Better Plants
U.S. DEPARTMENT OF ENERGY

Industrial Steam Systems
Virtual INPLT Training & Assessment

Session 3
Tuesday – April 20, 2021
10 am – 12:30 pm

U.S. DEPARTMENT OF ENERGY

Agenda – Session THREE

- Safety and Housekeeping
- Today's Content:
  - <u>**Discussion of Homework**</u>
  - <u>**Quick Review from Session 2**</u>
  - <u>**Steam System Generation**</u>
    - Boiler Efficiency Methods & Comparisons, Special Cases
    - Impact Boiler
    - Cogeneration
  - <u>**US DOE MEASUR Tool**</u>
    - Boiler Calculator
    - Building a steam system model
- Kahoot Quiz Game
- Q&A

Better Buildings is an initiative of the U.S. Department of Energy

Safety and Housekeeping

- Safety Moment
  - Stay within marked walking paths during the plant walk-through
  - Make sure you know where emergency exits and gathering places are located
- Break points after each sub-section where you can ask questions
- When you are not asking a question, please MUTE your mic and this will provide the best sound quality for all participants
- We will be recording all these webinars and by staying on-line and attending the meeting you are giving your consent to be recorded
  - A link to the recorded webinars will be provided, afterwards

Steam Virtual INPLT Agenda

- **Week 1 (April 6) – Industrial Steam Systems Fundamentals and Introduction to SSST**
- **Week 2 (April 13) – Focus on Steam System Generation and Introduction to DOE's MEASUR Tool**
- **Week 3 (April 20) – Steam System Generation & Cogeneration (CHP)**
- **Week 4 (April 27) – Steam System Distribution, End-Use & Condensate Recovery**
- **Week 5 (May 4) – Energy Efficiency Opportunities in the Generation Area**
- **Week 6 (May 11) – Energy Efficiency Opportunities in Cogeneration (CHP) Area**
- **Week 7 (May 18) – Energy Efficiency Opportunities in Distribution, End-use and Condensate Recovery**
- **Week 8 (May 25) – Industrial Steam System VINPLT Wrap-up Presentations**

Homework 2 Discussion

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Homework #2

- Pay a visit to your boiler plant (generation) area and make a list of all the boilers, their design steam flow, pressure, fuel used and heat (input or output) rating.
- Understand how the boiler plant is controlled – how many boilers are running, how many are hot standby, etc. How does seasonality and production change the operations of these boilers.
- Pick one or more boilers and complete the exercise to calculate direct boiler efficiency and indirect boiler efficiency with specific boiler losses. You can use 1Q 2021 average data or representative operating data.
- Calculate your steam cost ($/klb).

Polling Questions 1-3

Polling Question

1) Were you able to calculate boiler efficiency using the direct method?
   A. Yes
   B. No

2) Were you able to calculate stack loss for your boiler?
   A. Yes
   B. No

3) Were you able to install and use US DOE MEASUR?
   A. Yes
   B. No

Session 2 – Quick Review

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Steam Cost Indicator

$$Steam\ Cost = \frac{Fuel\ Cost}{Steam\ Produced}$$

$$Steam\ Cost = \frac{745}{100}$$

$$\boldsymbol{Steam\ Cost = 7.45\ \frac{\$}{klb}}$$

$$Steam\ Cost = \frac{6{,}526{,}200}{100 \times 8760}$$

$$\boldsymbol{Steam\ Cost = 7.45\ \frac{\$}{klb}}$$

Classic Boiler Efficiency

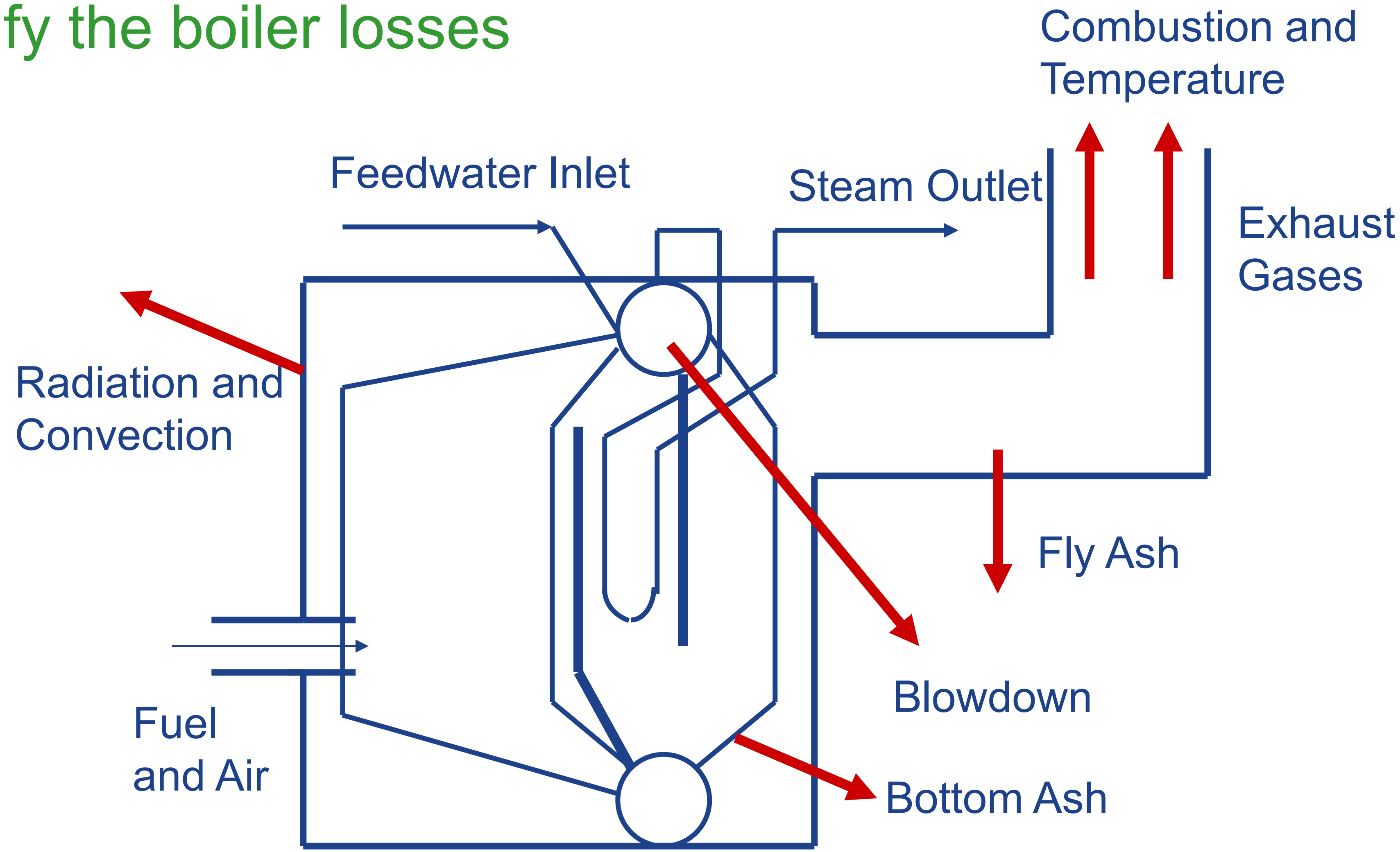
- Steam generating unit efficiency is defined as the heat absorbed by the steam divided by the fuel input energy

$$\eta_{boiler} = \frac{\text{energy desired}}{\text{energy that costs}}(100)$$

$$\eta_{boiler} = \frac{\dot{m}_{steam}\left(h_{steam} - h_{feedwater}\right)}{\dot{m}_{fuel} HHV_{fuel}}(100)$$

Boiler Losses

- Identify the boiler losses



Indirect Efficiency

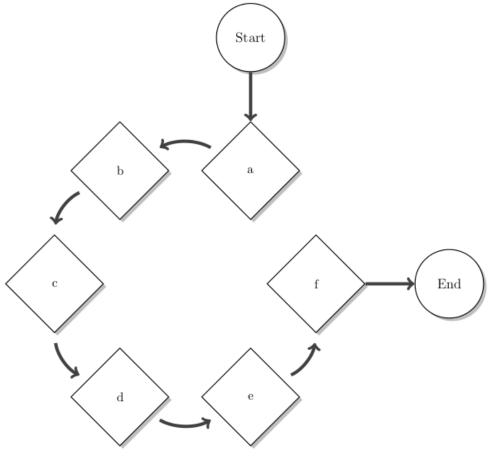
- Boiler efficiency can also be determined in an indirect manner by determining the magnitude of the losses
  - Primary losses are typically
    - Shell loss
    - Blowdown loss
    - Stack loss

$$\eta_{indirect} = 100\% - \sum_{losses} \lambda_i$$

$$\eta_{indirect} = 100\% - \lambda_{shell} - \lambda_{blowdown} - \lambda_{stack} - \lambda_{misc}$$

Which Method should be used?

Direct Method



InDirect Method

Boiler Efficiency Evaluation – Direct Method

- Advantages
  - All-in-one
  - Very quick and easy – minimal data required
  - Can be done for instantaneous, hourly, daily, monthly, annually or any time period
  - Trends, dashboards – programmable for operators
- Disadvantages
  - Need flow rates (steam and fuel) – maybe difficult to obtain – larger time periods needed with totalizers
  - Can have significant errors – calibration + human
  - No information on how to improve boiler efficiency

Boiler Efficiency Evaluation – InDirect Method

- Advantages
  - Can be very accurate since errors in measurements are very minimal
  - Provides gap analysis for boiler efficiency improvement
  - Stack loss, blowdown can be trended and programmed – main variable losses
- Disadvantages
  - Significant data collection (in-situ and portable instruments + human intervention)
  - Mostly done instantaneously or over shorter periods of time only
  - Boiler shutdown maybe needed to initiate data collection

Example Boiler – US DOE MEASUR

- Boiler fired with natural gas
  - HHV is 1,000 Btu/scf
- Steam conditions: 400 psig, 700°F
- Output: 100,000 lb/hr (steady)
- Fuel cost: $5.00 per MMBtu
- Blowdown: 6%
- Deaerator: 10 psig
- Combustion efficiency: 78.7%
  - Shell loss can be added to more accurately reflect the energy flow numbers but it is generally not an impact parameter

Example Boiler – US DOE MEASUR

BOILER

Deaerator Pressure	10	psig
Combustion Efficiency Calculate Efficiency	78.7	%
Blowdown Rate	6	%

Steam

Pressure	400	psig.
Known Variable	Temperature	
Temperature Value	700	°F
Steam Mass Flow	100000	klb/hr

Generate Example | Reset Data

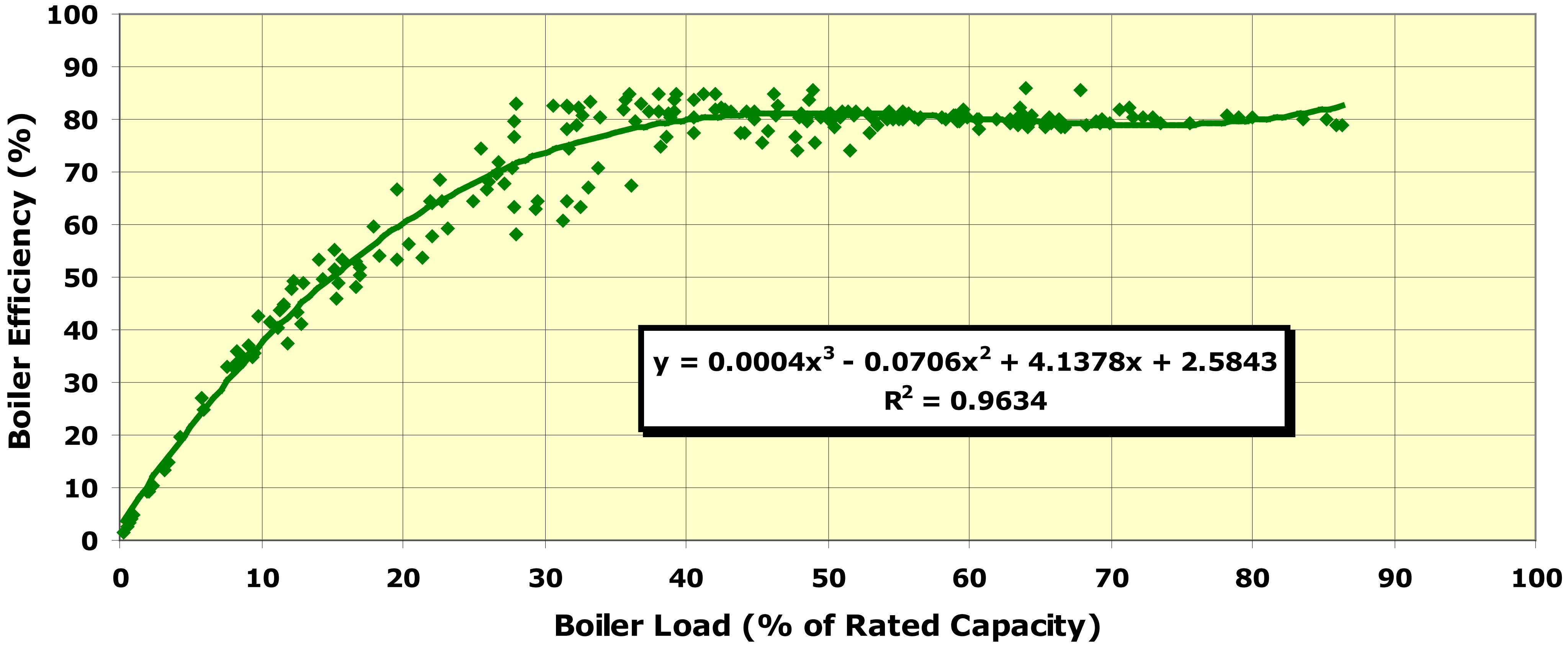
RESULTS | HELP

Blowdown Rate	6 %
Boiler Energy	116,825.4 MMBtu/hr
Combustion Efficiency	78.7 %
Fuel Energy	148,444 MMBtu/hr

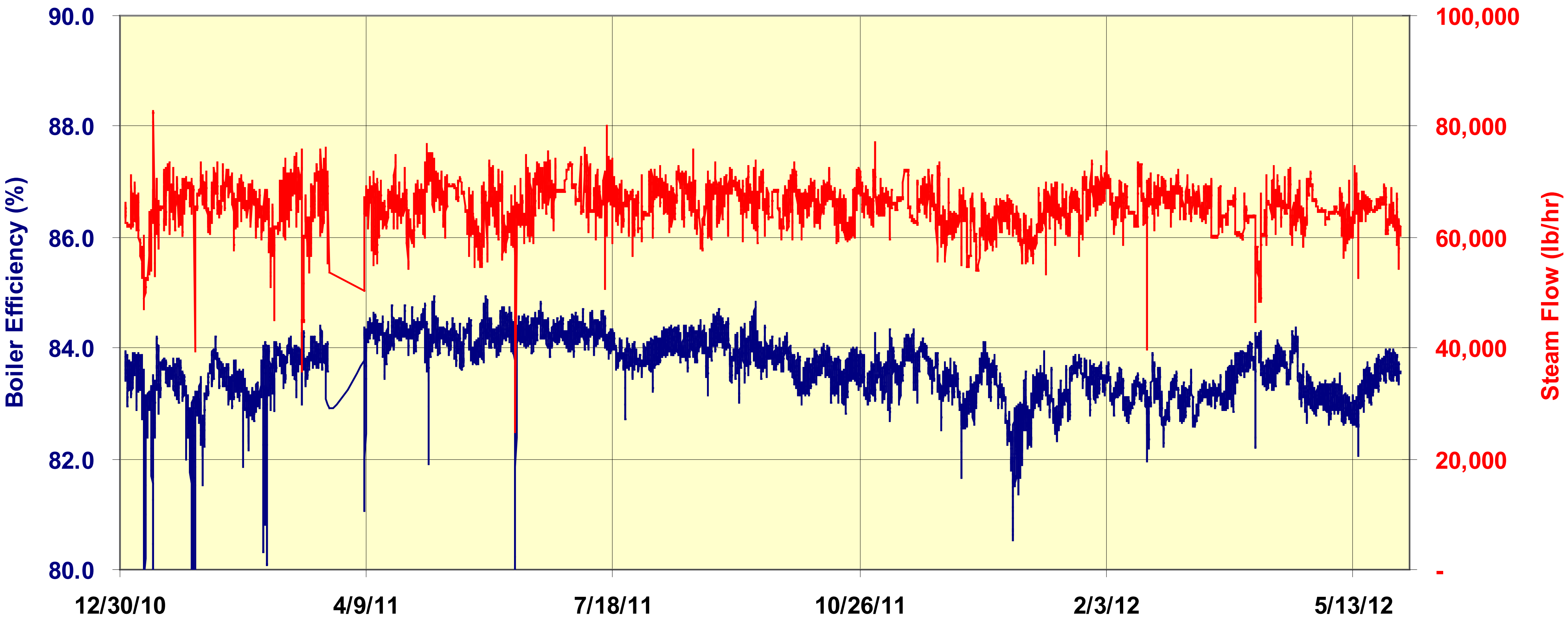
	Feedwater	Blowdown	Steam
Pressure (psig)	10	400	400
Temperature (°F)	239.4	448.2	700
Saturated	Liquid	Liquid	Gas
Mass Flow (klb/hr)	106,382.98	6,382.98	100,000
Sp. Enthalpy (Btu/lb)	207.8	428.2	1,362
Sp. Entropy (Btu/lb-°F)	0.352	0.626	1.636
Energy Flow (MMBtu/hr)	22,108.6	2,732.9	136,201.2

Copy Table

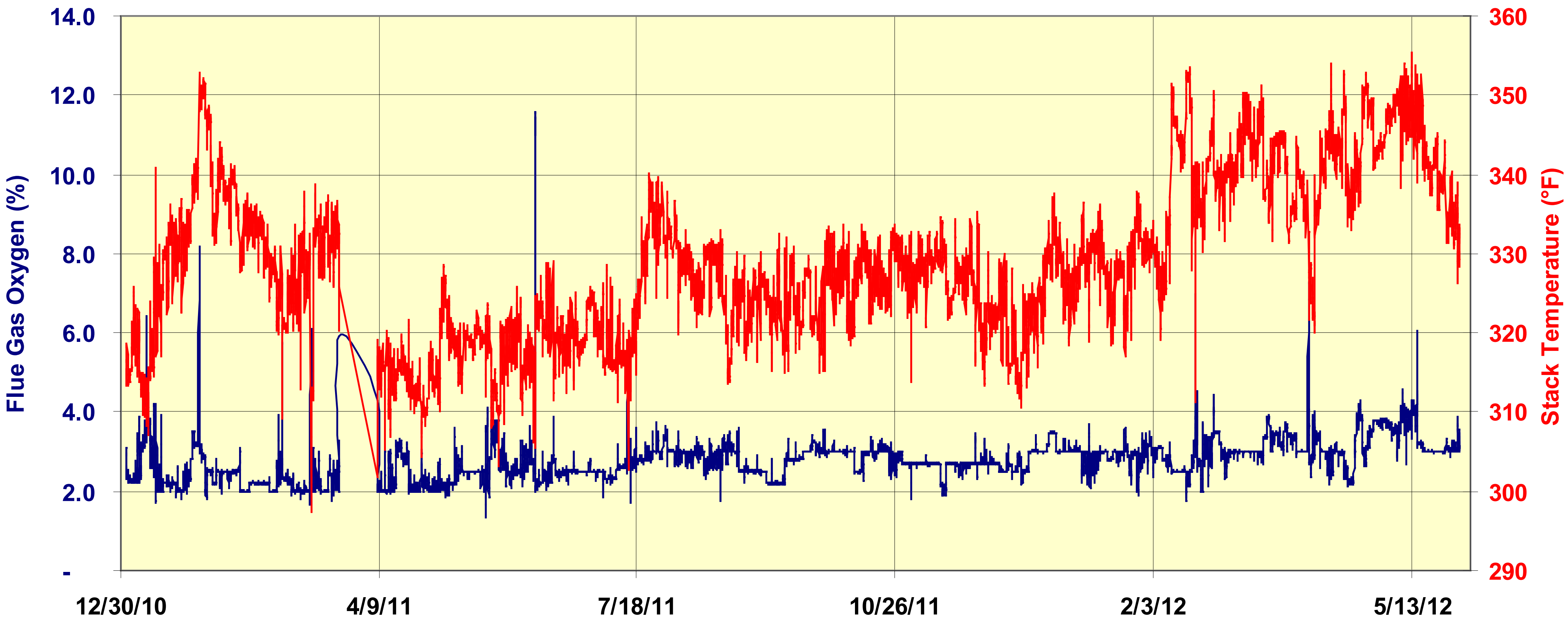
Typical Boiler Efficiency Curve



Boiler Efficiency Curve



Boiler Efficiency – Key Parameters Monitoring



What about Boiler Plant Direct Efficiency?

- If the fuel is the same for all boilers and boilers have same steam generation conditions and feedwater conditions

$$\eta_{plant} = \frac{m_{total-steam}\left(h_{steam} - h_{feedwater}\right)}{m_{total-fuel} \times HHV_{fuel}} \times 100$$

- If the fuel is different for boilers and boilers have different steam generation conditions and feedwater conditions

$$\eta_{plant} = \frac{\sum_1^n m_{steam}\left(h_{steam} - h_{feedwater}\right)}{\sum_1^n m_{fuel} \times HHV_{fuel}} \times 100$$

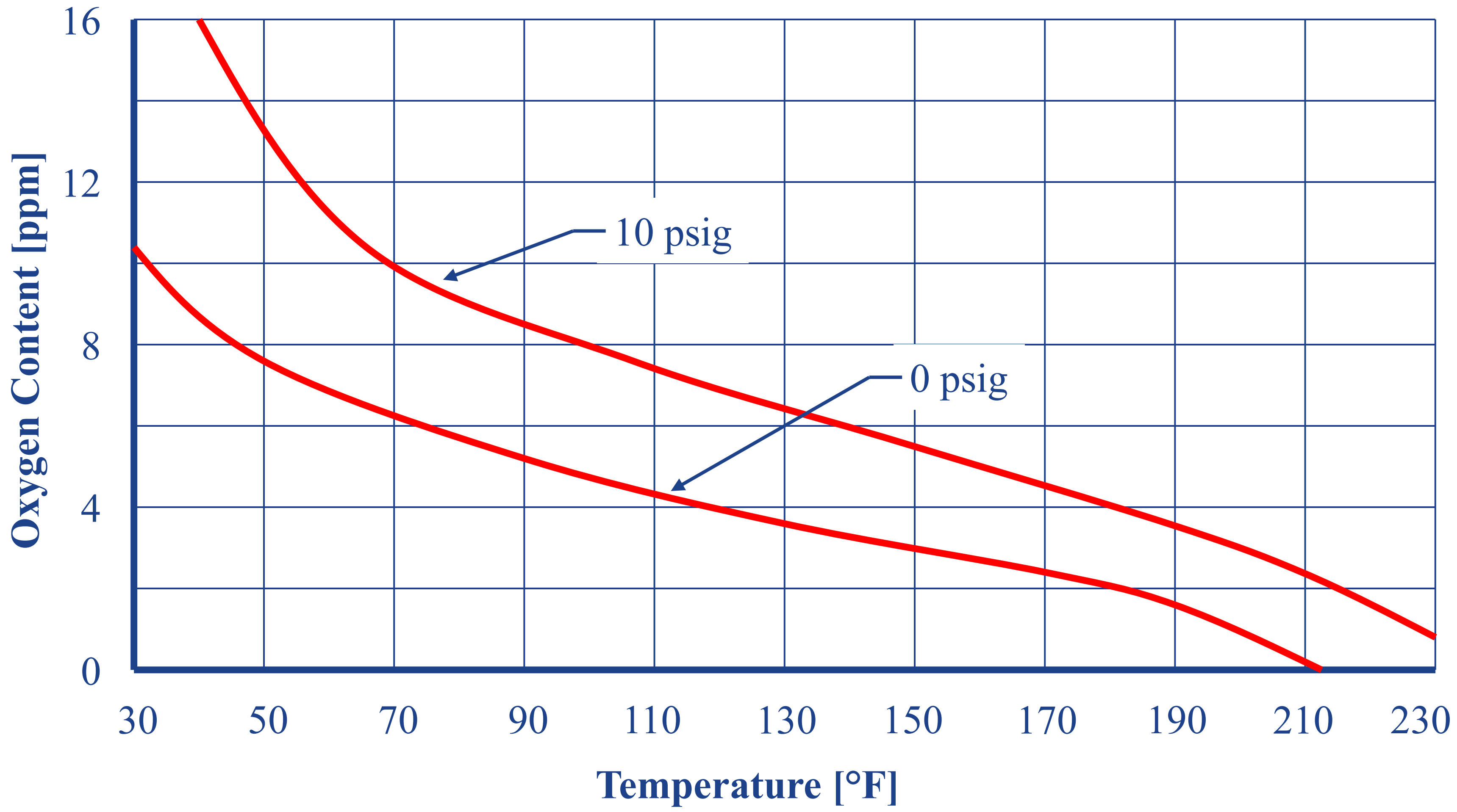
Generation Area

- Deaerator

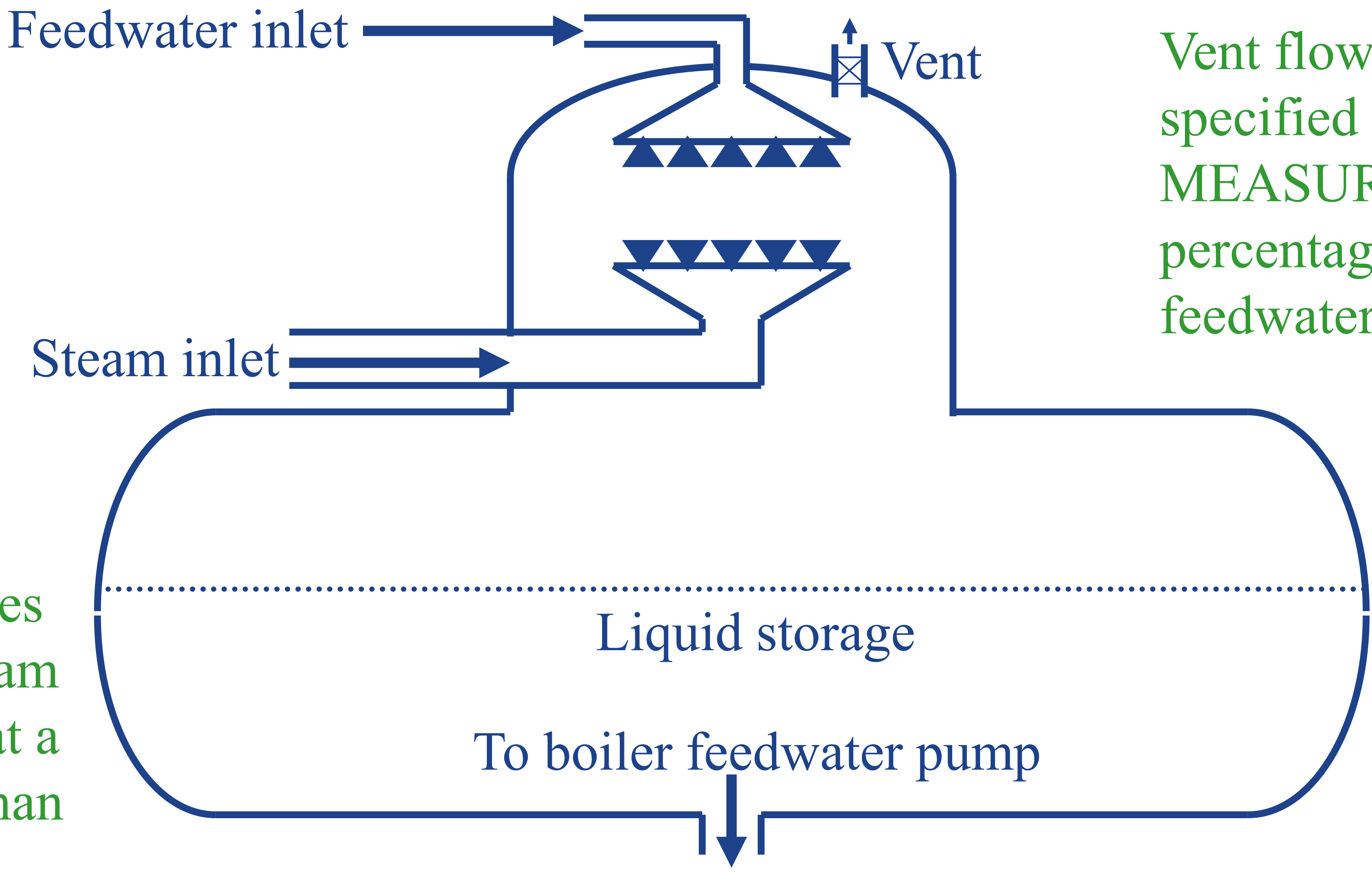
Deaeration

- Oxygen, carbon dioxide and other gases are soluble in water
  - These chemicals are detrimental to the steam system
    - Oxygen results in corrosion generally in the form of pitting
    - Carbon dioxide results in corrosion generally from acidic condensate
- Open condensate receivers are a location where gases can become dissolved in condensate
- Makeup water usually contains significant amounts of dissolved gases
- The solubility of gases in water decreases as temperature increases
  - Deaeration is used to reduce the effects of dissolved gases

Solubility of Oxygen in Water



Deaerator



Vent flow is specified in MEASUR as a percentage of boiler feedwater flow

Deaerator receives low-pressure steam but can operate at a pressure lower than this

US DOE MEASUR

- Plant / System Information Required
- Building a Steam System Model

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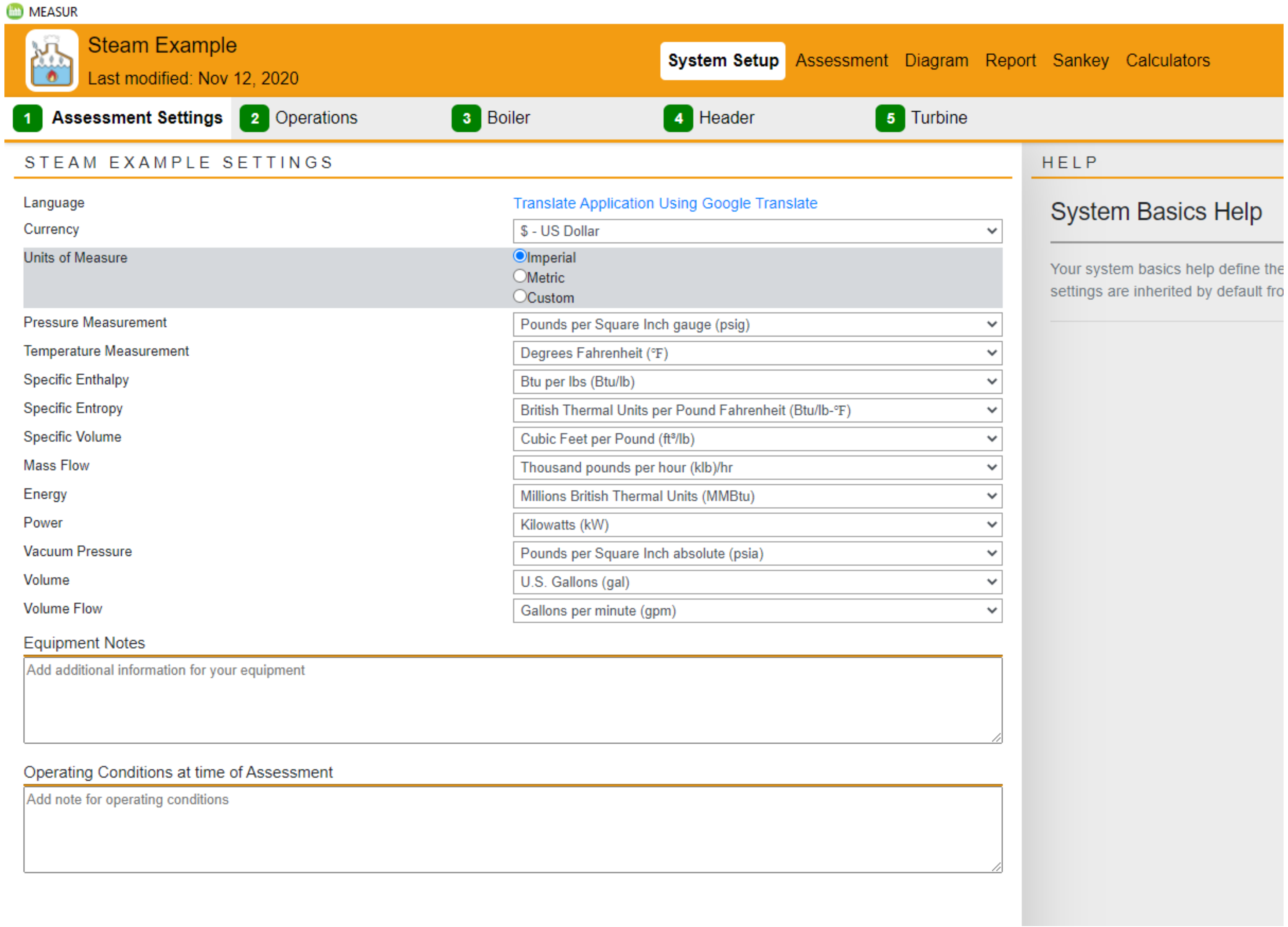
US DOE MEASUR Preferences

- Full flexibility is offered to the user to select default (IP) or choose Custom units for the parameters
- Generally, US$ is the easiest currency to work with but some other currencies are available
- HELP is always around



Site Power Import (or Export)

- MEASUR requires an input for the normal amount of import electrical power
- Import electrical power combined with site generated power is the site load
- If the site is a net exporter of power a negative value should be provided for the import power

Electric Rate Structure

- A thorough understanding of the electric rate structure is essential to evaluate the true impact of any process change
- The average electric cost is generally not the unit cost a facility will be impacted by as a result of an increase or decrease in electrical consumption

Makeup Water Costs

- Water purchase price
- Pumping costs
- Treatment costs
- Wastewater costs ???
- Makeup water temperature is an important variable

Fuel Pricing

Typical Fuel Properties					
Fuel	**Sales Unit**	**Example Price [$/sales unit]**	**HHV [Btu/lb]**	**LHV [Btu/lb]**	**Unit Price [$/MMBtu]**
Natural Gas	10^3std ft^3	5.00	23,311	21,032	5.00
Number 2 Fuel Oil	gallon	2.20	19,400	18,275	15.79
Number 6 Oil (LS)	gallon	1.50	18,742	17,757	9.77
Number 6 Oil (HS)	gallon	1.25	18,815	17,780	8.27
Eastern Coal	ton	45.00	13,710	13,201	1.64
Western Coal	ton	30.00	10,088	9,547	1.49
Green Wood	ton	11.00	5,250	4,357	1.05

Fuel Cost Structure – Impact Fuel

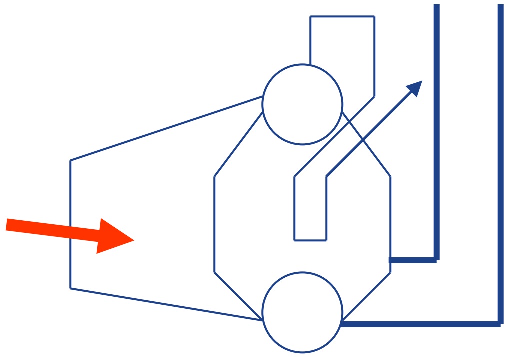
- Analyses should be completed utilizing *impact costs*
- Gross indications of savings opportunities can be attained by use of *average impact cost* or *projected cost*
- Multiple models may need to be developed reflecting various pricing conditions
  - Fuel prices typically vary seasonally
- The USDOE MEASUR fuel cost should be close to the actual energy related fuel cost for building confidence in the system model

Boiler & Fuel Selection

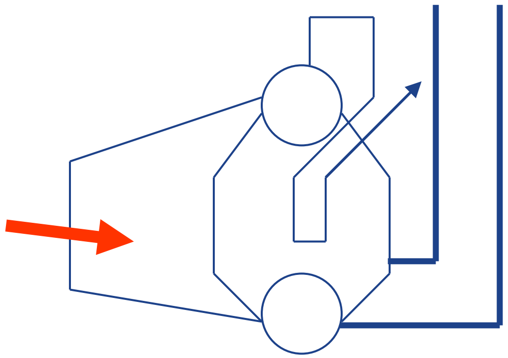
- What is Impact fuel?
  - The fuel that will change consumption if steam demand changes
  - Typically, the highest cost fuel in use
  - "Blended costs" generally do not reflect actual system changes
    - Blended costs **do** provide a confidence level in the model results

- What is Impact boiler(s)?
  - The boiler(s) that will change consumption if steam demand changes
  - Typically, the boiler with the highest steam cost indicator
  - "Blended boiler" configuration generally does not reflect actual system changes
    - Blended costs **do** provide a confidence level in the model results

Impact Boiler & Fuel Selection



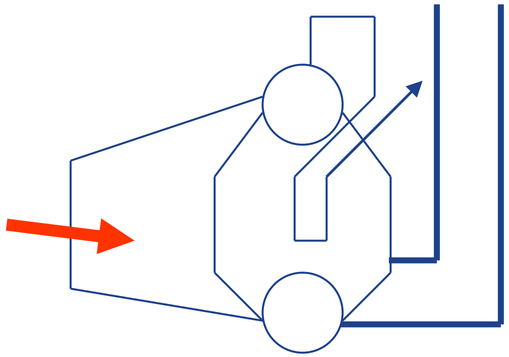
Fuel: Natural gas
Fuel cost: $5.00/MMBtu
Boiler capacity:
120,000 lbm/hr
Steam production:
100,000 lbm/hr
Boiler efficiency: 78%



Fuel: Number 2 fuel oil
Fuel cost: $15.79/MMBtu
Boiler capacity:
50,000 lbm/hr
Steam production:
10,000 lbm/hr
Boiler efficiency: 85%

- For the example system, variations in steam demand and reliability concerns will require both boilers to operate

Impact Boiler & Fuel Selection



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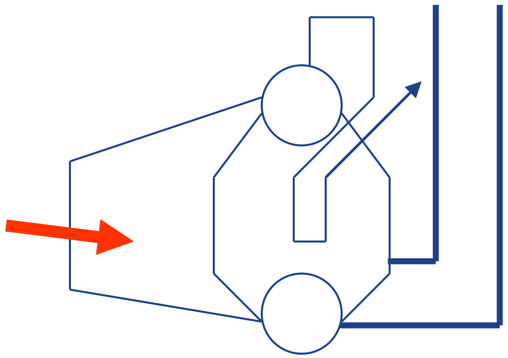

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Boiler efficiency: 85%

- The natural gas boiler is the **IMPACT boiler** because it responds to steam demand changes
- The #2 fuel oil boiler is a fixed operation boiler

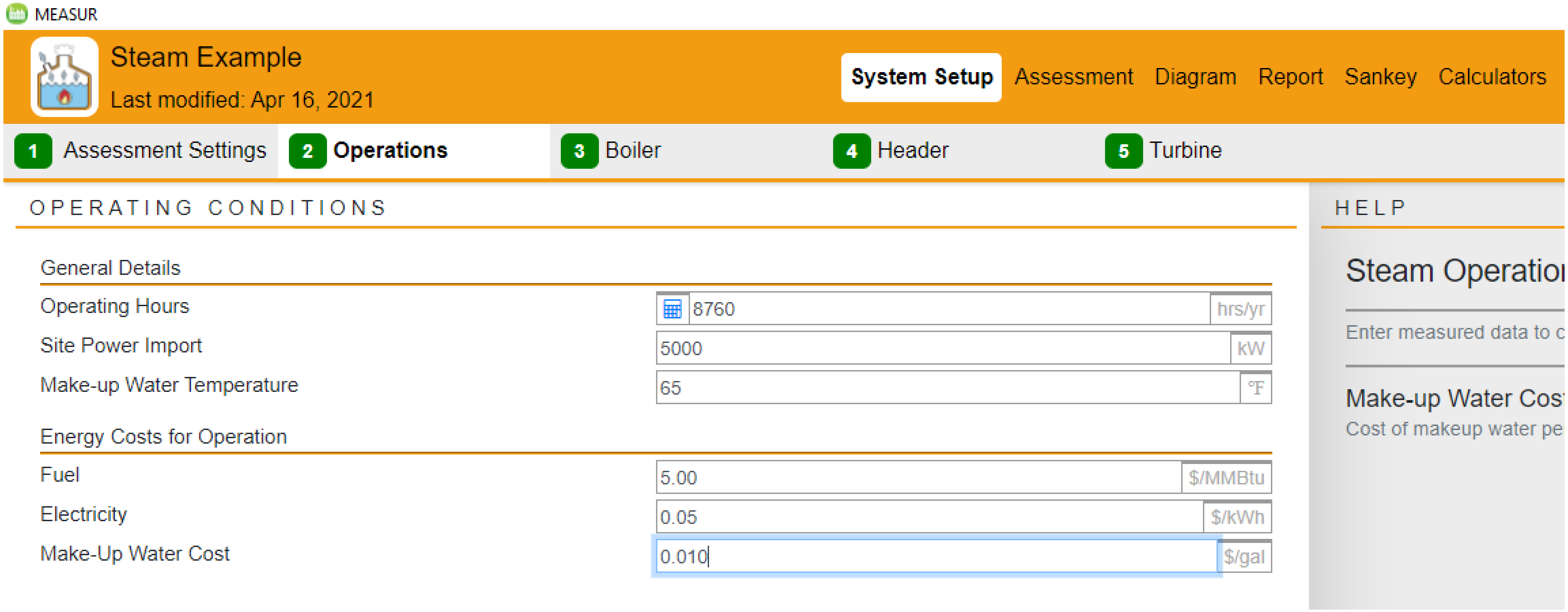
Plant Information

- The industrial plant chosen for this assessment is a Pulp & Paper Mill
- Typical electrical demand for the plant is 5 MW
- The plant has the following electrical costs
  - Energy charge is $0.030/kWh
  - Demand charge: $14.6/kW on a monthly basis
  - If both charges are applicable to a load contributing to the billing demand the electrical cost can be considered $0.050/kWh
- The site operates 24 hours each day 365 days each year
  - 8760 hours

Plant Information

- Average annual bundled cost for water is $10/kgal (0.01 $/gal)
- Impact fuel – Natural gas
  - Fuel cost - $5.00/MMBtu
- Make-up water temperature – 65°F

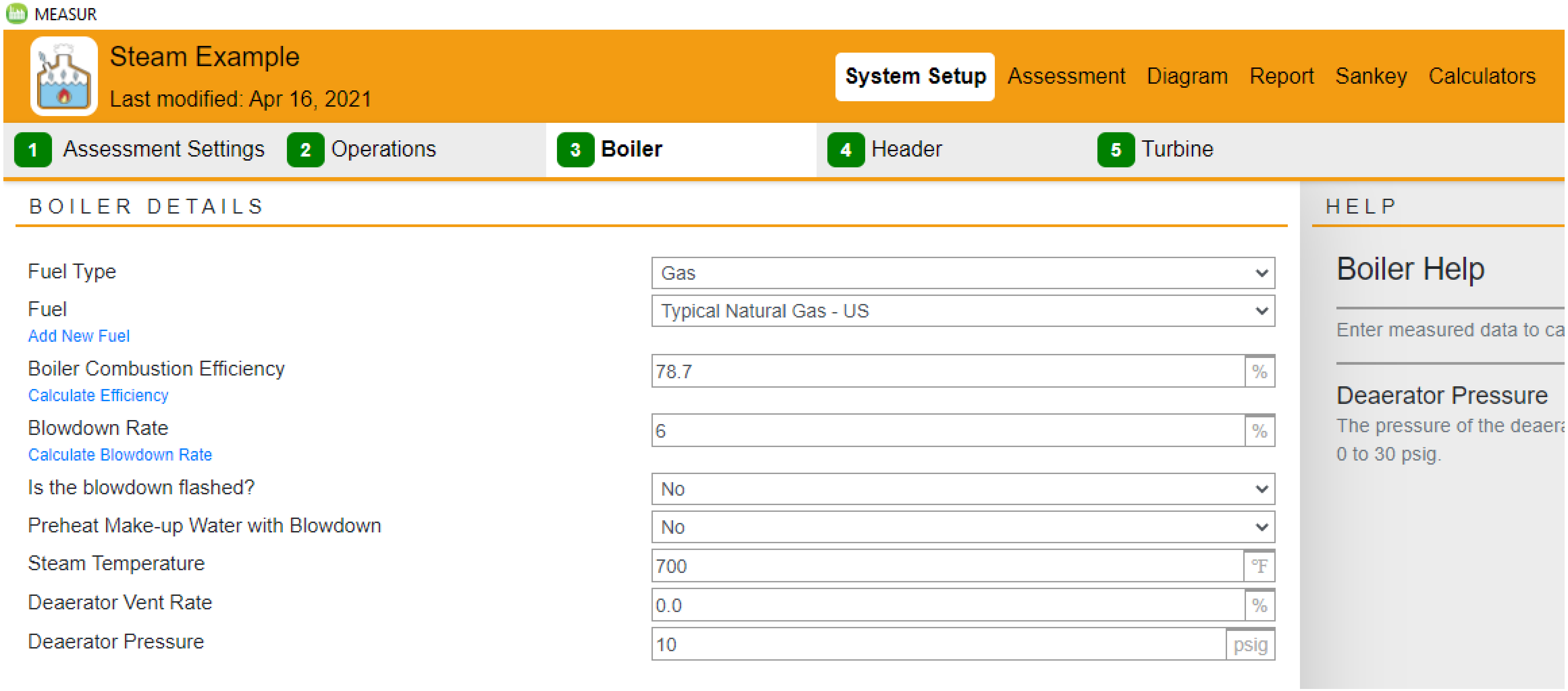
MEASUR – System Setup



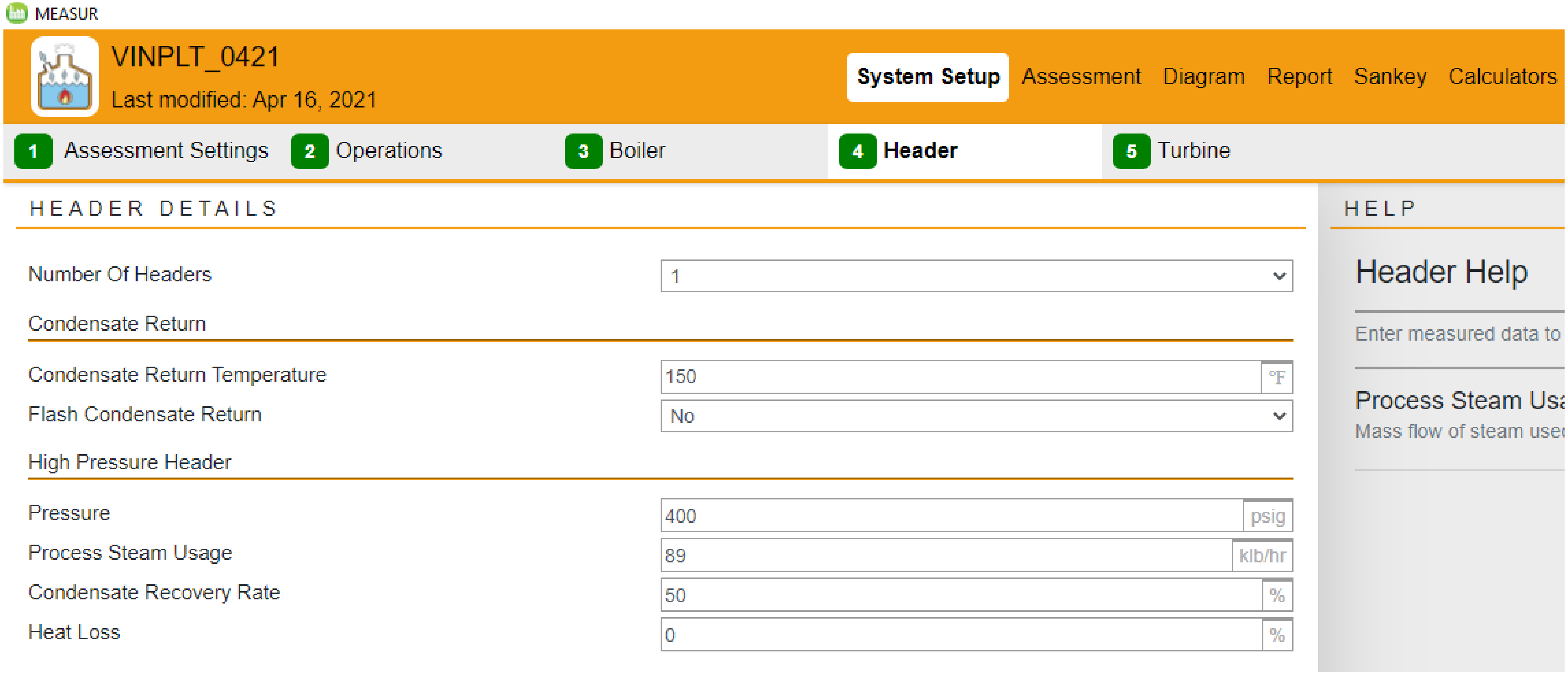
Plant Information

- Impact boiler efficiency to be used in the US DOE MEASUR tool
  - Combustion efficiency – 78.7%
  - Blowdown rate – 6%
- Boiler blowdown is sent to drain/sewer directly
  - No heat recovery
  - No flash steam generation
- Deaerator operating pressure – 10 psig
- Deaerator vent is NOT (generally) an impact parameter
  - Can be set to 0
- Steam generation conditions: 400 psig, 700°F

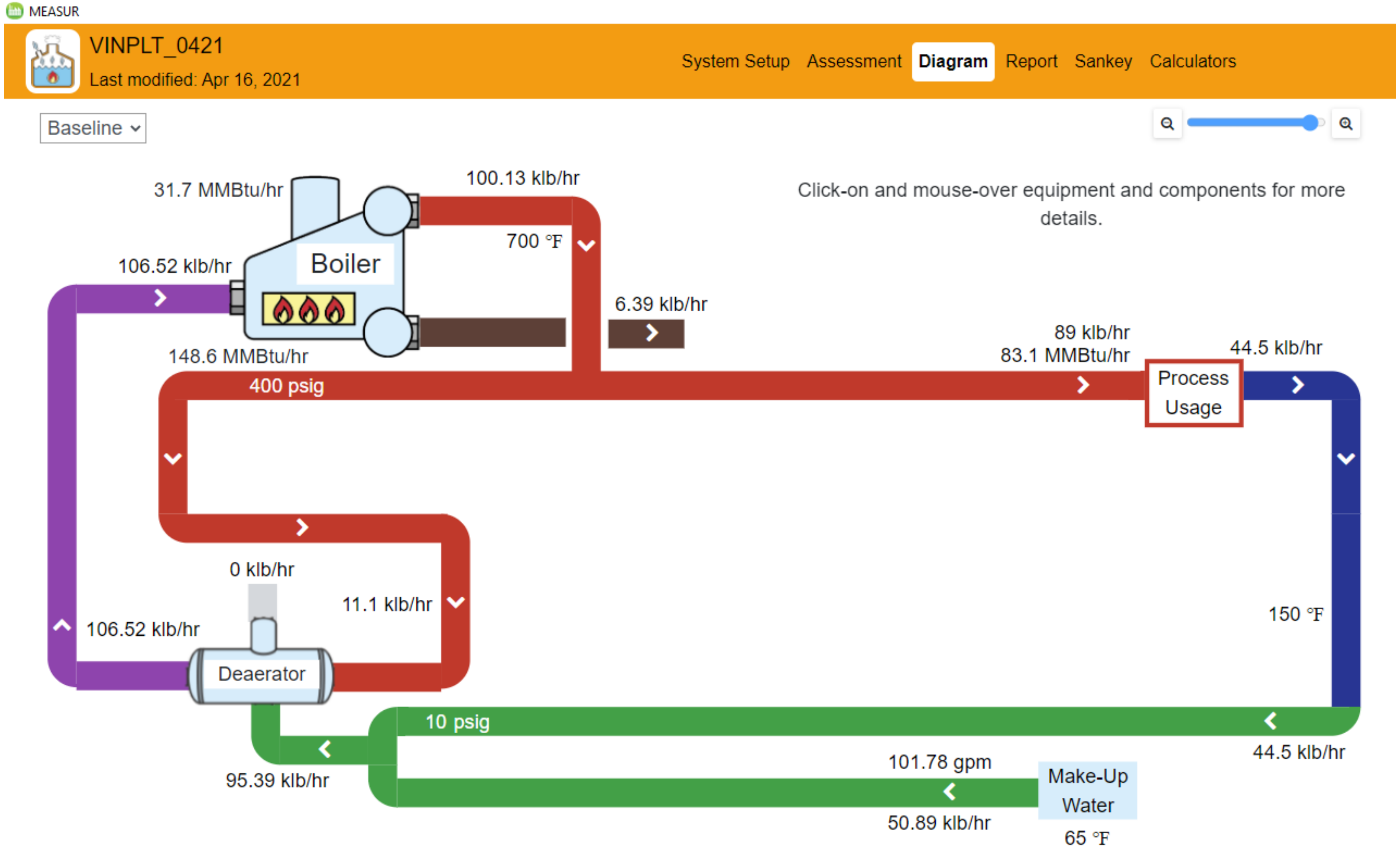
MEASUR – System Setup



MEASUR – System Setup



MEASUR – System Diagram



MEASUR – System Cost Summary

COST SUMMARY

Power Balance	
Generation	0 kW
Demand	5,000 kW
Import	5,000 kW
Unit Cost	$0.05 /kWh
Total $/yr	$2,190,000

Fuel Balance	
Boiler	148.63 MMBtu/hr
Unit Cost	$5.00 /MMBtu
Total $/yr	$6,510,187

Make-Up Water	
Flow	101.78 gpm 53,497,740.14 gal
Unit Cost	$0.01 /gal
Total $/yr	$534,977

Total Operating Cost
$9,235,164

MARGINAL STEAM COST

High Pressure	$9.04 /klb
Medium Pressure	$0.00 /klb
Low Pressure	$0.00 /klb

CoGeneration (Combined Heat & Power)

- Steam Turbines

Turbines 101

- What is a Turbine?
  - Energy Conversion Device

Potential / Kinetic / Pressure / Thermal Energy

↓

Rotational Shaft Energy

Market Penetration

- No easy reference to determine number and size of steam turbines out in the field
  - Some estimates indicate ~85% US power generated by steam turbines
- Some studies state that U.S. industry employs ~20 GW of power generation from steam turbines
  - Shaft power generation (direct drive and electrical generator drives)
- Industrial turbines range in capacity from 10 kW (13.5 hp) to several hundred MW

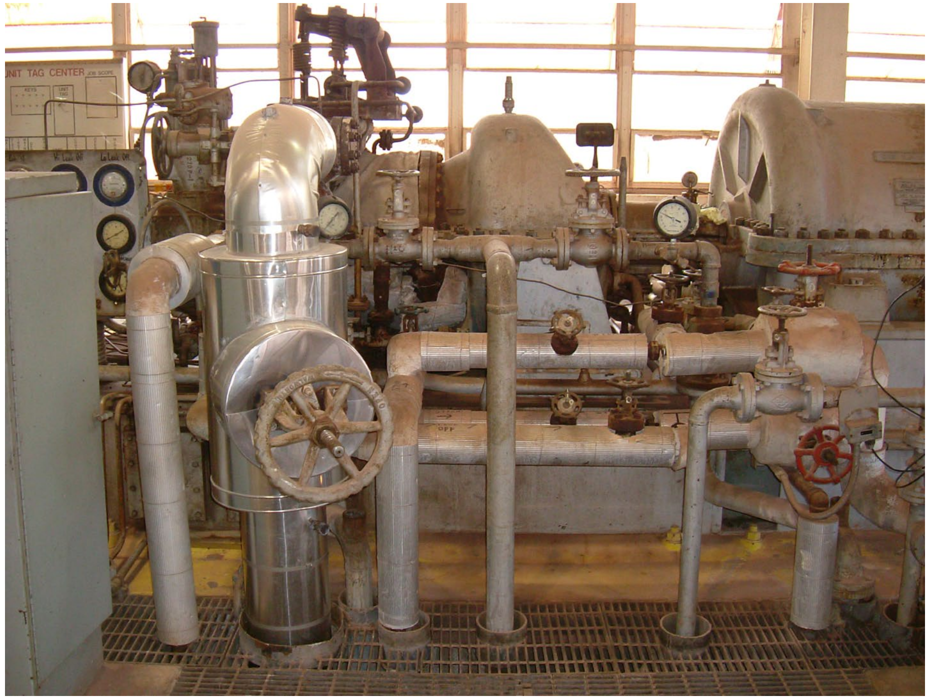
Examples of Industrial Systems

- Very common in industry
  - Direct power generation
  - Boiler feed water pumps
  - Cooling tower water pumps
  - Chilled water pumps
  - Boiler forced draft fan
  - Exhaust fans
  - Air compressors
  - Refrigeration machines
  - Chiller systems
  - Other utility services

- Less common in industry
  - Process equipment drives
  - Highly critical equipment

Examples of other Industrial Systems

Backpressure Steam Turbine-driven Air Compressors



Industrial Applications

4,000 RT Steam Turbine Driven Chiller

Compressor

Direct Drive Shaft

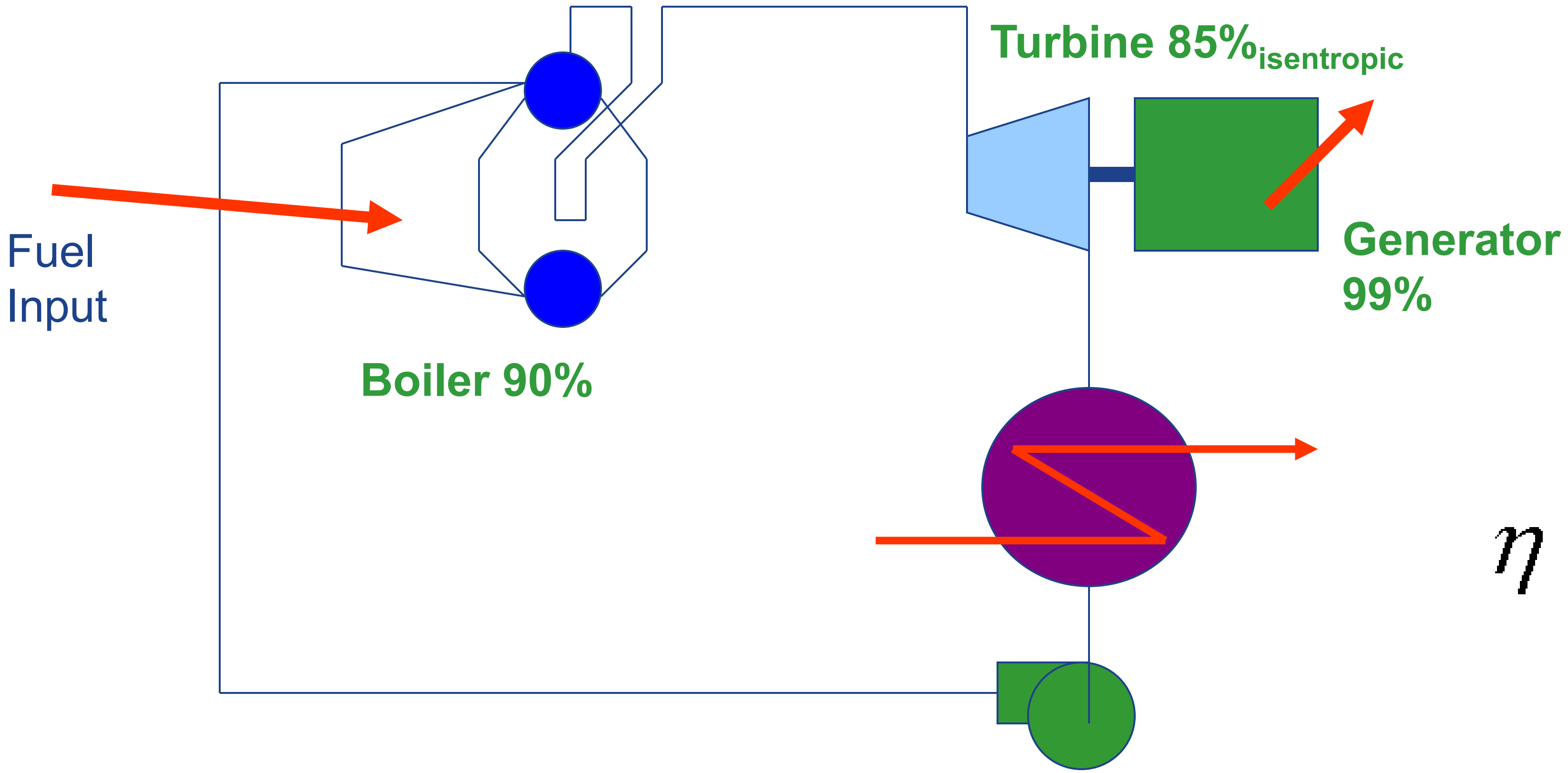
Condensing
Steam Turbine

An Industrial System

2,250 hp backpressure steam turbine (600/200)

2-stage refrigeration (R134a) compressor

Simple Utility Power Station



$$\eta = \frac{\dot{W}_{electrical}}{\dot{E}_{fuel}}$$

What would be the overall fuel to power conversion efficiency?

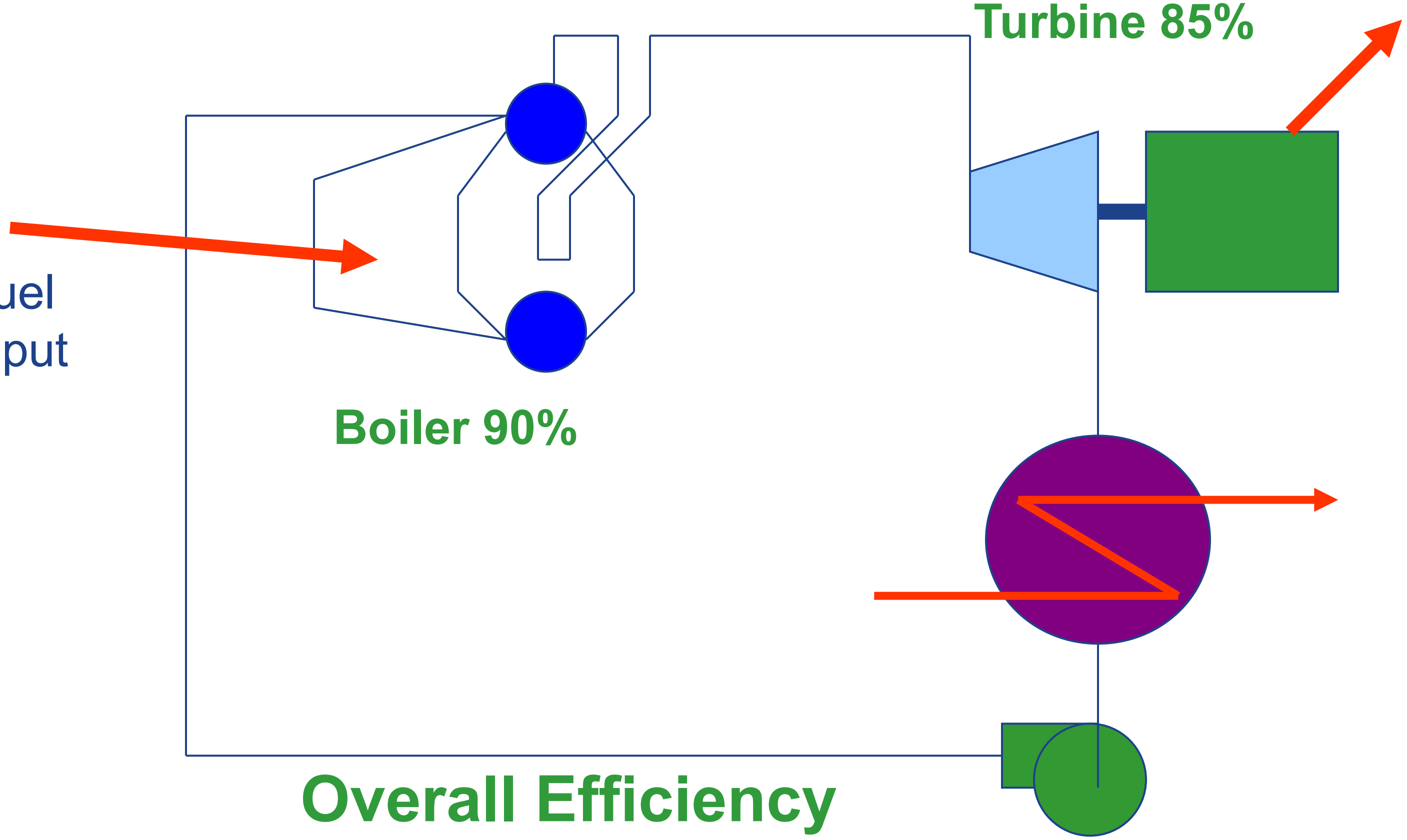
Polling Question 4

Polling Question

4) What would you expect to be the efficiency of the simple utility power station?

A. 25%
B. 35%
C. 50%
D. 75%

Simple Utility Power Station



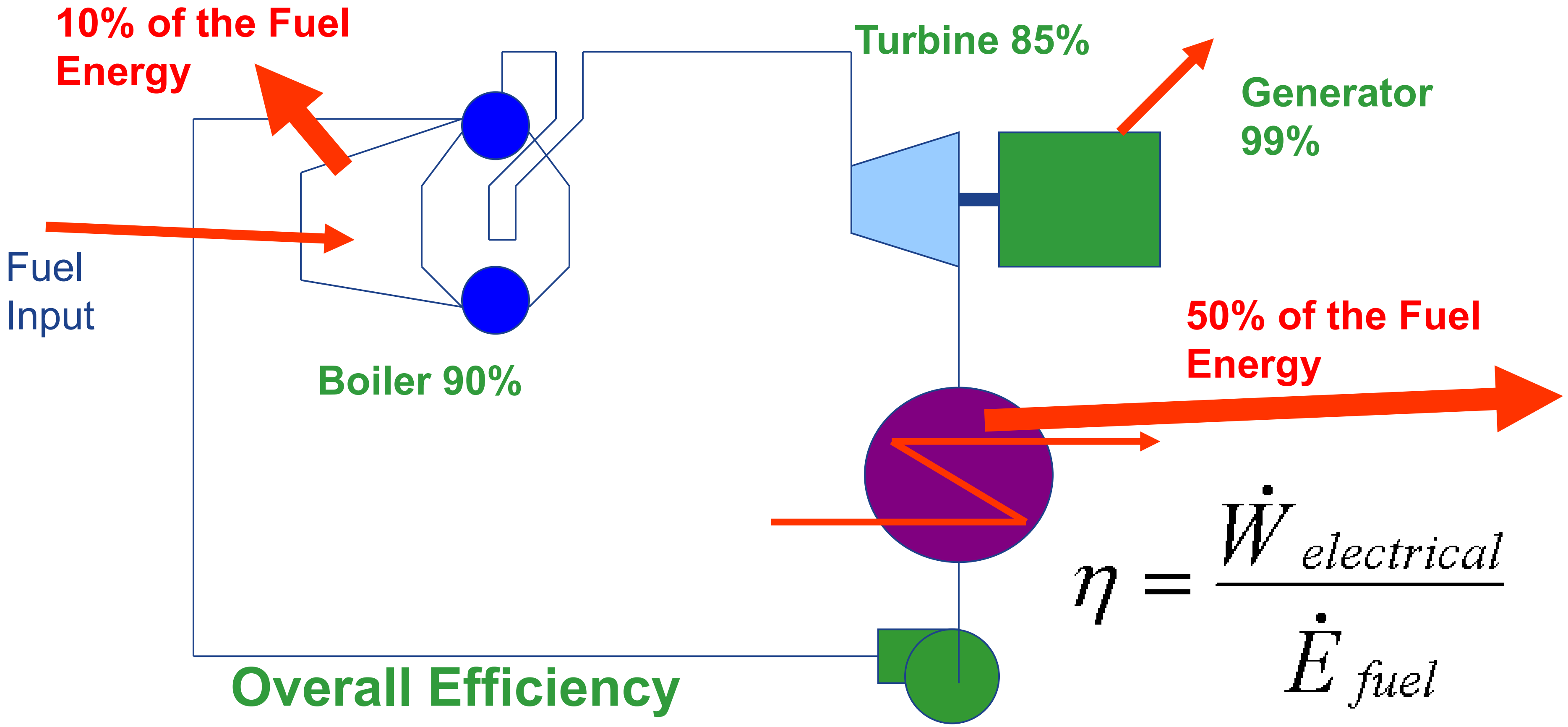
$$\eta = \frac{\dot{W}_{electrical}}{\dot{E}_{fuel}}$$

Overall Efficiency

35%

modified cycles can attain 42%

Simple Utility Power Station



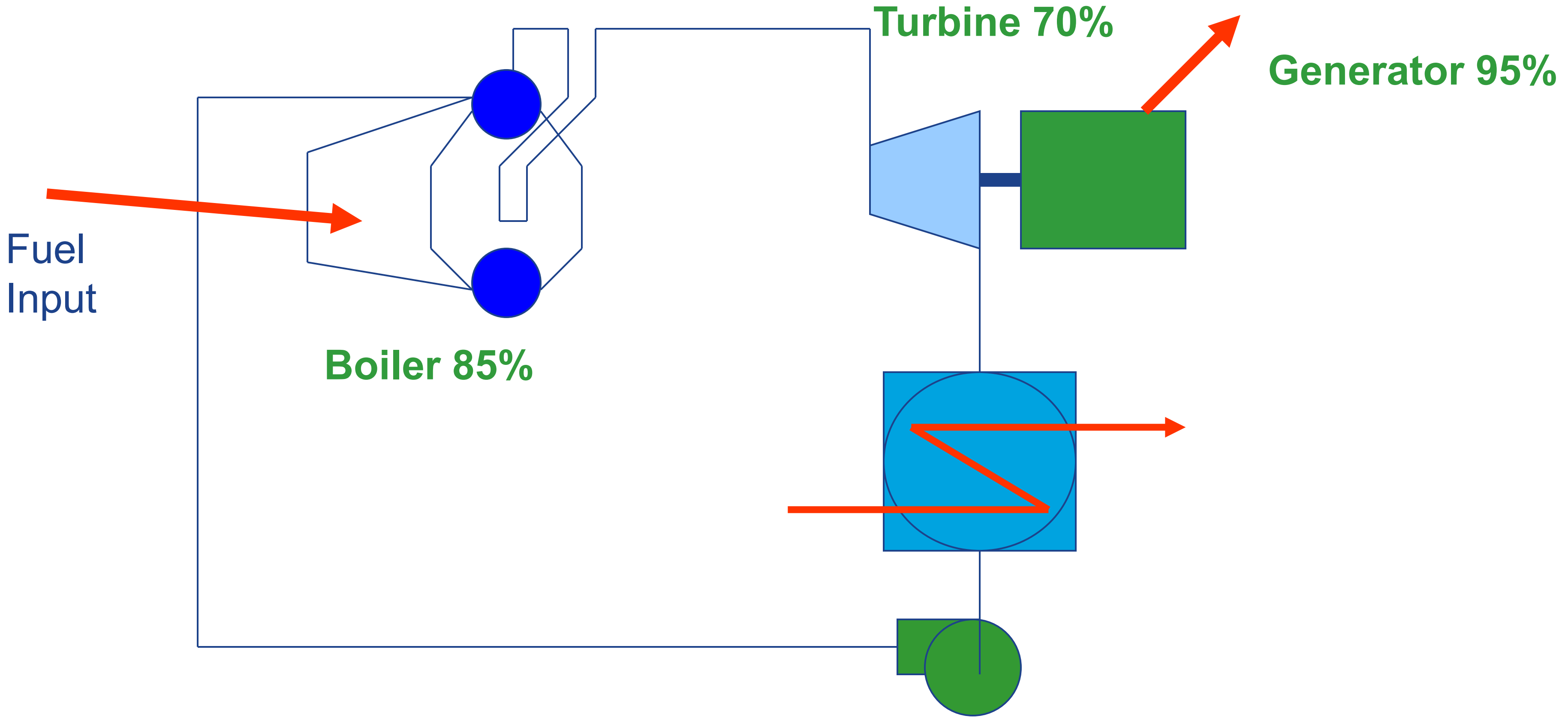
$$\eta = \frac{\dot{W}_{electrical}}{\dot{E}_{fuel}}$$

Overall Efficiency

35%

modified cycles can attain 42%

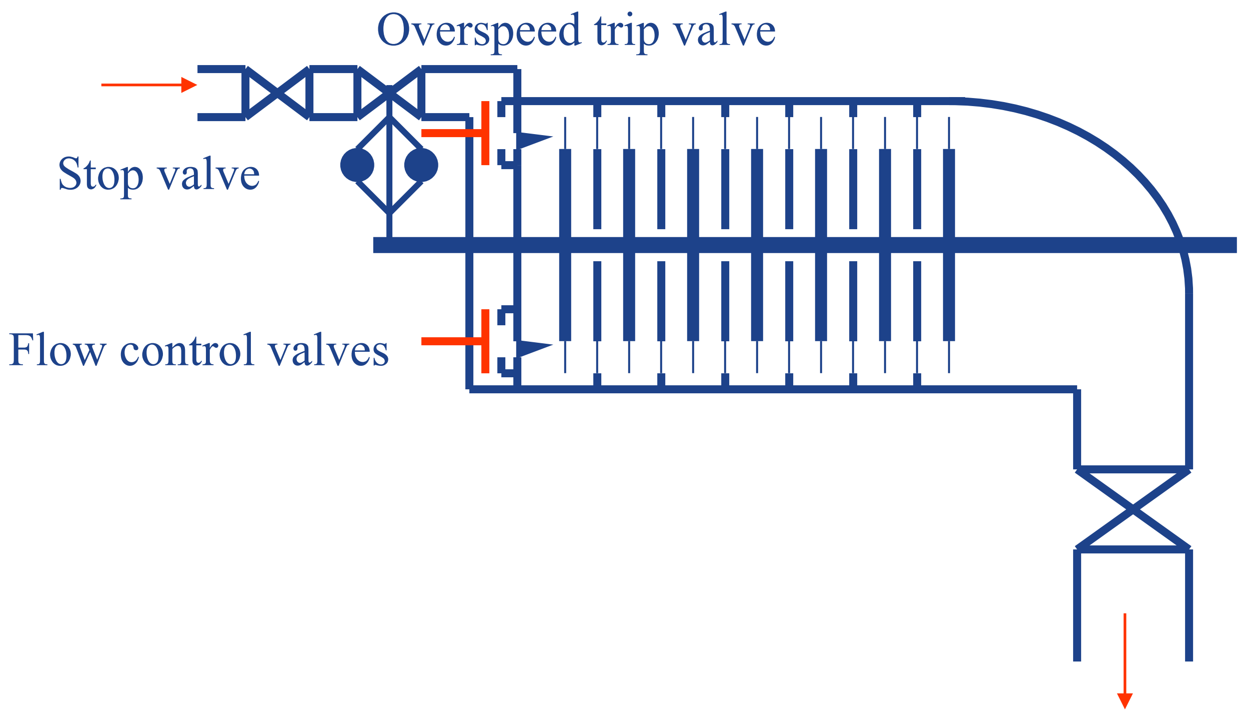
Industrial Power Station



Lower efficiency components can be utilized at industrial facilities and the "overall efficiency" can approach 70% because industrial facilities have a need for thermal energy

Steam Turbines

- Steam turbines are devices used to convert thermal (steam) energy into shaft energy
  - High-pressure steam enters and low-pressure steam exhausts

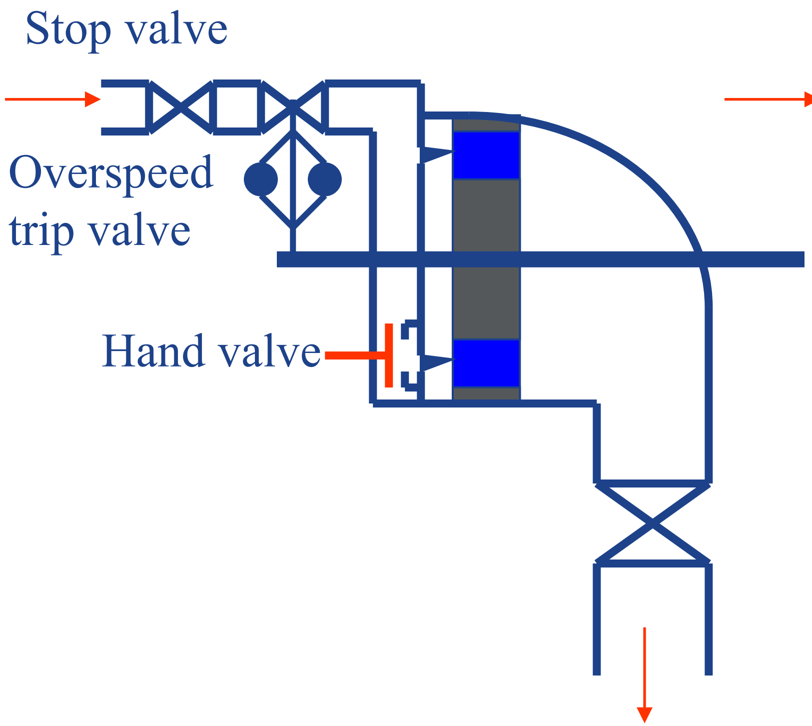


Steam Turbine Types

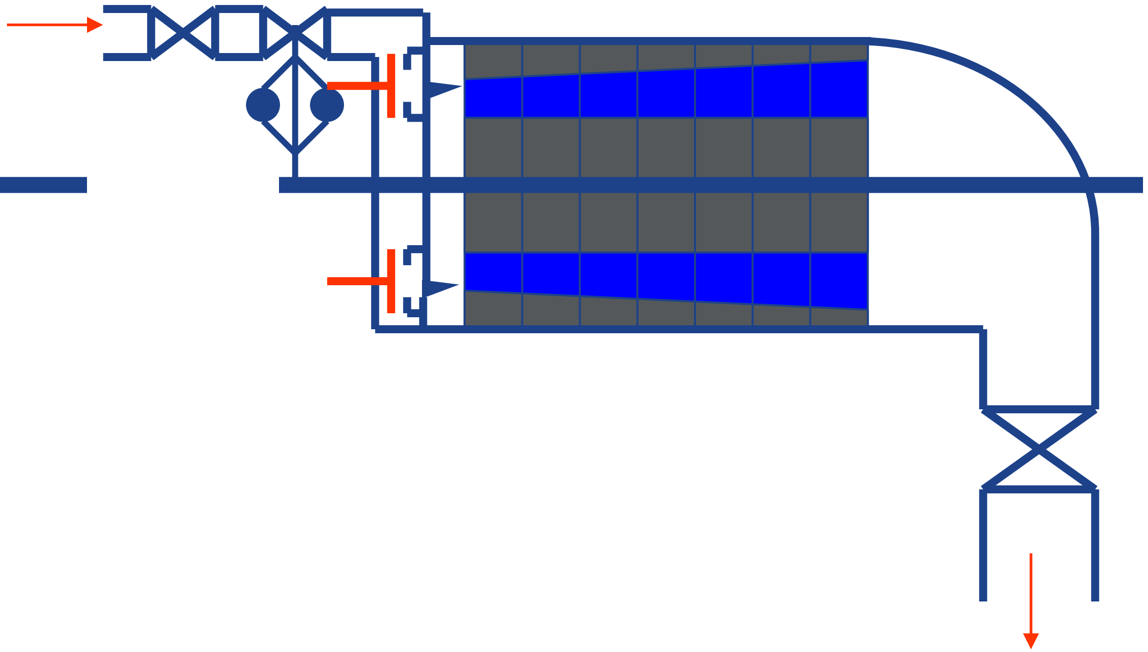
- Topping turbine (backpressure)
- Extraction turbine
- Extraction condensing turbine
- Straight condensing turbine
- Multiple extraction

Backpressure Steam Turbines

- Backpressure steam turbines discharge steam at a pressure greater than (or equal to) atmospheric pressure

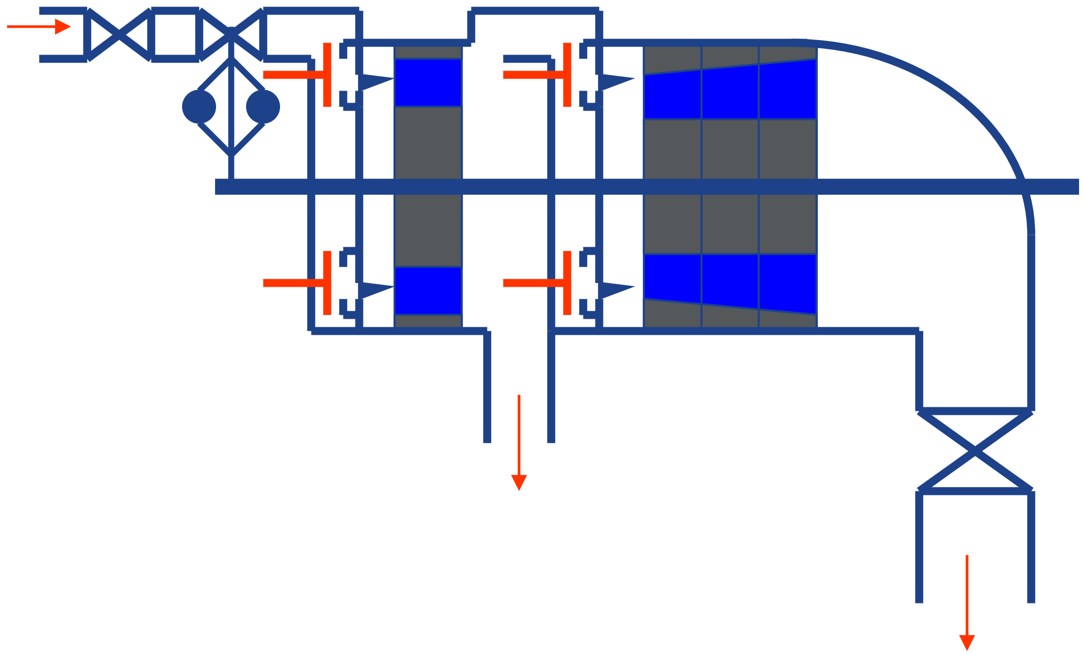


Single Stage Backpressure Turbine



Multistage Backpressure Turbine

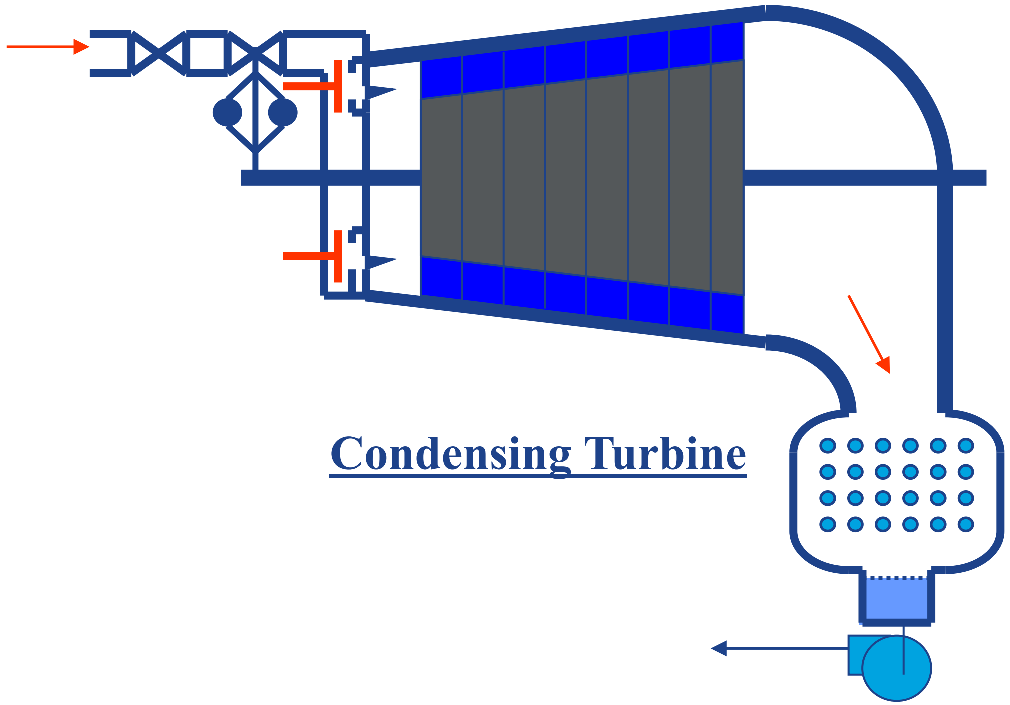
Extraction Steam Turbines



Extraction Turbine

Condensing Steam Turbines

- Condensing steam turbine discharge steam at a pressure less than atmospheric pressure
- The steam must be condensed to pump it back into the boiler
- Exiting steam quality is typically much greater than 90%



Condensing Turbine

Typical Steam Turbines Operations

- Operating pressures
  - Minimum – 150 psig
  - Maximum – 3,000 psig
  - Vacuum conditions at the exhaust!
- Operating steam temperatures
  - Few degrees of superheat
  - Significantly superheated
- Summary – Steam turbine technology is very diverse and operates over a broad range of pressures and temperatures

Pressure Ratio

- This is the DRIVING FORCE
- Pressure Ratio = $\pi = \dfrac{Inlet\ \mathrm{Pr}essure\,(psia)}{Outlet\ \mathrm{Pr}essure\,(psia)}$
- This is the first dependent variable that should be calculated
- Pressure Ratio >2.5

Turbine First Law Efficiency

- An energy balance conducted on a steam turbine will reveal an exceptionally high efficiency
  - Essentially all of the energy taken out of the steam is converted into shaft energy

$$\eta_{first\ law} = \frac{\dot{W}_{shaft}}{\dot{m}_{steam}\left(h_i - h_e\right)} \approx 100\%$$

- Steam turbines operate with only minor “losses”
  - Bearing friction
  - Heat transfer
  - Gland losses

The Perfect Turbine

- Steam turbines are evaluated using the *Second Law of Thermodynamics*
  - The Second Law of Thermodynamics identifies that *thermal energy* cannot be converted completely into *power*
    - *Power* can be converted completely into *thermal energy*
  - This defines the maximum amount of shaft power that could possibly be produced (based on the laws of physics)
    - This defines a *perfect turbine*, which would operate *isentropically*
      - *Isentropic* is *constant entropy (no losses)*
        - No entropy generation

Isentropic Efficiency

- Steam turbine efficiency is described as *isentropic efficiency*
  - A comparison of the actual work produced compared to a perfect (isentropic) turbine

$$\eta_{isentropic} = \frac{Actual\ Work}{Isentropic\ Work} = \frac{\dot{W}_{actual}}{\dot{W}_{isentropic}}$$

$$\eta_{isentropic} = \frac{\dot{m}_{steam}\left(h_{inlet} - h_{exit}\right)_{actual}}{\dot{m}_{steam}\left(h_{inlet} - h_{exit}\right)_{isentropic}} = \frac{\left(h_i - h_e\right)_{actual}}{\left(h_i - h_e\right)_{isentropic}}$$

Typical Steam Turbine Efficiency

- Major contributors to isentropic efficiency
  - Turbine design
  - Control valve type
    - Single valve – throttle
    - Multi-valve – flow nozzles

$$\eta_{isentropic} = \frac{(h_{in} - h_{out})_{actual}}{(h_{in} - h_{out})_{isentropic}} = 20\% \; to \; 80\%$$

Turbine Efficiency Summary

- US DOE MEASUR requires turbine isentropic efficiency

- Methods of obtaining isentropic efficiency:
  - Manufacturer specifications
    - Turbine Map / Curve
  - Actual operating conditions (superheated cases)
    - Steam inlet and outlet conditions known
  - Steam inlet conditions and power generation known
    - Typically, used for electrical power generation units

MEASUR – Steam Turbine Calculator

STEAM TURBINE

Solve For

Isentropic Efficiency

Inlet Steam

Pressure	400 psig
Known Variable	Temperature
Temperature Value	700 ℉

Turbine Properties

Selected Turbine Property	Mass Flow
Mass Flow	40 klb/hr
Generator Efficiency	95 %

Outlet Steam

Pressure	20 psig
Known Variable	Temperature
Temperature Value	350 ℉

RESULTS | HELP

Isentropic Efficiency	64.1 %
Energy Out	6 MMBtu/hr
Generator Efficiency	95 %
Power Out	1,660.1 kW

	Inlet	Outlet Ideal	Outlet
Pressure (psig)	400	20	20
Temperature (℉)	700	350	350
Phase	Gas	Gas	Gas
Sp. Enthalpy (Btu/lb)	1,362	1,213	1,213
Sp. Entropy (Btu/lb-℉)	1.636	1.748	1.748
Mass Flow (klb/hr)	40	— —	40
Energy Flow (MMBtu/hr)	54.5	— —	48.5

Copy Table

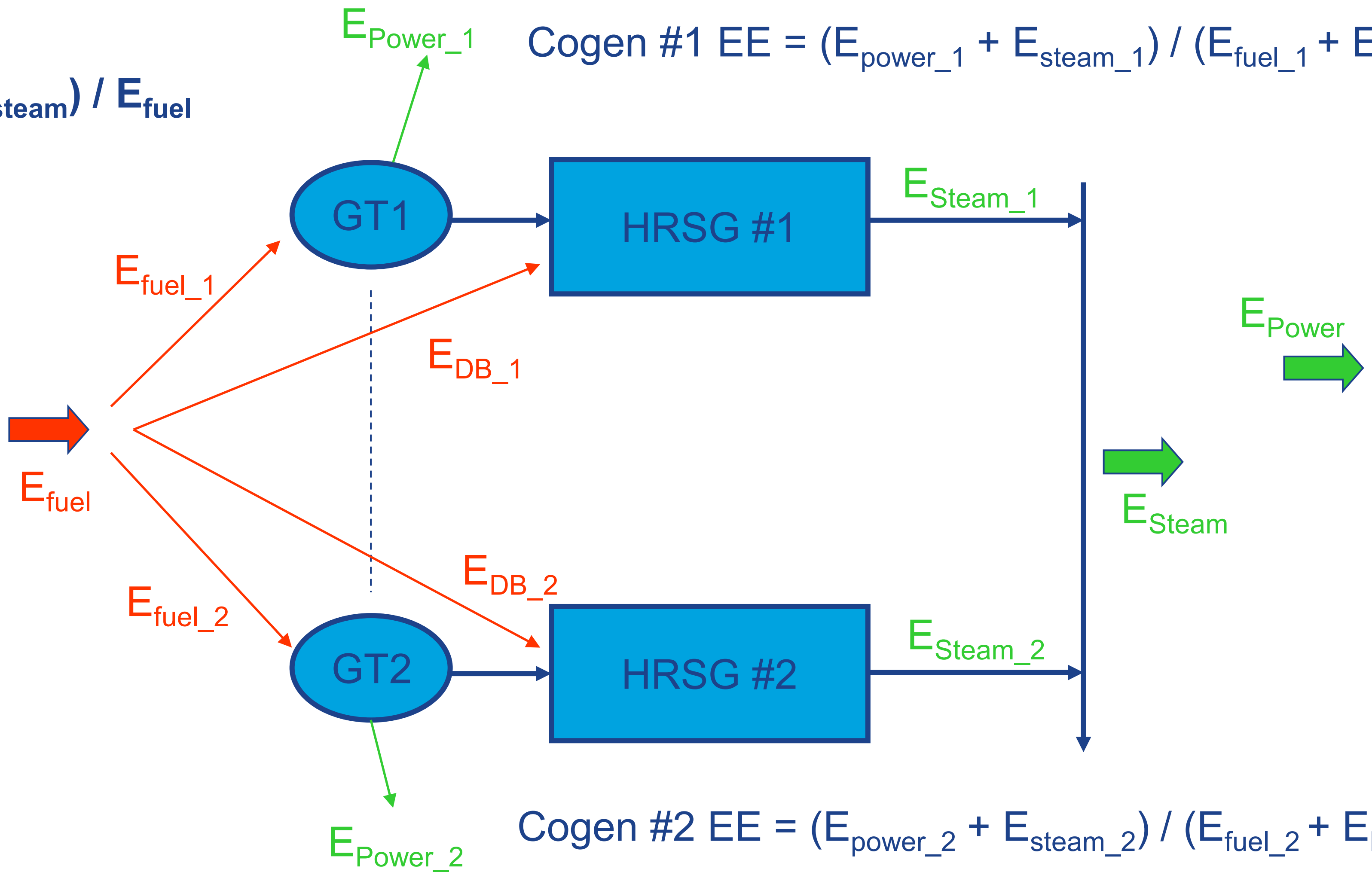
CoGeneration (Combined Heat & Power)

- Gas Turbines

An Example Gas Turbine / HRSG Cogeneration System

Overall Cogen EE = $(E_{power} + E_{steam}) / E_{fuel}$

Cogen #1 EE = $(E_{power\_1} + E_{steam\_1}) / (E_{fuel\_1} + E_{DB\_1})$

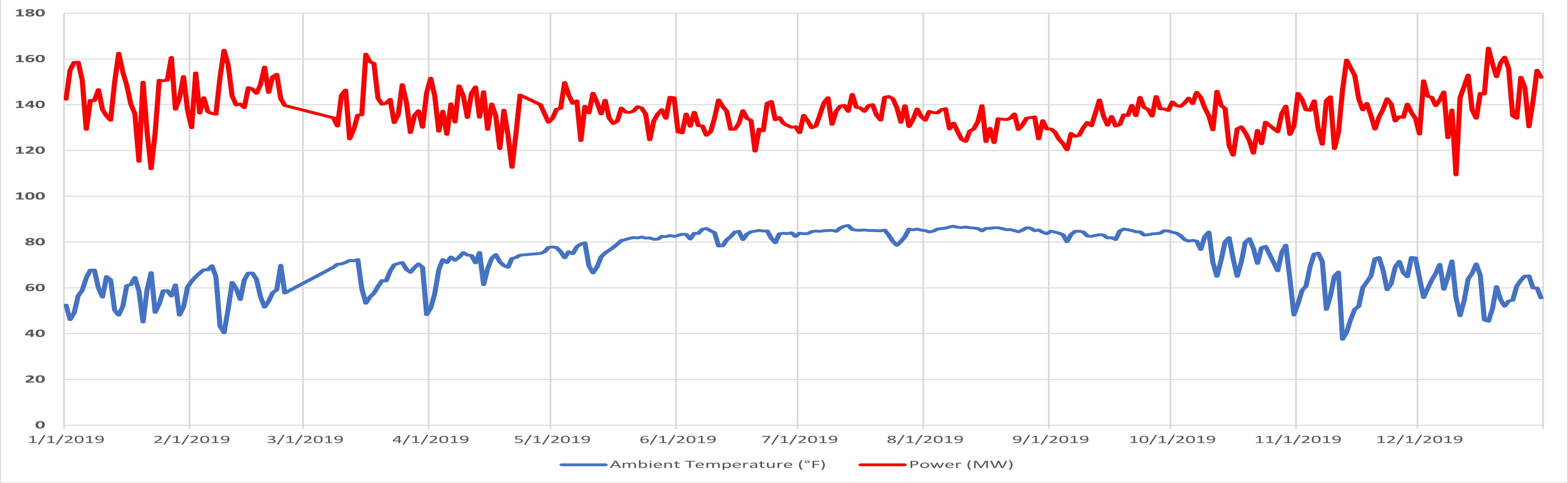


Cogen #2 EE = $(E_{power\_2} + E_{steam\_2}) / (E_{fuel\_2} + E_{DB\_2})$

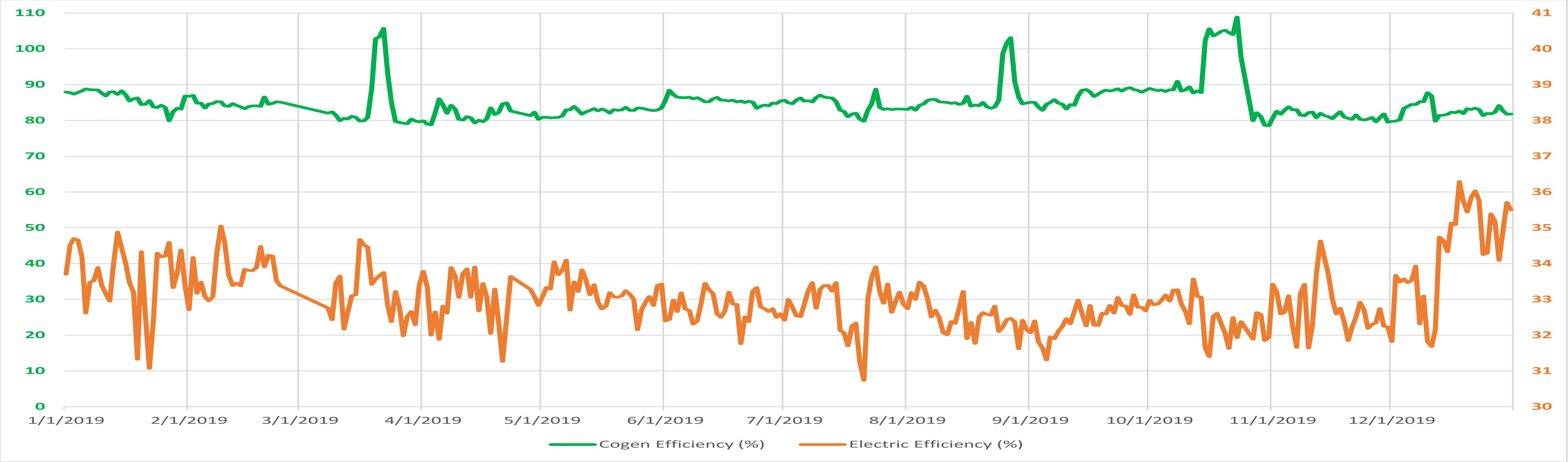
Metrics for Cogeneration

- Heat Rate
  - Heat Rate = E_{fuel} / E_{Power}
  - E_{fuel} is in Btu/hr – using LHV (or net)
  - E_{power} is in kW
- Net Electric Efficiency
  - $\eta_E = E_{Power} / E_{Fuel}$
- Cogeneration System Efficiency
  - $\eta_{Cogen} = (E_{Power} + E_{steam}) / E_{Fuel}$
- Cogeneration Electric Effectiveness
  - $\varepsilon_{EE} = E_{Power} / (E_{Fuel} - E_{steam} / \eta_{boiler})$

Example System Cogeneration Trending



Example System Cogeneration Trending



Homework #3

- Install and get comfortable using the MEASUR tool.
- Decide on a specific header model and work with your line diagram and develop a high-level steam system model for your facility. Use your numbers and values wherever you can otherwise use default information provided in the Steam System Assessment template.
- Use your plant's utility costs to calculate your marginal steam cost ($/klb)
- Send a screenshot of the MEASUR diagram and cost summary page

Thank You all for attending today's webinar.

See you all on next Tuesday – April 27, 2021 – 10 am ET

If you have specific questions, please stay online and we will try and answer them.

Alternately, you can email questions to me at
rapapar@c2asustainable.com