Optimizing Clean Energy Systems with Thermal Energy Storage and/or Turbine Inlet Cooling

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Outline

- **Introduction**
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- **Thermal Energy Storage (TES)**
  - Technologies, Examples and Economics
- **Turbine Inlet Cooling (TIC)**
  - Technologies, Examples and Economics
- **TES-TIC Systems**
  - Examples, Economics and Comparison with other electric energy storage technologies
- **Summary and Conclusions**

Introduction

- **Clean Energy Systems**
  - Renewable energy systems
  - Combined heat & power (cogeneration) systems
  - District energy systems

- **Clean Energy System Characteristics**
  - Some don't provide/generate electric or thermal energy uniformly 24/7, for example: wind-energy, solar-energy, gas-turbine systems
  - Electric or thermal energy requirements of the systems served are not uniform 24/7, for example: office buildings, convention centers

Introduction

TES and/or TIC Systems Enhance Efficiency and Economics of Clean Energy Systems

- **Minimize the Impacts**
  - Non-uniformity of Generation
  - Non-uniformity of Demand
- **Optimize Energy Efficiency and Economics**

California ISO Report

"Storage will be critical for large scale implementation of sustainable energy."

- The November 2007 Report "Integration of Renewable Resources"

TES Technologies

- **Hot-Water Storage:** Stores sensible thermal energy
- **Chilled-Fluid Storage:** Directly stores sensible heat and indirectly stores electric energy
- **Ice Storage:** Directly stores latent heat and indirectly stores electric energy

Hot-Water TES Systems

- Use thermal energy available from clean energy systems during periods of low thermal demand
- Provide thermal energy during periods of high thermal energy demand
- Stored hot water could also be used for providing cooling (via absorption chillers) during high cooling demand periods

Hot-Water TES System Example

Freedom Field, Rockford, IL

- Hot-water storage tanks (2,450 Gallons) store hot water produced by solar thermal panels (175,000 Btu/hr) during periods of sunlight
- Hot water is used for providing space heat during winter
- Hot water is used for operating an absorption chiller (10 tons) that provides chilled water for cooling during summer

Hot-Water TES System Example

District Energy System at California State University, Fullerton, CA

- 158 Million Btu TES System (0.5 Million Gallons)
- TES system stores pre-heated steam condensate return for use as feed water for boilers during non-peak heating demand periods, to increase heating capacity during peak demand periods

Chilled-Fluid TES Systems

- Store chilled fluids produced by using thermal or electric energy available from clean energy systems during periods of low thermal or electric demand
- Provide chilled fluid for cooling during periods of high-cooling demand
- Minimize the need to use high-cost electric energy during on-peak periods

Chilled-Fluid TES Example

Princeton University CHP District Energy System, Princeton, NJ

- **40,000 Ton-hr Chilled-Fluid TES System**
- **14.6 MW simple-cycle CT in CHP service**

Chilled-Fluid TES System Example

CHP-Based District Energy System, St. Paul, MN

- Two chilled-water TES systems (65,400 Ton-hrs)
- Store chilled-water produced off-peak by absorption chillers and electric chillers
- Absorption chillers operate on hot-water produced by part of the 25 MW biomass (waste wood)-fired CHP system

TES System Economics

Factors Affecting the Economics

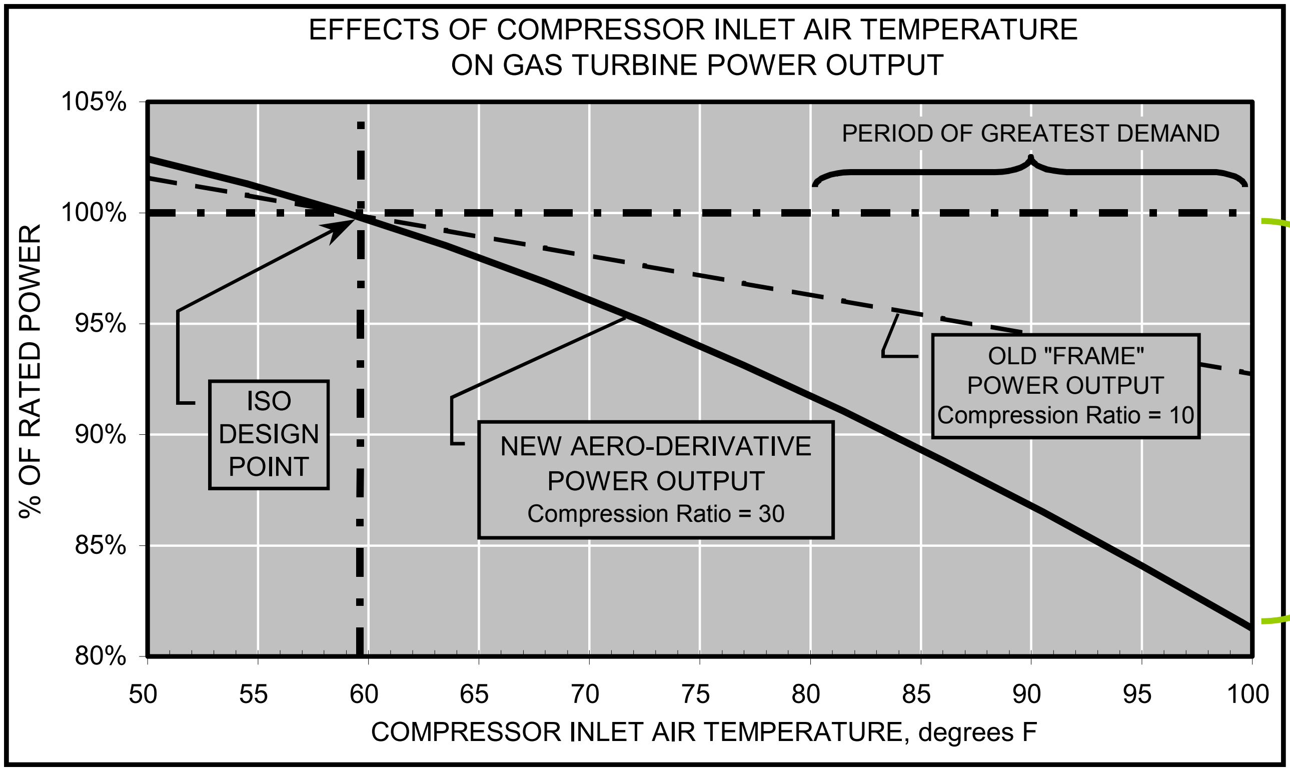
- Cost of purchased fuel
- Difference between the on-peak and off-peak charge for power demand and electric energy
- Capital cost of the TES system

Gas/Combustion Turbine System Characteristics

Effect of Hot Weather

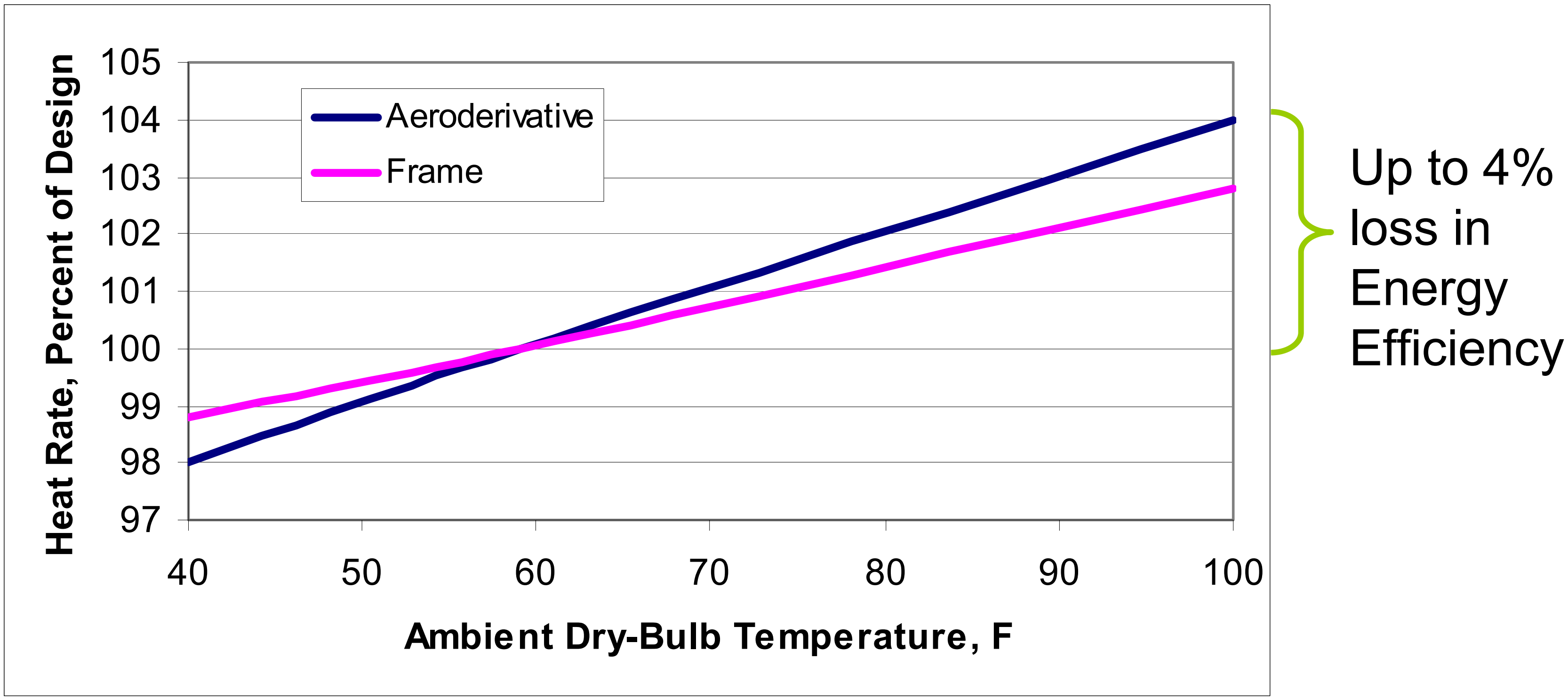
- Reduced electric power output, by up to 35%
- Reduced energy efficiency, by up to 8%
- Increased owner cost of buying grid power

Generation Capacity Decreases with Increase in Ambient Temperature; Amount Depends on the CT Selection



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

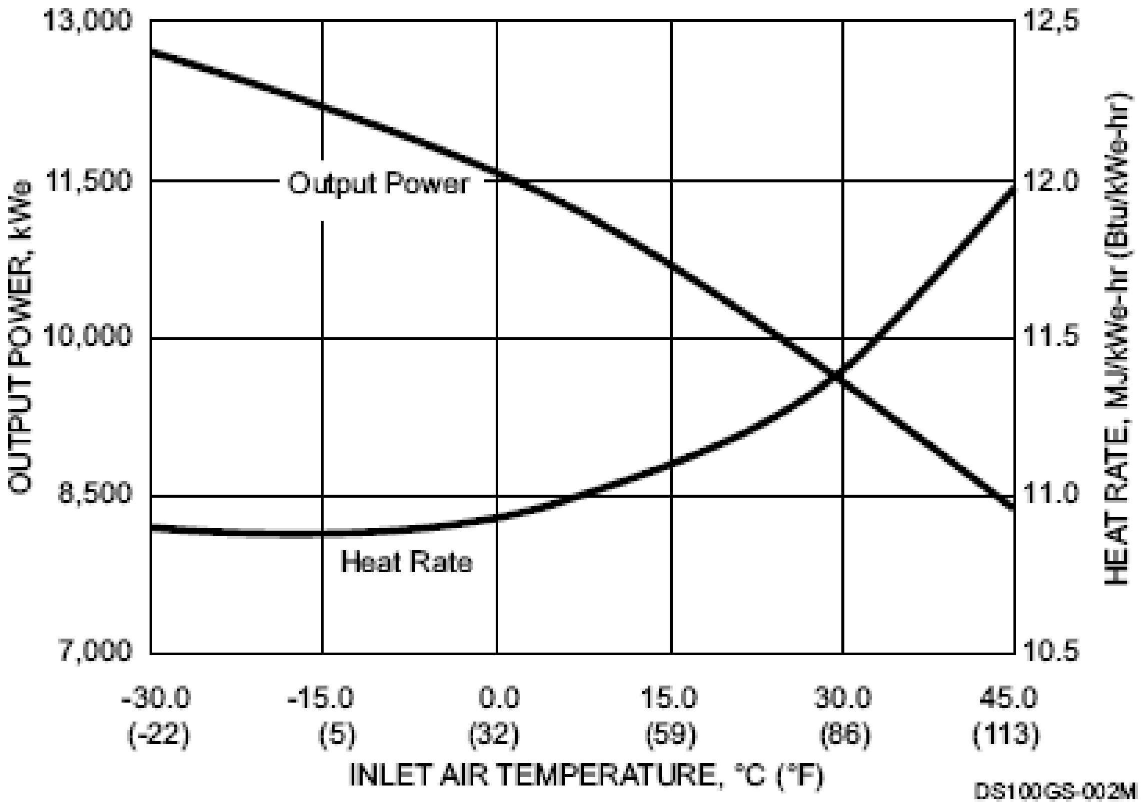
Heat Rate Increases (i.e. Energy Efficiency Decreases) with Increase in Ambient Temperature



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

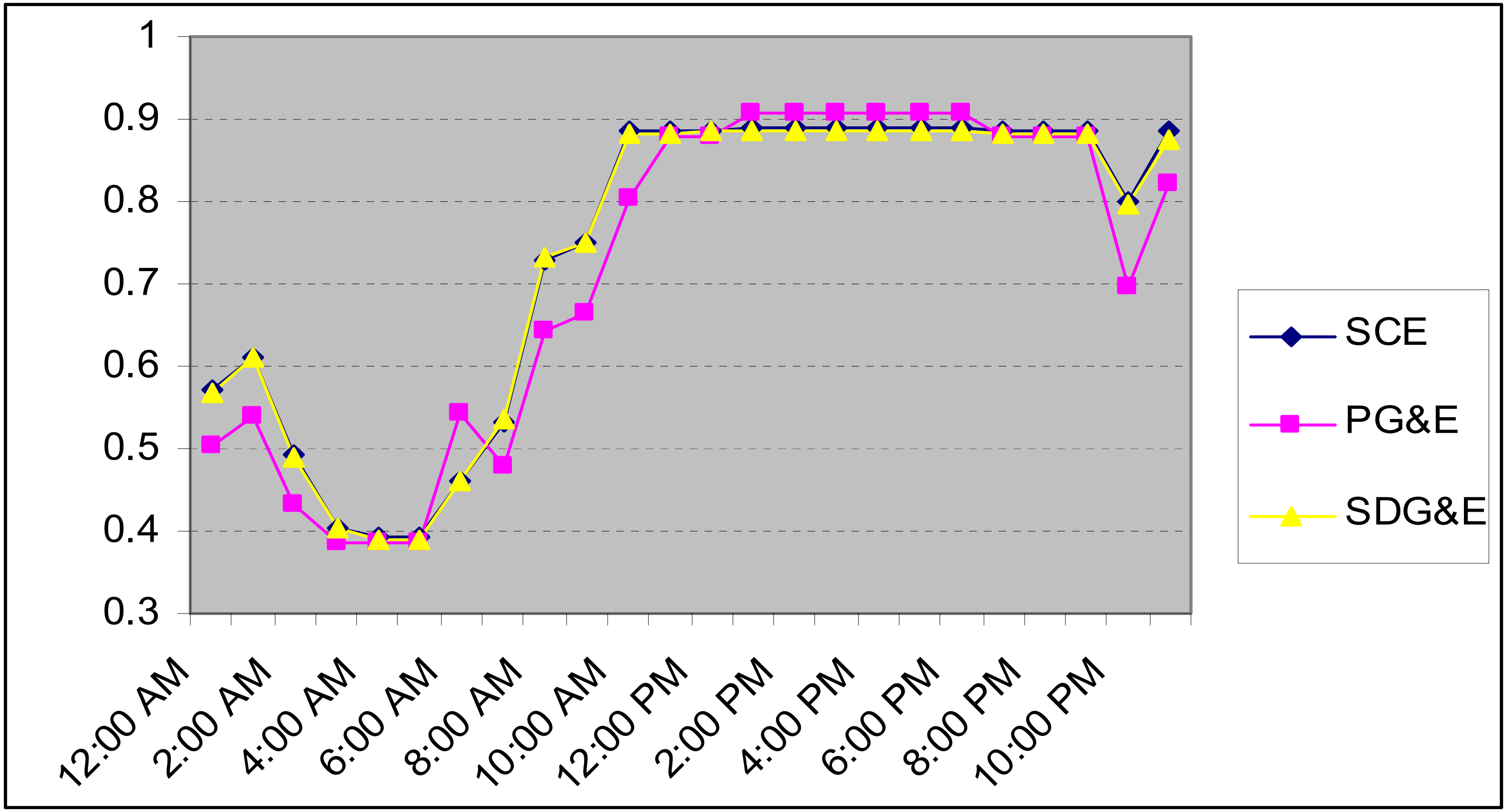
Smaller Capacity Systems More Sensitive to Ambient Temperature

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

CO_2 Emissions (lbs/kWh) During Peak Period California Summer Example



Y-Axis Unit: CO_2 Emissions, Lbs/kWh

Source: Scot Duncan Presentation at ASHRAE June 2007

Fuel Use* Carbon Footprint

System	Carbon Footprint
Cogeneration/CHP	Lowest**
CT in Combined-Cycle	
CT in Simple-Cycle	
Steam-Turbine	Highest***

* Total fuel used for generating electric and thermal energy

** Utilizes thermal energy in the CT exhaust to meet some of the thermal energy needs

*** Old plants used primarily for peak shaving

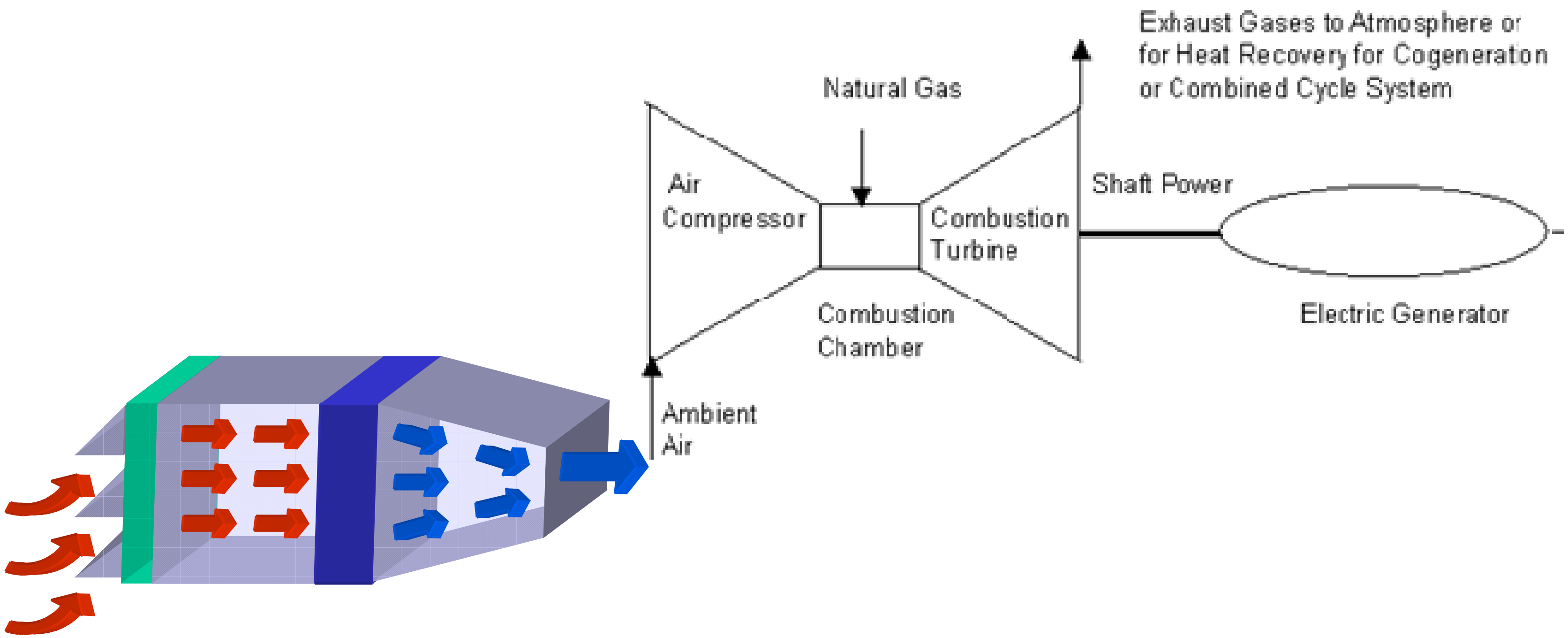
TIC Systems

- Cool the inlet air to the GT/CT system

Benefits

- Minimize the detrimental impacts of hot weather on CT system performance
- Reduce the owner cost for buying power from grid
- Minimize the operation of low-efficiency power generation system connected to the grid during hot weather

Turbine Inlet Cooling



- Cooling the inlet air before or during compression in the compressor that supplies high-pressure compressed air to the combustor of a combustion turbine

TIC System Technologies

Two Categories

- Reduce Temperature of Inlet Air to Compressor
- Reduce Temperature of Inlet Air During Compression

TIC System Technologies

Reduce Inlet Air Temperature

- **Direct Evaporation**
  - Wetted Media
  - Fogging
- **Indirect Evaporation**
- **Chilled Fluid**
  - Indirect Heat Exchange
  - Direct Heat exchange
- **Chilled Fluid in TES**
- **Hybrid**
  - Some combination of two or more cooling technologies

TIC System Technologies

Reduce Inlet-Air Temperature During Compression

- Wet Compression (or Fog Overspray)

TIC Example

McCormick Place
Exposition Center
District Energy System
Chicago, Illinois

- Inlet air is cooled for the 3.3 MW CHP system that uses three 1.1 MW gas turbines
- Air is cooled by indirect heat exchange with evaporating ammonia from ammonia chillers

TIC Example

Calpine Clear Lake Cogeneration, Pasadena, TX

- 318 MW (3 x 106 MW)
- Hybrid TIC system:

  absorption chillers (8,300 Tons) in series with an electric chiller (1,200 Tons)

DOE Survey* Results of CHP Installations with TIC

Technology	Number of Systems
Chillers (w/ or w/o TES)	21
Ammonia Evaporation in Coil	4
Wetted Media	2
Fogging	1
Wet Compression	1
Total	29

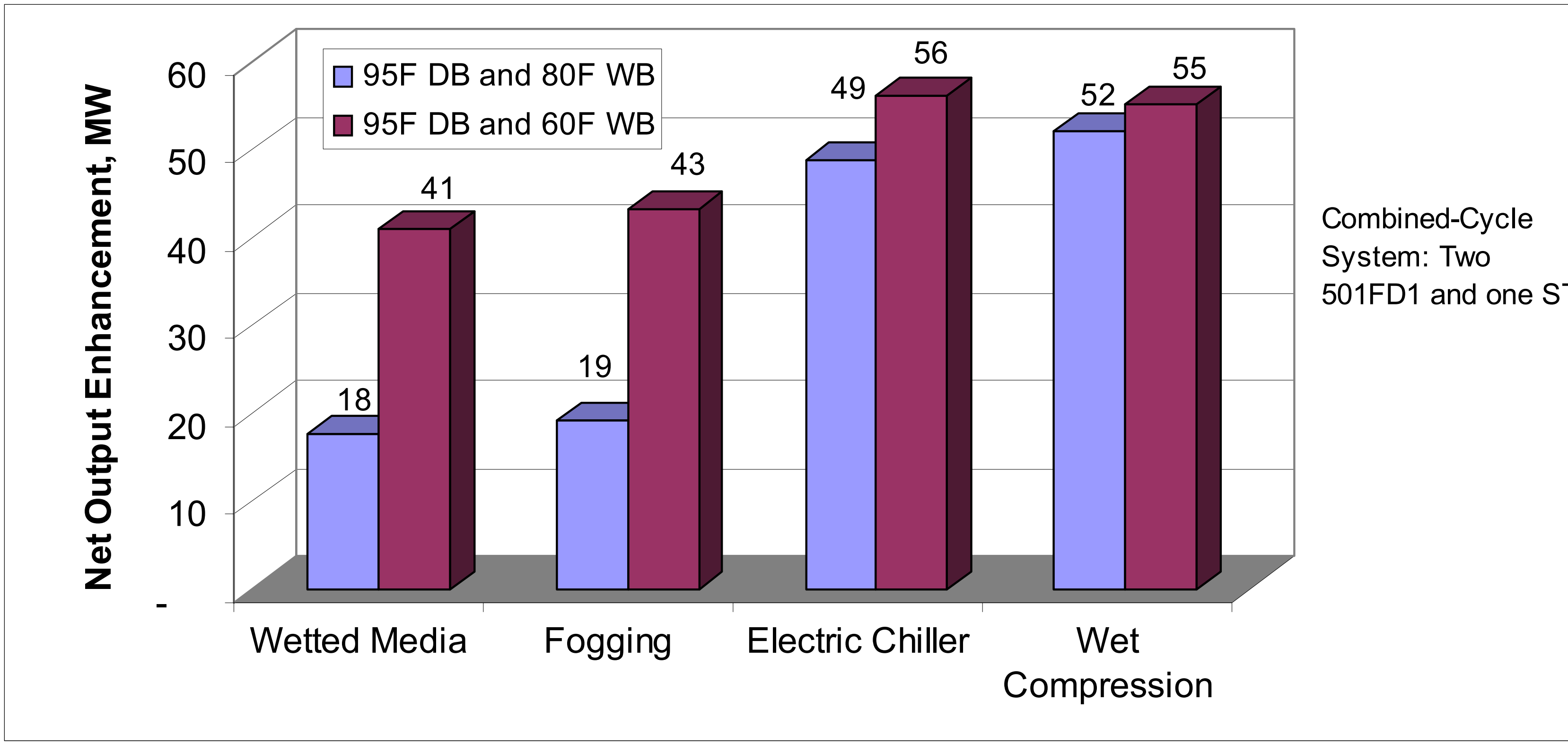
* Performed by The Cool Solutions Company and Avalon Consulting, Inc (2004)

TIC System Economics

Factors Affecting the Economics

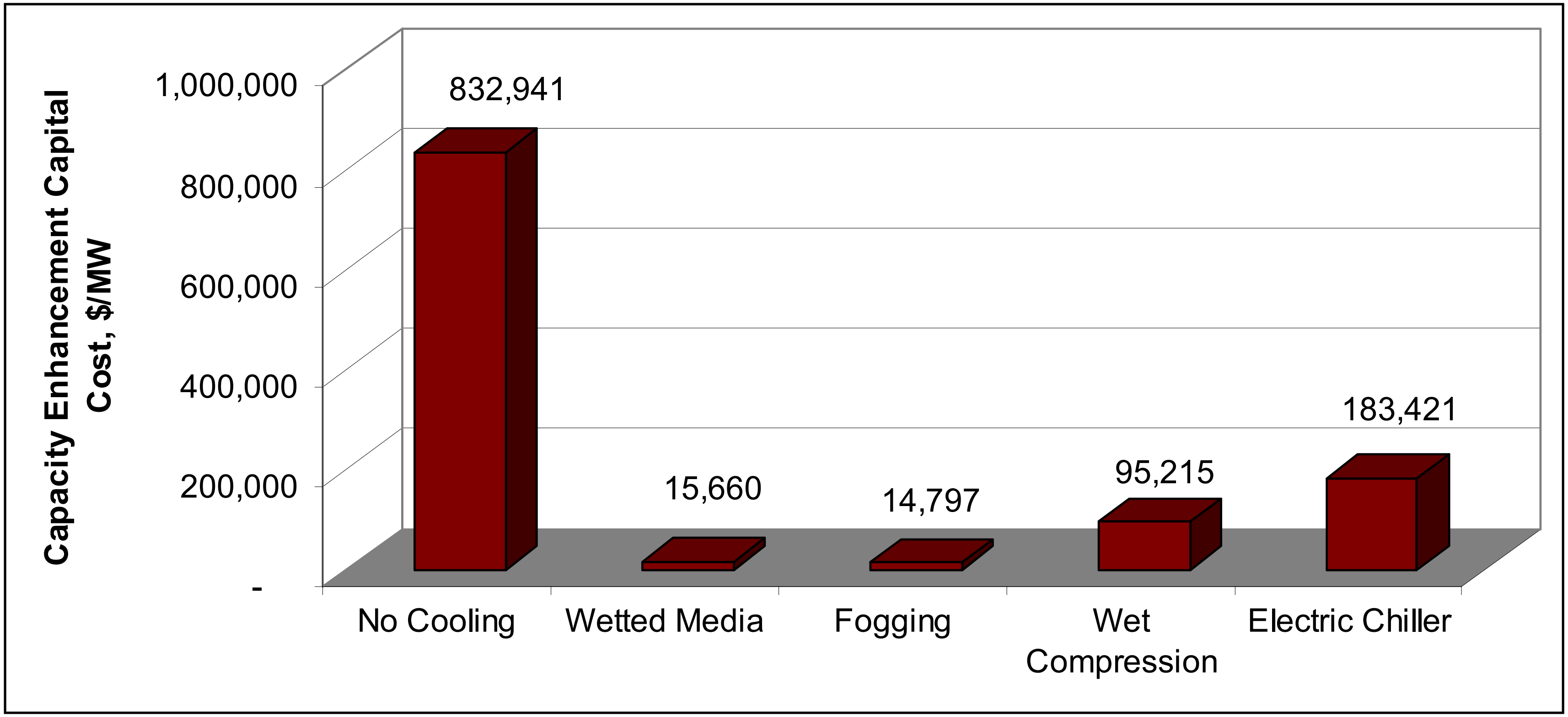
- Market value of additional power generation capacity and electric energy produced by TIC
- Hourly weather data for the plant location
- TIC Technology
- CT model
- TIC system capital cost
- Cost of purchased fuel

Effect of TIC Technology on Net Capacity Enhancement



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

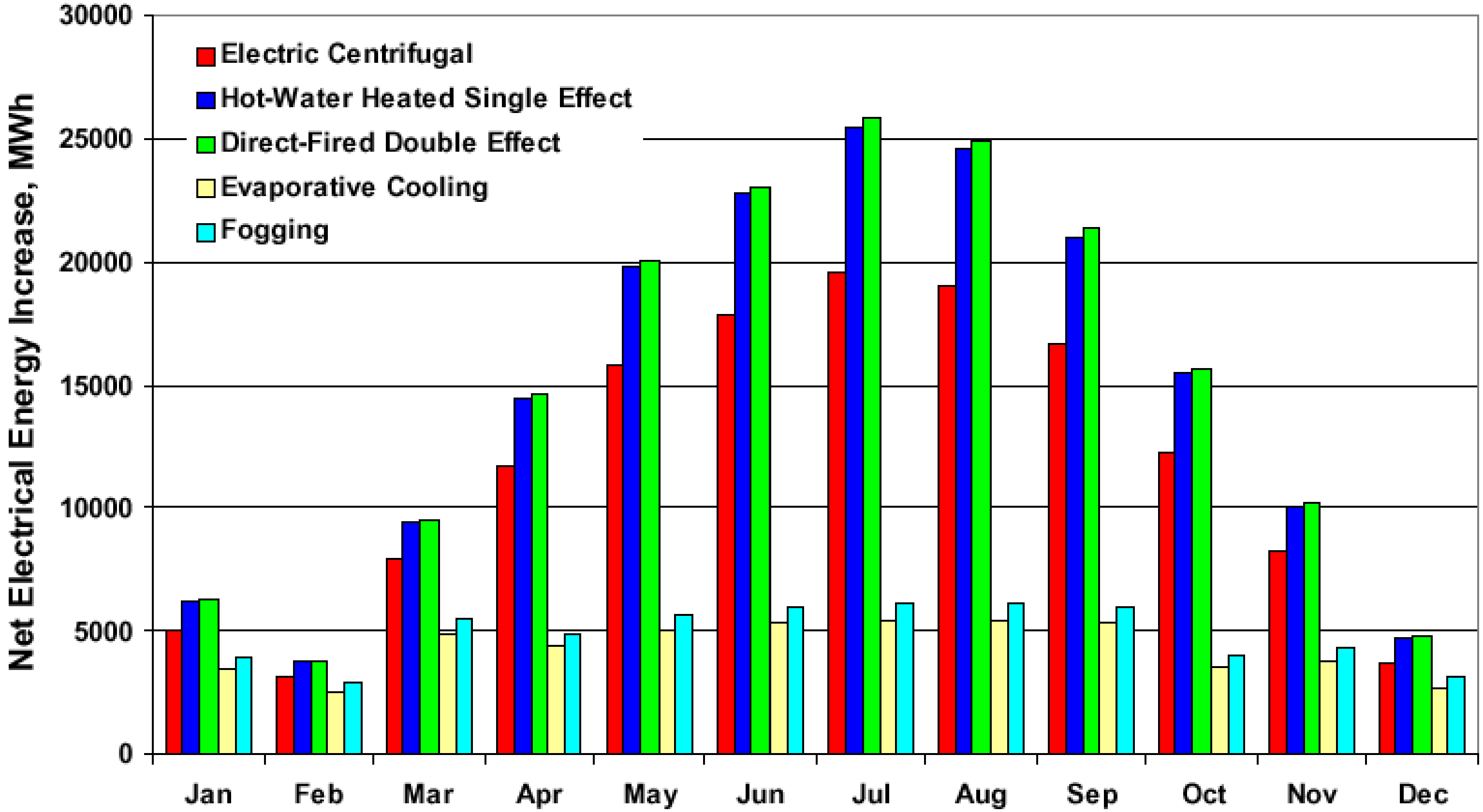
Effect of TIC Technology on Capital Cost for Incremental Capacity



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

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

Effect of TIC Technology on Net Increase in Electric Energy Output



Increased generation Relative to uncooled CT

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

TES-TIC System Technologies

- Full-Shift: No chiller operated during on-peak periods; only chilled water from TES tanks is used
- Partial-Shift: Chillers as well as chilled water from TES tank are used during on-peak periods

TES-TIC System

Benefits

- Provides more net electric energy generation capacity during on-peak period than systems without TES
- Reduces chiller installed capacity and capital cost

TES-TIC System Economics

	TIC w/o TES	TIC w/ TES*
Chiller plant capacity	31,000 tons	11,000 tons
TES capacity	none	190,000 ton-hrs
Total project capital cost	~$75 million	~$45 million
Net power increase (6 h/d)	~140 MW	~170 MW
Unit capital cost	~$535/kW	~$265/kW

* Ten GE 7EA CTs (750 MW) in Saudi Arabia

Economics of TES for TIC System

Comparison with Other Multi-hour Electric Energy Storage Systems

System	Cost, $/kW	Efficiency, %	Technology Status
TES for TIC	100 - 500	~ 100	Commercial
Compressed Air	900 (Target)	~70	Developmental
Pumped Hydro	2,000+	70-80	Commercial
Flywheel	3,400	80-90	Demonstration
Advanced Battery	4,500	~70	"Pioneering"

Details are shown in the Appendix

Source: John S. Andrepont, Electric Power 2009

Summary & Conclusions

- TES has been successfully deployed for enhancing the energy efficiency and the economics of numerous clean energy systems
- TIC has been successfully deployed for enhancing the power output, energy efficiency and the economics of numerous CT-based clean energy systems in hot weather/climates
- TES for TIC is a lower cost and a higher-efficiency option for electric energy storage than the proven pumped-hydro and the developing storage systems of compressed-air, flywheels and batteries
- No single Energy Storage technology fits all cases; but TES-TIC is a commercially viable and attractive option.

For Questions or Follow-up

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Appendix

Detailed Comparison Between TES-TIC and Other Energy Storage Technologies

Pumped Hydro ES vs. TES-TIC

	Pumped Hydro Energy Storage	Turbine Inlet Cooling with CHW TES
Location	Michigan	Saudi Arabia
Year in operation	circa 1990	2005
Peak power	1,200 MW	48 MW
Energy storage	9,600 MWh	288 MWh
Projected life	30+ years	30+ years
Round-trip eff.	~70-80%	near 100%
Classification	commercial	commercial
Unit capital cost	$2,000+/kW	$83/kW
Dispatch period	8 hours/day	6 hours/day

Compressed Air ES vs. TES-TIC

	Compressed Air Energy Storage	Turbine Inlet Cooling with CHW TES
Location	Iowa	Saudi Arabia
Year in operation	201X (planned)	2005
Peak power	268 MW	48 MW
Energy storage	1,608 MWh	288 MWh
Projected life	20+ years	30+ years
Round-trip effic'cy	~70%	near 100%
Classification	developmental	commercial
Unit capital cost	$900/kW (target)	$83/kW
Dispatch period	6 hours/day	6 hours/day

Advanced Battery ES vs. TES-TIC

	"Utility-scale" Na-S Advanced Batteries	Turbine Inlet Cooling with CHW TES
Location	West Virginia	Saudi Arabia
Year in operation	2006	2005
Peak power	1.2 MW	48 MW
Energy storage	7.2 MWh	288 MWh
Projected life	15 years	30+ years
Round-trip effic'cy	~70%	near 100%
Classification	"pioneering"	commercial
Unit capital cost	$4,500/kW	$83/kW
Dispatch period	6 hours/day	6 hours/day

Flywheel ES vs TES-TIC

	Flywheel Energy Storage	Turbine Inlet Cooling with CHW TES
Location	New York	Saudi Arabia
Year in operation	2011 (1st 20%)	2005
Peak power	20 MW	48 MW
Energy storage	5 MWh	288 MWh
Projected life	20 years	30+ years
Round-trip effic'cy	~80-90%	near 100%
Classification	demonstration	commercial
Unit capital cost	$3,440/kW	$83/kW
Dispatch period	15 minutes	6 hours/day