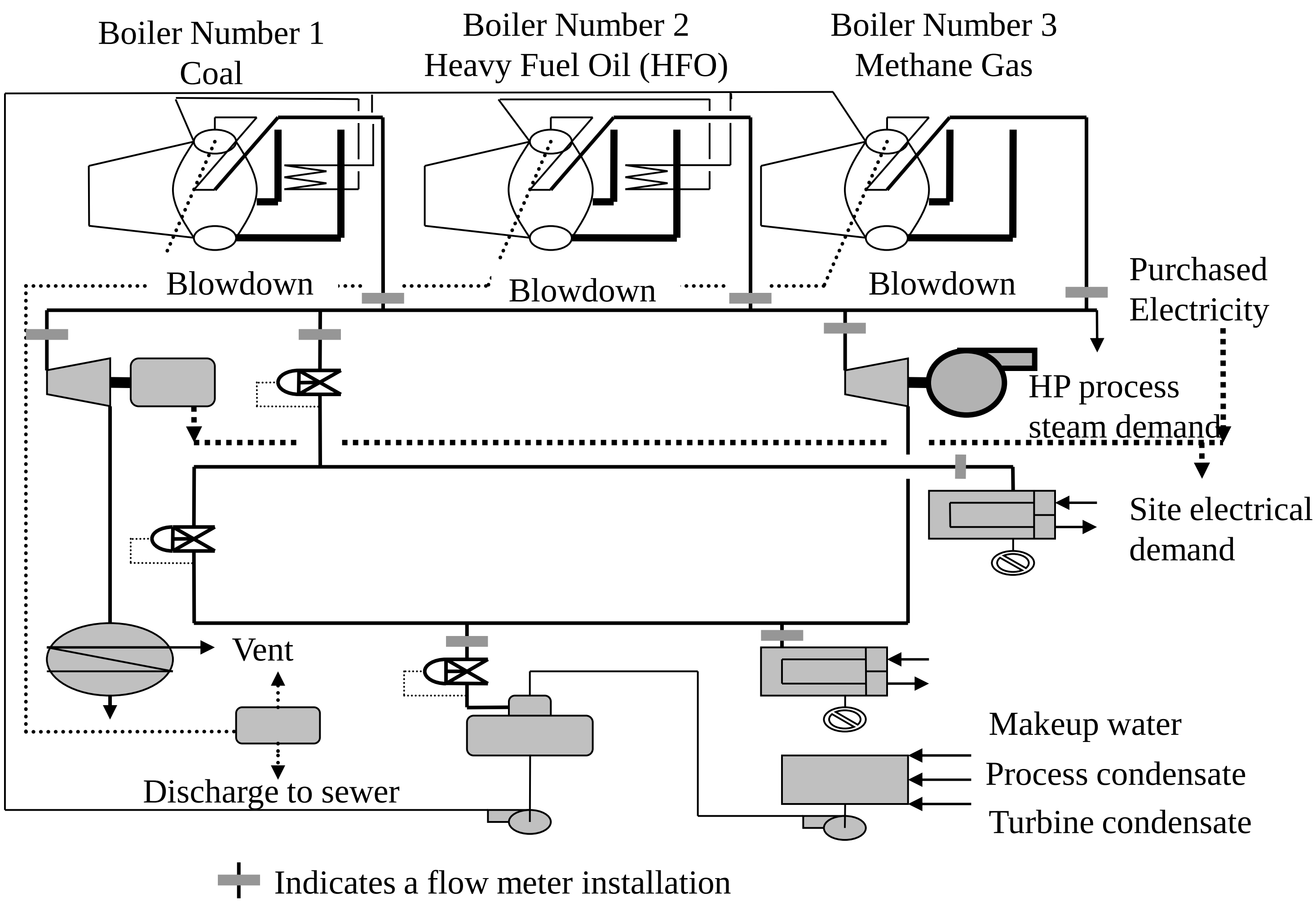
Section 3

Steam System Assessment Tool – P1

General Plant Information
Overview of SSAT
Basic Inputs – 1, 2 and 3 Header Models
Quick Start Section
Impact Utility Costs
Boiler Efficiency
1-header Student Hands-On Exercise

Steam System



Steam System Assessment Tool (SSAT)

- Developed for the U.S.DOE under contract with the Oak Ridge National Laboratory by:
  - KBC Linnhoff March
  - Spirax Sarco Inc.
  - Greg Harrell, Ph.D., P.E.

- Steam System Assessment Tool (SSAT)
  - Steam system modeling software
  - Common energy recovery projects built into the model
  - Allows “what if” evaluations

Steam System Assessment Tool (SSAT)

- A Steam System Opportunity Assessment Tool
- Produces mass, energy, and economic balances for a steam system
- Completes evaluations of energy utilization improvement projects
- Version 3.0.0 now available
  - Metric (SI units) capability
- Downloadable from the US DOE ITP website
  - http://www1.eere.energy.gov/industry/bestpractices/software.html

Key SSAT Features

- Choice of 1, 2, or 3 Header Pressure Models
- Schematics of Model Steam Systems
- Estimates of Site & Global Environmental Emissions

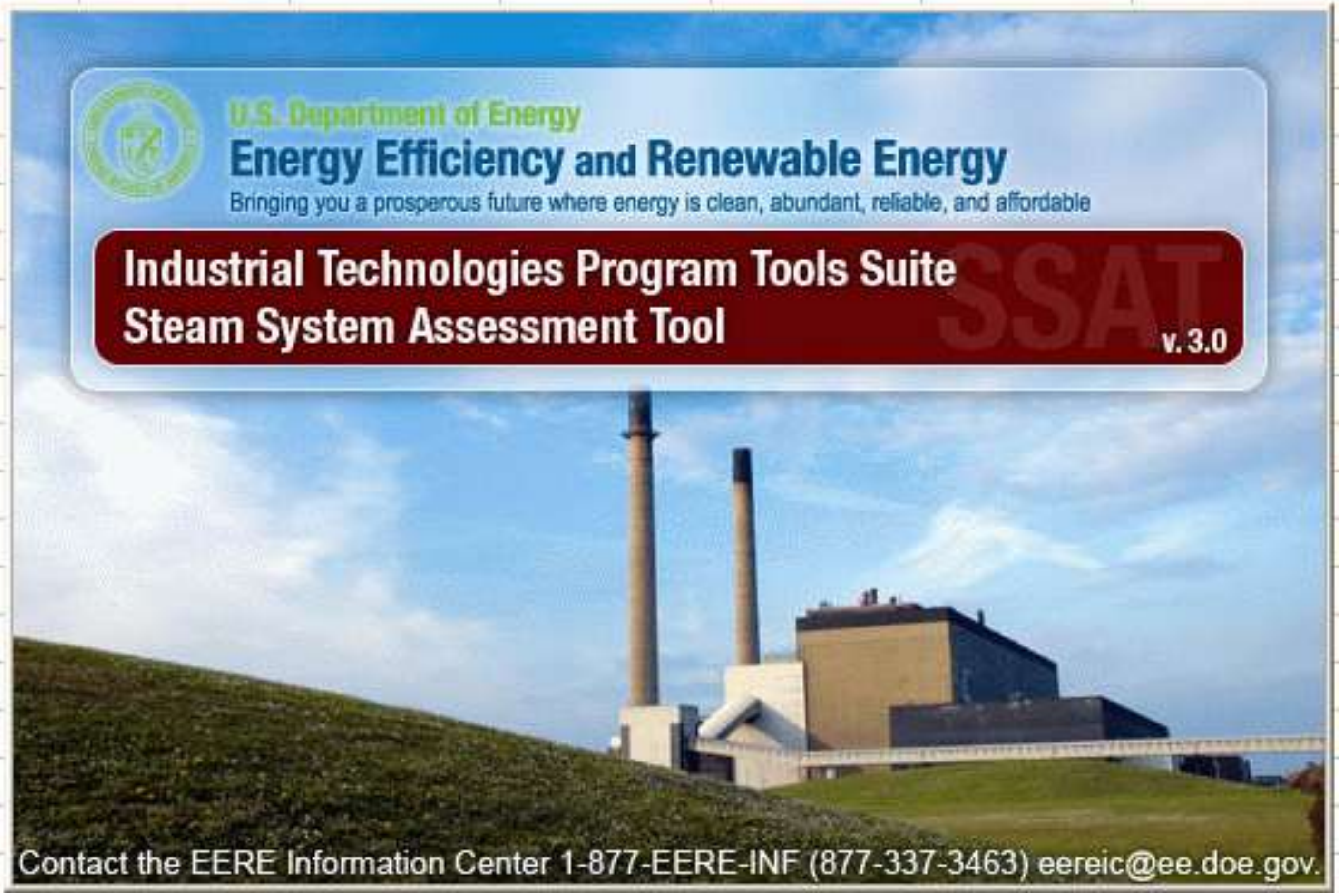
- Major Equipment Simulated:
  - Boiler(s)
  - End-uses
  - Back-pressure turbines
  - Condensing turbine
  - Deaerator
  - Steam traps, leaks, insulation losses
  - Letdowns
  - Flash vessels
  - Feedwater preheat exchangers
  - Heat recovery exchangers

SSAT Can Evaluate Key Steam Improvement Projects

- Steam Demand Changes
- Boiler Efficiency
- Alternative Fuels
- Steam Turbines vs PRVs
- Boiler Blowdown Energy Recovery
- Condensate Recovery
- Heat Recovery
- Flash Steam Recovery

SSAT Worksheets

- Input
  - Builds the model
- Model
  - Graphical representation of the system
  - Base case
- Projects Input
  - Allows projects to be activated
  - Allows custom project operation
- Projects Model
  - Graphical representation of the system
  - The modified system
- Results
  - Side-by-side comparison of the major system operating factors
- Stack Loss Calculator
  - Calculate boiler stack losses for SSAT fuels
- User Calculations
  - Open worksheet to allow individual calculations

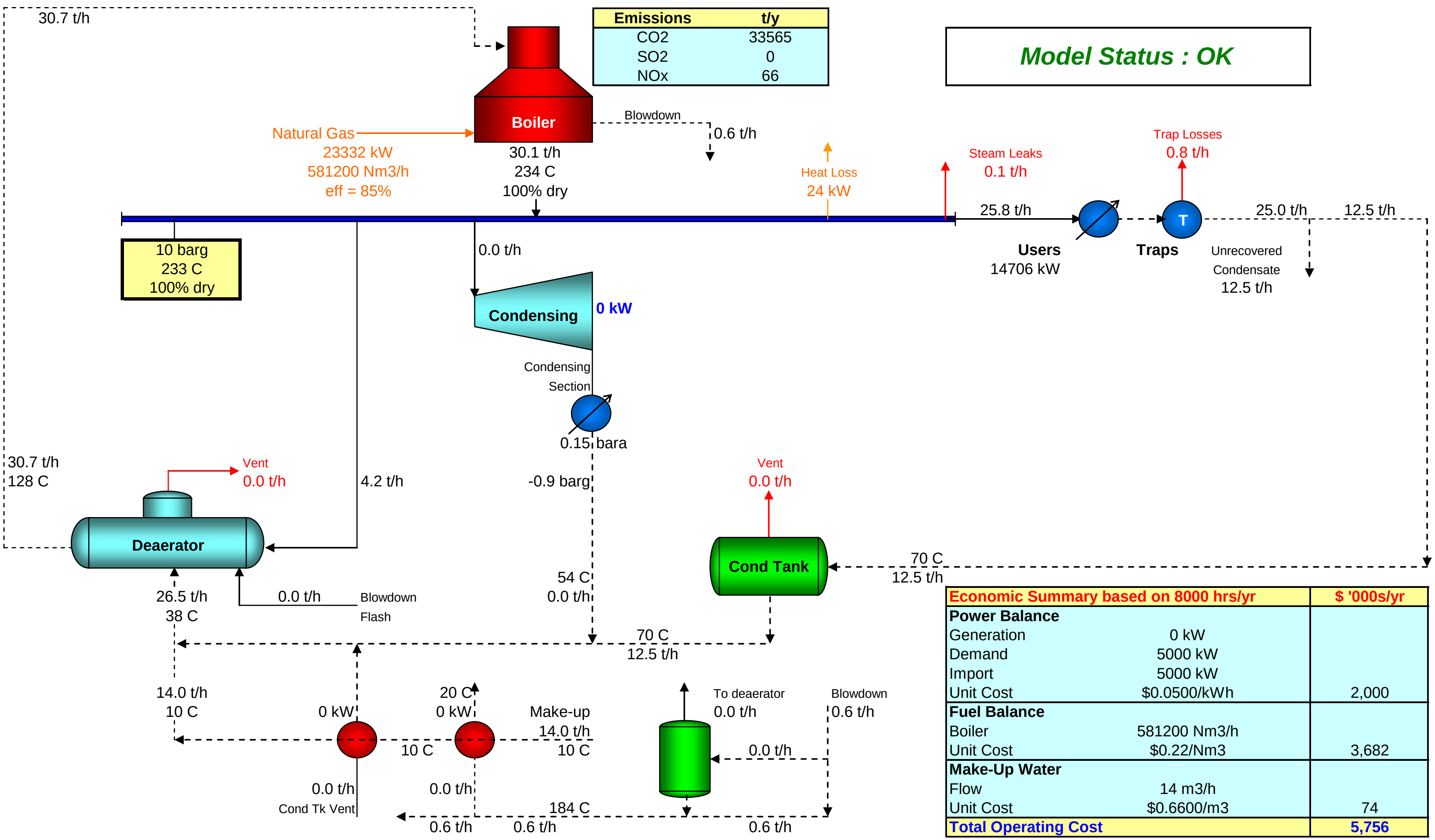


Review the 1-header, 2-header and 3-header SSAT models

Steam System Assessment Tool
Current Operation

SSAT Default 1 Header Metric Model

Model Status : OK



Emissions	t/y
CO_2	33565
SO_2	0
NOx	66

Economic Summary based on 8000 hrs/yr		$ '000s/yr
Power Balance		
Generation	0 kW	
Demand	5000 kW	
Import	5000 kW	
Unit Cost	$0.0500/kWh	2,000
Fuel Balance		
Boiler	581200 Nm3/h	
Unit Cost	$0.22/Nm3	3,682
Make-Up Water		
Flow	14 m3/h	
Unit Cost	$0.6600/m3	74
Total Operating Cost		**5,756**

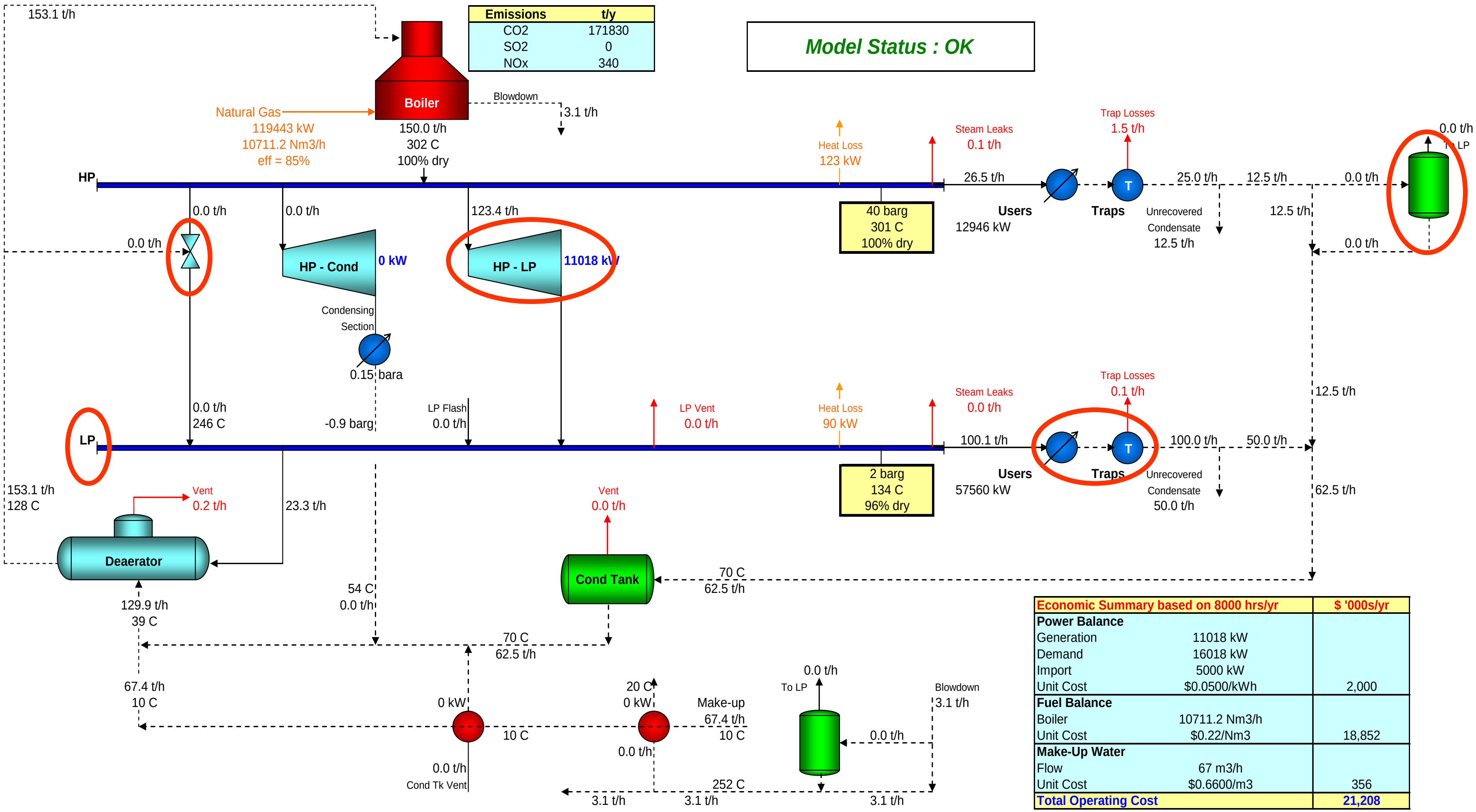
Steam System Assessment Tool

SSAT Default 2 Header Metric Model

Current Operation

Emissions	t/y
CO_2	171830
SO_2	0
NOx	340

Model Status : OK



Economic Summary based on 8000 hrs/yr		$ '000s/yr
Power Balance		
Generation	11018 kW	
Demand	16018 kW	
Import	5000 kW	
Unit Cost	$0.0500/kWh	2,000
Fuel Balance		
Boiler	10711.2 Nm3/h	
Unit Cost	$0.22/Nm3	18,852
Make-Up Water		
Flow	67 m3/h	
Unit Cost	$0.6600/m3	356
Total Operating Cost		21,208

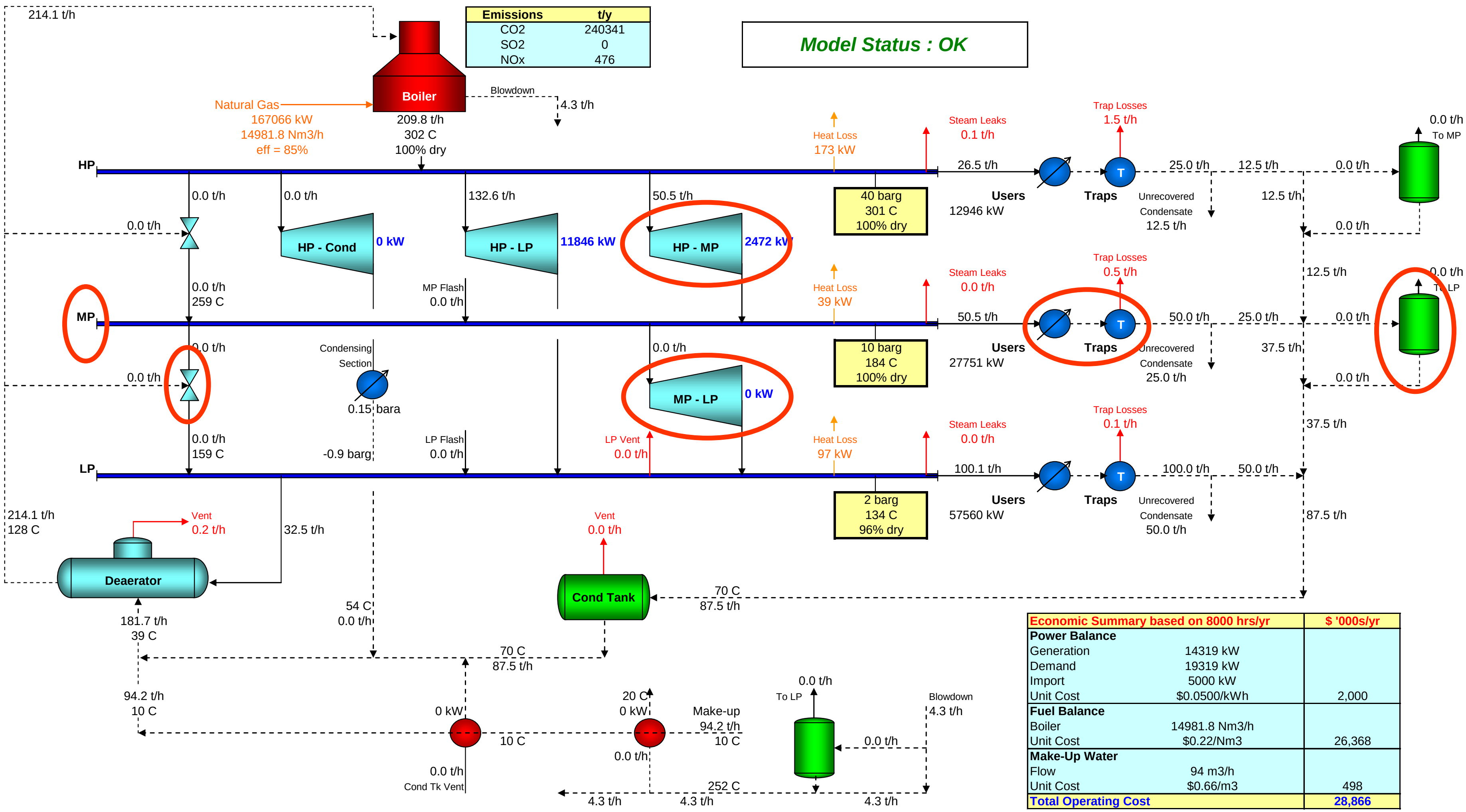
Steam System Assessment Tool

SSAT Default 3 Header Metric Model

Current Operation

Emissions	t/y
CO2	240341
SO2	0
NOx	476

Model Status : OK



Economic Summary based on 8000 hrs/yr		$ '000s/yr
Power Balance		
Generation	14319 kW	
Demand	19319 kW	
Import	5000 kW	
Unit Cost	$0.0500/kWh	2,000
Fuel Balance		
Boiler	14981.8 Nm3/h	
Unit Cost	$0.22/Nm3	26,368
Make-Up Water		
Flow	94 m3/h	
Unit Cost	$0.66/m3	498
Total Operating Cost		**28,866**

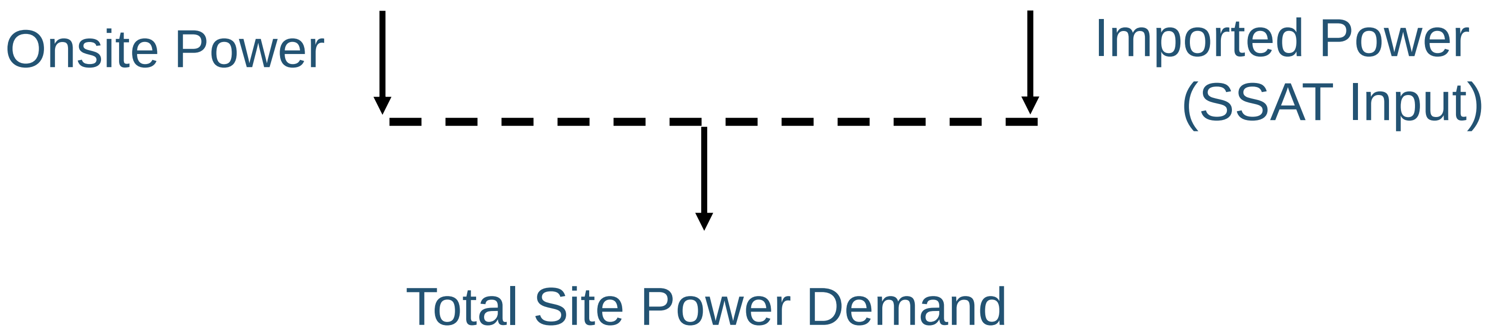
Quick Start Section

General Site Data	Input Data	Notes / Warnings
Site Power Import (+import, - export)	5000 kW	Power import + site generated power = site electrical demand
Site Power Cost	0.1000 $kWh	Typical 2003 value: $0.05kWh
Operating hours per year	8,760 hrs	
Site Make-Up Water Cost	0.6600 $/m3	Typical 2003 value: $0.66/m3
Boiler Fuel		Natural Gas
Site Fuel Cost	1$ / Nm3	Typical 2003 value: $0.22/Nm3

- Economic units used by SSAT are fixed as “US $”
- Two options:
  - The unit is just a TEXT character and so it doesn’t matter what currency is used
  - Convert costs to “US $” and then re-convert to local currency

Site Power Import (or Export)

- SSAT 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
- Fixed costs should NOT be included in SSAT impact-type analysis

Electric Utility Costs

- 1st Level of Information
  - Annual electric utility bill: $486,000
  - Annual electrical energy consumption: 4,380 MWh

- Electric utility cost can be calculated as follows

$$\boxed{ElectricCost = \frac{486{,}000}{4{,}380{,}000} = 0.111\frac{\$}{kWh}}$$

- But this cost may be INCORRECT for use in SSAT analysis

Electric Utility Costs

- 2nd Level of Information
  - Annual electric utility bill: $486,000
  - Annual electrical energy consumption: 4,380 MWh
  - Fixed Charges: $48,000
- Reducing energy consumption will NOT change the fixed charges and hence, they shouldn't be included in SSAT
- Electric utility cost can be calculated as follows

$$\boxed{ElectricCost = \frac{(486{,}000 - 48{,}000)}{4{,}380{,}000} = 0.10 \frac{\$}{kWh}}$$

- This cost may be CORRECT for use in SSAT analysis, if Electric Demand is going to be impacted

Electric Utility Costs

- 3rd Level of Information
  - Annual electric utility bill: $486,000
  - Annual electrical energy consumption: 4,380 MWh
  - Annual Fixed charges: $48,000
  - Annual Demand charges: $87,600
  - Annual Energy charges: $350,400
- If electric Demand is NOT impacted then Demand charges should NOT be included in SSAT
- Electric utility cost can be calculated as follows

$$\boxed{ElectricCost = \frac{(486{,}000 - 48{,}000 - 87{,}600)}{4{,}380{,}000} = 0.08\frac{\$}{kWh}}$$

Electric Utility Costs

- Different configuration
  - Demand charge: $14.60 per kW per month
  - Energy charge: $0.08 per kWh
- SSAT has only one cell ($/kWh) for input

$$\kappa_{energy} = 0.080 \frac{\$}{kWh}$$

$$\kappa_{demand} = 14.6 \frac{\$}{kW\ month}\left(\frac{1\,month}{730\ hrs}\right) = 0.020 \frac{\$}{kWh}$$

$$ElectricCost = \kappa_{energy} + \kappa_{demand} = 0.10 \frac{\$}{kWh}$$

Makeup Water Costs

- Water purchase price
- Pumping costs
- Treatment costs
- Wastewater costs ???
- Makeup water temperature is an important variable
- A typical cost is $0.66/m^3

SSAT Fuel Selection

- Gas
  - Natural gas
- Liquid
  - Number 2 fuel oil
  - Number 6 fuel oil
    - Low sulfur
    - High sulfur
- Solid
  - Coal
    - Eastern coal
    - Western coal
  - Green Wood
- User defined fuel

Fuel Heating Value

- The energy content of a fuel is determined by a combustion process
  - The combustion process begins and ends at ambient temperature
    - Constant pressure analysis provides the most accurate heating value
  - The energy released during the combustion process is measured
    - The energy released is the *Heat of Combustion* for the fuel
      - This is also the *calorific value* and the *heating value*

- Fuels containing hydrogen will form water during combustion

$$\boxed{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{Energy Release}}$$

Higher Heating Value (HHV)

- Water (H_2O) formed during the combustion process is initially steam but condenses during the heating value test
  - Each kg of water releases ~2,325 kJ of energy by condensing
    - This energy release is measured in the **Higher Heating Value**

- In the United States *HHV* is the common convention
  - The primary exception is the combustion turbine arena

$$\boxed{CH_4 + 2O_2 \rightarrow CO_2 + \underbrace{2H_2O}_{condensate} + \text{Energy Release}}$$

Lower Heating Value (LHV)

- The Lower Heating Value is the energy liberated from a combustion process with no latent energy release from condensation
- The Lower Heating Value is generally determined by calculation from the higher heating value and the fuel composition
- In most boiler operations the flue gas will exit the boiler with no condensate
- The Lower Heating Value is the convention in most of the world

$$CH_4 + 2O_2 \rightarrow CO_2 + \underbrace{2H_2O}_{Steam} + \text{Energy Release}$$

Higher and Lower Heating Value

- The numeric difference between the higher and lower heating values depends on the hydrogen content of the fuel
  - Natural gas difference is 10%
  - Fuel oil difference is 6%
  - Coal difference is ~4%
  - Green wood difference can be more than 20%

- In the United States most fuels are marketed based on the fuel higher heating value
- The primary point of concern is consistency

Common Fuels in SSAT

Fuel	Sales Unit	Typical Cost ($/Sales Unit)	HHV (kJ/kg)	Unit Price ($/GJ)
Natural Gas	NM^3	1.00	54,220	26.35
Number 2 Fuel Oil	Tonne	1,500	45,125	33.24
Number 6 Oil (LS)	Tonne	785	43,595	18.01
Number 6 Oil (HS)	Tonne	797	43,764	18.21
Bituminous Coal	Tonne	171	31,890	5.36
Sub Bituminous Coal	Tonne	129	23,465	5.50
Green Wood	Tonne	22	12,215	1.80

Default values in SSAT are based on US prices, are from 2003 and should not be used for fuel pricing

Currency Exchange: 1 US$ = 12 Moldovian Leu (MDL)

Fuel Composition in SSAT

Reference Fuel Composition (in lbmi / lbmfuel)							
Component	**Natural Gas**	**Number 2**	**Number 6 LS**	**Number 6 HS**	**East Coal**	**West Coal**	**Wet Wood**
C	0.000	0.856	0.873	0.847	0.750	0.524	0.180
H2	0.000	0.120	0.105	0.110	0.050	0.041	0.035
CH4	0.905	0.000	0.000	0.000	0.000	0.000	0.000
N2	0.018	0.005	0.007	0.002	0.015	0.038	0.001
CO	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C2H4 (Ethylene)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C2H6 (Ethane)	0.061	0.000	0.000	0.000	0.000	0.000	0.000
C3H8 (Propane)	0.016	0.000	0.000	0.000	0.000	0.000	0.000
O2	0.000	0.006	0.006	0.004	0.067	0.109	0.222
S	0.000	0.004	0.008	0.037	0.010	0.006	0.000
H2O	0.000	0.000	0.000	0.000	0.038	0.145	0.537
CO2	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ash	0.000	0.010	0.000	0.000	0.070	0.137	0.025

Common Fuels (in Moldova)

Fuel	Sales Unit	(MDL / Sales Unit)	(kJ / Sales Unit)	(MDL / GJ)
Natural Gas	NM^3	6.2	40,144	154.4
Petrol	Liter	18.0	35,218	511.1
Diesel (No 2 Oil)	Liter	18.0	39,539	455.2
Heavy Fuel Oil (No 4 - 5 Oil)	Tonne	12000	43,675,000	274.7
Coal	Tonne	3000	31,890,000	94.0
LPG	Tonne	7,455.0	46,100,000	161.7
Wood	Tonne	xxx	12,215,000	yyyy

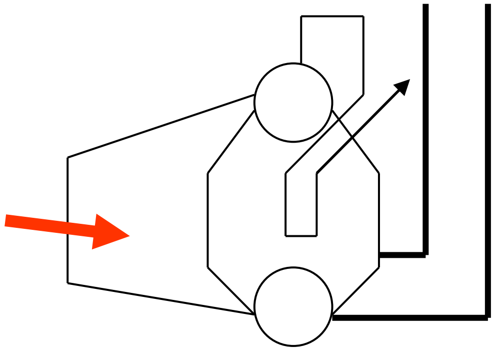
Fuel Cost Structure – Impact Fuel

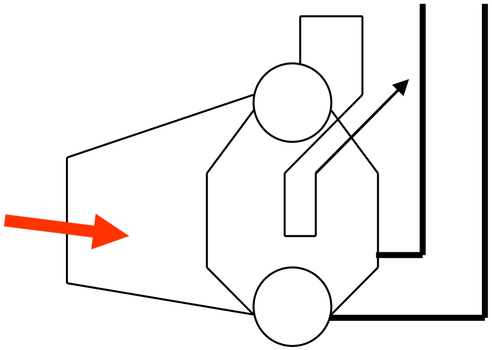
- Analyses should be completed utilizing *impact costs*
- Gross indications of savings opportunities can be attained by use of *average impact cost* or *projected cost*
- Multiple models may need to be developed reflecting various pricing conditions
    - Fuel prices typically vary seasonally
- When the site fuel is not an SSAT fuel the most similar SSAT fuel should be used
    - The SSAT fuel cost should equal the actual energy related fuel cost

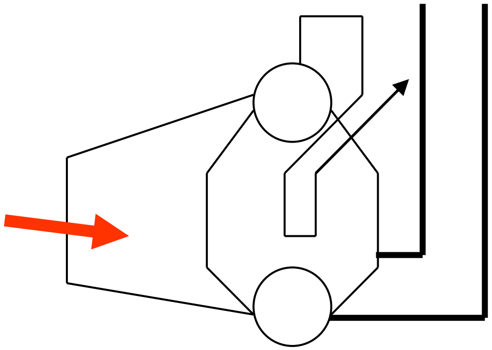
Fuel Selection

- How should multi-fuel sites be modeled?
  - Impact fuel cost should be utilized
    - The fuel that will change consumption if steam demand changes
    - Typically, highest cost fuel in use but NOT always
    - "Blended costs" generally do not reflect actual system changes
      - Blended costs **do** provide a confidence level in the model results

Fuel Selection







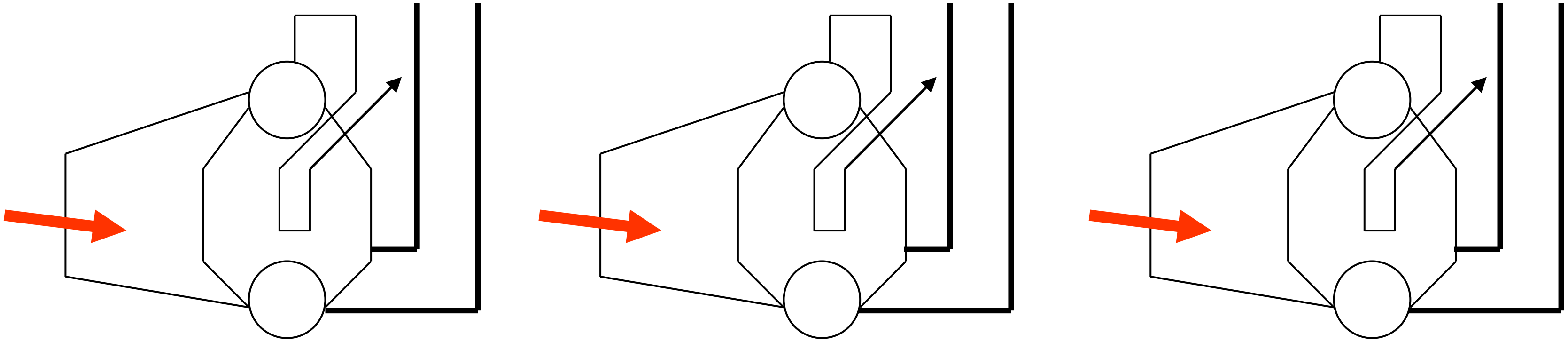
Fuel: Coal
Fuel cost: $250/tonne
Boiler capacity: 30 T/h
Steam production: **0 T/h**
Boiler efficiency: 85%

Fuel: Heavy Fuel Oil
Fuel cost: $1000/tonne
Boiler capacity: 30 T/h
Steam production: **0 T/h**
Boiler efficiency: 84%

Fuel: Natural gas
Fuel cost: $6.2/Nm^3
Boiler capacity: 30 T/h
Steam production: 20 **T/h**
Boiler efficiency: 80%

- Turndown issues limit minimum fire operation
- Maximum fire issues limit continuous output
- **What is the impact fuel in this operation?**

Fuel Selection



Fuel: Coal
Fuel cost: $7.8/GJ
Boiler capacity: 30 T/h
Steam production: **0 T/h**
Boiler efficiency: 85%

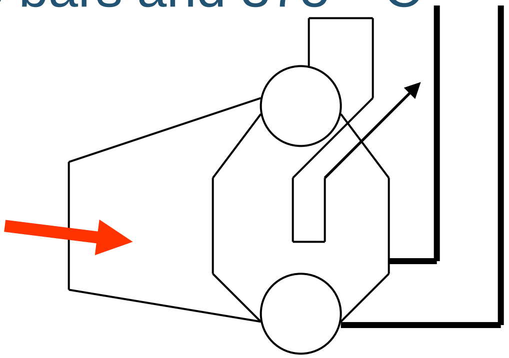
Fuel: Heavy Fuel Oil
Fuel cost: $22.9/GJ
Boiler capacity: 30 T/h
Steam production: **0 T/h**
Boiler efficiency: 84%

Fuel: Natural gas
Fuel cost: $12.8/GJ
Boiler capacity: 30 T/h
Steam production: 2**0 T/h**
Boiler efficiency: 80%

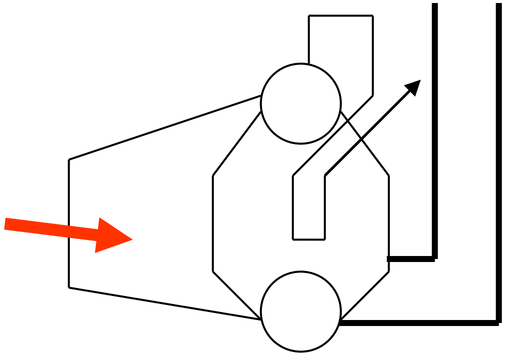
- From a pure cost perspective – Natural gas fired boiler is the impact boiler
  - **It has the highest steam production cost!**

Steam conditions:
25 bars and 375° C

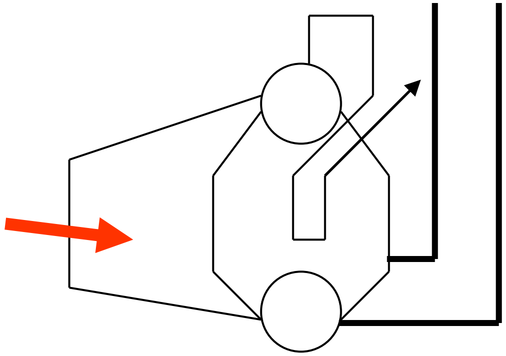
Average Fuel Cost



Fuel: Coal
Fuel cost: $7.8/GJ
Boiler capacity: 30 T/h
Steam production: **0 T/h**
Boiler efficiency: 85%



Fuel: Heavy Fuel Oil
Fuel cost: $22.9/GJ
Boiler capacity: 30 T/h
Steam production: **0 T/h**
Boiler efficiency: 84%



Fuel: Natural gas
Fuel cost: $12.8/GJ
Boiler capacity: 30 T/h
Steam production: 2**0 T/h**
Boiler efficiency: 80%

- **For this operating condition the “average fuel cost” is ~$12.8/GJ**
- **Combined boiler plant efficiency is 80%**
- This is good to use to check overall utilities agreement

Steam Generation Cost for Natural Gas Boiler

- Boiler fired with Natural gas which has a higher heating value of 54,220 kJ/kg
  - HHV is 40,144 kJ/Nm³

- Steam generation: 20 T/h (steady all year round)
- Fuel supply: 1,693 Nm³/hr (28 Nm³/min)
- Fuel cost: $0.52/Nm³
- **Determine the operating cost?**

$$K_{boiler} = m_{fuel} \times k_{fuel} = 1693 \times 0.52 = \$872/hr$$
$$K_{boiler} = \$872/hr \times 8,760 \approx \$7,636,250/yr$$

Steam Generation Cost for Methane Gas Boiler

$$K_{boiler} = m_{fuel} \times k_{fuel} = 1693 \times 0.52 = \$872 / hr$$
$$K_{boiler} = \$872 / hr \times 8,760 \approx \$7,636,250 / yr$$

- Steam generation: 20 T/h (steady all year round)
- **Determine the steam cost?**

$$\kappa_{steam} = \frac{Boiler\ Operating\ Cost}{Steam\ Generation}$$
$$\kappa_{steam} = \frac{872}{20} = 43.6 \frac{\$}{tonne}$$

Quick Start Section

Steam Distribution	Input Data	Warnings
High Pressure (HP)	25 barg	
Medium Pressure (MP)	10 barg	
Low Pressure (LP)	2 barg	
HP Steam Use by Processes	5 t/h	
MP Steam Use by Processes	10 t/h	
LP Steam Use by Processes	10 t/h	

Steam Turbines	
Do you have a steam turbine installed between HP and LP?	No
Do you have a steam turbine installed between HP and MP?	No
Do you have a steam turbine installed between MP and LP	No
Do you have an HP to condensing turbine installed?	No

Process Steam Demand Evaluation

- SSAT is a “pull type” model
  - Process steam flows “pull” steam through the boiler
  - Typically modeling activities strive to match general boiler load

- Process steam flows are established by:
  - Direct continuous flow measurement
  - Direct intermittent flow measurement
  - Mass balance
  - Energy balance
  - System or Process design information
  - Empirical standards or data

Flow Measurements

- Steam flow measurement is typically completed by conventional flow meters
  - Orifice plates

- Condensate flow measurement is often completed by intermittent field observations
  - Timed volume capture
    - Condensate receiver fill and discharge
    - Known volume fill

Mass & Energy Balances

- Conservation of mass principle can often be applied very effectively

$$\boxed{\sum \dot{m}_i = \sum \dot{m}_e}$$

- The first law of thermodynamics (energy balance) for heat exchange is typically applied to:
  - Steam alone
  - Heated material alone

$$\boxed{\dot{Q}_x = \dot{m}_x \left(C_p\right)_x \left(T_e - T_i\right)_x}$$

For constant specific heats and when enthalpy is a function of temperature only

$$\boxed{\dot{Q}_x = \dot{m}_x \left(h_e - h_i\right)_x}$$

When material enthalpies are known

$$\boxed{\dot{Q}_{steam} = -\dot{Q}_x}$$

Typical heat exchanger applications

Example Steam System

- Pressure levels for steam distribution (end use)
  - High pressure – 25 bars (g)
  - Medium pressure – 10 bars (g)
  - Low pressure – 2 bars (g)

- Process Demands
  - High pressure – 5 T/h
  - Medium pressure – 5 T/h
  - Low pressure – 10 T/h

- Assume “NO” turbines in the system

Quick Start Section

Steam Traps	Input Data	Warnings
Number of traps at each pressure level		
Traps on HP header	250 traps	
Traps on MP header	300 traps	
Traps on LP header	500 traps	

Select the approximate timing of your last trap testing and maintenance program	3-5 years ago

The information you have entered above will allow you to start using the model. A closer match to your actual site operation can be obtained using the ***"Site Detail"*** options below.

- Provides information about the site distribution losses (except insulation)
- Uses the "number of traps" and "last maintenance program" as proxy for determining steam losses

Steam Traps

- Input the number of active traps installed in each pressure subsystem
- Provide a characterization of the intensity of the steam trap maintenance program
- Trap failure estimate is based on the frequency of the steam trap maintenance program
- **Trap failures release steam to the atmosphere**
  - Closed condensate recovery systems with flash steam recovery should be considered carefully
  - Trap failure losses are included in the process steam demand

Steam Trap Loss Estimate

- Steam trap loss is a *gross order of magnitude* estimate of possible loss
  - Based on typical experience reflective of maintenance effort
    - The number of traps failed open is estimated
    - System pressure, assumed condensate system pressure, and trap orifice diameter are used to determine theoretical flow rate based on compressible flow analysis
    - Order of magnitude loss is based on a blockage factor
      - Blockage factor results in a flow of ½ of theoretical flow
  - *Site Detail* section allows modification of this estimate

Steam Trap & Steam Leaks Model Basis

Steam Trap and Leak Model Basis				
Test Timing	**Traps Failed Ope (% of steam traps)**	**Orifice Diameter (mm)**	**Steam Leaks (% of steam traps)**	**Orifice Diameter (mm)**
<than 1 year	3	3.18	1	1.59
1 – 2 years ago	5	3.18	2	1.59
3 – 5 years ago	10	3.18	4	1.59
6 – 8 years ago	15	3.18	6	1.59
9 – 10 years ago	30	3.18	8	1.59

The number of steam traps is often indicative of the extent of the steam system

Steam Leak Estimate

- Steam leak estimate is also a *gross order of magnitude* estimate of possible loss
  - Based on typical experience reflective of maintenance effort
    - The number of traps in a steam system is often indicative of the extent of the system
    - System pressure and assumed leak orifice diameter are used to determine theoretical flow rate based on compressible flow analysis
    - Order of magnitude loss is based on a blockage factor
      - Blockage factor results in a flow of ½ of theoretical flow
      - This is also representative of discharge coefficient
  - *Site Detail* section allows modification of this estimate

Example Steam System

- Number of steam traps
  - High pressure – 250
  - Medium pressure – 300
  - Low pressure – 500

- There is NO effective steam trap maintenance program at the plant
  - It has been 3-5 years since a trap survey was done and traps were repaired based on the results of the survey

Site Detail – Boiler Efficiency

Site Detail

Boiler		
Method for specifying boiler efficiency	Option 2 - Enter user-defined value	

Note: Model default efficiencies represent Best Practice values assuming good operation and the installation of an economizer

→ | **Option 2** - Enter efficiency (%) | 81.7 % | | ←

Note: Boiler efficiency is defined as 100% - Stack Loss (%) - Shell Loss (%). The "Stack Loss" sheet gives more information on heat losses

Note: Efficiency is based on Higher Heating Value. Economizers are included in the boiler efficiency. Boiler blowdown losses are excluded

Blowdown Rate (% of feedwater flow)	5 %	
Do you have blowdown flash steam recovery to the LP system?	No	

- Uses default information or user specified
    - Classic Boiler Efficiency
    - SSAT Boiler Efficiency

ASME Boiler Efficiency

- American Society of Mechanical Engineers (ASME) has established a comprehensive testing standard for fired boilers
  - ASME Power Test Code 4 (ASME PTC–4)
    - Fuel efficiency (the same as the classic equation)
    - Gross efficiency (includes auxiliary input streams)
  - ASME PTC–4 describes two investigation methods
    - Input/output (direct method)
    - Energy balance (indirect method)

ASME – PTC 4 Determination of Boiler Efficiency

- Two generally accepted methods
  - Input-Output method

$$Efficiency = \frac{Output}{Input} \times 100$$

  - Energy Balance method

$$Efficiency = \left[\frac{Input + Credits - Losses}{Input} \right] \times 100$$

$$Efficiency = \left[1 - \frac{(Losses - Credits)}{Input} \right] \times 100$$

- Primary difference between the methods lies in accuracy of measurements and identification of losses

Source: ASME PTC 4 – 2008; Section 3-1.3; Pages 19-20

Classic Boiler Efficiency

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

$$\boxed{\eta_{boiler} = \frac{Energy\ absorbed\ by\ steam}{Fuel\ input\ energy} \times 100}$$

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

- This equation can be applied to a boiler or a boiler plant
- This equation can be applied for an instantaneous snapshot or any defined time-period (daily, month, annual, etc.)

Typical Boiler Efficiency

- A typical boiler will have an efficiency of ----?

75%	to 82%	to 87%
Wood	Methane Gas	Oil and Coal

- Efficiency is dependent on several factors:
  - Type of fuel
  - Installed equipment and controls
  - Boiler load, etc.

Steam Generation Efficiency

- Boiler fired with Natural gas which has a higher heating value of 54,220 kJ/kg
  - HHV is 40,144 kJ/m^3
- Steam generation: 20 Tph (steady all year round)
- Steam conditions: 25 bars, 375°C
- Boiler feedwater: 30 bars, 110°C
- Fuel supply: 1,693 Nm^3/hr (28 Nm^3/min)
- Fuel cost: \$0.52/Nm^3
- **Determine the boiler operating efficiency?**

Steam Generation Efficiency

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

- m_{steam} = 20,000 kg/hr
- h_{steam} = 3,181 kJ/kg
  - 25 bars, 375°C - superheated
- $h_{feedwater}$ = 463.5 kJ/kg
  - 30 bars, 110°C
- M_{fuel} = 1,693 m^3/hr
- HHV_{fuel} = 40,144 kJ/m^3

*Steam tables provide thermodynamic information for steam and feedwater

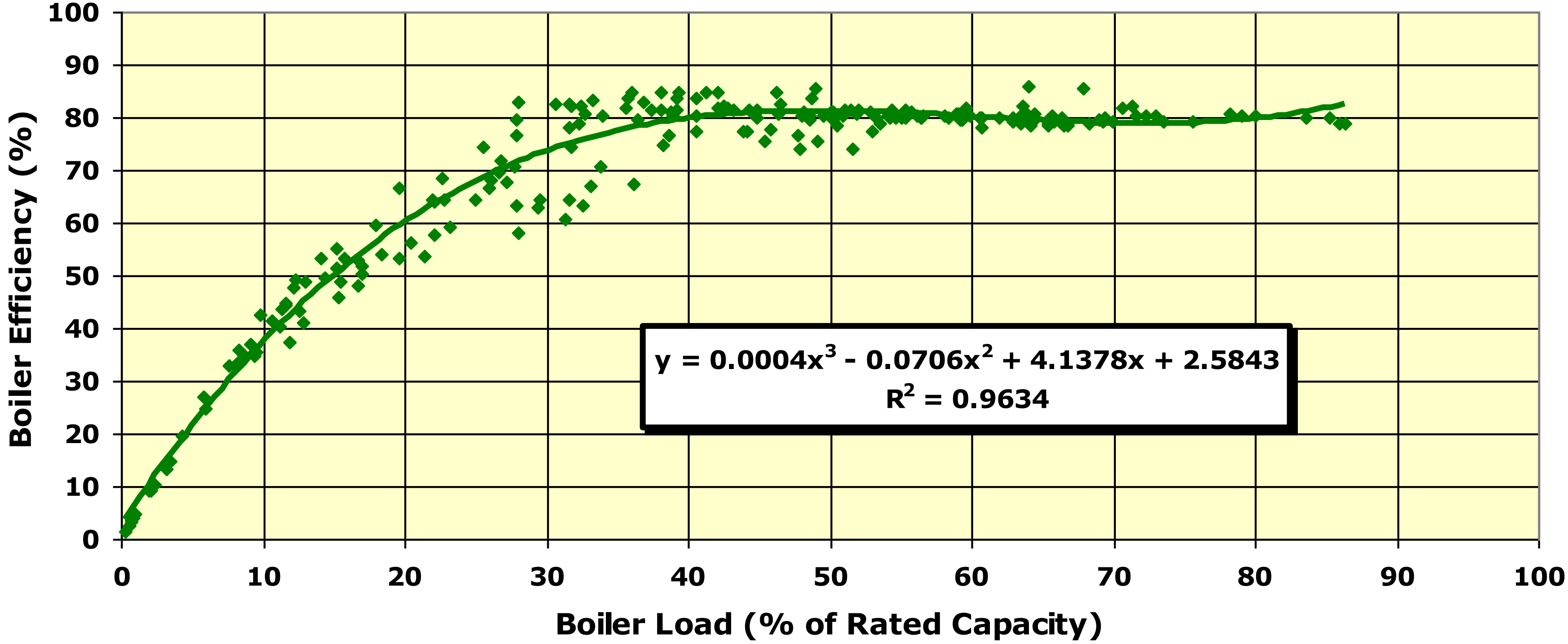
Steam Generation Efficiency

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

$$\eta_{boiler} = \frac{20{,}000\left(3{,}181 - 463.5\right)}{1{,}693 \times 40{,}144} \times 100$$

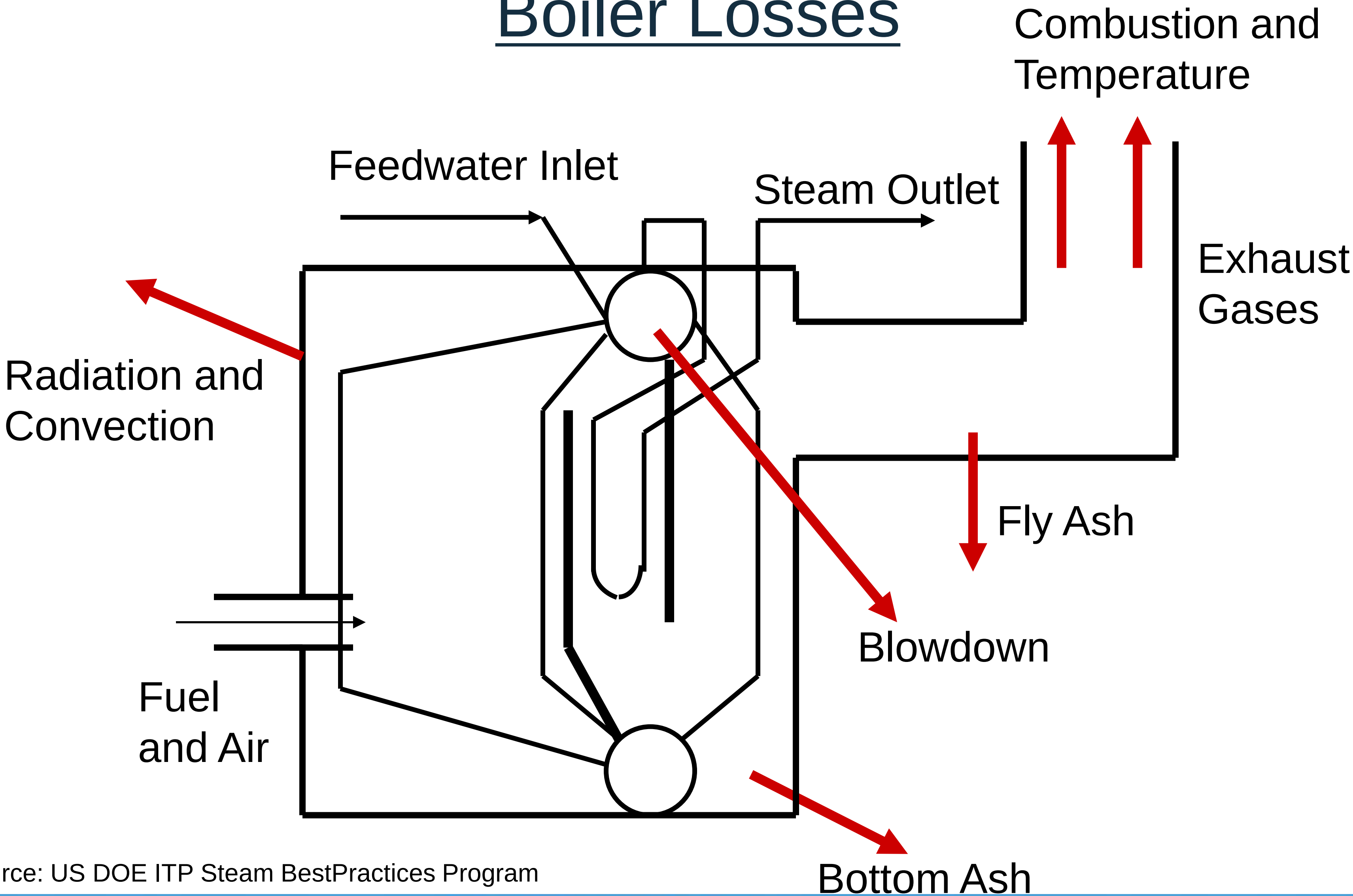
$$\eta_{boiler} = 80.0\%$$

Typical Boiler Efficiency Curve



- Why is the efficiency not 100%?

Boiler Losses



Source: US DOE ITP Steam BestPractices Program

Boiler Losses

- 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

$$\eta_{boiler} = 100 - Losses$$

$$\eta_{boiler} = 100 - \lambda_{shell} - \lambda_{blowdown} - \lambda_{stack} - \underbrace{\lambda_{other}}_{0}$$

Key Points / Action Items

1. *Determine boiler plant operating cost*
2. *Determine unit cost of steam generation*
3. *Determine boiler operating efficiency*

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

4. *There are three major losses in steam generation – shell loss, blowdown loss and stack loss*

$$\boxed{\eta_{boiler} = 100 - \lambda_{shell} - \lambda_{blowdown} - \lambda_{stack} - \cancelto{0}{\lambda_{other}}}$$

Shell Loss Magnitude

- This is a very difficult number to evaluate accurately
- It has to be done with extensive field measurements and heat transfer calculations
- The American Society of Mechanical Engineers (ASME) Power Test Code 4 (PTC-4) identifies a calculation procedure to *estimate* boiler shell loss.
  - ASME PTC-4-2008, Section 5.14.9, pages 91-92.

- Typically, this is NOT a big loss compared to the other losses
- Can be estimated based on load using Best Practices data
- Nevertheless, can be a potential improvement opportunity

First Order Shell Loss Guide

Shell Loss Gross Estimate Field Evaluations				
Boiler Type	Steam Production Rating		Boiler Full-Load Shell Loss Estimate	
	Minimum (Tph)	Maximum (Tph)	Maximum (% fuel input energy)	Minimum (% fuel input energy)
Water-Tube	5	50	2.0	0.3
Water-Tube	50	500	0.6	0.1
Water-Tube	500	5,000	0.2	0.1
Fire-Tube	0.5	20	1.0	0.1

Source: US DOE ITP Steam BestPractices Program

Example Boiler Shell Loss

- From an *ASME type* investigation the radiation and convection loss of the boilers is ~0.5% of the total fuel energy input to the boilers
- Total fuel energy cost ~$7,636,250 per year
- This represents a boiler shell loss of ~$38,200/yr for the Natural gas fired boiler
- Note: Actual monetary loss for each boiler will be different due to different fuel prices and boiler sizes

Shell Losses

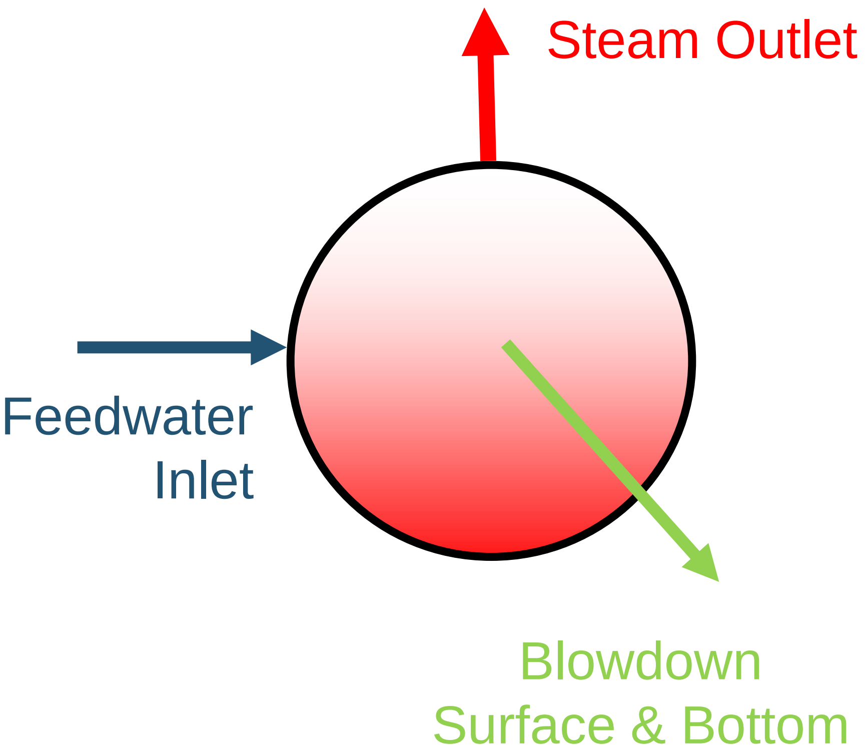
- Full-load radiation and convection losses are typically:
  - Less than 1.0% for water-tube boilers
  - Less than 0.5% for fire-tube boilers

- Shell loss _percentage_ increases as boiler load decreases because _shell loss magnitude is essentially constant_
  - Shell loss of ~0.5% *at full-load* will become ~2.0% *at quarter-load*
  - The primary opportunity in this area is to reduce the number of boilers in operation to reduce the total site shell loss
    - Stack loss impacts must be considered

- Reducing steam demand will NOT result in any change in shell loss….. Unless a boiler is shut down!

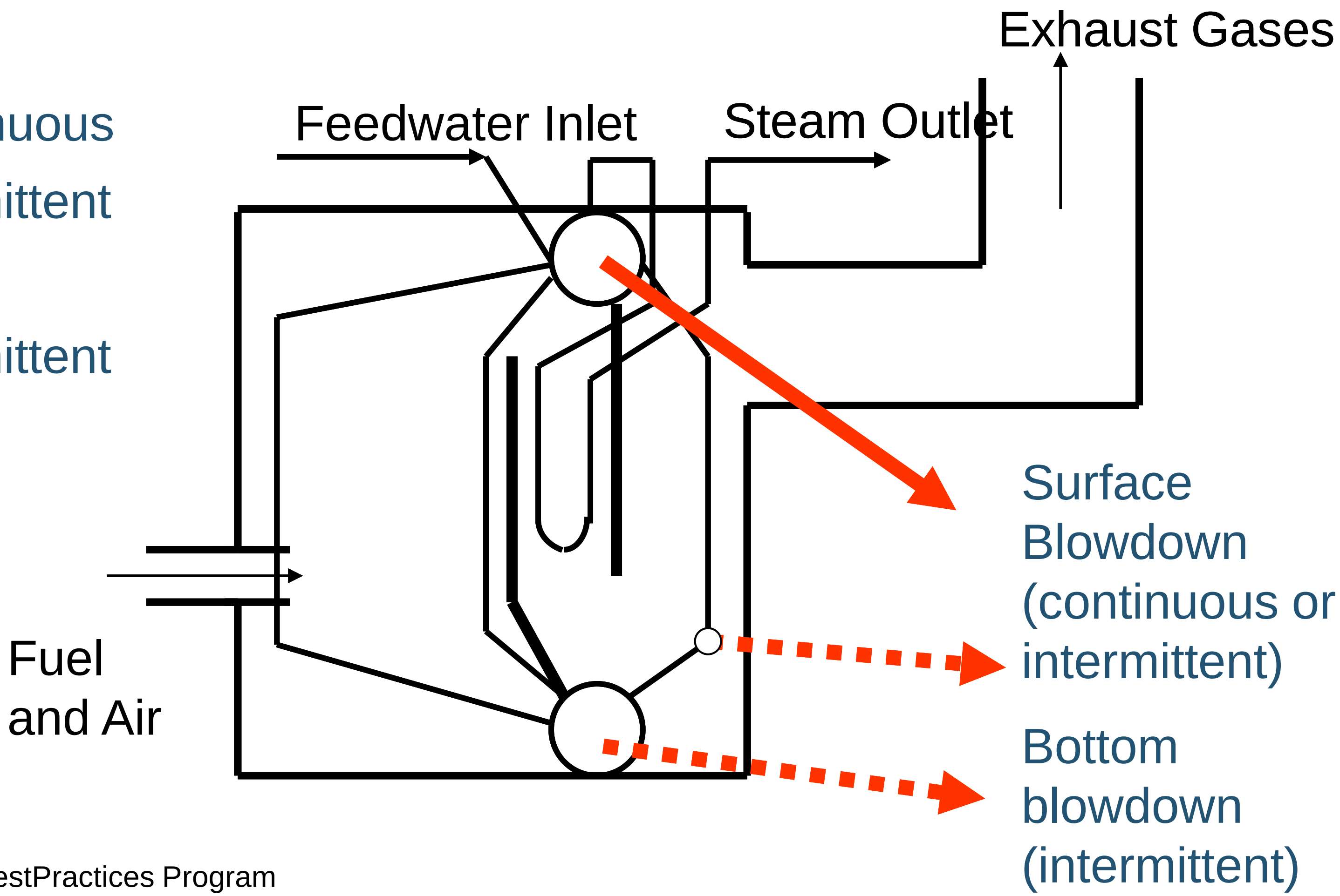
Blowdown Losses

- Boiler water contains dissolved minerals that are insoluble in steam
- These minerals do NOT leave with steam
- The concentration of these chemicals increases in the drum water as time goes on
- Water from the drum is removed from the boiler to maintain proper water chemistry



Blowdown Control

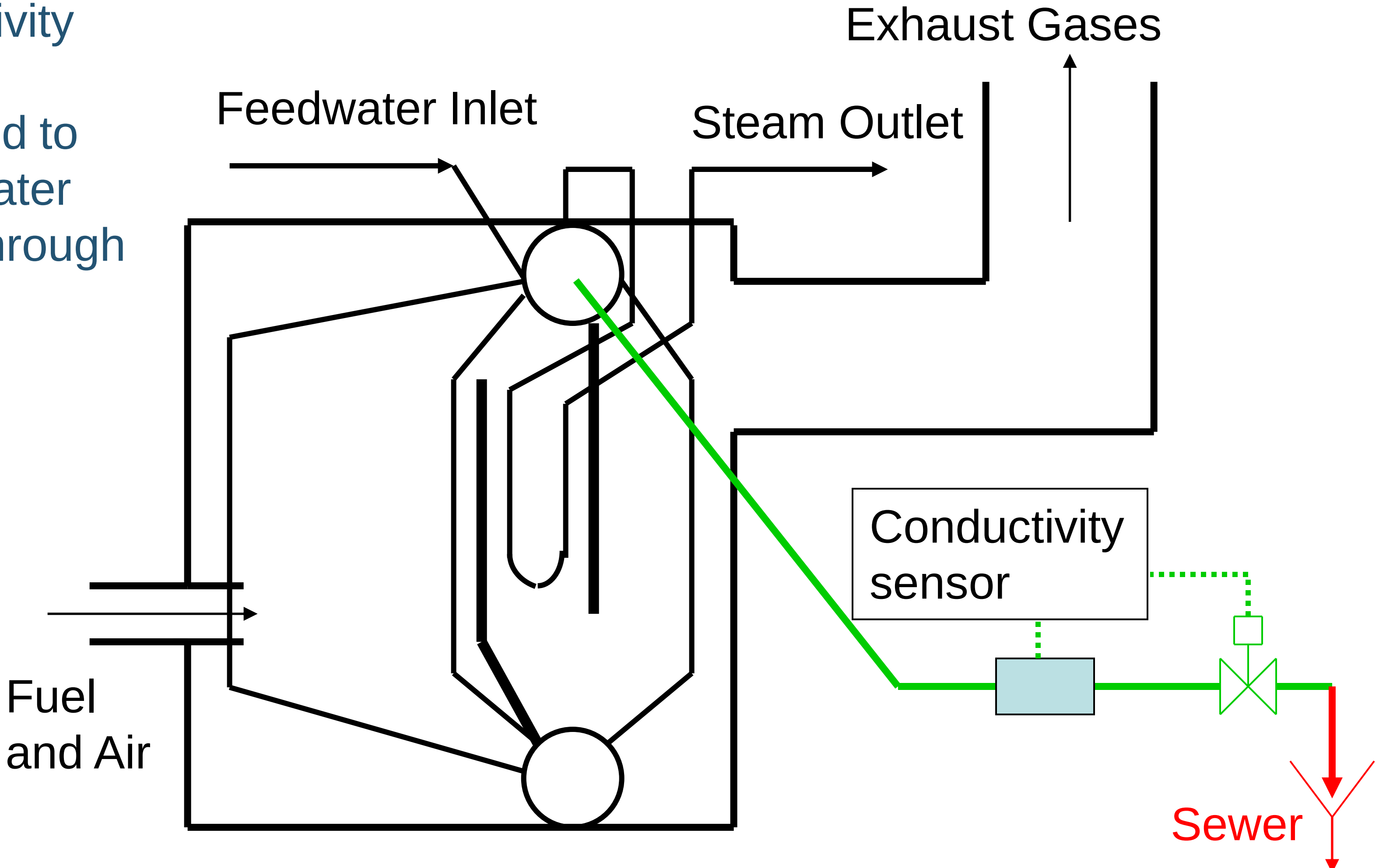
- Boiler blowdown takes several forms
  - Surface
    - Continuous
    - Intermittent
  - Bottom
    - Intermittent



Source: US DOE ITP Steam BestPractices Program

Blowdown Control

- Conductivity must be correlated to actual water quality through specific analysis



Source: US DOE ITP Steam BestPractices Program

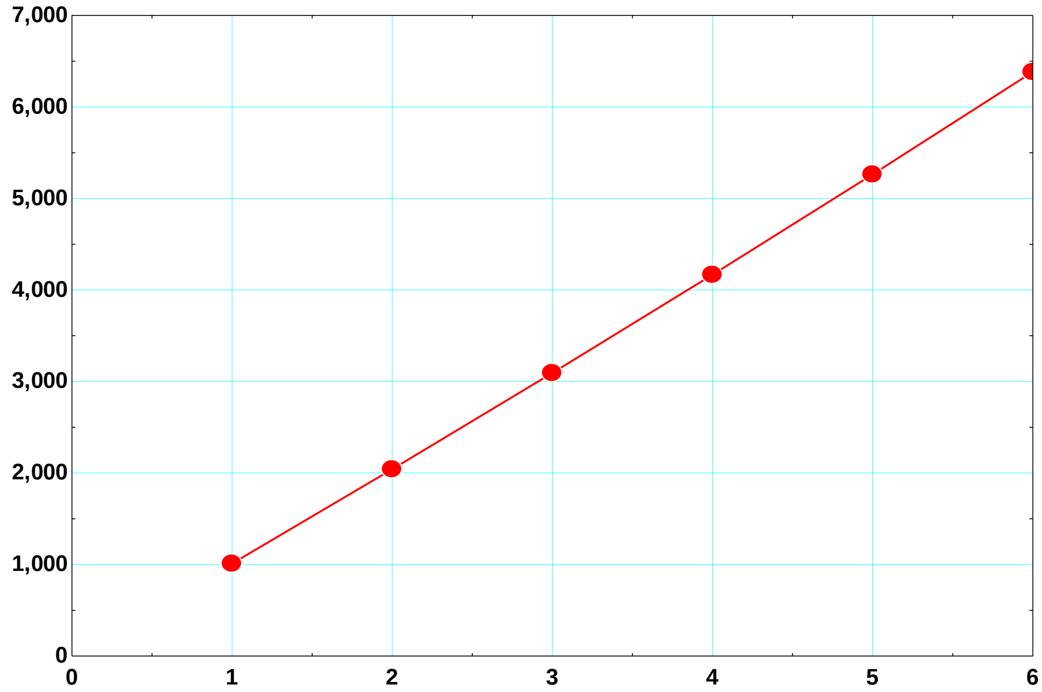
Boiler Blowdown Energy

- Boiler blowdown thermal energy loss typically focuses on continuous surface blowdown
- Blowdown flow is represented as percent of feedwater flow

$$\beta = \frac{Blowdown\ Flow}{Feedwater\ \ Flow} \times 100$$

- Mass balance on the boiler provides blowdown flow

$$m_{blowdown} = \left(\frac{\beta}{1-\beta} \right) m_{steam}$$



Graph for boiler operating at 100 Tph steam flow rate

Blowdown Estimate

- It is very rare to find a flowmeter that measures blowdown
  - Blowdown stream is saturated and flashes
  - Two-phase flow is very difficult to measure
  - Flowmeters are subject to high fouling and two-phase conditions
- Chemical concentrations (such as chlorides and other chemicals) can be measured to determine blowdown rate
- These concentrations can be correlated to conductivity
- Ratio of feedwater conductivity to blowdown conductivity provides a very good estimate of boiler blowdown

Example Natural Gas Boiler / Steam System

- Boiler fired with natural gas which has a higher heating value of 54,220 kJ/kg
  - HHV is 40,144 kJ/m³

- Steam generation: 20 T/h (steady all year round)
- Steam conditions: 25 bars; 375°C
- Boiler feedwater: 30 bars, 110°C
- Fuel supply: 1,693 Nm³/hr (28 Nm³/min)
- Fuel cost: $0.52/Nm³
- Conductivity for blowdown = 2,000 μmhos/cm
- Conductivity for feedwater = 100 μmhos/cm
- Makeup water temperature: 20°C
- **Determine the amount of blowdown and the possible energy loss?**

Blowdown Energy Loss

$$\beta \approx \frac{Feedwater\ Conductivity}{Blowdown\ Conductivity} \times 100$$

$$\beta \approx \frac{100}{2{,}000} \times 100 = 5.0\%$$

$$m_{blowdown} = \left(\frac{\beta}{1-\beta}\right) m_{steam} = \left(\frac{0.05}{1-0.05}\right) 20{,}000 = 1053\ \mathrm{kg/hr} = 0.29\ \mathrm{kg/s}$$

$$Q_{blowdown} = m_{blowdown}\left(h_{blowdown} - h_{feedwater}\right) = 0.29\,(971.8 - 463.5) = 148.4\ \mathrm{kW}$$

Boiler Evaluation

$$Q_{blowdown} = m_{blowdown}\left(h_{blowdown} - h_{makeup}\right) = 0.29(971.8 - 83.9) = 259.6\ \mathrm{kW}$$

System Evaluation

Blowdown Energy Loss

- Boiler Efficiency Evaluation

$$\lambda_{blowdown} = \frac{m_{blowdown}\left(h_{blowdown} - h_{feedwater}\right)}{m_{fuel}\ HHV_{fuel}} \times 100 = \frac{0.29\left(971.8 - 463.5\right)}{1693\left(40{,}144\right)} \times 3{,}600 \times 100 = 0.79\%$$

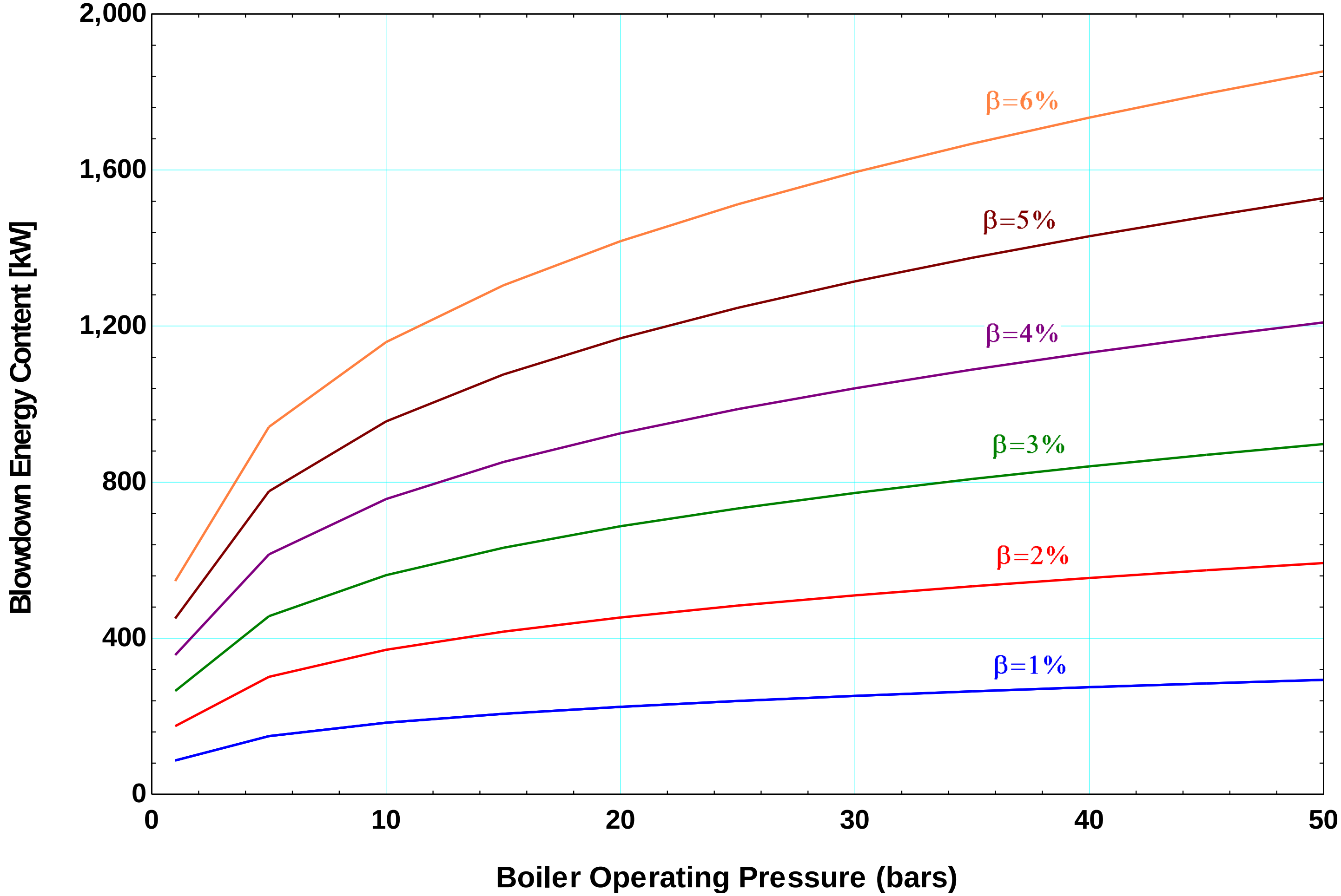
$$Energy\ Cost_{blowdown} = \lambda_{blowdown} \times Operating\ Cost = \frac{0.79}{100} \times 7{,}636{,}250 \approx \$60{,}100$$

- System Efficiency Evaluation

$$\lambda_{blowdown} = \frac{m_{blowdown}\left(h_{blowdown} - h_{makeup}\right)}{m_{fuel}\ HHV_{fuel}} \times 100 = \frac{0.29\left(971.8 - 83.9\right)}{1693\left(40{,}144\right)} \times 3{,}600 \times 100 = 1.38\%$$

$$Energy\ Cost_{blowdown} = \lambda_{blowdown} \times Operating\ Cost = \frac{1.38}{100} \times 7{,}636{,}250 \approx \$104{,}800$$

Boiler Blowdown Energy Loss



Graph for boiler operating at 100 Tph steam flow rate; Make-up Water at 20° C

Total Steam System Blowdown Energy Loss

$$m_{blowdown} = \left(\frac{\beta}{1-\beta} \right) m_{steam} = \left(\frac{0.05}{1-0.0505} \right) 20{,}000 = 1{,}053\ \text{kg/hr} = 0.29\ \text{kg/s}$$

- Will require total fuel energy supplied to all the boilers
  - Can be calculated by doing analysis on each boiler or using average boiler efficiency
  - Example system – 100 GJ/hr

- Will require total fuel cost for all the boilers
  - Can be calculated by doing analysis on each boiler or using average fuel cost
  - Example system – 1280 $/hr

Total Steam System Blowdown Energy Loss

- Boiler Efficiency Evaluation

$$\lambda_{blowdown} = \frac{m_{blowdown}\left(h_{blowdown} - h_{feedwater}\right)}{m_{fuel}\ HHV_{fuel}} \times 100 = \frac{0.44\left(971.8 - 463.5\right)}{100 \times 1000 \times 1000} \times 3{,}600 \times 100 = 0.81\%$$

$$Energy\ Cost_{blowdown} = \lambda_{blowdown} \times Operating\ Cost = \frac{0.81}{100} \times 1283 \times 8{,}760 \approx \$90{,}500$$

- System Efficiency Evaluation

$$\lambda_{blowdown} = \frac{m_{blowdown}\left(h_{blowdown} - h_{makeup}\right)}{m_{fuel}\ HHV_{fuel}} \times 100 = \frac{0.44\left(971.8 - 83.9\right)}{100 \times 1{,}000 \times 1{,}000} \times 3{,}600 \times 100 = 1.41\%$$

$$Energy\ Cost_{blowdown} = \lambda_{blowdown} \times Operating\ Cost = \frac{1.41}{100} \times 1283 \times 8{,}760 \approx \$158{,}000$$

Stack Losses

- *Stack losses* are the largest of the boiler losses

- *Stack losses* are made up of two parts and defined as
  - Temperature losses
  - Combustion losses

- *Combustion analysis* is the method generally used to determine stack losses

Stack Loss Evaluation & Opportunities

- Need a minimum number of measurements
- Can be via in-situ or portable instruments
- These measurements include:
  - Stack exhaust gas temperature
  - Flue gas oxygen content
  - Ambient temperature
  - Fuel composition
  - Flue gas combustibles concentration
- Stack loss tables
- Combustion models (software)

Stack Loss - Natural Gas

Stack loss table is developed for negligible combustibles and no condensation

Stack Loss Table For			Typical Natural Gas											
Flue Gas Oxygen Content Wet Basis (%)	Flue Gas Oxygen Content Dry Basis (%)	Comb Conc (ppm)	Stack Loss (% of fuel Higher Heating Value input) Net Stack Temperature (ΔºC) (Difference between flue gas exhaust and ambient temperature)											
			100	128	156	183	211	239	267	294	322	350	378	406
1.0	1.2	0	13.6	14.7	15.8	16.9	18.0	19.1	20.2	21.3	22.4	23.6	24.7	25.9
2.0	2.4	0	13.8	14.9	16.1	17.2	18.4	19.5	20.7	21.9	23.1	24.2	25.4	26.6
3.0	3.6	0	14.0	15.2	16.4	17.6	18.8	20.0	21.3	22.5	23.7	25.0	26.3	27.5
4.0	4.7	0	14.2	15.5	16.7	18.0	19.3	20.6	21.9	23.2	24.5	25.8	27.2	28.5
5.0	5.8	0	14.5	15.8	17.2	18.5	19.9	21.2	22.6	24.0	25.4	26.8	28.2	29.6
6.0	6.9	0	14.8	16.2	17.6	19.1	20.5	22.0	23.4	24.9	26.4	27.8	29.3	30.8
7.0	8.0	0	15.1	16.6	18.1	19.7	21.2	22.8	24.3	25.9	27.5	29.1	30.7	32.3
8.0	9.1	0	15.5	17.1	18.8	20.4	22.1	23.7	25.4	27.1	28.8	30.5	32.2	33.9
9.0	10.1	0	16.0	17.7	19.5	21.2	23.0	24.8	26.6	28.5	30.3	32.1	34.0	35.8
10.0	11.1	0	16.5	18.4	20.3	22.2	24.2	26.1	28.1	30.1	32.1	34.1	36.1	38.1
Actual Exhaust T (ºC)			121	149	177	204	232	260	288	316	343	371	399	427
Ambien T (ºC)			21	21	21	21	21	21	21	21	21	21	21	21

Steam System Assessment Tool

Stack Loss Calculator

Based on user inputs of Stack Temperature, Ambient Temperature and Stack Oxygen Content, an estimate will be provided of the heat loss from the boiler stack. Losses are expressed as a percentage of the heat fired.

Stack losses are related to SSAT Boiler Efficiency as follows:

SSAT Boiler Efficiency = 100% - Stack Loss (%) - Shell Loss (%)

Shell Loss refers to the radiant heat loss from the boiler. Typically <1% at full load, 1-2% at reduced load.

Input Data

Stack Gas Temperature (°F)	200 °C	Stack Temperature - Ambient Temperature = 180°C
Ambient Temperature (°F)	20 °C	

Stack Gas Oxygen Content (%)	5 %	

Note: Stack gas oxygen content is expressed on a molar or volumetric basis

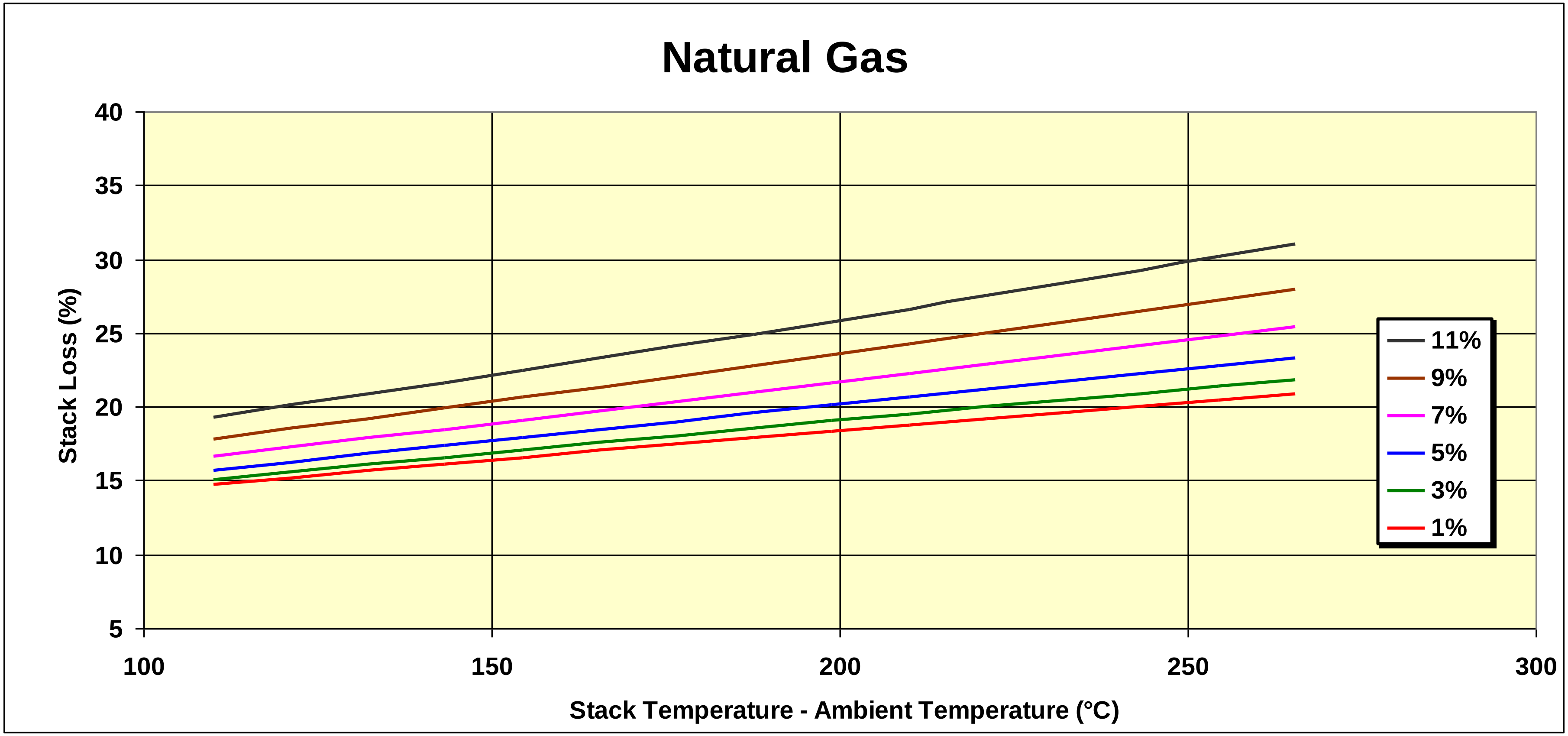
Results

Estimated Stack Losses for each of the default fuels are as follows:

Natural Gas	**18.3 %**
Number 2 Fuel Oil	**14.0 %**
Number 6 Fuel Oil (Low Sulfur)	**13.5 %**
Number 6 Fuel Oil (High Sulfur)	**13.7 %**
Typical Eastern Coal (Bituminous)	**12.0 %**
Typical Western Coal (Subbituminous)	**13.6 %**
Typical Green Wood	**24.7 %**

Reference: Combustion model developed by Greg Harrell, Ph.D., P.E.

Stack Loss Chart



Reference: Combustion model developed by Greg Harrell, Ph.D., P.E.

Example Natural Gas Boiler

- Boiler fired with natural gas which has a higher heating value of 54,220 kJ/kg
  - HHV is 40,144 kJ/m³
- Steam generation: 20 T/h (steady all year round)
- Steam pressure: 25 bars; 375°C
- Boiler feedwater: 30 bars, 110°C
- Fuel supply: 1693 Nm³/hr (28 Nm³/min)
- Fuel cost: $0.52/Nm³
- Stack temperature: 200°C
- Flue gas oxygen: 5%
- Negligible combustibles were found in stack gas analysis
- Ambient air temperature: 20°C
- **Determine the stack loss and identify possible energy saving opportunities?**

Steam System Assessment Tool

Stack Loss Calculator

Based on user inputs of Stack Temperature, Ambient Temperature and Stack Oxygen Content, an estimate will be provided of the heat loss from the boiler stack. Losses are expressed as a percentage of the heat fired.

Stack losses are related to SSAT Boiler Efficiency as follows:

SSAT Boiler Efficiency = 100% - Stack Loss (%) - Shell Loss (%)

Shell Loss refers to the radiant heat loss from the boiler. Typically <1% at full load, 1-2% at reduced load.

Input Data

Stack Gas Temperature (°F)	200 °C	Stack Temperature - Ambient Temperature = 180°C
Ambient Temperature (°F)	20 °C	

Stack Gas Oxygen Content (%)	5 %	

Note: Stack gas oxygen content is expressed on a molar or volumetric basis

Results

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Typical Eastern Coal (Bituminous)	**12.0 %**
Typical Western Coal (Subbituminous)	**13.6 %**
Typical Green Wood	**24.7 %**

λ_{stack}

Example Methane Gas Boiler Efficiency

$$\eta_{boiler} = 100 - Losses$$

$$\eta_{boiler} = 100 - \lambda_{shell} - \lambda_{blowdown} - \lambda_{stack} - \lambda_{other}$$

$$\eta_{boiler} = 100 - 0.5 - 0.79 - 18.3 - 0$$

$$\eta_{boiler} = 80.4\%$$

Example SSAT Boiler Efficiency

$$\eta_{boiler} = 100 - \lambda_{shell} - \lambda_{blowdown} - \lambda_{stack} - \lambda_{other}$$

FIXED (Magnitude)
Does NOT change for IMPACT analysis

SSAT calculates this internally

$$\eta_{SSAT\_boiler} = 100 - \lambda_{stack} - \lambda_{other}$$

$$\eta_{SSAT\_boiler} = 100 - 18.3 - 0$$

$$\eta_{SSAT\_boiler} = 81.7\%$$

Example System Coal Sample

Component	Mole Fraction [kmoli/kmolfuel]	Mass Fraction [kgmi/kgmfuel]	Molecular Weight [kgm/kmol]
C	0.4942	0.4400	12.000
H_2	0.3677	0.0550	2.016
CH_4	0.0000	0.0000	16.043
N_2	0.0144	0.0300	28.013
CO	0.0000	0.0000	28.011
C_2H_4 (Ethylene)	0.0000	0.0000	28.054
C_2H_6 (Ethane)	0.0000	0.0000	30.020
C_3H_8 (Propane)	0.0000	0.0000	44.097
O_2	0.0295	0.0700	31.999
S	0.0021	0.0050	32.060
H_2O (intrinsic)	0.0374	0.0500	18.015
H_2O (extrinsic)	0.0000	0.0000	18.015
CO_2	0.0000	0.0000	44.010
$C_6H_{10}O_5$ (Cellulose)	0.0000	0.0000	162.140
Ash (Total)	0.0546	0.3500	
Ash Components			
Al_2O_3	0.0097	0.0735	101.961
SiO_2	0.0345	0.1540	60.085
Fe_2O_3	0.0103	0.1225	159.692
Total	1.0000	1.0000	
Fuel Molecular Weight	13.4790	kgfuel/kmolfuel	
HHV	9,582 Btu/lbm	22.28 MJ/kgh	5,322 kcal/kg
LHV	9,013 Btu/lbm	20.96 MJ/kgh	5,006 kcal/kg

Stack Loss – Example System Coal

Stack loss table is developed for negligible combustibles and no condensation

Stack Loss Table For			Typical Natural Coal											
Flue Gas Oxygen Content Wet Basis (%)	Flue Gas Oxygen Content Dry Basis (%)	Comb Conc (ppm)	Stack Loss (% of fuel Higher Heating Value input)											
			Net Stack Temperature (∆ºC) (Difference between flue gas exhaust and ambient temperature)											
			100	128	156	183	211	239	267	294	322	350	378	406
1.0	1.1	0	9.7	10.8	11.8	12.9	14.0	15.1	16.2	17.4	18.5	19.6	20.8	21.9
2.0	2.2	0	9.9	11.0	12.1	13.3	14.4	15.6	16.7	17.9	19.1	20.3	21.4	22.6
3.0	3.4	0	10.1	11.2	12.4	13.6	14.8	16.0	17.3	18.5	19.7	21.0	22.2	23.5
4.0	4.4	0	10.3	11.5	12.8	14.0	15.3	16.6	17.9	19.2	20.5	21.8	23.1	24.4
5.0	5.5	0	10.5	11.8	13.2	14.5	15.8	17.2	18.5	19.9	21.3	22.7	24.0	25.4
6.0	6.6	0	10.8	12.2	13.6	15.0	16.4	17.9	19.3	20.7	22.2	23.7	25.1	26.6
7.0	1.6	0	11.1	12.6	14.1	15.6	17.1	18.6	20.2	21.7	23.3	24.8	26.4	28.0
8.0	8.6	0	11.5	13.1	14.7	16.3	17.9	19.5	21.2	22.8	24.5	26.2	27.8	29.5
9.0	9.7	0	11.9	13.6	15.3	17.1	18.8	20.6	22.4	24.1	25.9	27.7	29.5	31.3
10.0	10.7	0	12.4	14.3	16.1	18.0	19.9	21.8	23.7	25.7	27.6	29.6	31.5	33.5
Actual Exhaust T (ºC)			121	149	177	204	232	260	288	316	343	371	399	427
Ambien T (ºC)			21	21	21	21	21	21	21	21	21	21	21	21

Unburned Fuel Loss

- Fuels containing ash commonly present an energy loss in the form of unburned fuel in the ash
  - The unburned fuel component is typically carbon
    - The other fuel components are generally more reactive than carbon
      - Also carbon is usually the dominant fuel component

Loss On Ignition (LOI) Analysis

1. Measure the mass of the raw collected sample (ash and carbon)

2. Expose the collected sample to a combustion source for an extended period to ensure all combustible material has reacted

3. Measure the mass of the remaining sample, which is ash alone.

$$\boxed{LOI = \frac{m_{Carbon}}{m_{Carbon} + m_{Ash\,alone}} = \frac{m_C}{m_C + m_A} = \frac{m_C}{m_{Full\ Sample}}}$$

$$\boxed{m_C = \frac{LOI\,(m_A)}{(1 - LOI)}}$$

Loss On Ignition (LOI) Analysis

$$\boxed{m_C = \frac{LOI\,(m_A)}{(1 - LOI)}}$$

$$\boxed{\frac{m_C}{m_{Fuel}} = \phi_{uf} = \frac{LOI\left(\dfrac{m_A}{m_{Fuel}}\right)}{(1 - LOI)}}$$

$$\lambda_{uf} = \phi_{uf}\,\frac{HHV_c}{HHV_{fuel}}$$

$$\lambda_{uf} = \phi_{uf}\,\frac{32{,}806\,\frac{kJ}{kg}}{HHV_{fuel}}$$

SSAT 1-Header Model Student Exercise

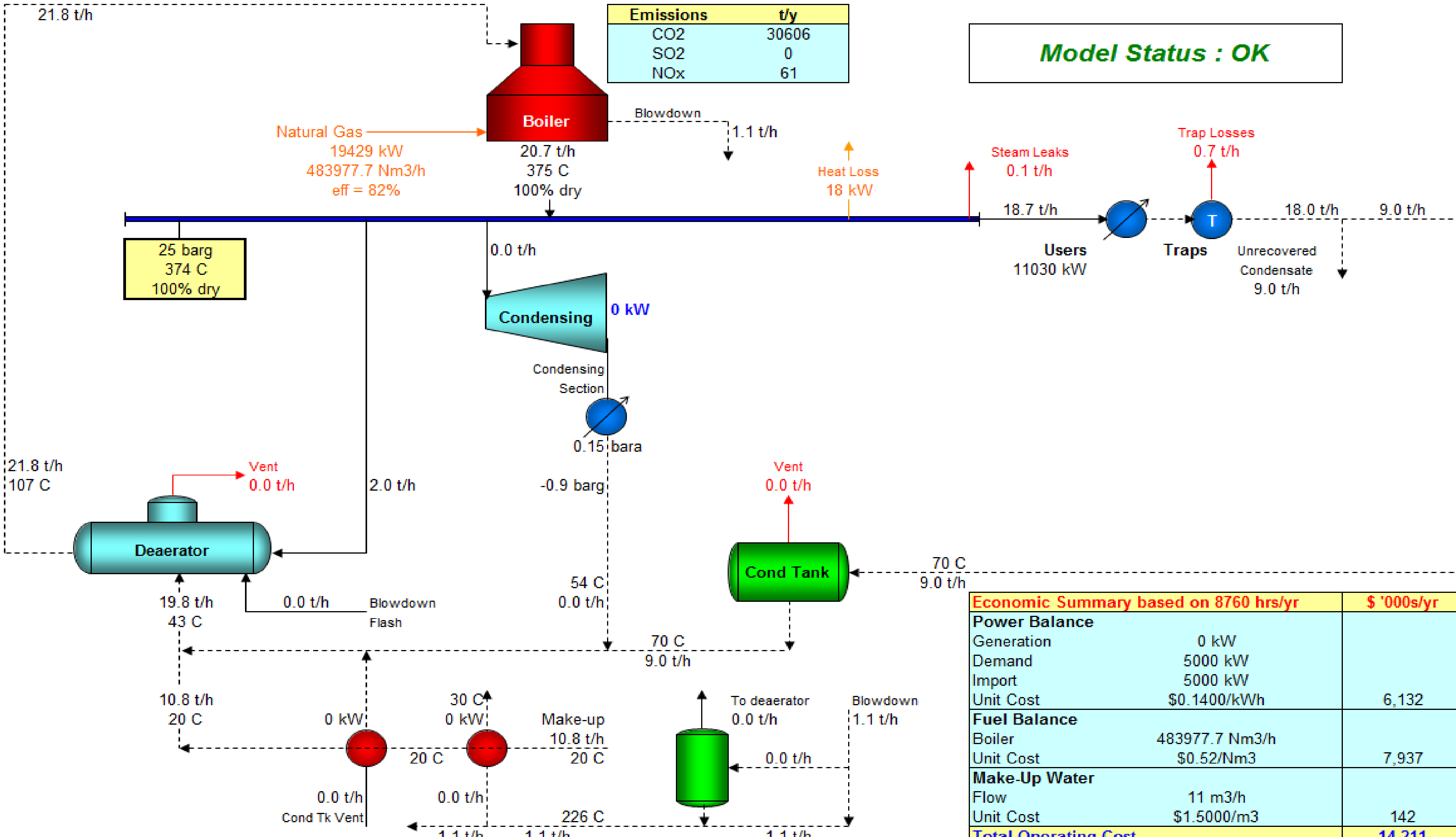
- Open the “SSAT 1-Header v3 Metric” template
- Using the example system with the Natural gas boiler as the impact boiler, build a model to accurately reflect steam impact (marginal) costs and economic benefits of saving 1 Tph of steam
- Steam generated ~20 Tph from the Natural gas boiler
- Steam conditions: 25 bars, 375°C
- Make up water: 20°C

Steam System Assessment Tool
Current Operation

SSAT Default 1 Header Metric Model Moldova Ex 1

Emissions	t/y
CO_2	30606
SO_2	0
NO_x	61

Model Status : OK



Economic Summary based on 8760 hrs/yr		$ '000s/yr
Power Balance		
Generation	0 kW	
Demand	5000 kW	
Import	5000 kW	
Unit Cost	$0.1400/kWh	6,132
Fuel Balance		
Boiler	483977.7 Nm3/h	
Unit Cost	$0.52/Nm3	7,937
Make-Up Water		
Flow	11 m3/h	
Unit Cost	$1.5000/m3	142
Total Operating Cost		14,211

Summary Results

SSAT Default 1 Header Metric Model Moldova Ex 1

Model Status : OK

Cost Summary ($ '000s/yr)	Current Operation	After Projects	Reduction	
Power Cost	6,132	6,132	0	0.0%
Fuel Cost	7,937	7,937	0	0.0%
Make-Up Water Cost	142	142	0	0.0%
Total Cost (in $ '000s/yr)	**14,211**	**14,211**	**0**	**0.0%**

On-Site Emissions	Current Operation	After Projects	Reduction	
CO2 Emissions	30606 t/yr	30606 t/yr	0 t/yr	0.0%
SOx Emissions	0 t/yr	0 t/yr	0 t/yr	N/A
NOx Emissions	61 t/yr	61 t/yr	0 t/yr	0.0%

Power Station Emissions	Reduction After Projects	Total Reduction	
CO2 Emissions	0 t/yr	0 t/yr	-
SOx Emissions	0 t/yr	0 t/yr	-
NOx Emissions	0 t/yr	0 t/yr	-

Note - Calculates the impact of the change in site power import on emissions from an external power station. Total reduction values are for site + power station

Utility Balance	Current Operation	After Projects	Reduction	
Power Generation	0 kW	0 kW	-	-
Power Import	5000 kW	5000 kW	0 kW	0.0%
Total Site Electrical Demand	5000 kW	5000 kW	-	-
Boiler Duty	19429 kW	19429 kW	0 kW	0.0%
Fuel Type	Natural Gas	Natural Gas	-	-
Fuel Consumption	483977.7 Nm3/h	483977.7 Nm3/h	0 Nm3/h	0.0%
Boiler Steam Flow	20.7 t/h	20.7 t/h	0.0 t/h	0.0%
Fuel Cost (in $/MWh)	46.63	46.63	-	-
Power Cost (as $/MWh)	140.00	140.00	-	-
Make-Up Water Flow	11 m3/h	11 m3/h	0 m3/h	0.0%

Turbine Performance	Current Operation	After Projects	Marginal Steam Cost
HP to Condensing steam rate	Not in use	Not in use	(based on current operation)

Marginal Steam Cost

- It is the impact cost (savings) of producing (reducing) 1 Tph of additional steam

Marginal Steam Cost	
(based on current operation)	
$/t	49.10

- Comparing it to Steam Cost Indicator

$$\kappa_{steam} = \frac{Boiler\ Operating\ Cost}{Steam\ Generation}$$

$$\kappa_{steam} = \frac{973}{20} = 48.6\ \frac{\$}{tonne}$$

SSAT Project 1Exercise

Project 1 - Steam Demand Savings (Changing the process steam requirements)
Current steam use : 18 t/h Calculated heat duty : 10588 kW

Do you wish to specify a steam demand saving?	Yes
If yes, enter steam saving	1 t/h

Note: A negative saving can be entered to model an increase in steam demand

Note: This specified steam saving has been converted to a heat duty of 588 kW based on header enthalpy for current operation

Note: This heat duty is then used to determine the actual flow change in the Projects Model based on the calculated header enthalpy

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Cost Summary ($ '000s/yr)	Current Operation	After Projects	Reduction	
Power Cost	6,132	6,132	0	0.0%
Fuel Cost	7,937	7,514	423	5.3%
Make-Up Water Cost	142	135	7	5.2%
Total Cost (in $ '000s/yr)	**14,211**	**13,781**	430	3.0%

On-Site Emissions	Current Operation	After Projects	Reduction	
CO2 Emissions	30606 t/yr	28975 t/yr	1630 t/yr	5.3%
SOx Emissions	0 t/yr	0 t/yr	0 t/yr	N/A
NOx Emissions	61 t/yr	57 t/yr	3 t/yr	5.3%

SSAT Project 1Exercise

SSAT Default 1 Header Metric Model Moldova Ex 1

Model Status : OK

Cost Summary ($ '000s/yr)	Current Operation	After Projects	Reduction	
Power Cost	6,132	6,132	0	0.0%
Fuel Cost	7,937	7,514	423	5.3%
Make-Up Water Cost	142	135	7	5.2%
Total Cost (in $ '000s/yr)	**14,211**	**13,781**	**430**	**3.0%**

On-Site Emissions	Current Operation	After Projects	Reduction	
CO2 Emissions	30606 t/yr	28975 t/yr	1630 t/yr	5.3%
SOx Emissions	0 t/yr	0 t/yr	0 t/yr	N/A
NOx Emissions	61 t/yr	57 t/yr	3 t/yr	5.3%

$$\kappa_{steam} = \frac{Boiler\ Operating\ CostSavings}{Steam\ Savings}$$

$$\kappa_{steam} = \frac{430{,}000}{1.0 \times 8{,}760} = 49.1 \frac{\$}{tonne}$$