LEADING THE WAY
CampusEnergy2022

Feb. 15-18 | Westin Boston Seaport District Hotel | Boston, Mass.

INTERNATIONAL DISTRICT ENERGY ASSOCIATION

BLACKSTONE COMBUSTION TURBINE INLET COOLING RETROFIT

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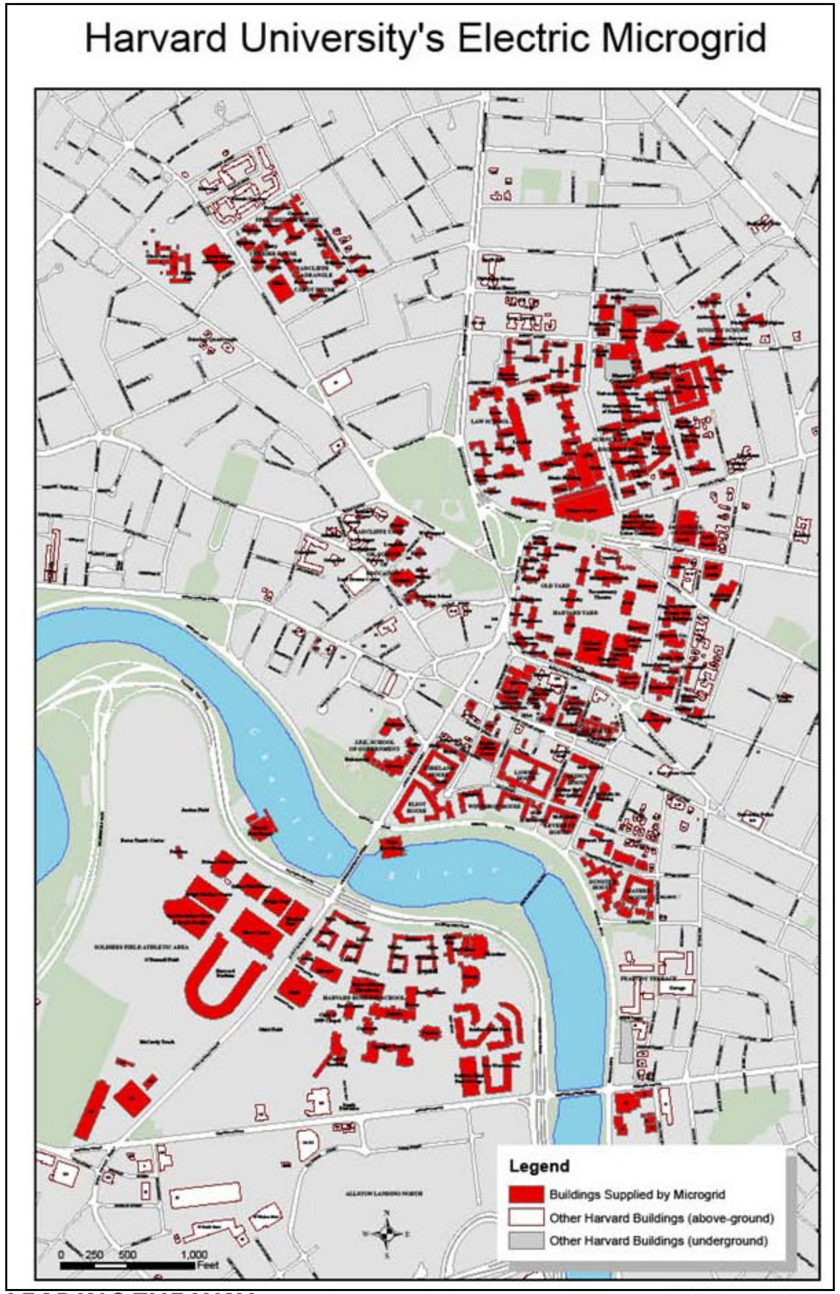
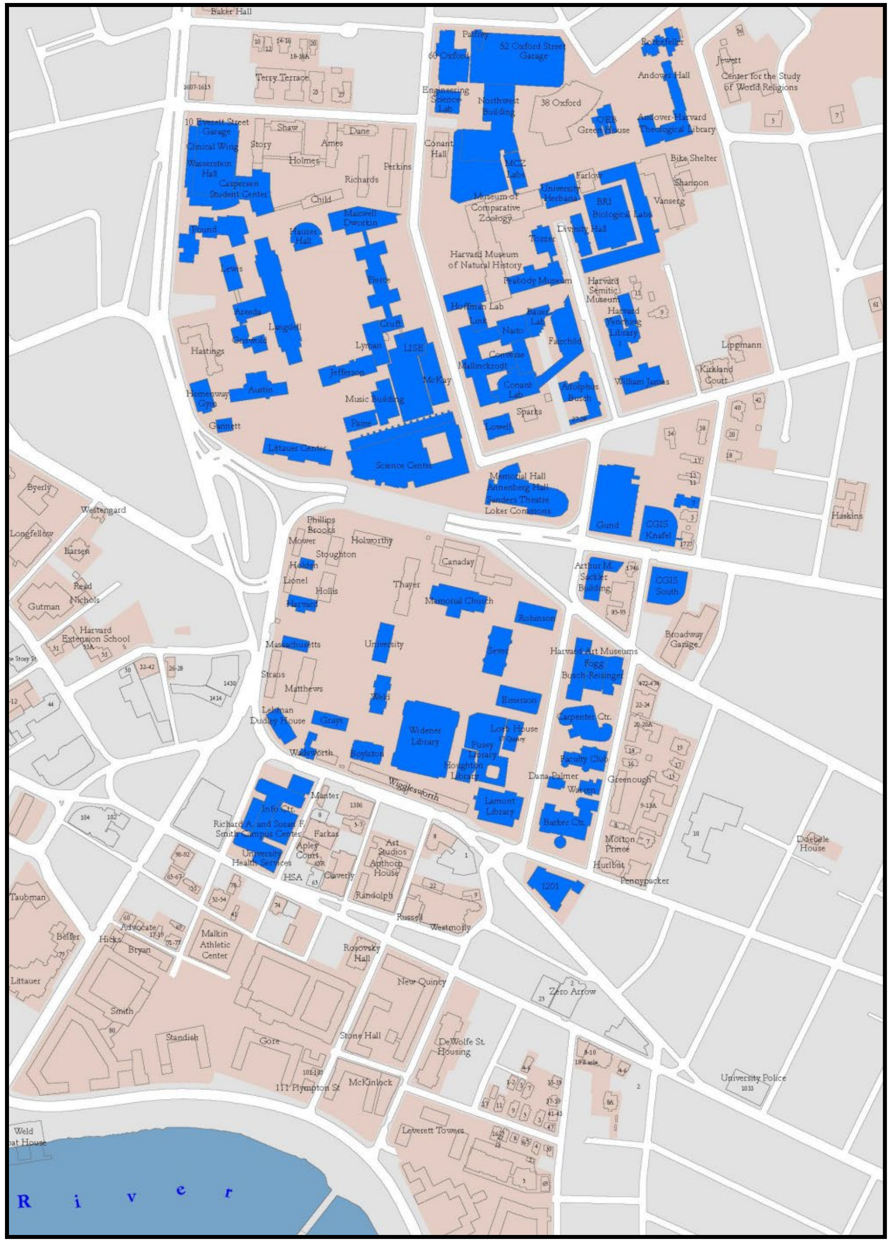


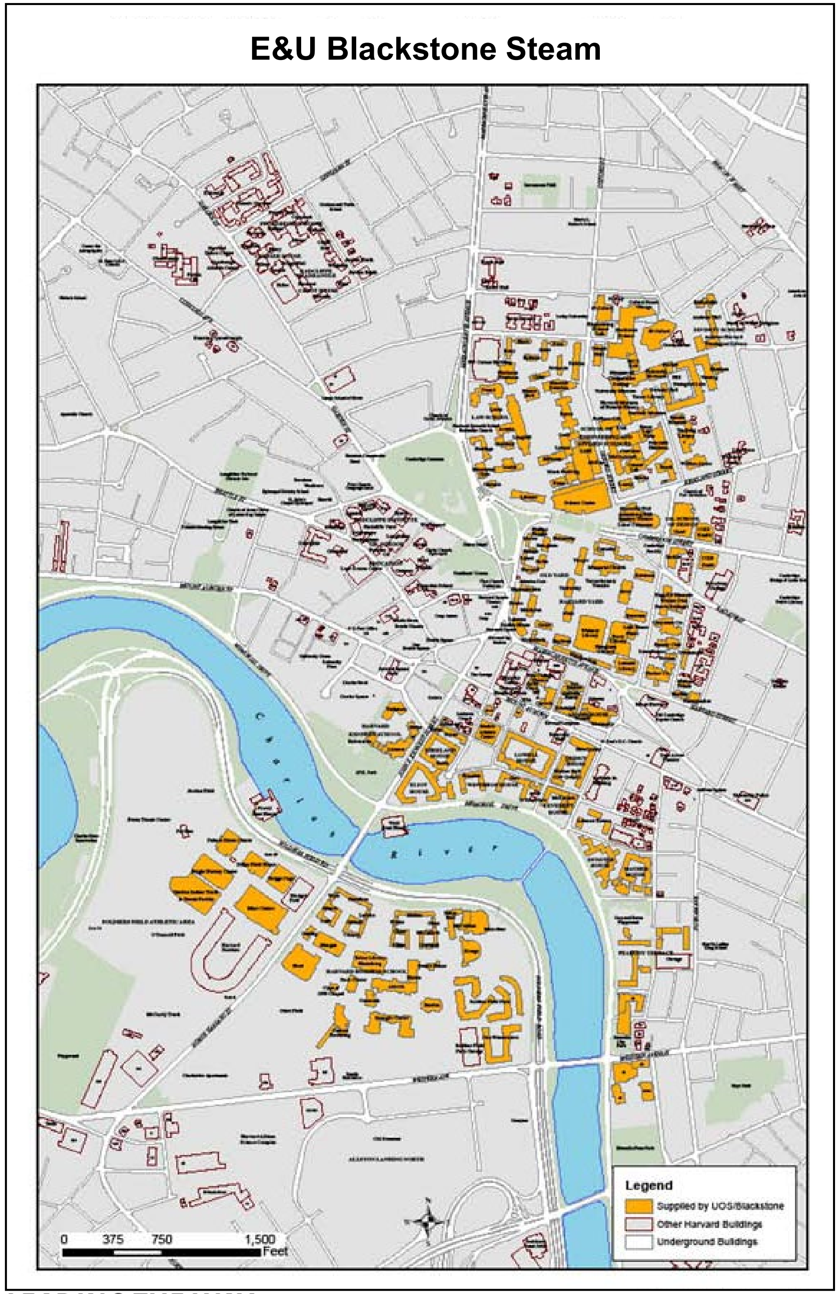
Electric Distribution

- Provides electricity through Harvard-owned microgrid
- 180 buildings served in Cambridge/Allston
- Utility delivers at seven separate Harvard switching locations
- Each Harvard station supplies a different area of the campus
- Delivery from stations via underground duct and manhole system
- Over 50 circuit-miles though 300 manholes



Chilled Water Service

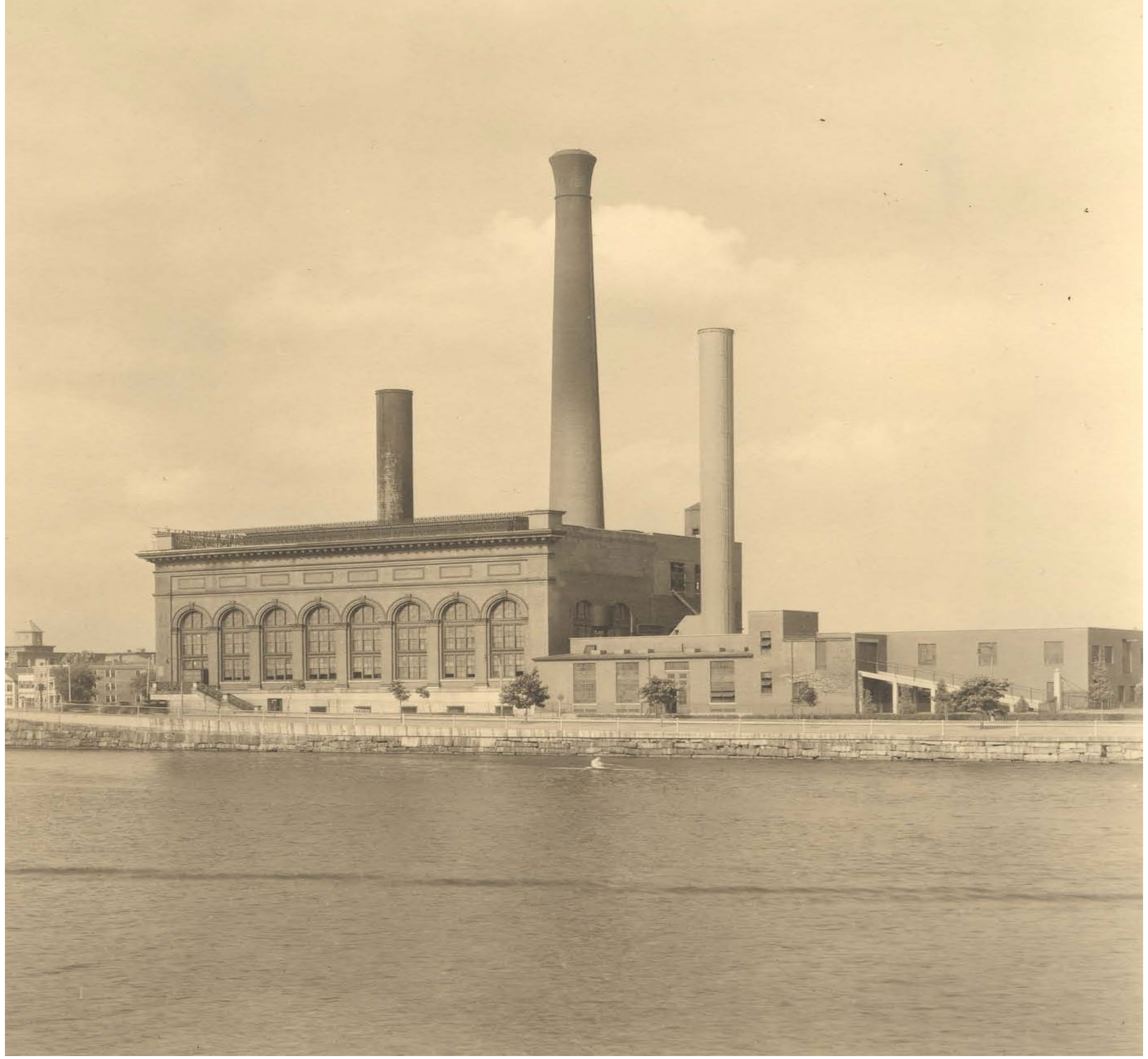
- Provides chilled water for space cooling, and process (equipment) cooling
- 77 buildings served in Cambridge/Allston
- Two below grade production plants
  - Science Center
  - Northwest Labs
- 19,000 Tons production capacity
  - Seven chillers (2,000 to 5,000 Tons)
  - All electric
- Common distribution network
  - Two plants feed common distribution
  - ~3 ½ miles direct buried supply and return piping



Steam Service

- Provides thermal energy for space heat, domestic hot water, and high pressure processes
- 170 buildings served in Cambridge/Allston
- One steam production plant, Blackstone
- 7.5 MW gas turbine/HRSG with 5 MW backpressure steam turbine for combined cycle CHP configuration
- Three direct-fired boilers with supply to steam turbine
- Multiple line distribution backbone through 2-1/2 miles of walkable tunnel

Blackstone Steam Plant, Utility Operation



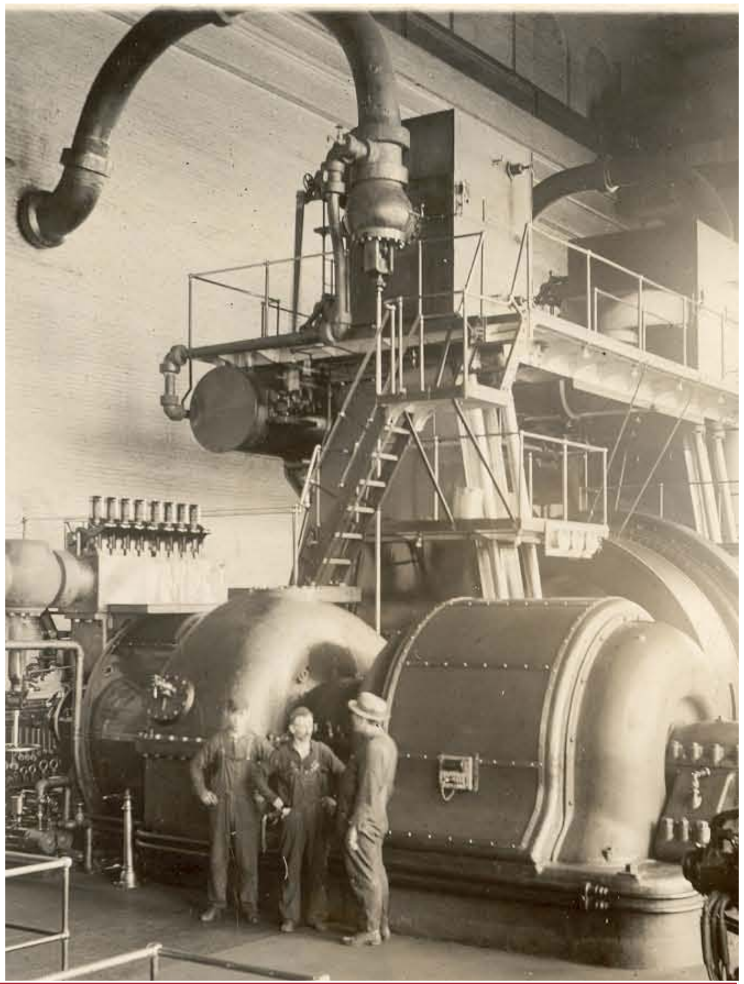
1909 – Operation by Cambridge Electric Light Co.

1930 – Modernization project adds two boilers and replaces reciprocating steam engines with steam turbines. Initiates steam supply service to Harvard campus.

1962 – Two boilers added for additional steam production capacity.

1962 Onward–Operation continues with progressively diminished capability, efficiency and reliability.

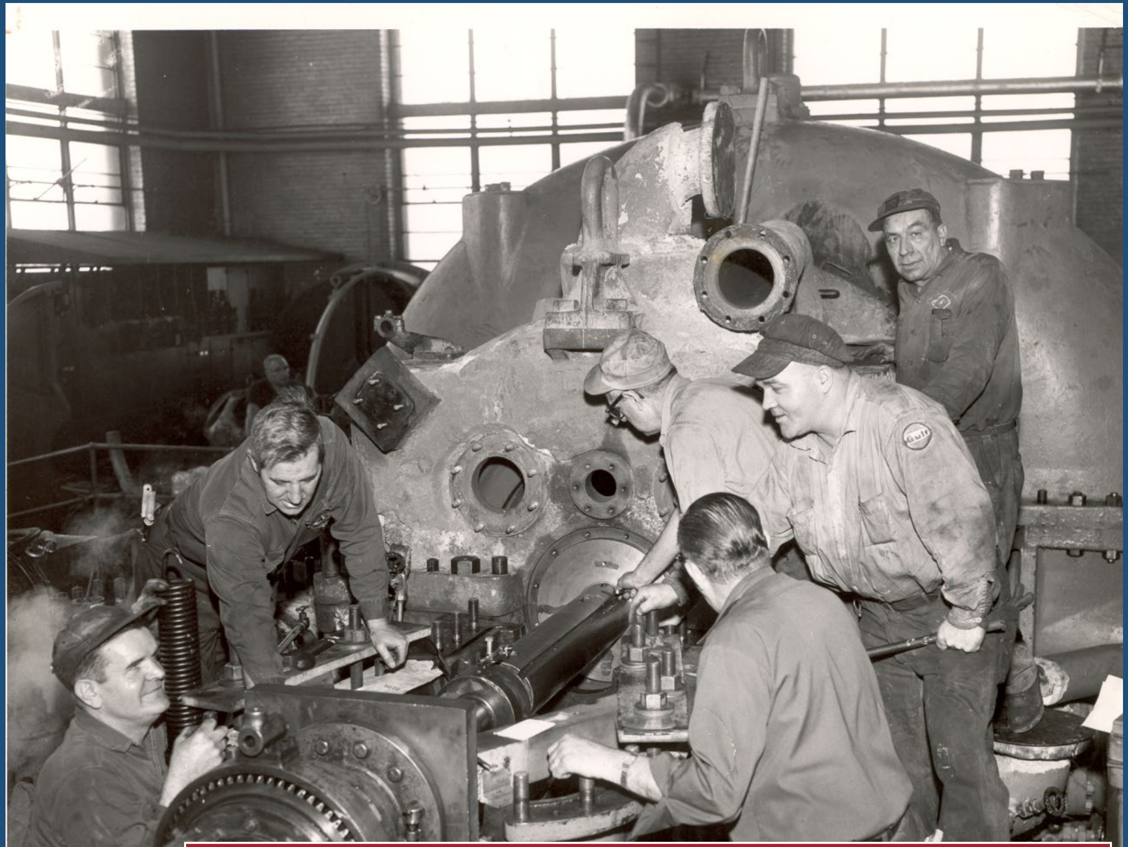
Blackstone Steam Plant, Utility Operation



Reciprocating Engine-Generator

1930 Plant Modernization

Blackstone Steam Plant, Utility Operation



1960s Turbine Maintenance

2003 Retired Steam Turbine

Blackstone Steam Plant, Harvard Operation

<u>2004</u> – Acquired by Harvard to ensure security of campus steam supply.

<u>2004 - Steam Plant Upgrade Project</u>

- New boiler and 5 MW backpressure steam turbine for CHP capability.
- Replaced major BOP systems.
- Replaced plant electrical distribution.
- Critical structural repairs.

<u>2014 - CHP Expansion Project</u>

- 7.5 MW gas turbine and HRSG for combined cycle CHP operation
- Associated BOP additions and upgrades

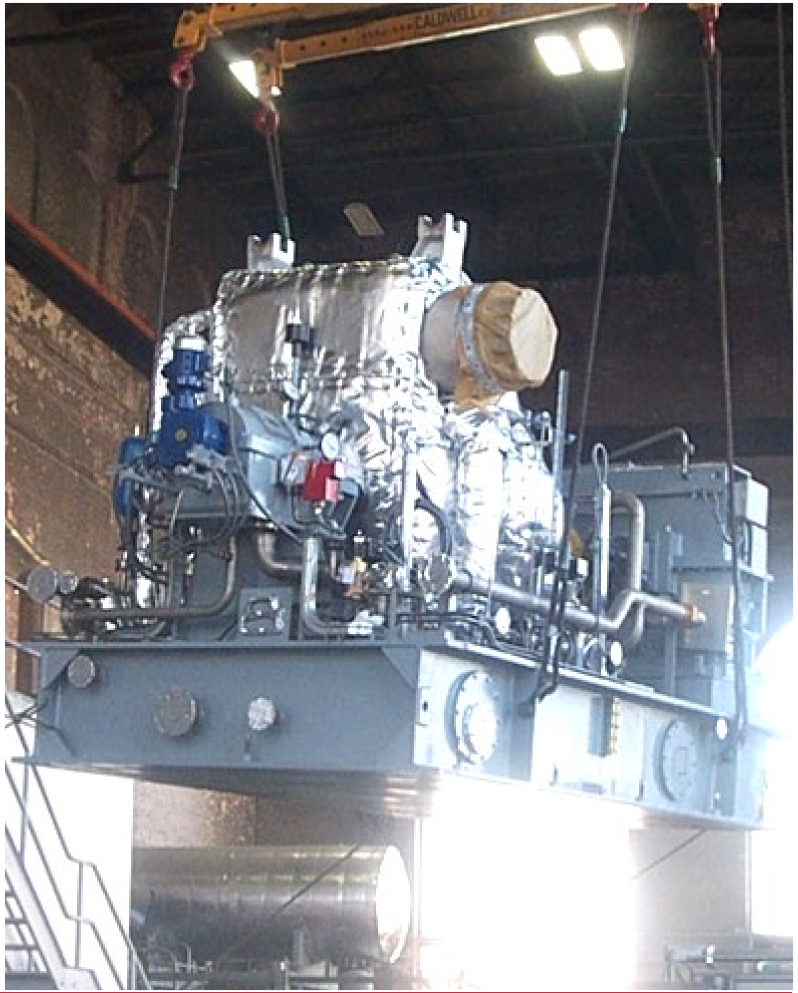
Blackstone Steam Plant, Harvard Operation

Rigging In Boiler Economizer

Boiler Field Assembly

Blackstone Steam Plant, Harvard Operation

Steam Turbine Pedestal Steel



Steam Turbine Rigged to Pedestal

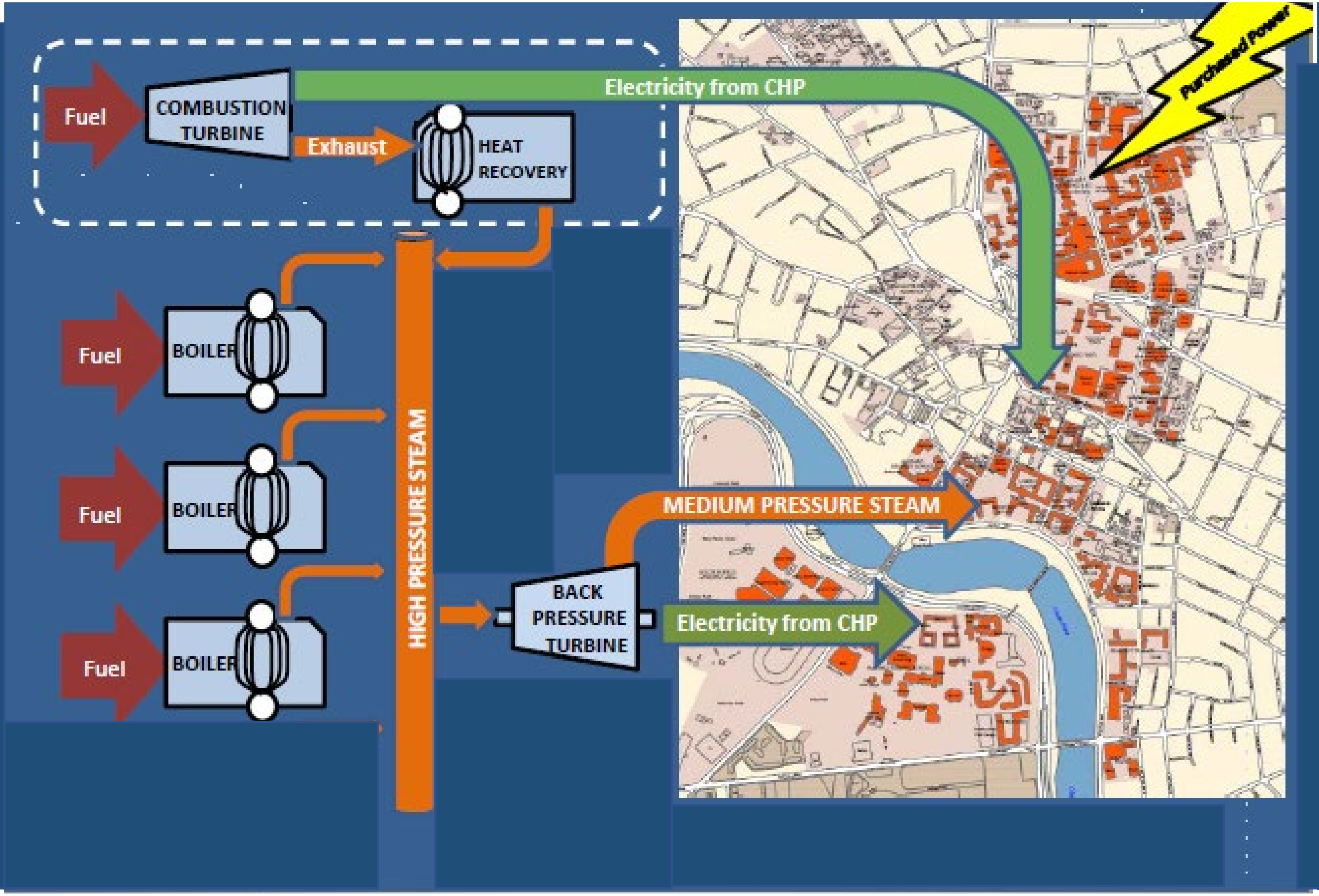
Blackstone Steam Plant, Harvard Operation

Taurus 70 Gas Turbine Rigged Into Turbine Hall

Blackstone Steam Plant, Harvard Operation

HRSG Delivered to Blackstone Street

Blackstone Steam Plant, CHP/Combined Cycle

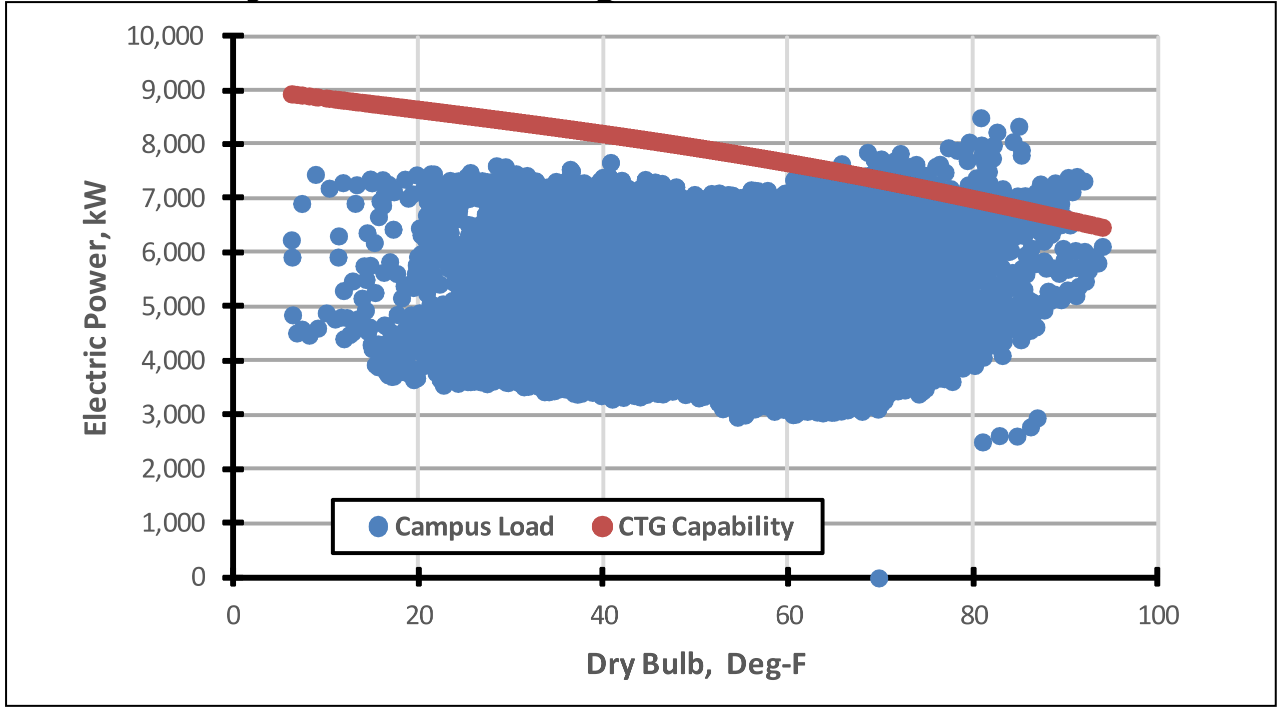


Current Blackstone Operation

- ✓ Combined cycle/combined heat and power
- ✓ Up to 84% overall production efficiency
- ✓ Increased campus energy supply reliability
- ✓ Improved environmental performance
- ✓ Positive economic performance

What could be better?

CTG Capability and Campus Load vs. Dry Bulb Temperature



Room for Improvement

- Increased campus electrical load during warm weather
- CTG capability decreased by as much as 20% from 7.5 MW nominal rating as ambient temperature increases
- Increased need for costly import power characterized by decreased reliability

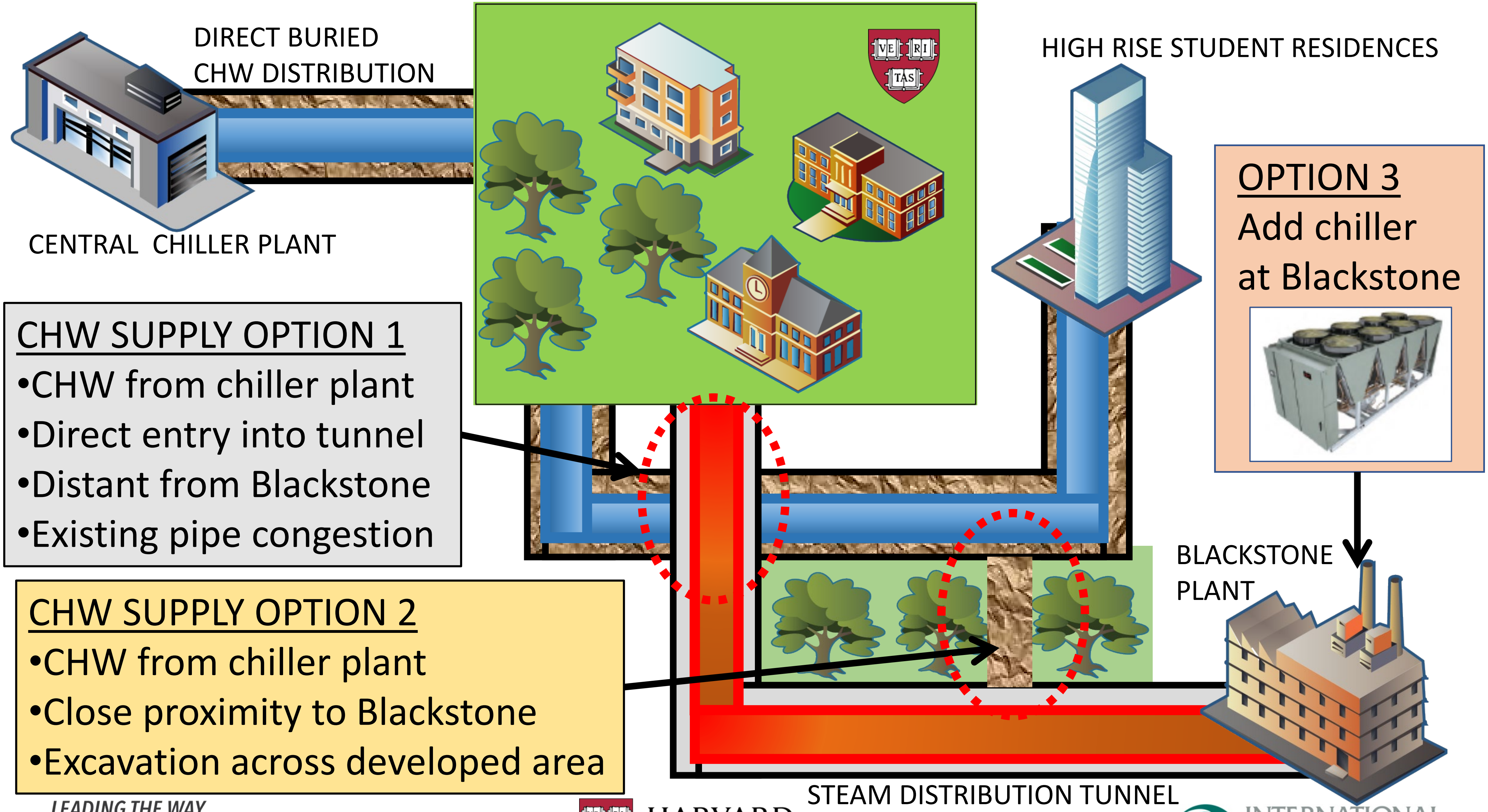
Potential Solution

- Gas turbine inlet cooling

Inlet Cooling Options

- Evaporative Cooling
  - \+ Low initial cost
  - − Cooling capability limited to within 1 to 2 degrees of wet bulb

- Chilled Water Cooling
  - Extensively utilized, well proven technology
  - Inlet air cooling to within the 45 to 50 deg-F range
  - Existing campus chilled water production and distribution infrastructure
  - CHW distribution nearby Blackstone steam distribution tunnel
  - Original CTG project design provision for future inlet air cooling
  - Ability to install indoors precludes Blackstone building structural and aesthetic concerns


DIRECT BURIED
CHW DISTRIBUTION
CENTRAL CHILLER PLANT
HIGH RISE STUDENT RESIDENCES
OPTION 3
Add chiller
at Blackstone
CHW SUPPLY OPTION 1
•CHW from chiller plant
•Direct entry into tunnel
•Distant from Blackstone
•Existing pipe congestion
CHW SUPPLY OPTION 2
•CHW from chiller plant
•Close proximity to Blackstone
•Excavation across developed area
BLACKSTONE
PLANT
STEAM DISTRIBUTION TUNNEL

Blackstone Inlet Cooling Dispatch Modeling

	No Inlet Cooling	Central CHW	Blackstone Chiller
Gross Power (kWh)	Base	696,203	696,203
Net Power (kWh)	Base	568,103	542,531
Steam Production (Lb)	Base	142,675	142,675
Steam Vented (Lb)	Base	398,032	398,032
Electric Demand (kW)	Base	-813	-719
Electric Purchased (kWh)	Base	-174,470	-148,898
Electric Sold (kWh)	Base	393,632	393,632
Chilled Water Use (Ton-Hrs)	Base	144,146	142,122
Heat Input (MMBtu)	Base	5,371	5,371

Hourly Dispatch Basis

- Dispatch for steam production
- Coil design at 90.6 F DB/ 72.7 F WB
- Air leaving coil = 59 F
- Coil operates when Tamb >/= 75 F
- 30 kW loss for coil delta-P
- 18 kW for Option 3 circ pump

Blackstone Inlet Cooling Economic Review

	Annual Saving	Payback (Yrs)
Without Additional Load		
Central Plant, Long Pipe Run	$92,000	28.6
Central Plant, Short Pipe Run	$92,000	20.8
Blackstone Chiller	$78,000	20.6
With Central Plant Chiller Load Added		
Central Plant, Long Pipe Run	$138,000	19.5
Central Plant, Short Pipe Run	$138,000	14.2
Blackstone Chiller	$120,000	13.1

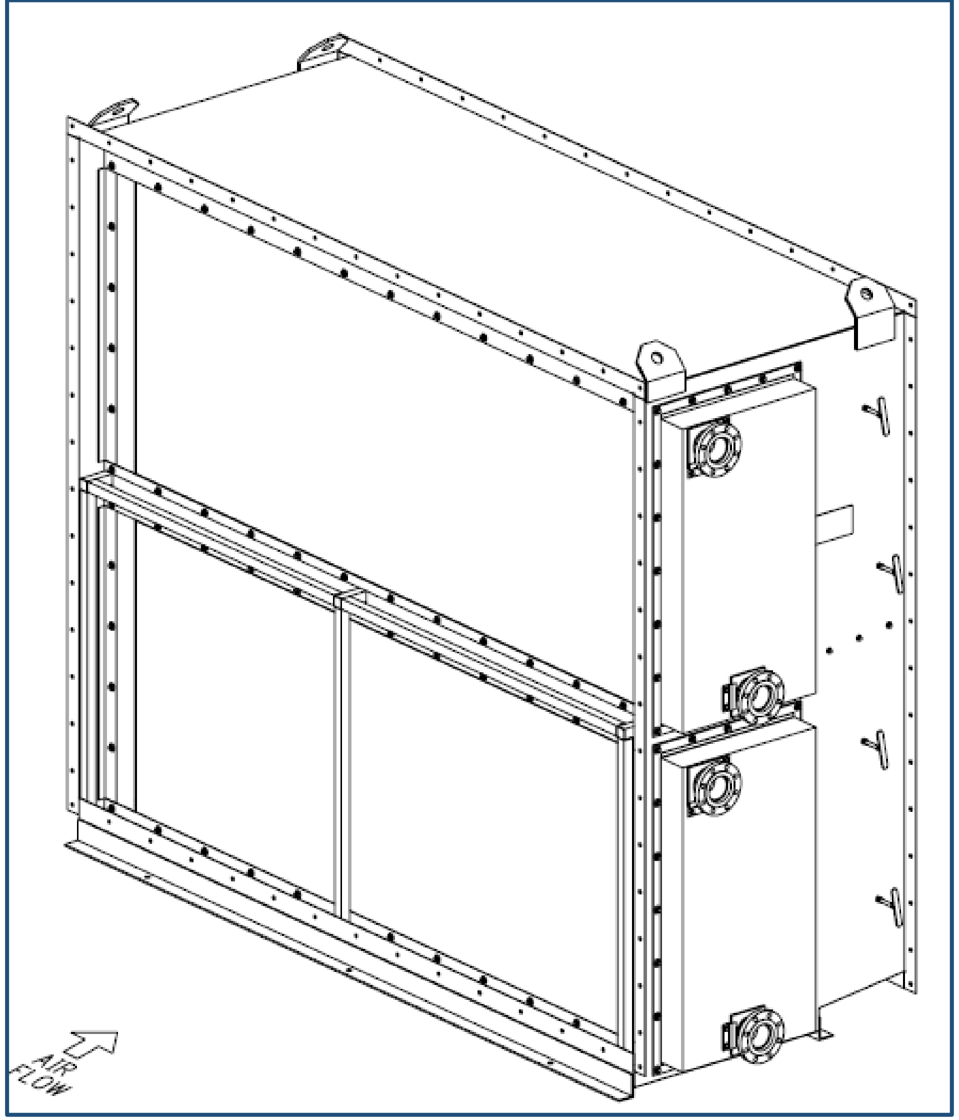
Economic Basis

- 30-Year operating life
- Natural Gas $8.19/MMBtu
- Import Power $0.1506/kWh
- Export Power $0.04/kWh
- Capacity $120/kW-Yr

Blackstone Chiller

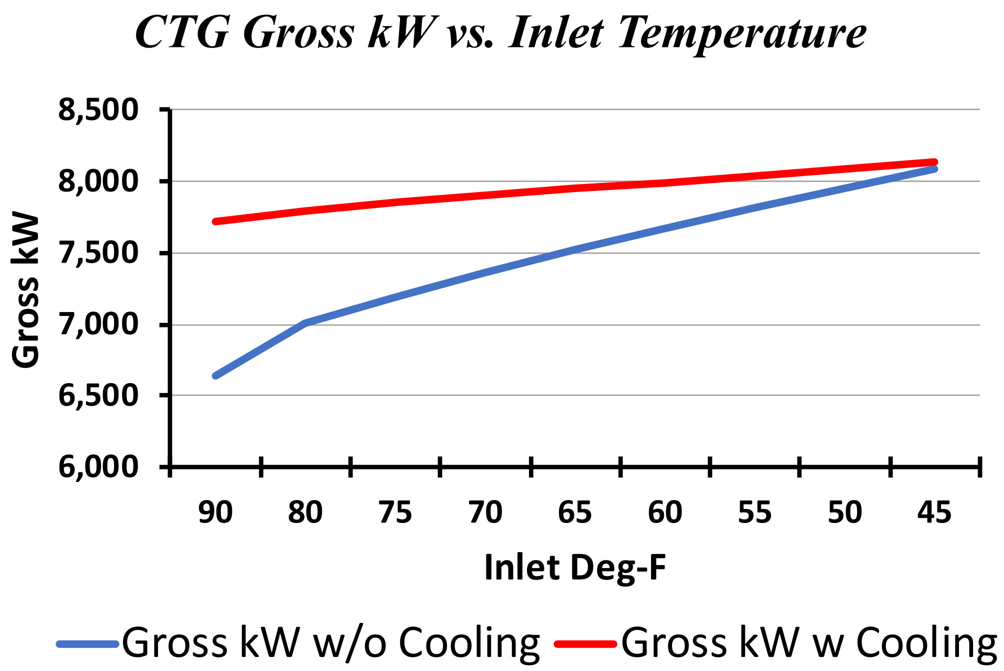
- 300 Ton Air Cooled Chiller
- 730 gpm coolant flow
- 42 deg-F supply/51 deg-F return temperature
- 309 kW power requirement
- Two separate refrigeration circuits, each with variable speed compressor
- 70% /40% water/glycol coolant
- Low noise design
  - 63 dBA at 30-feet
  - Low noise condenser fans
  - Full acoustic insulation including compressors

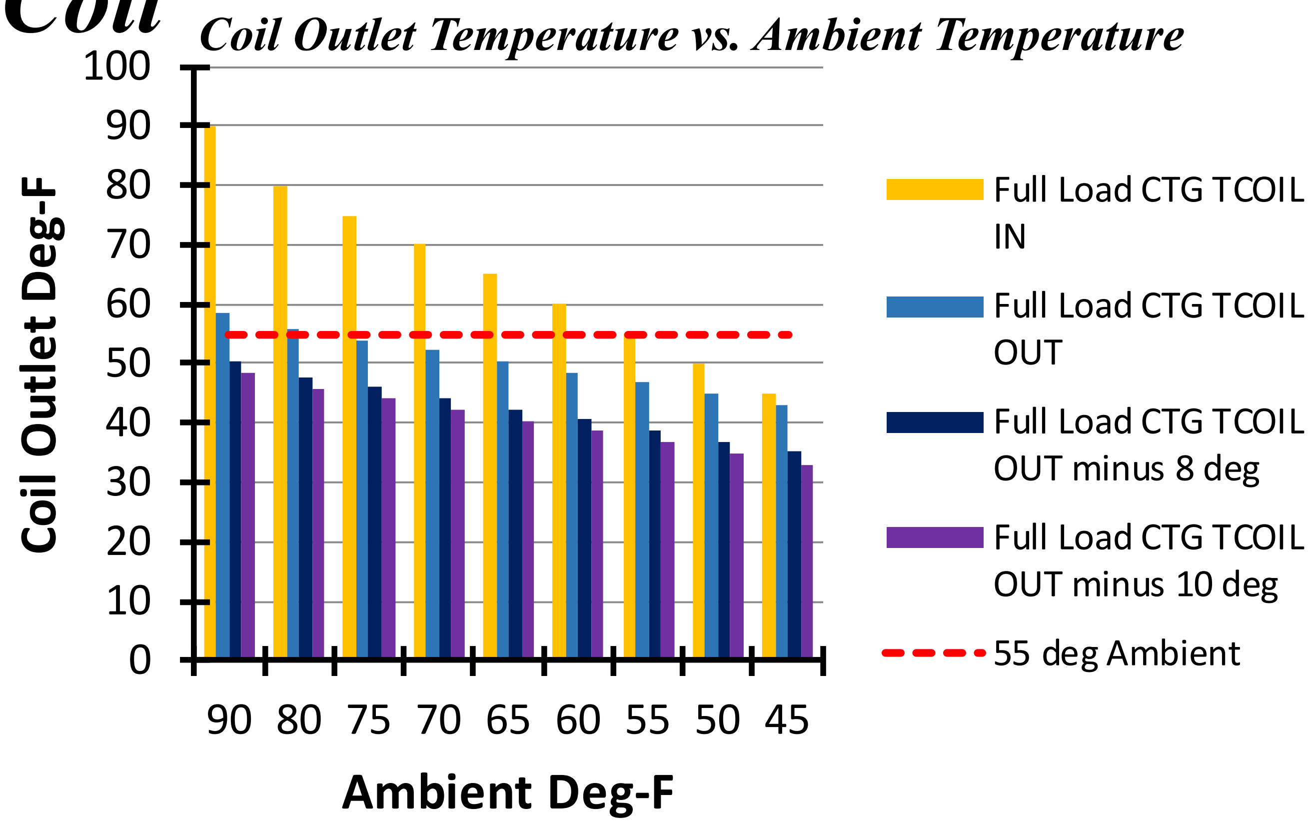
Blackstone Inlet Cooling Coil



- Standard OEM design for Taurus 70 turbine
  - –95 F DB/76 F WB air side in
  - –60 F DB/59 F WB air side out
  - –42 deg-F supply/51 deg-F return coolant
- OEM installation/operation guidelines
  - –Minimum 8-feet straight duct at coil outlet
  - –No coil operation below 55 F ambient
  - –Add insulation to inlet air plenum within turbine enclosure

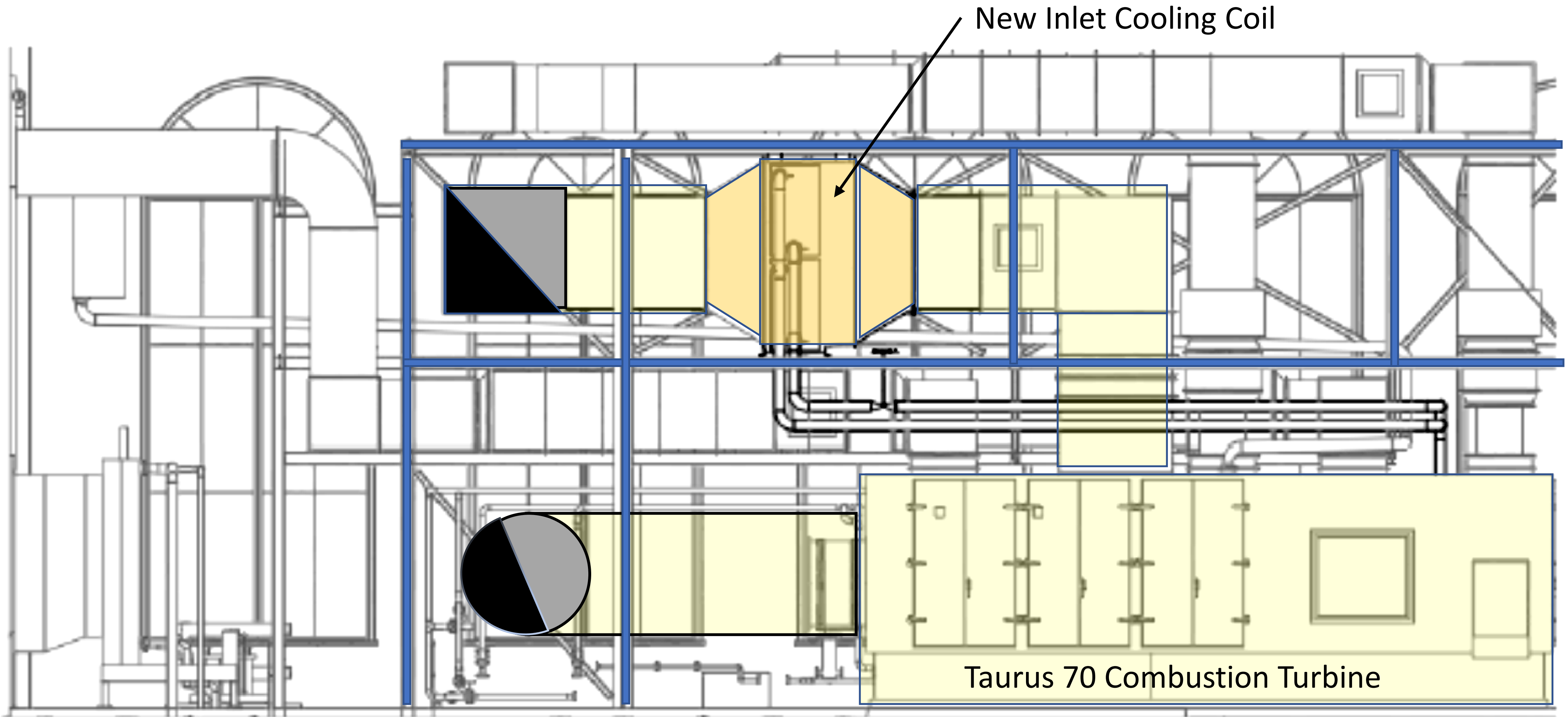
Blackstone Inlet Cooling Coil





- Diminished Inlet cooling benefit as ambient temperature decreases
- Risk of freezing and ice ingestion with coil operation below 55 deg-F ambient
  - Accelerated air flow at compressor inlet decreases dynamic temperature by 8 deg-F to 10 deg-F

Inlet Cooling Coil Installation Elevation

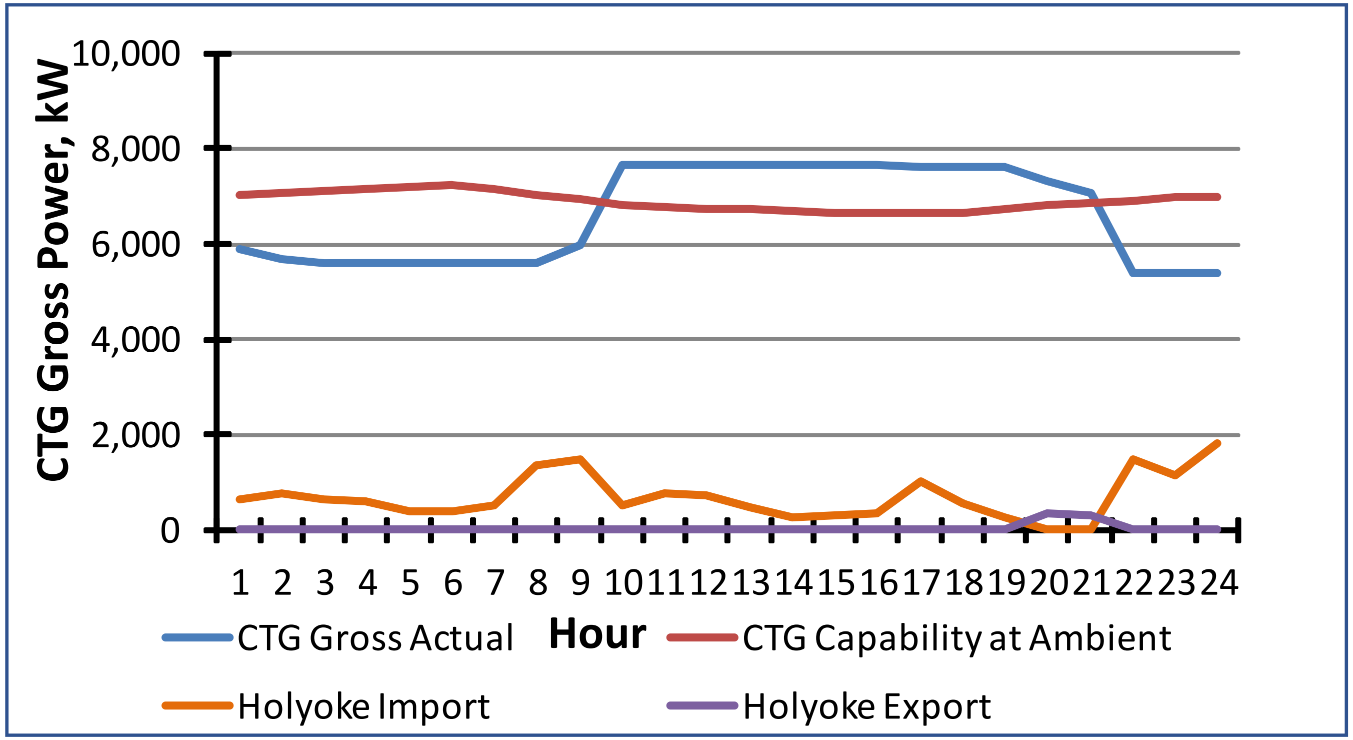


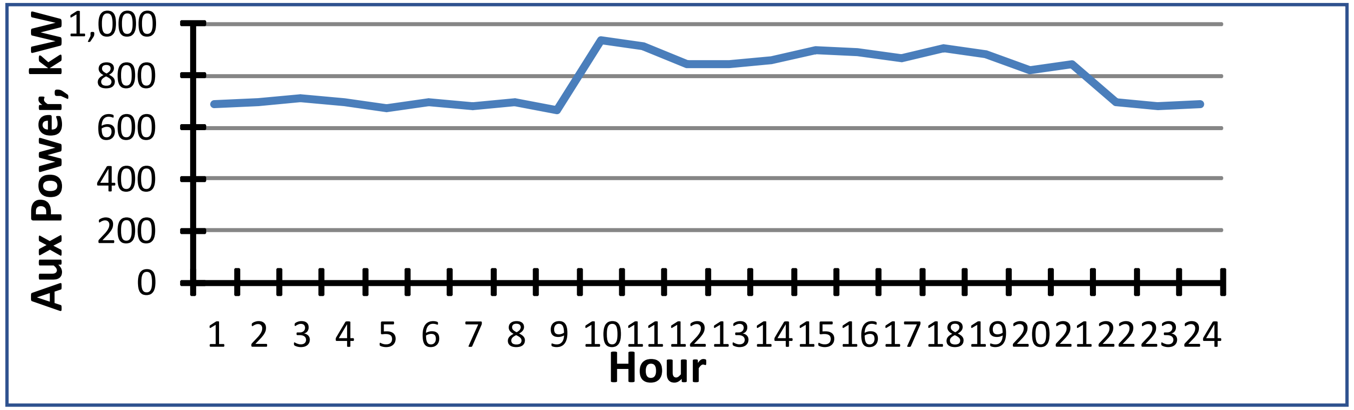
Chiller Installation and Final Setting

Coil Field Assembly

Coil Installation and Final Setting

Inlet Cooling Operation





JULY 21, 2020

<u>7:00 AM, No Inlet Cooling</u>

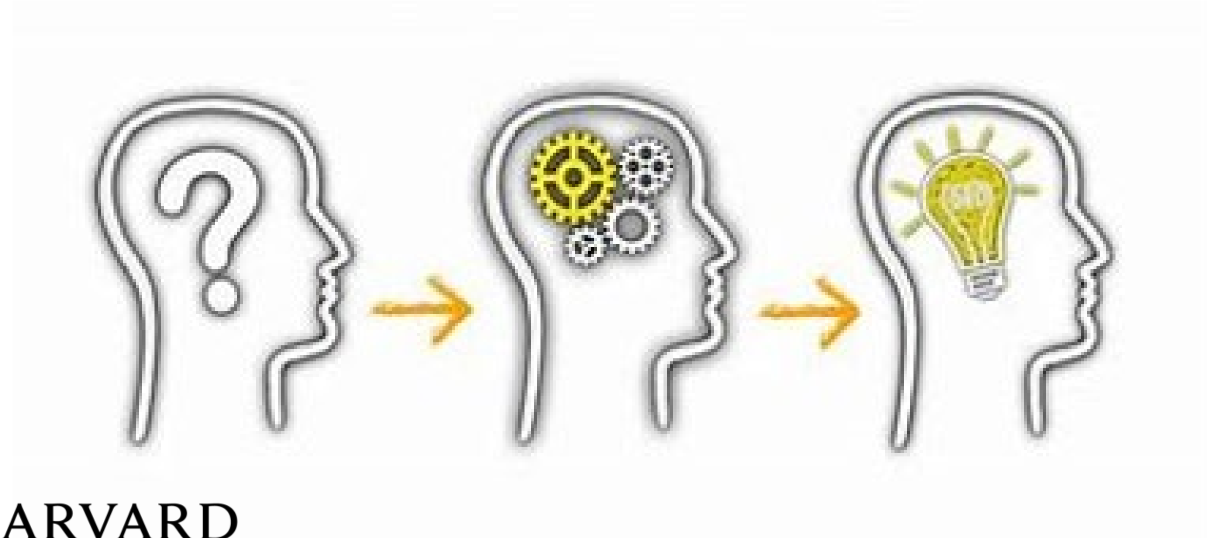
CTG Gross = 5,603 kW
Ambient Capability = 7,043 kW
Power Import = 1,376 kW
Power Export = 0 kW
Blackstone Aux = 700 kW

<u>12:00 PM, Inlet Cooling</u>

CTG Gross = 7,670 kW
Ambient Capability = 6,746 kW
Power Import = 478 kW
Power Export = 0 kW
Blackstone Aux = 841 kW

Lessons Learned

- ❑ Consider designing for inlet cooling even if not installing immediately.
- ❑ The seemingly obvious source for chilled water may not be the best.
- ❑ Work closely with turbine OEM during design and procurement.
- ❑ Added electric load maximizes inlet cooling benefit.
- ❑ Understand project goals and operating environment.



QUESTIONS

THANK YOU

DOUGLAS SCHMIDT

HARVARD
Campus Services
ENGINEERING & UTILITIES