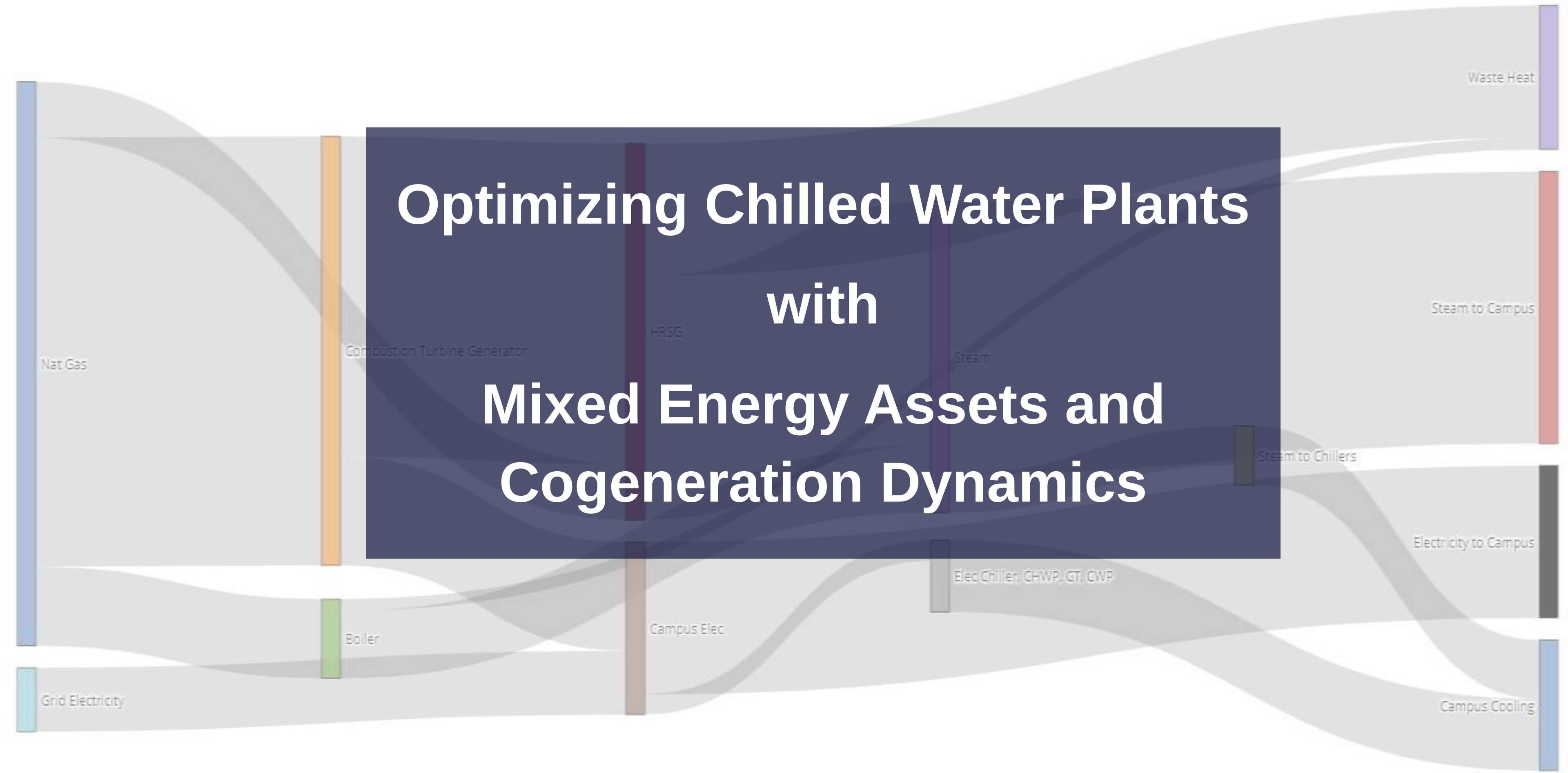
Optimizing Chilled Water Plants with Mixed Energy Assets and Cogeneration Dynamics



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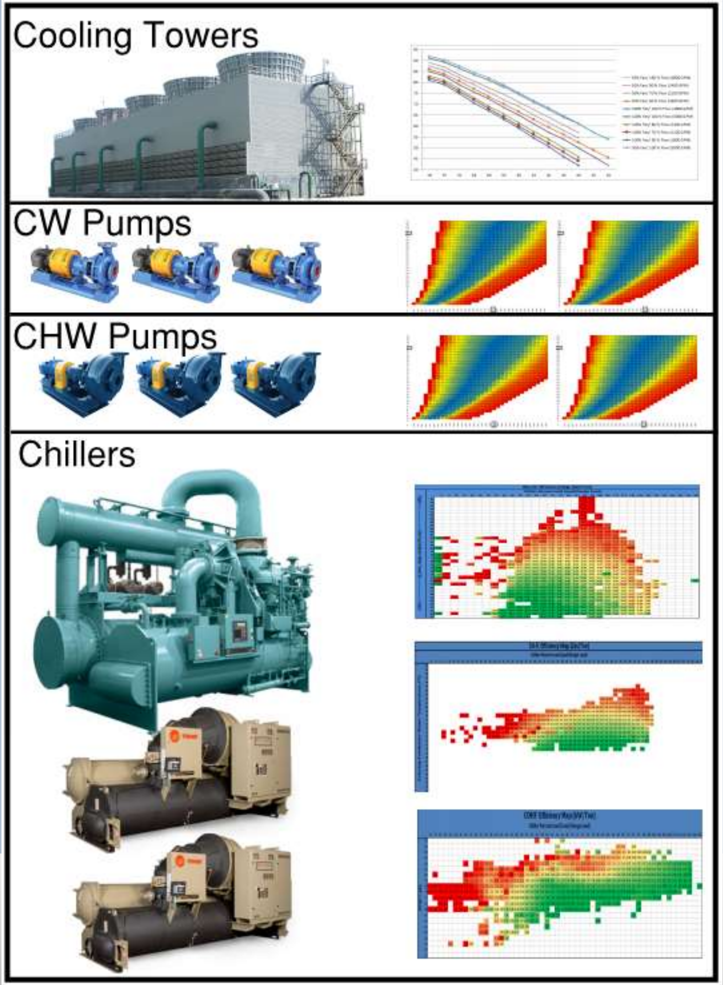
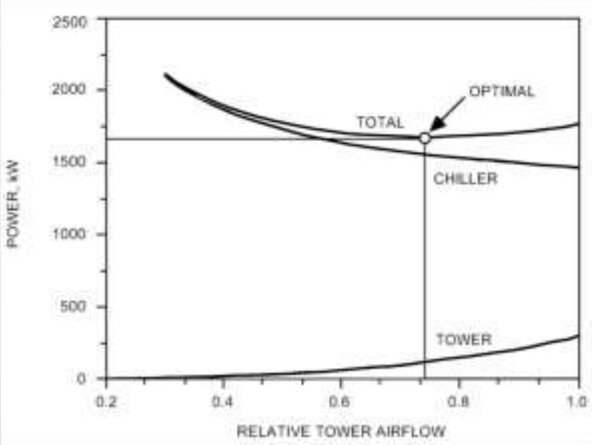
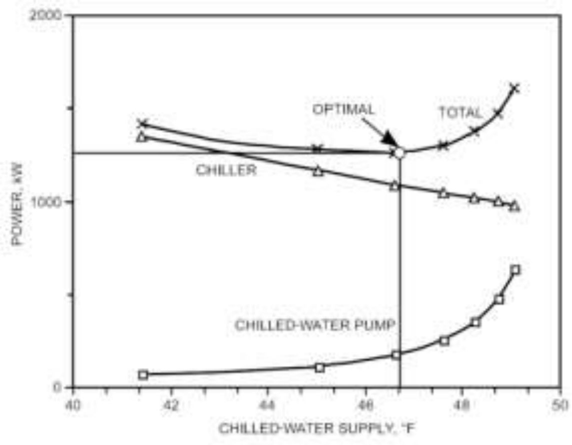
CHILLED WATER PLANT OPTIMIZATION



- **Chilled Water plant optimization finds lowest energy balance of all components at any given time**





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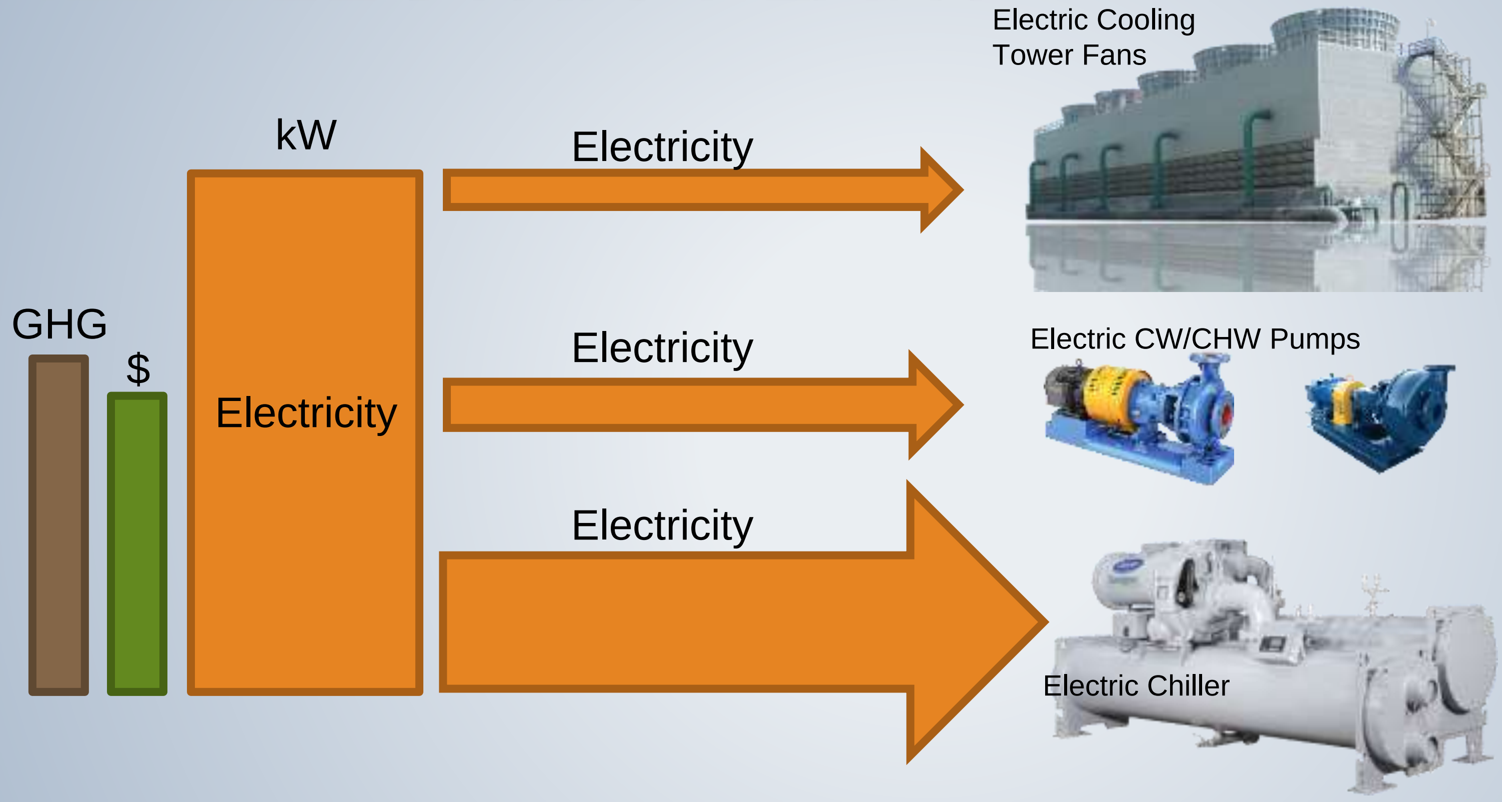
ALL-ELECTRIC PLANT



Operating Parameters

- CWST
- CW Flow
- # Cells
- Etc.

- CW/CHWST
- CW Flow
- Diff. Press
- # Pumps
- Etc.

- #/Combination of Chillers
- CHWST
- Chiller Load Balancing
- Etc.

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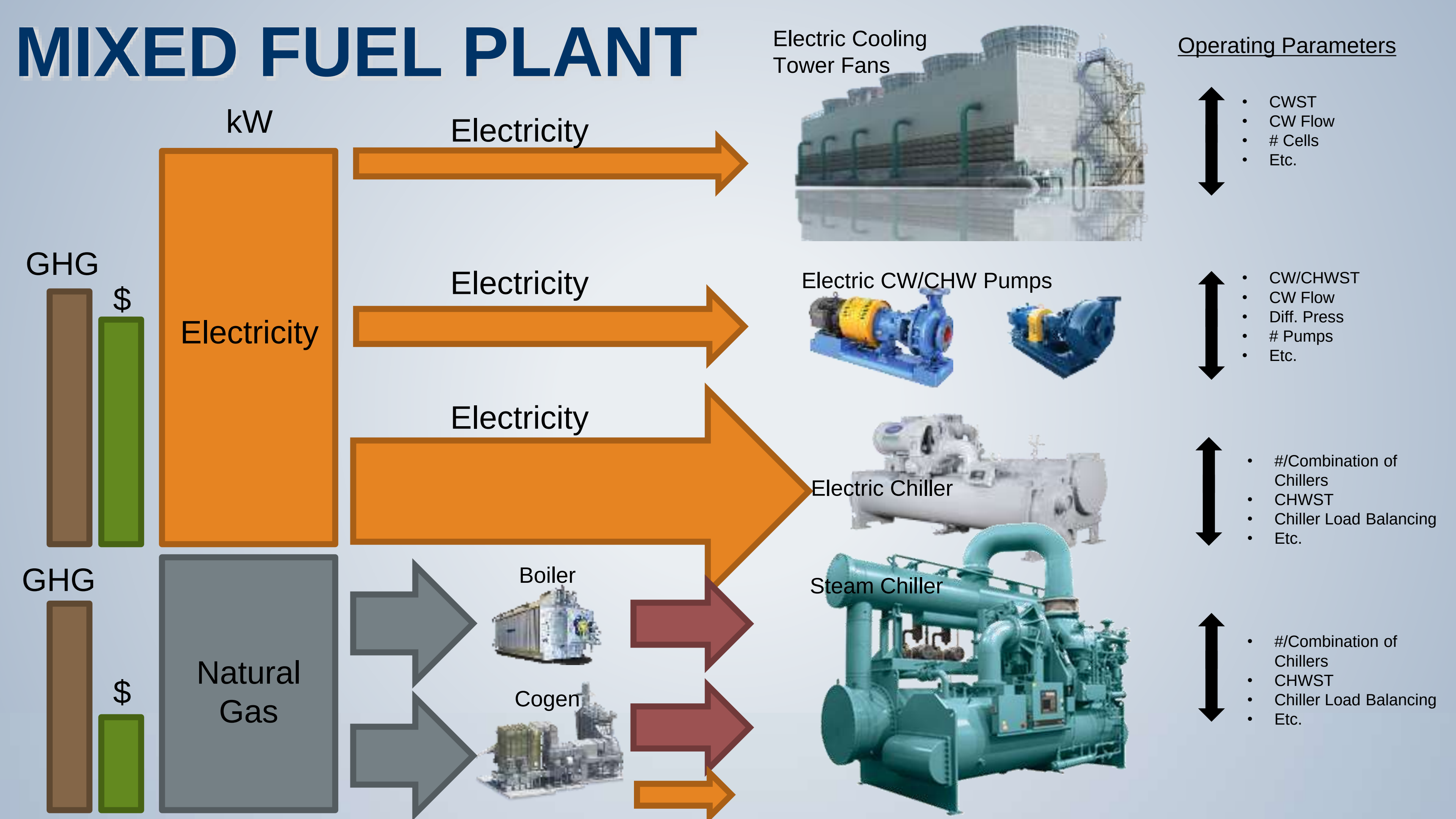
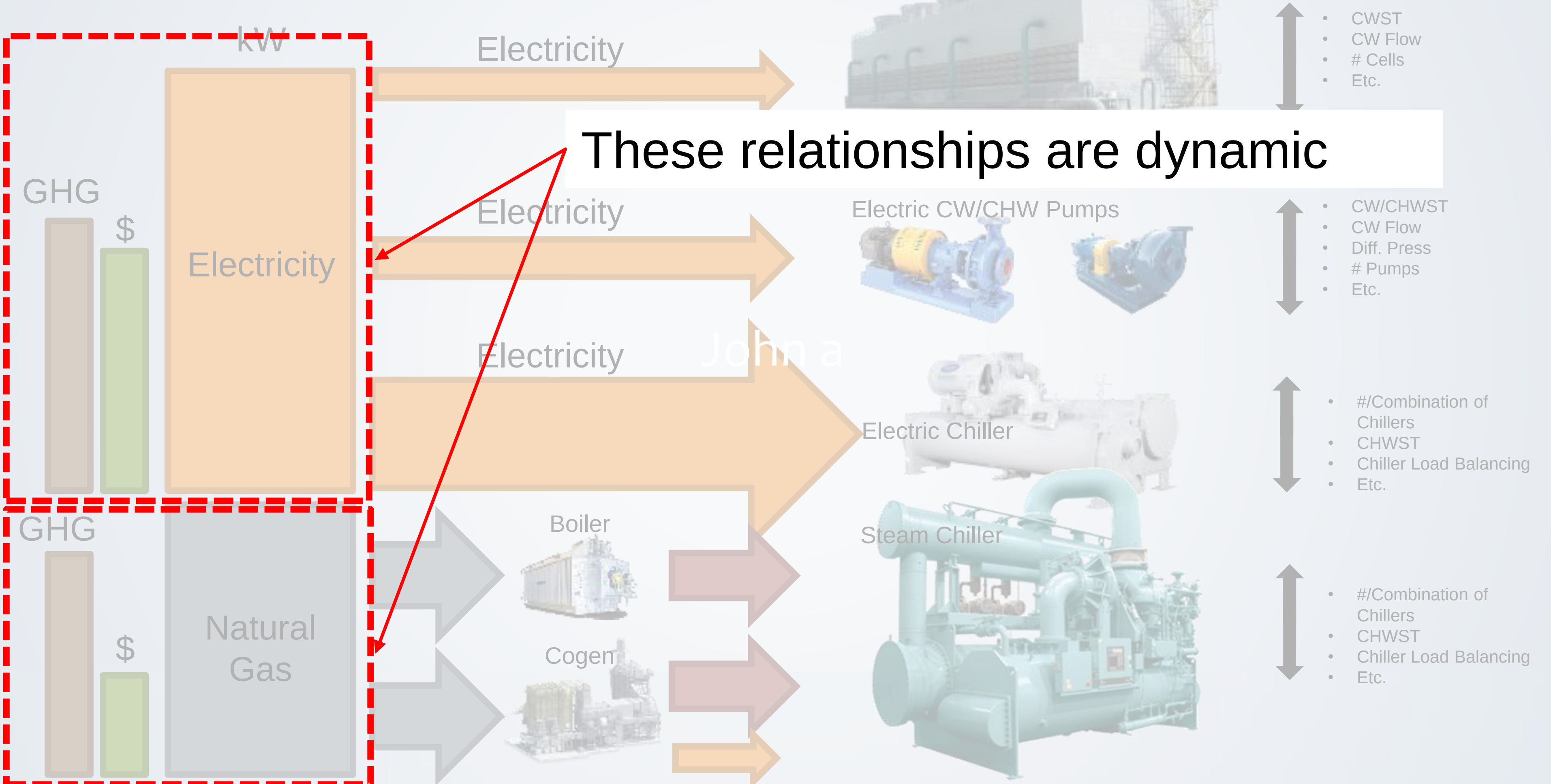
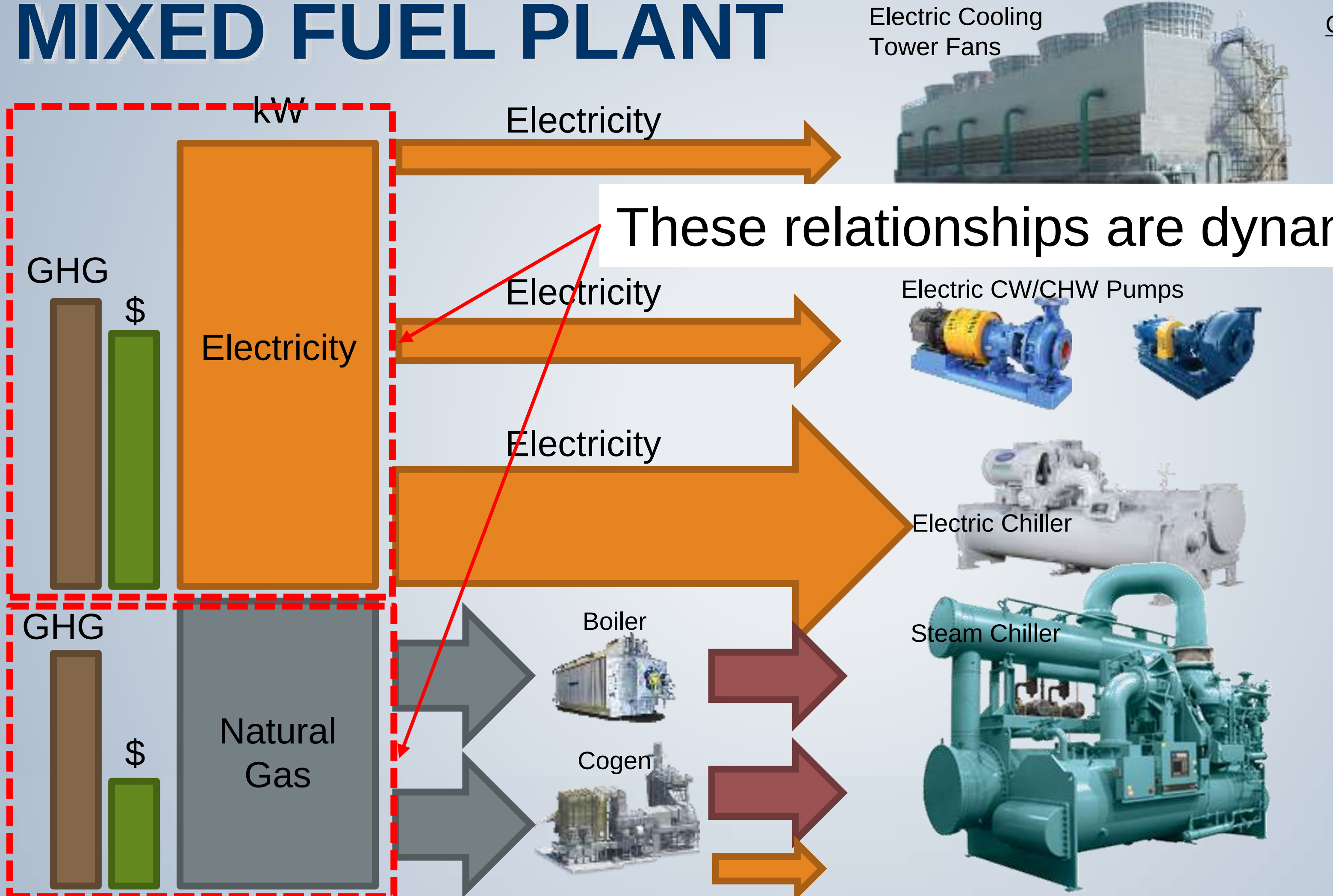

MIXED FUEL PLANT
kW
Electricity
Electricity
Electricity
Electricity
GHG
$
GHG
$
Natural Gas
Boiler
Cogen
Electric Cooling Tower Fans
Electric CW/CHW Pumps
Electric Chiller
Steam Chiller
Operating Parameters
• CWST
• CW Flow
• # Cells
• Etc.
• CW/CHWST
• CW Flow
• Diff. Press
• # Pumps
• Etc.
• #/Combination of Chillers
• CHWST
• Chiller Load Balancing
• Etc.
• #/Combination of Chillers
• CHWST
• Chiller Load Balancing
• Etc.

MIXED FUEL PLANT



MIXED FUEL PLANT



Operating Parameters

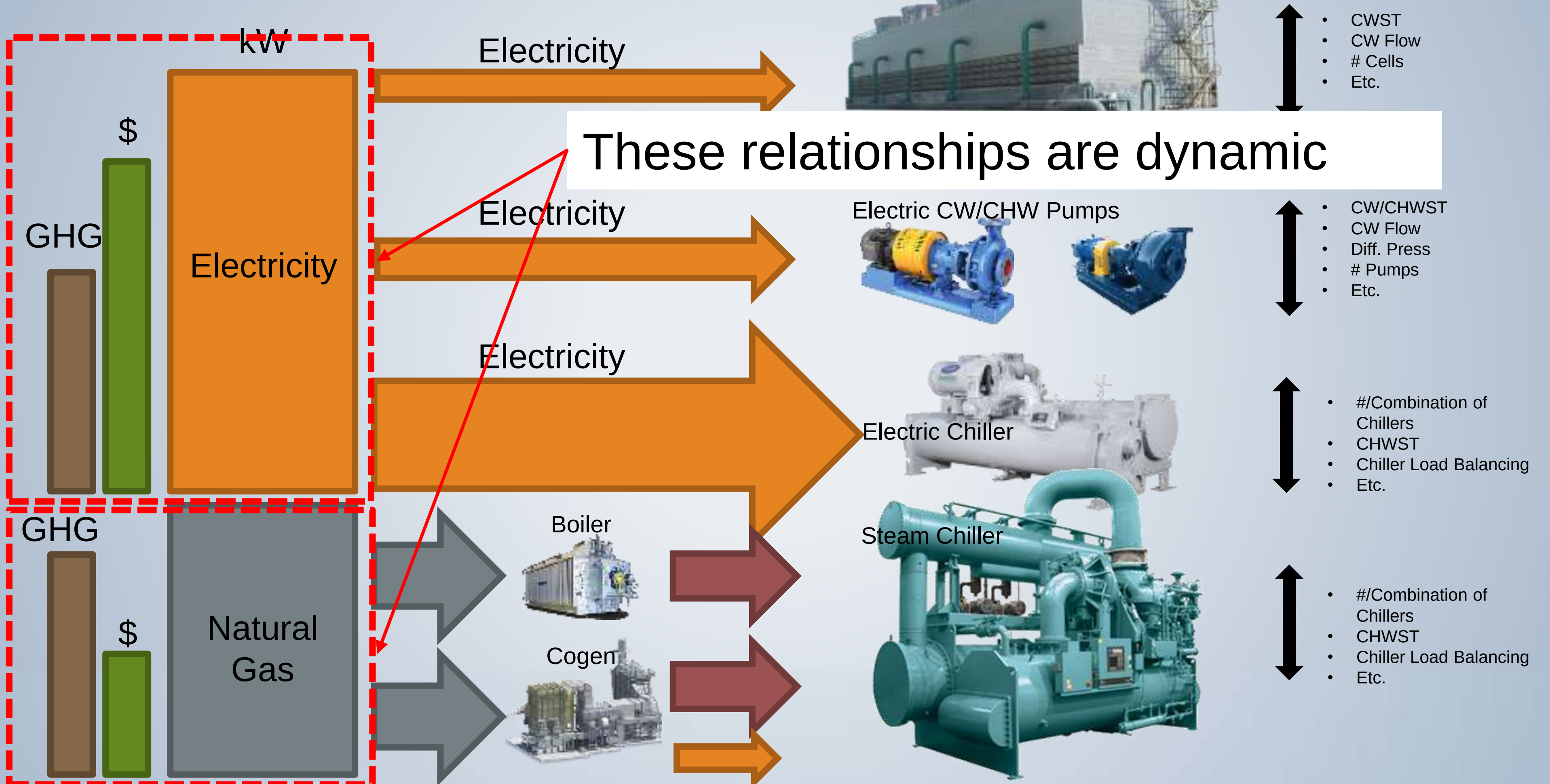
- CWST
- CW Flow
- # Cells
- Etc.

- CW/CHWST
- CW Flow
- Diff. Press
- # Pumps
- Etc.

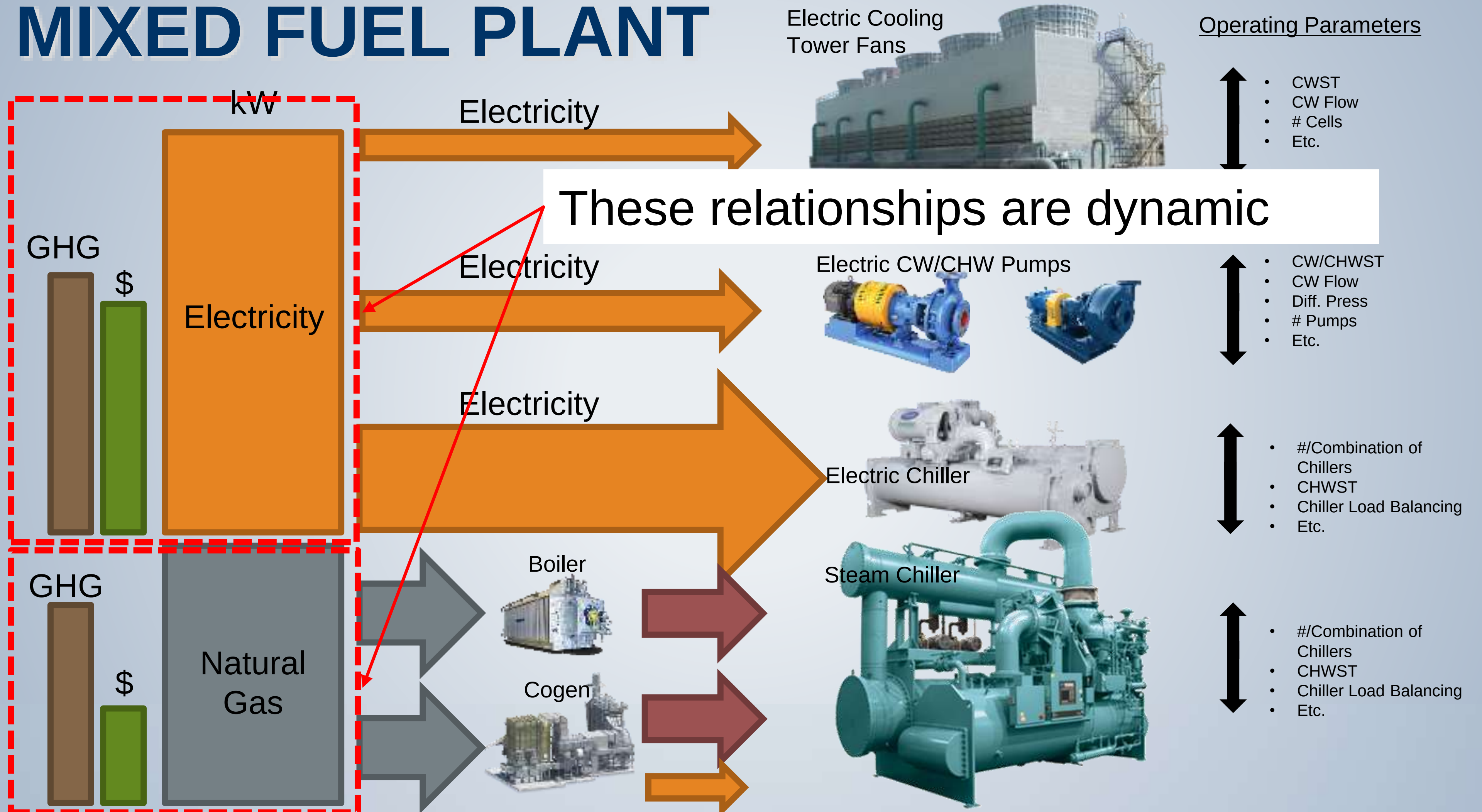
- #/Combination of Chillers
- CHWST
- Chiller Load Balancing
- Etc.

- #/Combination of Chillers
- CHWST
- Chiller Load Balancing
- Etc.

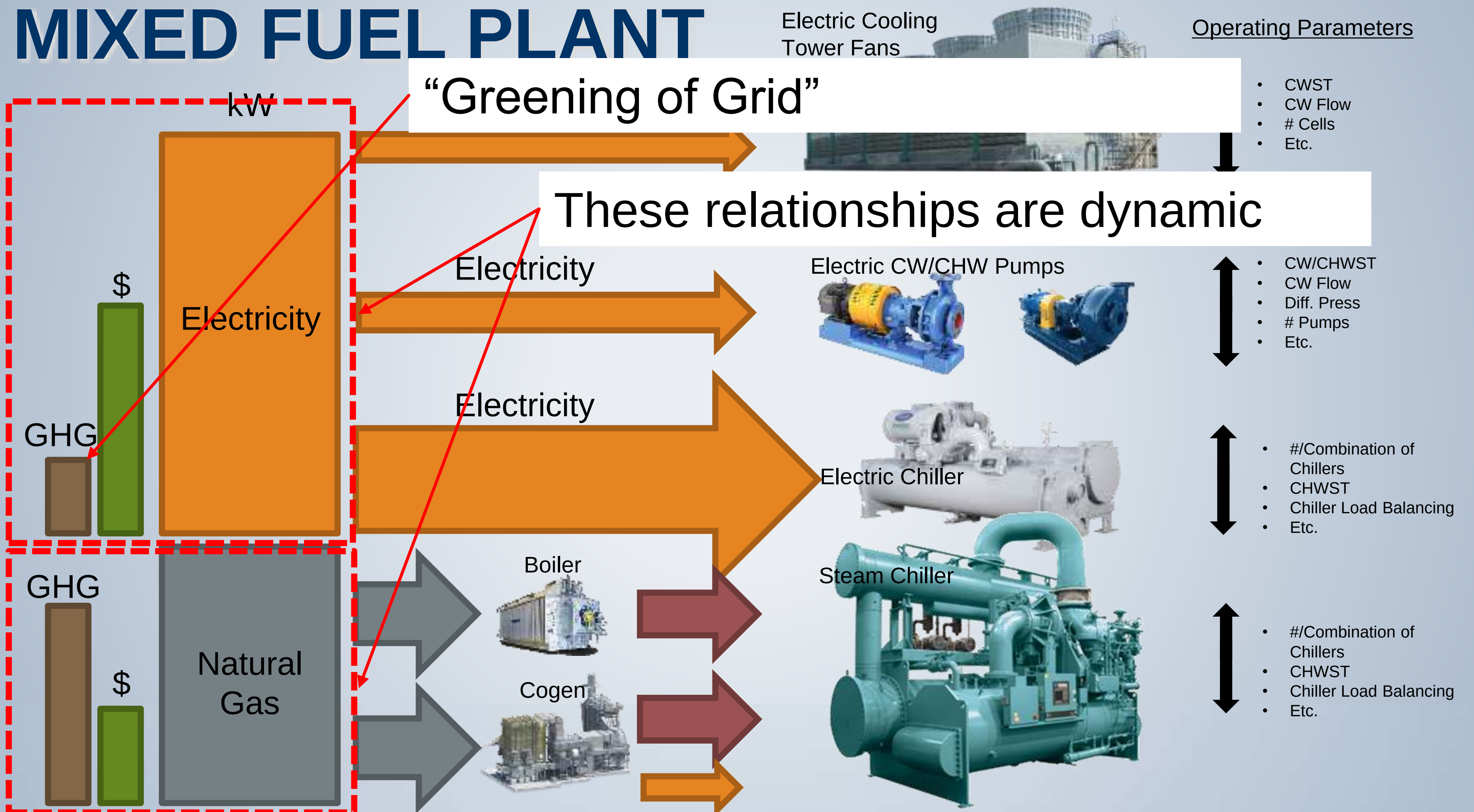
MIXED FUEL PLANT



MIXED FUEL PLANT

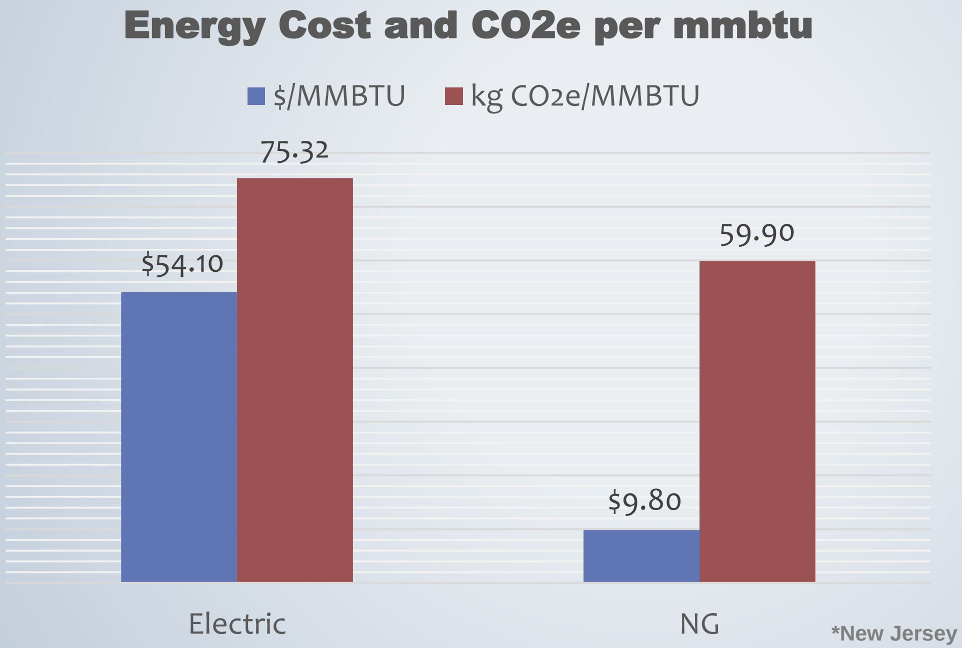


MIXED FUEL PLANT



HOW CLEAN IS THE GRID?

- **Grid emission rates (lb/MWh) are regional and dynamic**



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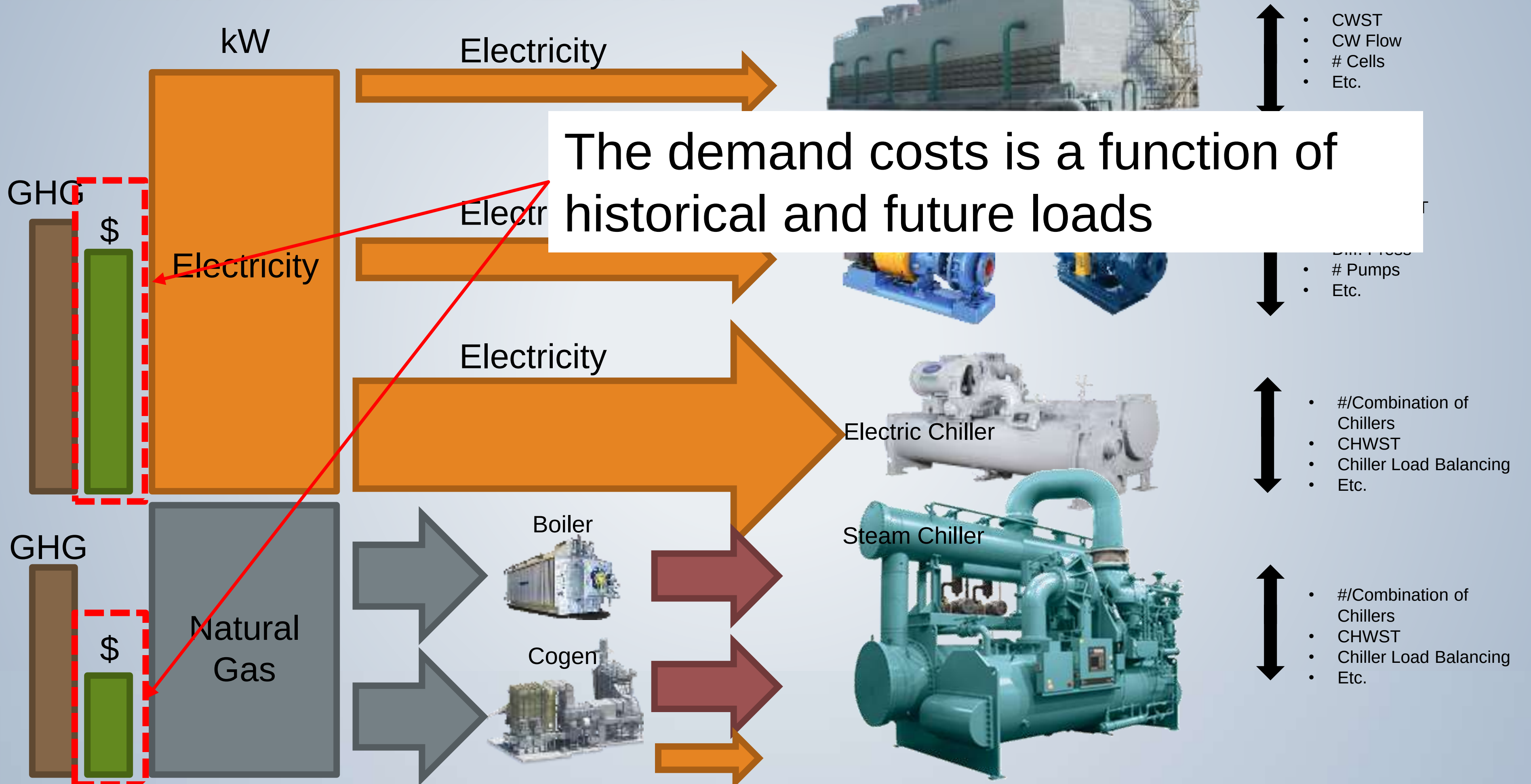
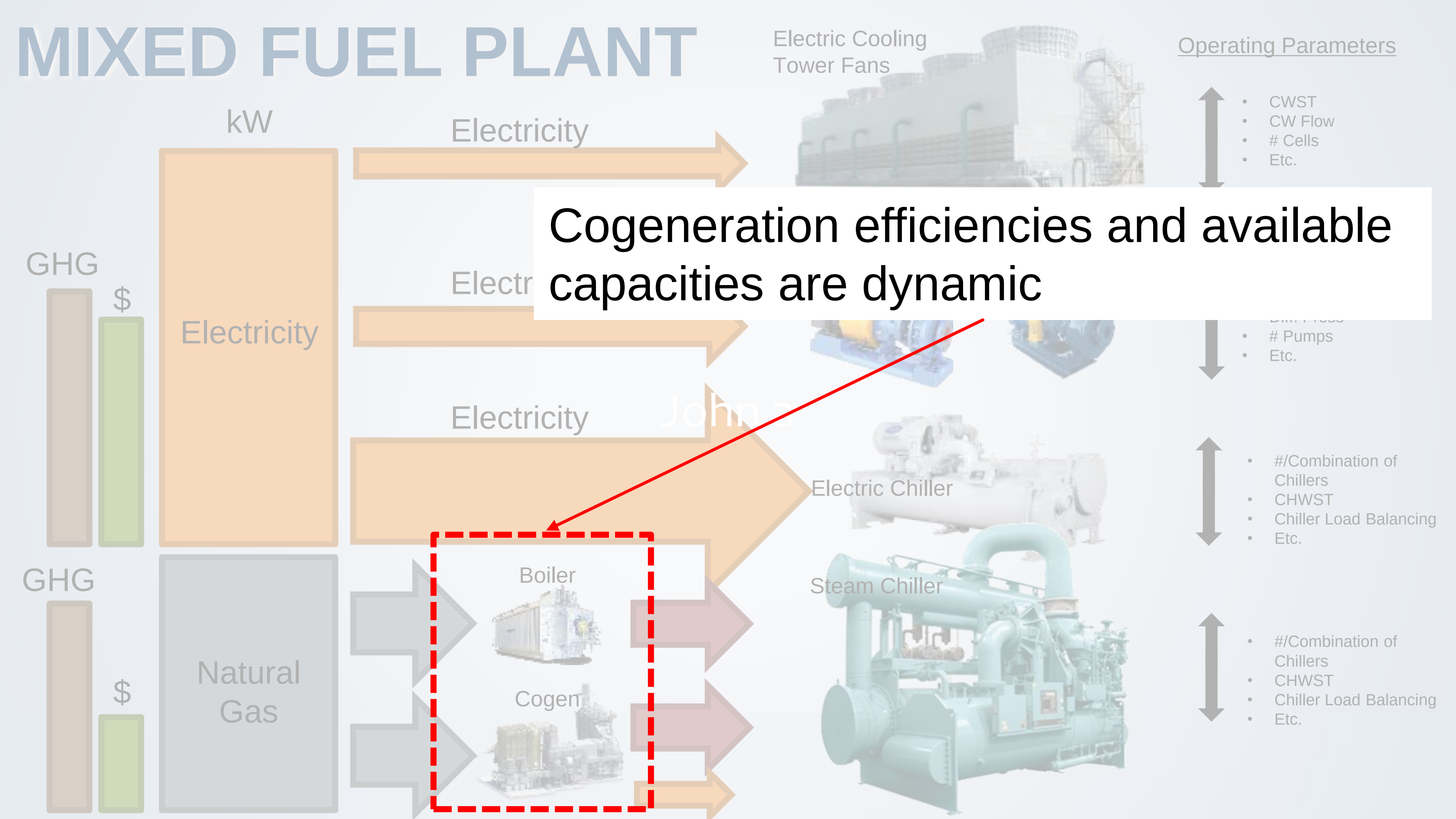
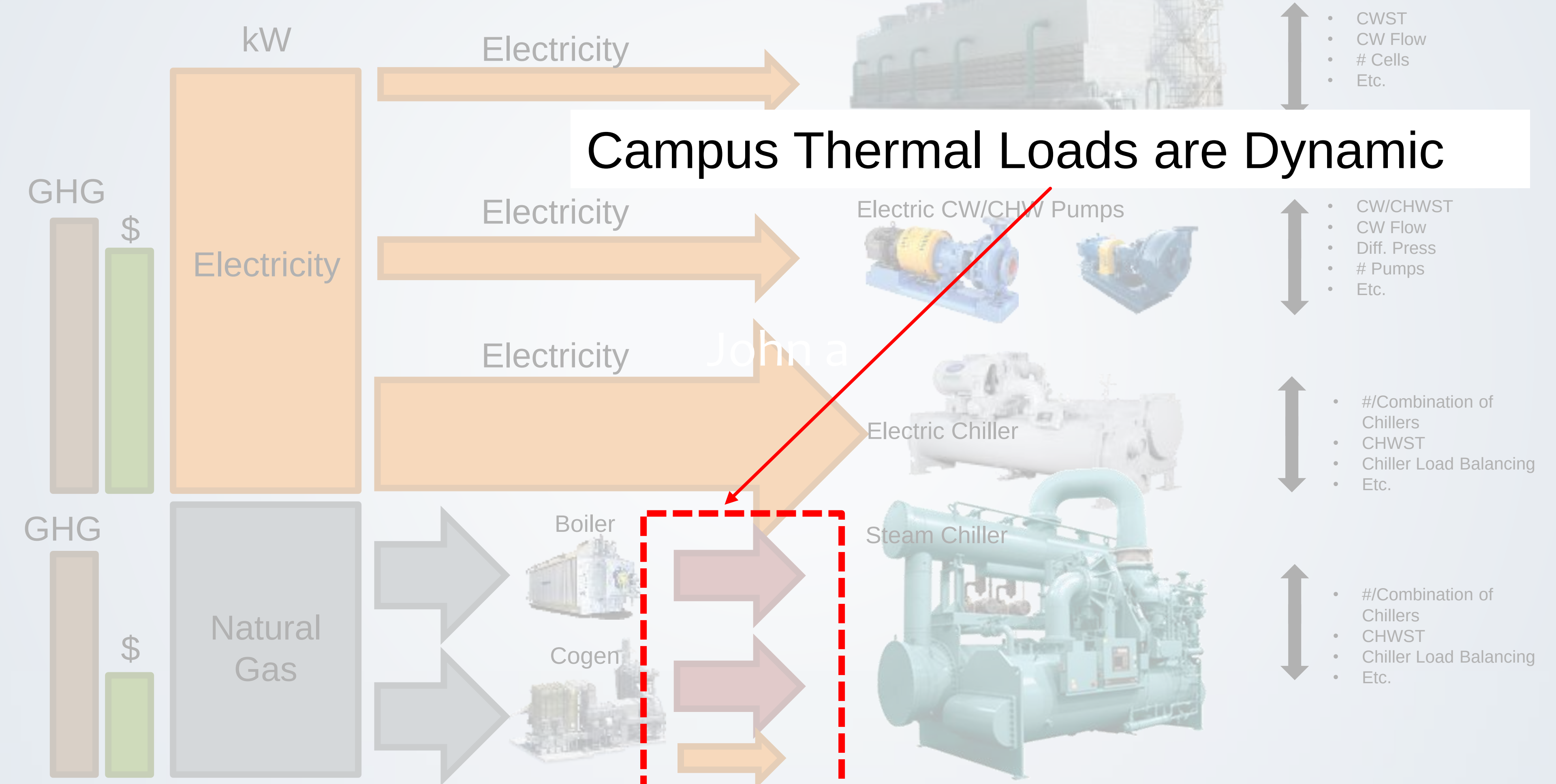
MIXED FUEL PLANT

The demand costs is a function of historical and future loads




MIXED FUEL PLANT
Electric Cooling Tower Fans
Operating Parameters
CWST
CW Flow
Cells
Etc.
kW
Electricity
Cogeneration efficiencies and available capacities are dynamic
GHG
$
Electricity
Pumps
Etc.
Electricity
Electric Chiller
#/Combination of Chillers
CHWST
Chiller Load Balancing
Etc.
GHG
Boiler
Steam Chiller
$
Natural Gas
Cogen
#/Combination of Chillers
CHWST
Chiller Load Balancing
Etc.

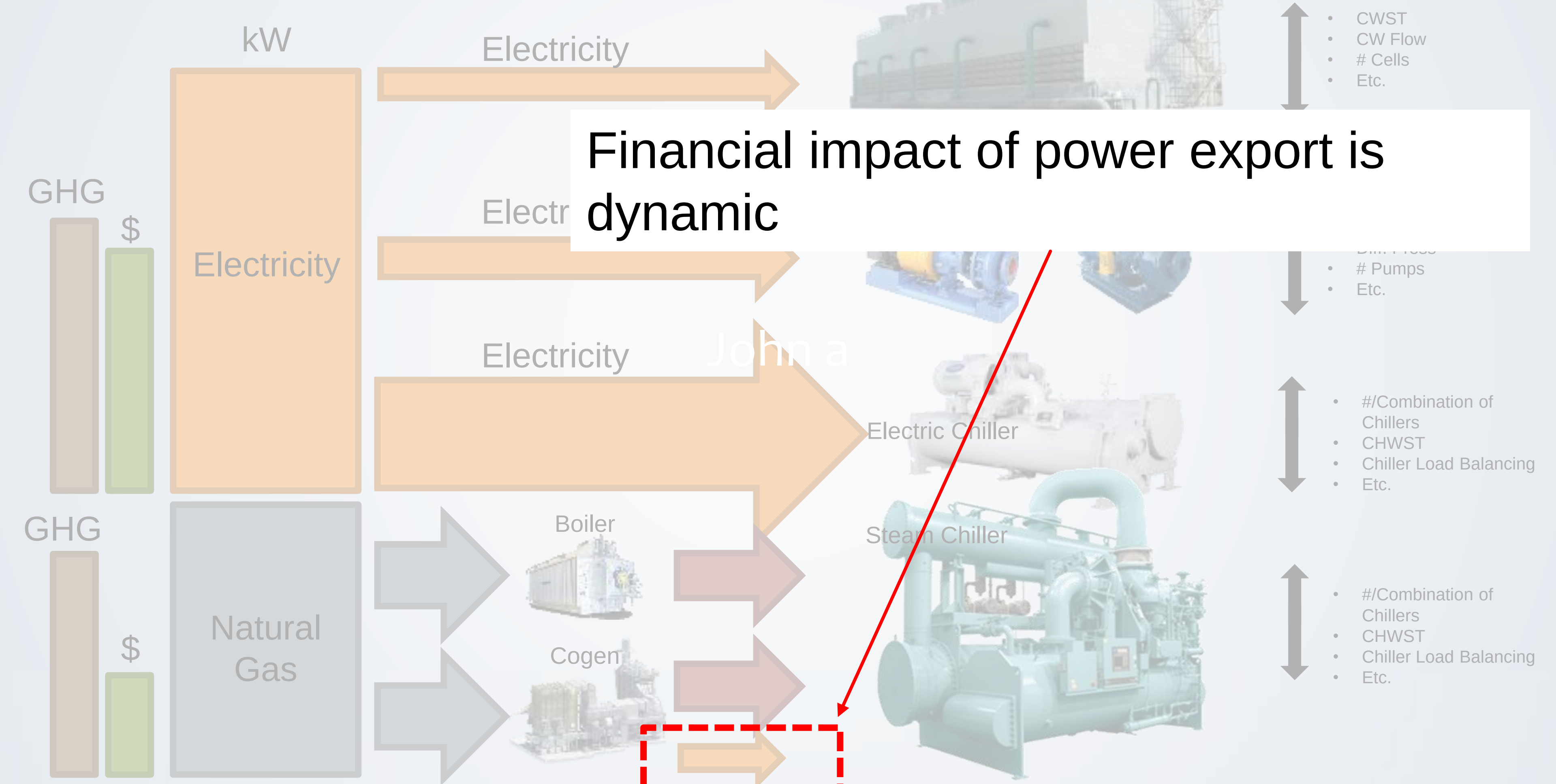
MIXED FUEL PLANT



Campus Thermal Loads are Dynamic

MIXED FUEL PLANT

Financial impact of power export is dynamic

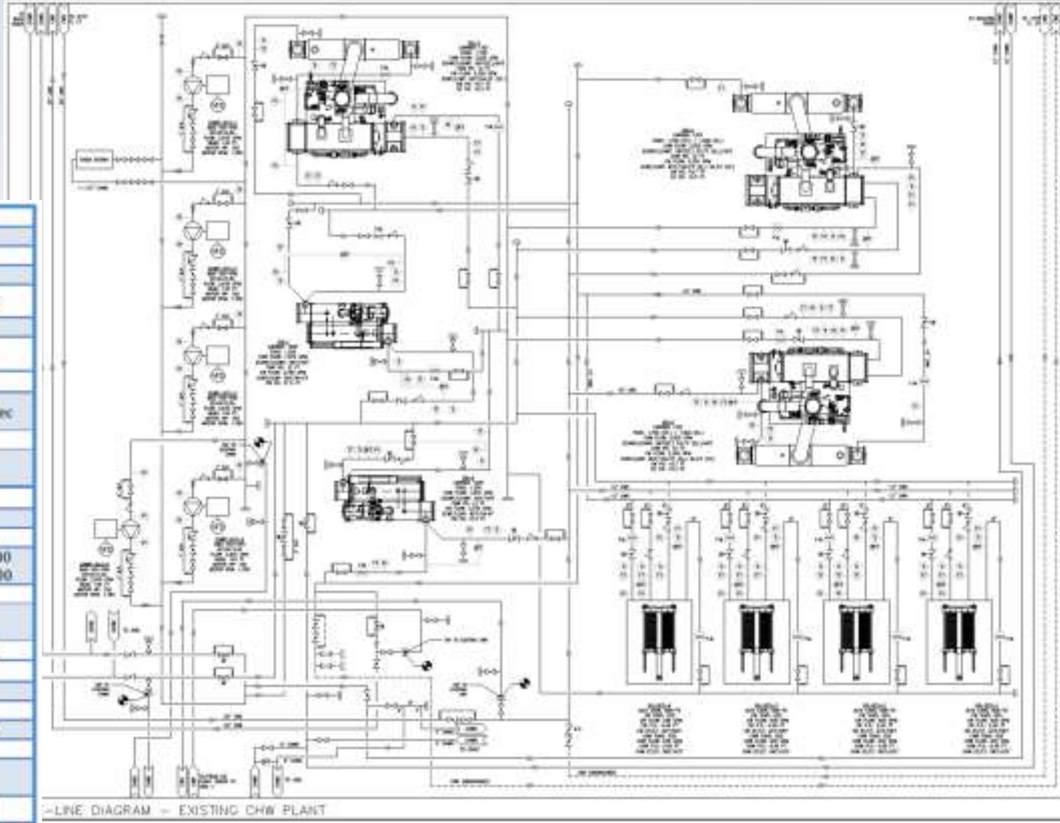


LARGE COMMERCIAL BANK NYC GLOBAL HEADQUARTERS

LARGE FINANCIAL BANK – GLOBAL HEADQUARTERS

PLANT

Chiller ID		CH-SC3-1	CH-SC3-2	CH-SC3-3	CH-SC3-4	CH-SC3-5
Location		SC3	SC3	SC3	SC3	SC3
Service						
Make		Carrier	Carrier	Carrier	Carrier	Carrier
Model Number		19XRV8687586 EMH64	17EX4857587-5	17EX4857587-5	19XRV868758 6EMH64	17EX4857587-5
Serial Number		18136	75750	77001	18137	75752
Nominal Capacity	Tons	1,250	Stm: 1,750 Elec 1,500	1,750	1,250	Stm: 1,750 Elec 1,500
Design – Compressor						
Type		Elec Centrifugal	Hybrid Steam/Elec	Steam Centrifugal	Elec Centrifugal	Hybrid Steam/Elec
Refrigerant		R-134a	R-134a	R-134a	R-134a	R-134a
Stages		1	Steam: 2 Elec: 1	2	1	Steam: 2 Elec: 1
Design – Evaporator						
Fluid		Water	Water	Water	Water	Water
Flow	GPM	1,872	2,625	2,625	1,872	2,625
Temp. (E/L)	°F	56.00 / 40.00	Stm: 56.00 / 40.00 Elec: 53.70 / 40.00	56.00 / 40.00	56.00 / 40.00	Stm: 56.00 / 40.00 Elec: 53.70 / 40.00
Passes	No.	2	2	2	2	2
Pressure Drop	Ft. of H2O	12.0	11.1	11.1	12.0	11.1
Min / Max Flow	GPM	1,411 / 4,704	2,269 / 7,565	2,269 / 7,565	1,411 / 4,704	2,269 / 7,565
Design – Condenser						
Fluid		Water	Water	Water	Water	Water
Flow	GPM	3,750	5,250	5,250	3,750	5,250
Temp. (E/L)	°F	85.00 / 94.40	85.00 / 94.30	85.00 / 94.30	85.00 / 94.30	85.00 / 93.10
Passes	No.	2	2	2	2	2
Pressure Drop	Ft. of H2O	21.5	18.7	18.7	21.5	18.7
Min / Max Flow	GPM	1,609 / 5,365	2,206 / 7,353	2,206 / 7,353	1,609 / 5,365	2,206 / 7,353
Design – Surface Condenser						
Flow	GPM	-	5,250	5,250	-	5,250
Temp. (E/L)	°F	-	94.30 / 100.20	94.30 / 100.20	-	94.30 / 100.20
Pressure Drop	Ft. of H2O	-	10.3	10.3	-	10.3
Min / Max Flow	GPM	-	2,206 / 7,353	2,206 / 7,353	-	2,206 / 7,353



LARGE FINANCIAL BANK – GLOBAL HEADQUARTERS

UTILITY RATES

ELECTRIC RATES - DEMAND (2016)

SC9 - EL9 General Large Rate II - Time of Day	
Demand Delivery Charges	
June - Sept	$/kW
G&T Demand - Mon- Fri 8AM to 6PM	$8.03
Pri Demand - Mon- Fri 8AM to 10 PM	$15.03
Sec. Demand - All hours All Day	$16.12
Other Months	
Pri Demand - Mon- Fri 8AM to 10 PM	$11.08
Sec. Demand - All hours All Day	$5.17
Billable Reactive Demand	$1.10
Applies when power factor < 95%	
Energy Delivery Charges	**$/kWh**
All Months	$0.0080

STEAM RATES (2016)

SC 2 Annual Power Service Rate I		
May- Oct	Mlb	$/Mlb
	250	13.078
	750	18.113
	1,000	16.805
Nov- Apr	250	15.045
	1,250	42.778
	3,500	39.559
	20,000	37.908
	25,000	35.488

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LARGE FINANCIAL BANK – GLOBAL HEADQUARTERS

ELECTRIC VS STEAM

	Normalized Energy Cost $/kTon-Hr
Electric Chiller (0.6 kW/Ton)	$ 75.00
Steam Chiller (10 lbs/Ton-Hr)	$ 165.00

Key trade-off

	Peak Demand $/kTon
Electric Chiller (0.6 kW/Ton)	$ 23,400.00

Non Electric Peak Reducing - Steam kTon-Hr Cost Vs Electric kTon-Hr Cost	**$ (90.00)**	**Loss**
Electric Peak Reducing - Steam kTon-Hr Cost Vs Electric kTon-Hr Cost	**$ 23,310.00**	**Gain**

- **260 Hours of runtime of a 1,000 Ton machine spends the $29,000 in demand reduction (730 Hours in a month)**
- **Therefore, the steam chiller must run for less than 35% of the month to break even**

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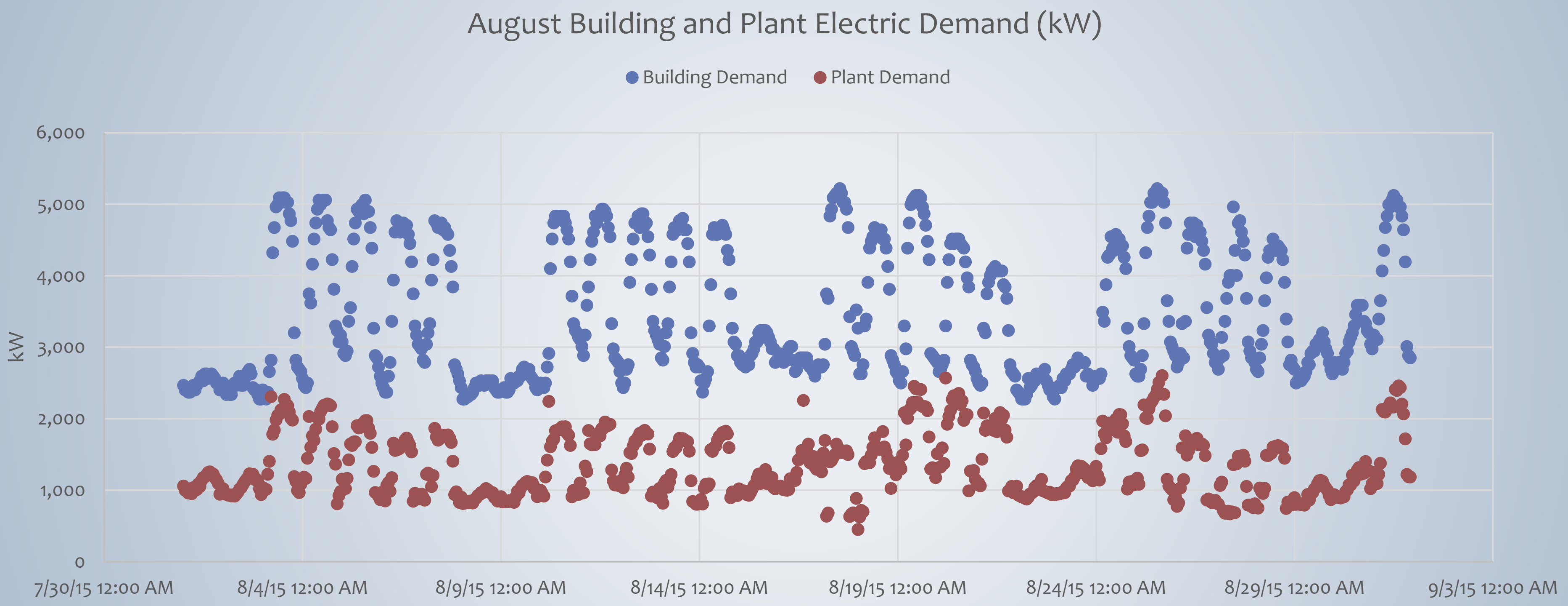
ELECTRIC VS STEAM



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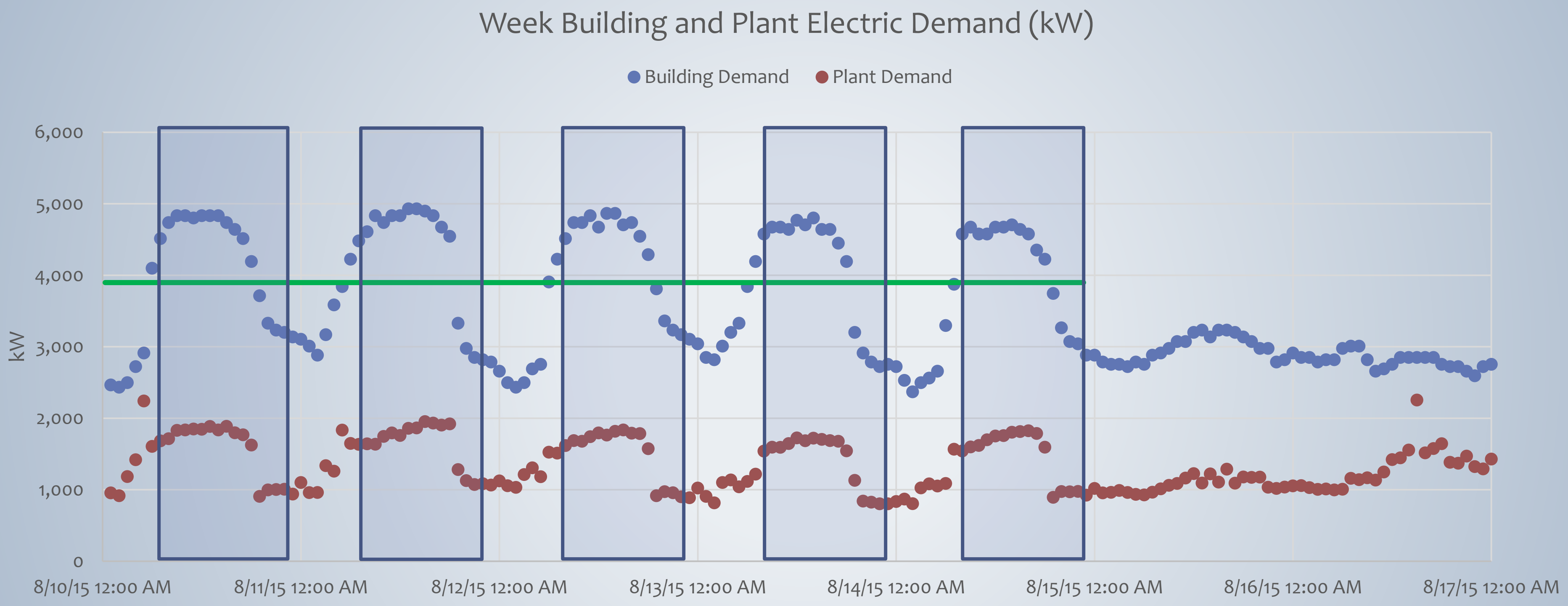
DISPATCH 1MW REDUCTION POTENTIAL - PASSIVE



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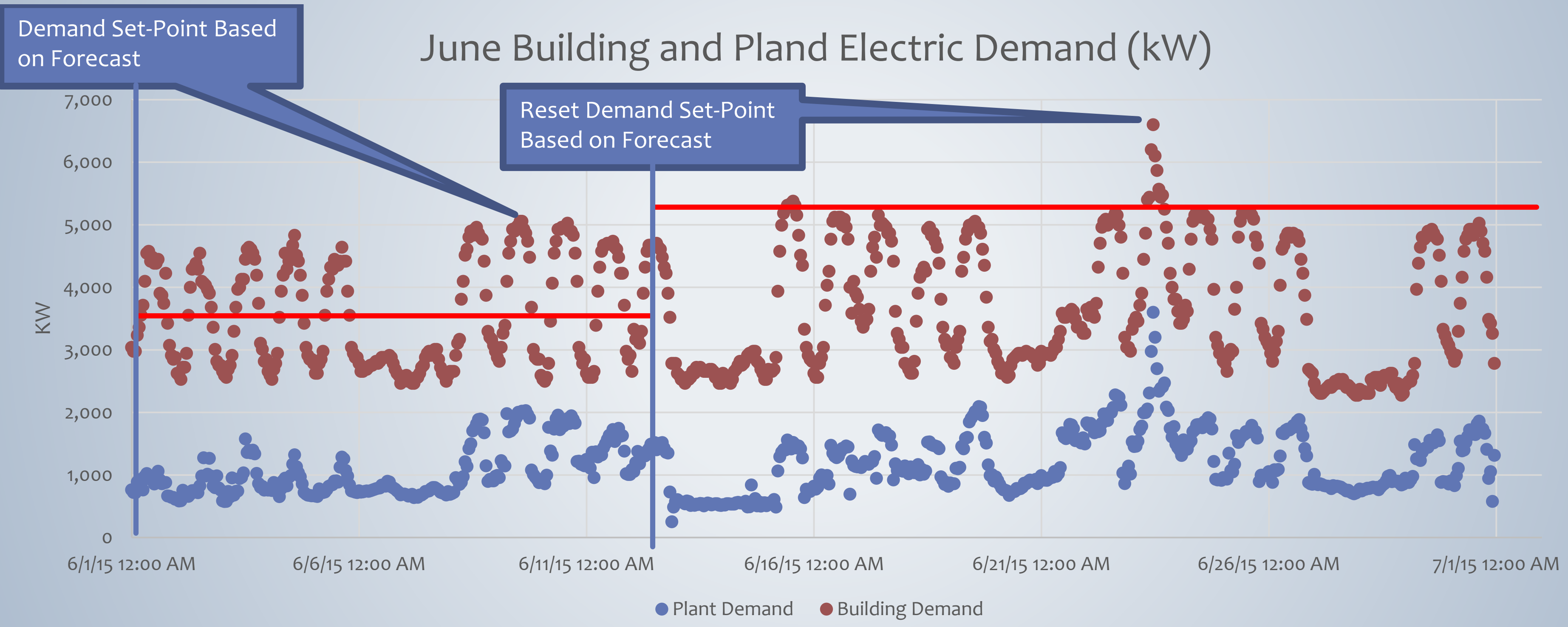
OPTIMAL DISPATCH (PREDICTIVE) – TWO 1,400 TON STEAM CHILLERS AVAILABLE (1,400 KW DEMAND REDUCTION POTENTIAL)



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RESULTS-PREDICTIVE

Passive Strategy

Reactive Strategy

	Steam Chiller Use June - September	Chiller Steam Cost June - September	Chiller Peak Electric Demand* June - September	Chiller Electric Usage June - September	Chiller Electric Cost June - September	Total Chiller Cost June - September	Annual Savings
	Mlbs	$	kW	kWh	$	$	$
Steam Baseload	23,245	$ 385,867.00	5,938	976,902	$ 357,819.75	$ 743,686.75	
Steam Avoidance	3,540	$ 58,764.00	10,126	1,631,139	$ 610,425.21	$ 669,189.21	$ 74,497.54
Optimized Dispatch	9,279	$ 154,031.40	6,053	1,304,702	$ 406,622.96	$ 560,654.36	$ 108,534.85

* Sum of four Peaks

Predictive Strategy

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UNL

STEAM VS ELECTRIC

	Steam	Electric	
Total operational cost	$284	$82	/hr

Chiller 3 Demand Savings Potental	**$**	**300,000.00**	**/Year**
Cost Per Hour To Run Vs Electric	**$**	**202.00**	**/Hr**
Break Even Hours		**1,485**	**/Year**
Loss per 24 Hours	**$**	**4,848.00**	**/Day**

Inputs		Steam	Electric	Units
	Tons	4,500	4,500	
Steam	Flow to chiller 3	37,000		lb/hr
	Pressure	550		psig
	Temperature	840		F
	Enthalpy	1420		Btu/lb
Exhaust	Pressure	24.5		inHg vacuum
	Enthalpy	1060		Btu/lb
Steam Turbine	kW	3314		
	HP	4443		
Comp Motor	kW		2790	cfm
	energy cost		$0.0244	/MMBtu
	Hourly cost		$68.08	$/hr
Condensate	Pressure	2.1		psi
	Temperature	127		°F
	Enthalpy	95		Btu/lb
Boiler	Heat output	49.0		MMBtu/hr output
	Efficiency	81%		%
	Heat input	60.5		MMBtu/hr input
Gas	Gas flow	960		cfm
	Gas cost	$4.36		/MMBtu
	Hourly cost	$263.80		$/hr
Air	Air flow	25210		cfm
	Static	18		inWC
	Fan input HP	119		HP
	Fan input kW	89		kW
	energy cost	$0.0244		/kWh
	Hourly cost	$2.16		$/hr
Boiler Water	Density	59.5		lb/ft3
	Unit conversion	7.5		gal/ft3
	Density	8.0		lb/gal
	Flow	79		gpm
	Pump static	1387		ftH2O
	Pump input HP	43		HP
	Pump input kW	32		kW
	Pumping Energy	$0.78		$/hr
	Makeup %	5.0		%
	Makeup flow	0.32		CCF/hr
	Water cost	$1.911		/CCF
	Makeup cost	$0.61		$/hr
Tower Water	Water flow	13,500	13,500	GPM
	Hotwell dP	75	75	ftH2O
	Pump input HP	393	393	HP
	Pump input kW	293	293	kW
	Pumping Energy	$7.16	$7.16	/hr
	Steam condenser ΔT	15	10	°F
	Heat rejection	101.3	67.5	MMBtu/hr
	Heat rejection efficiency	4.00	4.00	kW/MMBtu/hr
	Heat rejection electricity	405.00	270.00	kW
	Heat rejection cost	$9.88	$6.59	$/hr
Total operational cost		$284	$82	/hr

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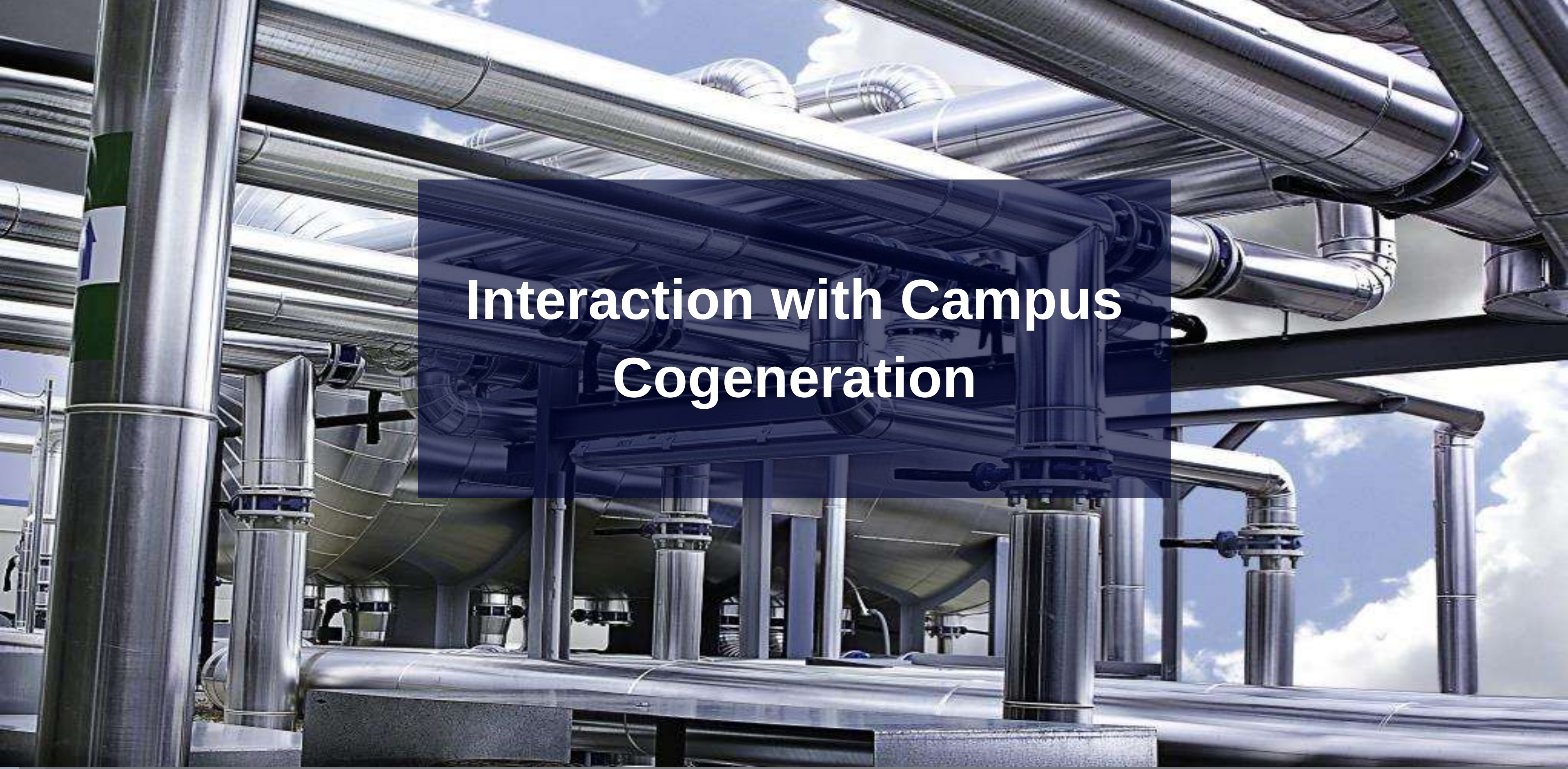

Interaction with Campus Cogeneration

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ECONOMIC INTERACTION WITH COGENERATION

1. The chilled water plant is the largest single campus factor for the energy balance (fuel and electricity) of the cogeneration
2. Decide what you are optimizing for ($? MtCO2e?)
3. What is incremental impact if increasing or decreasing steam and electric loads?
    - Coincident campus load dynamics
    - Grid cost and GHG dynamics
    - Understand performance dynamics of the plant and sub-components
    - Understand available system capacities

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WHAT DO WE WANT TO OPTIMIZE FOR?

- **Cost?**
- **Greenhouse gas?**
- **Overall energy?**

- **With current energy dynamics, generally speaking, recommend to optimize to minimize cost as the baseline option**
- **Then, compare cost of optimizing for GHG vs. investing in system improvements**

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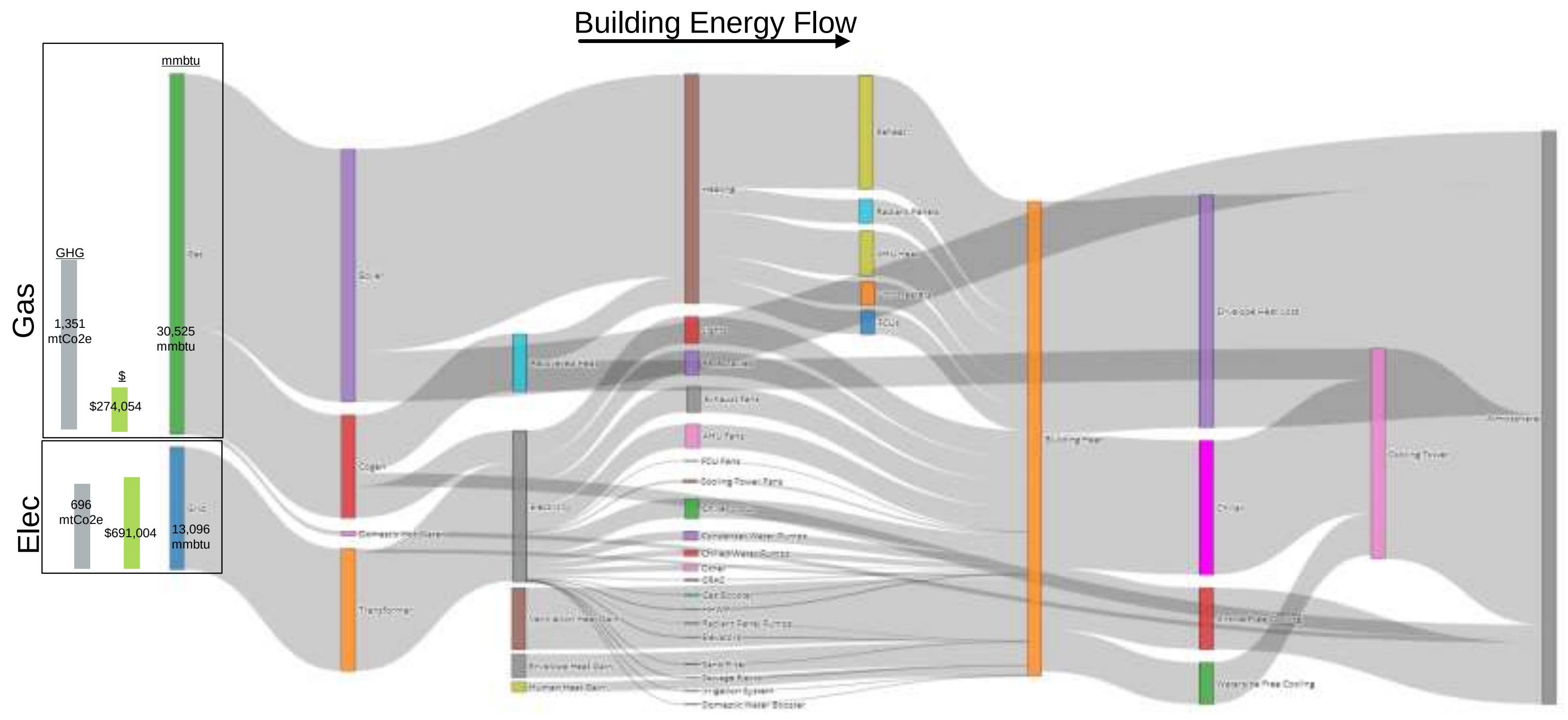
TOOL #1: SANKEY DIAGRAM



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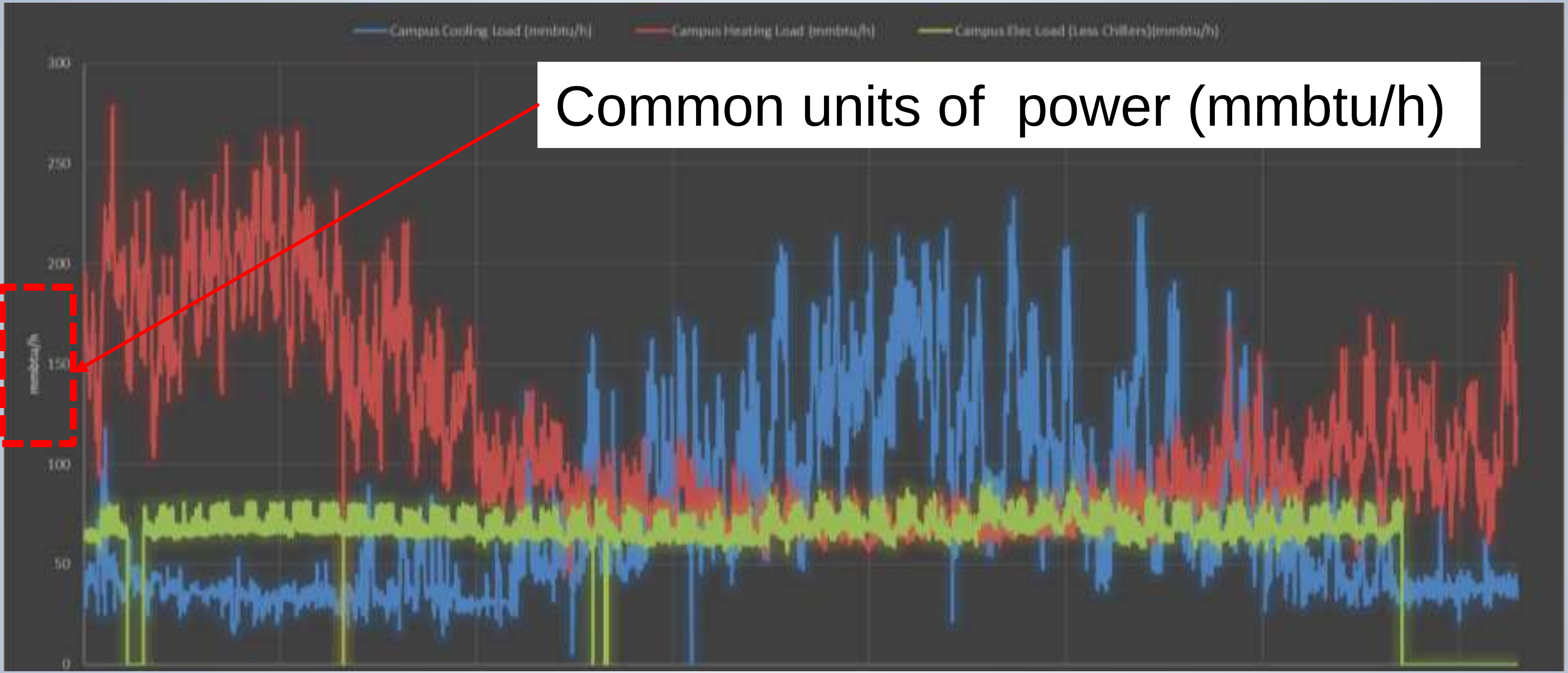
TOOL#2: NORMALIZED ANNUAL PROFILE



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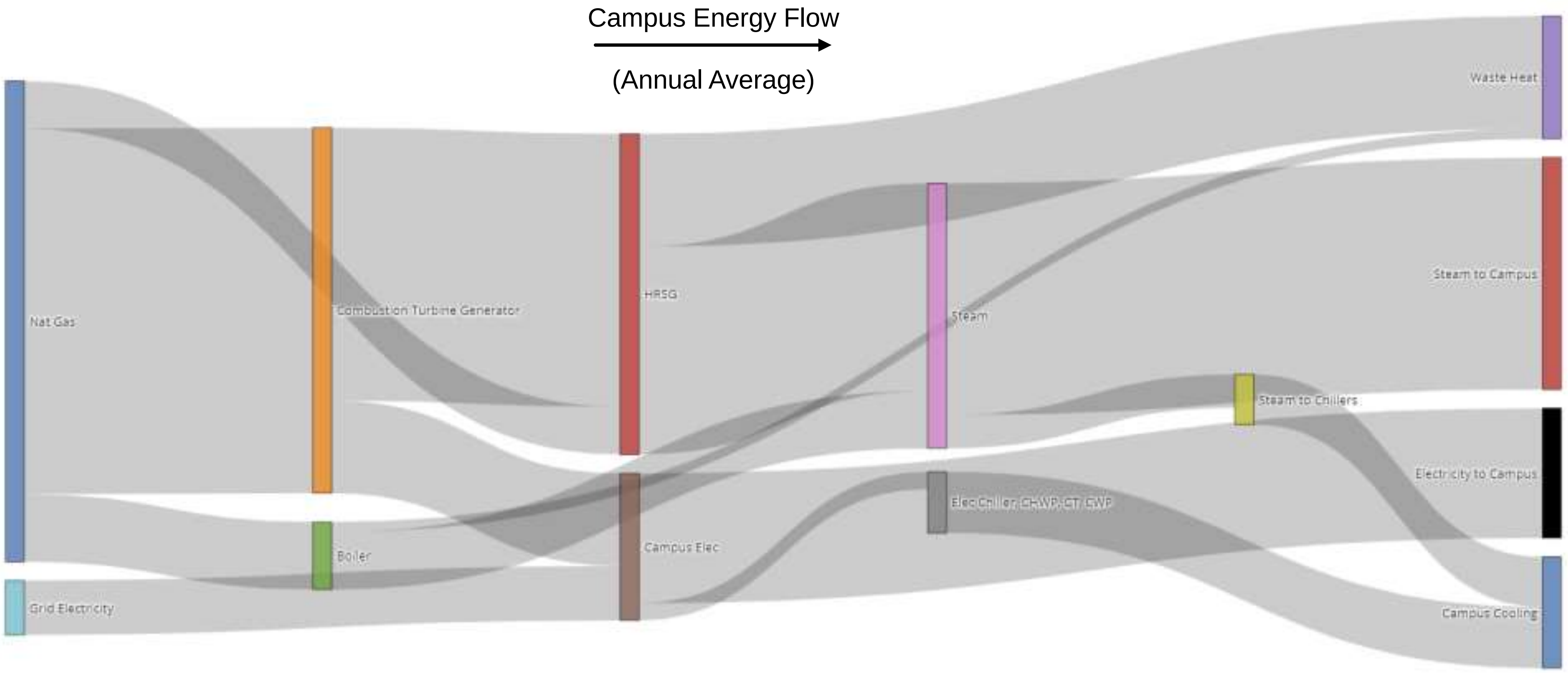
ANNUAL AVERAGE ENERGY FLOWS



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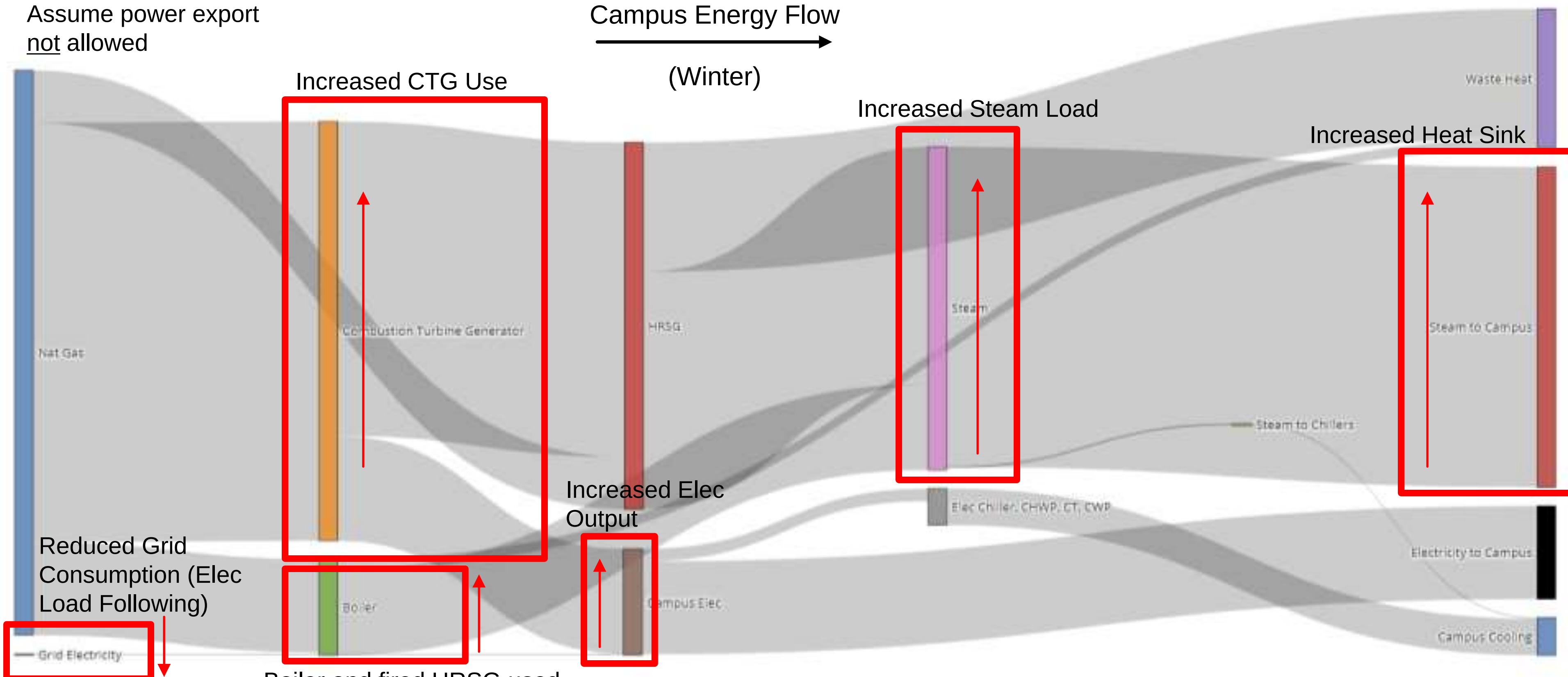
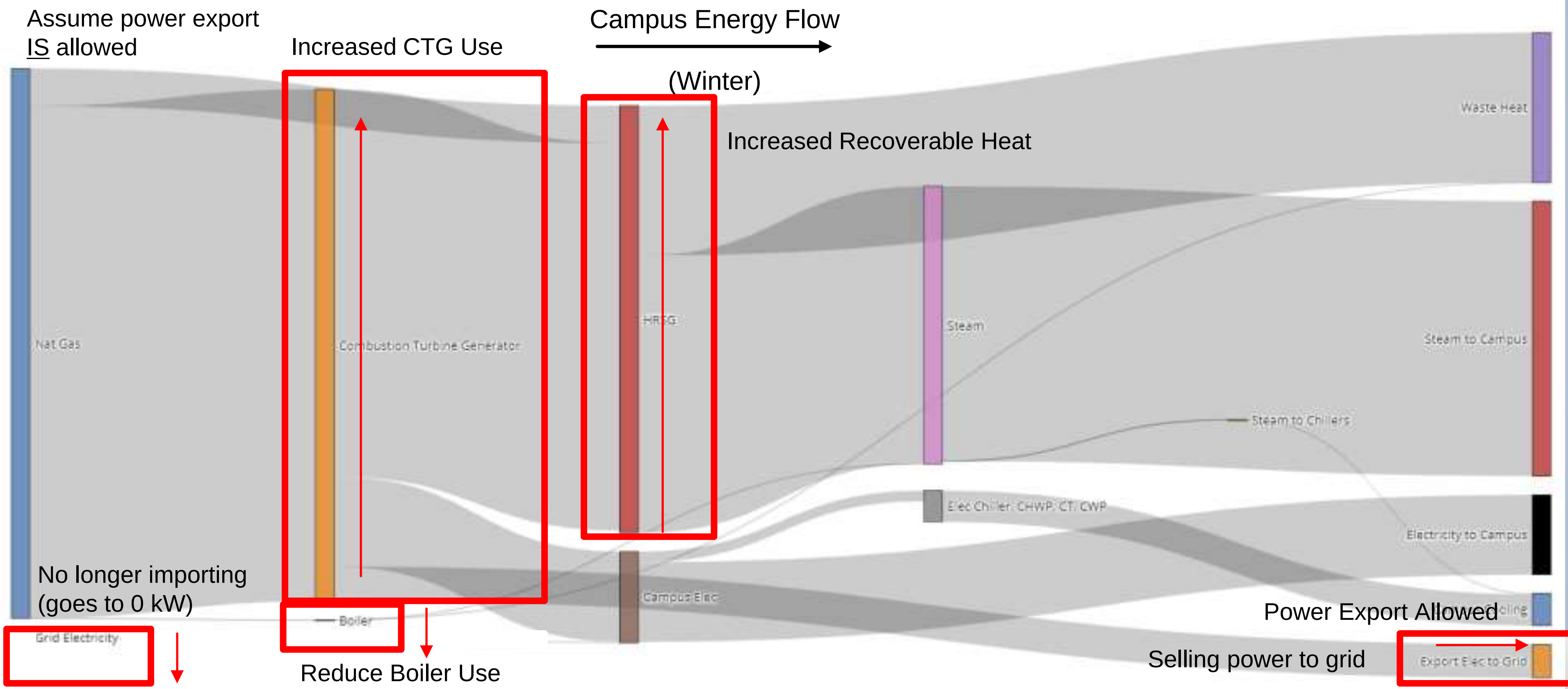
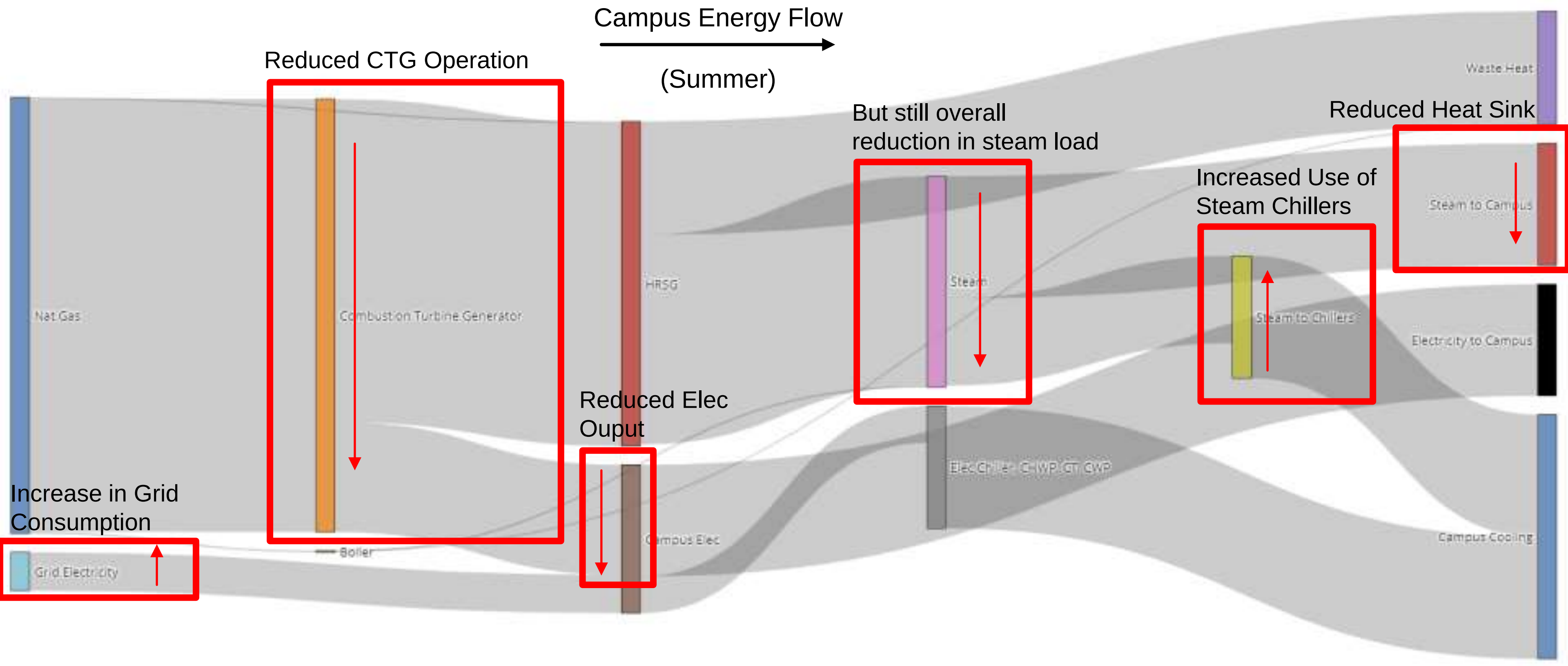
WINTER


Assume power export not allowed
Campus Energy Flow
(Winter)
Increased CTG Use
Increased Steam Load
Increased Heat Sink
Waste Heat
Nat Gas
Combustion Turbine Generator
HRSG
Steam
Steam to Campus
Steam to Chillers
Elec Chiller, CHWP, CT, CWP
Increased Elec Output
Electricity to Campus
Reduced Grid Consumption (Elec Load Following)
Boiler
Campus Elec
Campus Cooling
Grid Electricity
Boiler and fired HRSG used to meet remainder of heat

WINTER (EXPORT ALLOWED)



SUMMER



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SCENARIO 1: (WINTER/SHOULDER) ELECTRICALLY LOAD FOLLOWING,
NOT THERMALLY LIMITED

1. Campus steam load is large relative to available electrical capacity (not thermally limited)
2. Cogen is "load following" the campus electrical profile
3. Incremental value/cost of electricity = cost of gas to produce this electricity MINUS offset savings from additional thermal generation
4. Incremental value/cost of steam = gas cost needed to make steam with boiler/fired HRSG

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SCENARIO 2 (WINTER/SHOULDER): EXPORTING TO GRID, OPERATING AT MAXIMUM ELECTRICAL CAPACITY NOT THERMALLY LIMITED

1. Campus steam load is large relative to available electrical capacity (not thermally limited)
2. Campus exporting electricity to grid, running at maximum electrical capacity
3. Incremental value/cost of electricity = grid rate MINUS offset savings from additional thermal generation
4. Incremental value/cost of steam = gas cost needed to make steam with boiler/fired HRSG

SCENARIO 3 (SUMMER/SHOULDER): IMPORTING FROM GRID THERMALLY LIMITED

1. Campus steam load is small relative to available electrical capacity (thermally limited)
2. Campus importing electricity from grid
3. Incremental value/cost of electricity = grid rate
4. Incremental value/cost of steam = gas cost needed to make steam with CTG MINUS offset savings resulting form associated electrical production

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SCENARIO 4 (SUMMER/SHOULDER): EXPORTING TO GRID, PARTIALLY LOADED ELECTRICALLY THERMALLY LIMITED

1. Campus steam load is small relative to available electrical capacity (thermally limited)
2. Campus exporting electricity to grid
3. Incremental value/cost of electricity = grid rate
4. Incremental value/cost of steam = gas cost needed to make steam with CTG MINUS offset savings resulting form associated electrical production

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COMPONENT OPTIMIZATION

1. Plant optimization choices for mixed fuel plant are typically made on condenser side

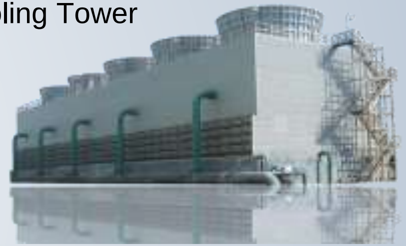
Steam Efficiency

Vs.

Elec Efficiency

Condenser Water Loop

Electric Cooling Tower Fans



Electric CW Pumps

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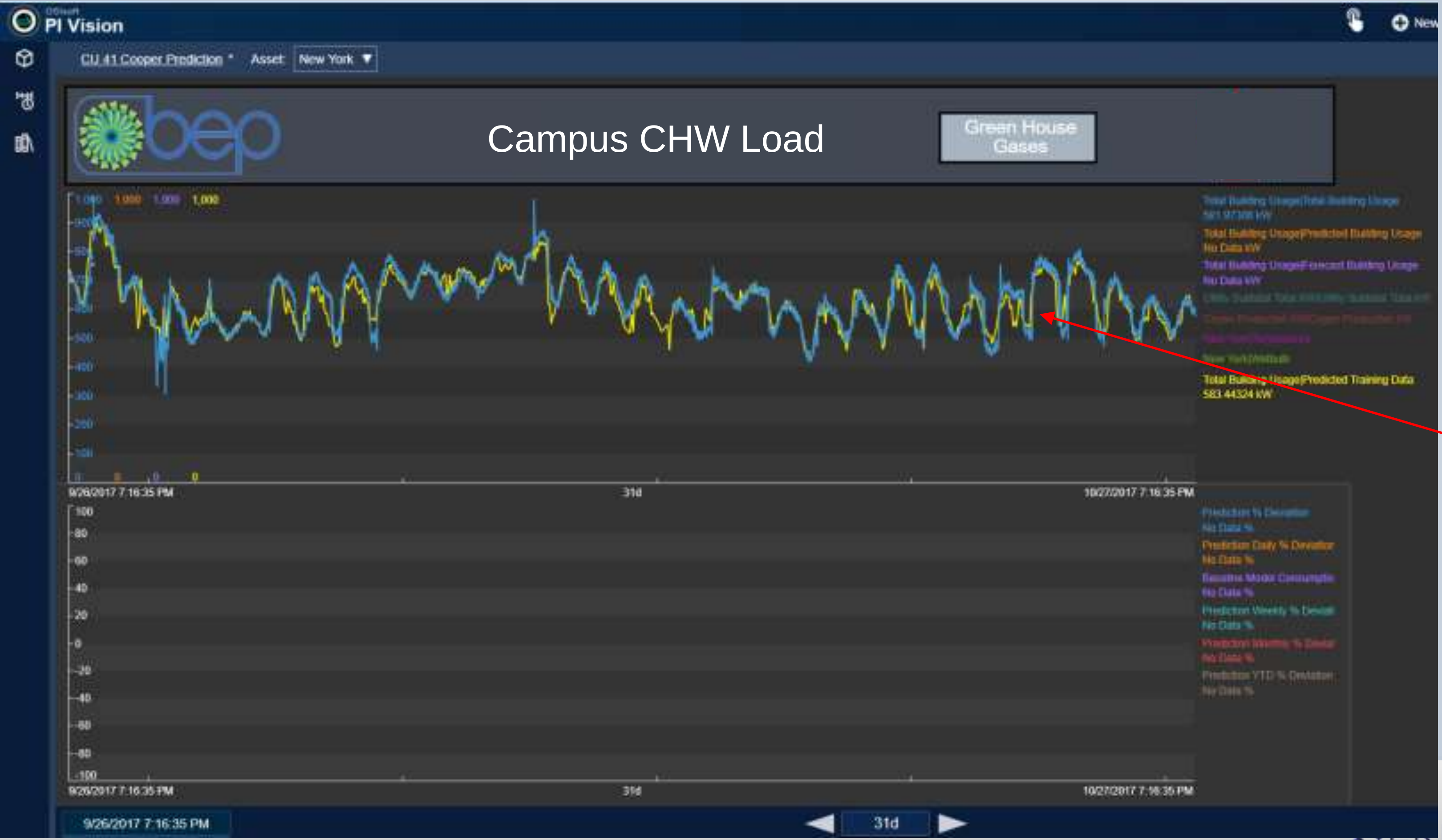
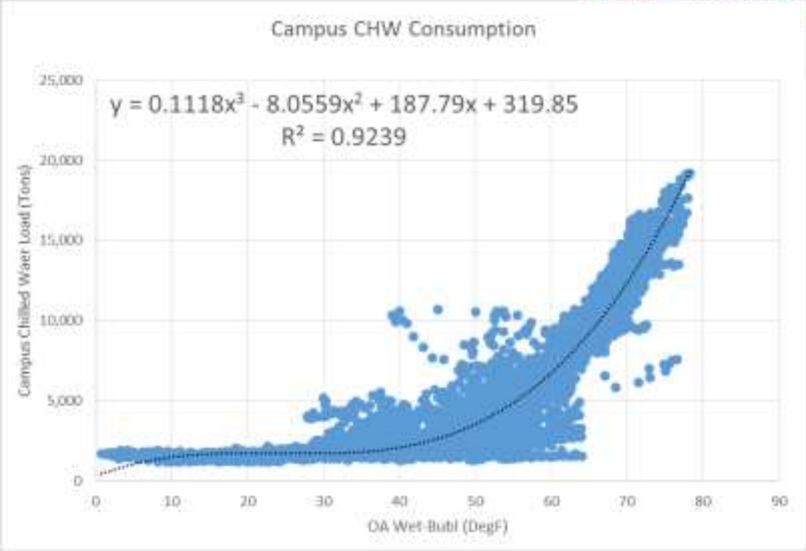
LOAD FORECASTING USING MACHINE LEARNING



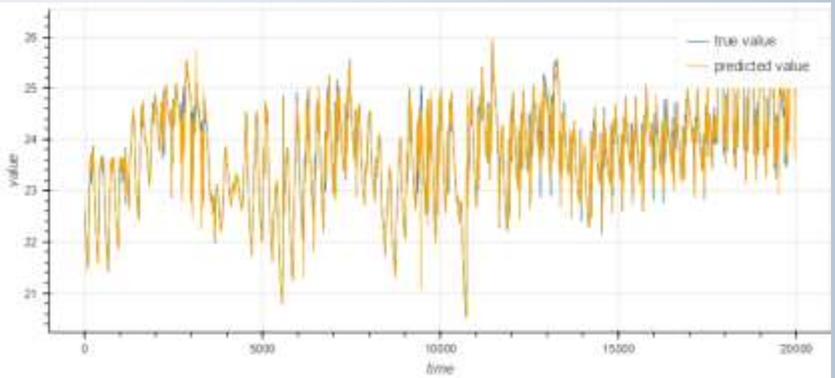
Accurate machine learned profile

MACHINE LEARNING VS LINEAR REGRESSION

Traditional non-linear regression analysis allows 2D M&V normalization



Machine learning allows for limitless dimensional normalization and prediction



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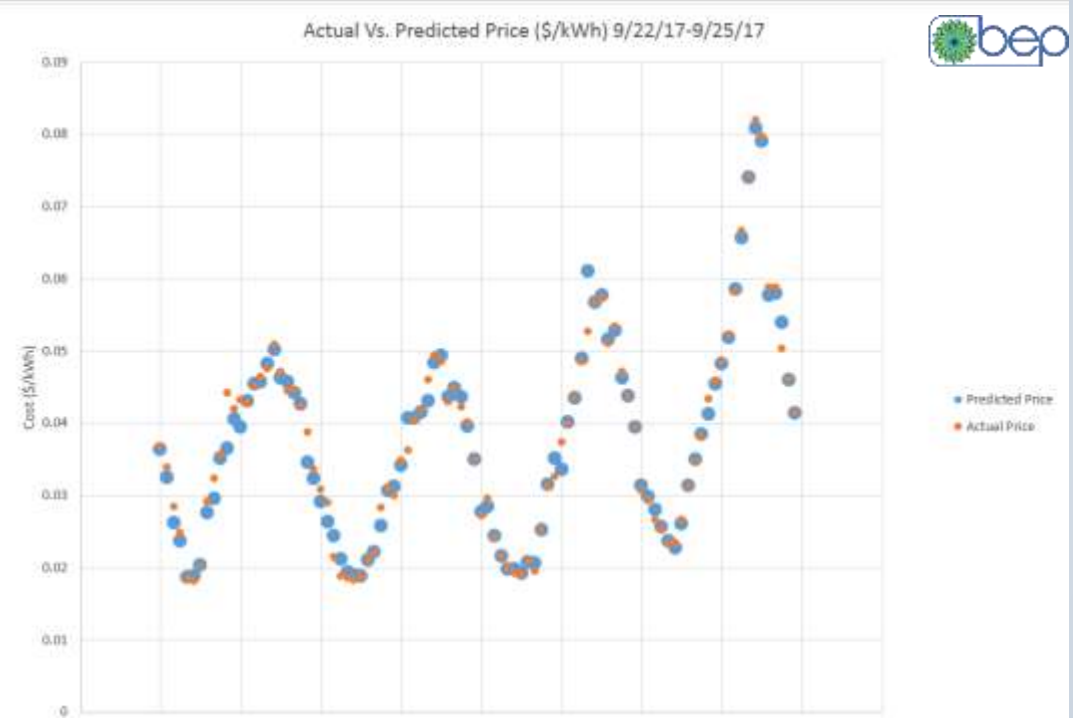
PRICE FORECASTING FOR TIME OF DAY ENERGY RATES



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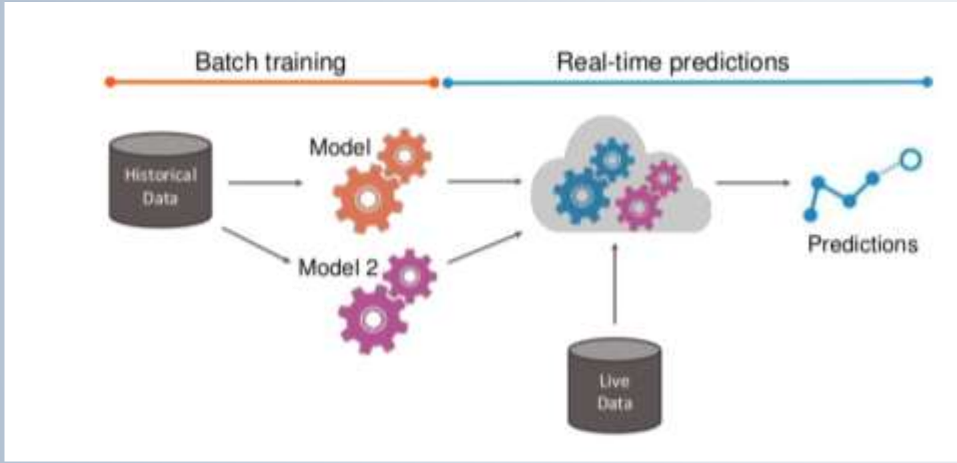
DATA HISTORIAN AS MACHINE LEARNING GATEWAY

- **Integrate with data historians to empower it with machine learning**



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SUMMARY

Optimization of mixed fuel plants requires:

1. Decide what you are optimizing for ($? MtCO2e?)
2. What is incremental impact if increasing or decreasing steam and electric loads?
   - Coincident campus load dynamics
   - Grid cost and GHG dynamics
   - Understand performance dynamics of the plant and sub-components
   - Understand available system capacities
3. Accurate predictions (using machine learning) facilitates optimal consideration of the above dynamics

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Thank You

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