Thermodynamic Analysis Of Combined Cycle District Heating Plant

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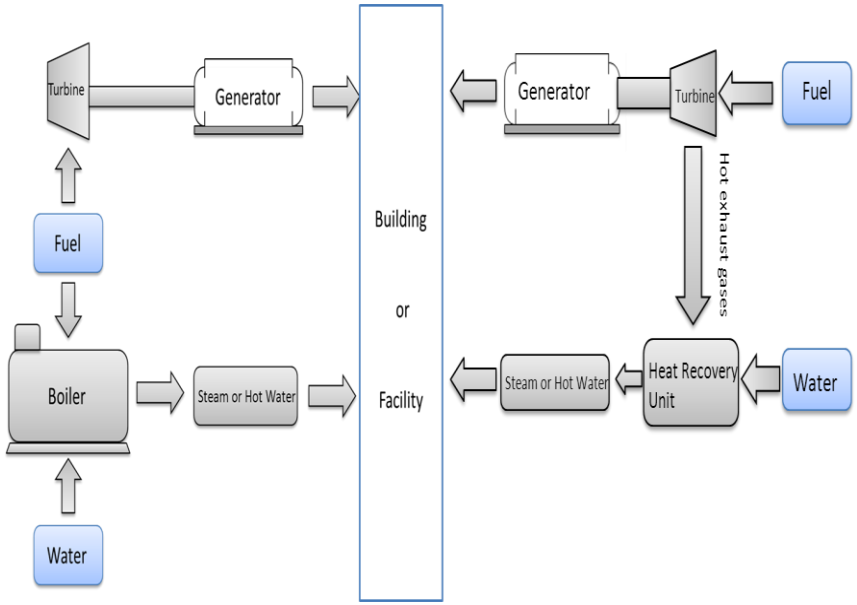
What is a district heating system?

- One that generates and circulates hot water and steam for domestic purposes.
- When the system is also used to produce electric power apart from steam and hot water, it is called a Combined Heat and Power (CHP) plant.
- Combined cycle consists of the combination of Brayton and Rankine Cycles



Conventional System vs. CHP

- CHP : Higher Overall Efficiency, Reduced greenhouse emissions, Reduced overall cost of Energy

Why Thermodynamic Analysis?

- Evaluation of power plant performance.
- System optimization.
- Energy analysis gives a picture about system efficiencies.
- Exergy analysis is used to compare components or systems to help make informed design decisions.
- By exergy analysis, we can see where we should be focusing our efforts to improve system efficiency.

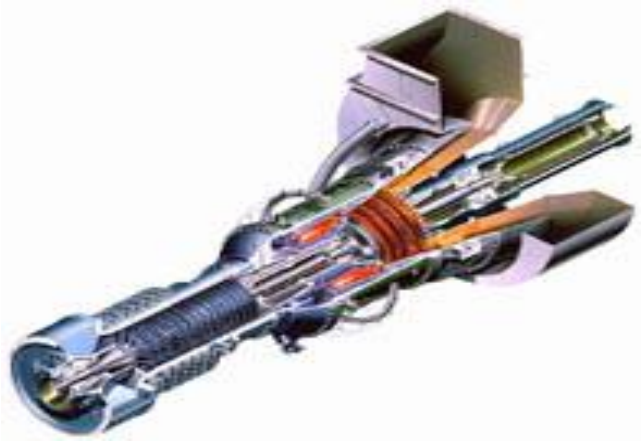
UMASS CHP PLANT

- Started operation in December 2008.
- Replaced the 1918 coal fired power plant to increase electrical power generation and reduce emissions.
- Satisfies nearly all of the campus' electric demand and all steam demand.

Power Generation Systems

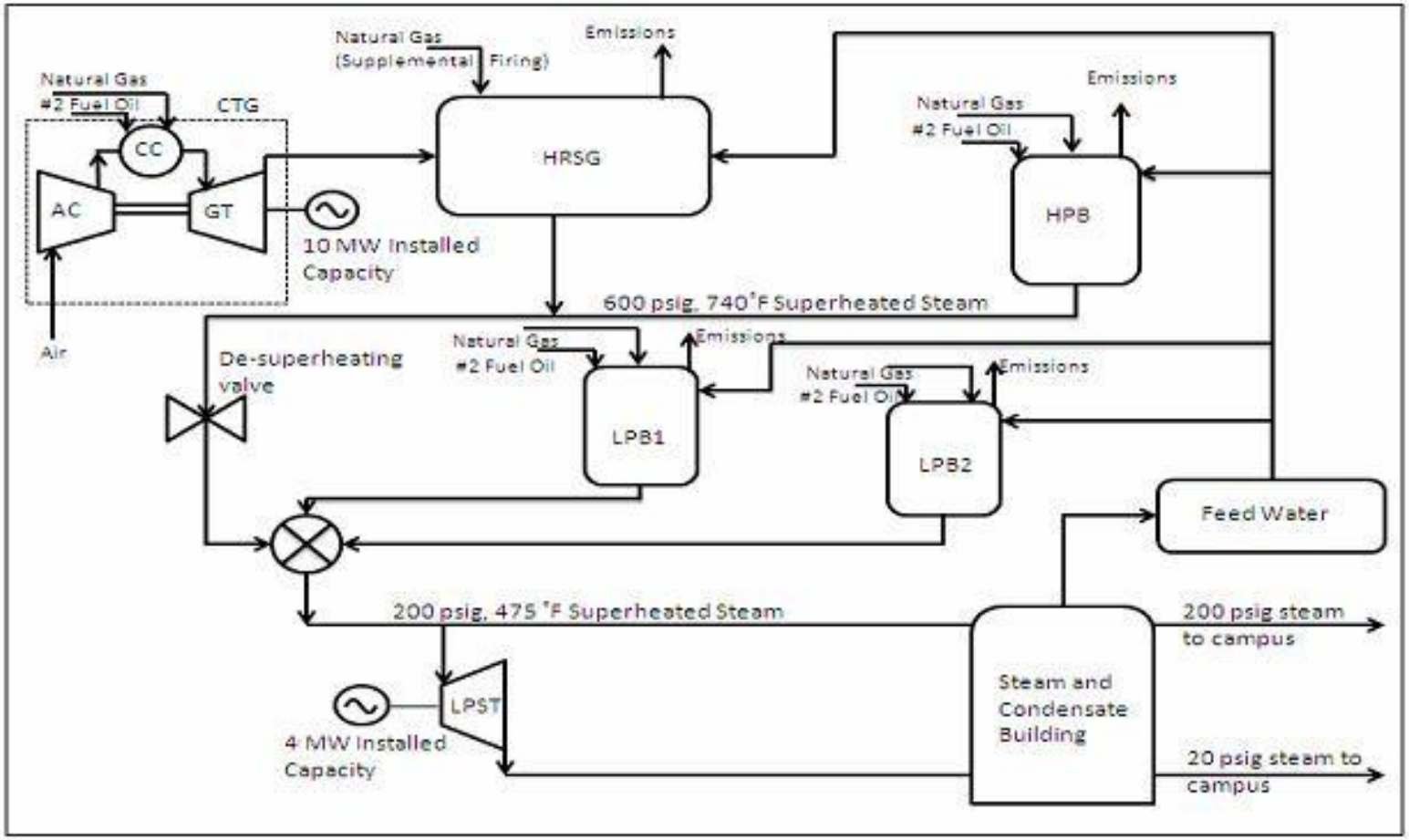
- 10 MW Solar Combustion Gas Turbine

  Solar Gas Turbines - MARS 100



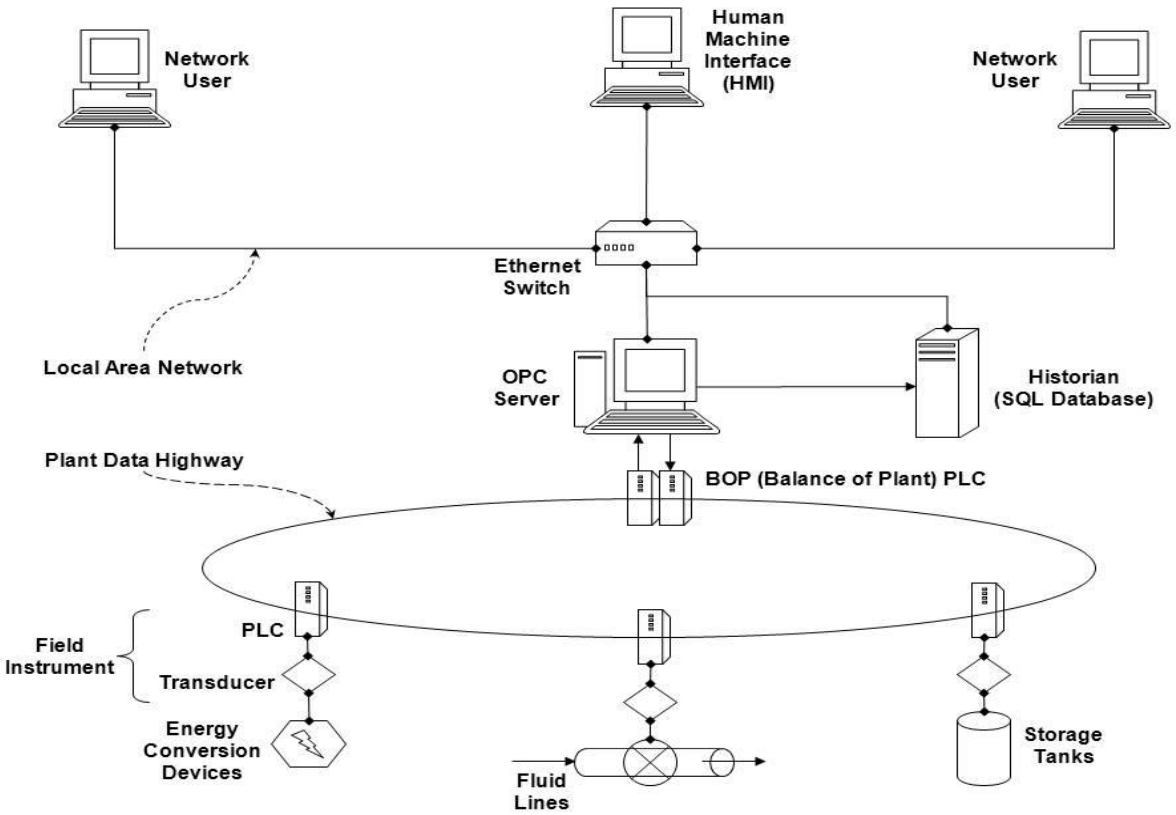
- 4 MW Steam Turbine
- 100,000 lbs/hr Heat Recovery Steam Generator (HRSG) @ 625 psig, 740°F steam flow (40,000 lbs/hr without duct burner)
- One 125,000 lbs/hr Package Boiler @ 625 psig, 740°F steam flow
- Two 125,000 lbs/hr Package Boilers @ 200 psig, 466°F steam flow

UMASS CHP Flow Diagram (2010)



PRESENT STUDY

- Based on actual system data from different field instruments in the plant.



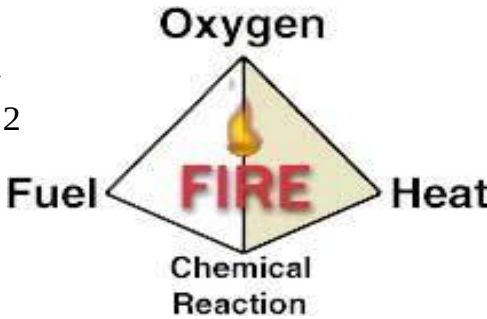
- Study done for a whole year (2010) on an hourly basis.

COMBUSTION

- The CTG and the boilers are capable of firing with either natural gas or #2 fuel oil.

- The combustion reaction:

$$a\ Fuel + \underbrace{b(O_2 + 3.76N_2)}_{\text{Air}} \rightarrow \underbrace{xCO_2 + yH_2O + zO_2 + wN_2}_{\text{Products of Combustion}}$$



a, b: Calculated from their corresponding mass flow rates every hour.

x, y, z, w : Determined from mole balancing of each element in the equation.

- Fuel Gas Composition (by volume percent):

CH_4 – 92.79%	C_2H_6 – 4.16%	C_3H_8 – 0.84%	C_4H_{10} – 0.18%
C_5H_{12} - 0.04%	C_6H_{14} – 0.04%	CO_2 – 0.44%	N_2 – 1.51%

FIRST LAW ANALYSIS

- From first law of thermodynamics, energy is conserved for any real process.

$$\eta_I = \frac{Useful\ Energy\ Output}{Energy\ Supplied\ to\ the\ Component}$$

- Useful Energy output: Electric Work for turbines, Energy gained by steam for boilers.

- For the whole plant,

$$\eta_{I,plant} = \frac{P_{total} + \Delta Q_{steam}}{Q_{input}}$$

$$\Delta Q_{steam} = m_{HPS} h_{HPS} + m_{LPS} h_{LPS} - m_{fw} h_{fw}$$

$$Q_{input} = m_{gas} e_{gas} + m_{oil} e_{oil}$$

SECOND LAW ANALYSIS

- From second law of thermodynamics, exergy (*X*) is the maximum useful work that can be obtained as the system interacts with the environment/dead state.

- Physical exergy of the working fluid and chemical exergy of the fuel stream is considered for the plant analysis.

Physical flow exergy : $$X_{ph,i} = m_A\left[\left(h_i - h_0\right) - T_0\left(s_i - s_0\right)\right]$$

Chemical exergy of fuel: $$X_{ch} = \varphi(NCV)^o$$

(***φ***: Ratio of constituent chemicals in the fuel)

- For a system with steady flow process,

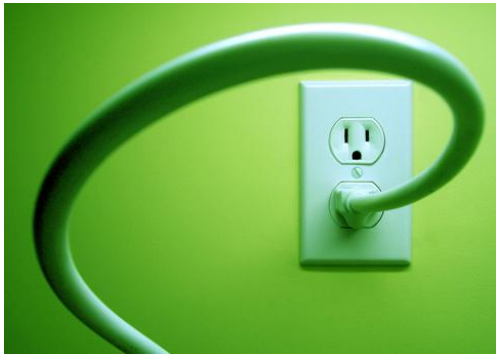
$$X_{dest} = X_{in} - X_{out}$$

- Second law efficiency or Exergy Efficiency is given by:

$$\eta_{II} = \frac{Exergy\ Output}{Exergy\ Input} = 1 - \frac{X_{dest}}{X_{in}}$$

PRODUCTION (2010)

- Electricity Supplied to the Campus – 82,546,185 kWh



- Steam Supplied to the Campus
  - 572,253,335 lbs @ 200 psig
  - 368,758,327 lbs @ 20 psig

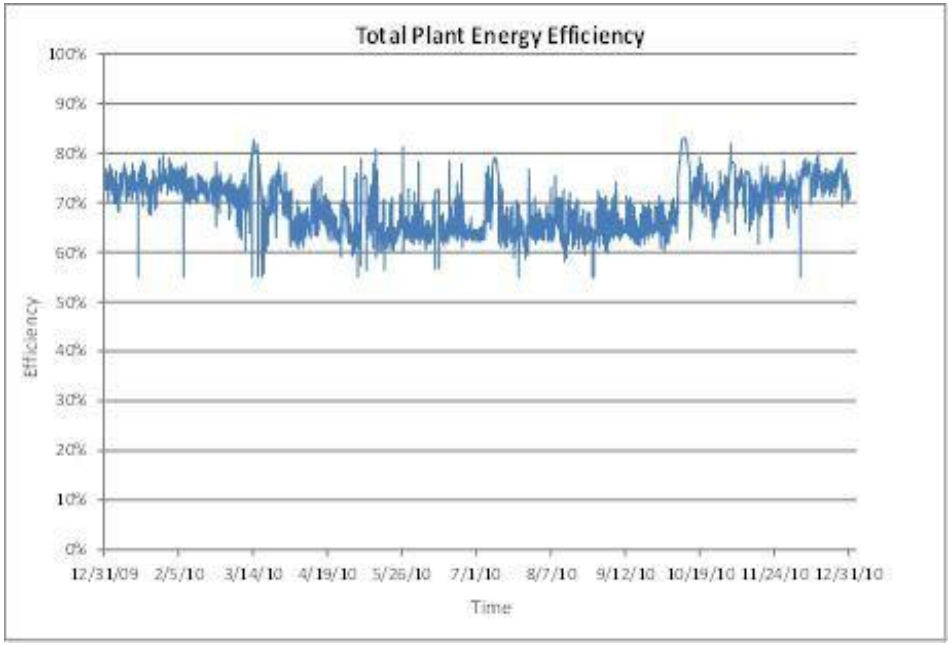
First law Efficiencies and Exergy loss from Components

Component	Operating Hours in 2010	Efficiency	Exergy Destruction per hour (kW)
CTG	8,152	η_I = 31.71%	7,001
HRSG	8,152 (4,431 Duct Burner On hours+ 3,721 Duct burner Off hours)	η = 82.31% (Duct Burner On) η = 68.13% (Duct Burner Off)	2,141
HPB	1,173	η_B = 85.94%	2,569
LPB1	4,368	η_B = 82.57%	1,959
LPB2	3,776	η_B = 81.63%	1,999
LPST	5,461	η_{isen} = 85.49%	902

Table: Operating hours, Efficiency and Exergy Destruction from plant components

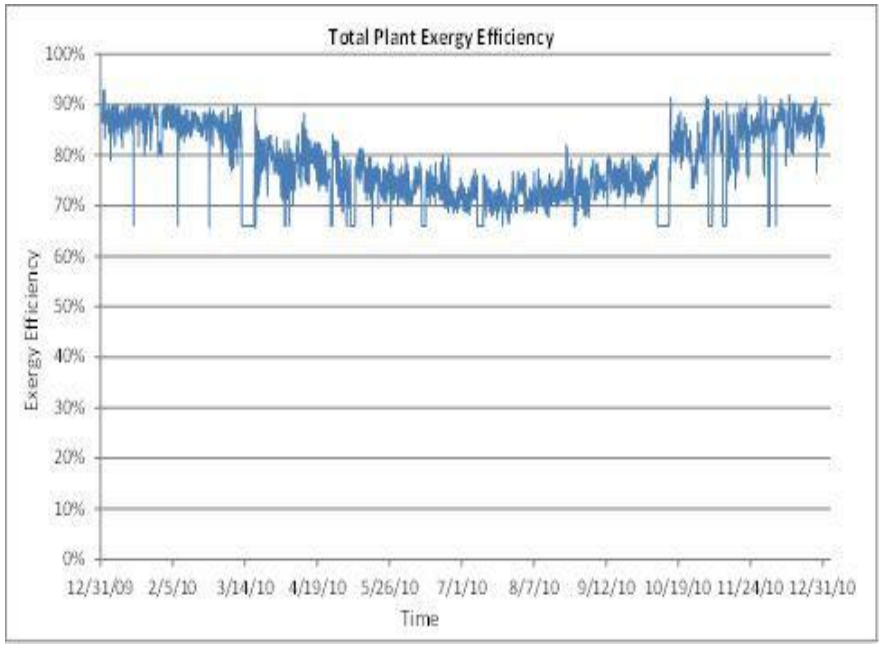
From Fuel Analyses done in UMASS CHP Plant,
LHV of Natural Gas – 19,700 Btu/lb
LHV of #2 Fuel Oil – 18,360 Btu/lb

Plant I law Efficiency



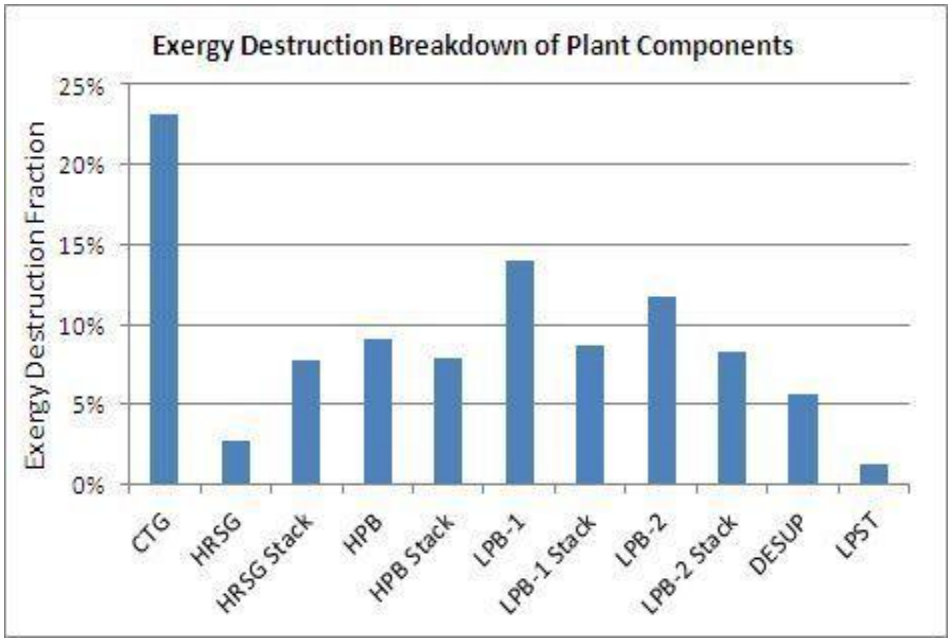
- The first law efficiency of the plant varies from 60% to 80%.
- The energy efficiency of the central heating plant has a seasonal behavior.
- With high requirements of steam during winter, energy efficiency of the plant increases

Plant II law Efficiency



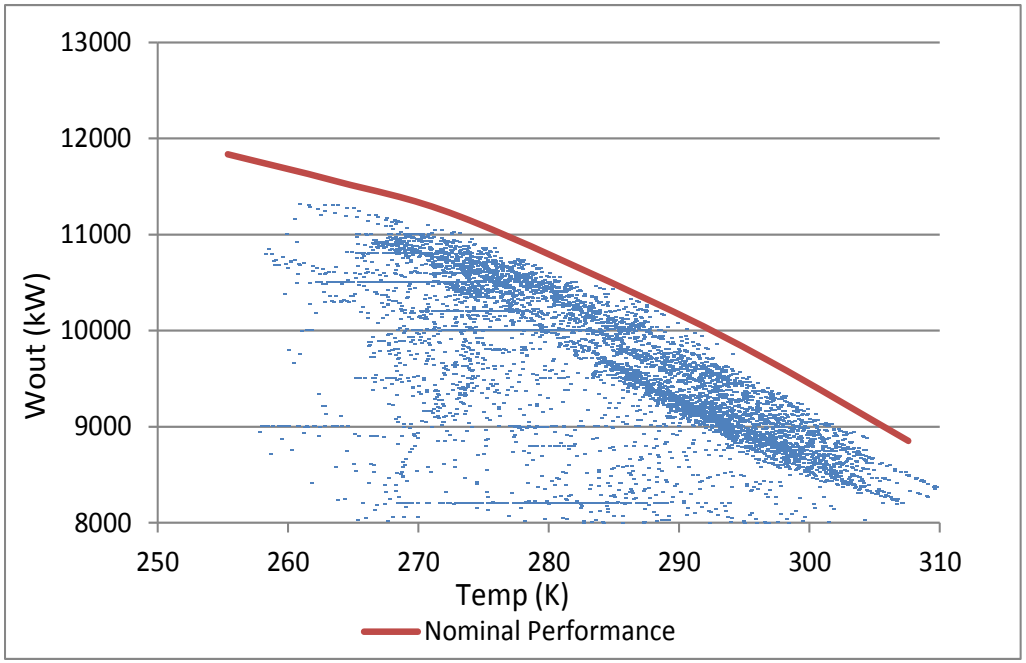
- The exergy efficiency of the central heating plant varies from 68% to 90%.
- The overall plant efficiencies are higher for winter (November till April) compared to summer (May till October).
- These can be attributed to the variations in plant productivity in the form of electric power and steam generated.

Normalized Exergy Loss from Components



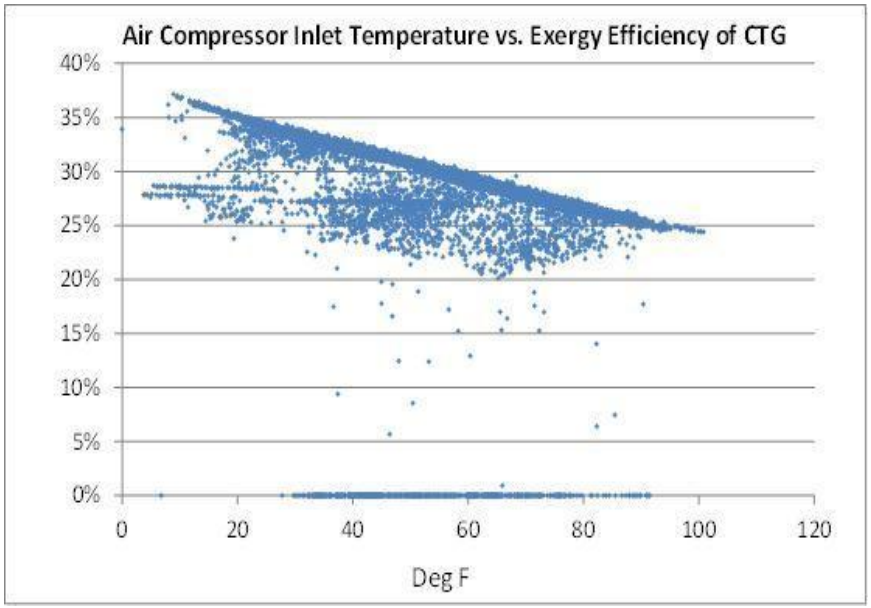
- Exergy Analysis can be used as a tool for analyzing components which are totally different in functionalities
- The CTG and the three boilers have the maximum contribution to exergy destruction.
- The 4-MW steam turbine has least amount of exergy destruction, contributing less than 2% of total losses.

Variation of Power Generated with Inlet Air Temperature



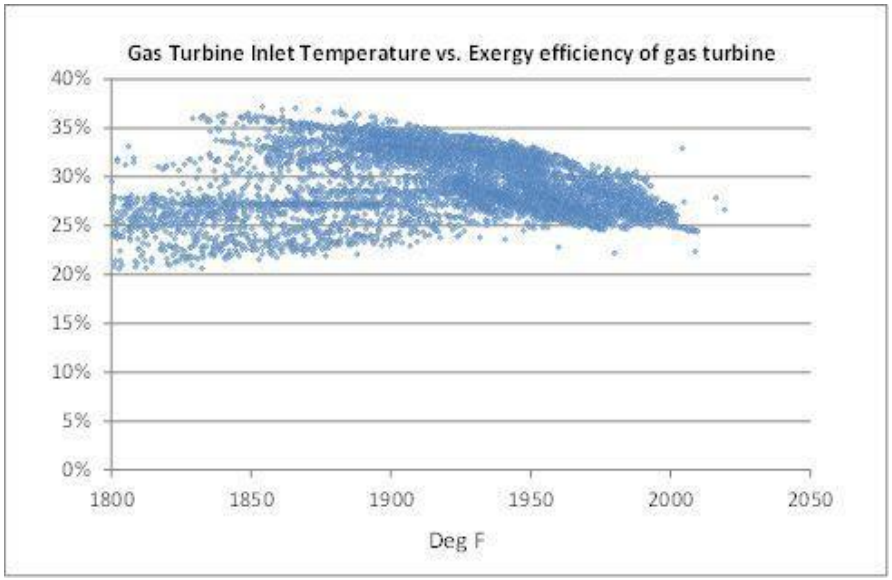
- Comparison of actual performance with manufacturer's standards.
- Inlet and exhaust losses.

Variation of Exergy Efficiency with Inlet Air Temperature



- The maximum exergy efficiency of the gas turbine is 37.2%
- The exergy efficiency of the combustion gas turbine is dependent on the ambient air temperature.
- For improved efficiency, the inlet air can be cooled with an absorption chiller utilizing the heat energy available from the HRSG.

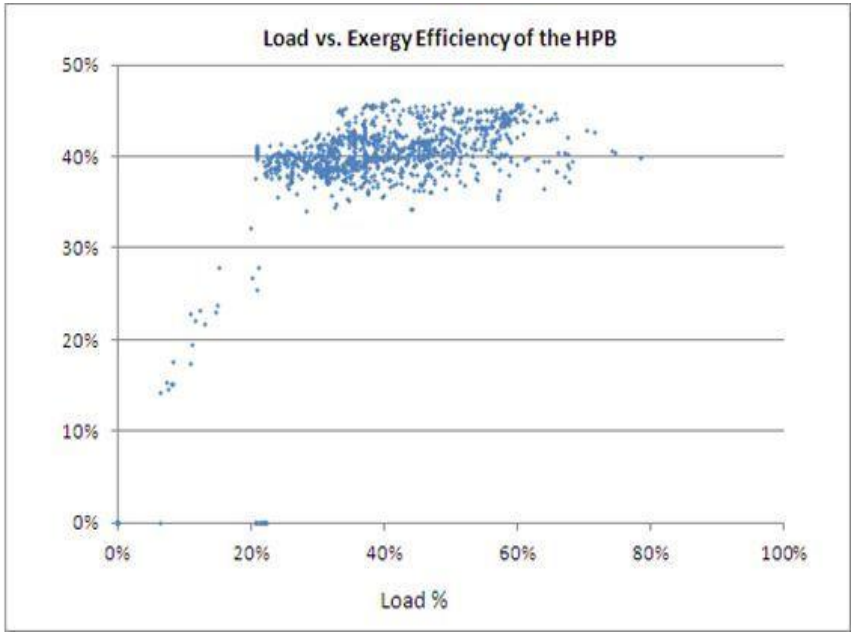
Variation of Exergy Efficiency with Turbine Inlet Temperature



- From the figure, the optimum temperature at turbine inlet for maximum efficiency is approximately 1860°F.

- The exergy efficiency increases with turbine inlet temperature till 1860°F and then drops with increase in temperature.

Variation of Exergy Efficiency with Boiler Load



- The graph of load vs. exergy efficiency for the low pressure boilers show similar profile.
- The data obtained from the power plant shows that there were times when both the low pressure boilers were running at loads below 50%.
- An improved way will be to run either of the low pressure boilers with the necessary steam requirement.

CONCLUSIONS

- Energy and exergy efficiencies and exergy of the plant for all the 8,760 hours in 2010 were evaluated.
- It is observed that the major source of irreversibility in the plant is the CTG, contributing 23.10% of total exergy losses.
- The CTG and the boilers collectively contribute to approximately 60% of the total plants' exergy loss since there is a large temperature difference between the flame and the working fluids in these combustion machines.
- The exergy efficiency of the CTG decreases with increase in inlet air temperature.
- The low pressure boilers must be run in a more effective way to increase exergy efficiency.
- The results show thermodynamic analysis can be used to compare various components in a power plant based on their performance.

QUESTIONS & COMMENTS