Better Plants
U.S. DEPARTMENT OF ENERGY

Industrial Steam Systems
Virtual INPLT Training & Assessment

Session 3
Thursday – November 5, 2026
2 pm – 4:30 pm ET



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Welcome

- Welcome to the third Steam Virtual INPLT training series
- Eight, 2-1/2 hour webinars, focused on Industrial Steam Systems Energy Assessment and Optimization
- These webinars will help you gain a significant understanding of your industrial steam system, undertake an energy assessment using a systems approach, evaluate and quantify energy and cost-saving opportunities using US DOE tools and resources
- Thank you for your interest!



Steam Virtual INPLT Agenda

- Session 1 (October 22) – Industrial Steam Systems Fundamentals and Introduction to SSST
- Session 2 (October 30) – Focus on Steam System Generation and Introduction to DOE's MEASUR Tool
- **Session 3 (November 5) – Steam System Generation & Cogeneration (CHP)**
- **Session 4 (November 12) – Steam System Distribution, End-Use & Condensate Recovery**
- **Session 5 (November 19) – Energy Efficiency Opportunities in the Generation Area**
- **Session 6 (December 3) – Energy Efficiency Opportunities in Cogeneration (CHP) Area**
- **Session 7 (December 10) – EE Opportunities in Distribution, End-use and Condensate Recovery**
- **Session 8 (December 17) – Industrial Steam System VINPLT Wrap-up Presentations**

Agenda – Session THREE

- Safety and Housekeeping
- Today's Content:

  Discussion of Homework

  Quick Review from Session 2

  Steam System Generation
  - Impact Boiler
  - Cogeneration

  US DOE MEASUR Tool
  - Boiler Calculator
  - Building a steam system model
- Kahoot Quiz Game
- Q&A

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



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 2Q or 3Q 2026 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 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

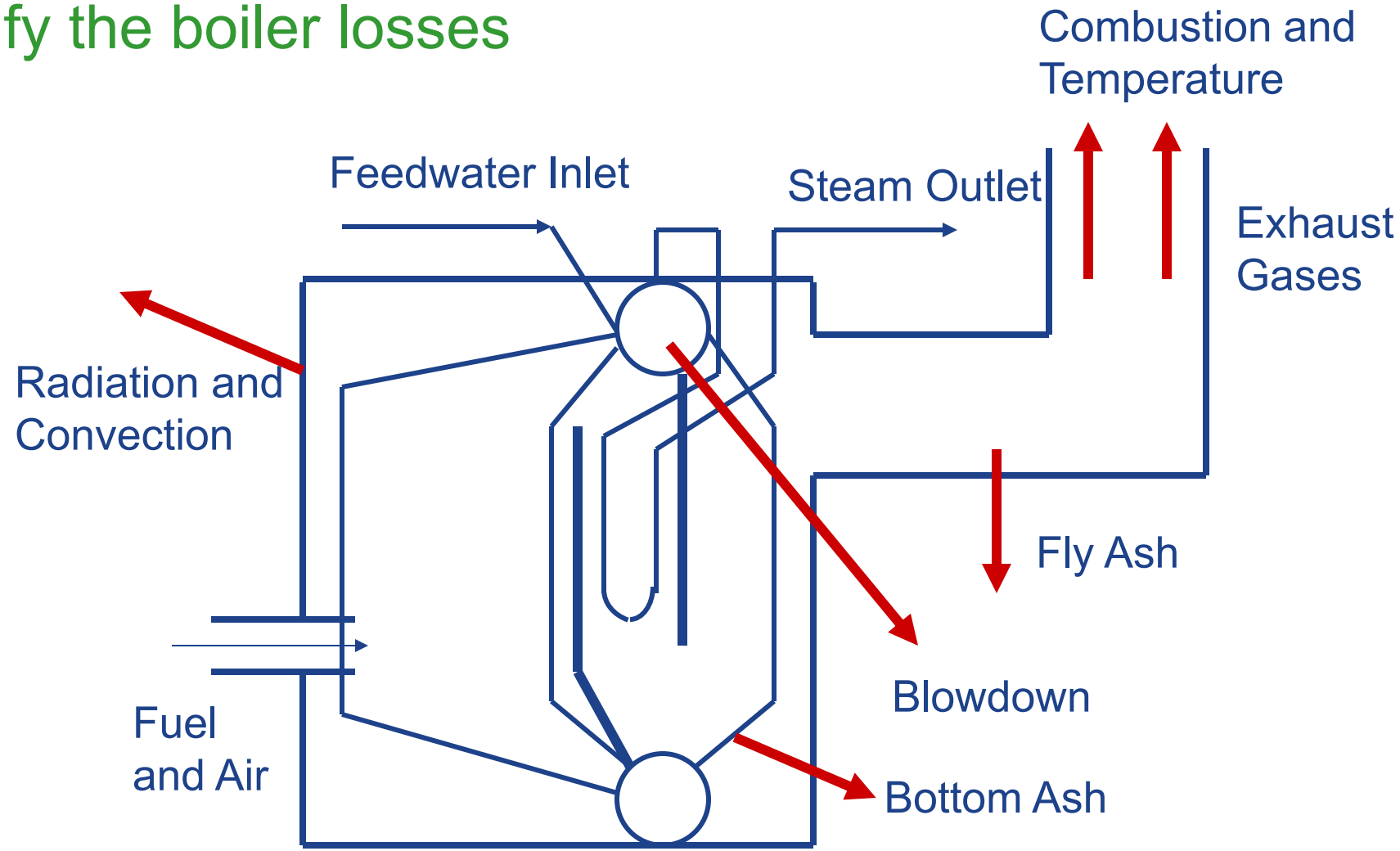
- Steam generating unit efficiency is defined as the heat absorbed by the steam divided by the fuel input energy

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

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

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

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

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

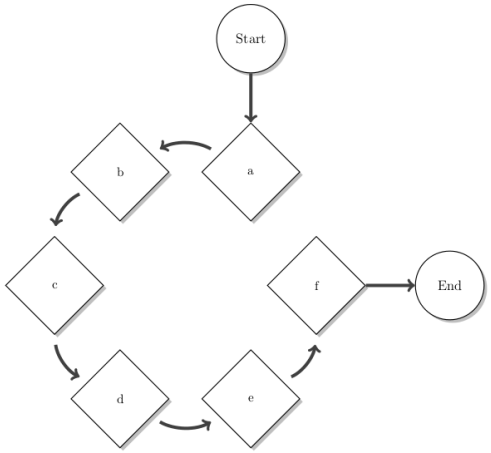
Which Method should be used?





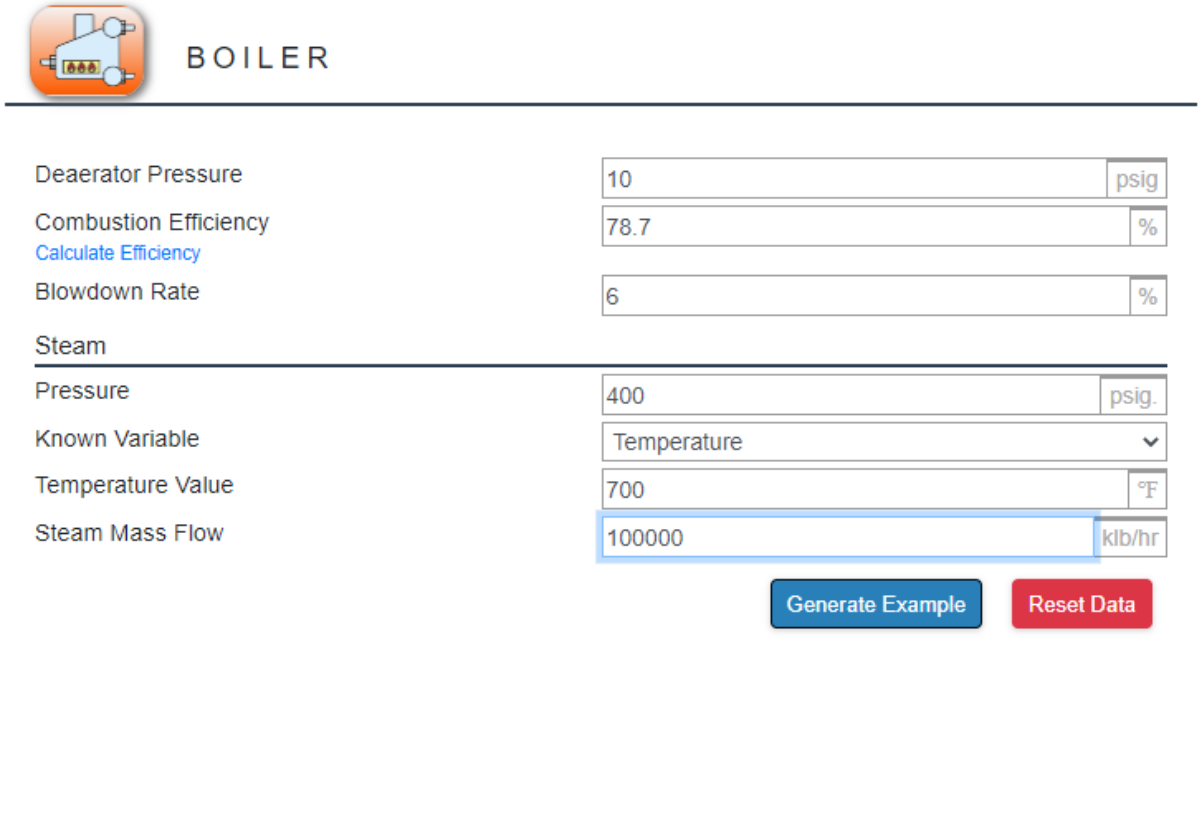
Direct Method

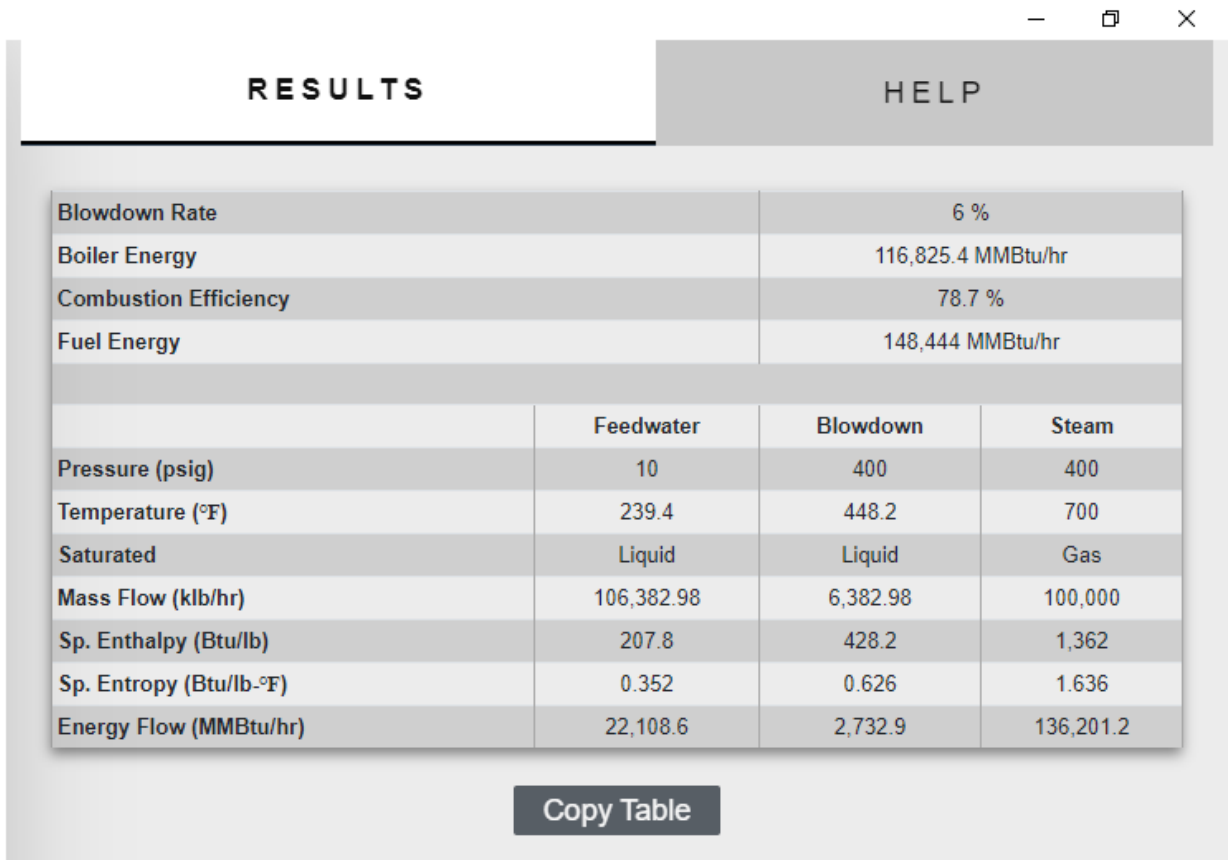




InDirect Method

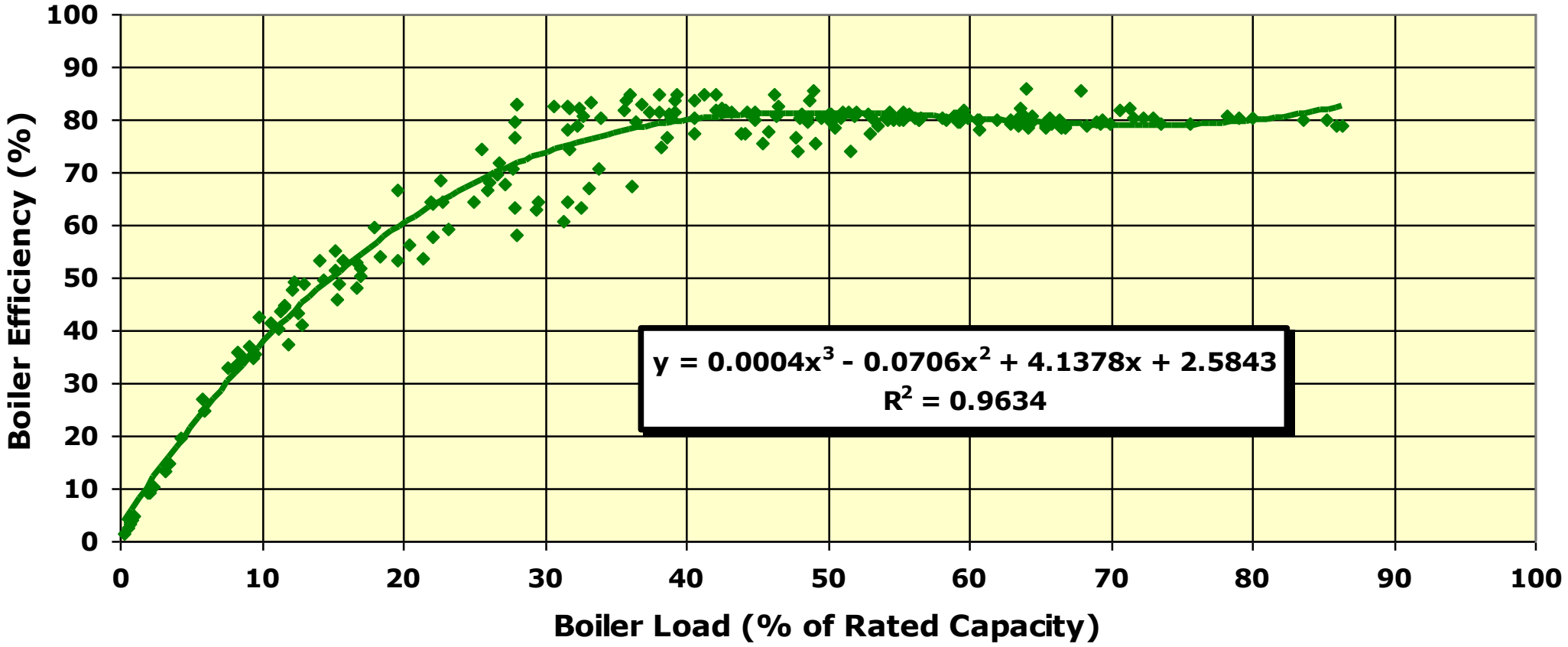
Example Boiler – US DOE MEASUR





	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

Typical Boiler Efficiency Curve



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

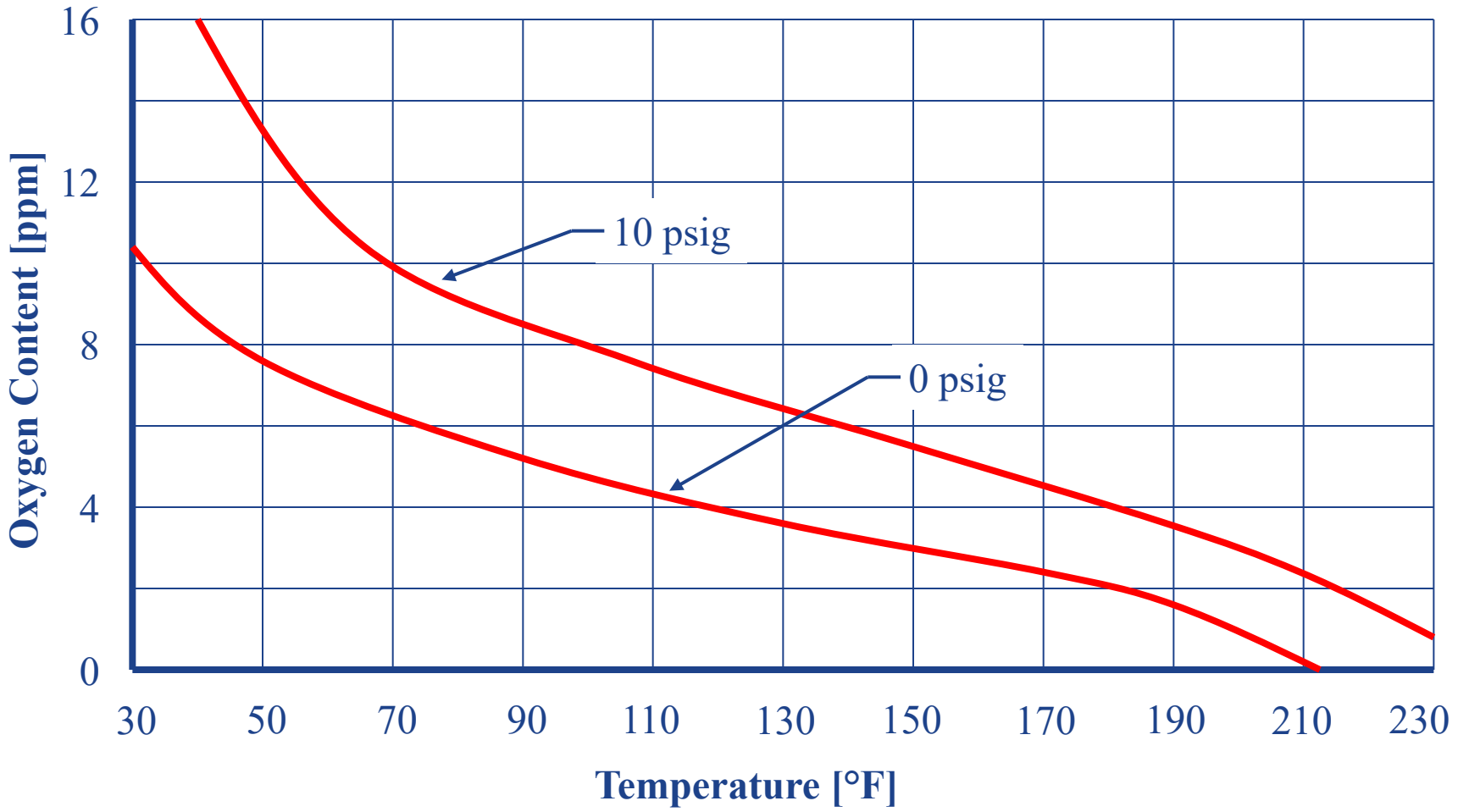
- Deaerator

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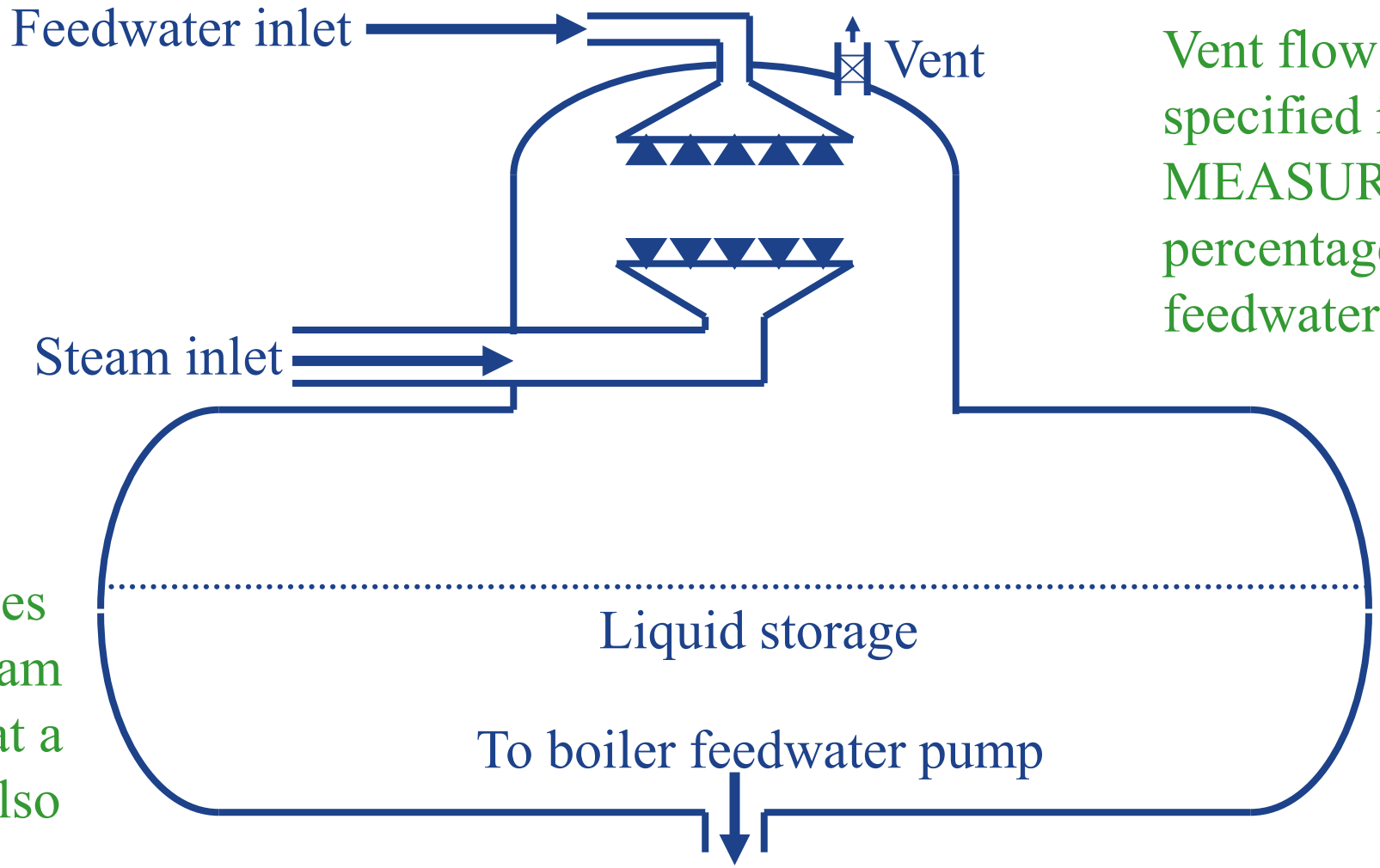
Deaeration

- 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 also

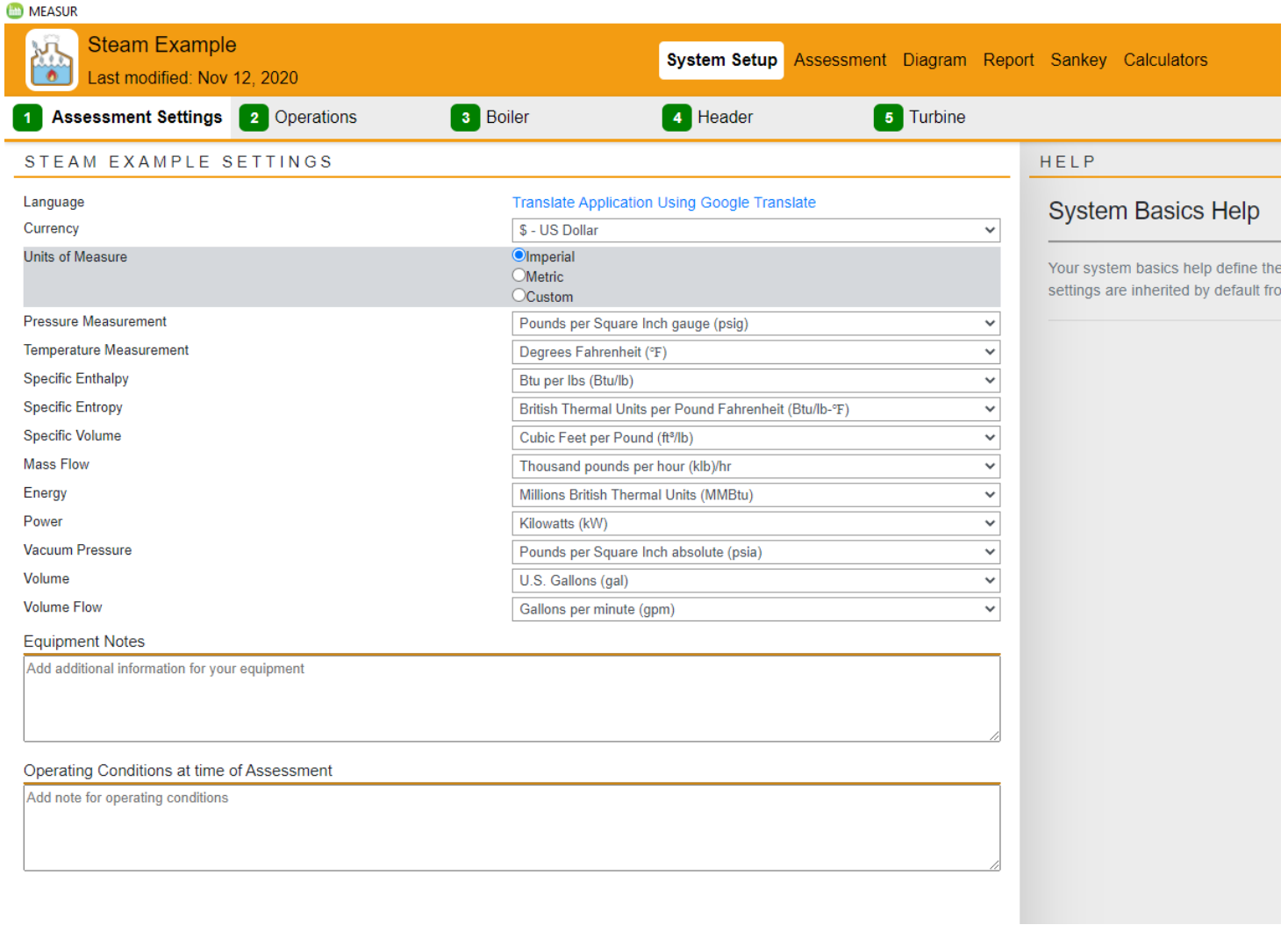
US DOE MEASUR

- 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

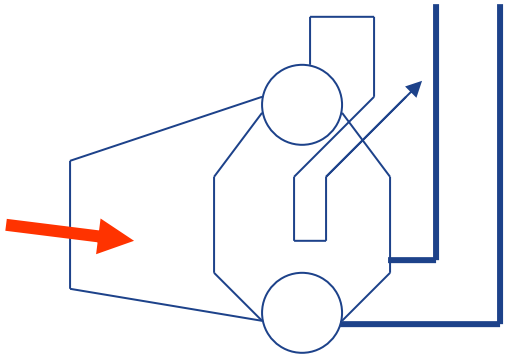
- Analyses should be completed utilizing *impact costs*
- Gross indications of savings opportunities can be attained by use of *average impact cost* or *projected cost*
- Multiple models may need to be developed reflecting various pricing conditions
  - Fuel prices typically vary seasonally
- The USDOE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

Boiler & Fuel Selection

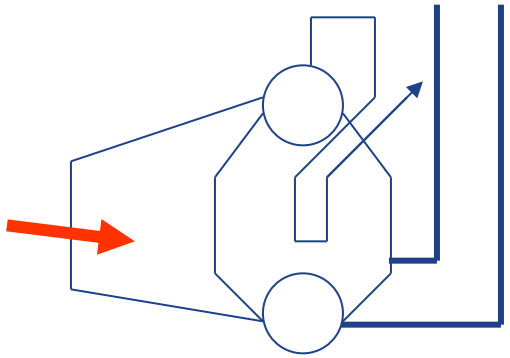
- What is Impact fuel?
  - The fuel that will change consumption if steam demand changes
  - Typically, the highest cost fuel in use
  - “Blended costs” generally do not reflect actual system changes
    - Blended costs **do** provide a confidence level in the model results

- 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



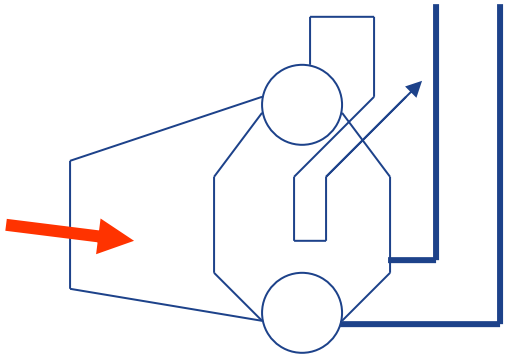
Fuel: Natural gas
Fuel cost: $5.00/MMBtu
Boiler capacity:
120,000 lbm/hr
Steam production:
100,000 lbm/hr
Boiler efficiency: 78%



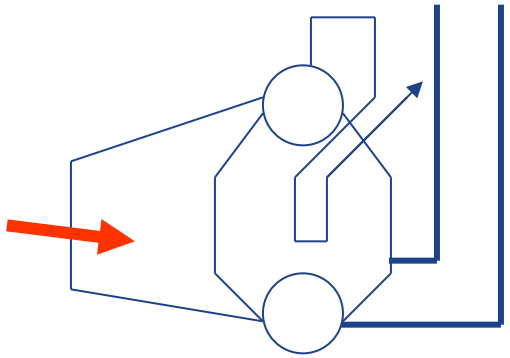
Fuel: Number 2 fuel oil
Fuel cost: $15.79/MMBtu
Boiler capacity:
50,000 lbm/hr
Steam production:
10,000 lbm/hr
Boiler efficiency: 85%

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

Impact Boiler & Fuel Selection



Fuel: Natural gas
Fuel cost: $5.00/MMBtu
Boiler capacity:
120,000 lbm/hr
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- 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

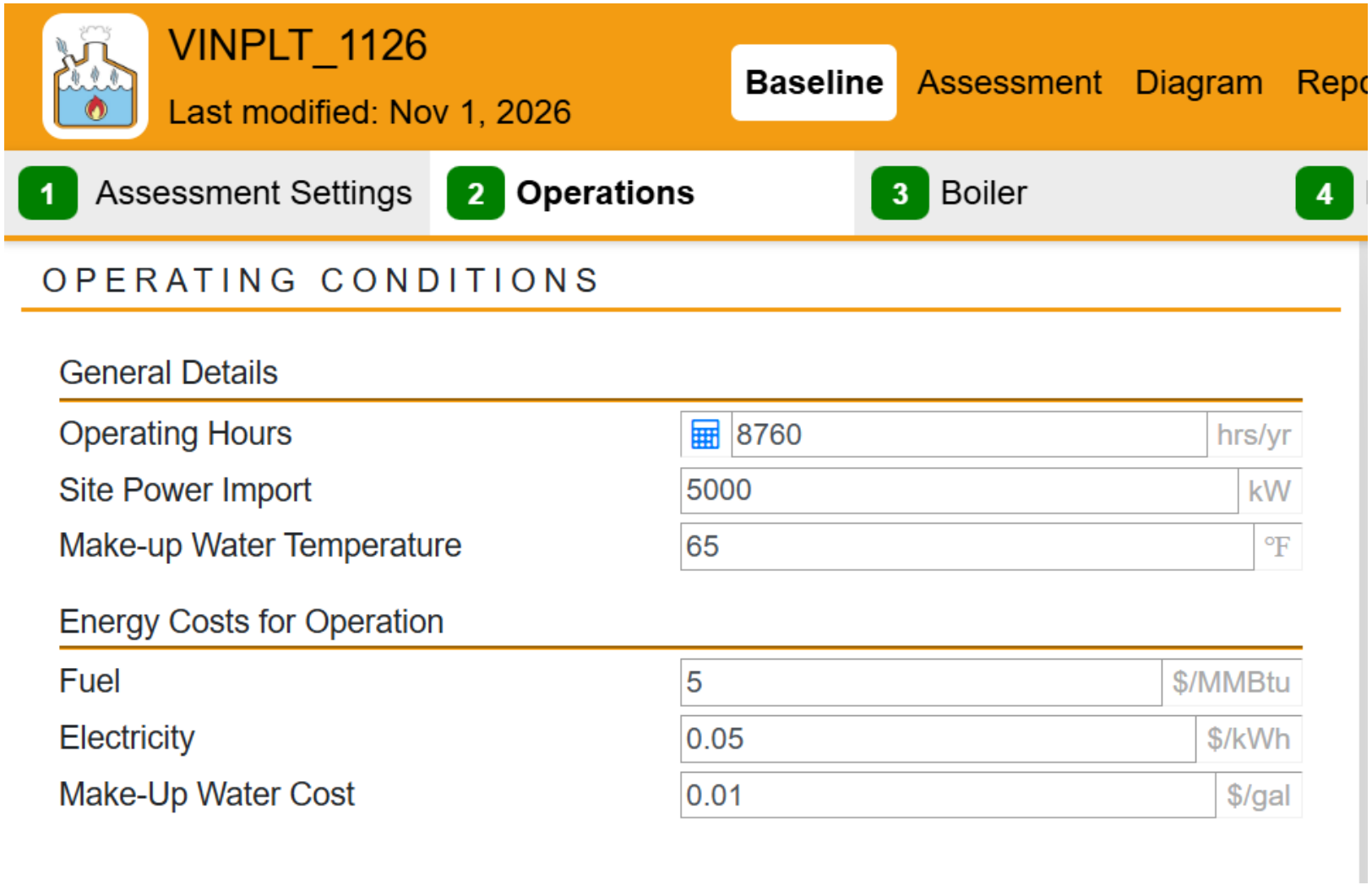
Plant Information

- 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

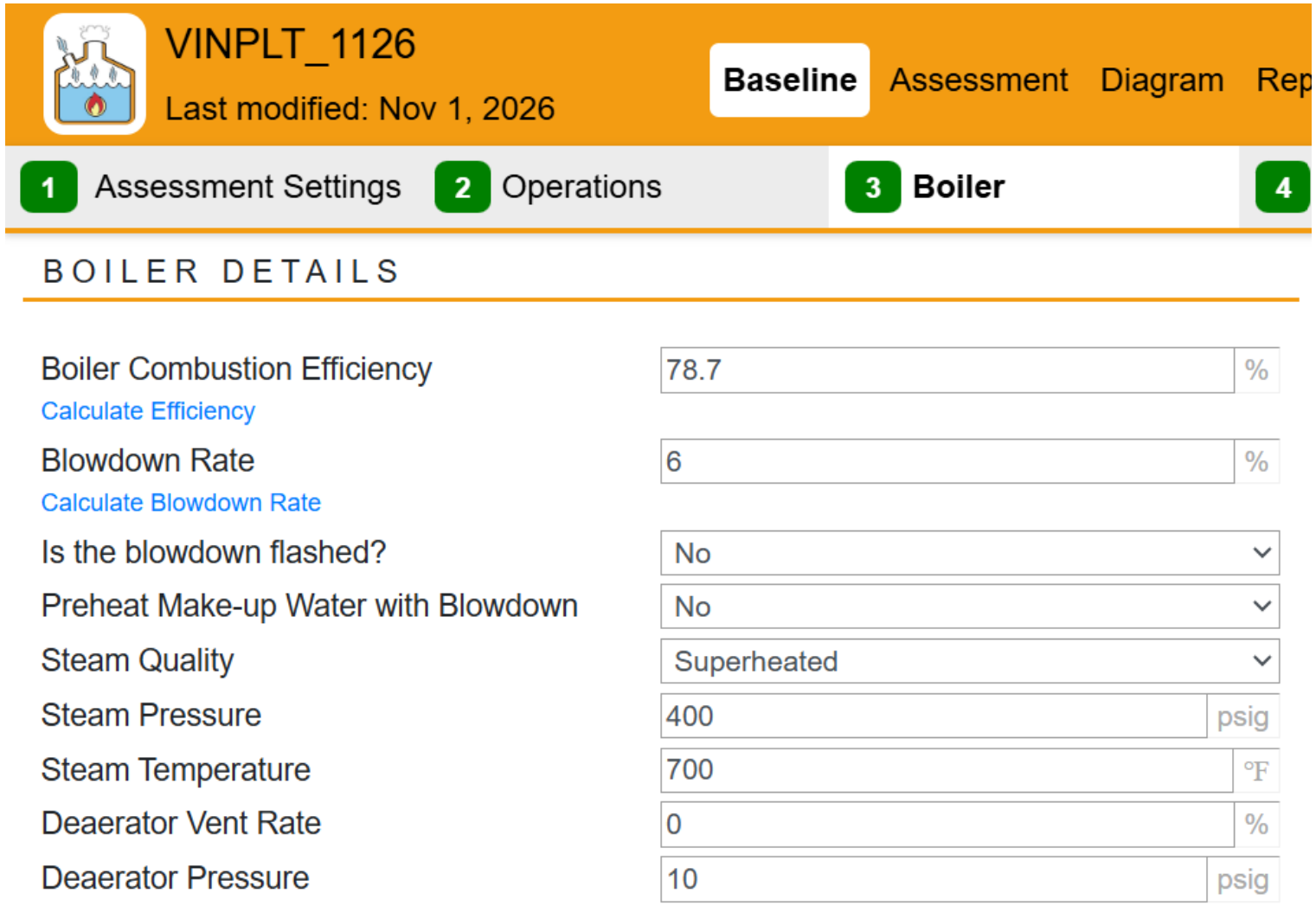
MEASUR – System Setup



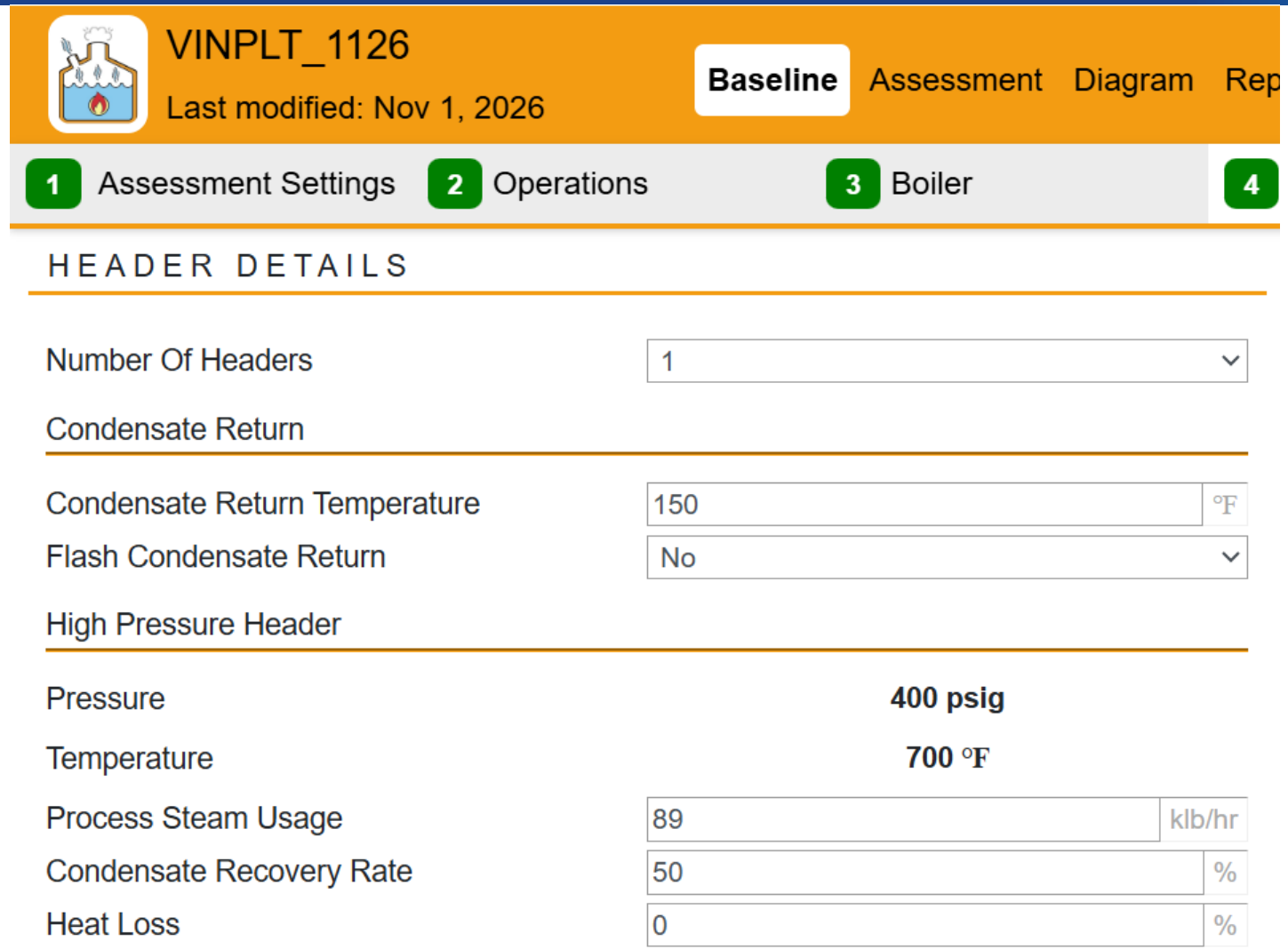
Plant Information

- 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

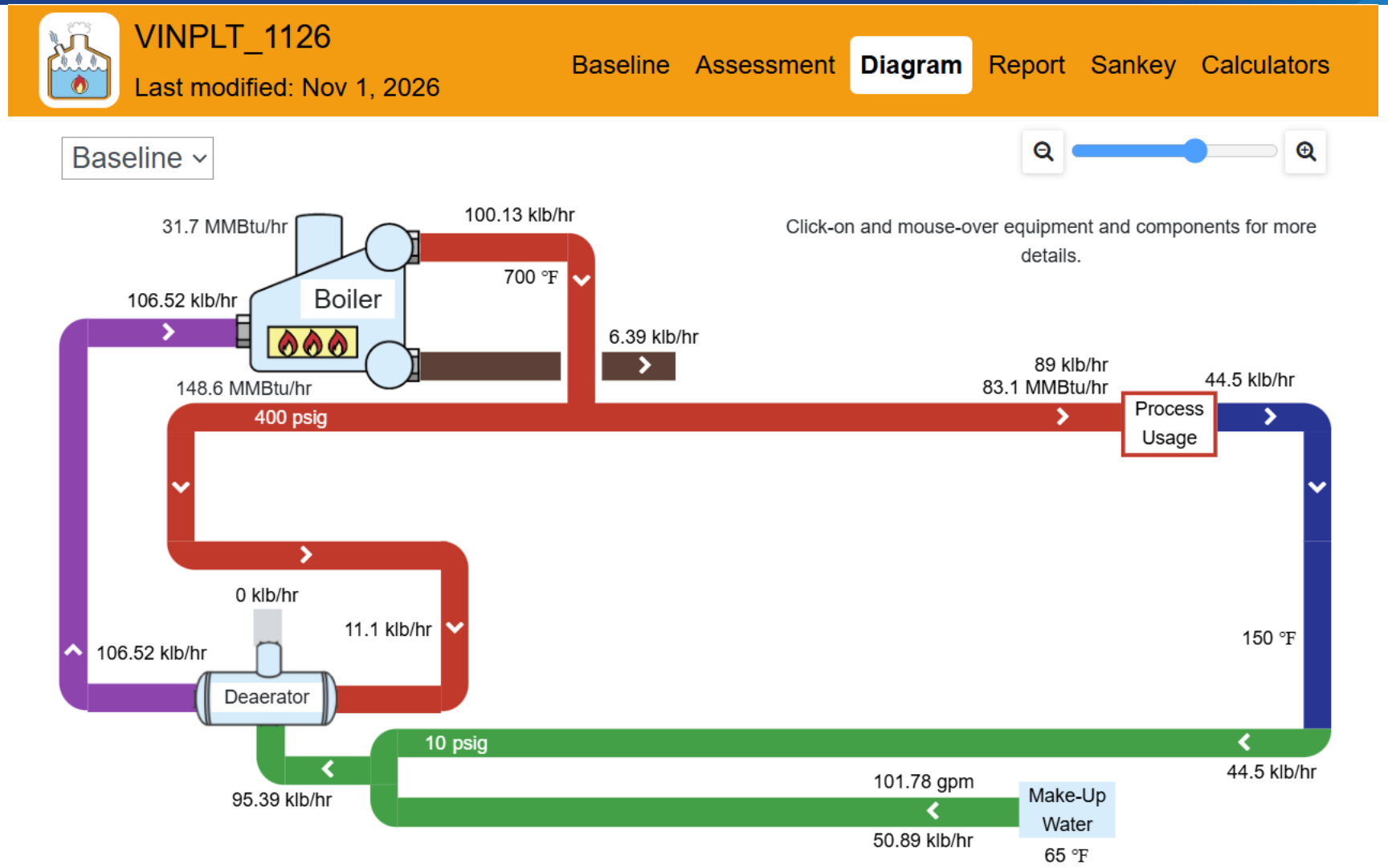
MEASUR – System Setup



MEASUR – System Setup



MEASUR – System Diagram



MEASUR – System Cost Summary

Steam Generated
100.1 klb/hr
Total Operating Cost
$9,235,164

Fuel	
Boiler Fuel Use	1,302,037.35 MMBtu/yr
Boiler Fuel Cost ($)	$6,510,187

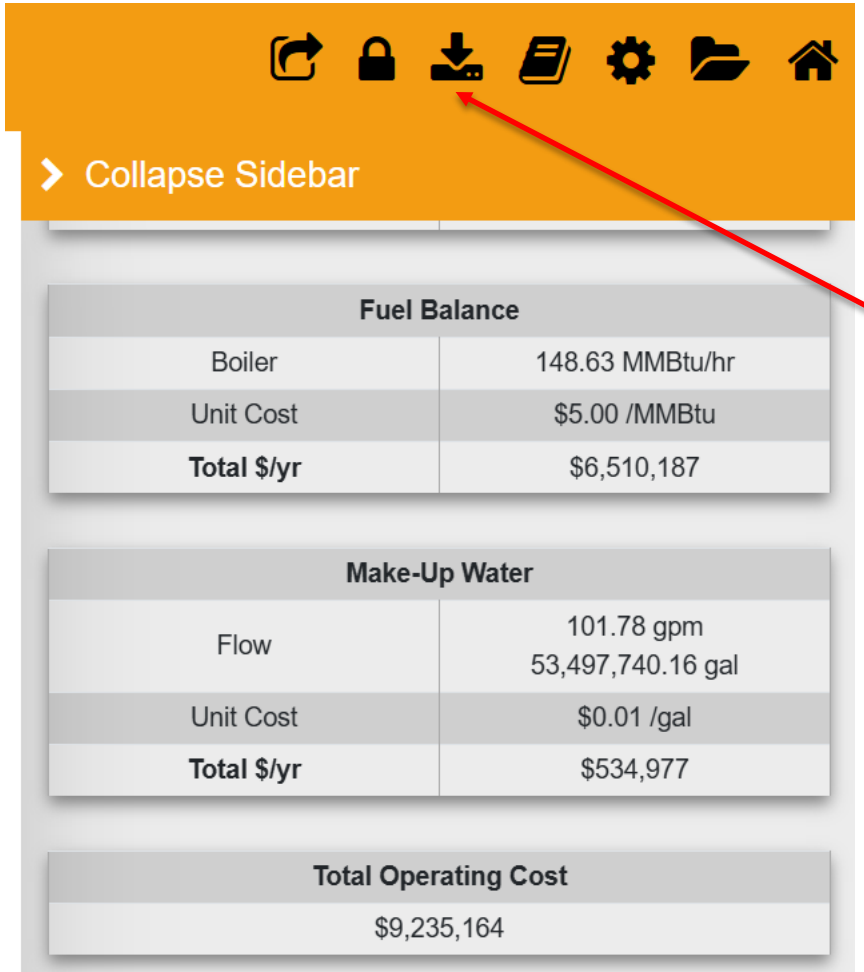
Electricity	
Electricity Generated	0 kW
Electricity Imported	5,000 kW
Electricity Cost ($)	$2,190,000

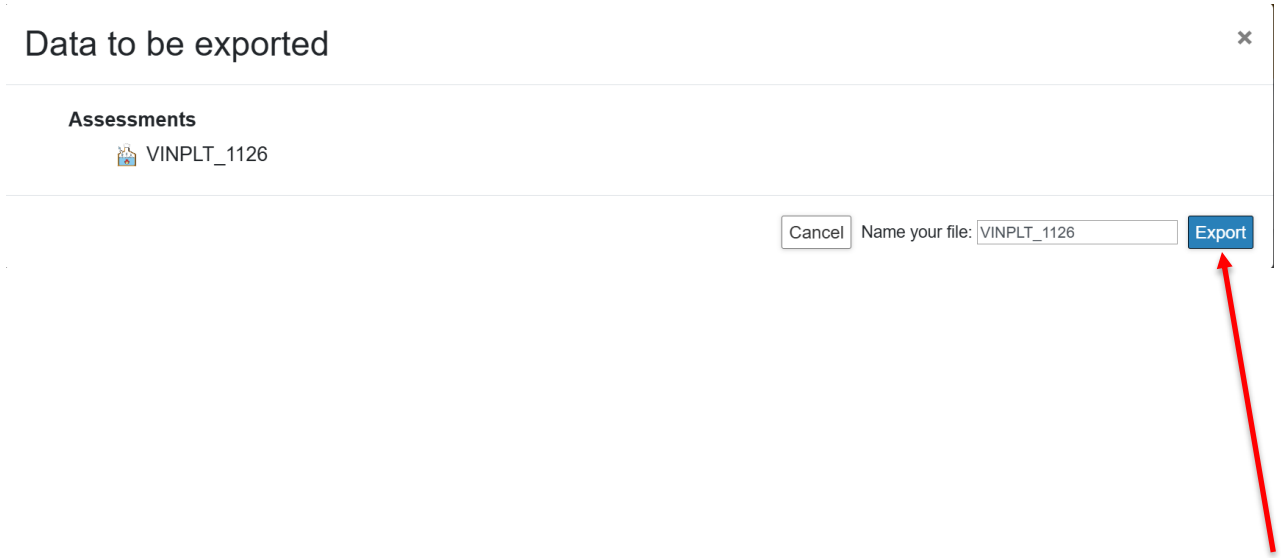
Make-Up Water	
Make-Up Water Required	53,497,740.16 gal
Make-up Water Cost ($)	$534,977

MARGINAL STEAM COST

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

MEASUR – SAVE the MODEL!





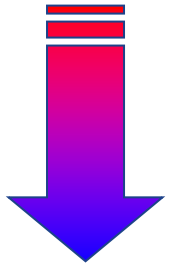
CoGeneration (Combined Heat & Power)

- 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

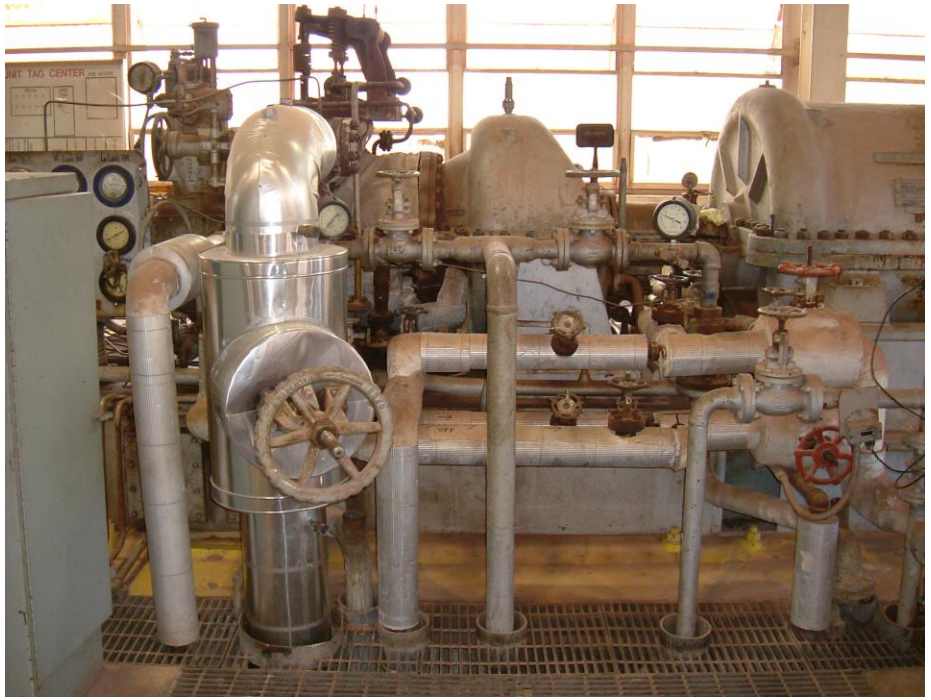
Examples of Industrial Systems

- 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 Application





Industrial Applications



4,000 RT Steam Turbine Driven Chiller



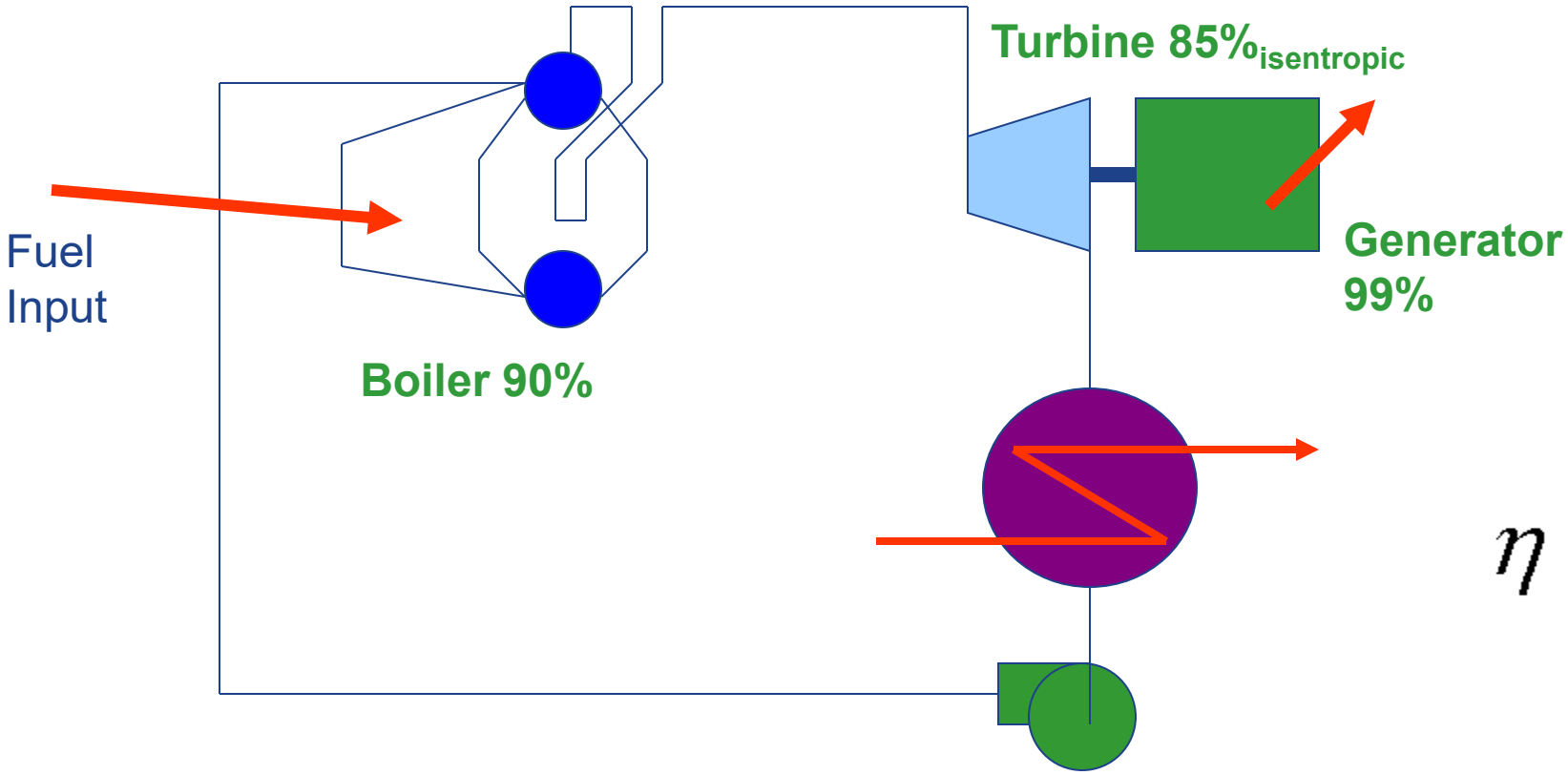
An Industrial System



2-stage refrigeration (R134a) compressor

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

Simple Utility Power Station



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

What would be the overall fuel to power conversion efficiency?

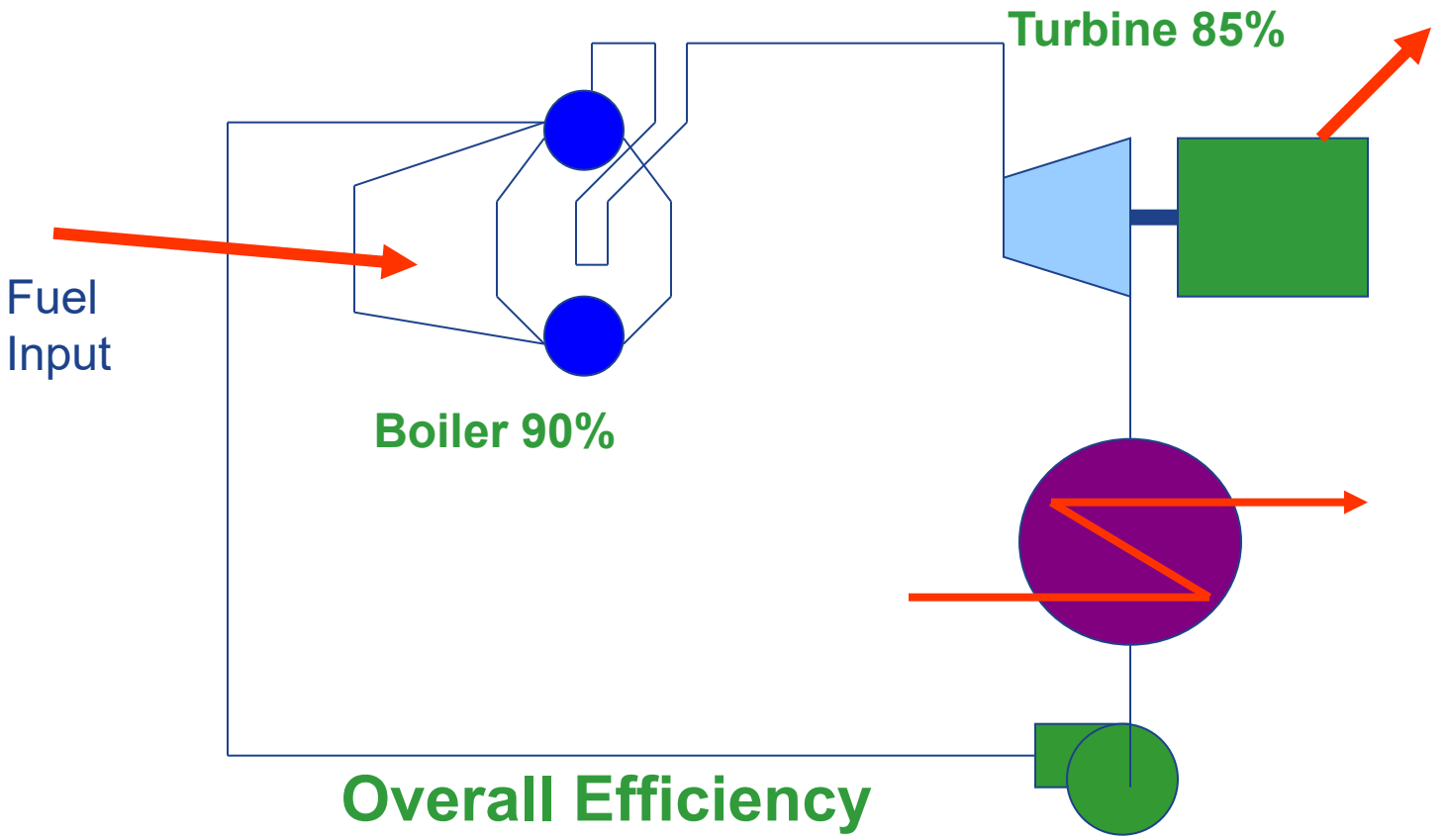
Polling Question 4

Polling Question

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

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

Simple Utility Power Station



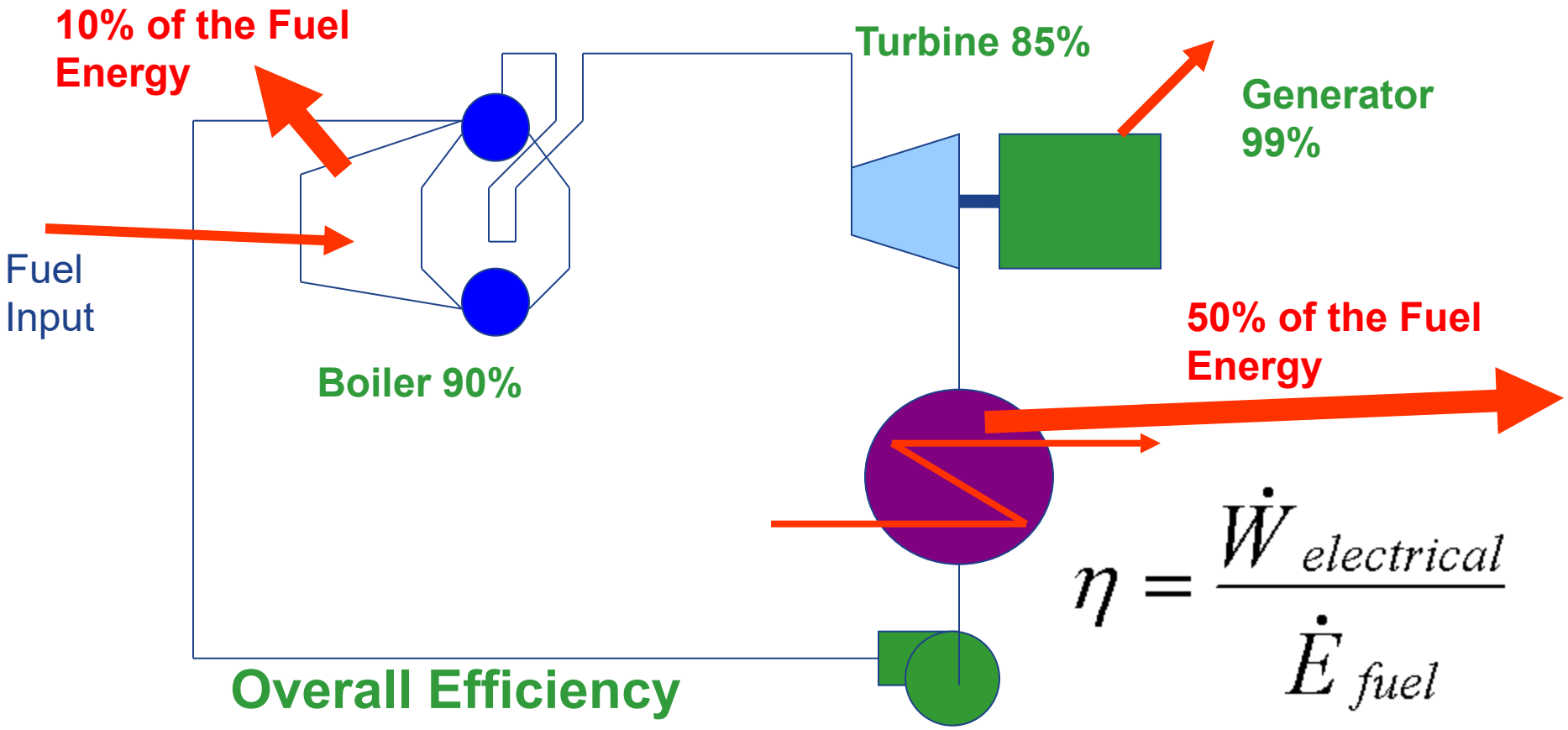
$$\eta = \frac{\dot{W}_{electrical}}{\dot{E}_{fuel}}$$

Overall Efficiency

35%

modified cycles can attain 42%

Simple Utility Power Station

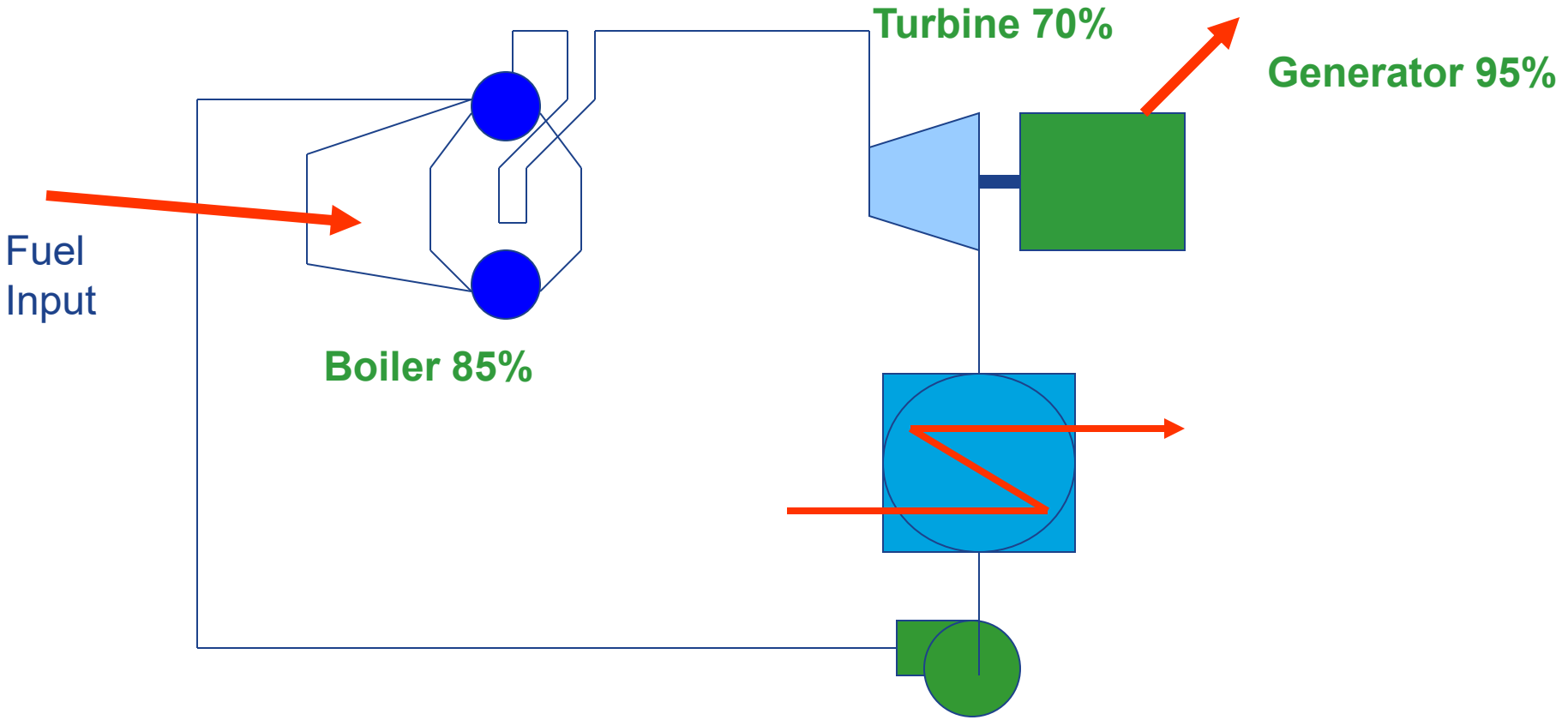


Overall Efficiency

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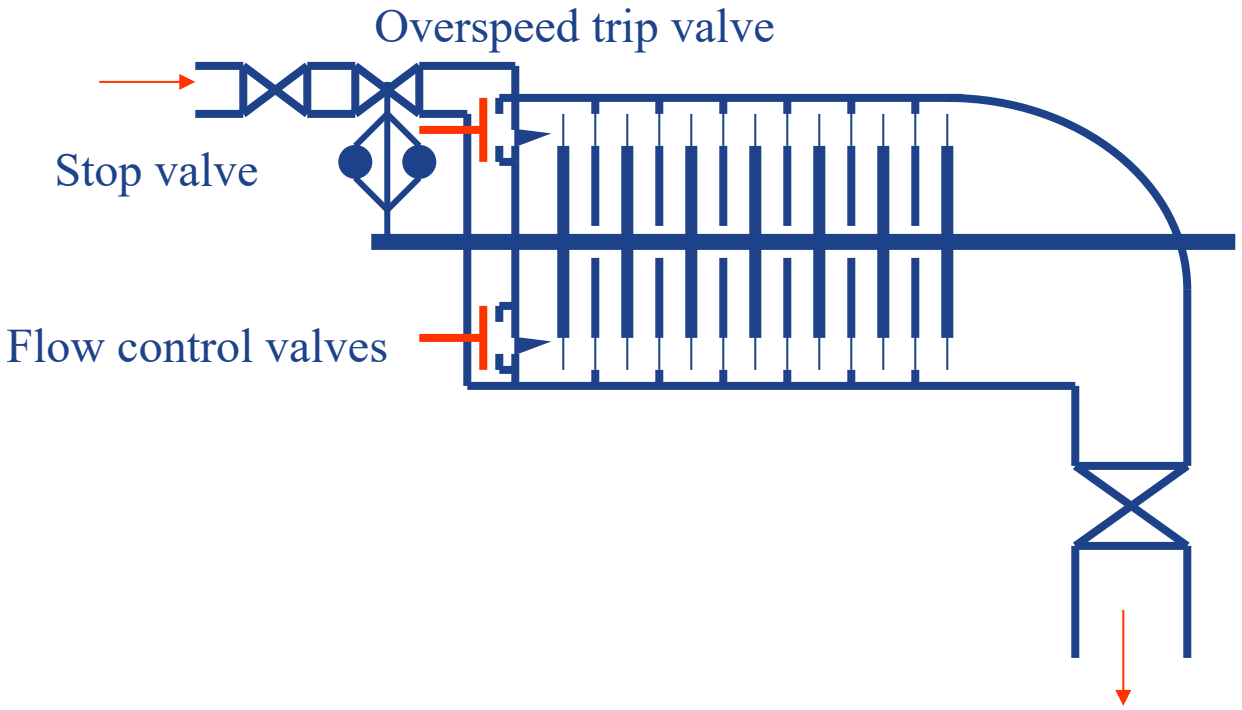
Industrial Power Station



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

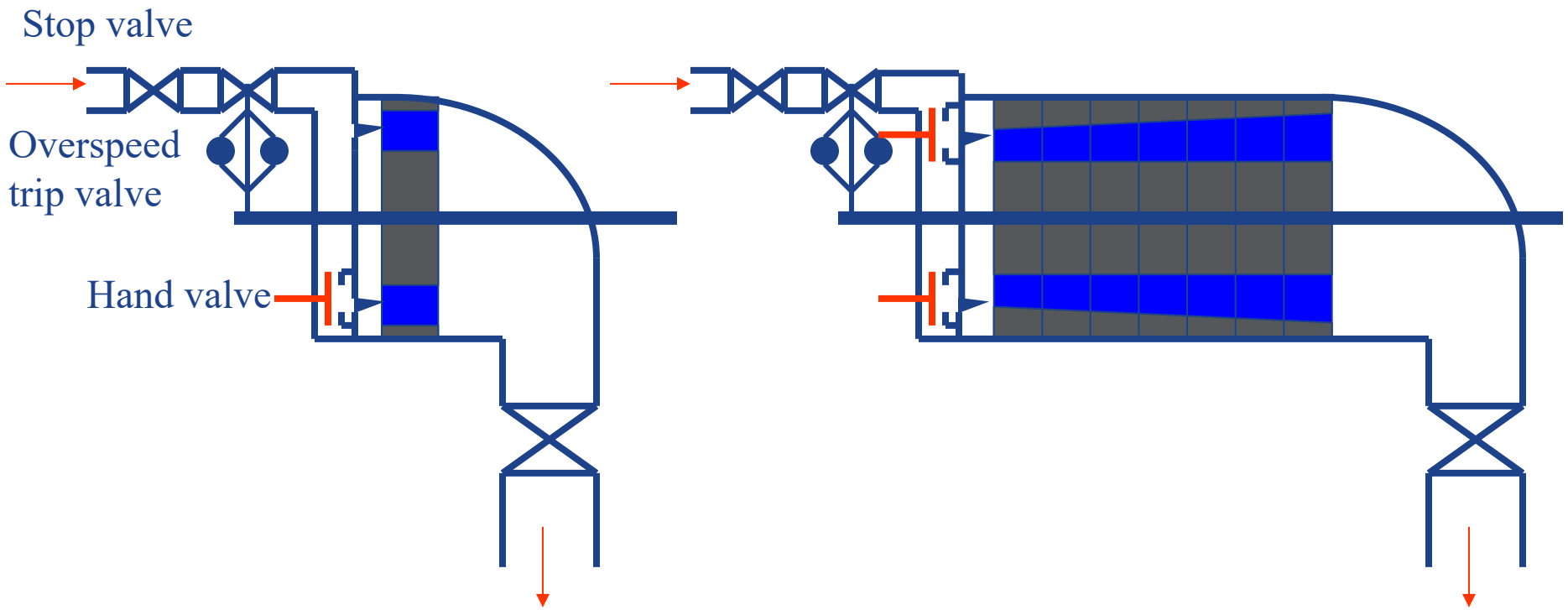


Steam Turbine Types

- 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

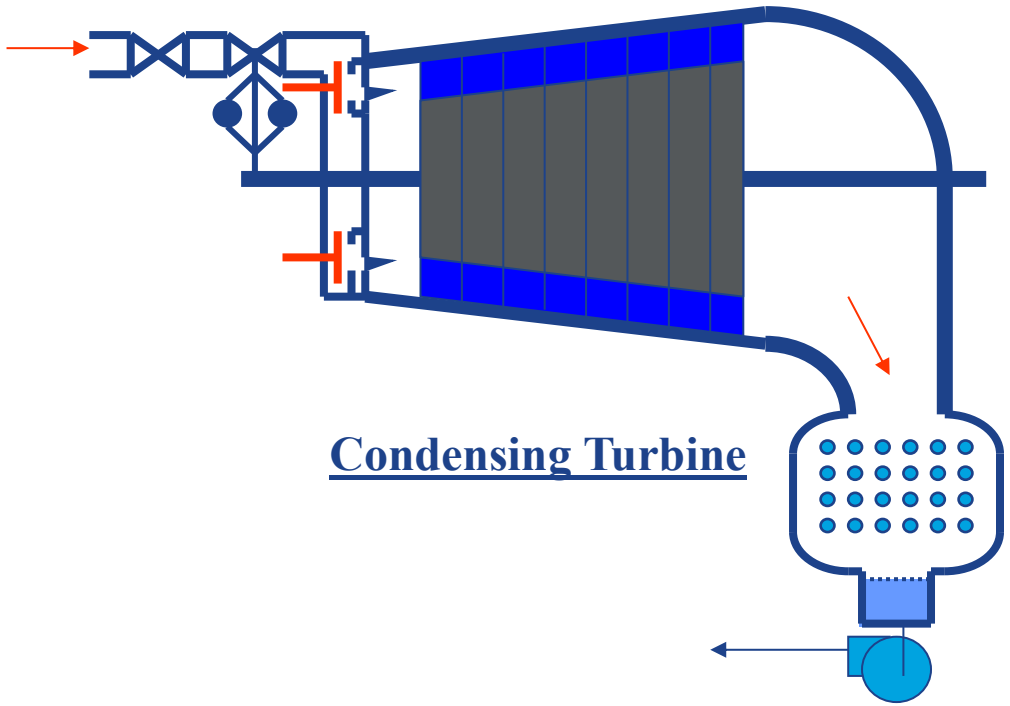


Single Stage Backpressure Turbine

Multistage Backpressure Turbine

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%



Typical Steam Turbines Operations

- Operating pressures
  - Minimum – 150 psig
  - Maximum – 3,000 psig
  - Vacuum conditions exist at the exhaust in condensing turbines!
- 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

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

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 - Old



STEAM TURBINE

RESULTS | HELP

Solve For

Isentropic Efficiency

Inlet Steam

Pressure	400	psig
Known Variable	Temperature	
Temperature Value	700	°F

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	°F

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 (°F)	700	350	350
Phase	Gas	Gas	Gas
Sp. Enthalpy (Btu/lb)	1,362	1,213	1,213
Sp. Entropy (Btu/lb-°F)	1.636	1.748	1.748
Mass Flow (klb/hr)	40	— —	40
Energy Flow (MMBtu/hr)	54.5	— —	48.5

Copy Table

MEASUR – Steam Turbine Calculator

Solve For

Isentropic Efficiency

Inlet Steam

Pressure	400	psig
Temperature	700	°F

Turbine Properties

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

Outlet Steam

Pressure	20	psig
Temperature	350	°F

Generate Example | Reset Data

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 (°F)	700	258.7	350
Phase	Gas	0.96	Gas
Sp. Enthalpy (Btu/lb)	1,362	1,129.4	1,213
Sp. Entropy (Btu/lb-°F)	1.636	1.636	1.748
Mass Flow (klb/hr)	40	— —	40
Energy Flow (MMBtu/hr)	54.5	— —	48.5

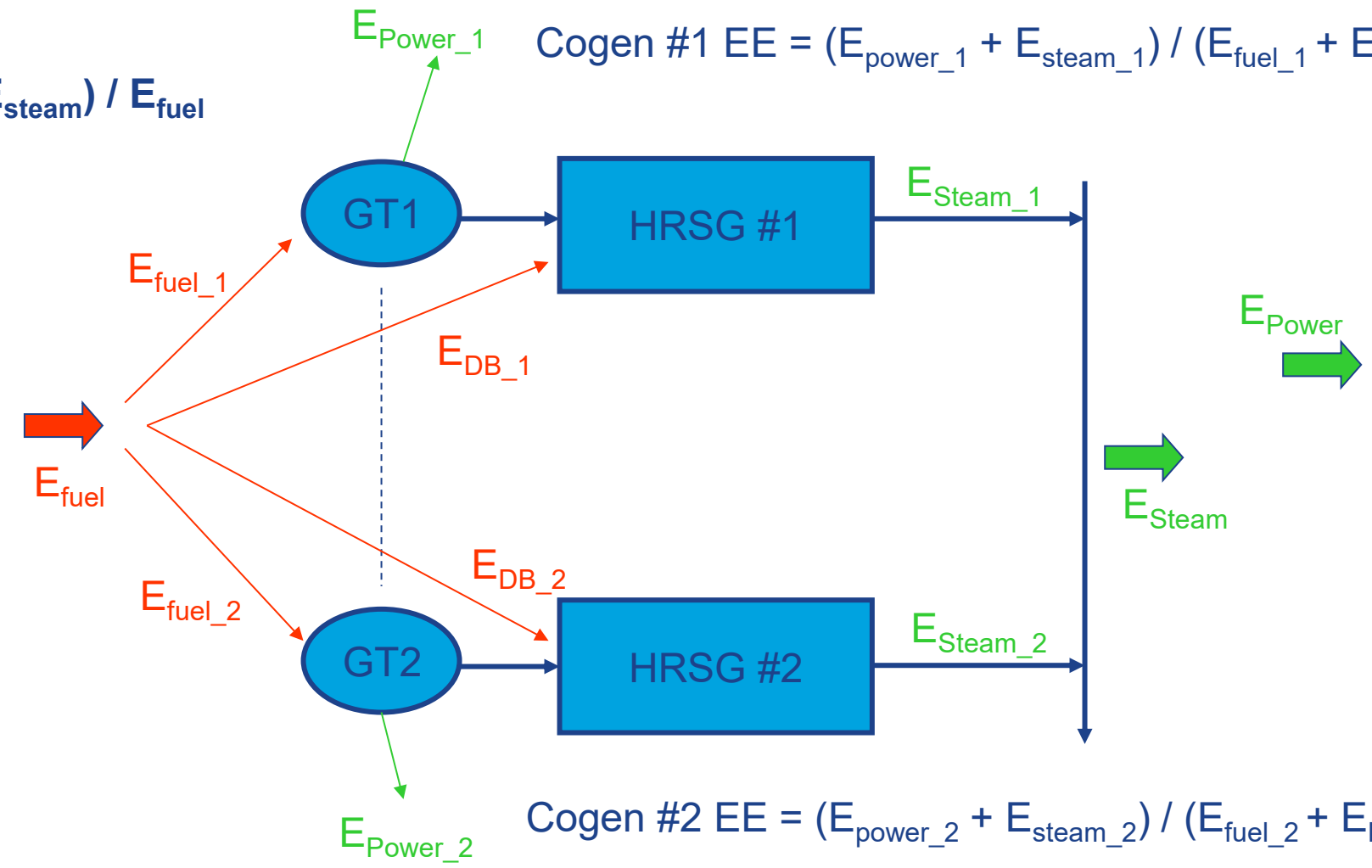
CoGeneration (Combined Heat & Power)

- Gas Turbines

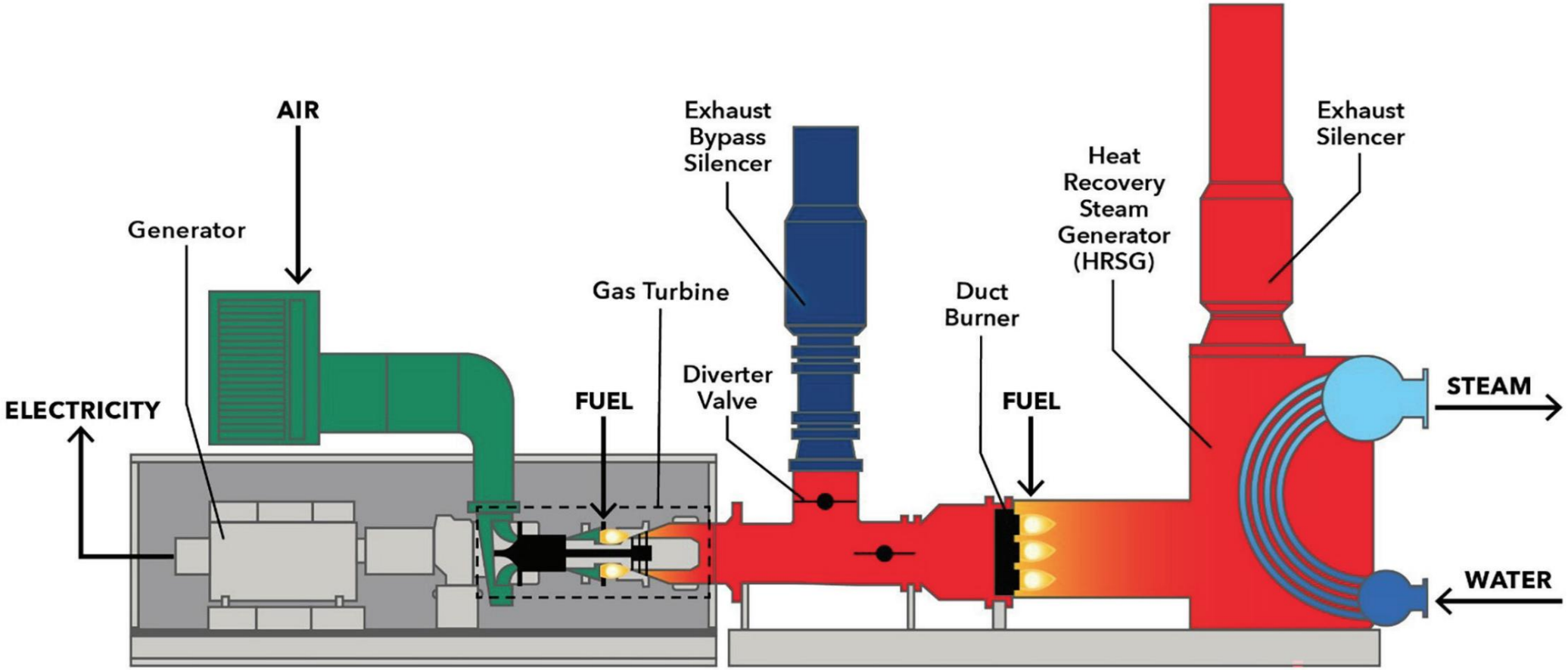
U.S. DEPARTMENT OF ENERGY

An Example Gas Turbine / HRSG Cogeneration System

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



Simple Cycle Gas Turbine with Duct Burner and HRSG

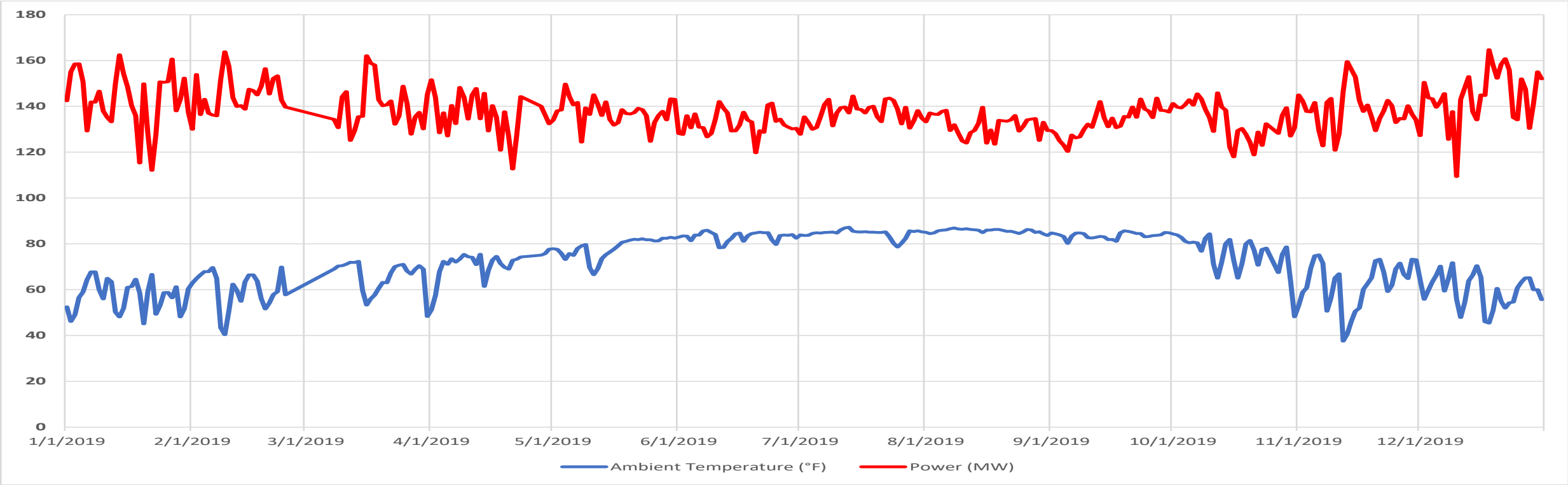


U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. (2024, April 29). *CHP technologies: Gas turbines* [Fact sheet]

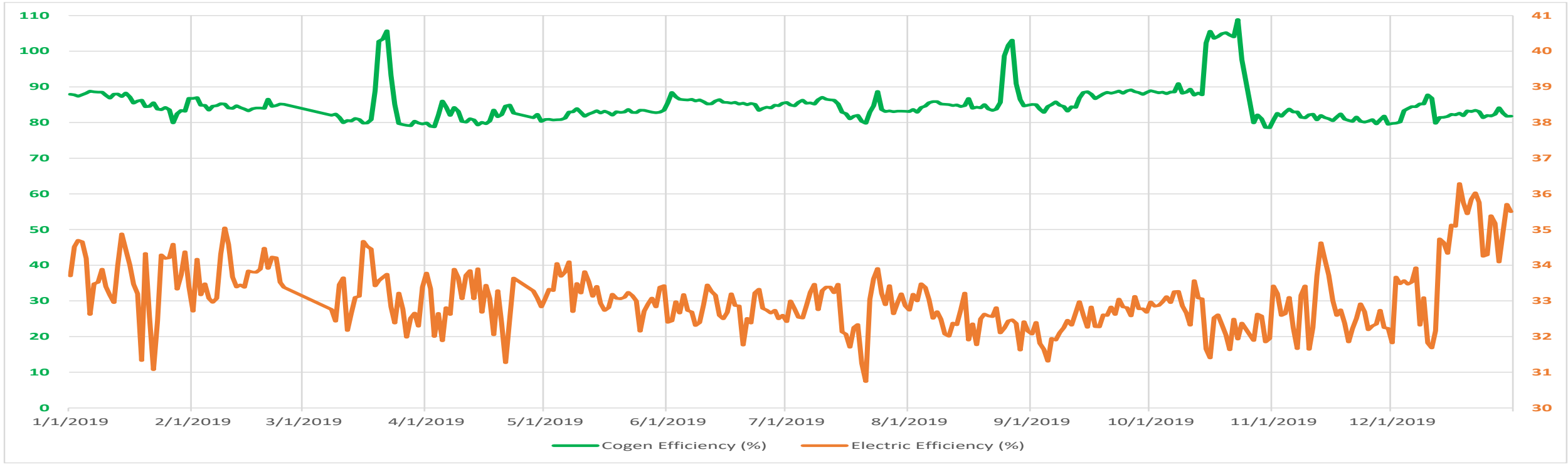
Metrics for Cogeneration

- 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

- 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 tomorrow Thursday – November 12, 2026 – 10 am ET

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

Alternately, you can email questions to us at paparra@ornl.gov and guow@ornl.gov

U.S. DEPARTMENT OF ENERGY