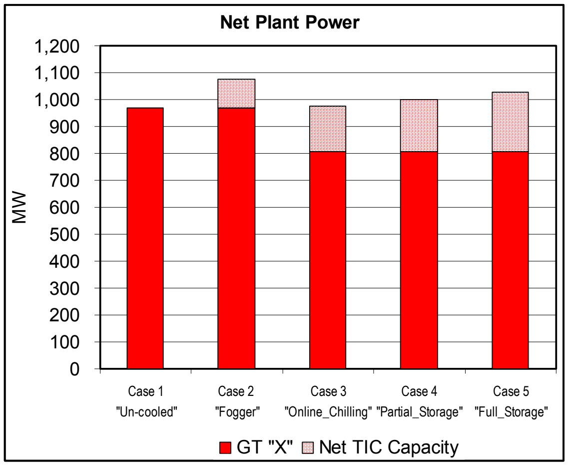

Figure 14
For GT "X", it is possible to displace approximately 160 MW of GT/CC capacity with chiller capacity, "tuning" the Proposal for best economic results

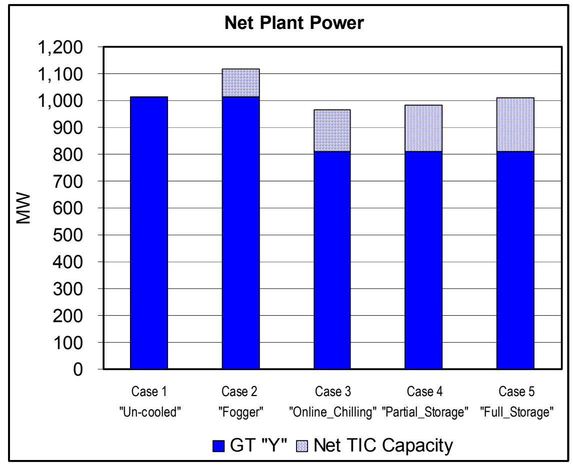

Figure 15
For GT "Y", it is possible to displace approximately 200 MW of GT/CC capacity

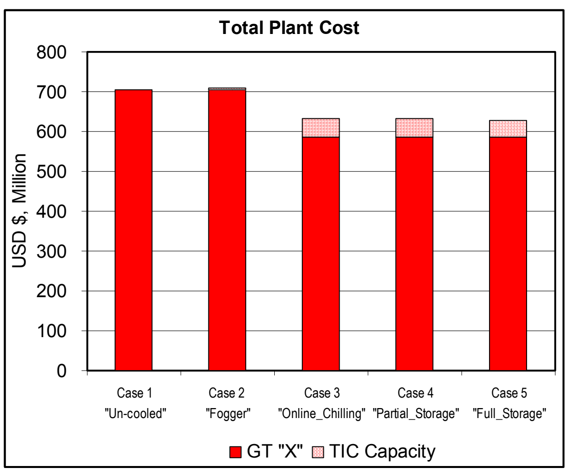

Figure 16
For GT "X", it is possible to produce a NET cost savings of between $70 and $75 million USD

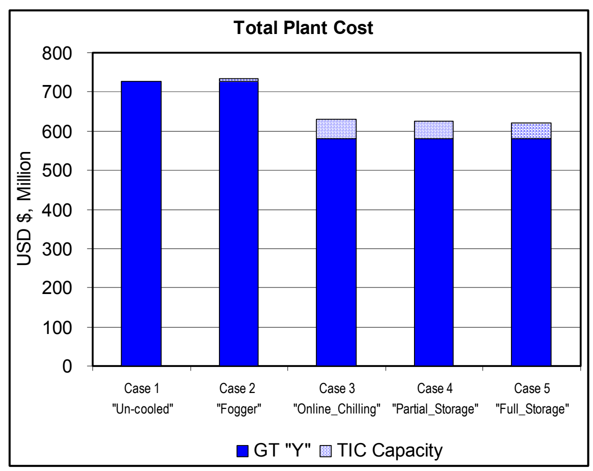

Figure 17
For GT "Y", it is possible to produce a NET cost savings of between $95 and $105 million USD

Note that in Figures 16 and 17, Case 2 for fogging shows the highest overall first price for the project. Of course, Case 2 also shows the highest gross power output, but the power provided is in excess of the +5% guideline. However, in order to keep the fogging options in the evaluation process, we will assume a liberal interpretation of the guidelines and allow for the extra power to be included in the bid evaluation process.

Unit cost ($ per kW) is the primary bid evaluation criterion. It is here that the fogging technology in Case 2 shows its major benefit versus the Base Case 1, dramatically reducing the unit cost of the project.

Nonetheless, even the most expensive mechanical refrigeration case, # 3, is less expensive on a unit cost basis than the Fogging Case 2. This is because a single GT/CC train will be removed from the overall project offering in Cases 3, 4 & 5, replaced by TIC capacity. Cases 4 and 5 show additional improvements as more chillers are removed from the system, and replaced with slightly less expensive tank capacity, and as on-peak parasitic electrical demand is shunted to off-peak periods.

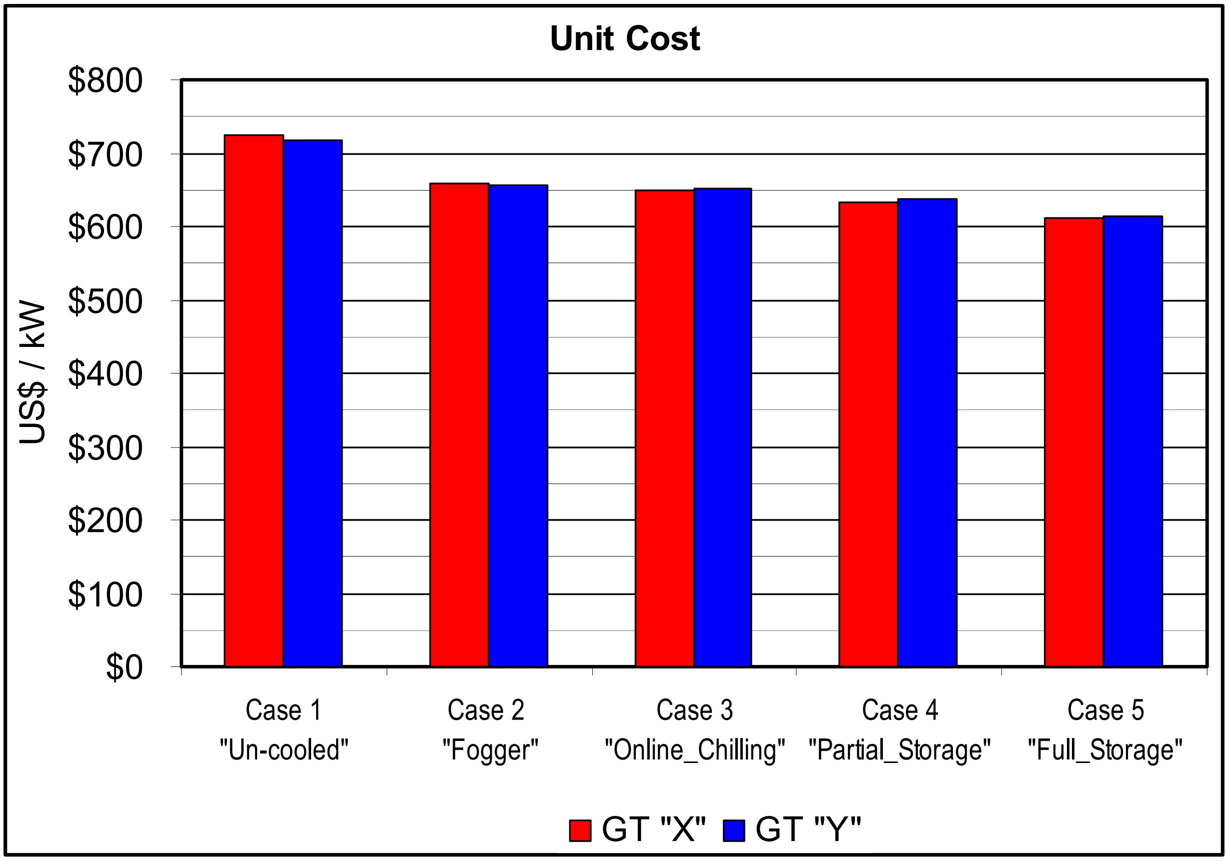

Figure 18

Unit cost of project.

Project cost savings of between 9% and 16% are possible.

Contrary to popular misconception, the unit costs of the plants with the mechanical chiller options in Cases 3, 4 and 5 are LESS than the unit cost of the Case 2 option with Foggers.

CONCLUSION

A summary of benefits and conclusions include:

1. In all cases TIC was found to be more cost effective than simply building additional non-TIC power plant capacity in the GCC region.

2. Evaporative or fog cooling methods (case 2) can provide a significant amount of low cost capacity to the power plant (base case 1), but not nearly as much as the three refrigeration systems, cases 3, 4, and 5. This would also hold true if water were assumed available in Scenario A, for a simple cycle plant.

3. The three packaged refrigeration systems using chillers, with and without storage, had better economics than fog systems in Scenario B, combined cycle. The refrigeration based systems (cases 3, 4 and 5) had the lowest installed unit $ / kW cost when compared to non-TIC (base case 1) and fog (case 2).

4. The use of partial (case 4) and full (case 5) TES resulted in additional economic benefit. The two TES cases provided the lowest first cost in Scenario A and the lowest unit $ / kW cost in Scenarios A and B.

5. The major benefit of TES (cases 4 and 5) is that the parasitic electrical loads are reduced by approximately half for partial TES and near completely for full TES during the daytime peak period. These loads are not eliminated; they are instead deferred to nighttime operation. This arrangement allows for an improved daily capacity factor on the chillers, which might otherwise not see nighttime operation. Furthermore, by running the chillers more in the nighttime period, the station can artificially create off-peak demand, which could decrease the number of GT unit starts per year.

6. A Partial TES system is ideal where the plant operates on a nearly base-load basis through the evening.

Figure 19

Installation of chiller coils in a large gas turbine filter house

7. The Full TES arrangement allows for the maximum load shifting of the chiller system. This system is best when summer peak loads are of short hourly duration such as when largely driven by comfort cooling demand. The Full TES system also provides the lowest installed cost, both on a first-cost basis and a unit $ per kW cost basis, when the discharge period is kept to reasonably low times such as 4 to 8 hours per day. Full Storage is one of the most cost-effective ways to shift system demand megawatt-hours from on-peak to off-peak periods, and system capacity megawatt-hours from off-peak to on-peak..

8. Operating and maintenance costs of a power plant with TIC are considerably lower on a unit kWHr cost than a power plant operating without TIC.

BIOGRAPHIES

Christopher M. Landry is a Vice President and Regional Director of Sales for Turbine Air Systems, Ltd. (TAS) of Houston, Texas, USA. TAS is the world-leading supplier of gas turbine inlet air cooling solutions for the energy industry and a provider of packaged central plants for cooling applications. His work at TAS involves business development, system sales and sales management in the Southeast USA, Europe, Africa, India and Middle East regions.

Mr. Landry began his career teaching at the University of Wisconsin. Over the years he has lived in Saudi Arabia negotiating contracts and licensing agreements for a TRANE Company Licensee, developed and implemented a business plan of a new gas turbine inlet air-cooling product line for the Henry Vogt Machine Company and provided field technical services and consulting in the power industry.

Mr. Landry has held Chair positions for ASHRAE and a Board position for the Association of Energy Engineers. He holds a Bachelor of Science in Mechanical Engineering from the University of Wisconsin (USA).

Thomas C. Tillman is the Vice President of Strategic Development of Turbine Air Systems, Ltd. (TAS) of Houston, Texas, USA. Mr. Tillman joined TAS October 2000. Mr. Tillman is a Registered Professional Engineer, and is the founding member and the past President of the Turbine Inlet Cooling Association (TICA), an international industry trade group, representing all major manufacturers, end-users, and government agencies. He is a long-standing member of the ASHRAE Committee 9.13 for Combustion Turbine Inlet Cooling, and is a committee member for the newly formed ASME PTC 51 for turbine inlet cooling testing.

Mr. Tillman began his career with Eastman Kodak as an engineer with the maintenance engineering group. In following years Mr. Tillman spent time with Yankee Atomic Electric; with the City of Colorado Springs, Department of Utilities as a Senior Construction Engineer; as a combined cycle plant engineer at Altresco / JMA / PG&E; and Engineering Director for EDM Services.

Prior to his current position at TAS, Mr. Tillman developed new turbine inlet cooling technologies with Polar Works, LLC, a research and development firm funded in part by the Gas Research Institute.

Mr. Tillman completed his Bachelor of Science in Mechanical Engineering at Worcester Polytechnic Institute and his MBA at State University of New York.