Turbine Inlet Cooling:
A Pathway for Maximizing the Economic Performance and Electric Grid Decarbonization Potentials of Combined Cycle Systems

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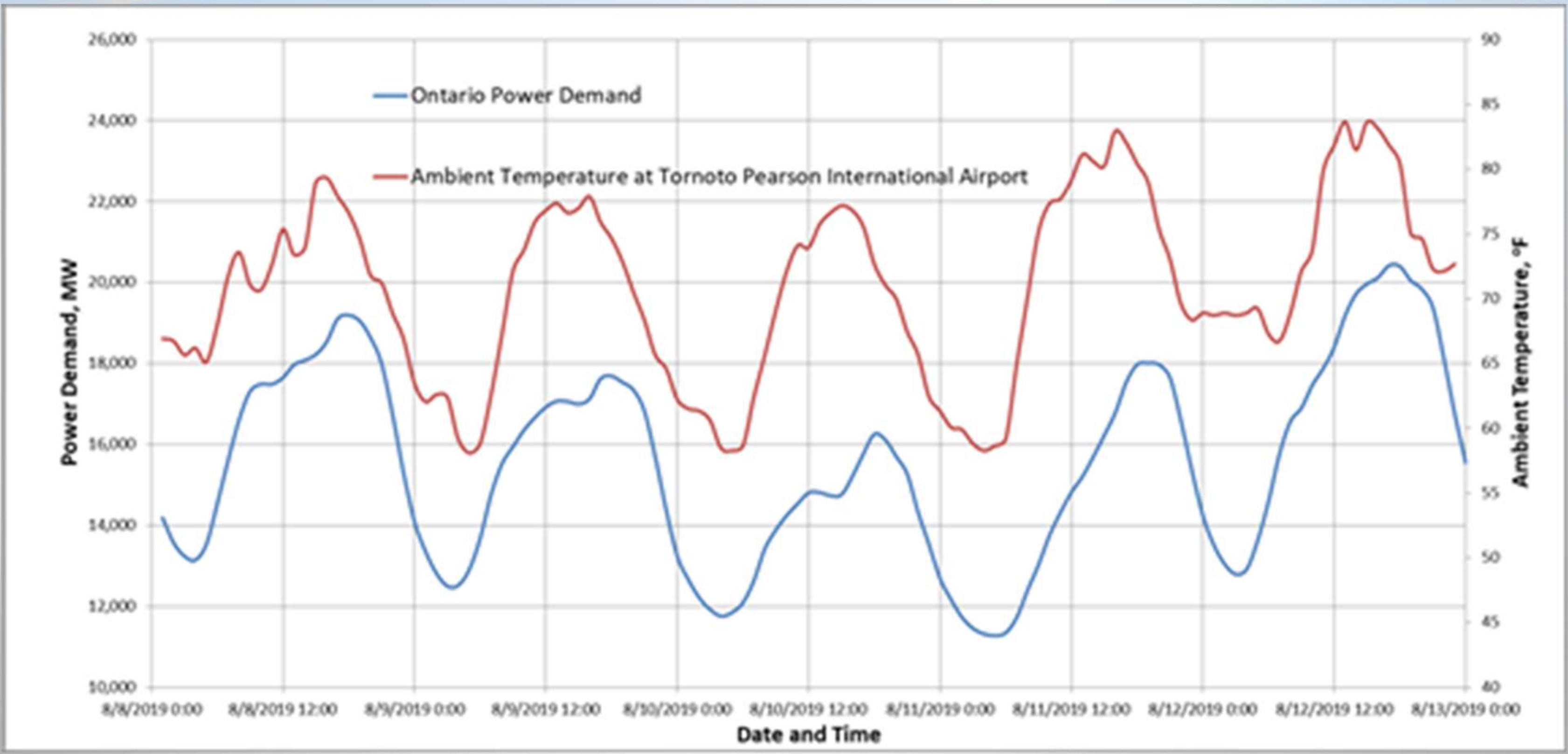
Presentation Outline

1. Hot weather impacts on electricity demand, price, and carbon emissions
2. Benefits of combined cycle systems
3. Hot weather problems for combustion turbines (CTs)
4. Hot weather impacts on combined cycle (CC)
5. How to overcome the impacts of hot weather?
6. What is turbine inlet cooling (TIC) and its experience
7. Benefits of TIC for economic performance and electric grid decarbonization potentials of CC
8. TIC technology options and the factors affecting technology selection
9. Examples of effects of TIC technology on CT performance and economics
10. TICA Database of CC Systems wiih TIC
11. Conclusions
12. Recommendations

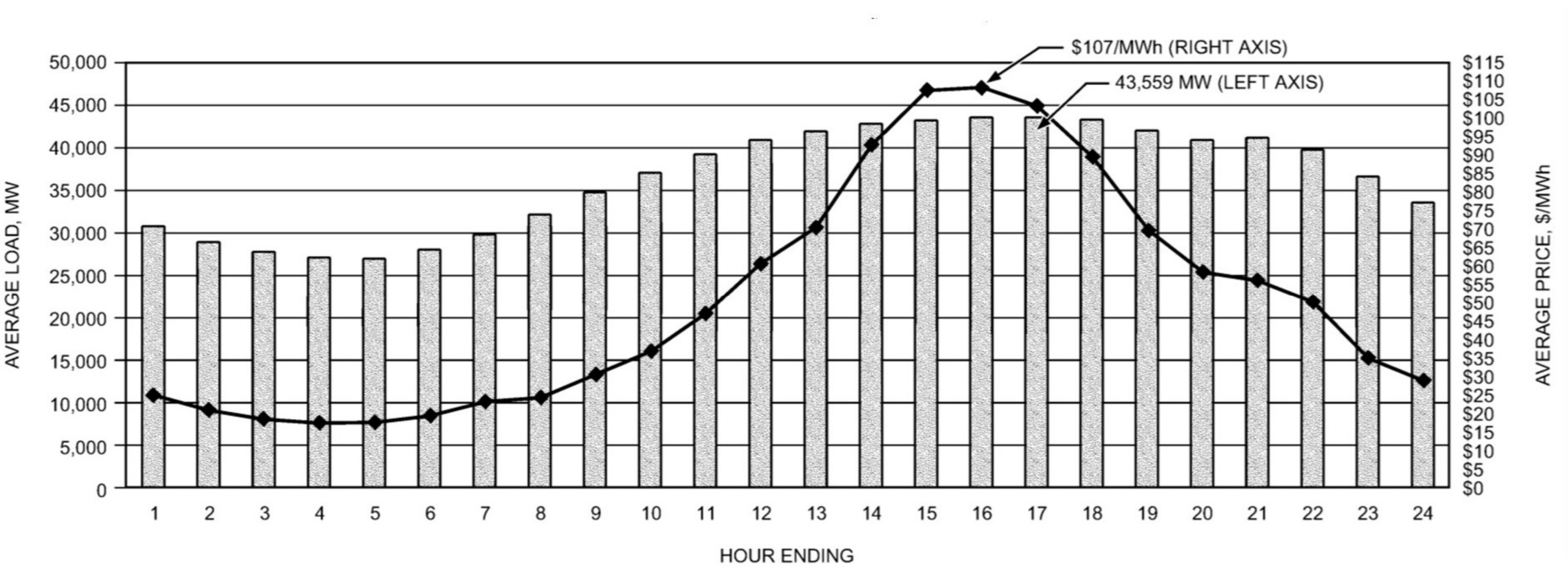
Hot Weather Increases Electric Power Demand



Example of Hourly Ambient Temperature and System Load Profiles in Ontario, Canada

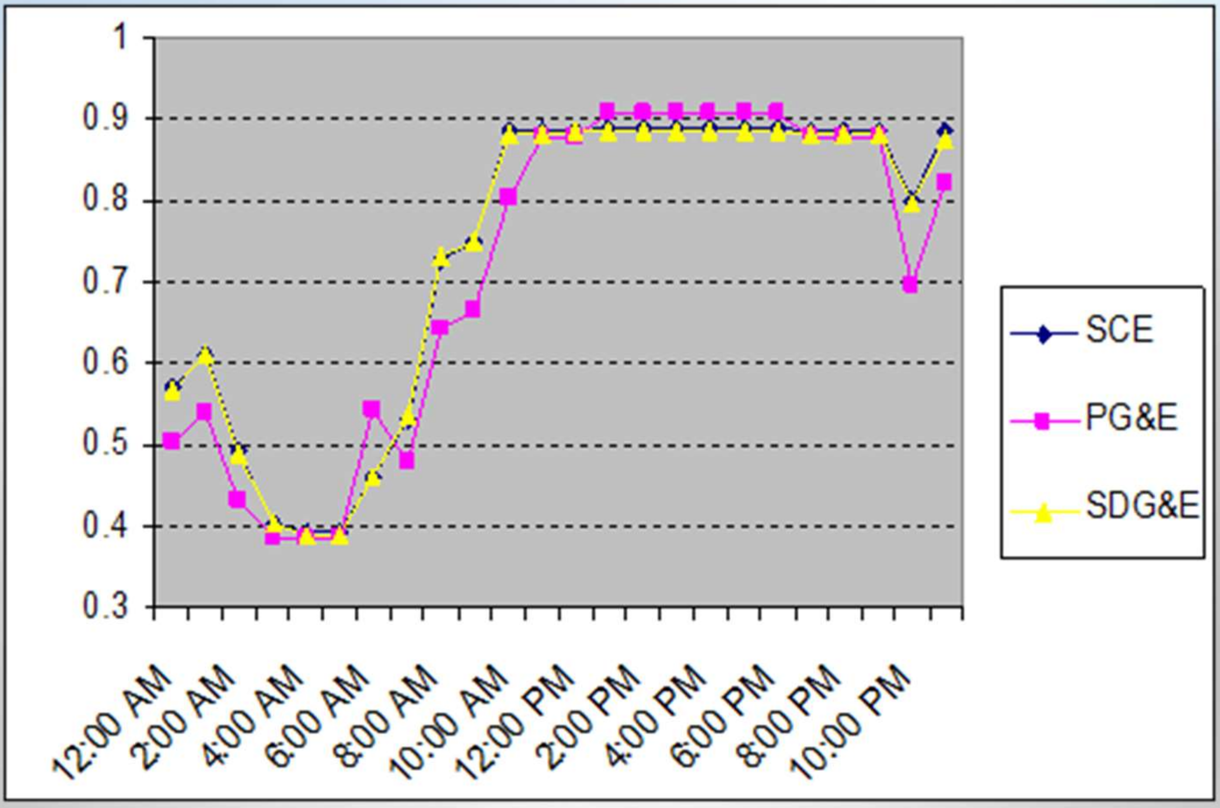
(Punwani, D., et al, “ASHRAE Design Guide for Combustion Turbine Inlet Cooling, 2022”)

Hot Weather Increases the Price of Electric Energy



- Actual price of electric energy depends on the mix of power generation systems connected to the grid

Increase in Power Demand Increases CO_2 Emissions



Notes:

- *Y-Axis Scale Shows lb. of CO_2/kWh*
- *PG&E (Pacific Gas & Electric); SCE (Southern California Edison); SDG&E (Diego Gas & Electric)*

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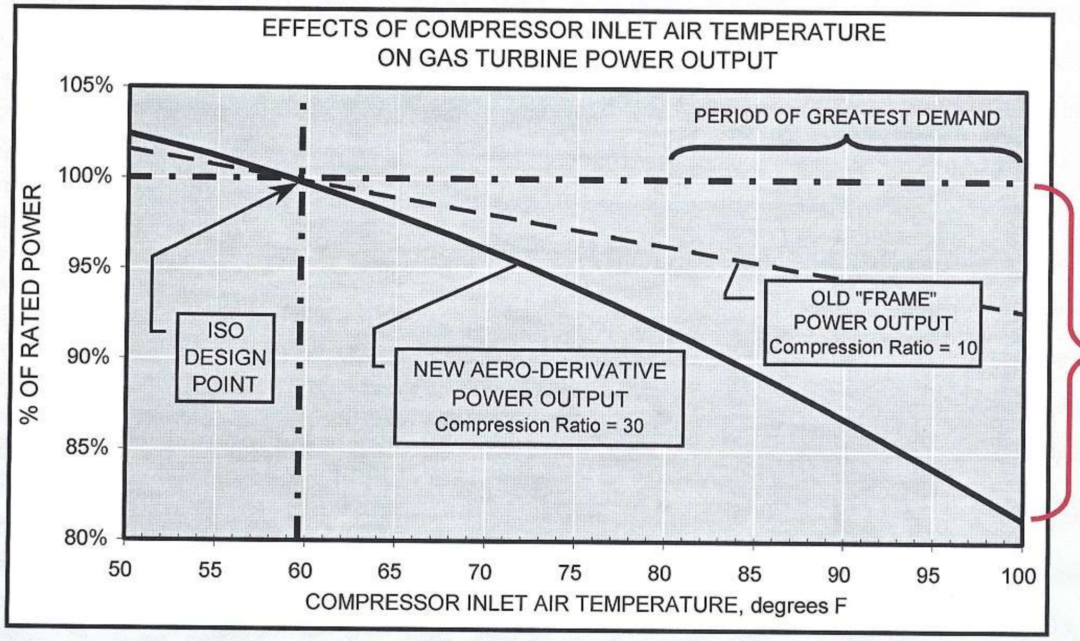
Benefits of Combined Cycle Systems

1. Most energy efficient option for generating electric energy
2. Minimum carbon emissions, per unit of electric energy, at site
3. Minimum fuel cost, per unit of electric energy
4. CC systems that supply to electric grids minimize grid-wide carbon emissions and thus, help decarbonize the grid

Hot Weather Decreases CT Output Capacity

1. High ambient temperatures decrease output capacity below its rated capacity

2. Quantitative impact of ambient temperature varies with CT design



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

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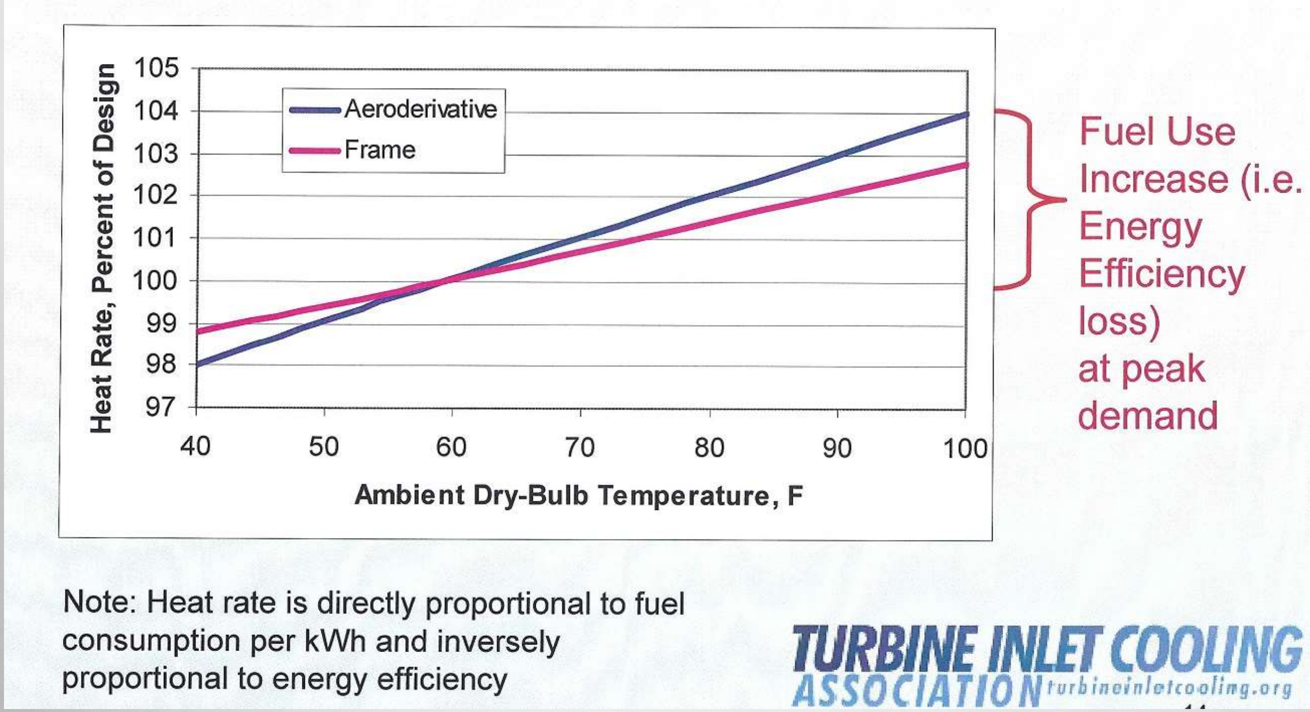
Hot Weather Reduces the Energy Efficiency of CTs

- Energy efficiency decreases (heat rate increases) below its rated efficiency
- Quantitative impact varies with the CT Design



Fuel Use Increase (i.e. Energy Efficiency loss) at peak demand

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

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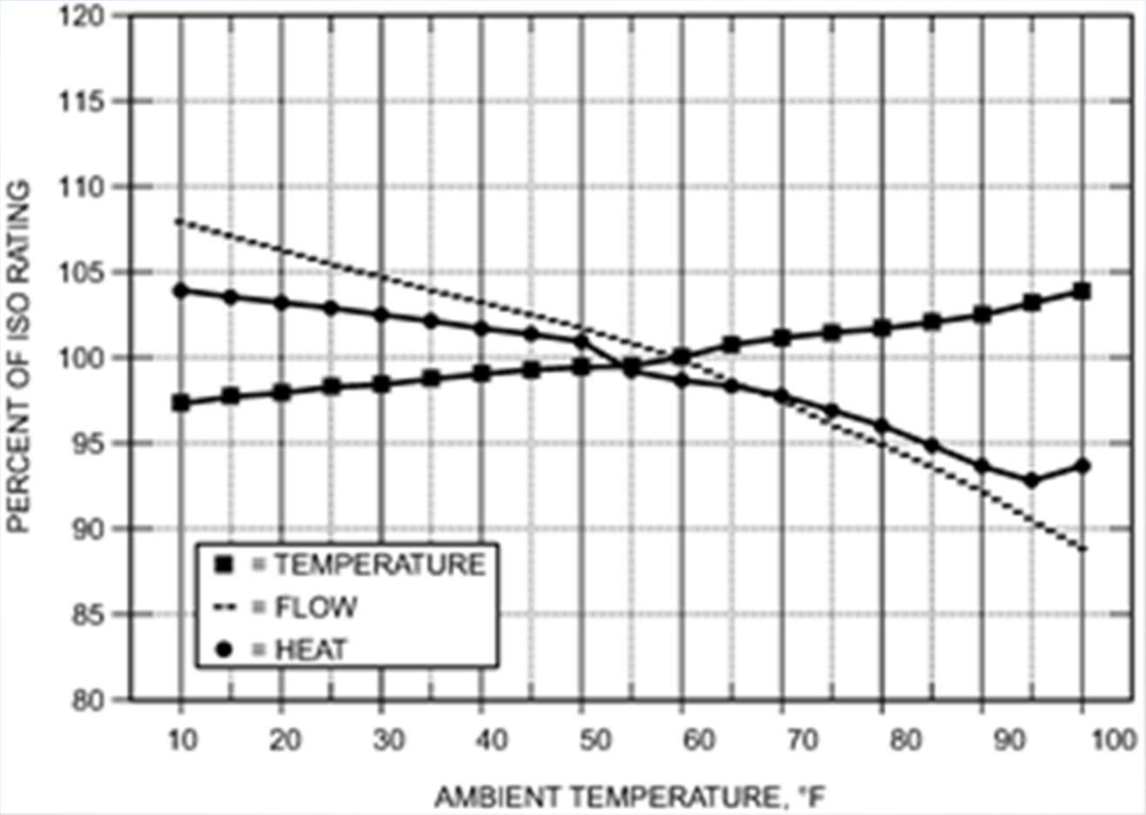
Hot Weather Decreases Availability of Useful Thermal Energy from CTs for CC



Source: ASHRAE Combined Heat and Power Design Guide (1996)

Effect of Hot Weather on CC Systems

1. **Decreases power output capacity**

    - Reduces revenue from the sale of electricity
    - Increases electric grid's need to order operation of less efficient and higher carbon emitting systems and thus, increases grid-wide carbon emissions

2. **Decreases electricity generation efficiency**

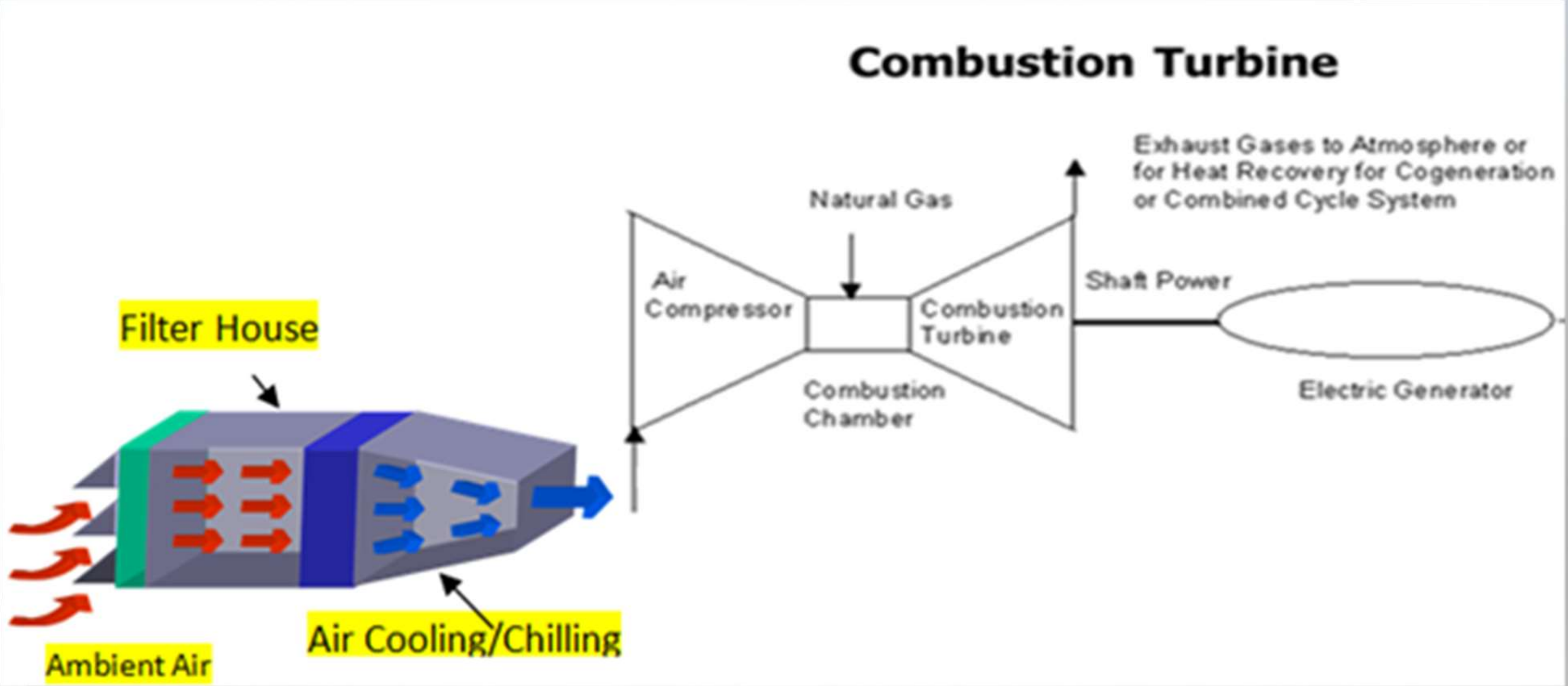
    - Increases the need to burn more fuel per unit of electric energy
    - Increases fuel cost per unit ot electric energy
    - Increases on-site carbon emissions, per unit of electric energy
    - Increases grid-wide carbon emissions, per unit of electric energy

Mitigate the Impacts of Hot Weather on CC Systems by Turbine Inlet Cooling

Since hot weather creates the problems, logical solution: Cool the turbine inlet air

Turbine Inlet Cooling (TIC)

Cools the inlet air to the compressor of the CT system



Turbine Inlet Cooling Technology Experience: ~50 Years

1. TIC is not a new technology
2. It has been successfully used since as early as 1975.
3. TICA's* limited database has over 400 installations, including about 80 CC systems
4. TICA database* show s TIC has been installed on at least 1,165 CTs of 125 models, from 21 OEMs
5. Capacities of the CT systems with TIC range from 1 MW to 3,162 MW*

Note:
*Turbine Inlet Cooling Association (TICA) Database (https://turbineinletcooling.org/data/ticadatap.pdf)
Actual number of TIC installations is in thousands

Turbine Inlet Cooling Technology Options

1. Adiabatic Wetted-Media Evaporative Cooling
2. Non-Adiabatic Wetted-Media Evaporative Cooling
3. Fogging for Evaporative Cooling
4. Indirect Evaporative Cooling
5. Wet Compression (Fog Overspray)
6. Indirect-Heat Exchange with Chilled Water
7. Thermal Energy Storage for Chilled Water Indirect-Heat Exchange
8. Indirect Heat Exchange with Refrigerant Evaporation
9. Indirect-Heat Exchange with Liquefied Natural Gas
10. Hybrid Cooling Systems

TIC Information Resources: www.turbineinlettcooling.org and ASHRAE Design Guide for Combustion Turbine Inlet Cooling (2022)

Factors Affecting Turbine Inlet Cooling Selection

1. Each TIC technology has its pros and cons.
2. No one technology is best for all power plants
3. Factors affecting technology selection include:
    * Value of the additional electricity by TIC
    * 8,760 hours/year of weather data for the plant location
    * Plant's annual operating schedule
    * CT design
    * Fuel cost
    * Capital cost limitation
    * Physical space limitation

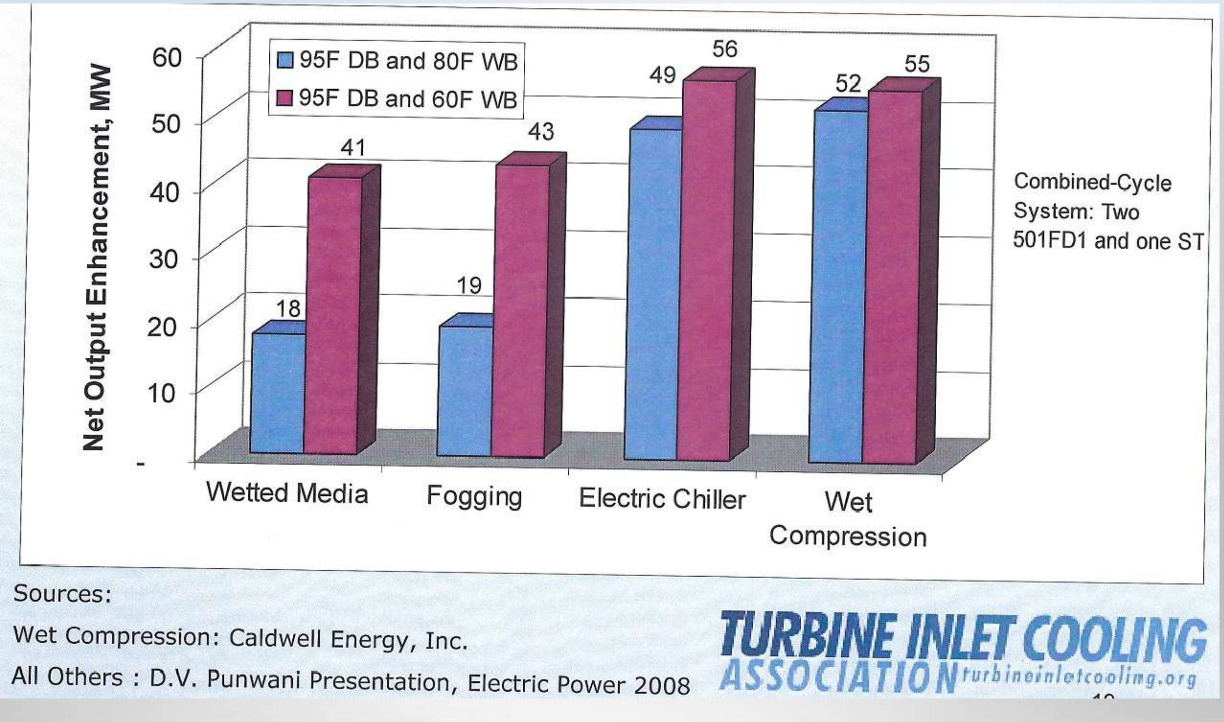
Turbine Inlet Cooling Benefits

Overall: Overcomes all the negative impacts of hot weather

1. Increased power output capacity and energy efficiency
2. Reduced on-site carbon emissions per unit of electric energy (lb/kWh)
3. Reduced grid-wide carbon emissions
4. Reduced unit capital cost ($/kW) for Increased capacity compared to a new uncooled CT
5. Reduced unit fuel cost ($/kWh) compared to an uncooled CT
6. Increases opportunity for higher revenues from electric energy sale

Effect of Technology and Humidity on Net Output Power Capacity Gain

Note: Each case study's results are only applicable to the SPECIFIC site evaluated and should not be generalized



Sources:

Wet Compression: Caldwell Energy, Inc.

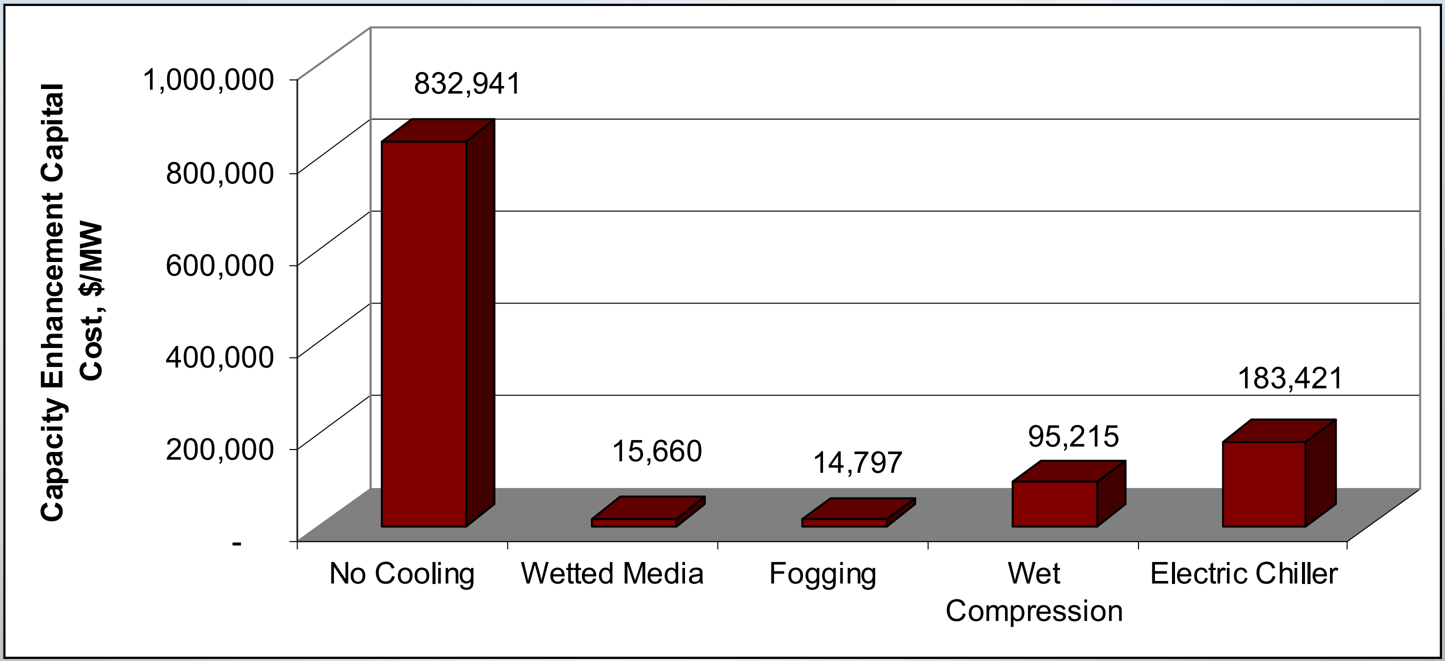
All Others : D.V. Punwani Presentation, Electric Power 2008

A Case Study Example

- Wetted media and fogging are more sensitive to humidity and produce less capacity gain at higher humidity

Effect of Technology on Unit Capital Cost ($/MW) for Net Output Power Capacity Gain

Note: Each case study's results are only applicable to the SPECIFIC site evaluated and should not be generalized

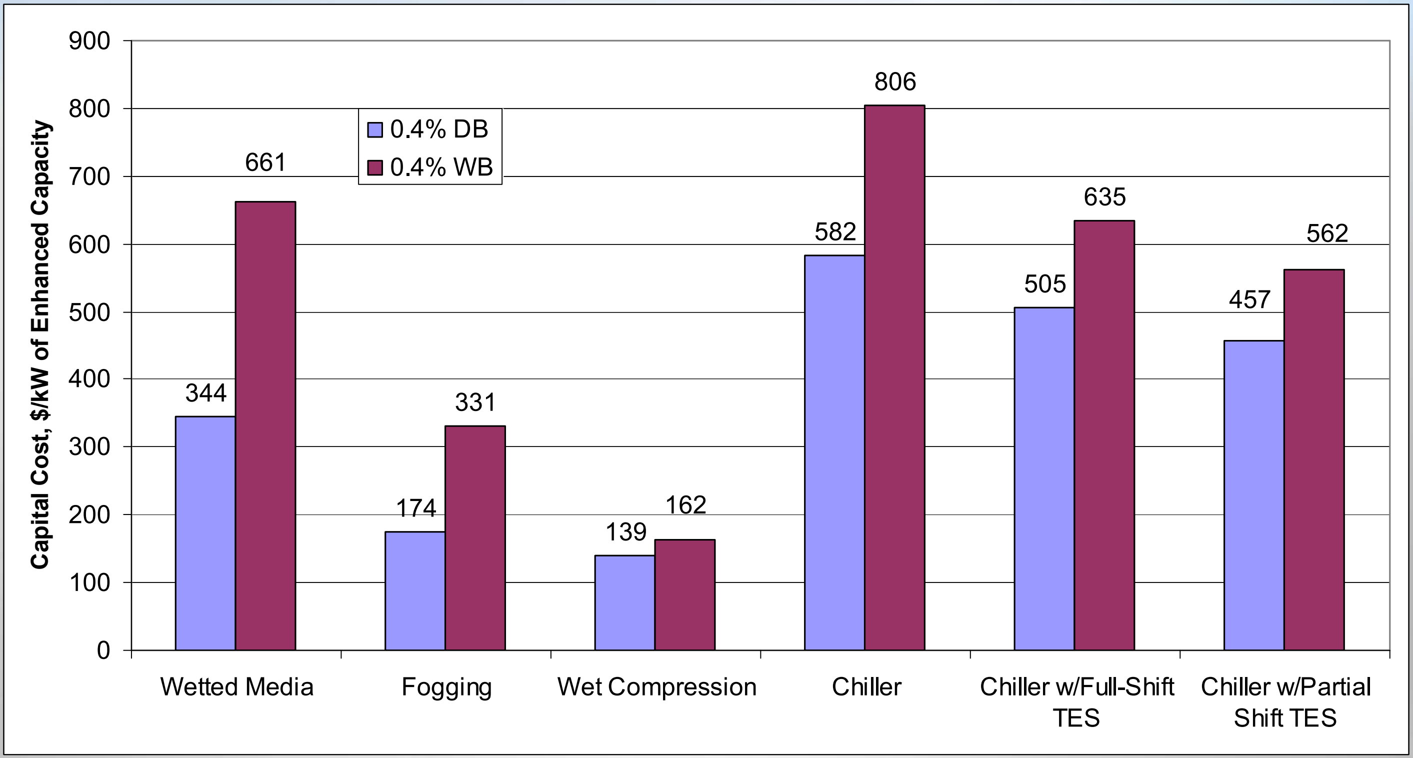


A Case Study Example

- Capacity gain by **all** TIC technologies costs significantly less than that for another uncooled CT.
- The unit capital cost is the lowest for the wetted-media and fogging

Effect of Technology on Unit Capital Cost for Capacity Gain ($/MW)

Note: Each case study's results are only applicable to the SPECIFIC site evaluated and should not be generalized

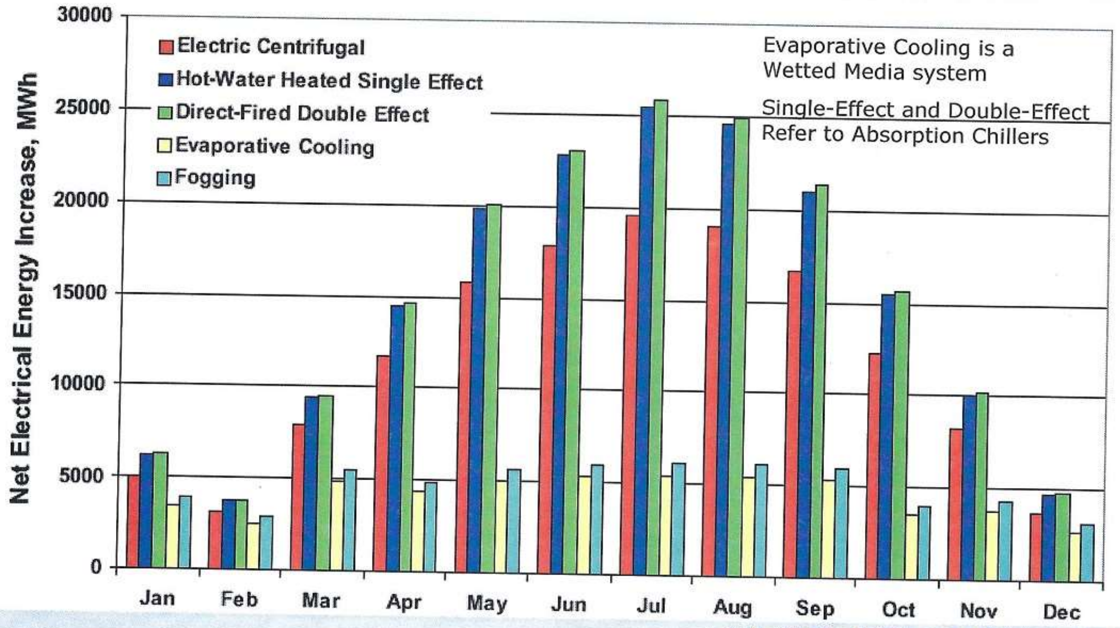


A Case Study Example

- The unit capital cost for all technologies is higher at higher humidity
- Thermal energy storage (TES) helps reduce unit capital cost for chilled water systems

Effect of Technology on
Monthly Net Incremental Electric Energy Generated

Note: Each case study's results are only applicable to the SPECIFIC site evaluated and should not be generalized



Evaporative Cooling is a Wetted Media system

Single-Effect and Double-Effect Refer to Absorption Chillers

Source: D.V. Punwani et. al. Presented at ASHARE 2001

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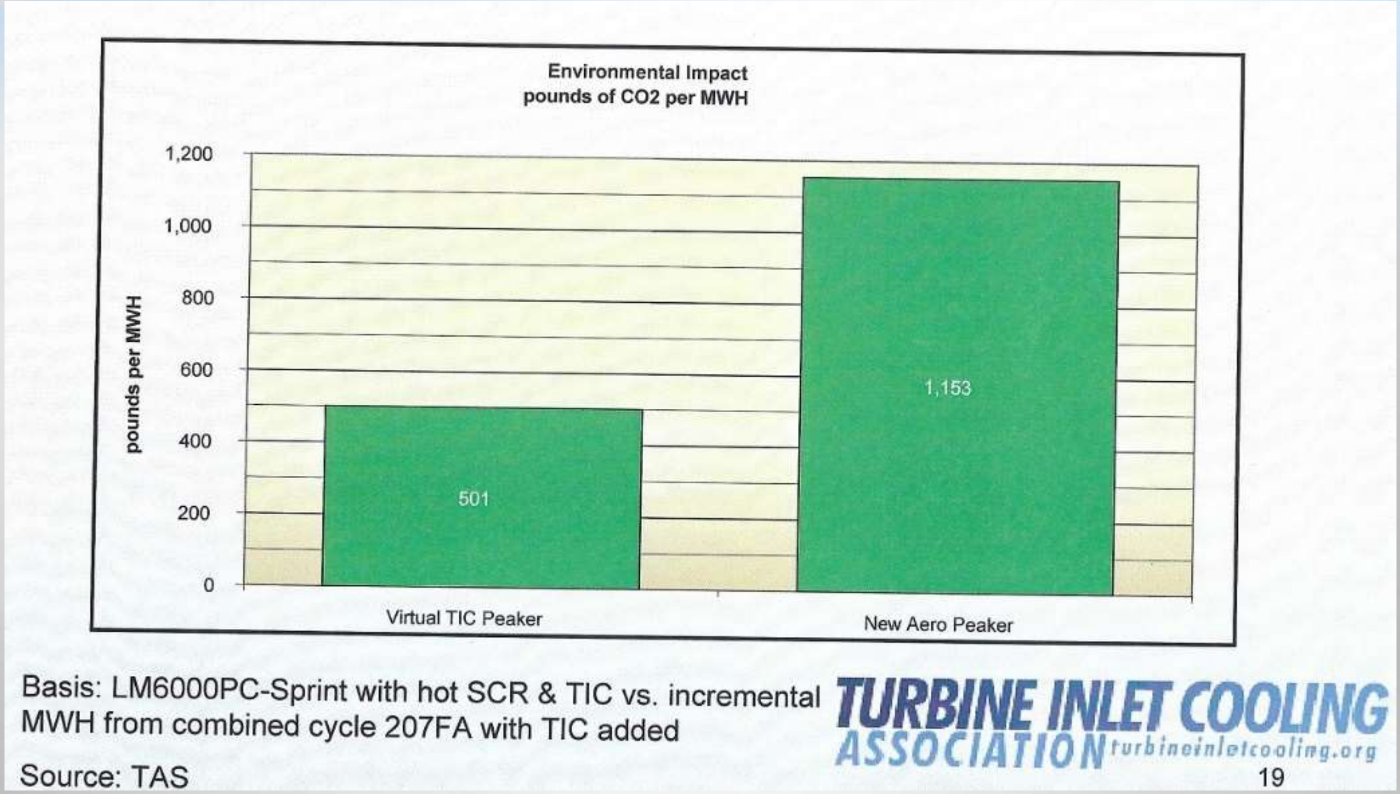
A Case Study Example

- TIC can produce gains through out the year
- The highest gains occur during the summer months

TIC of CCs Reduces Grid-wide Emissions of CO_2

TIC of a 500 MW CC increases its output by about 50 MW and emits 500 lb. CO_2 per MWh.



Basis: LM6000PC-Sprint with hot SCR & TIC vs. incremental MWH from combined cycle 207FA with TIC added

Source: TAS

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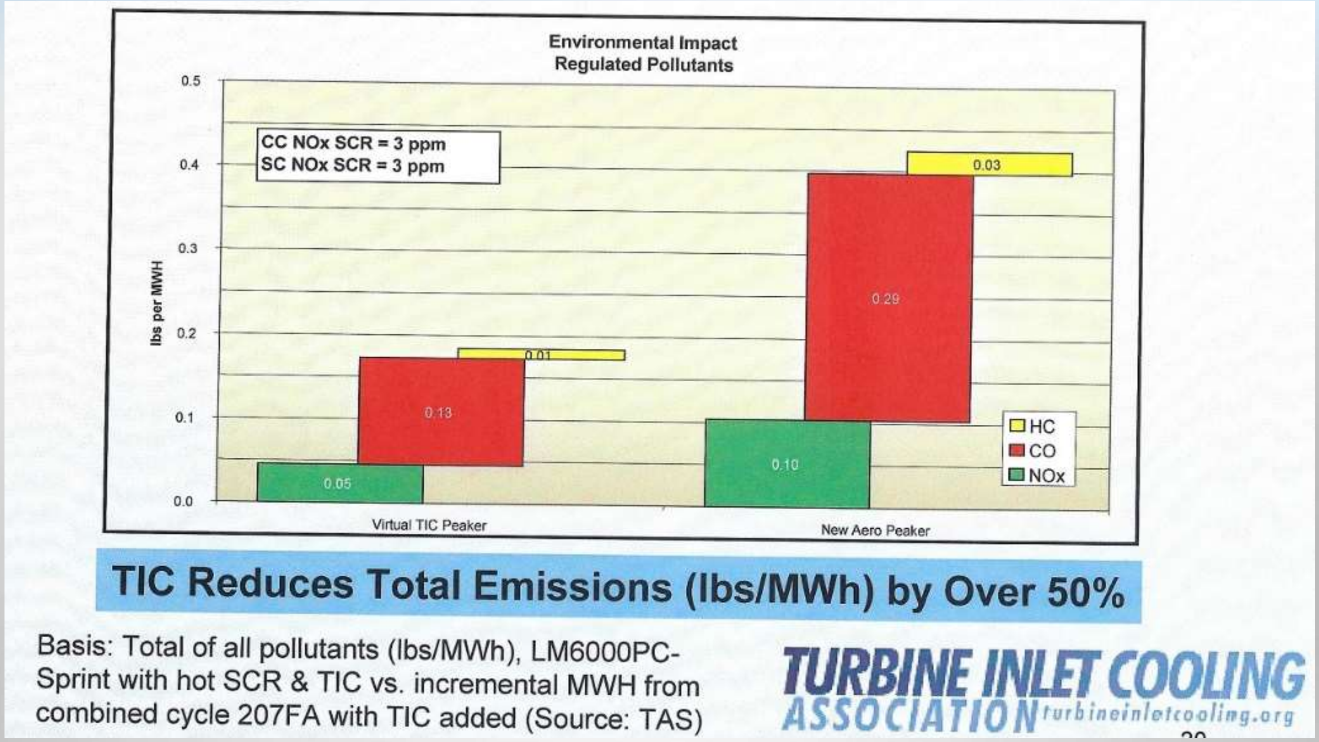
TIC of 500 MW CC eliminates grid's need to operate a 50 MW SC peaker that would have emitted over 1150 lb. CO_2/MWh.

TIC of a 500 MW CC helps reduce CO_2 emissions by over 600 lb/MWh or over 57% of that of a 50 MW SC Peaker

TIC of CCs also Reduces Grid-wide Emissions of CO, NO$_x$ and HC

TIC of a 500 MW CC increases its output by about 50 MW and emits only 0.13, 0.05 and 0.01 lb/MWh of CO, NO$_x$ and HC, respectively.



TIC Reduces Total Emissions (lbs/MWh) by Over 50%

Basis: Total of all pollutants (lbs/MWh), LM6000PC-Sprint with hot SCR & TIC vs. incremental MWH from combined cycle 207FA with TIC added (Source: TAS)

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TIC of 500 MW CC eliminates grid's need to operate a 50 MW SC peaker that would have emitted 0.2, 0.10 and 0.03 lb/MWh of CO, NO$_x$ and HC, respectively.

TIC of CCs helps reduce grid-wide emissions of CO, NO$_x$ and HC by 35%, 50% and 67%, respectively compared to a 50 MW SC Peaker.

Electric Grid Decarbonization Potential of TIC of Combined Cycle Systems in the Top 20 States in the U.S.

1. Total CC Generation Name plate Capacity: 183,881 MW*
2. Potential CC Generation Capacity Gain from TIC: 15,767 MW**
3. Average Annual Hours per State at Ambient Temperature above 59°F: 4,674 Hours
4. Avoided Annual Fuel Burned by preventing the need for SC Operation: 382,321,683 MMBtu/Yr
5. Reduced Annual Grid-wide CO_2 Emissions Reduced by Avoided SC Operations: >22 Million Tons
6. NOx Emission Reduced by Avoided SC Operations: 152,929 Tons

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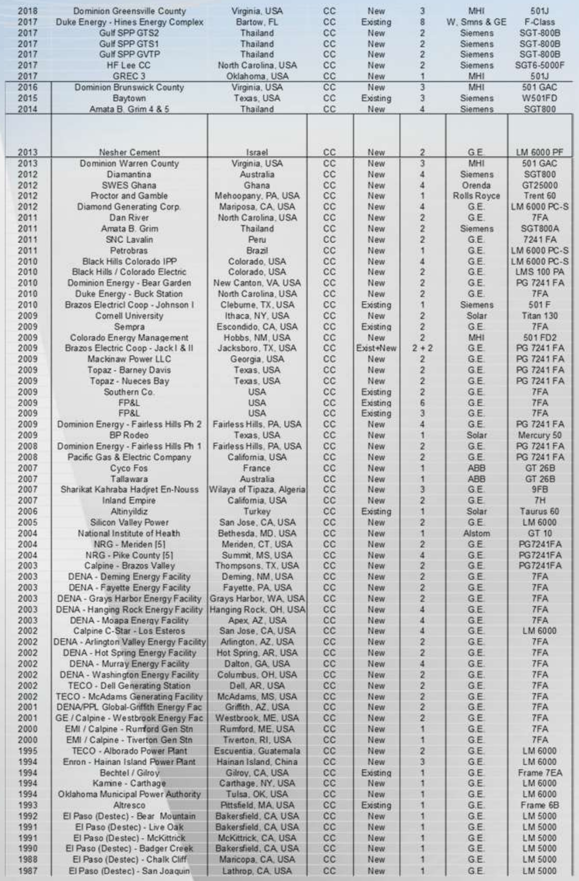
Source: * TICA Estimates Based on US Department of Energy's Energy Information Agency)

* * https://turbineinletcooling.org/News/Capacity&EmissionBenefits-2016Aug31.pdf

TICA Database* List of 77 CC Systems Using TIC



2018	Dominion Greensville County	Virginia, USA	CC	New	3	MHI	501J
2017	Duke Energy - Hines Energy Complex	Bartow, FL	CC	Existing	8	W, Smns & GE	F-Class
2017	Gulf SPP GTS2	Thailand	CC	New	2	Siemens	SGT-800B
2017	Gulf SPP GTS1	Thailand	CC	New	2	Siemens	SGT-800B
2017	Gulf SPP GVTP	Thailand	CC	New	2	Siemens	SGT-800B
2017	HF Lee CC	North Carolina, USA	CC	New	2	Siemens	SGT6-5000F
2017	GREC 3	Oklahoma, USA	CC	New	1	MHI	501J
2016	Dominion Brunswick County	Virginia, USA	CC	New	3	MHI	501 GAC
2015	Baytown	Texas, USA	CC	Existing	3	Siemens	W501FD
2014	Amata B. Grim 4 & 5	Thailand	CC	New	4	Siemens	SGT800
2013	Nesher Cement	Israel	CC	New	2	G.E.	LM 6000 PF
2013	Dominion Warren County	Virginia, USA	CC	New	3	MHI	501 GAC
2012	Diamantina	Australia	CC	New	4	Siemens	SGT800
2012	SWES Ghana	Ghana	CC	New	4	Orenda	GT25000
2012	Proctor and Gamble	Mehoopany, PA, USA	CC	New	1	Rolls Royce	Trent 60
2012	Diamond Generating Corp.	Mariposa, CA, USA	CC	New	4	G.E.	LM 6000 PC-S
2011	Dan River	North Carolina, USA	CC	New	2	G.E.	7FA
2011	Amata B. Grim	Thailand	CC	New	2	Siemens	SGT800A
2011	SNC Lavalin	Peru	CC	New	2	G.E.	7241 FA
2011	Petrobras	Brazil	CC	New	1	G.E.	LM 6000 PC-S
2010	Black Hills Colorado IPP	Colorado, USA	CC	New	4	G.E.	LM 6000 PC-S
2010	Black Hills / Colorado Electric	Colorado, USA	CC	New	2	G.E.	LMS 100 PA
2010	Dominion Energy - Bear Garden	New Canton, VA, USA	CC	New	2	G.E.	PG 7241 FA
2010	Duke Energy - Buck Station	North Carolina, USA	CC	New	2	G.E.	7FA
2010	Brazos Electricl Coop - Johnson I	Cleburne, TX, USA	CC	Existing	1	Siemens	501 F
2009	Cornell University	Ithaca, NY, USA	CC	New	2	Solar	Titan 130
2009	Sempra	Escondido, CA, USA	CC	Existing	2	G.E.	7FA
2009	Colorado Energy Management	Hobbs, NM, USA	CC	New	2	MHI	501 FD2
2009	Brazos Electric Coop - Jack I & II	Jacksboro, TX, USA	CC	Exist+New	2 + 2	G.E.	PG 7241 FA
2009	Mackinaw Power LLC	Georgia, USA	CC	New	2	G.E.	PG 7241 FA
2009	Topaz - Barney Davis	Texas, USA	CC	New	2	G.E.	PG 7241 FA
2009	Topaz - Nueces Bay	Texas, USA	CC	New	2	G.E.	PG 7241 FA
2009	Southern Co.	USA	CC	Existing	2	G.E.	7FA
2009	FP&L	USA	CC	Existing	6	G.E.	7FA
2009	FP&L	USA	CC	Existing	3	G.E.	7FA
2009	Dominion Energy - Fairless Hills Ph 2	Fairless Hills, PA, USA	CC	New	4	G.E.	PG 7241 FA
2009	BP Rodeo	Texas, USA	CC	New	1	Solar	Mercury 50
2008	Dominion Energy - Fairless Hills Ph 1	Fairless Hills, PA, USA	CC	New	2	G.E.	PG 7241 FA
2008	Pacific Gas & Electric Company	California, USA	CC	New	2	G.E.	PG 7241 FA
2007	Cyco Fos	France	CC	New	1	ABB	GT 26B
2007	Tallawara	Australia	CC	New	1	ABB	GT 26B
2007	Sharikat Kahraba Hadjret En-Nouss	Wilaya of Tipaza, Algeria	CC	New	3	G.E.	9FB
2007	Inland Empire	California, USA	CC	New	2	G.E.	7H
2006	Altinyildiz	Turkey	CC	Existing	1	Solar	Taurus 60
2005	Silicon Valley Power	San Jose, CA, USA	CC	New	2	G.E.	LM 6000
2004	National Institute of Health	Bethesda, MD, USA	CC	New	1	Alstom	GT 10
2004	NRG - Meriden [5]	Meriden, CT, USA	CC	New	2	G.E.	PG7241FA
2004	NRG - Pike County [5]	Summit, MS, USA	CC	New	4	G.E.	PG7241FA
2003	Calpine - Brazos Valley	Thompsons, TX, USA	CC	New	2	G.E.	PG7241FA
2003	DENA - Deming Energy Facility	Deming, NM, USA	CC	New	2	G.E.	7FA
2003	DENA - Fayette Energy Facility	Fayette, PA, USA	CC	New	2	G.E.	7FA
2003	DENA - Grays Harbor Energy Facility	Grays Harbor, WA, USA	CC	New	2	G.E.	7FA
2003	DENA - Hanging Rock Energy Facility	Hanging Rock, OH, USA	CC	New	4	G.E.	7FA
2003	DENA - Moapa Energy Facility	Apex, AZ, USA	CC	New	4	G.E.	7FA
2002	Calpine C-Star - Los Esteros	San Jose, CA, USA	CC	New	4	G.E.	LM 6000
2002	DENA - Arlington Valley Energy Facility	Arlington, AZ, USA	CC	New	2	G.E.	7FA
2002	DENA - Hot Spring Energy Facility	Hot Spring, AR, USA	CC	New	2	G.E.	7FA
2002	DENA - Murray Energy Facility	Dalton, GA, USA	CC	New	4	G.E.	7FA
2002	DENA - Washington Energy Facility	Columbus, OH, USA	CC	New	2	G.E.	7FA
2002	TECO - Dell Generating Station	Dell, AR, USA	CC	New	2	G.E.	7FA
2002	TECO - McAdams Generating Facility	McAdams, MS, USA	CC	New	2	G.E.	7FA
2001	DENA/PPL Global-Griffith Energy Fac	Griffith, AZ, USA	CC	New	2	G.E.	7FA
2001	GE / Calpine - Westbrook Energy Fac	Westbrook, ME, USA	CC	New	2	G.E.	7FA
2000	EMI / Calpine - Rumford Gen Stn	Rumford, ME, USA	CC	New	1	G.E.	7FA
2000	EMI / Calpine - Tiverton Gen Stn	Tiverton, RI, USA	CC	New	1	G.E.	7FA
1995	TECO - Alborado Power Plant	Escuentia, Guatemala	CC	New	2	G.E.	LM 6000
1994	Enron - Hainan Island Power Plant	Hainan Island, China	CC	New	3	G.E.	LM 6000
1994	Bechtel / Gilroy	Gilroy, CA, USA	CC	Existing	1	G.E.	Frame 7EA
1994	Kamine - Carthage	Carthage, NY, USA	CC	New	1	G.E.	LM 6000
1994	Oklahoma Municipal Power Authority	Tulsa, OK, USA	CC	New	1	G.E.	LM 6000
1993	Altresco	Pittsfield, MA, USA	CC	Existing	1	G.E.	Frame 6B
1992	El Paso (Destec) - Bear Mountain	Bakersfield, CA, USA	CC	New	1	G.E.	LM 5000
1991	El Paso (Destec) - Live Oak	Bakersfield, CA, USA	CC	New	1	G.E.	LM 5000
1991	El Paso (Destec) - McKittrick	McKittrick, CA, USA	CC	New	1	G.E.	LM 5000
1990	El Paso (Destec) - Badger Creek	Bakersfield, CA, USA	CC	New	1	G.E.	LM 5000
1988	El Paso (Destec) - Chalk Cliff	Maricopa, CA, USA	CC	New	1	G.E.	LM 5000
1987	El Paso (Destec) - San Joaquin	Lathrop, CA, USA	CC	New	1	G.E.	LM 5000

Selected Highlights of CC Systems Using TIC

1. First CC system in the US: El Paso (Destec) in 1987
2. Number of Dominion systems since 2008: Six
3. Number of Calpine systems since 2001: Five
4. Total Nameplate Capacity of Dominion and Calpine CC Systems with TIC: 7,633 MW
5. Total Nameplate Capacity of TICA Database of CC: 29,490 MW

* TICA Database (https://turbineinletcooling.org/data/ticadatap.pdf). Actual number is much higher

Conclusions

Turbine inlet cooling is a pathway for maximizing the economic performance and the electric grid decarbonization potentials of combined cycle (CC) systems during hot weather because, it

1. Increases revenues of the CC owners selling electric energy to the grid
2. Decreases cost of buying electric energy from the grid for CC owners using power at site
3. Decreases grid-wide carbon emission by preventing grid's need to operate lower efficiency and higher carbon emitting systems
4. Decreases fuel cost at the plant site
5. Decreases carbon emissions at the plant site

TIC has an extensive experience base of CC systems at least since 1987.

Recommendations

1. More CC system owners/operators should consider evaluation and implementation of turbine inlet cooling
2. Consider joining TICA. Membership of all gas turbine users is complimentary
3. Use the following source of information about turbine inlet cooling:

- TICA website as a one-stop source of turbine inlet cooling information for all technologies
- ASHRAE Design Guide for Combustion Turbine Inlet Cooling (Published in 2022), jointly funded by ASHRAE and TICA
- TICA LinkedIn Page

2024 TICA Awardee for Combined Cycle System: Nebras Power IPPI/Jordan PSC

2024 Excellence Award

for outstanding implementation of

Fogging System

for Turbine Inlet Cooling

Presented to

Nebras Power IPP1/Jordan

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An Energy Solution that's good for the Environment, Rate Payers and Plant Owners

Combined Cycle System Case Study
Nebras Power IPPI/Jordan PSC

1. **System:** 2 x 140 MW AE94.2 Ansaldo Gas Turbines
2. **Name Plate Capacity**: 480 MW
3. **TIC Technology:** Fogging Installed in 2013
4. **TIC Benefits:**
   - Increase Capacity by 25-35 MW
   - Decreased Heat Rate: 28,400 Btu/MWh
   - Reduced NOx: 10 ppm
   - Simple Payback Period: 2 Years
   - Internal Rate of Return (IRR): 105% (at Discount Rate of 12%)

Contact Information

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- LinkedIn: https://www.linkedin.com/company/turbine-inlet-cooling-association
- TICA Membership is complimentary to all gas turbine users