
"Well, back to the old drawing board."

Advantages of Compound Cycle Cogeneration

27 February 2019

Agenda

1. Start With Why
2. System Comparison - Overview
3. Cogeneration Analysis Techniques
4. System Comparison - Results
5. Conclusions & Recommendations
6. Question and Answers

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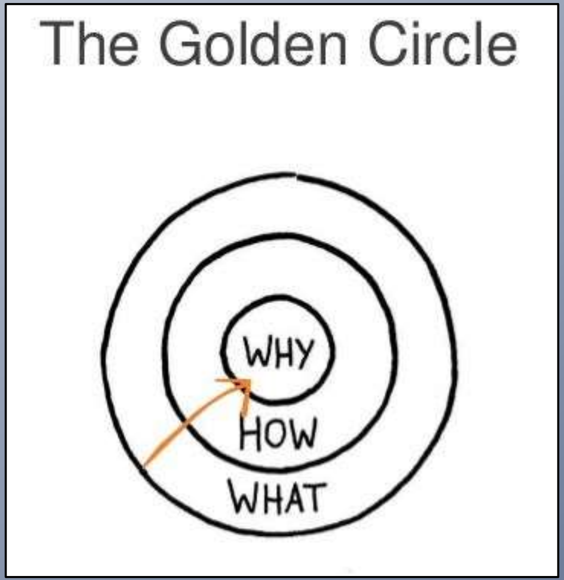
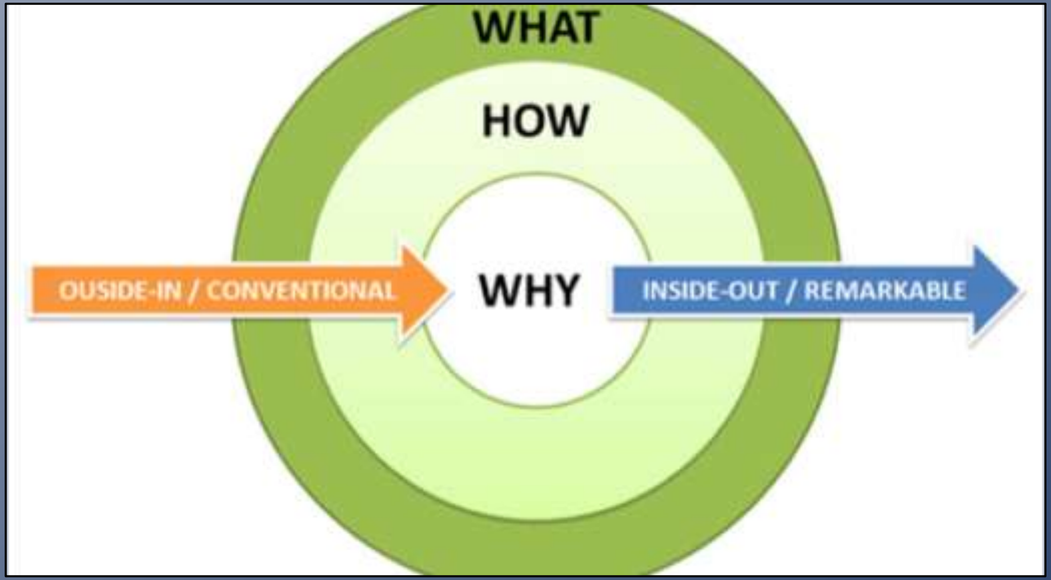
Start With Why

- The Golden Circle:
  1. Why = Our Cause, Our Beliefs
  2. How = The Actions We Take
  3. What = Daily Tasks

- Why = Deliver Energy More Efficiently
- "What Tools Do We Have?"
- "What Role Do We Take?"
- "What Information Do We Share?"





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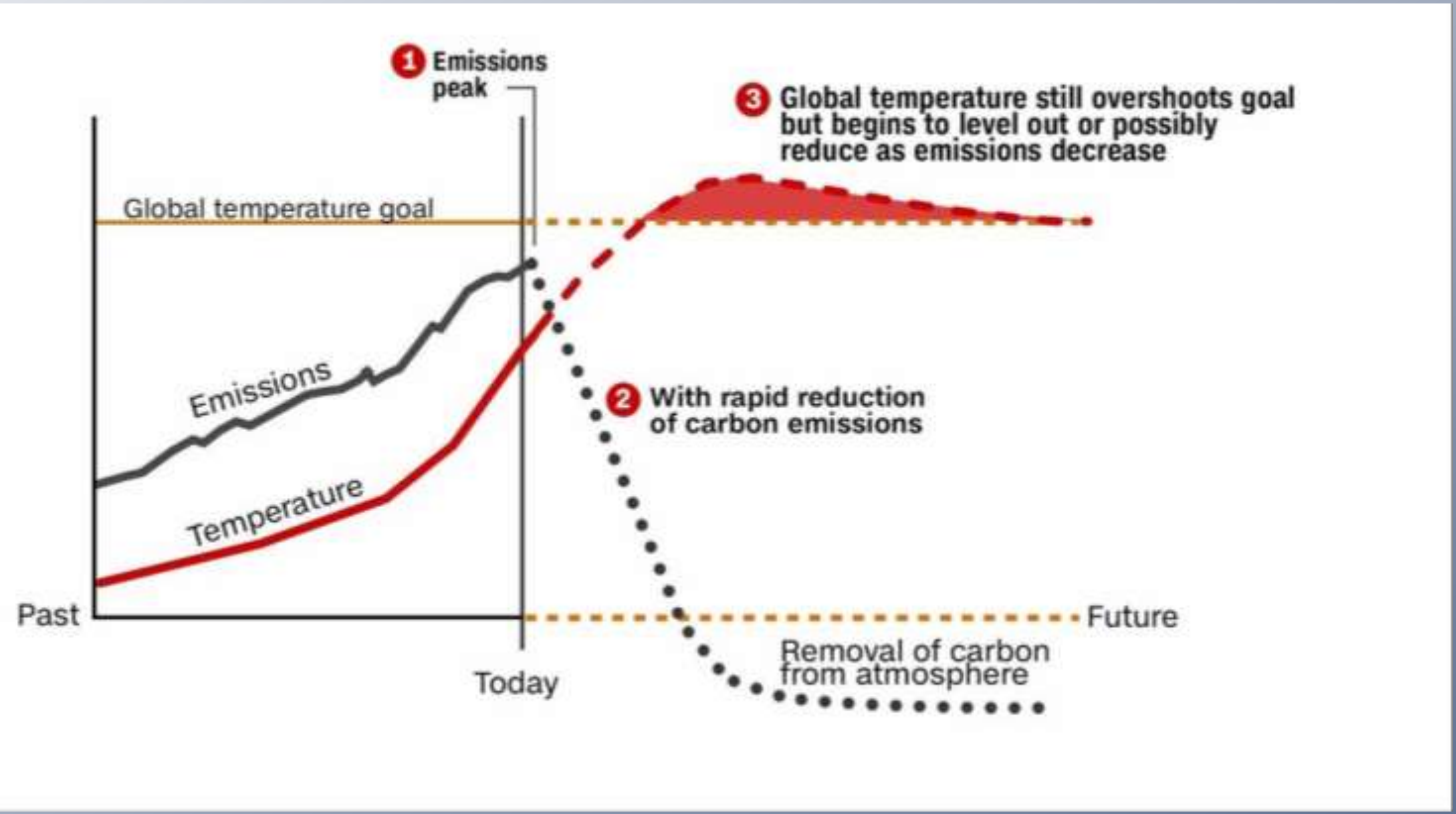
Business As Usual (BAU)



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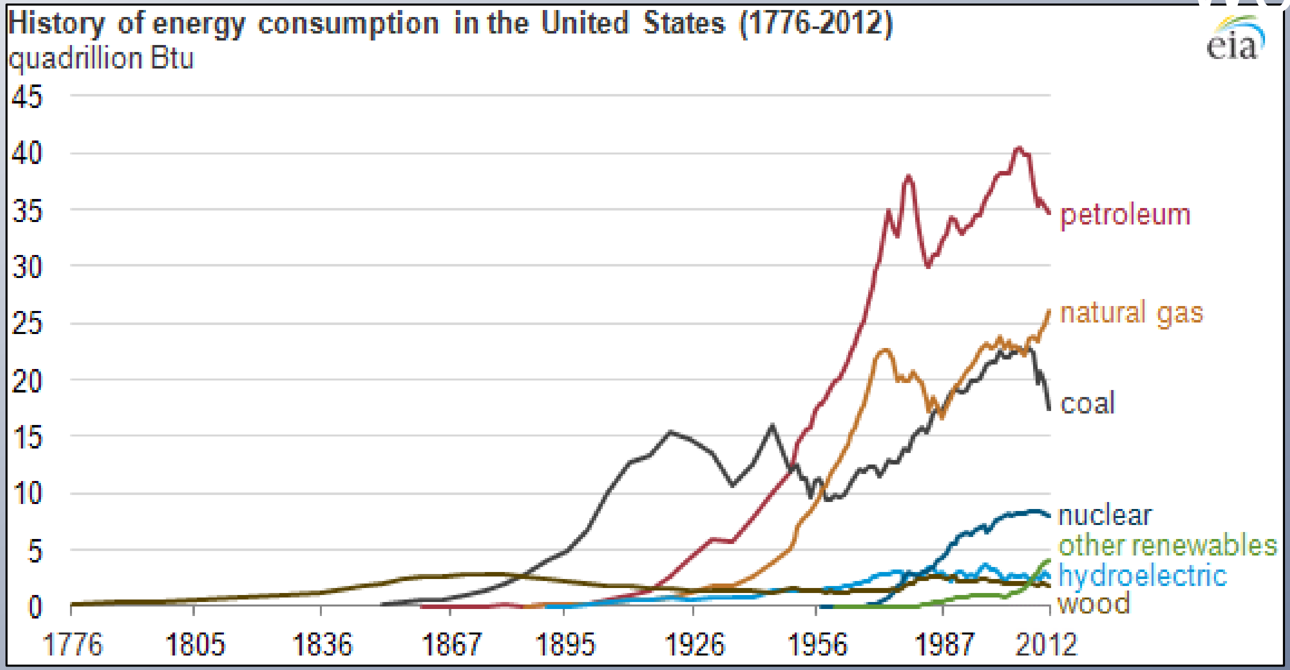
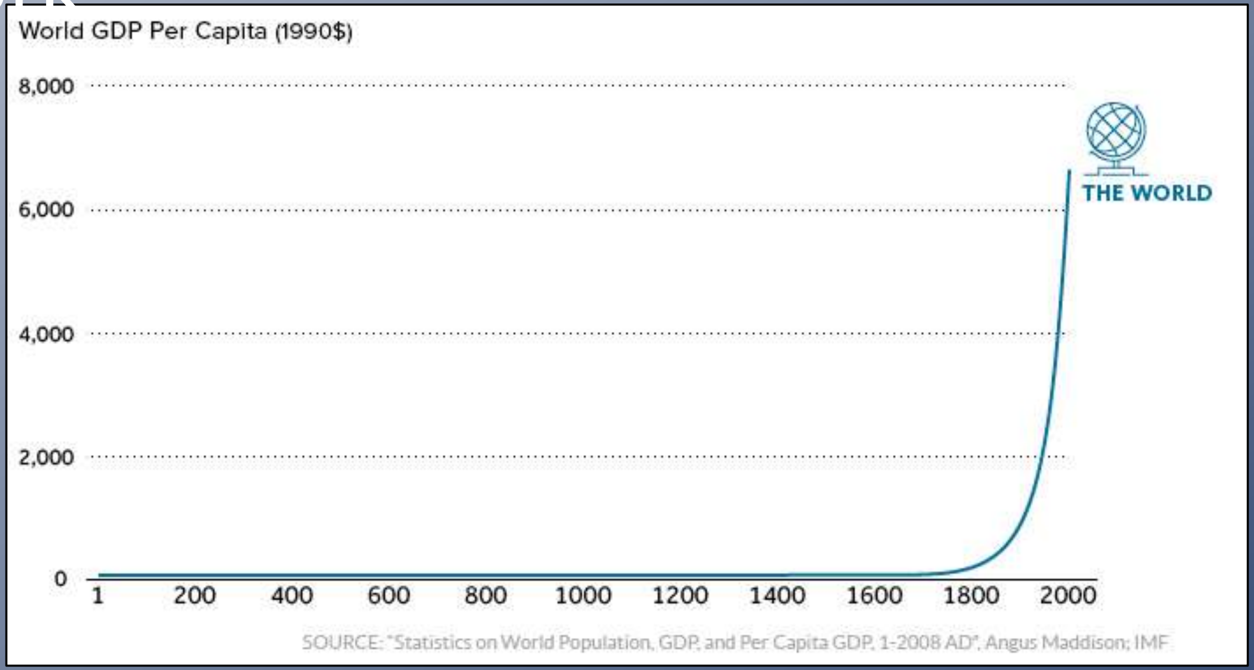
Why Energy Efficiency

"Energy Is Work Or The Capacity To Do Work"





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Impact Of Increased Efficiency

- Incandescent Bulb = 13 Lum/W
- Total Watts Required = 61 W
- Grid Efficiency = 95%
- Generated Watts = 64 W
- Generation Efficiency = 42.5%
- Total Watts Required = 151 W

- LED Fixture = 95 Lum/W
- Total Watts Required = 8 W
- Grid Efficiency = 95%
- Generated Watts = 8.4 W
- Generation Efficiency = 42.5%
- Total Watts Required = 19.8 W

One Lightbulb Retrofit Can Save
131 Watts

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Start With Why

1. Second Law of Thermodynamics:
    - "A Machine Whose Working Fluid Undergoes A Cycle Cannot Absorb Heat From A High Temperature Sink And Produce Shaft Work Without Rejecting Heat To A Lower Temperature Receiver."
2. More Effective Use of Rejected Heat:
    - "The Obvious Way To Improve The Effectiveness Of Use Of The Input Energy, Then, Is To Put The Heat Rejected By The Cycle To Some Beneficial Use." – Bill Coad

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Compound Generation

- Burn Natural Gas To Generate Electricity (Gas Turbine)
- Utilize A Duct Burner and Heat Recovery Steam Generator
- Condense Steam To Generate Electricity (Steam Turbine Generator)
- Distribute Steam And Electricity To Campus

- Are All The Added Complexities Worth The Additional Step?
- One Field Trip Sparked The Following Analysis

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System Descriptions

1. Conventional System
   - Purchase Electricity And Natural Gas
2. System “X”
   - Purchase Natural Gas To Generate Electricity
3. System “Y”
   - Compound Cycle With Condensing Steam (Mizzou Setup)
   - Solar Titan 130-20500 Gas Turbine (13.5 MW @ 13.8kV)
4. System “Z”
   - Compound Cycle Without Condensing Steam By Cooling Towers
   - Matching Campus Heating Needs And Heating Production Exactly

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System Descriptions - Assumptions

System	Electrical Output (kW)	Annual Electrical Output (kWh)	Annual Natural Gas Use (MMBtu)	Recovered Heat (MMBtu)
System "X"	13,477	112,155,594	1,404,060	440,580
System "Y"	21,446	178,470,277	2,014,204	440,580
System "Z"	18,429	153,365,527	2,014,060	799,375

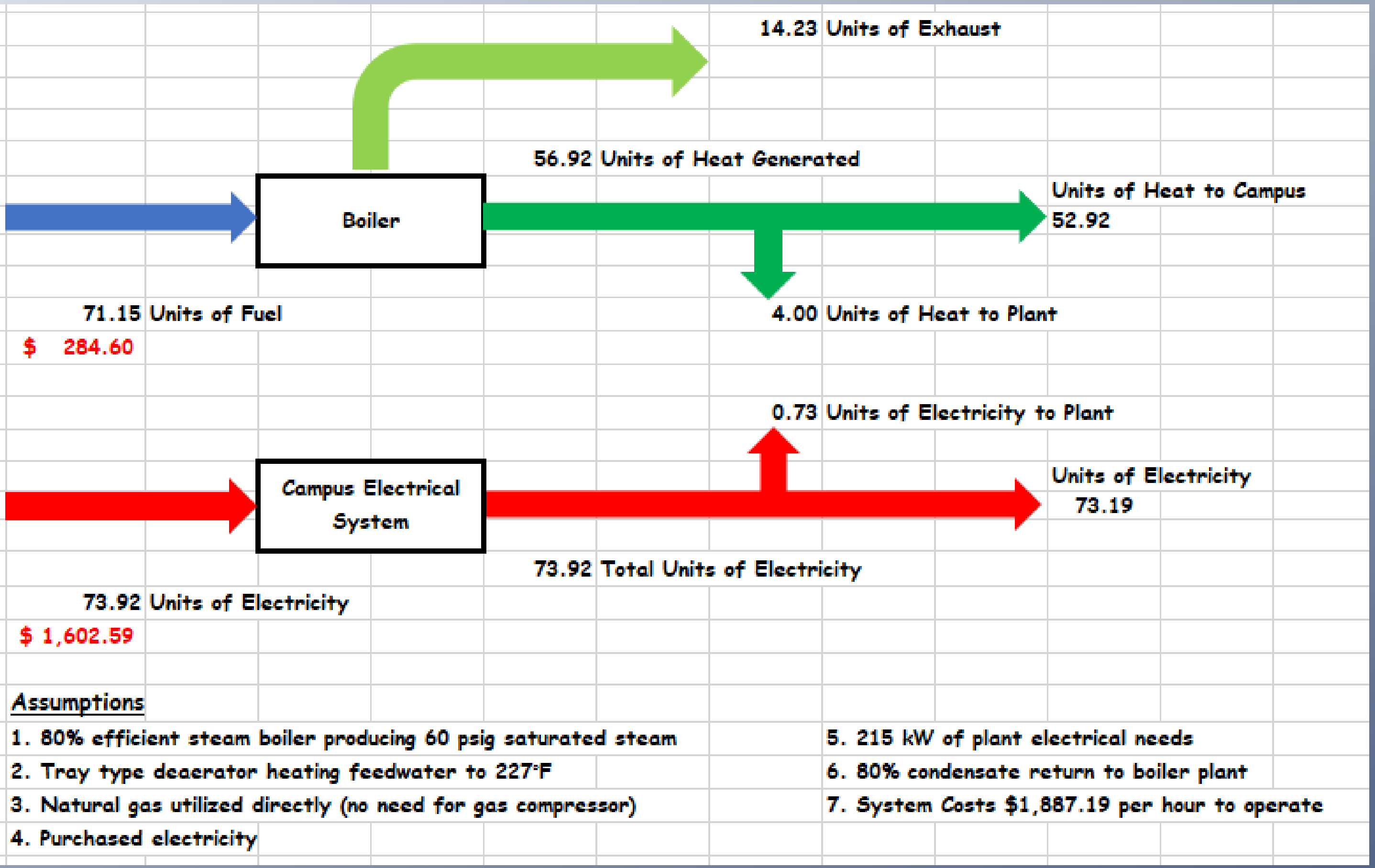
Plant Assumptions and Pro Forma

Natural Gas Cost =	$4.00	per MMBtu
Purchased Electricity Cost =	$0.074	per kWh
Steam Utilization =	100%	
Electrical Utilization =	100%	
Plant Availability =	95%	

Annual Plant Utility Production

Annual Steam Production =	957,717,000	lbs
Annual Electrical Production =	216,266,000	kWh
Cooling Production =	57,071,426	ton-hours
Annual Biomass Use =	120,000	tons
Assumed Biomass Combustion Efficiency =	72%	
Assumed Gas Boiler Combustion Efficiency =	80%	
Assumed Biomass Heat content =	5,160	Btu/lb
Annual Biomass Heat Production =	891,648	MMBtu
Annual Biomass Steam Production =	814,513,565	lbs

Conventional System



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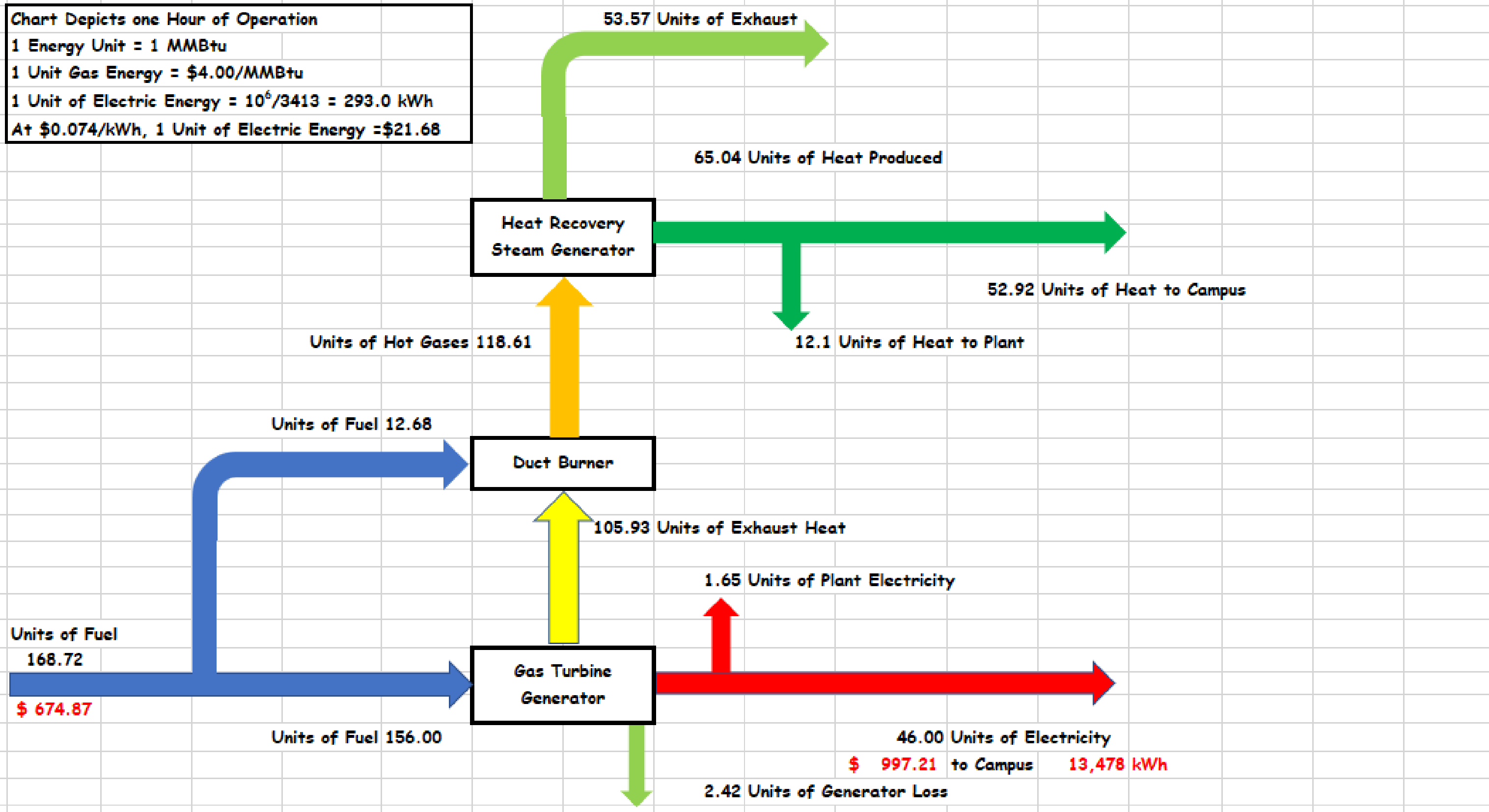
System "X" – Standard Cogeneration

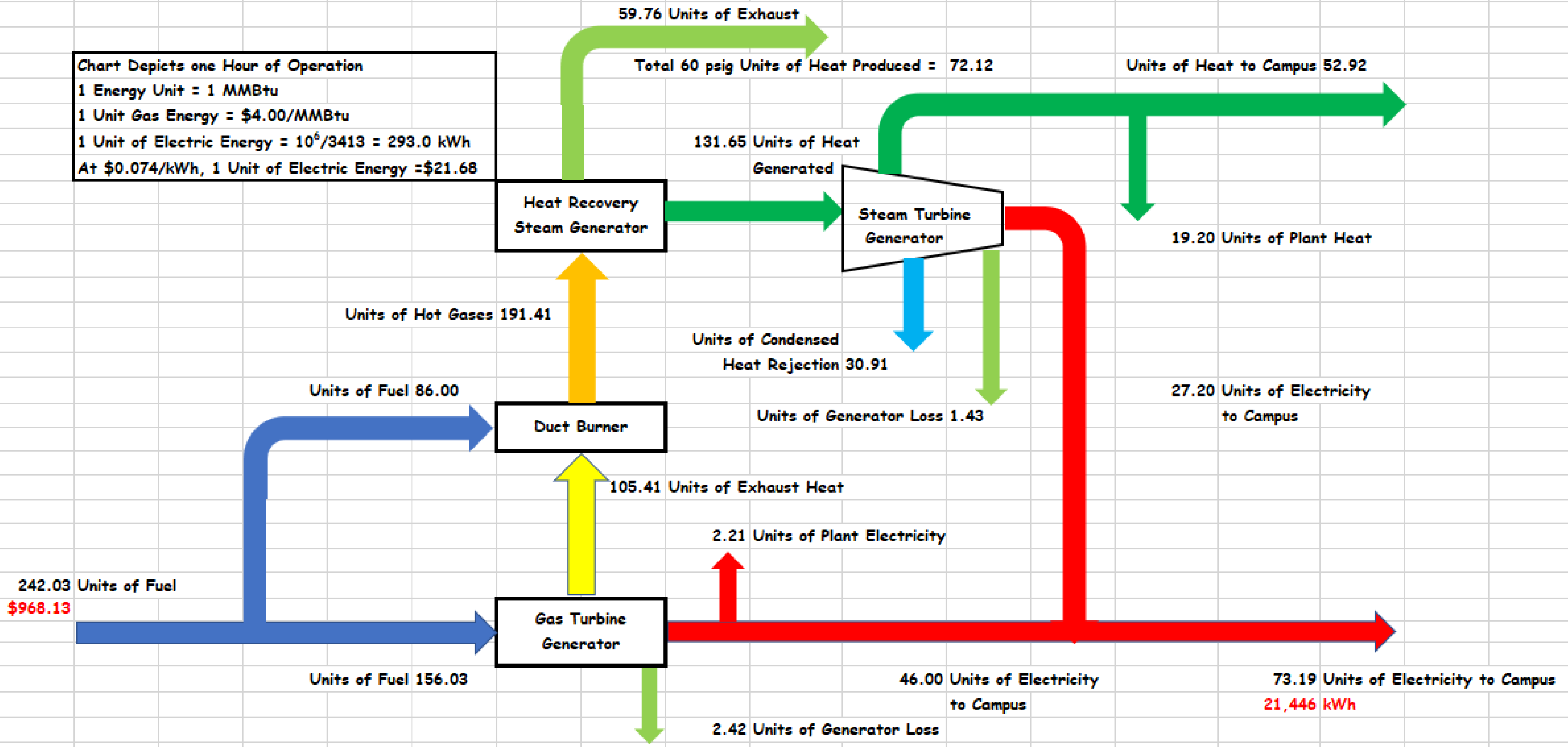


<u>Assumptions</u>

1. Gas Turbine Generator 30% efficient
2. Heat Recovery Steam Generator 55% efficient
3. Maximum duct firing based on the oxygen content available in the turbine exhaust
4. Pressure and temperature off the HRSG is 60 psig saturated
5. ~~Extraction Steam is at 60 psig and condensing steam is at 1.5 psia (115°F)~~
6. ~~Isentropic steam turbine efficiency is 75%~~
7. ~~Steam Turbine and~~ Gas Turbine Generator Efficiency is 95%
8. ~~Steam Turbine Operation considered at 70% Extraction and 30% Condensing~~
9. ~~Steam Turbine Heat Rate at 60 psig Extraction = 22,702 Btu/kWh~~
10. ~~Steam Turbine Heat Rate at 1.5 psia Condensing = 9,829 Btu/kWh~~
11. Plant Heat includes Deaerator and Feedwater Heater
12. Plant Electricity includes Gas Compressor, Condensate Pump, Feedwater Pump, and Turbine Auxiliaries

Cost of Fuel =	$ 674.87
Value of Electricity Produced =	$ 997.21
Value of Heat Produced =	$ 264.60
Savings per Hour of Operation =	$ 586.95

System "Y" – Compound Cogeneration

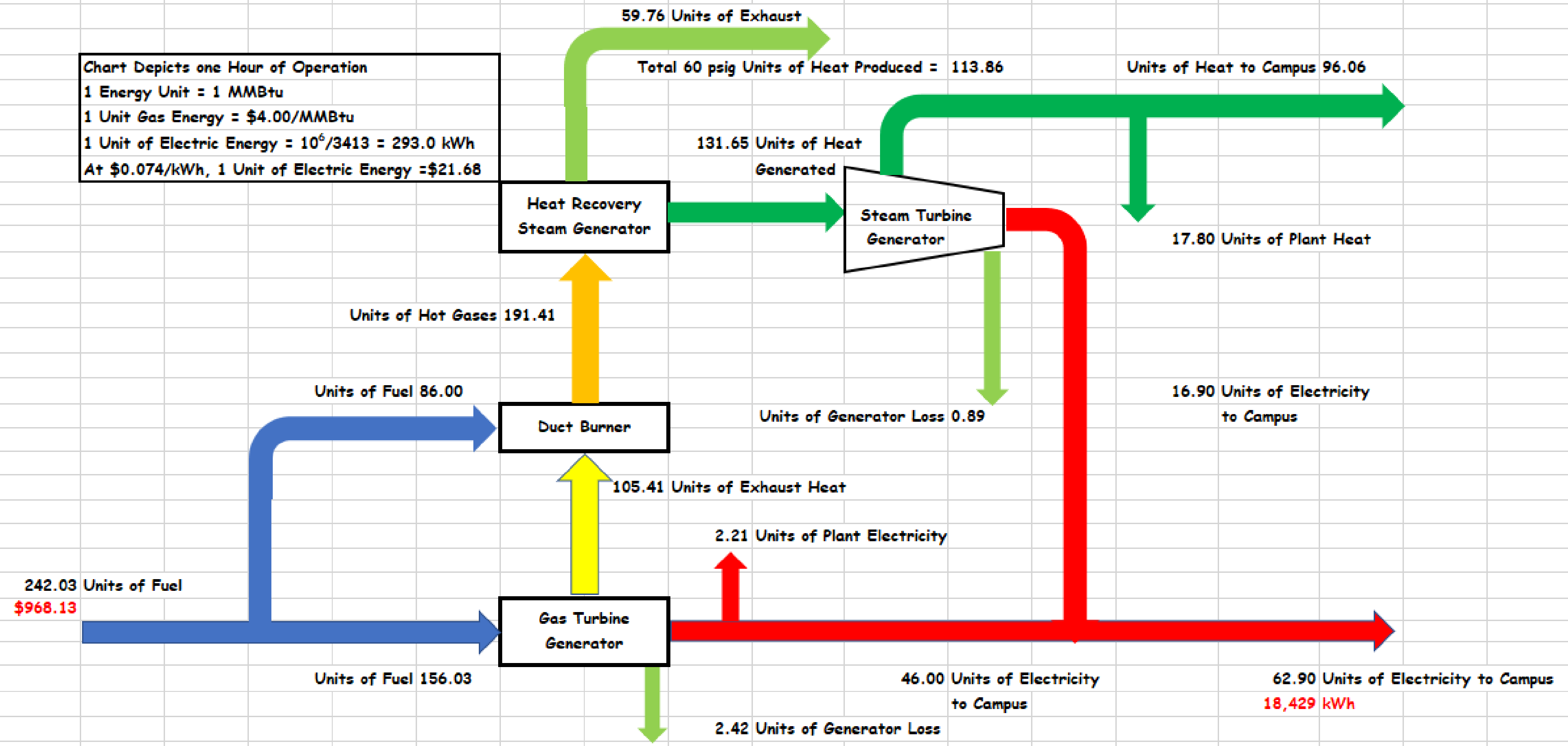


Net Electrical Efficiency η_E =	30.2%	Value of Input Energy =	968.13
Overall CHP System Efficiency η_o =	60.0%	Value of Output Electrical Energy =	1,586.99
Electric Effectiveness ε_{EE} =	48.2%	Value of Output Heat =	360.58
		Total Value of Output Energy =	1,947.57
		Savings per Hour of Operation =	979.43

Assumptions

1. Gas Turbine Generator 30% efficient
2. Heat Recovery Steam Generator 69% efficient
3. Maximum duct firing based on the oxygen content available in the turbine exhaust
4. Pressure and temperature off the HRSG is 900 psig, 850°F
5. Extraction Steam is at 60 psig and condensing steam is at 1.5 psia (115°F)
6. Isentropic steam turbine efficiency is 75%
7. Steam Turbine and Gas Turbine Generator Efficiency is 95%
8. Steam Turbine Operation considered at 70% Extraction and 30% Condensing
9. Steam Turbine Heat Rate at 60 psig Extraction = 22,702 Btu/kWh
10. Steam Turbine Heat Rate at 1.5 psia Condensing = 9,829 Btu/kWh
11. Plant Heat includes Deaerator and Feedwater Heater
12. Plant Electricity includes Gas Compressor, Condensate Pump, Feedwater Pump, and Turbine Auxiliaries

System "Z" – Compound Cogeneration



Net Electrical Efficiency η_E = 26.0%		Value of Input Energy =	968.13
Overall CHP System Efficiency η_o = 73.0%		Value of Output Electrical Energy =	1,363.75
Electric Effectiveness ε_{EE} = 63.1%		Value of Output Heat =	569.30
		Total Value of Output Energy =	1,933.06
		Savings per Hour of Operation =	964.92

Assumptions

1. Gas Turbine Generator 30% efficient
2. Heat Recovery Steam Generator 69% efficient
3. Maximum duct firing based on the oxygen content available in the turbine exhaust
4. Pressure and temperature off the HRSG is 900 psig, 850°F
5. Extraction Steam is at 60 psig ~~and condensing steam is at 1.5 psia (115°F)~~
6. Isentropic steam turbine efficiency is 60%
7. Steam Turbine and Gas Turbine Generator Efficiency is 95%
8. Steam Turbine Operation 100% Extraction and 0% Condensing
9. Steam Turbine Heat Rate at 60 psig Extraction = 29,253 Btu/kWh
10. ~~Steam Turbine Heat Rate at 1.5 psia Condensing = 9,829 Btu/kWh~~
11. Plant Heat includes Deaerator and Feedwater Heater
12. Plant Electricity includes Gas Compressor, Condensate Pump, Feedwater Pump, and Turbine Auxiliaries

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3. **Cogeneration Analysis Techniques**
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Typical Cogeneration Analysis Techniques

1. Single Equation For Cogeneration
   - Developed By Bill Coad
   - Approach To Producing Chilled Water
2. Life Cycle Cost Analysis
   - Published in ASHRAE by Michael Schwarz
3. "Best Case" Simple Payback
   - The Jerry Williams Approach
   - First Pass Estimate (With Great Detail)
4. Monte Carlo Simulation
   - Since No System Is Ever Static

Single Equation For Cogeneration

$$K_G = F(10^{-4})\left[R - \left(\frac{1}{\lambda_B}\right)(H_r U_H)\right] - (\frac{1}{A_R})(E_R U_C H_R K_P) + M + I + X$$

K_G = cost to generate electricity, cents per kWh

R = prime mover fuel rate, Btu per kWh

F = cost of fuel, $ per million Btu

H_r = salvage heat available, Btu per kWh

λ_B = boiler efficiency in producing heat from fuel

U_H = utilization ratio for recovered heat

M = cost of maintenance, cents per kWh

I = amortized investment cost, cents per kWh

X = any other fixed cost, cents per kWh

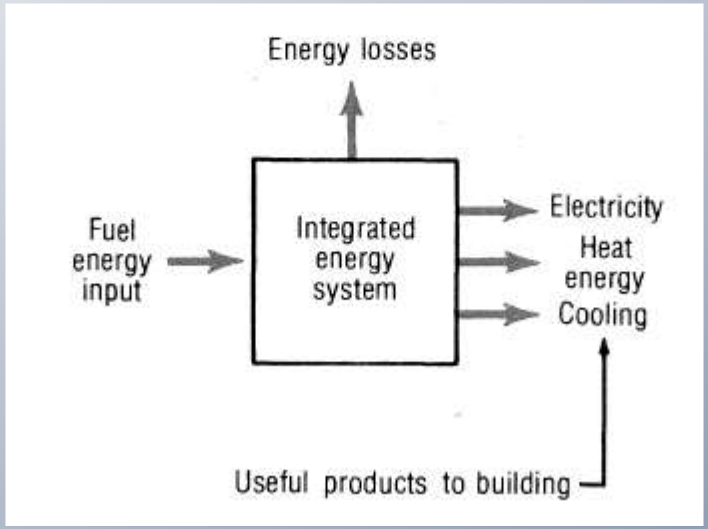
A_R = fluid heat rate for absorption cooling, Btu per ton-hr

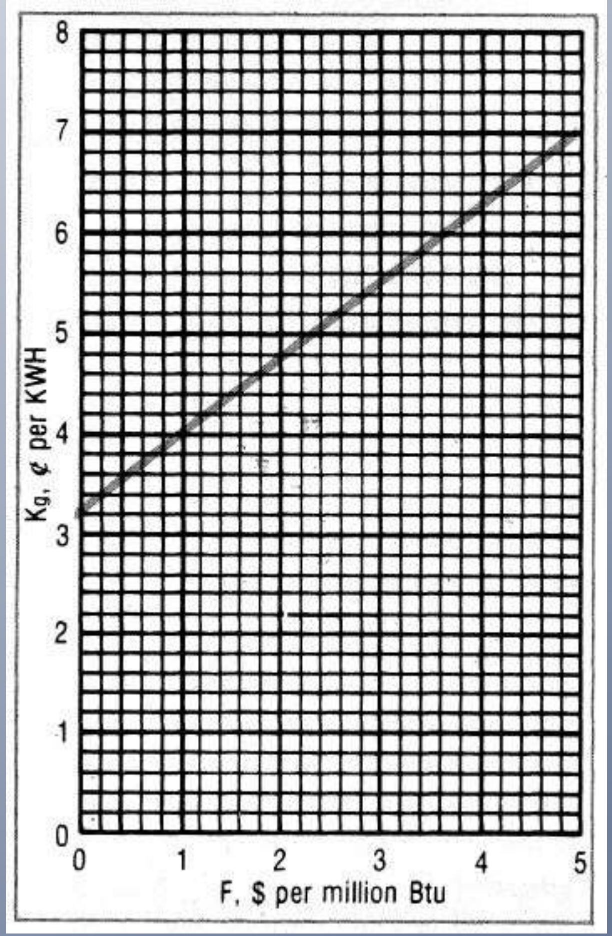
E_R = energy requirement for compression refrigeration, Kw per ton

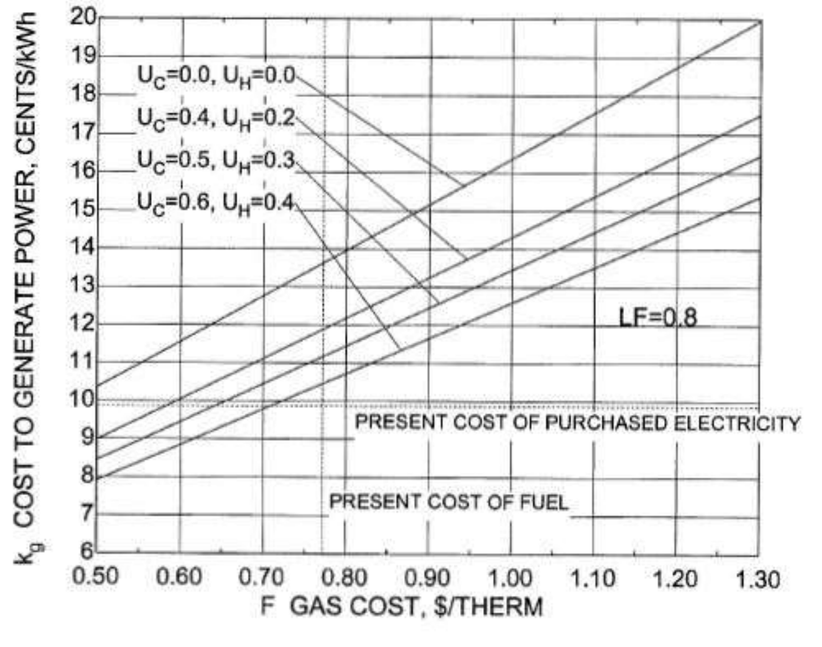
K_P = cost of purchased electricity, cents per kWh generated

U_C = utilization ratio for heat recovered for cooling

Single Equation For Cogeneration







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Life Cycle Cost Analysis
Michael Schwarz

TABLE 3 CHP reciprocating engine example life-cycle cost analysis.

	PURCHASED ELECTRICITY (Existing Condition)	CHP (On-Site 2500 kW CHP)	NOTES
UNIT DATA			
Installed Power Generation Capacity (kW)	N/A	2500	CHP Size
Average Annual Energy Available (kWh)	21,900,000	21,900,000	
CapEx			
Total Installation Costs	$0	$3,750,000	Assumes $1500/kW Installed CHP Plant Capacity and That System is Being Installed as a Retrofit; Therefore, No Capital cost Offset is Assumed for Displaced Boilers or Other Equipment.
OpEx			
Electric Utility Rate ($/kWh), Consumption	$0.11	$0.11	
Electric Utility Rate ($/kW), Demand	$2.35	$2.35	Monthly Peak Demand Rate
Electric "Sell-Back" Rate for Unused Power ($/kWh)	-	$0.06	
Natural Gas Utility Rate ($/therm)	$0.91	$0.91	
CHP System Availability (% of year)	-	90%	
Building Power Utilization (% Annual Generation)	-	75%	
Annual Electric Consumption/Generation (kWh)	14,782,500	-19,710,000	
Annual Electric Cost ($)	$1,696,575	-$295,650	Purchased Electricity Cost Includes Monthly 2,500 kW Additional Demand
Annual Gas Consumption (therms)	-	2,069,333	Assumes 32.5% Power Generation Efficiency
Annual Gas Cost ($)	-	$1,883,093	
Annual Waste Heat Available (Mbtu)	-	96,076,170	Thermal Credit. Assumes CHP Power-to-Heat Ratio of 0.7.
Waste Heat Thermal Utilization (%)	75%	-	Measure of Available CHP Thermal Energy That is Used
Annual Waste Heat Equivalent Gas Cost ($)	$1,008,800	-	Displaced Thermal Fuel Cost. Assumes 65% Total Efficiency for Steam Boiler Plant Operation in Base Case for Energy Comparison
Annual Maintenance Cost ($)	$0	$295,650	$0.015/kWh Maintenance Cost
Total Year 1 OpEx	-$2,705,375	-$1,883,093	
Incentive(s)	N/A	$375,000	Federal Renewable Energy Investment Tax Credit of 10% of Construction Cost Included in Year 1 (No Maximum Credit)
Unit Replacement Cost	N/A	N/A	

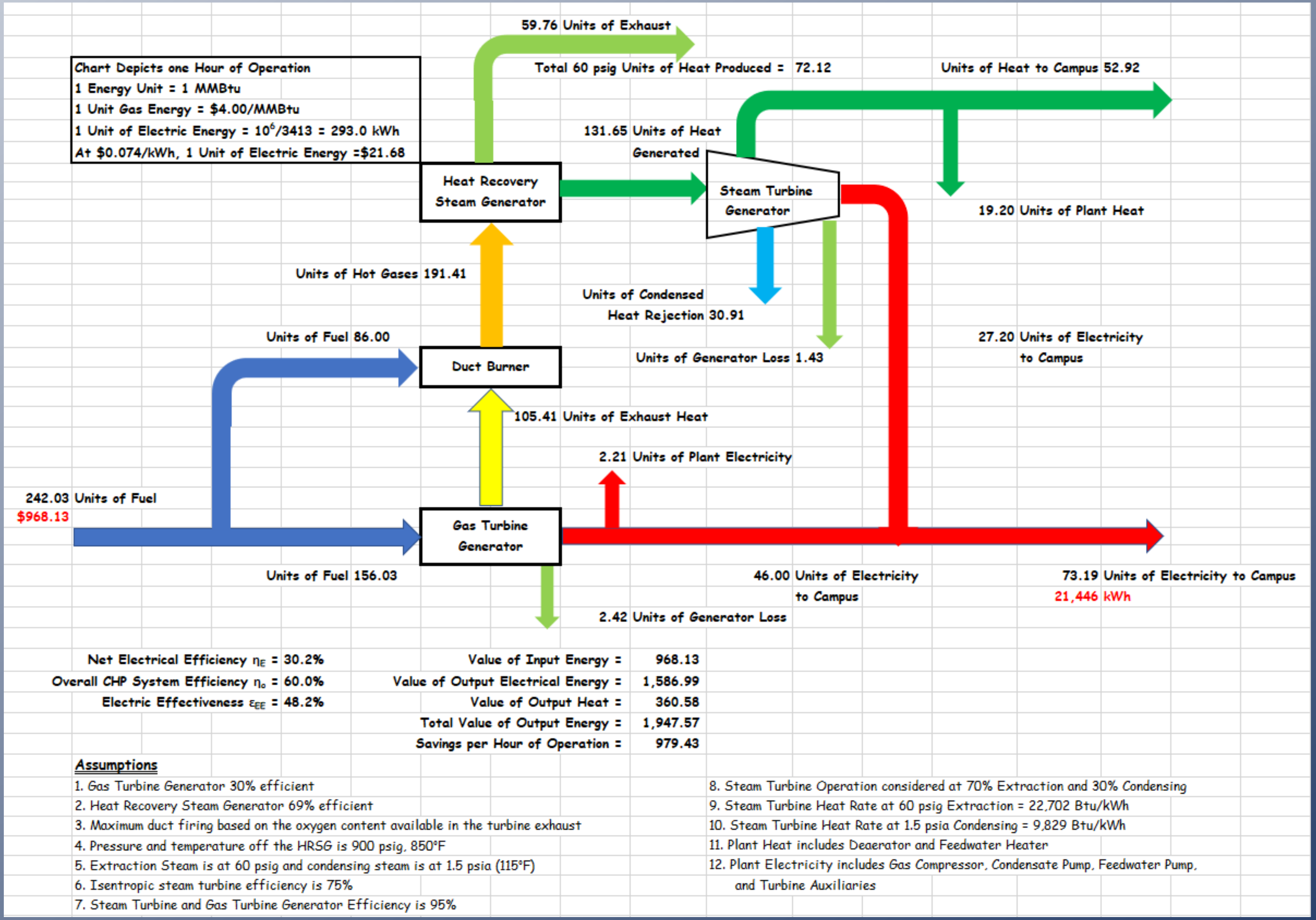
Life Cycle Cost Analysis Michael Schwarz (cont.)

TOTAL COST OF OWNERSHIP (TCO)			
Discount Rate	15%	15%	The Interest Rate Used for Discounting (Rate That Reflects an Investor's Opportunity Cost of Money Over Time and Minimum Acceptable Rate of Return)
Operating Cost Inflation Rate	5%	5%	
Initial Cost of Investment	$0	-$3,375,000	
2	-$2,840,644	-$1,977,248	OpEx - Year 2, Adjusted for Inflation
3	-$2,982,676	-$2,076,110	OpEx - Year 3, Adjusted for Inflation
YEARS 4 THROUGH 19 HIDDEN FOR CLARITY			
20	-$6,836,347	-$4,758,482	OpEx - Year 20, Adjusted for Inflation
Simple Payback (Years), No Incentives	-	4.6	Total Installation Costs/Difference In Total Year 1 OpEx
Simple Payback (Years), with Incentives Included	-	4.1	(Total Installation Costs-Incentive)/Difference In Total Year 1 OpEx
5-Year NPV (With Incentives)	-$11,370,200	-$11,289,298	Year 1-5
10-Year NPV (With Incentives)	-$17,391,990	-$16,311,217	Year 6-10
15-Year NPV (With Incentives)	-$23,163,091	-$19,497,813	Year 11-15
20-Year NPV (With Incentives)	-$26,068,050	-$21,519,828	Year 15-20

- Published in August 2017 ASHRAE Journal
- Comparison To Business-As-Usual (BAU)
- 20-Year Timeline

Best Case Simple Payback

- Perfected By Jerry Williams
- Detailed Approach
- "Must Draw It To Understand It"
- Savings Over First Cost
- First Pass Analysis
- Typically Requires Further Analysis Before Final Recommendation (But Not Much)



Best Case Simple Payback

Combined Cycle Powerplant Performance Characteristics - Option X - Maximum Duct Firing

State Point	Media	Pressure (psig)	Pressure (psia)	Temperature (°F)	Quality (%)	Enthalpy (Btu/lb)	Entropy (Btu/lb-°R)	Specific Volume (ft^3/lb)	Specific Heat (Btu/lb-°R)	Heat Rate (Btu/kWh)	Steam Rate (lb/kWh)	Flow (scfh)	Flow (lb/hr)	HHV Flow (MMBtu/hr)	Voltage (kV)	Power (kW)
1	Total Natural Gas	50										231,833		242.0		
2	Natural Gas to Turbine	343										149,458		156.0		
3	Ambient Air		14.7	55												
4	Flue Gas Off Gas Turbine			944					0.280				384,450			
5	Superheated Steam	900		850	Steam	1,422.7	1.602	0.798								
6	Superheated Steam	60		375	Steam	1,218.7	1.673	6.455		22,702	18.48					
7	Steam Off Turbine		1.5	115	93.0	1,026.0	1.944	228.435		9,829	9.43					
8	Saturated Condensate		1.5	115	Liquid	83.0	0.156	0.016								
9	Subcooled Condensate				Liquid	83.0	0.156	0.016								
10	Subcooled Condensate		14.7	180	Liquid	148.0	0.263	0.017								
11	Subcooled Condensate		14.7	159	Liquid	124.0	0.225	0.016								
12	Saturated Condensate	5		227	Liquid	195.4	0.335	0.017								
13	Subcooled Condensate	900		227	Liquid	197.4	0.333	0.017								
14	Subcooled Condensate	900		300	Liquid	271.3	0.436	0.017								
15	City Water		14.7	60	Liquid	28.1	0.056	0.016								
16	Superheated Steam	5		380	Steam	1,228.3	1.784	16.653								
17	Generated Electricity														13.8	7,969
18	Generated Electricity														13.8	13,477
19	Generated Electricity														13.8	21,446
20	Flue Gas Off HRSG			422									384,450			
21	Natural Gas to Duct Burner											82,375		86.0		
22	Natural Gas to Compressor													156.0		
23	Flue Gas Off Duct Burner			1,645												

Steam Turbine Efficiency =	0.78	Gas Turbine Heat Rate (HHV - Btu/kWh) =	11,578	Steam Turbine Generation from Extraction (kW) =	4,331	HRSG Efficiency =	68.8%
Correction for Single Extraction =	0.96	Gas Turbine Heat Required (HHV - MMBtu/hr) =	156.0	Steam Turbine Generation from Condensing (kW) =	3,638		
Overall Steam Turbine Efficiency =	0.75	Equivalent Electrical Production (MMBtu/hr) =	46.0	Total Steam Turbine Production (kW) =	7,969		
Generator Efficiency =	0.95	Generator Losses (MMBtu/hr) =	2.4	Total Cycle Electrical Production (kW) =	21,446	Additional Capacity =	59.1%
Condensate Return from Campus =	80%	Duct Burner Input (MMBtu/hr) =	86.0	Overall Plant Electrical Efficiency =	30.2%		
Condensate Tank Temperature (°F) =	156	Gas Turbine Exhaust Heat (MMBtu/hr) =	191.4	Gas Turbine Only Electrical Efficiency =	29.5%		
Condensate Tank Enthalpy (Btu/lb) =	124.0	Total Natural Gas Input (MMBtu/hr) =	242.0	Heat Sent to Campus (MMBtu/hr) =	52.9		
Deaerator Steam Use (lb/hr) =	8,800	Final Exhaust Temp - Fedwater Temp (°F) =	122.0	Overall Plant Efficiency (Electricity + Heat) =	52.1%		
Deaerator Heat Required (MMBtu/hr) =	10.8	Exhaust Heat Captured (MMBtu/hr) =	131.7	Steam Turbine Generator Loss (MMBtu/hr)=	1.43		
Closed Heater Heat Required (MMBtu/hr) =	8.4	HRSG Steam Production (lb/hr) =	114,340	Plant Electrical Needs (kW) =	647.0		
Closed Heater Steam Use (lb/hr) =	6,800	Estimated Extraction Steam =	0.70	Plant Electrical Needs (MMBtu/hr) =	2.21		
Heat Flow Condensing (MMBtu/hr) =	38.8	Estimated Condensed Steam =	0.30	Remaining Turbine exit energy after electricity and losses =	103.02		
60 psig tubine exit steam energy flow		1.5 psia turbine exit steam energy flow					
mass flow rate *(h_6 - 277.0) (MMBtu/hr) =	75.37	mass flow rate *(h_7 - h_8) (MMBtu/hr) =	32.35				
By Straight Mass Flows (Mmbtu/hr) =	72.12	By Straight Mass Flows (Mmbtu/hr) =	30.91				

Monte Carlo Simulation

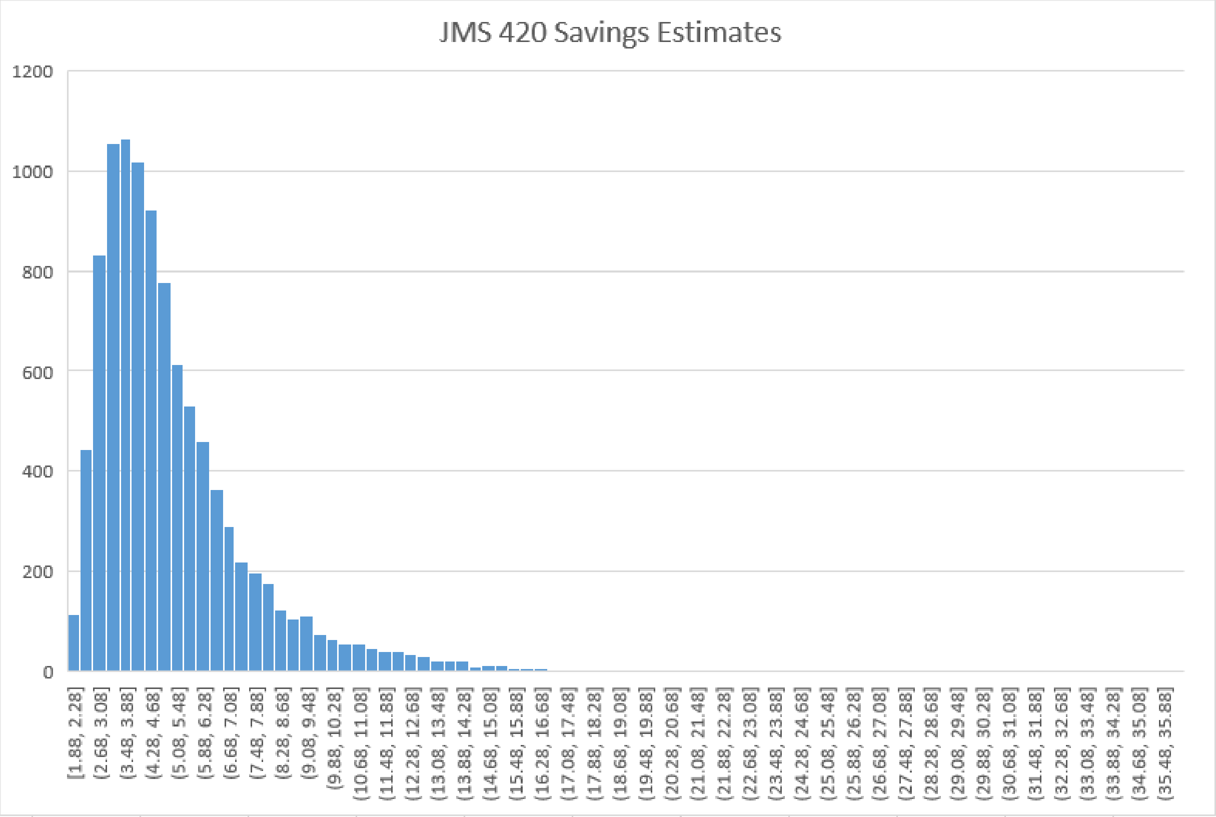
(Because No System Is Static)

- Technique Used To Understand The Impact Of Risk And Uncertainty
- Generate Draws From A Probability Distribution
- Require:
  - Input Variables (With Ranges)
  - Probability Of Different Outcomes
  - Repeated Random Sampling
- Deliver:
  - Mean And Standard Deviation
  - Confidence Interval
  - Regression Capabilities

Monte Carlo Simulation

(Because No System Is Static)

JMS 420 Savings Estimates			
Count	10,000	Std. Dev.	2.5
Max	35.9	CI	95%
Min	1.9	UCL	5.18
Average	5.1	LCL	5.08
Run	2.63		
1	4.32		
2	3.23		
3	5.52		
4	3.39		
5	5.71		
6	8.27		
7	6.83		
8	7.37		
9	4.96		
10	4.34		
11	4.93		
12	3.15		
13	5.99		
14	3.37		
15	10.99		
16	4.66		
17	11.67		
18	6.76		
19	4.15		
20	4.95		
21	6.60		
22	3.23		
23	3.25		
24	4.42		



ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	39310.13722	13103.37907	25.27682334	0.000102012
Residual	9	4665.555086	518.3950095		
Total	12	43975.69231			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-101.4333715	158.676969	-0.639244448	0.538591547	-460.3856135	257.5188705	-460.3856135	257.5188705
Adv ($M)	4.498539878	1.243311403	3.618192406	0.005587475	1.685974081	7.311105674	1.685974081	7.311105674
Inflation (%)	-23.4224818	6.264832032	-3.738724627	0.004634607	-37.59451646	-9.250447148	-37.59451646	-9.250447148
Price ($)	0.720809305	0.209099406	3.44720877	0.007306844	0.247793587	1.193825023	0.247793587	1.193825023

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Pro Forma Results

Net Of Chilled Water Production

System	Value Of Electricity Generated	Value Of Recovered Steam	Net Annual Savings	Total Plant Cost	Payback Period	Cost / kWh Produced
System “X”	$8,299,514	$2,202,901	$3,652,461	$30,323,250	8.3	$0.0414
System “Y”	$13,206,801	$2,201,834	$5,388,642	$39,487,139	7.3	$0.0438
System “Z”	$11,349,049	$3,996,876	$5,602,085	$33,740,079	6.0	$0.0375

With Absorption Refrigeration Cost And Savings

System	Absorption Chiller Capacity Available (Tons)	Value Of Ton-Hours Produced	Value of Additional Electricity	Net Annual Savings	Total Plant Cost	Paybac k Period	Cost / kWh Produced
System “X”	6,089	$2,493,526	$434,961	$3,418,401	$33,367,658	9.8	$0.0435
System “Y”	6,086	$2,495,228	$435,258	$5,104,002	$42,530,072	8.3	$0.0454
System “Z”	11,047	$4,524,177	$789,180	$5,217,514	$39,263,760	7.5	$0.0400

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Agenda

1 Start With Why

2 System Comparison - Overview

3 Cogeneration Analysis Techniques

4 System Comparison - Results

5 Conclusions & Recommendations

6 Question and Answers

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Conclusions

1. Never Forget The Opportunity Cost Of Electric Refrigeration
   - The Value Of The Recovered Steam For Absorption Refrigeration Is Of Less Value Than The Steam Recovered For Heating
2. Steam Turbine Addition Reduces Payback By 10%
3. What If Plant Operating Pressure Was 600 PSIG?
4. What If The Steam Turbine Exhausted At 60 PSIG?
5. What Are The Affects Of Standby Service Riders?
   - How Is Generation Calculated?

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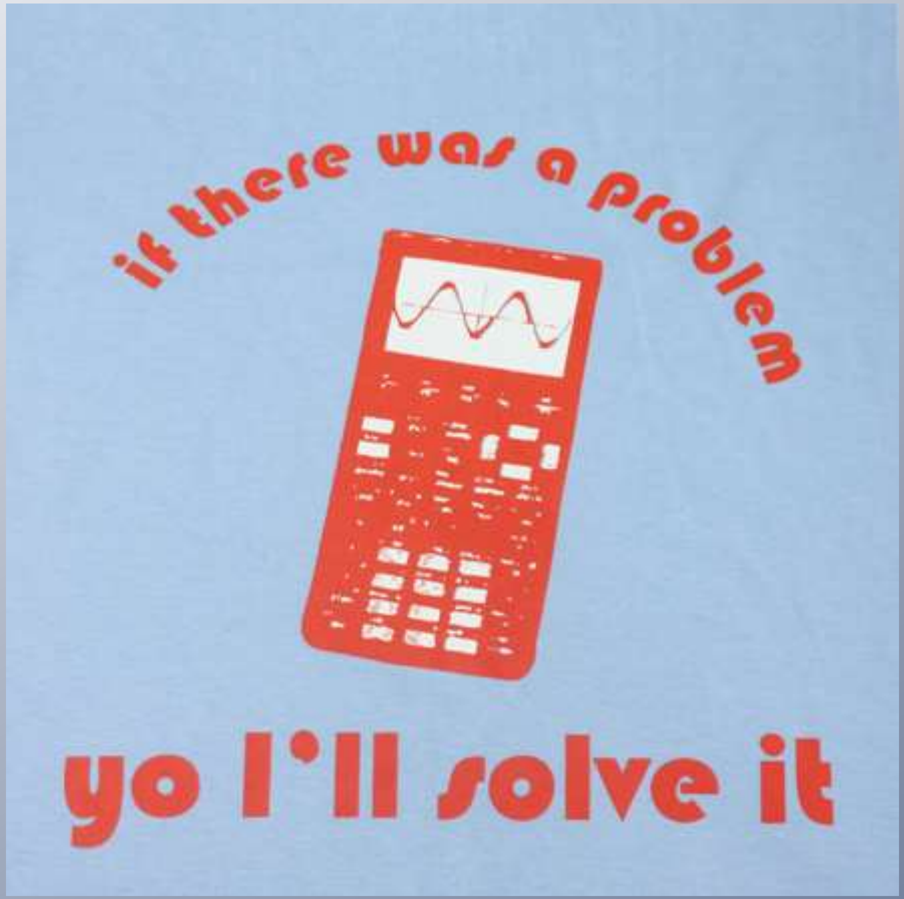
Question & Answers



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