HARVARD
Campus Services

Blackstone Combined Heat and Power Expansion

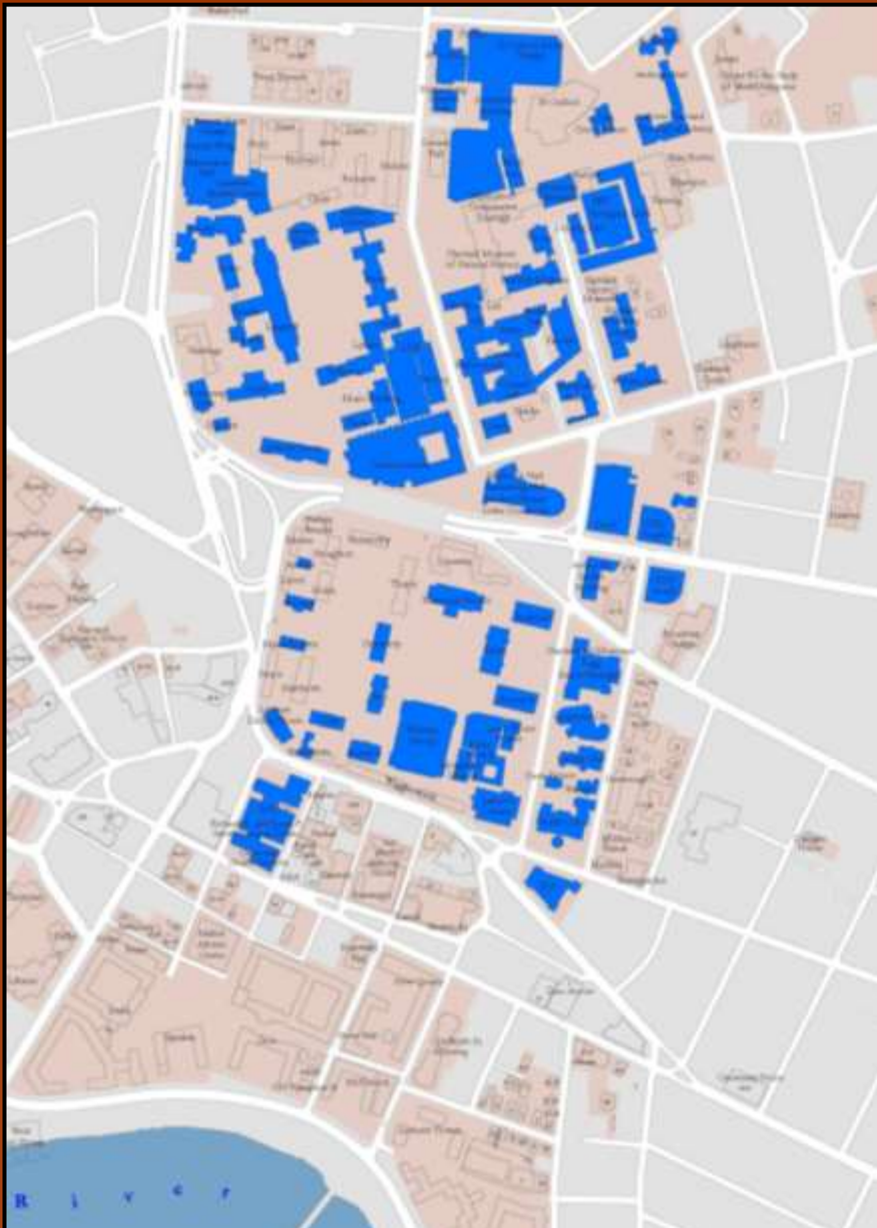
Engineering & Utilities

Responsible for managing University energy production and infrastructure including

- **Chilled water production and distribution**
- **Electrical distribution**
- **Thermal energy production and distribution**

Electric Distribution

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



Chilled Water Service

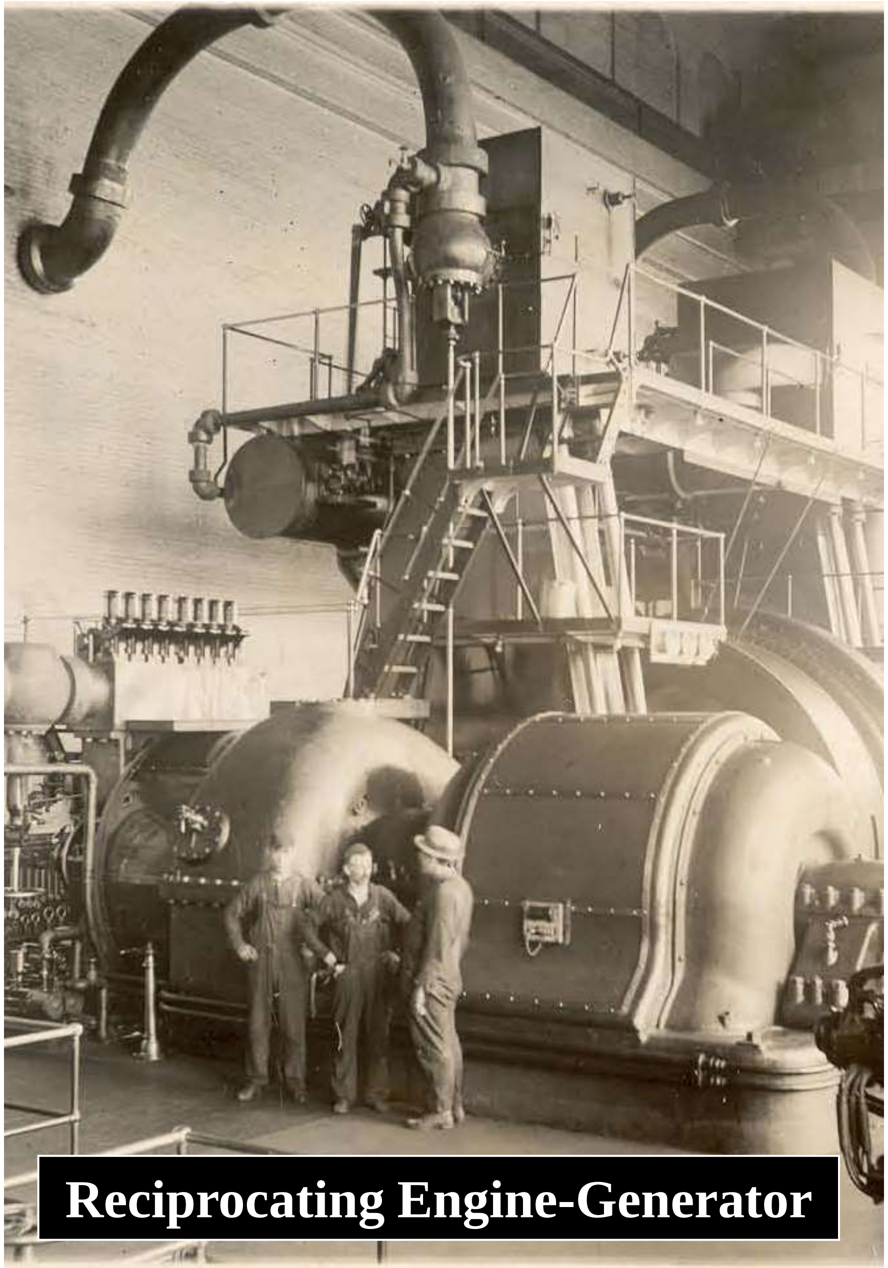
- **Provides chilled water for space cooling & process (equipment) cooling**
- **77 buildings served (Cambridge campus)**
- **System Configuration**
  - ❑ **Two below-grade production plants**
    - ➢ **Science Center**
    - ➢ **Northwest Lab**
  - ❑ **~19,000 tons generating capacity**
    - ➢ **7 chillers (2,000 – 5,000 tons)**
    - ➢ **All electric**
  - ❑ **Common distribution network**
    - ➢ **Both Plants feed into the same distribution system**
    - ➢ **~3½ miles of direct buried**

Steam Service

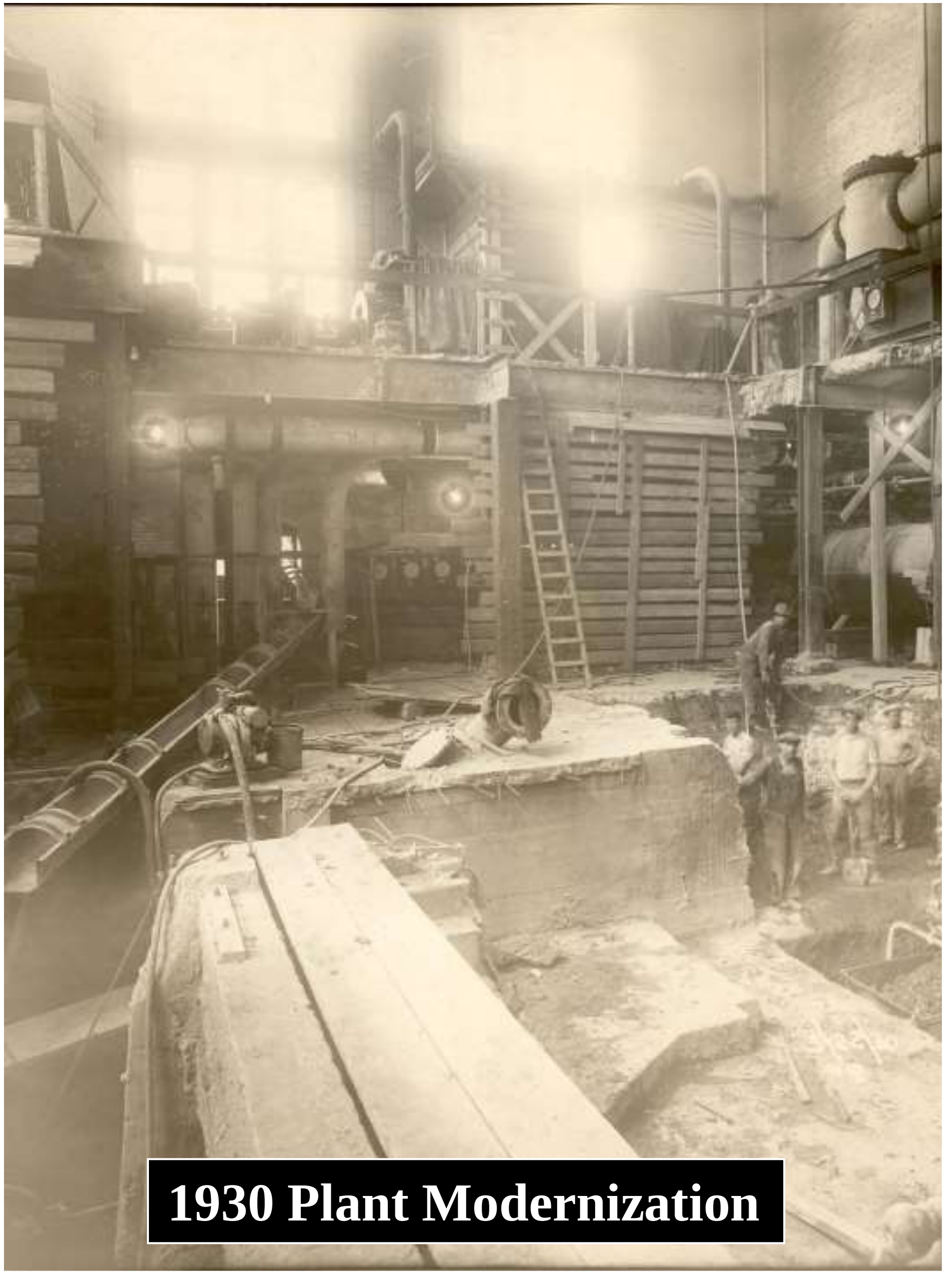
- Provides heat energy for space and domestic hot water heating, as well as high-pressure steam for process needs (in labs)
- ~170 buildings served Cambridge/Allston\
- System Configuration
  - ❑ One generating plant (Blackstone)
  - ❑ Four boilers (w/dual fuel capability)
  - ❑ Black start capable & self-sustaining electrically on-site 2 MW diesel generator 5 MW steam turbine generator
  - ❑ Multiple line distribution backbone in ~2½ miles of walk-through tunnel

Blackstone Steam Plant History

- Electric utility power generation operations began in 1904
- 1930 modernization replaced boilers, added steam turbines, and initiated steam supply service to Harvard
- 1962 expansion added two boilers
- Acquired by Harvard in 2003 to ensure security of campus steam supply
- Steam plant upgrade project completed in 2008 including backpressure steam turbine for CHP capability and improve steam supply quality and reliability.
- CHP expansion initiated in 2012 with goals of improved efficiency, environmental performance and campus energy supply reliability.



Reciprocating Engine-Generator

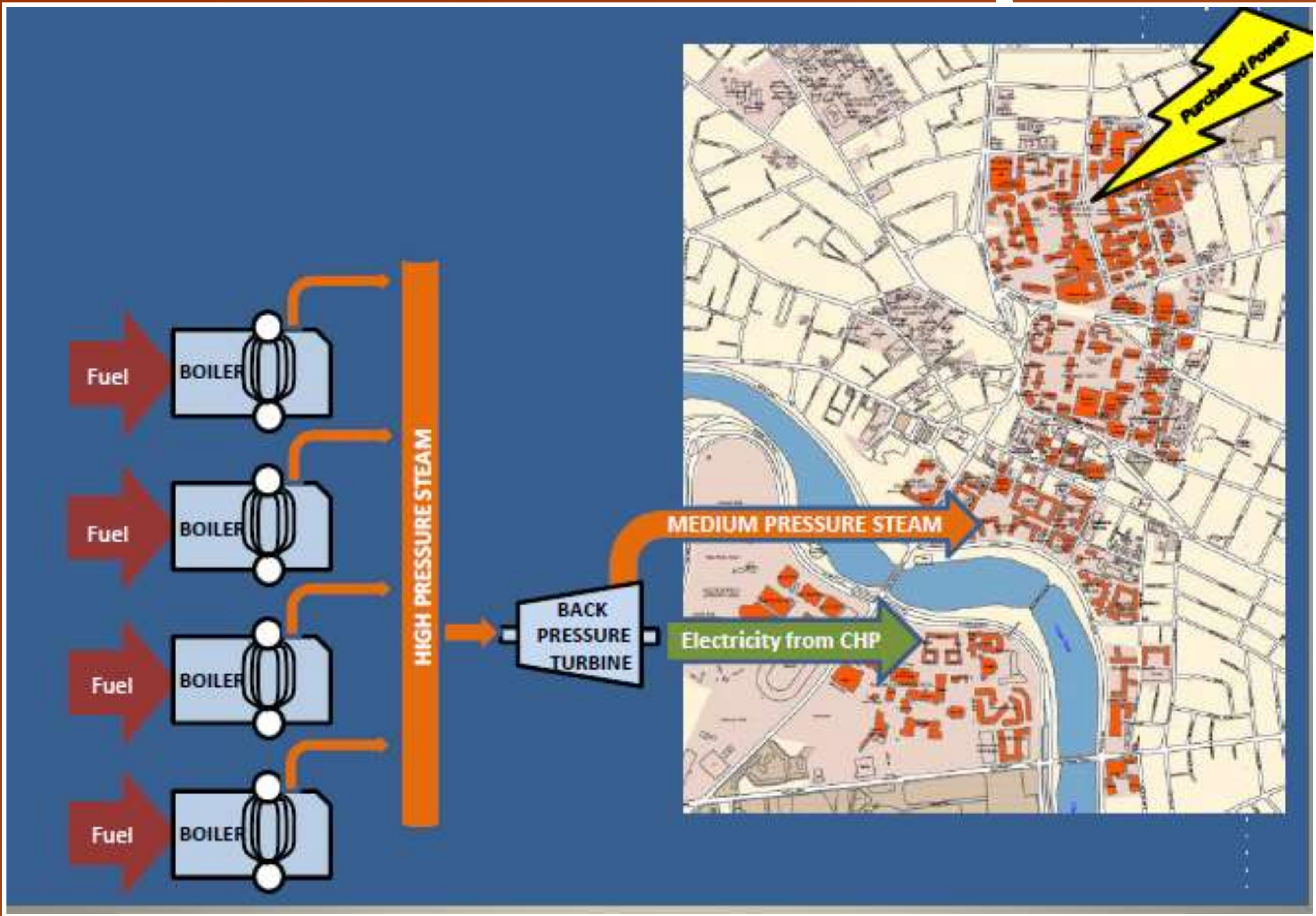


1930 Plant Modernization

Current Blackstone Steam Plant Operation

- Primary heat energy source to 160 Cambridge and Allston campus buildings (~11 million gsf)
- Operates four boilers, one 1930 vintage (Boiler 6) two 1962 vintage (Boilers 11 and 12), one commissioned in 2009 (Boiler 13 with low NOx burners and CO catalyst)
- Capability to meet campus steam demand with largest boiler out of service (firm capacity)
- Fuel mix consisting of natural gas, residual oil (0.5% sulfur), and ultra low sulfur diesel (0.003% sulfur)
- Nominal 5 MW steam turbine-generator set added in 2009.
- Operation by licensed staff 24 Hr/Day, 365 Days/Yr

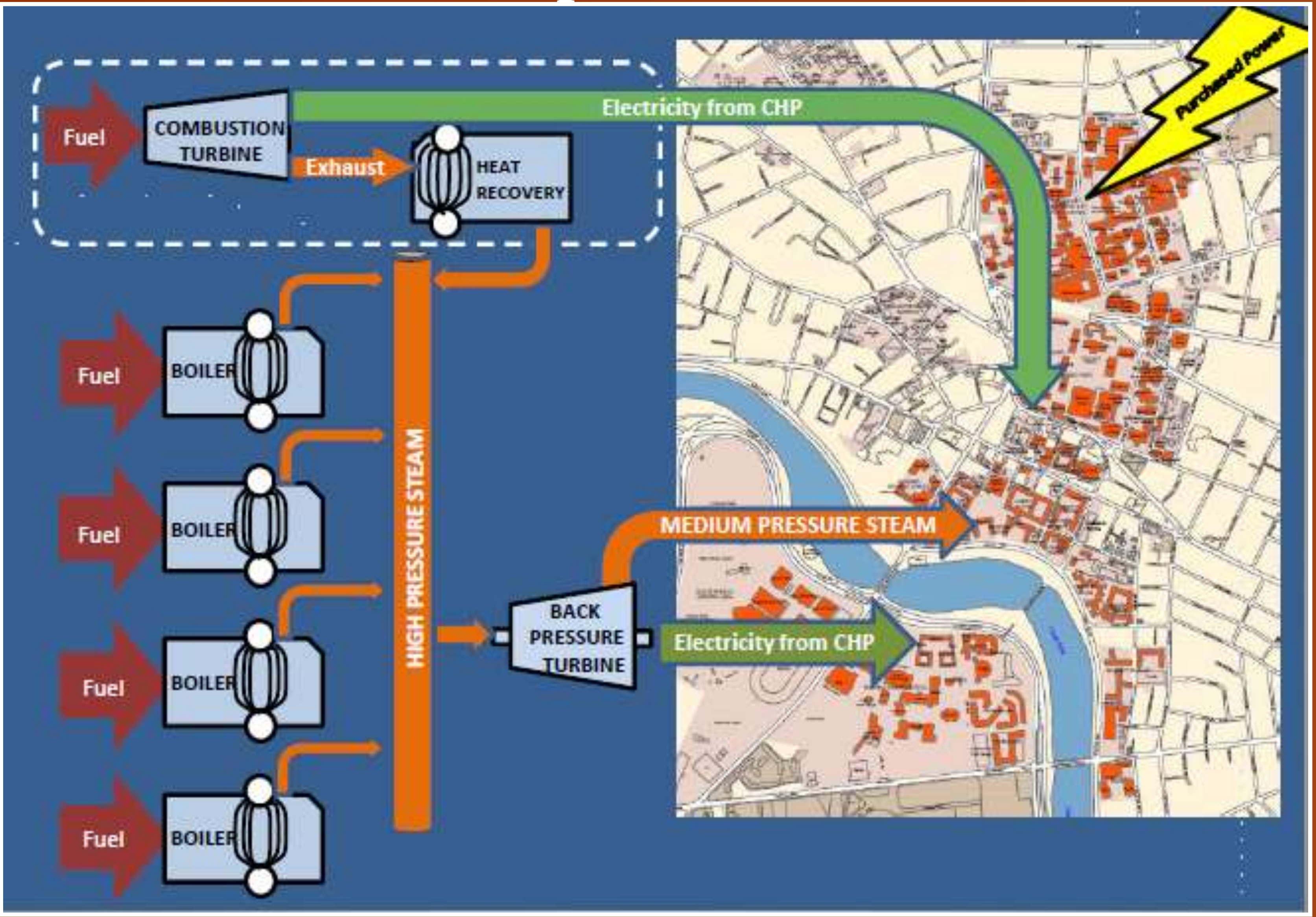
Current Blackstone Steam Plant Operation



CHP Expansion Equipment and Modifications

- Nominal 7.5 MW dry low NOx gas turbine, Solar Taurus 70
- Shop assembled heat recover steam generator, Rentech
  - Duct burner
  - CO reduction catalyst
  - Selective catalytic reduction
  - Urea conversion system
- Two 100% capacity fuel gas compressors, JJ Crewe
- 13.8 kV switchgear
- Fin fan cooler for closed cooling heat sink
- Motor control center for new BOP equipment
- Micro pile-supported CTG pedestal
- Structural steel modifications
- Harvard substation electrical modifications

Blackstone CHP Expansion



Concept Study

- **Prompted by need to meet emergent operating goals**
  - **Preserve steam production redundancy in view of aging resources**
  - **Improve steam production turndown capability to meet diminishing summer steam demand**
  - ***Ground Rule*: Confine all physical plant improvements to within the Blackstone building footprint.**
- **Study approach**
  - **Concept-level layout, estimate, and economic performance for three options at high, mid, and low end capacity of commercially available CTG/HRSG options**

Concept Study

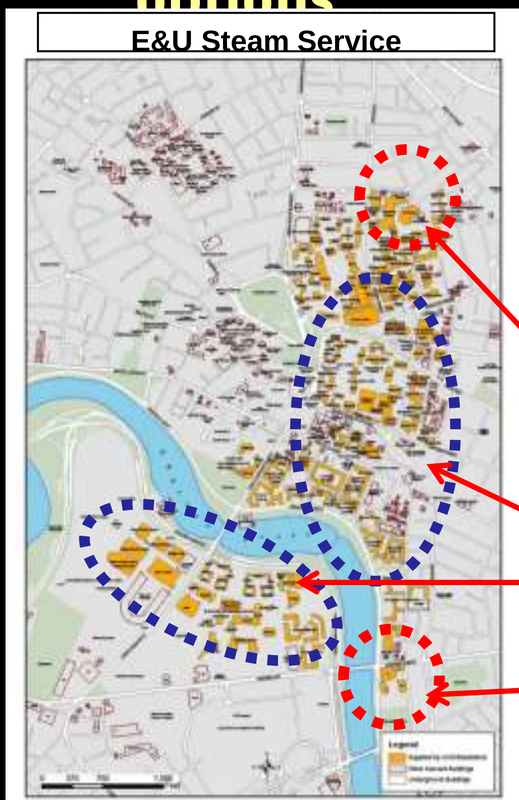
- **Positive study result**
  - **All options could be integrated into existing Blackstone facility including coordination with steam turbine**
  - **Each CTG/HRSG option showed positive economic and environmental benefit**
  - **Higher CTG/HRSG capacity yielded diminished economic benefit.**
- ***CONCLUSION*** **Study further and in more detail**
  - **Would finer granularity of capacity choices yield improved economics?**
  - **Will detailed understanding of retrofit within existing facility significantly impact cost and benefit?**

Comprehensive Study

- Goals
  - Establish strong confirmation of benefits identified by concept study
  - Consider a broader range of CTG/HRSG options at alternate locations and electrical interconnect points
  - Produce level of detail and confidence to support internal funding request
- Two-phased approach
  - *Screening Phase:* Identify and screen expanded inventory of candidate CTG/HRSG options
  - *Detailed Phase:* Quantify select option(s) with investment grade cost estimate and broad assessment highly specific to integration and operation at Blackstone facility and Harvard campus

Screening Phase, Incremental Analysis

- **Screening analysis for incremental comparison**
  - **Business as Usual: Status quo Blackstone operation**
  - **CHP Expansion: Blackstone and remote expansion options**



Remote Locations – Where and why?

Opposite end of campus from Blackstone

- ❑ Reduce steam pressure loss
- ❑ Improve access to electrical loads
- ❑ Increased steam service reliability

Remote Locations

Thermal Energy Customer Base

Blackstone

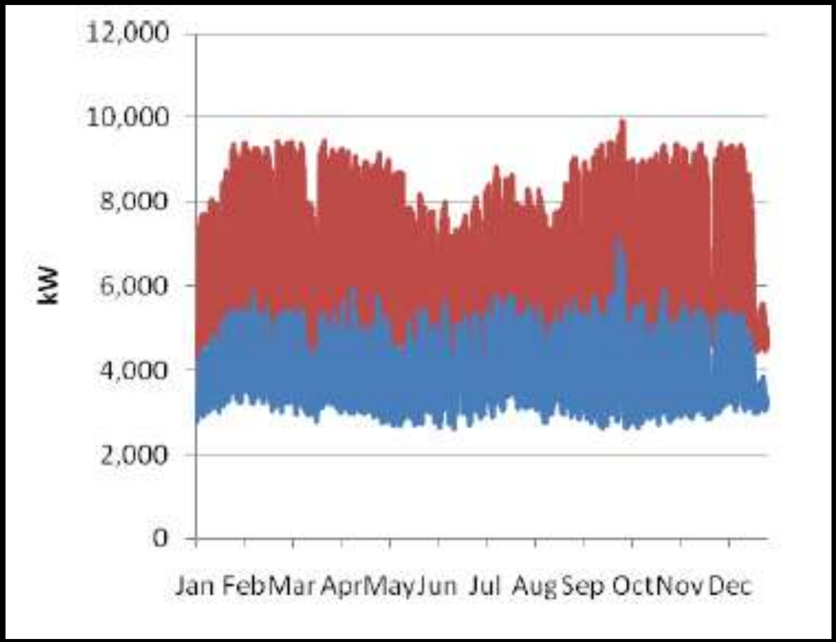
Screening Phase, Candidate Options

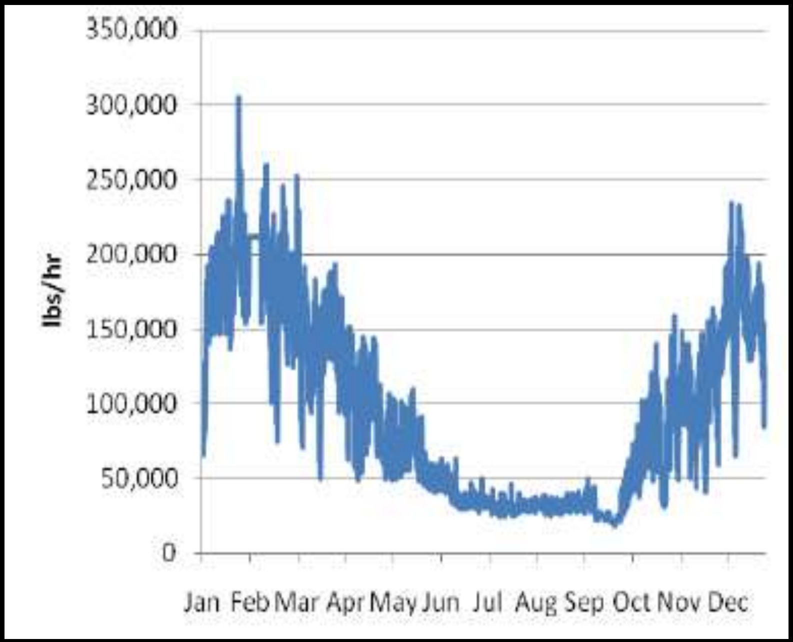
- **CHP expansion at Blackstone and remote locations**

OPTION	Turbine Choice	Turbine Location	Number of Turbines Turbines	Relative Interconnect Distance	Gross Output Each (kW)	Unfired Steam Each (Lb/Hr)	Steam Pressure (psig)	Steam Temperature (Deg-F)
1	Mercury 50	Blackstone	1	NEAR	4,406	9,656	400	700
2	Mercury 50	Blackstone and Remot	2	DISTANT	4,406	9,656	400	700
3	Mercury 50	Blackstone	1	DISTANT	4,406	9,656	400	700
4	Centaur 50	Blackstone	1	DISTANT	4,408	19,894	400	700
5	Taurus 65	Blackstone	1	DISTANT	6,045	26,048	400	700
6	Taurus 70	Blackstone	1	DISTANT	7,533	28,839	400	700
7	Mercury 50	Existing Remote Facilti	1	NEAR	4,406	9,656	125	353
8	Centaur 50	New Remote Facility	1	NEAR	4,408	19,894	125	353
9	Taurus 65	New Remote Facility	1	NEAR	6,045	26,048	125	353
10	Taurus 70	New Remote Facility	1	NEAR	7,533	28,839	125	353
11	Mercury 50	New Remote Facility	2	NEAR	4,406	9,656	125	353
12	Titan 130	New Remote Facility	1	NEAR	14,453	50,498	125	353

Screening Phase Elements, Energy

- Campus electrical and thermal load profiles
  - Historic hourly load information
  - Load growth projections

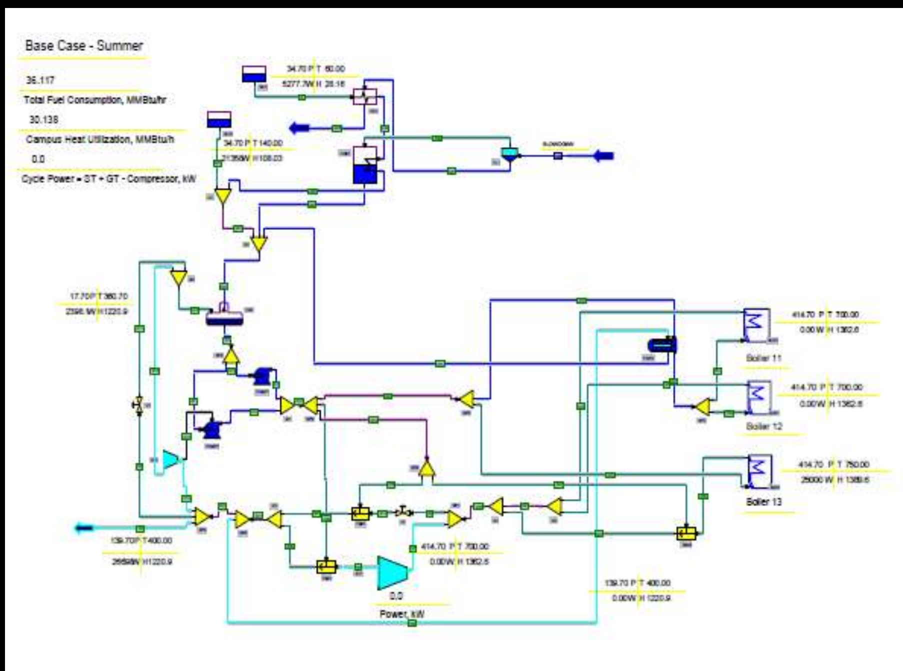


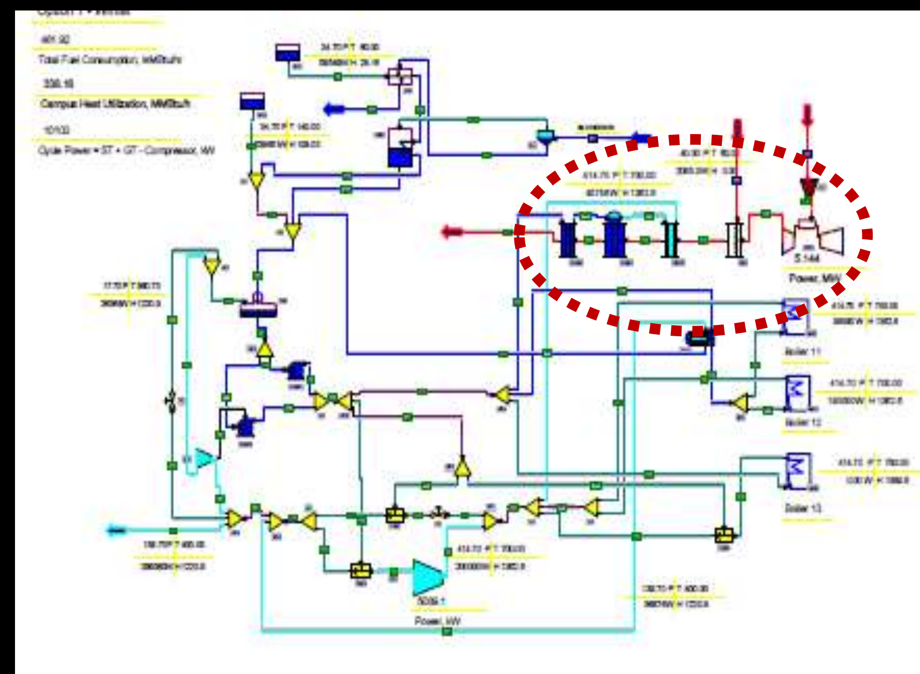


Electrical **Thermal**

Screening Phase Elements, Energy

- **Energy models**
  - Simulate thermodynamic and electrical performance of Blackstone base case and each CHP expansion option



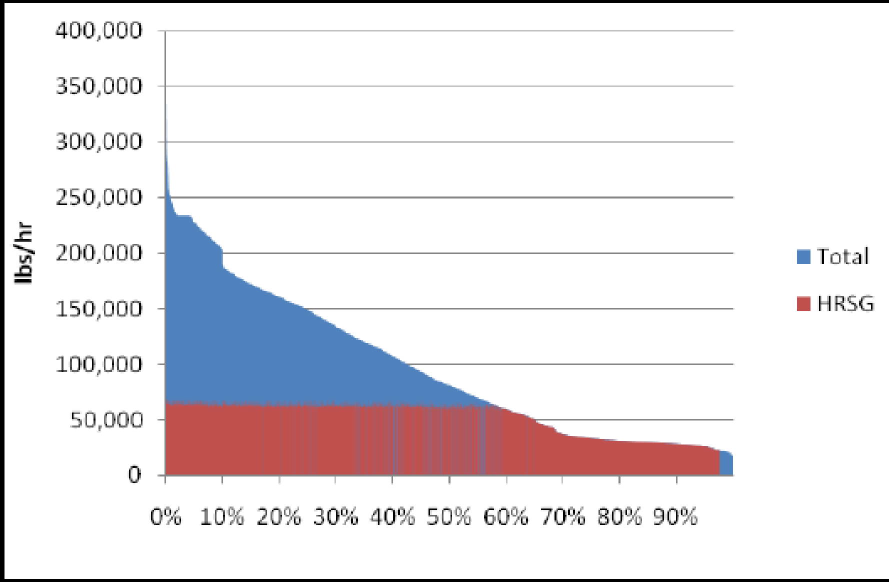


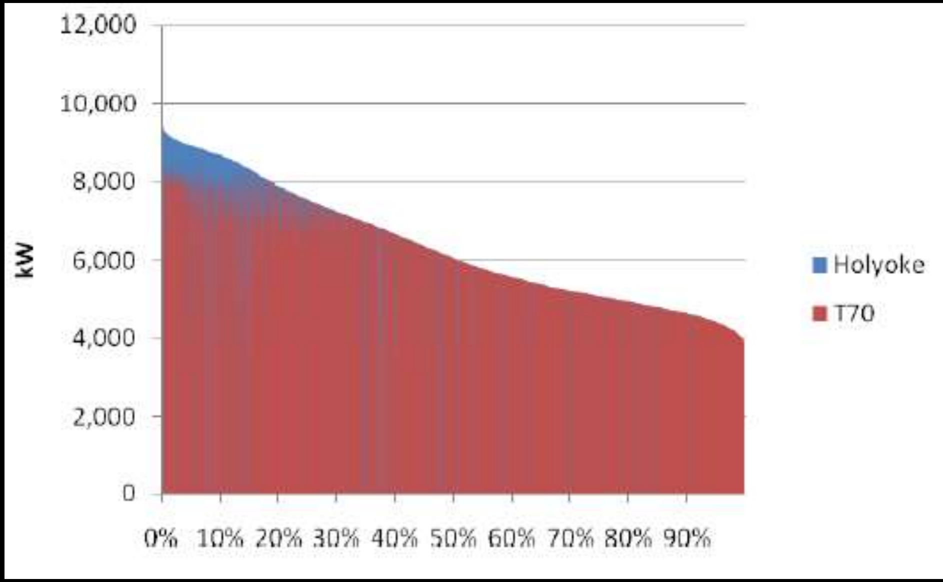
Blackstone Base Case

CHP Expansion at Blackstone

Screening Phase Elements, Energy

- Dispatch model
  - Operate thermodynamic models against hourly thermal load
  - Quantify annual heat input (fuel) and electric production

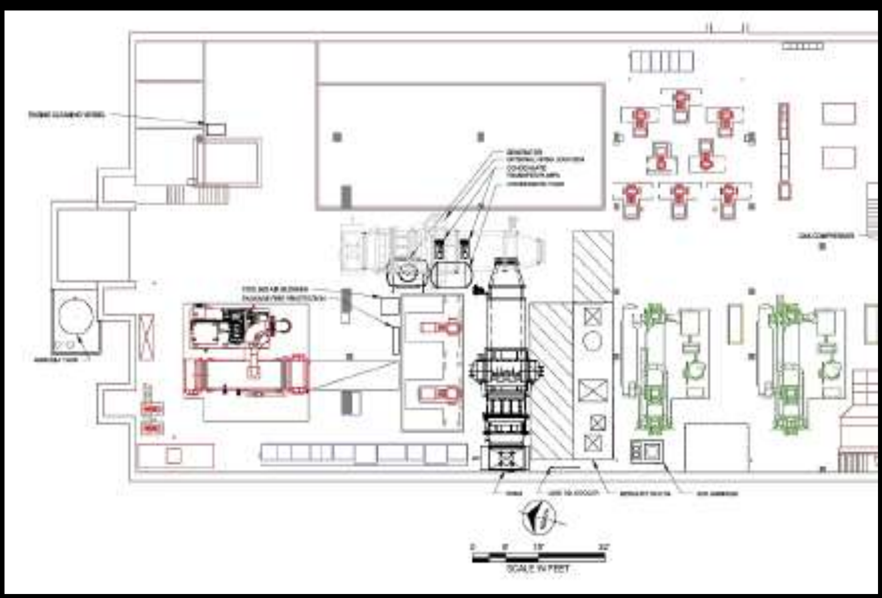




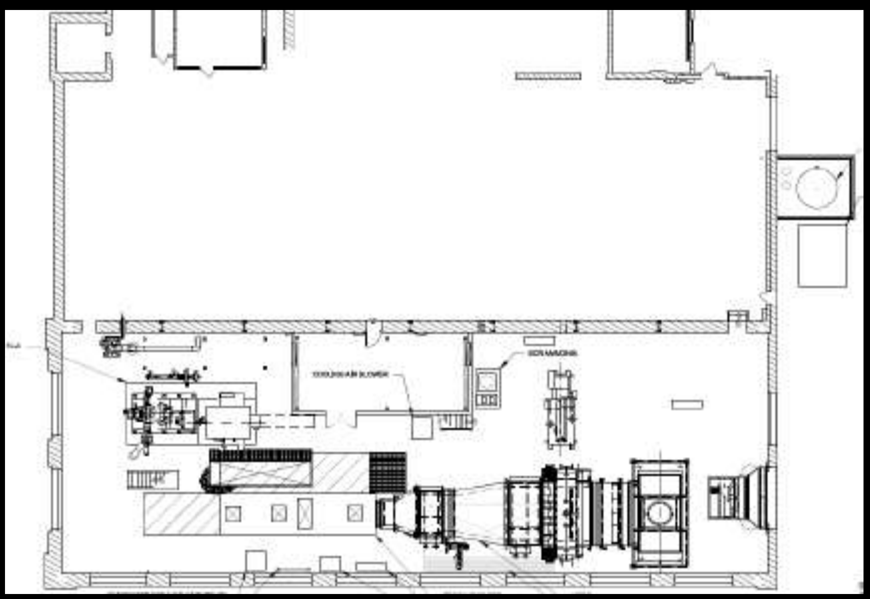
Thermal Load Duration **Electric Load Duration**

Screening Phase Elements, Cost

- **Cost estimates**
  - **Budget level estimate for each option based on layout at each location including campus infrastructure upgrades, regulatory compliance and soft costs based on vendor budget quotes and native estimating capability**



Option 2 Layout at Remote Location



Option 4 Layout at Blackstone

Screening Phase Elements, Cost

- **Commodity forecasts**
  - **Pricing for natural gas, residual, and distillate fuels**
  - **Wholesale electric energy purchase price, applicable to value of power supplied for direct campus use**
  - **Market price for electric energy sales, applicable to value of power not supplied for direct campus use**
  - **Electric power capacity market forecast**
  - **Compliance credits and Alternative Energy Certificates**
- ***All forecasts at multiple confidence levels to assess durability of each option***

Screening Phase Elements, Regulatory

- Permitting implication
  - Thresholds for applicable state and federal permitting
    - Assess permitting scope and difficulty
    - Establish scope of required environmental controls
  - Emission offset requirements to determine net generation or consumption of offsets
  - State and local noise regulations to establish required sound attenuation levels
  - Existing campus-wide permits to assess impact of incremental CHP addition
- Greenhouse gas
  - Current and future GHG rate for New England electric grid to quantify CHP GHG benefit

Combining the Screening Elements

Business as Usual
- Heat Balance
- Hourly Thermal Load
- Hourly Electric Load
- Dispatch Model

GHG Performance
- Business as Usual GHG
- CHP Expansion GHG
- New England Regional GHG

Operating Cost
- Natural Gas
- Fuel Oil
- Electric Power
- Environmental Markets
- Non Fuel O&M

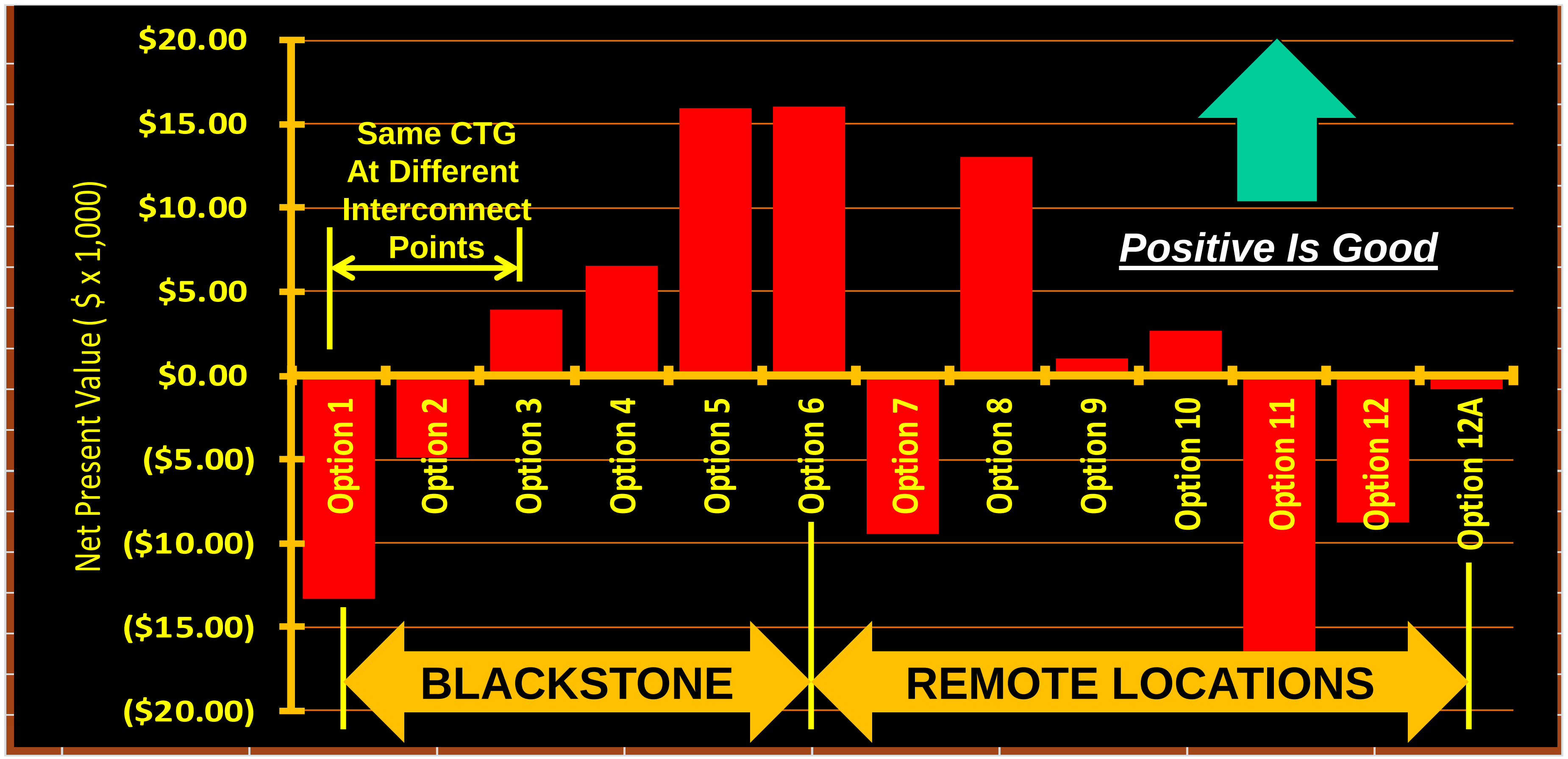
CHP Expansion
- Heat Balance
- Hourly Thermal Load
- Hourly Electric Load
- Dispatch Model

Incremental Analysis
- GHG Benefit
- Discounted Cash Flows
- Total and Line Item NPV
- Rate of Return and Payback

Project Cost
- Construction Estimate
- Construction Cash Flow
- Construction Loan Rate
- Discount Rate

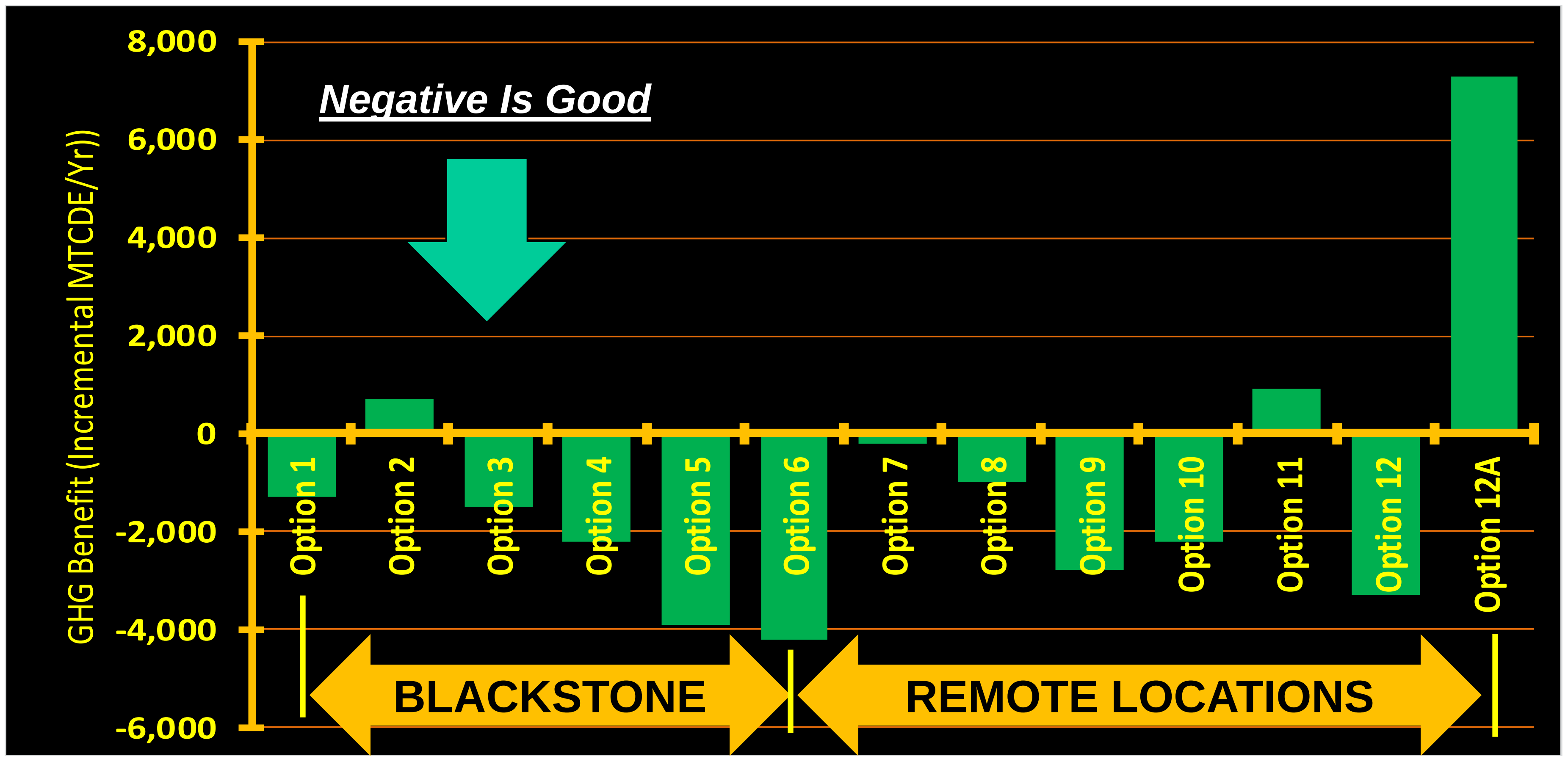
Screening Phase Result, Economic Benefit

- Larger Blackstone turbine yields increased benefit (Options 1- 6)
- Smaller turbine at existing remote yields negative benefit (Option 7)
- Larger turbine at new remote yields decreased benefit (Options 8- 12)
- Option 12 large turbine at new remote improves with steam chiller (12A)



Screening Phase Result, GHG Benefit

- GHG benefit at Blackstone parallels economic benefit (Option 1-6)
- GHG benefit at remote sites parallels economic benefit (Options 7- 12)
- Option 12 large turbine at new remote improves with steam chiller (12A)



Detailed Phase

- **Goals**
  - Detailed assessment of Option 6, Taurus 70 at Blackstone
    - Most favorable economic performance
    - Greatest GHG benefit
  - Provide basis for presentation of funding request
- **Method and Basis**
  - Incremental evaluation of each option vs. business as usual
  - 35% design level basis vs. budget level for screening
  - Contractor review of constructability and methods
  - Refined regulatory and environmental assessment
  - Pro forma with probabilistic uncertainty of variables
  - Correlation of interdependency between variables

Combining the Detailed Elements

Business as Usual

- Heat Balance
- Hourly Thermal Load
- Hourly Electric Load
- Dispatch Model

GHG Performance

- Business as Usual GHG
- CHP Expansion GHG
- New England Regional GHG

Operating Cost

- Natural Gas
- Fuel Oil
- Electric Power
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- Non Fuel O&M

CHP Expansion

- Heat Balance
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Project Cost

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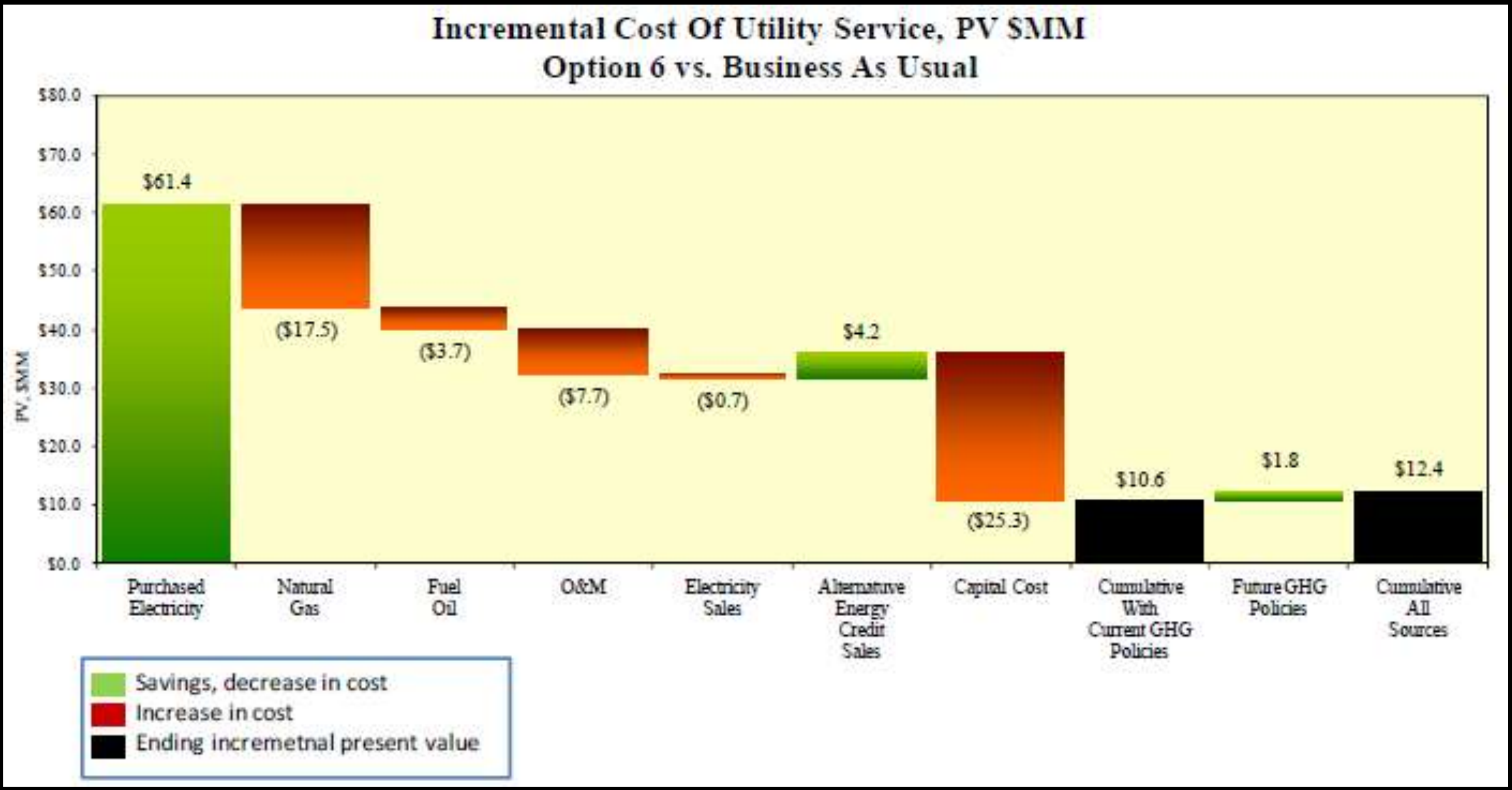
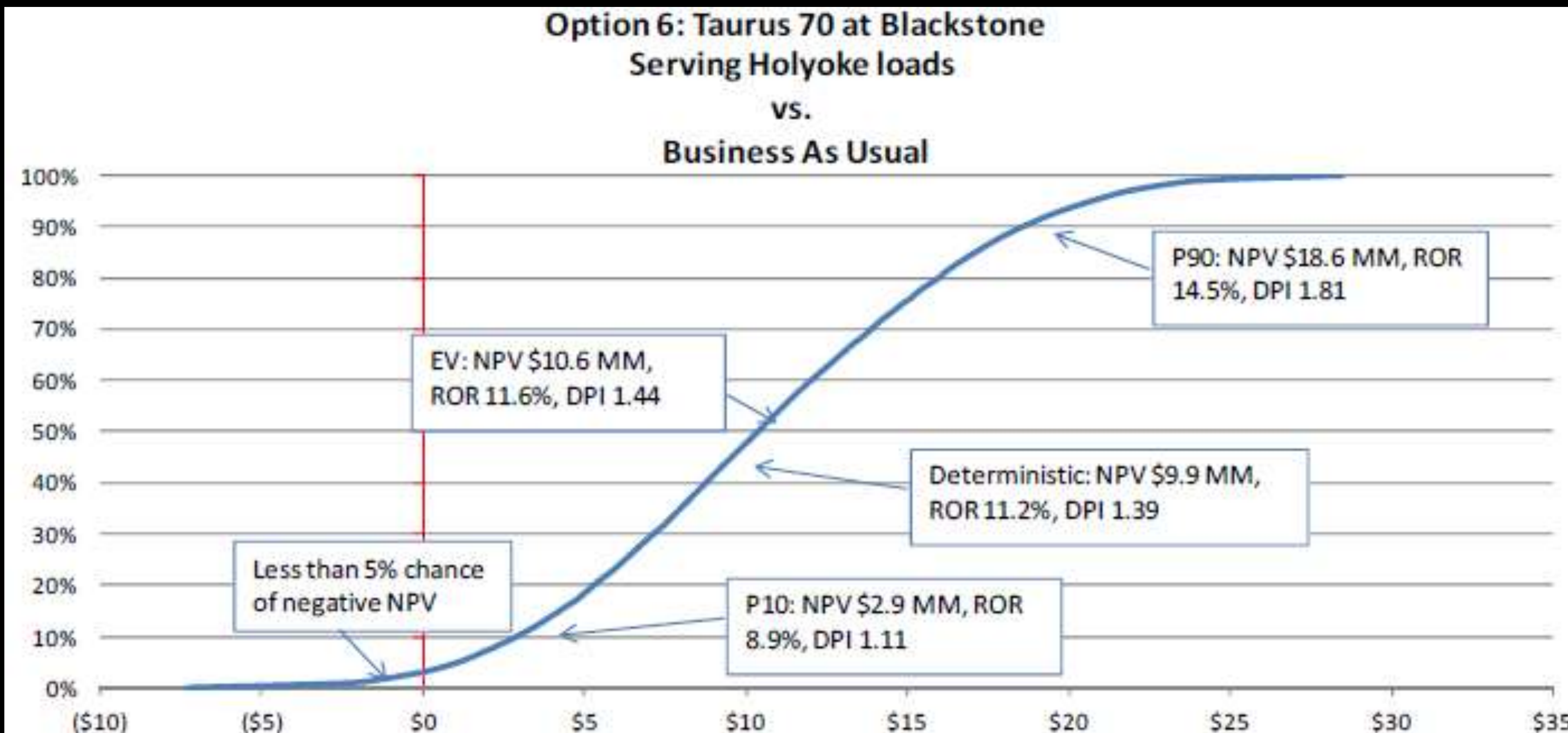
Detailed Phase Result

- Cumulative Flying Bar Graph, NPV of Cost Drivers



Detailed Phase Result

- **Project NPV vs. Probability of Outcome**



Conclusions and Lessons Learned

- **Assessment of granular options provided good perspective on impact of project size and location**
- **Work with vendors and prospective field contractors during detailed study phase supported construction estimate confidence.**
- **Detailed estimate, economic analysis, and probabilistic approach provided solid basis to support project funding request.**
- **Time taken to study in detail and the resulting work product facilitated smooth transition to project implementation phase.**

Rigging Gas Turbine Into Turbine Hall Window

Gas Turbine Entering Turbine Hall Window

HRSG Off-Load on Blackstone Street

Rigging Gas Compressor Down to Mezzanine

Lifting Closed Cooling Heat Exchanger to Roof