Turbine Inlet Cooling Technologies and Applications for Optimizing Cogeneration/CHP Systems

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Webinar Sponsored by:

Midwest Cogeneration Association

U.S. Midwest Clean Energy Application Center

August 25, 2011

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Outline

- Introduction
- Hot Weather Effects on CHP Systems using Gas Turbines / Combustion Turbines
- Turbine Inlet Cooling (TIC) & Its Benefits
- TIC Technologies
- TIC Technology Comparisons and Examples
- Summary and Conclusions

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Introduction

- **Cogeneration and CHP Systems**
  - Concurrently produce electric or mechanical power and recover/use thermal energy from prime movers using one fuel source
  - All CHP systems are cogeneration systems for on-site/near-site use (≤ 50 MW)
  - Cogeneration systems sell power to the grid and sell thermal energy near site
  - All cogeneration systems are not CHP systems

- **Cogeneration/CHP System Benefits**
  - Could be > 80% efficient compared to an average of <50% efficiency of conventional/traditional heat and power systems
  - Save fuel and reduce emissions
  - Installed only when economically attractive compared to conventional approach: Buying power from grid and burning fuel for meeting thermal energy needs

- **Maximum Utilization of Cogeneration/CHP Systems is Desirable for Improving Economics and Reducing Emissions**

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Carbon Footprint of Fuel Use* is the Lowest for Cogen/CHP Systems

System	Carbon Footprint
Cogeneration/CHP	Smallest
CT in Combined-Cycle	
CT in Simple-Cycle	
Steam-Turbine	Largest**

*   Total fuel used for generating electric and thermal energy

** Old plants used primarily for peak shaving

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Carbon Footprint (lbs/MWh) for Power Generation is High During Non-Baseload Periods

(Because of the need to use low-efficiency peaking power plants during period of peak demand)

State	Average	Non-Baseload
Illinois	1,200	2,200
Indiana	2,100	2,200
Iowa	1,900	2,400
Michigan	1,500	2,000
Minnesota	1500	2,000
Ohio	1,800	2,000
Wisconsin	1,700	2,100

Source: John Kelly Presentation at the MCA Meeting, March 13, 2008

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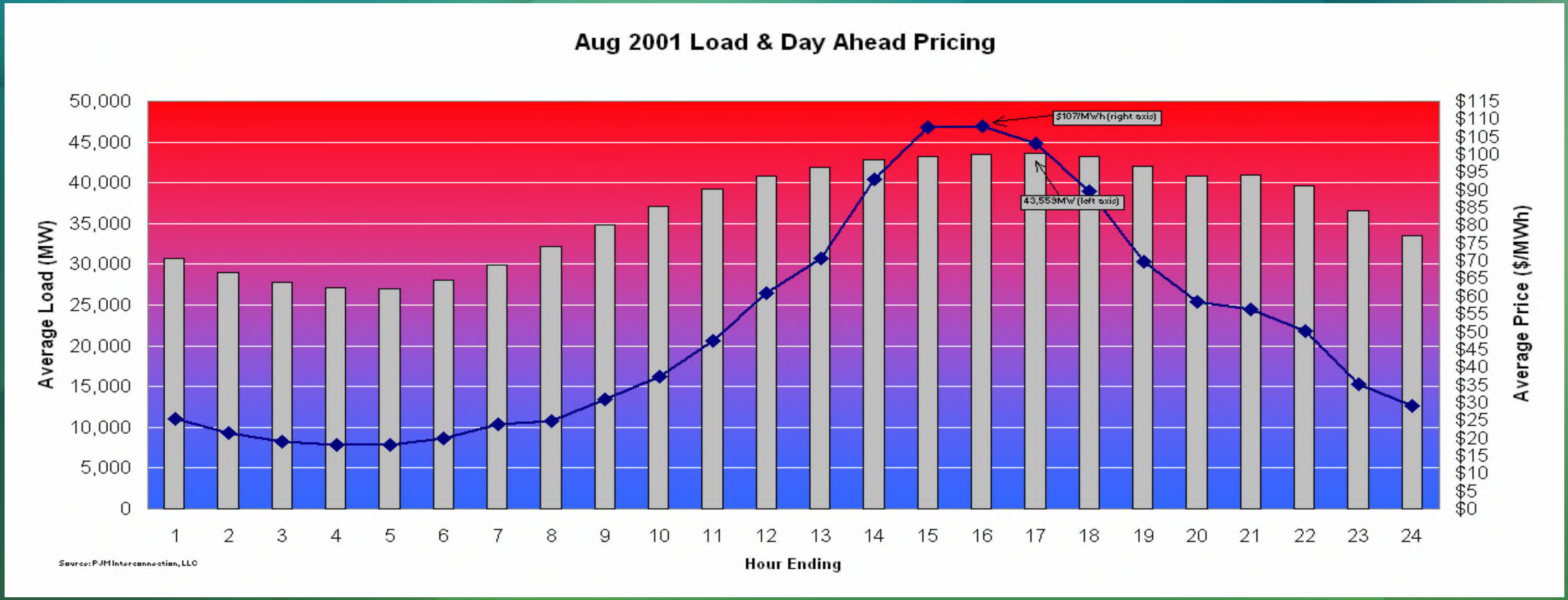
Power Demand and Electric Energy Price Rise with Hot Weather



- Market price of electric energy goes up during the peak demand period: as much as 4 times the value during the off-peak periods (In this example)

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Effects of Hot Weather on Gas/Combustion Turbine System Performance

- **Reduced Electric Power Output (up to 30%)**
  - Increases cost of buying grid power at premium price for CHP users
  - Reduces revenue for the seller of power and thermal energy
- **Reduced Energy Efficiency (up to 10%)**
  - Increases fuel cost, $/kWh
  - Increases environmental emissions, lb/kWh
- **Reduced Thermal Energy in Combustion Turbine (CT) Exhaust**
  - Reduces thermal energy available for heating, cooling or dehumidification, Btu/h
  - Increases fuel cost for meeting thermal energy needs
  - Reduces revenue for the seller of thermal energy

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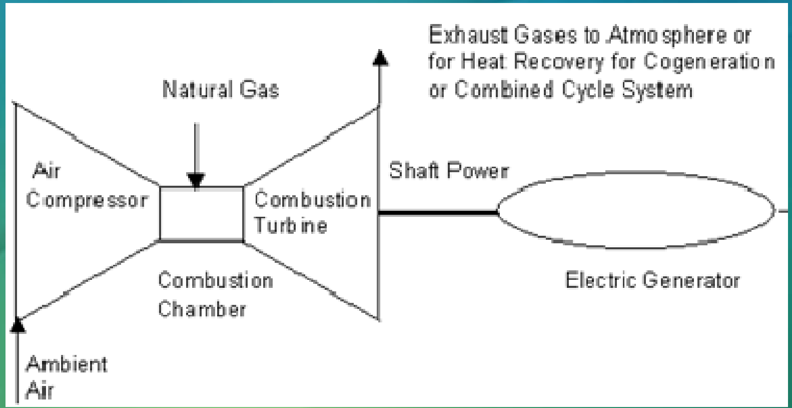
Why Hot Weather Affects GT/CT Performance?



- **Air Compressor Characteristics**
  - Capacity limited by the <u>volumetric</u> flow rate of inlet air
  - Requires more energy (per lb. of air) with increased air temperature
  - Consumes up to two-third of the turbine output
- **CT Characteristics**
  - Power and thermal energy outputs are proportional to the <u>mass</u> flow rate of air
- **Hot Weather Effects**
  - Reduced air density leads to reduced <u>mass</u> air flow rate to the turbine
  - Reduced air mass flow rate leads to reduced power and thermal energy outputs
  - Increased air temperature increases compressor power requirement

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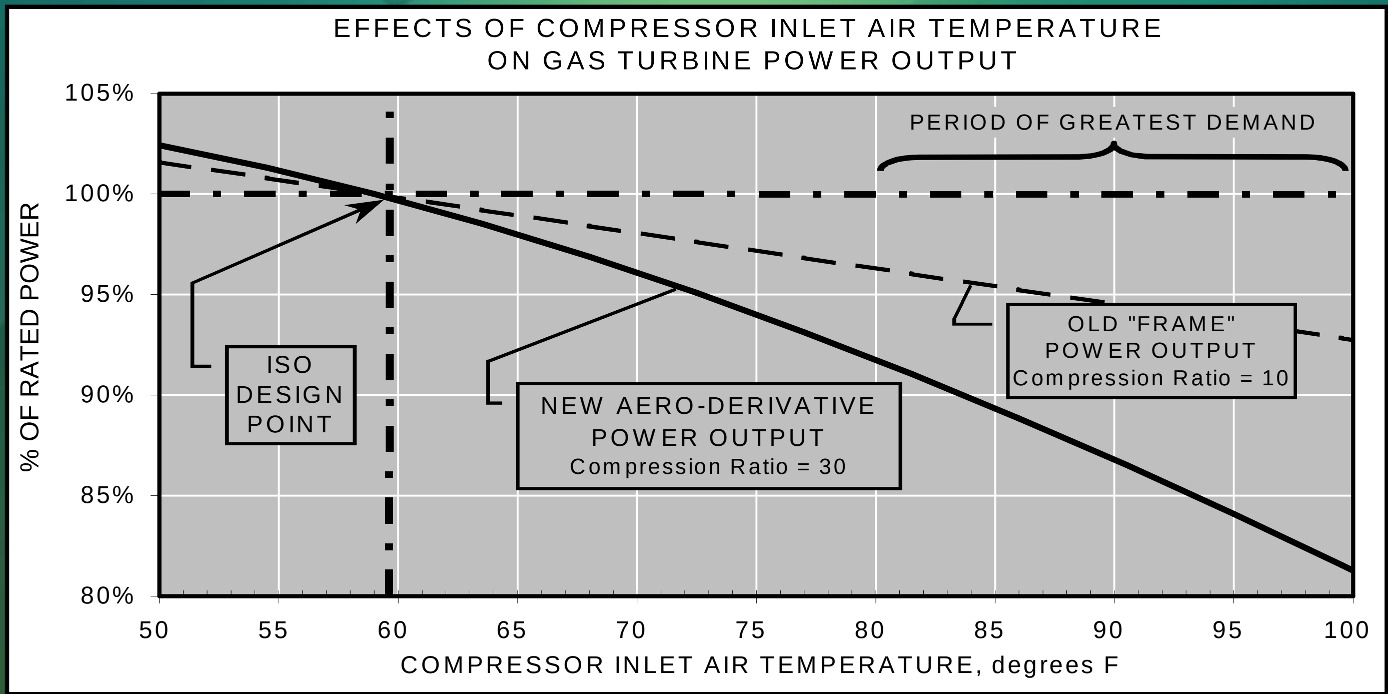
CT Generation Capacity Decreases with Increase in Ambient Temperature

(CTs Rated at 59ºF, 60% RH at Sea Level; Temperature Impact Depends on the CT Design)



Up to 19% capacity loss at peak demand for this CT

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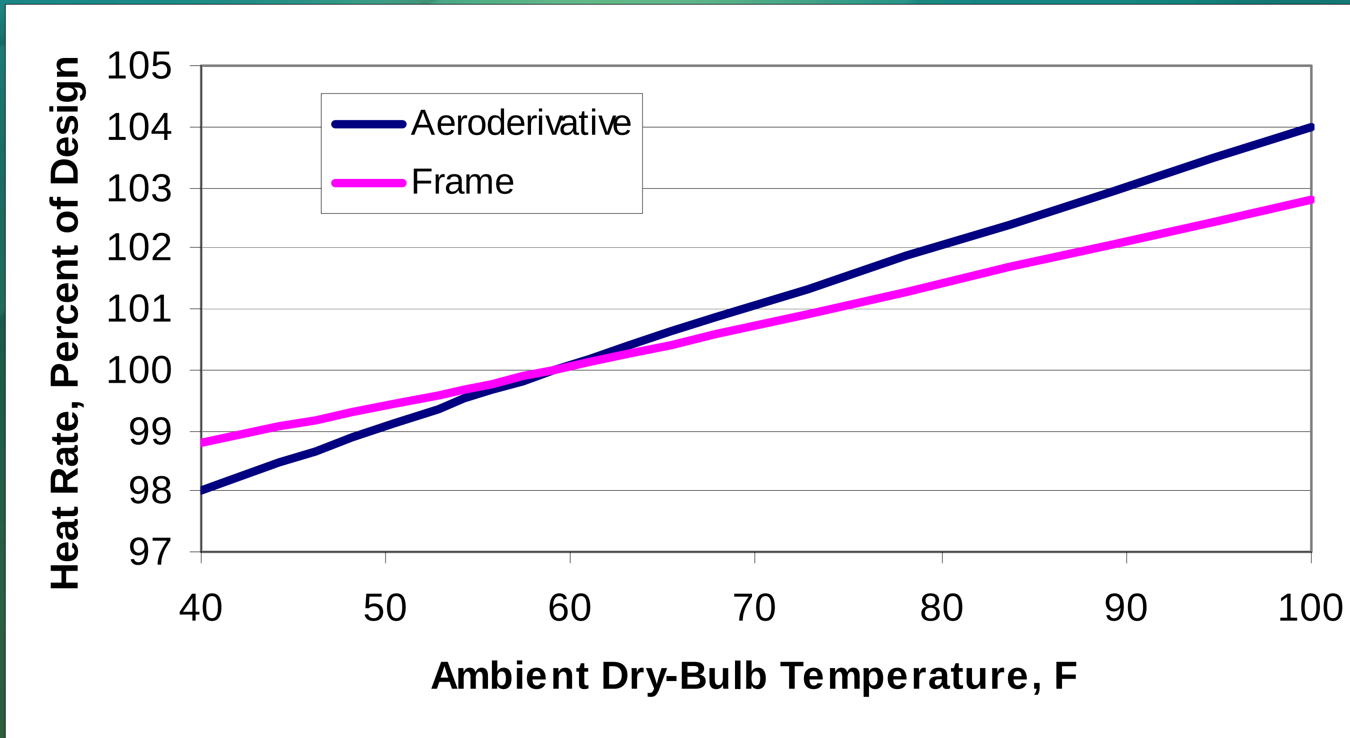
Heat Rate (Btu/kWh) Increases (i.e. Energy Efficiency Decreases) with Increase in Ambient Temperature



Up to 4% loss in Energy Efficiency

Note: Heat rate is directly proportional to fuel consumption per kWh and inversely proportional to energy efficiency

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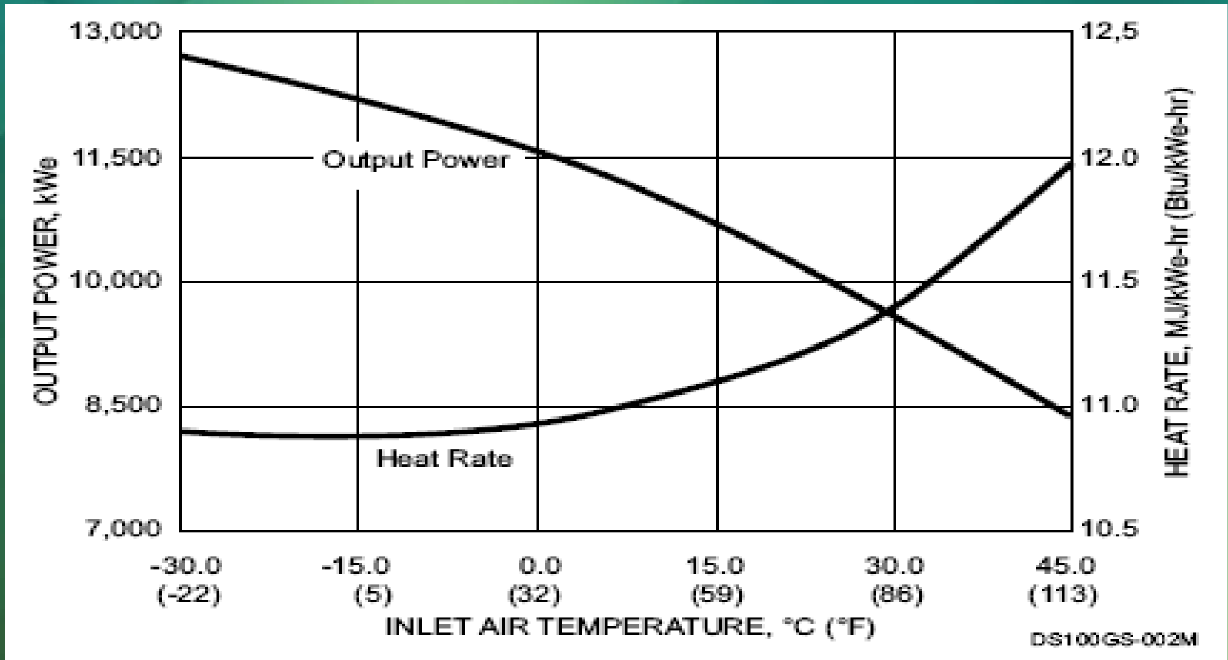
Smaller Capacity CTs are More Sensitive to Ambient Temperature

Capacity Loss of over 21% from ~10,750 kW to ~8,500 kW

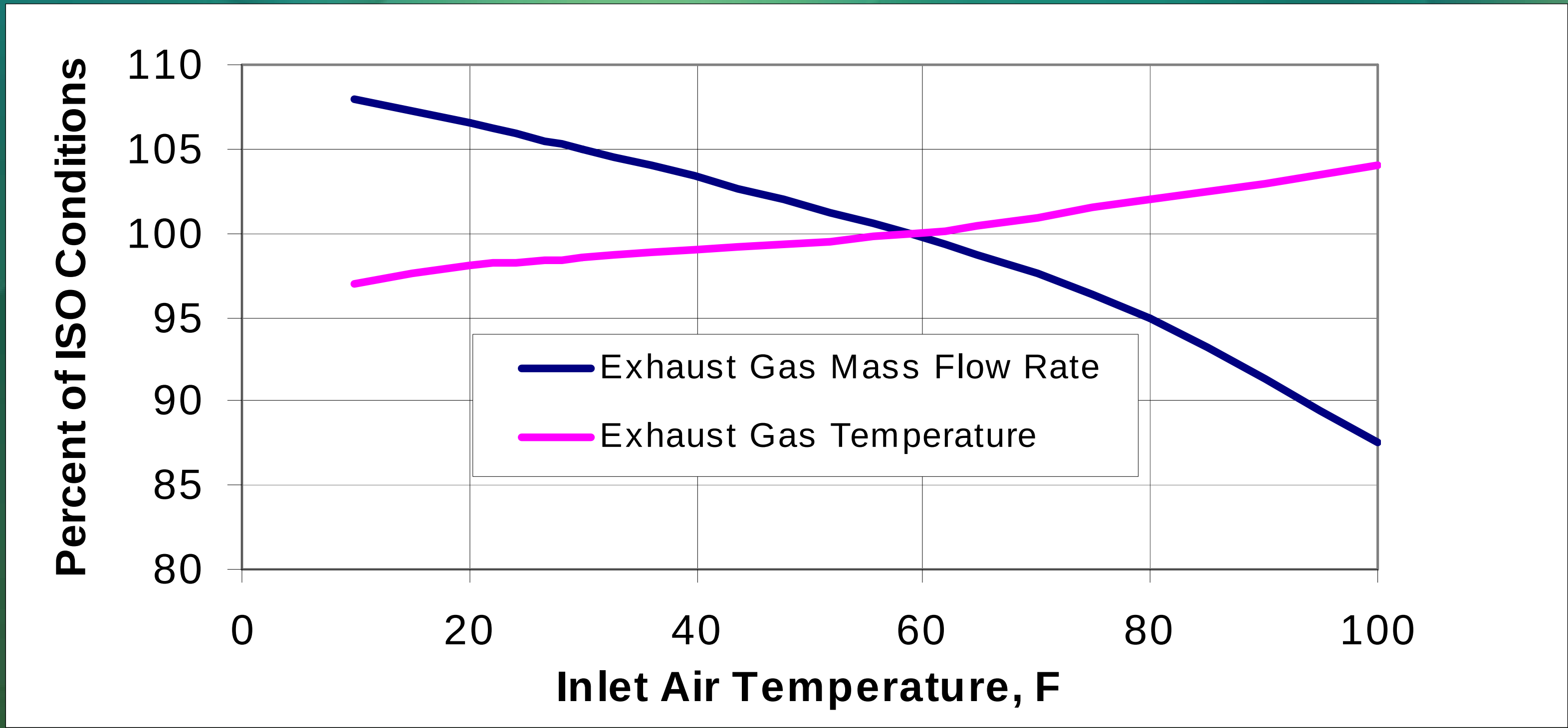


Efficiency loss of over 8 % from HR of ~ 11,100 to ~12,000 Btu/kWh

Source: Solar Turbines

Increase in Ambient Air Temperature Leads to Reduced Enthalpy of the Prime Mover Exhaust Gases

(Primarily because of decreased mass flow rate of exhaust gases, even though its temperature is slightly higher)



Source: Punwani, D.V. and Andrepont, J.S., *POWER-GEN International 2005*

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Midwest Ambient Temperature Characteristics

- Annual Number of Hours Temperatures in the Midwest are over 59ºF

  Range from over 2,500 to 3,800

State	Capital	Annual Hours > 59ºF
Illinois	Springfiled	3,867
Indiana	Indianapolis	3,528
Iowa	Des Moine	3,597
Kansas	Topica	3,730
Michigan	Lansing	2,912
Minnesota	St Paul	2,836
Missouri	Columbia	3,932
Nebraska	Lincoln	3,621
North Dakota	Bismark	2,511
Ohio	Columbus	3,565
South Dakota	Pierre	3,045
Wisconsin	Madison	2,876

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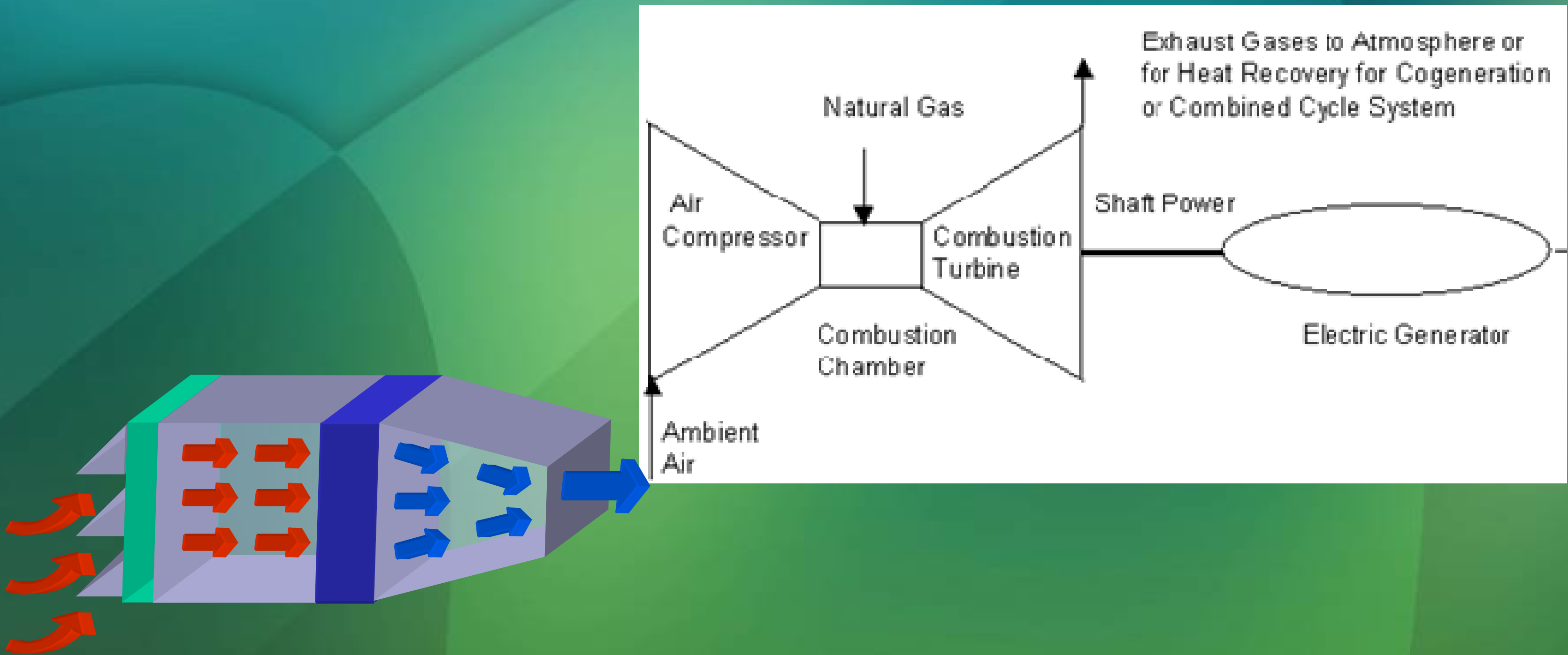
Turbine Inlet Cooling



- Cooling the inlet air before or during compression in the compressor

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TIC Benefits

- Minimize detrimental impacts of hot weather on CT system performance
- Reduce CHP user costs for buying grid power and fuel
- Increase revenues for the seller of power and thermal energy
- Reduce grid-wide emissions by minimizing the need to operate lower-efficiency peaking power generation systems
- May postpone or eliminate the need to site and build new power plants

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TIC Reduces Need for Operating Less Efficient or Building New Power Plants

- TIC for CTs in combined-cycle (CC) systems reduces the need to operate CTs in simple-cycle (SC) systems

  - Example: TIC for a 500 MW CC plant eliminates the need for operating or building a new 40-50 MW SC peaking plant; Also eliminates emissions higher emissions from SC compared to those from CC

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Hot Weather (Summer) Reduces U.S. Power Generation Capacity by Over 29,000 MW

Fuel	Winter Capacity, MW	Summer Capacity, MW	Capacity Loss in Summer, MW
Coal	315,556	313,380	2,176
Petroleum	61,171	58,548	2,623
Natural Gas	412,241	383,061	29,180

Source: U.S. Department of Energy's Energy Information Agency 2005 Database

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Disadvantages of TIC

- Permanent higher CT inlet pressure drop: 0.1 to 1.0 inch WC
- Increased inlet pressure drop results in small drop in CT output capacity even when inlet cooling is not being used:(~0.025 to 0.25% of the CT Output)
- Additional capital and maintenance costs of the cooling equipment

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TIC Technologies

Two Categories

- Reduce Temperature of Inlet Air Entering the Compressor
- Reduce Temperature of Inlet Air During Compression (Inter-stage cooling)

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Air-Temperature Reducing Technologies

- **Direct Evaporation**
  - Wetted Media
  - Fogging
- **Indirect Evaporation**
- **Chilled Fluid using mechanical or absorption chillers**
  - Indirect Heat Exchange
  - Direct Heat exchange
- **Chilled Fluid or ice TES**
- **Hybrid**
  - Some combination of two or more cooling technologies

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TIC Technology Parameters

- Pressure-drop due to component insertion loss: ~0.1 to 1.0 inch WC
- Sensitivity of degrees of cooling to the ambient humidity
- Water quality and flow rate requirements
- Capital and O&M costs

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Direct Evaporative Cooling

- Cooling is produced by evaporation of water added to the inlet air (Adiabatic Cooling)
- Degrees of cooling reduces with increased ambient air humidity
- Generation capacity enhancement varies with the ambient air humidity
- Most used TIC technology

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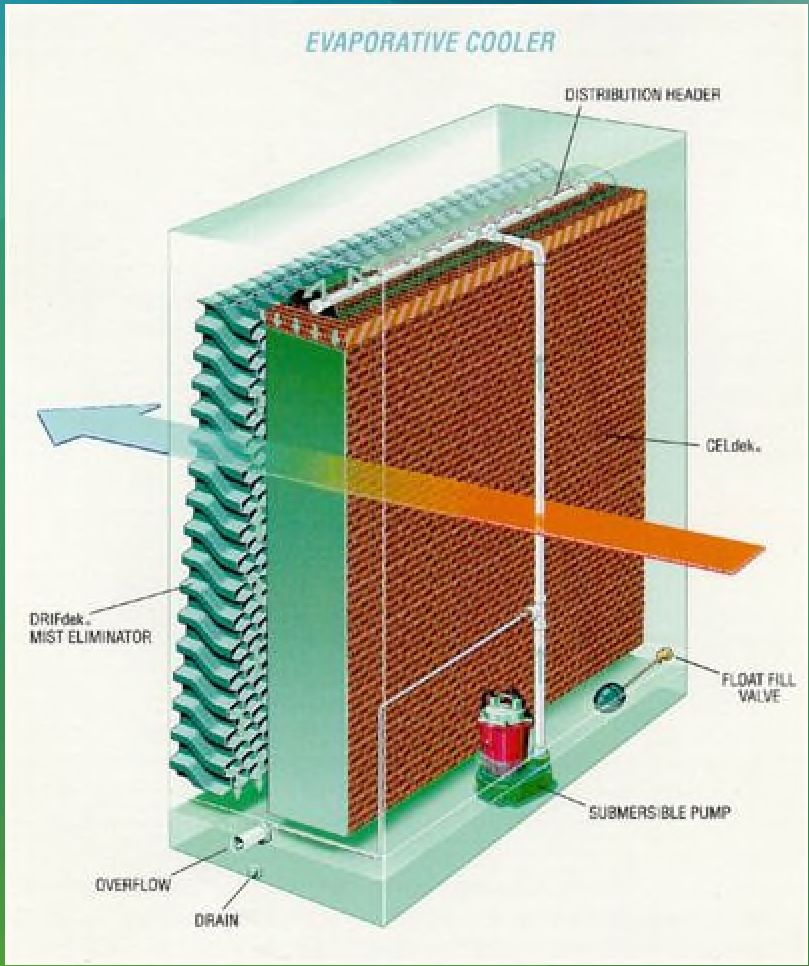
Wetted-Media System

- Water is sprayed on a media through which inlet air is flowing

- Typical Cooling Efficiency* = ~90%

- Insertion DP = 0.25 to 0.75 inch WC

- Water chemistry must be controlled to prevent build-up of scale of minerals



Source: Munters Corporation

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*= (Ambient air DB – Cooled air DB) x100 / (Ambient air DB – Ambient air WB)

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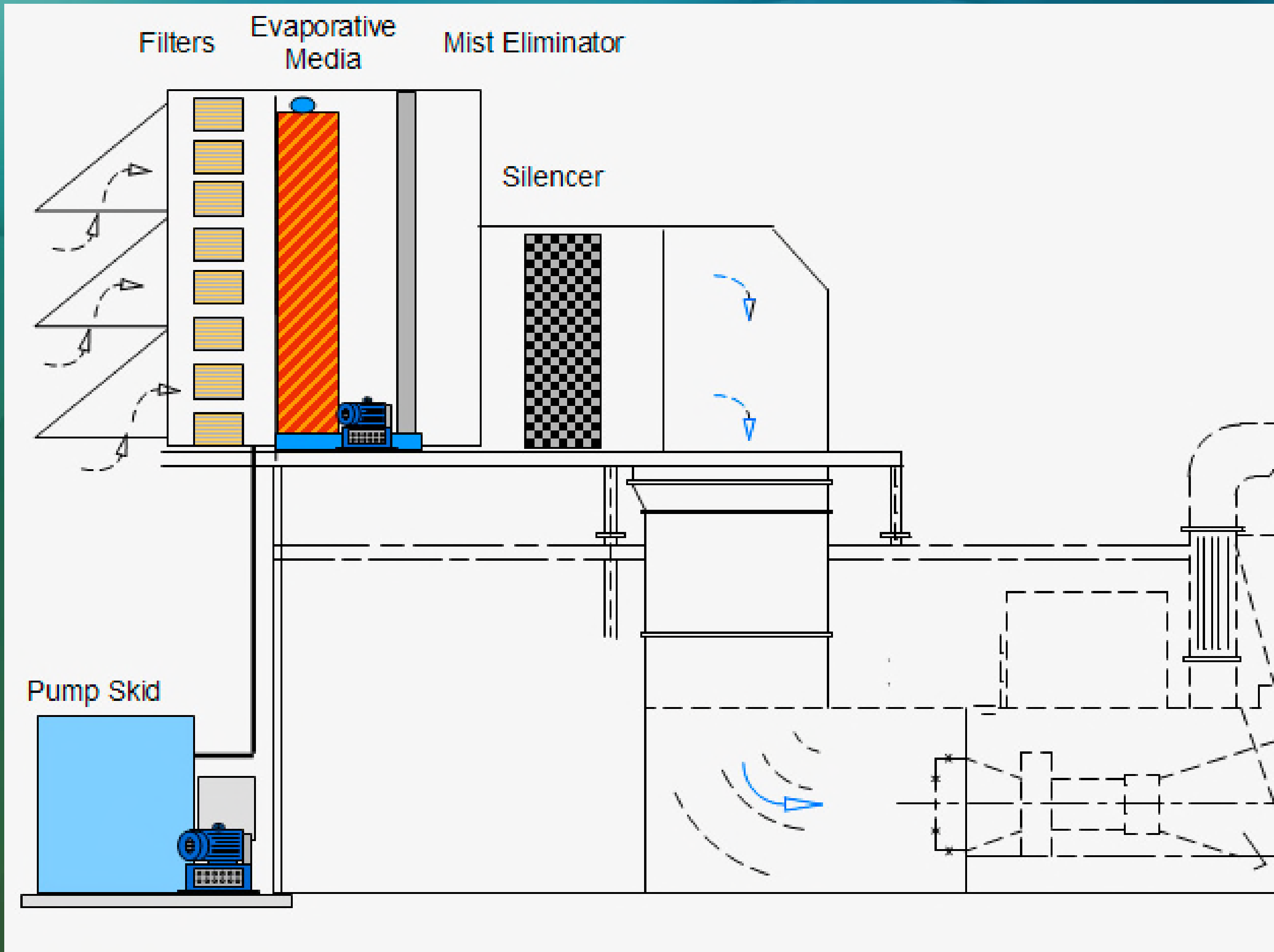
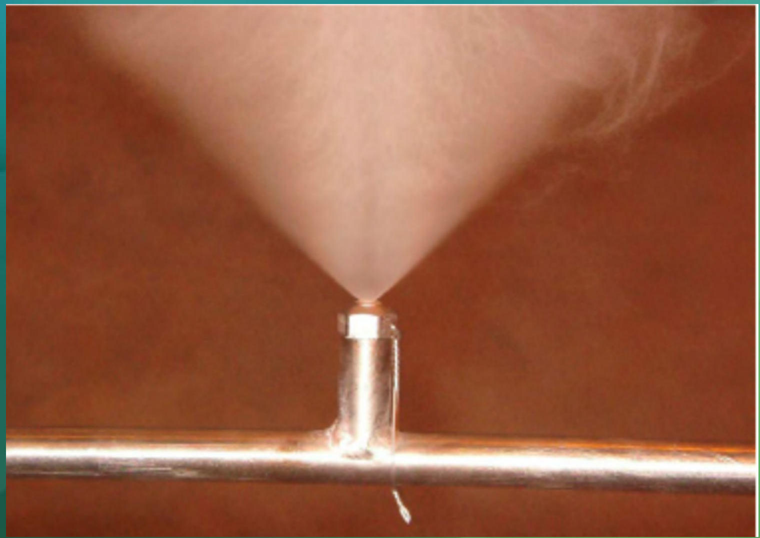
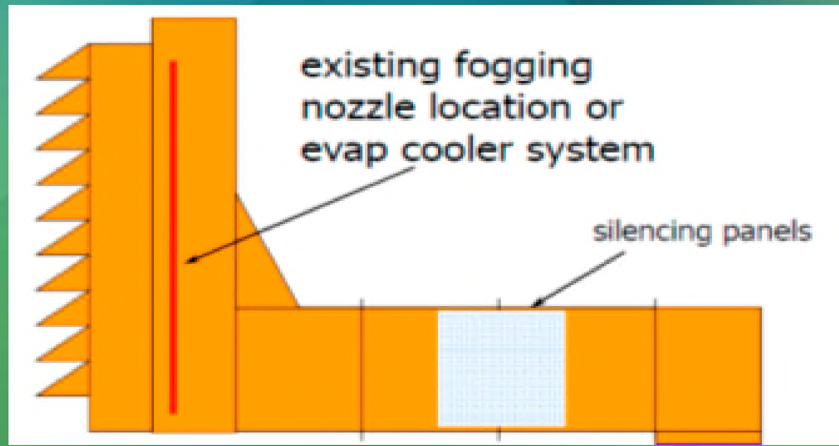
Location of Evaporative Cooler



Source: Munters Corporation

Fogging





Source: Caldwell Energy

- Water is sprayed as fog (droplet size<10 microns)
- Typical Cooling Efficiency = 95%
- Insertion DP = 0.05 to 0.2 inch WC
- Needs clean water to prevent nozzle plugging and erosion

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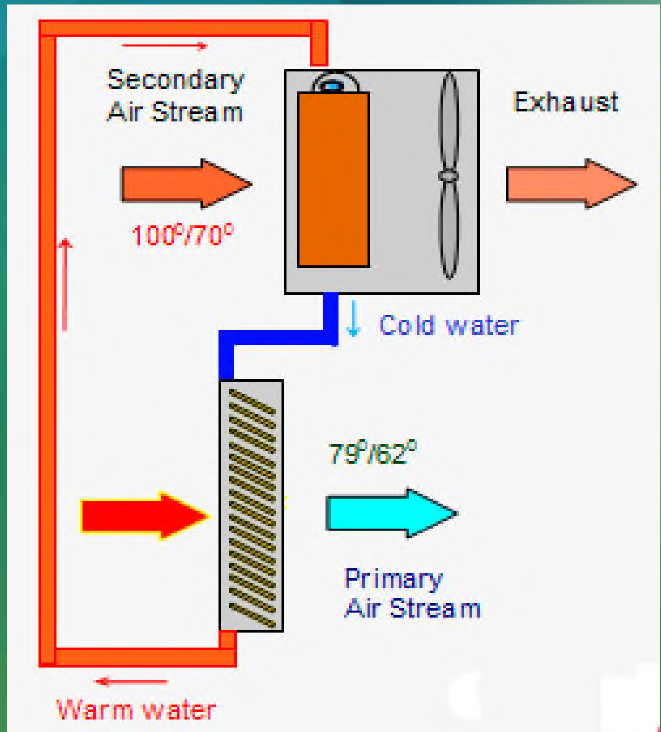
Indirect Evaporative Cooling

- Unlike direct evap, does not add moisture to the inlet air and thus, does not reduce air density
- Temperature reduction is a few degree less than that by direct evaporative of cooling
- Degrees of cooling reduces with increased humidity of the ambient air
- Generation capacity enhancement varies with the ambient air humidity
- Insertion DP higher than that for direct evap: 0.85 to 1.75 inch WC



Source: Munters Corp.

Chilled Fluid Systems

- Use chillers to produce a chilled fluid (water or ammonia)
- Inlet air is cooled by indirect heat exchange with chilled water or liquid ammonia, or direct exchange with chilled water
- Can cool the inlet air to any desired temperature (as low as 42°F*) at any humidity level (unlike evaporative cooling)
- Can maintain constant CT output irrespective of the ambient air humidity and temperatures

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* Any lower temperature may result in ice formation downstream of the compressor bell-mouth, in which up 10°F temperature drop may occur.

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Chilled Fluid Systems

- **MECHANICAL CHILLERS**
  - HCFCs, HFCs or Ammonia Refrigerant
  - Driven by Electricity, Steam-Turbine or Engines

- **ABSORPTION**
  - Water or Ammonia Refrigerant
  - Driven by Hot Water, Steam or CT Exhaust Gases

- **WITH OR WITHOUT THERMAL ENERGY STORAGE (TES)**
  - Chilled Fluid or Ice Produced and Stored During Off-Peak Period and Used During On-Peak Period

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THERMAL ENERGY STORAGE (TES)

- Chilled fluid or ice produced and stored during off-peak period and used during on-peak period
- Increases available net capacity during on-peak
- May reduce chiller capacity and capital cost, depending on the difference between the durations of on-peak and off-peak periods
- Two system design and operating modes:
  - *Full-Shift*: Only the stored chilled fluid or ice is used during on-peak (No chiller operated during on-peak period); maximizes on-peak capacity
  - *Partial-Shift System*: Both chiller and stored chilled fluid or ice are operated during on-peak; Both chiller and TES tanks are smaller capacity, and provides lower on-peak capacity compared to those for the full-shift system

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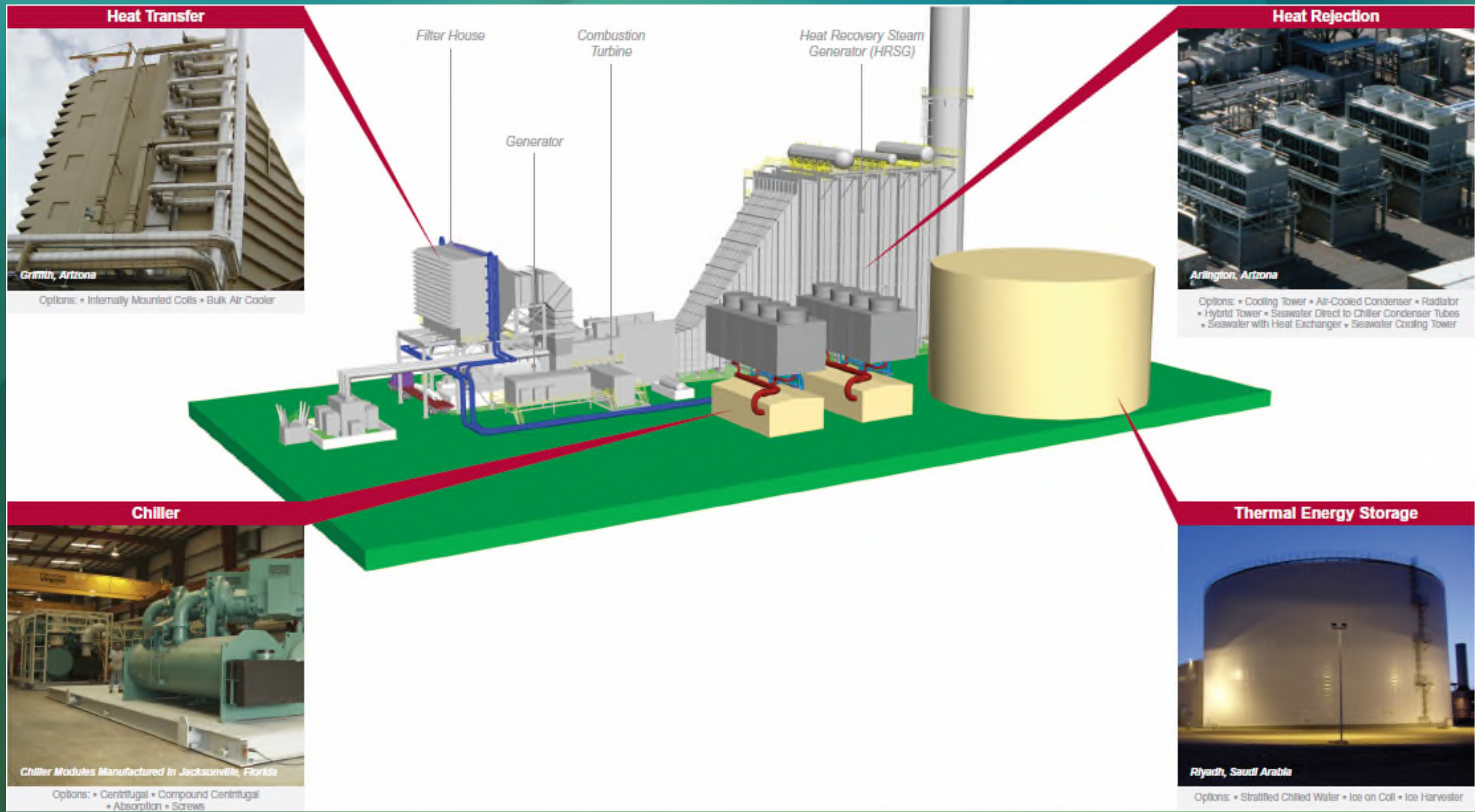
Chilled Fluid System



Source: Stellar Energy Systems

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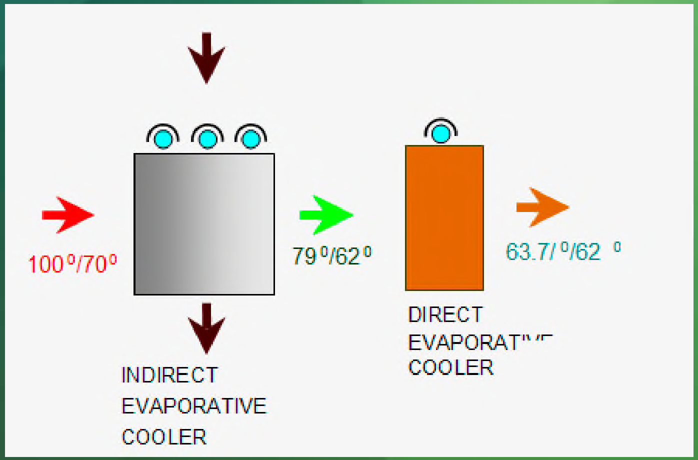
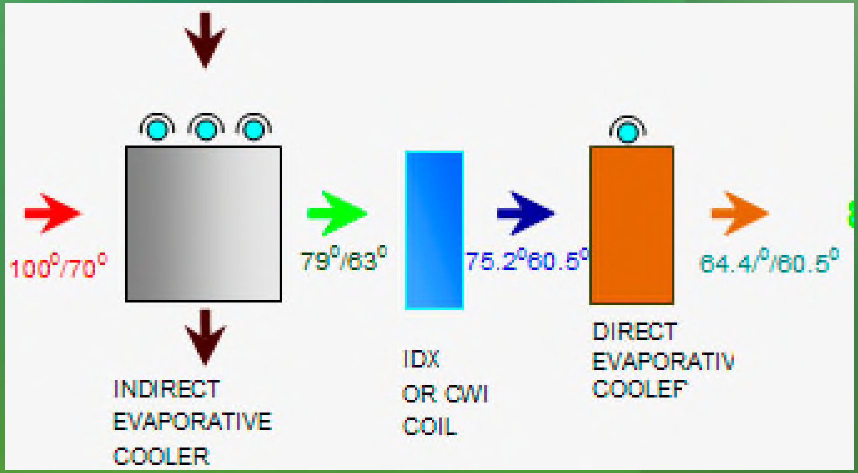
Hybrid Systems

- Simultaneously use two or more technologies in sequential processing
- Offer the flexibility of using each technology individually
- Reduce total parasitic load for cooling





Source: Annette Dwyer, ASME TurboExpo 2011

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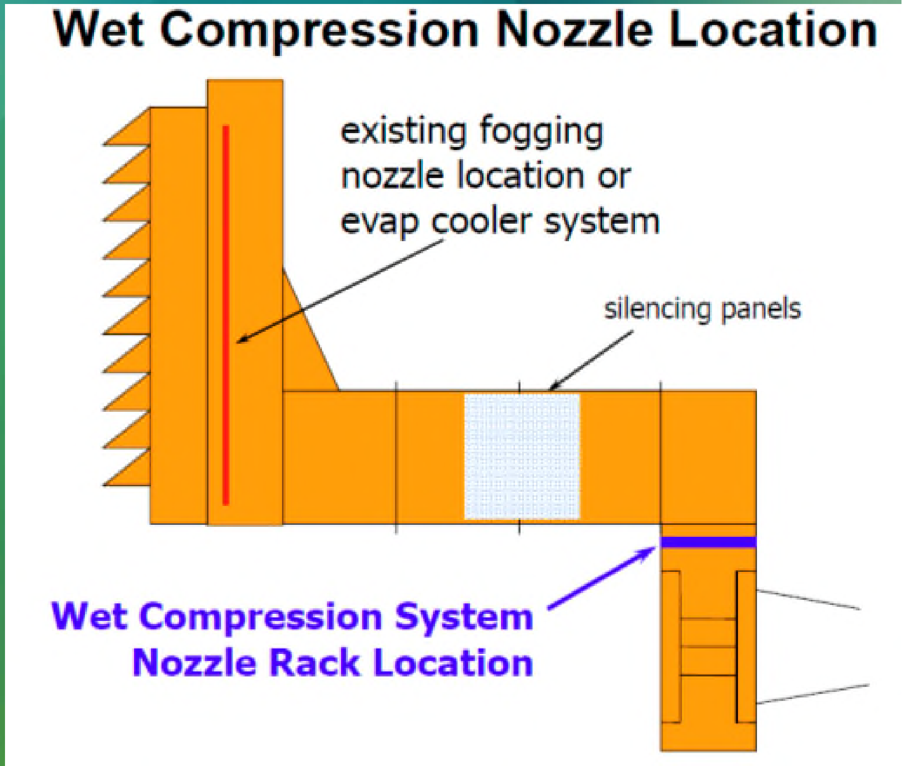
Wet Compression System

- Reduces Inlet-Air Temperature During Compression
- Reduces Power Consumed by the Air Compressor
- Fine Water Droplets (up to 2% of Mass Flow Rate of Inlet Air) Sprayed at the Compressor Bell-Mouth
- Increase Power Output Capacity by Two Factors:
  - Reducing Power Consumption by the Air Compressor
  - Increased Mass of Inlet Air Due to Water Added



Source: Caldwell Energy Company

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CHP Systems Using TIC

- **McCormick Place Exposition Center, Chicago, IL**
  3.3 MW (3 X 1.1 MW gas turbines) system
  uses indirect heat exchange with liquid ammonia
  from ammonia chillers

- **Caterpillar, Inc. Aurora, IL**
  15 MW (2 X 7.5 MW) system uses wetted-media
  direct evaporative cooling

- **A Food Processing Company, Bakersfield, CA**
  5 MW system uses hybrid cooling: Indirect + Direct evaporative
  Cooling

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Large Cogeneration Systems Using TIC

- **Calpine Clear Lake Cogeneration, Pasadena, TX**
  318 MW (3 x 106 MW) system uses six hot-water heated absorption chillers (8,300 Tons) in series with an electric chiller (1,200 Tons) and chilled water TES (107,000 Ton-hr)

- **Mulberry Cogeneration, Bartow, FL**
  127 MW (85 MW CT in Combined-Cycle) system uses 4,000-Ton ammonia chiller

- **Las Vegas Cogeneration, Las Vegas, NV**
  164 MW (4 X 41 MW) system uses hybrid cooling: fogging + absorption chiller

Calpine Clear Lake Cogeneration

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Resource for More Examples

Experience Database of the
Turbine Inlet Cooling Association (TICA):
http://www.turbineinletcooling.org/data/ticadatap.pdf

Shows information about hundreds of CT-based power plants already benefiting from TIC

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TIC Technologies & Economics

- All technologies have their pros and cons
- No one technology is best for all applications
- Each technology has some niche applications

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TIC System Economics

Factors Affecting the Economics

- Market value of additional power generation capacity and electric energy produced by TIC
- Hourly weather data for the plant location
- TIC Technology
- CT model
- TIC system capital cost
- Cost of purchased fuel

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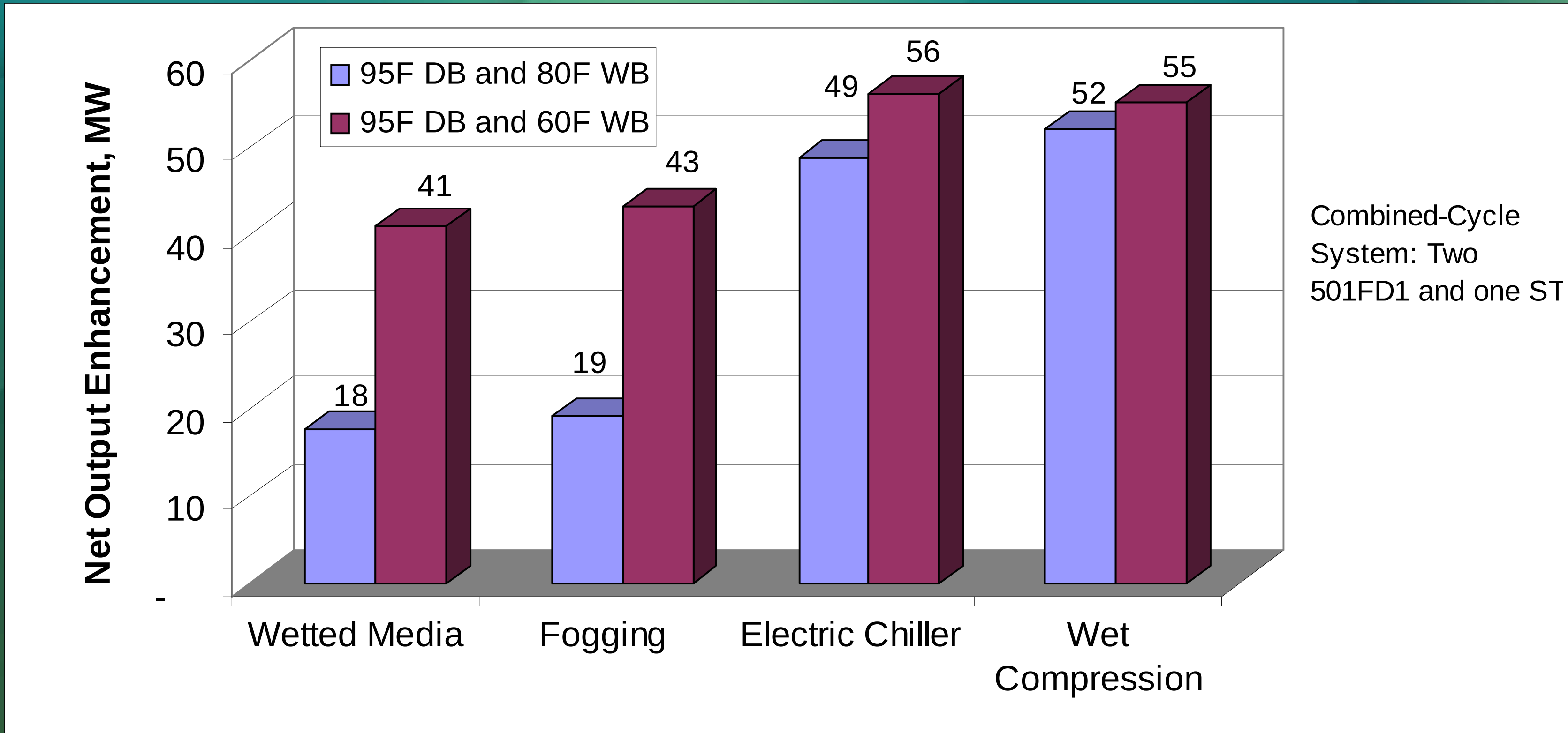
Effect of TIC Technology and Ambient Humidity on Net Capacity Enhancement



Source: White Paper of the Turbine Inlet Cooling Association (2009)

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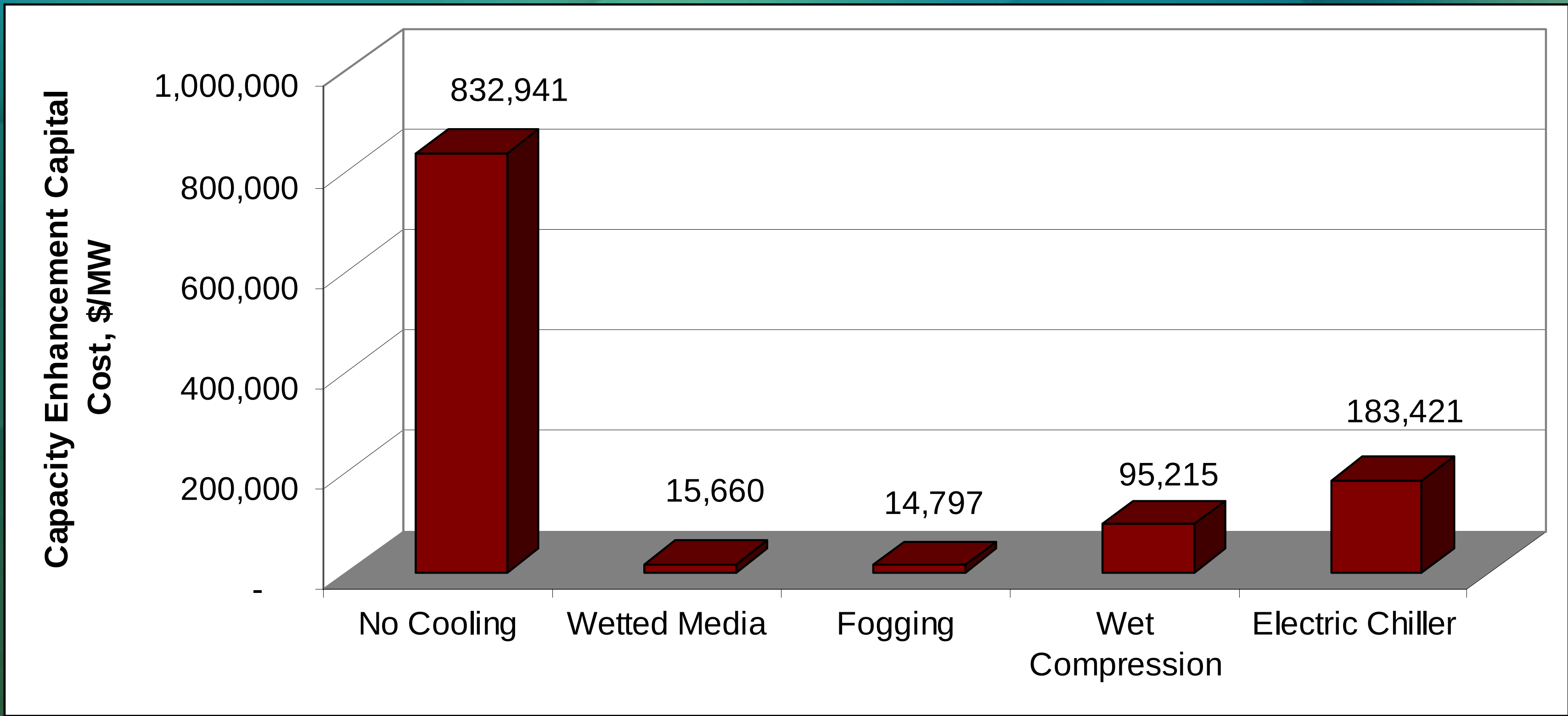
Effect of TIC Technology on Capital Cost for Incremental Capacity



317 MW Cogeneration System Snapshot at 95°F DB and 80°F WB

Source: White Paper of the Turbine Inlet Cooling Association (2009)

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TIC Calculator

Available on the Website of TICA:

http://www.turbineinletcooling.org/calculation_nonmem.php5

For Preliminary Comparative Estimates of Capacity Enhancement, and Fuel and Water Needs by Three TIC Technologies:

Wetted-Media, Fogging and Chillers at a selected ambient air condition

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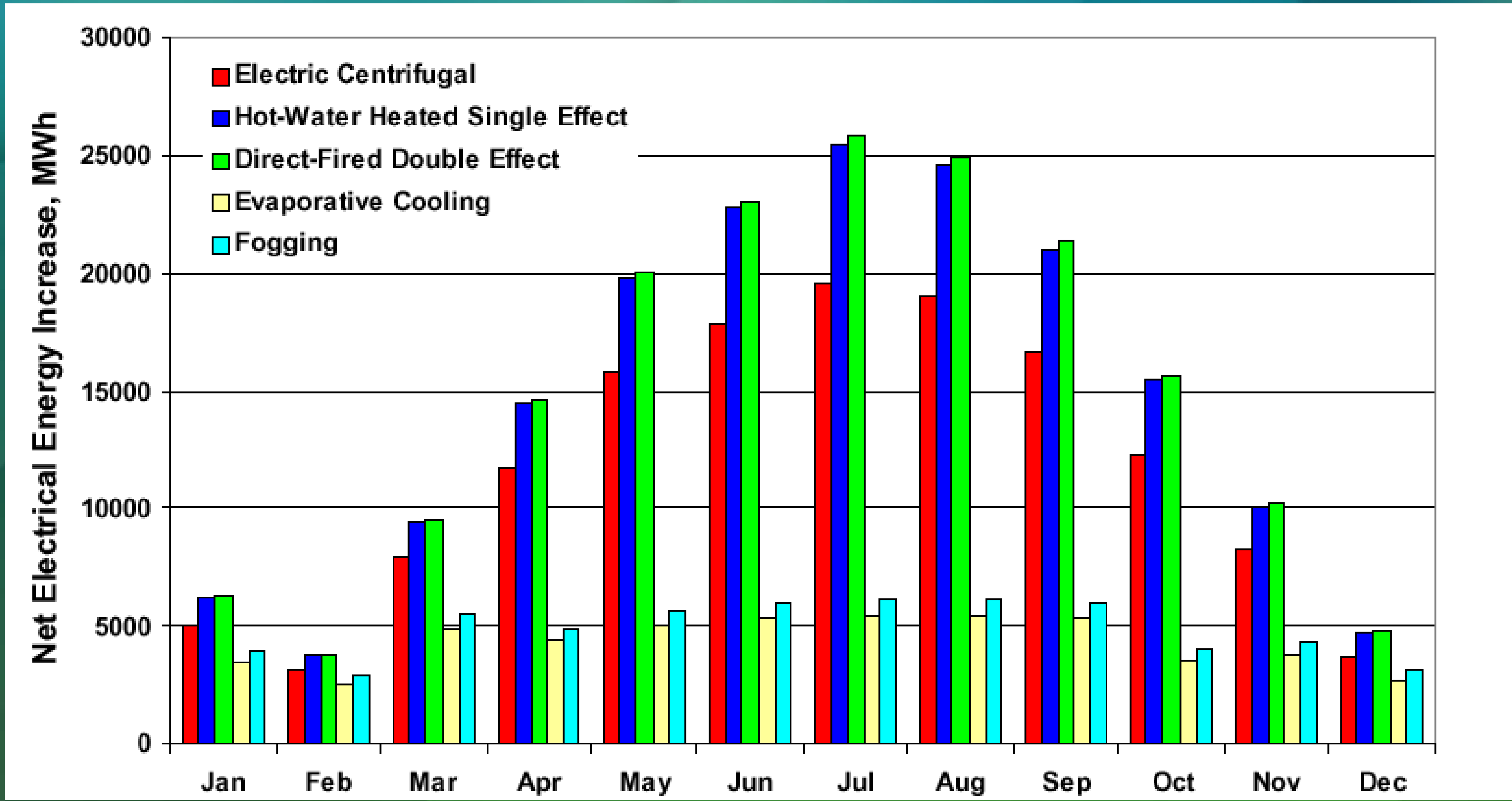
Effect of TIC Technology on Net Increase in Electric Energy Output

(Requires Calculations for all 8,760 hours/year of weather data)



Increased generation Relative to uncooled CT

Source: Punwani *et al* ASHRAE Winter Meeting, January 2001

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Summary & Conclusions

- TIC prevents De-rating of CT Power Capacity During Hot Weather, When Power is Most Needed
- TIC Costs Less for Providing Hot-Weather Capacity than a CT plant Without TIC
- TIC also Helps Reduce Emissions by Reducing or Eliminating the Need for Operating Lower-Efficiency Peaking Plants
- Multiple TIC Technology Options are Commercially Available
- Each TIC Technology has its Pros and Cons
- Thousands of CT plants are already successfully deploying TIC
- Determination of the optimum TIC system for a specific plant must be made based on the weather data for the 8,760 hours of a typical meteorological year (TMY) for the plant location, value of additional electric energy produced by TIC and other plant-specific cost factors.

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For Questions or Follow-up

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