# Backpressure Steam Power Generation in District Energy and CHP - Energy Efficiency Considerations

A 1st Law, 2nd Law and Economic Analysis of the Practical Steam Engine in a District Energy/CHP Application

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Practical Steam

# Energy Efficiency Engineering – How is efficiency calculated?

- What is the Status Quo?
  - Engineers currently focus on limiting energy losses as the primary point of focus for district energy and CHP systems
  - Only local energy losses are typically considered causing energy efficiency opportunities to be wasted
- Why?
  - Conventional wisdom tells us that minimizing local energy losses is ultimate goal
- How should we change?
  - Could a different approach improve global efficiency?

# Motivation

Common Questions:

1. How can installing an imperfect device in parallel to an isenthalpic pressure reducing valve (PRV) improve efficiency?
2. My analysis shows an incremental fuel cost with PRV parallel, how can this be more efficient?

# Analysis Overview

- Consider a Practical Steam Engine (PSE) in a Pressure Reducing Valve (PRV) parallel district energy application
- PSE operation is consistent with CHP application
- Consider 1st Law, 2nd Law and economic analysis for energy efficiency
- Draw conclusions

# Backpressure Application – Case Study

## Enwave Seattle - District Energy / CHP Application

### Assumptions

- 1.5 MW (5.118 MMBtu/hr) heating load is considered
- Condensate exiting load: Saturate liquid at 20 psig
- No heat losses in piping or equipment*

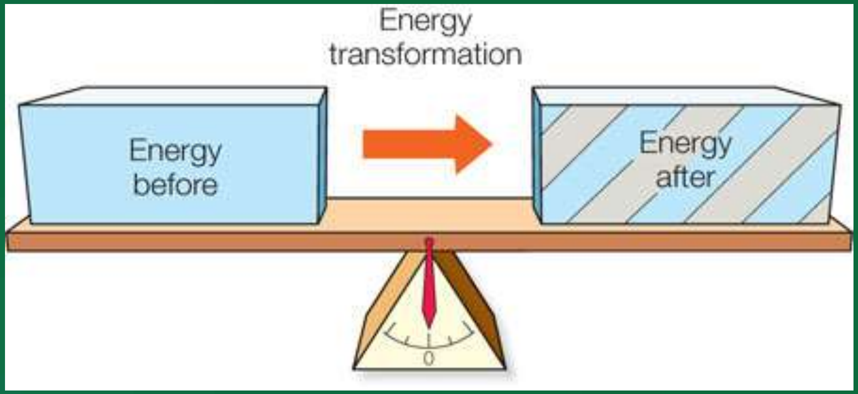
### Equipment

- Practical Steam Engine (PSE)
  - Isentropic efficiency of 80%
  - Mechanical efficiency of 80%
  - Generator efficiency of 95%
- Isenthalpic PRV
- 150 psig saturated steam boiler
- 80% boiler and feedwater pump efficiency

*Incorporating actual heat losses does not significantly affect results of analysis.

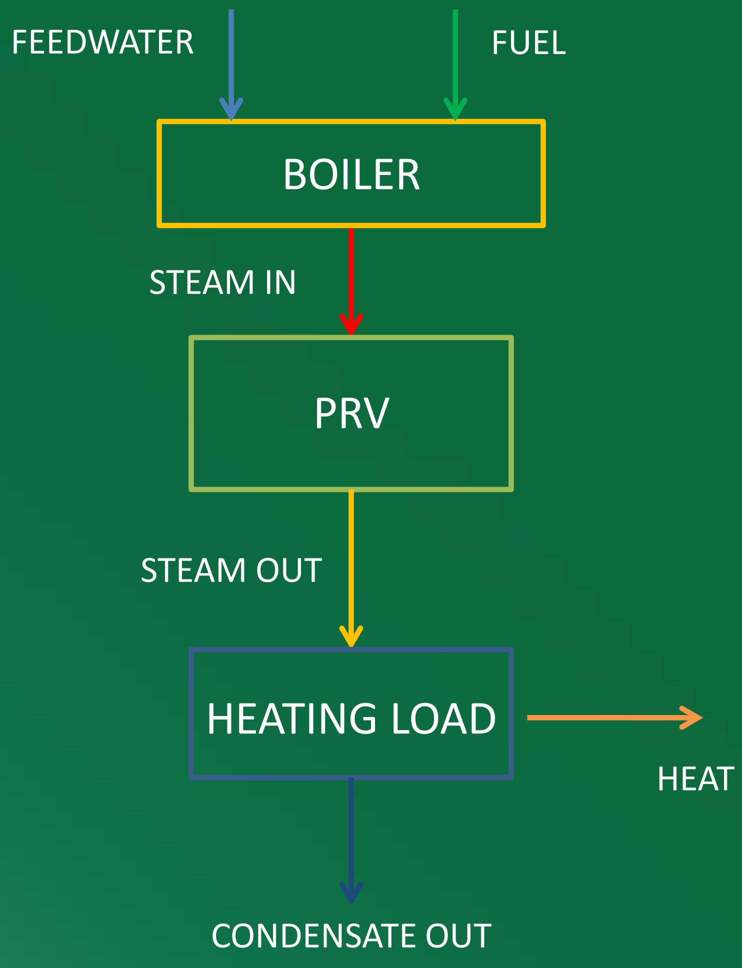
# 1st Law of Thermodynamics

- 1st law of thermodynamics is simply a conservation of energy
- All energy is conserved – no energy is destroyed.
- Steady State:
  - Sum of all energy into system = sum of energy out of system
- Considers only the quantity of energy, not the quality

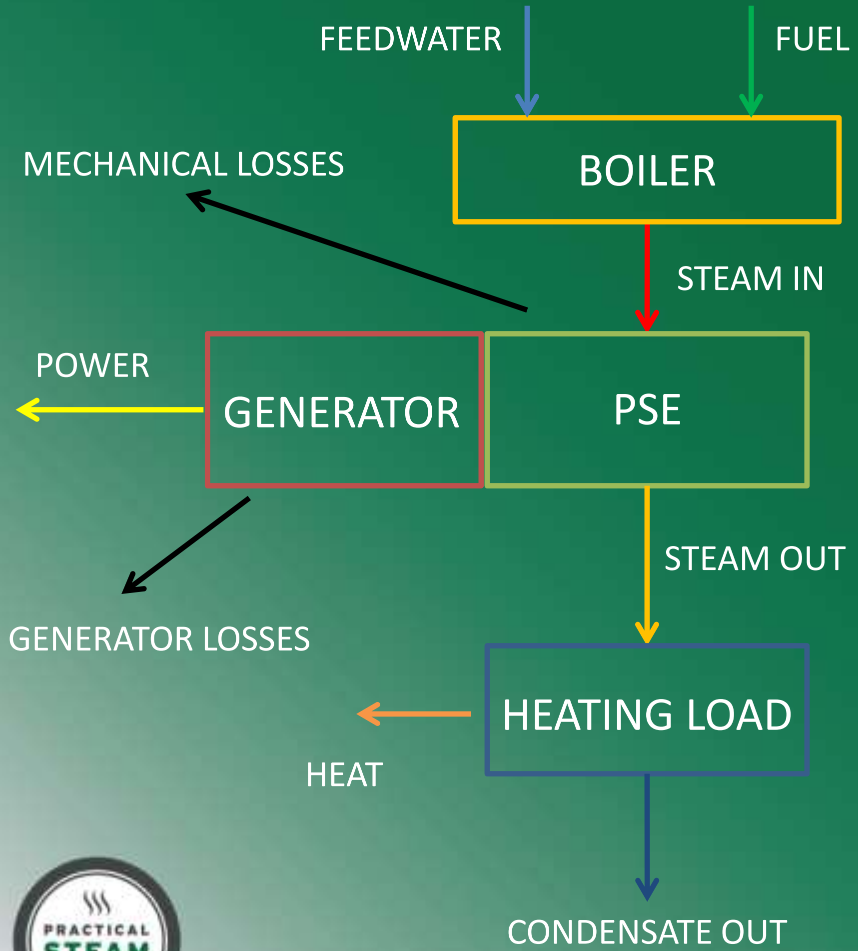


# $1^{st}$ Law Analysis – PRV Status Quo

- Heating Only
- $h_{out} = h_{in} = 1{,}196 \left[\frac{Btu}{lbm}\right]$
  - *Superheated Steam (57°F Superheat)*
- $\dot{m} = \frac{Q_{Out}}{h_{out} - h_{condensate}} = 5{,}285 \left[\frac{lbs}{hr}\right]$
- $E_{in} = Q_{in} + W_{in} = 6.398 \left[\frac{MMBtu}{hr}\right]$
- $E_{Out} = Q_{out} = 5.118 \left[\frac{MMBtu}{hr}\right]$
- $1^{st}\ Law\ Efficiency_{PRV} = \frac{E_{out}}{E_{in}} = 80\%$



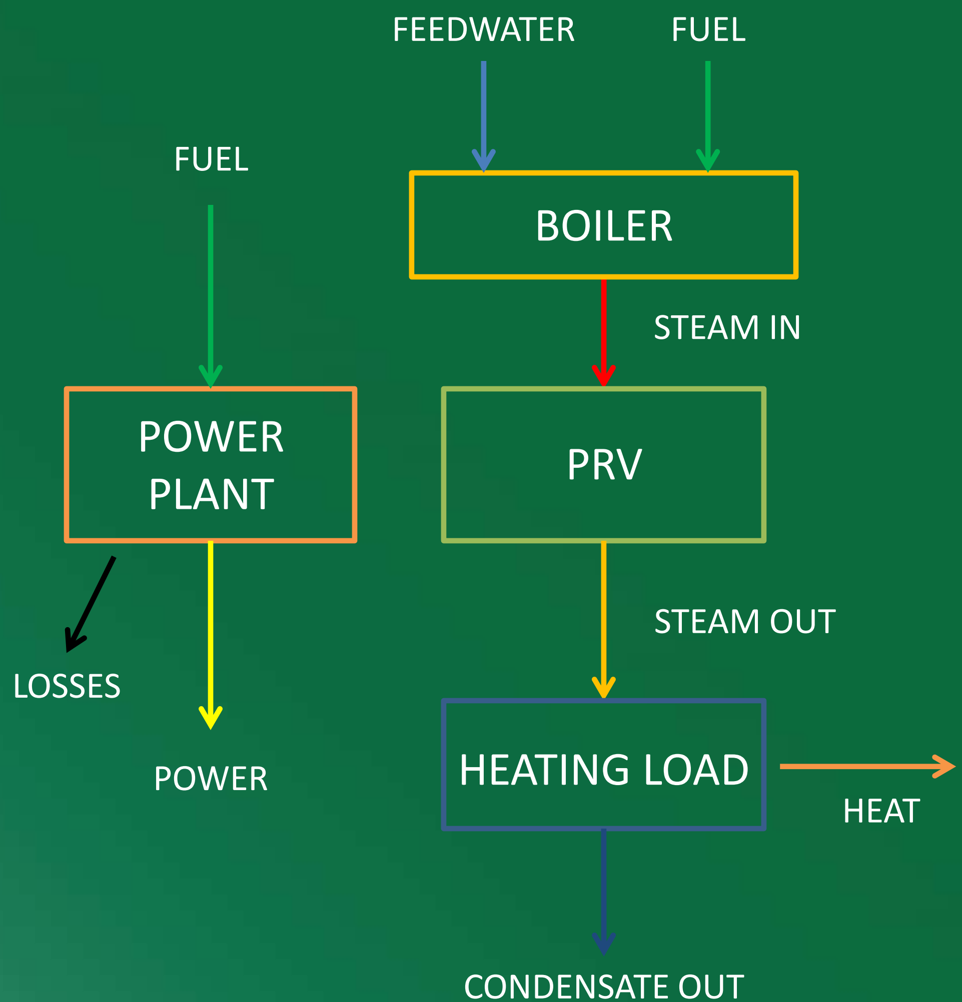
# 1st Law Analysis – PSE




- Combined Heat and Power
- $h_{out} = h_{in} - (h_{in} - h_{2_s})\eta_{isentropic} = 1{,}101 \left[\frac{Btu}{lbm}\right]$
  - *Saturated Vapor (92.9% Quality)*
- $\dot{m} = \frac{Q_{Out}}{h_{out} - h_{condensate}} = 5{,}862 \left[\frac{lbs}{hr}\right]$
- $E_{in} = Q_{in} + W_{in} = 7.096 \left[\frac{MMBtu}{hr}\right]$
- $\dot{W} = (h_{in} - h_{out})\eta_{mech}\eta_{generator} = 124.5\ [kW_e]$
- $E_{OUT} = Q_{OUT} + W_{OUT} = 5.543 \left[\frac{MMBtu}{hr}\right]$
- $1st\ Law\ Efficiency_{PSE} = \frac{E_{Out}}{E_{in}} = 78.1\%$

# 1st Law Analysis – PRV Broad Perspective

- Separate Heat and Power
- Consider Power Plant Thermal Efficiency = 40%*
- $Additional\ Fuel\ Input = \frac{P}{\eta_{Power\ Plant}} = 0.425\left[\frac{MMBtu}{hr}\right]$
- $E_{in} = Q_{in} + W_{in} = 7.672\left[\frac{MMBtu}{hr}\right]$
- $E_{Out} = Q_{out} + W_{Out} = 5.543\left[\frac{MMBtu}{hr}\right]$
- $1st\ Law\ Efficiency_{PSE} = \frac{E_{Out}}{E_{in}} = 72.2\%$




*33% US Average for steam generator power plants in 2013 (U.S. EIA)

# 1st Law Analysis - Comparison

## PRV**

### LOCAL PERSPECTIVE

- $1st\ Law\ Efficiency_{PRV} = 80\%$
- Heating Only

### BROAD PERSPECTIVE

- $Purchased\ Power = 124.5\ [kW_e]$
- $1st\ Law\ Efficiency_{PRV} = 72.2\%$
- Separate Heat and Power

## PSE**

- $Incremental\ Heat\ Addition = 0.619\ \left[\frac{MMBtu}{hr}\right]$
- $Power\ Output = 124.5\ [kW_e]$
- 68.6% Thermal Efficiency Power Production*
- $1st\ Law\ Efficiency_{PSE} = 78.1\%$
- Combined Heat and Power

*33% US Average for steam generator power plants in 2013 (U.S. EIA)

**PRV supplies 57° Superheated steam to heating load, PSE supplies 92.9% quality saturated steam to heating load.

# Economic Analysis

## Assumptions

- Fuel Cost: $5/MMBtu*
- Electricity Cost: $0.075/kWh*
- Annual Operation = 8500 hrs
- PSE Maintenance costs = $4,000/yr

## Results

- PRV
  - Fuel Costs  = $241K/yr
- PSE
  - Fuel Costs = $267K/yr
  - Incremental Fuel Costs = $26K/yr
  - Power = $80K/yr
  - Net Savings = $50K/yr**
  - Produces power at $0.025/kWh

*Based on Seattle industrial rates
**Including maintenance costs

# 2nd Law of Thermodynamics

- 2nd law of thermodynamics considers the quality of the energy, reversibility of processes and the ability of the energy to do work – EXERGY
- Exergy sometimes referred to as the "available energy" or "availability"
- Exergy is a measure of the maximum useful work possible during a process that brings the system to equilibrium with a heat reservoir
- Sum of exergy out of system ≤ sum of exergy into system
- Energy never destroyed (1st Law), exergy can be destroyed (2nd Law)

# $2^{nd}$ Law Analysis – Practical Example

- Consider heat dissipating from a boiler in which all heat energy could be retained in the surroundings and recovered.
  - $1^{st}$ law would consider this 100% efficient.
  - Recovered energy is at a lower temperature and therefore a lower quality, or exergy.
  - Not possible to take this energy and put it back into the boiler without some additional work or heat input.
  - Heat cannot be used to produce much useful work.
  - Some exergy, the ability to do work, was lost while all energy was retained. $1^{st}$ law efficiency = 100%; $2^{nd}$ law efficiency < 100%

# $2^{nd}$ Law Analysis – Fluid Flow Exergy

- Fluid Flow exergy is defined as a function of enthalpy and entropy in reference to dead state as follows (KE and PE neglected):
- $\psi = (h - h_0) - T_0(s - s_0)$
- $h_0 = dead\ state\ enthalpy$
- $T_0 = dead\ state\ temperature$
- $s_0 = dead\ state\ entropy$
- The dead state is the state that is in thermodynamic equilibrium with its surroundings.
    - Assumed in our study to be 70°F and 1 atm

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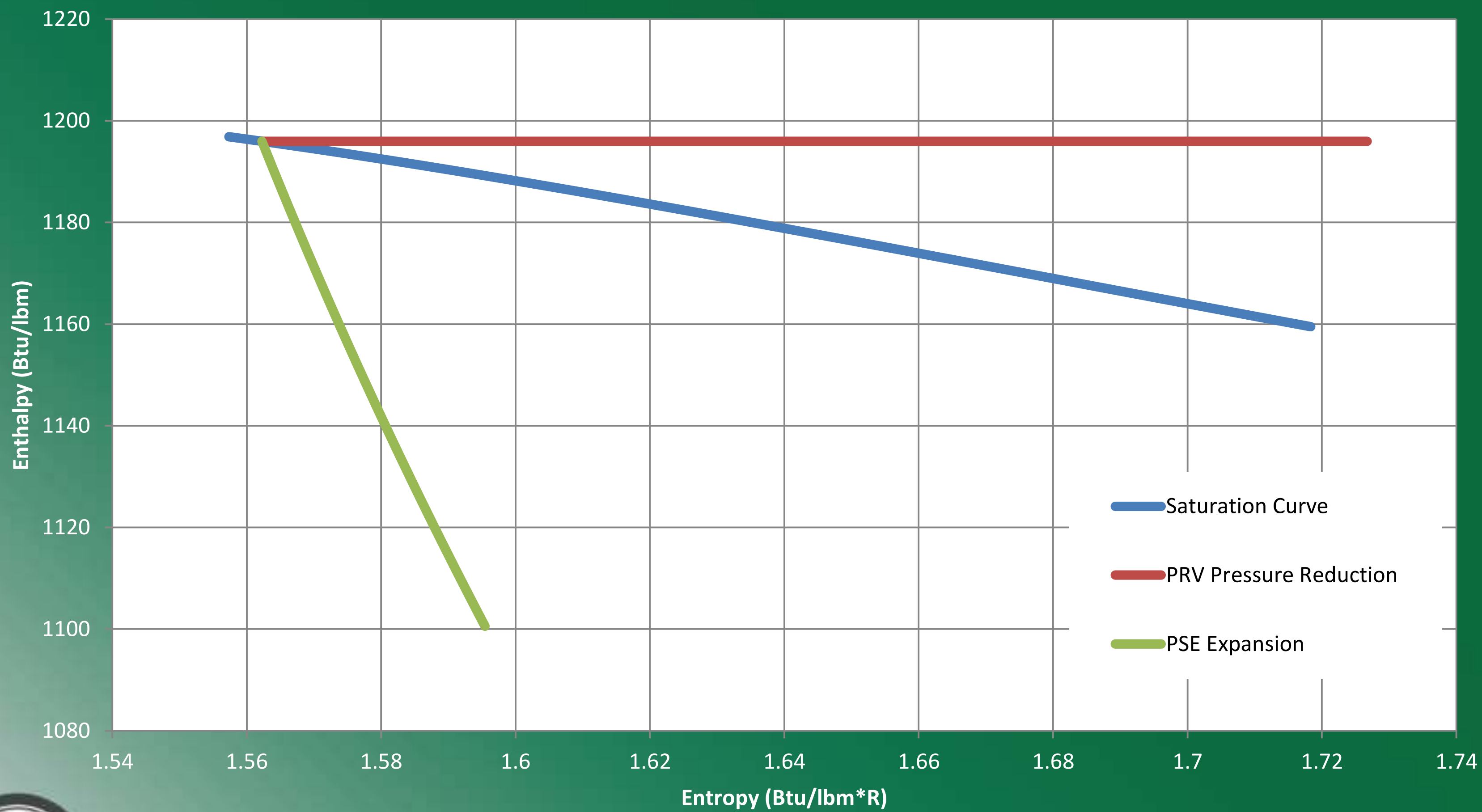
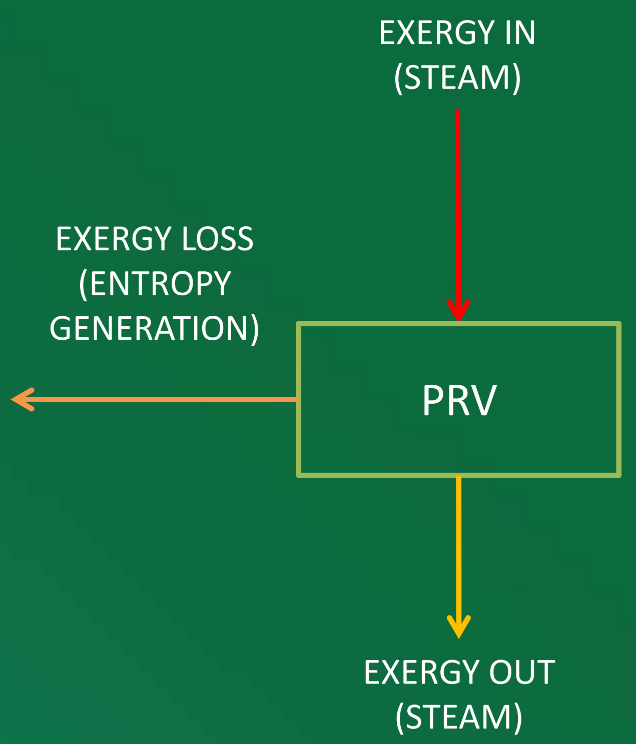
# Mollier Diagram – PSE vs PRV



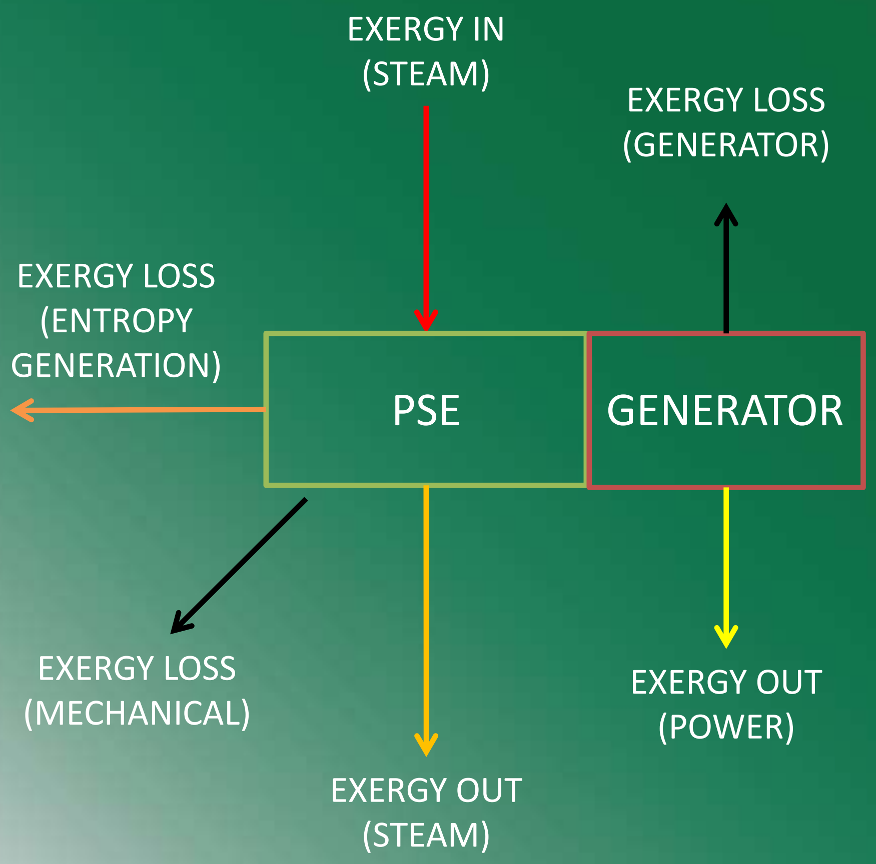

$$\psi = (h - h_0) - T_0(s - s_0)$$

# 2nd Law Analysis – PRV
# Local Perspective

- $X_{in} = \psi_{in} * \dot{m} = 1.952 \left[\frac{MMBtu}{hr}\right]$
- $X_{out} = \psi_{out} * \dot{m} = 1.491 \left[\frac{MMBtu}{hr}\right]$
- $Exergy\ Destruction = X_{in} - X_{out} = 0.461 \left[\frac{MMBtu}{hr}\right] = 23.6\%$
- $2nd\ Law\ Efficiency = \frac{X_{out}}{X_{in}} = 76.4\%$



# 2nd Law Analysis – PSE
# Local Perspective




- $X_{in} = \psi_{in} * \dot{m} = 2.165 \left[\frac{MMBtu}{hr}\right]$
- $X_{out} = \psi_{out} * \dot{m} + \dot{W} = 1.928 \left[\frac{Btu}{lbm}\right]$
- $Exergy\ Destruction = X_{in} - X_{out} = 0.237 \left[\frac{Btu}{lbm}\right] = 10.9\%$
- $2nd\ Law\ Efficiency = \frac{X_{out}}{X_{in}} = 89.1\%$

# 2nd Law Analysis - Comparison

**PRV**

- $X_{in} = 1.952 \left[\frac{MMBtu}{hr}\right]$
- $\psi_{out} = 282.2 \left[\frac{Btu}{lbm}\right]$
- $X_{out} = 1.491 \left[\frac{MMBtu}{hr}\right]$
- $Exergy\ Destruction = 23.6\%$
- $2nd\ Law\ Efficiency_{PRV} = 76.4\%$
- Did not consider exergy destruction at power plant

**PSE**

- $X_{in} = 2.165 \left[\frac{MMBtu}{hr}\right]$
- $\psi_{out} = 256.4 \left[\frac{Btu}{lbm}\right]$
- $\frac{\dot{W}}{\dot{m}} = 73.0 \left[\frac{Btu}{lbm}\right]$
- $X_{out} = 1.928 \left[\frac{Btu}{lbm}\right]$
- $Exergy\ Destruction = 10.9\%$
- $2nd\ Law\ Efficiency_{PSE} = 89.1\%$

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# Summary – PSE vs PRV District Energy and CHP

- 1st law efficiency
  - Thermal efficiency for PSE is less than for local perspective PRV but better than broad perspective PRV.
  - PSE produced power at > 68% thermal efficiency
- System economics
  - PSE power generation more than makes up for incremental fuel costs
  - PSE produced power at rate around $0.025/kWh, 1/3 of local purchased rate
- 2nd law efficiency
  - With PSE more “useful” energy was conserved
  - More broad perspective would prove increased efficiency differential between PRV and PSE

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# Conclusions

- A local 1st law analysis can hide energy efficiency improvement and cost saving opportunities
- Broad 1st law analysis can be more informative and consistent with economics
- A reduced local 1st law efficiency can coincide with improved economics, improved broad perspective 1st law analysis and an improved 2nd law efficiency
- Broad 1st law analysis, as well as economic and 2nd law analyses, should be used when considering system energy efficiency
- Use of the Practical Steam Engine in district energy and CHP applications can improve global energy efficiency as well as improve system economics

# New Status Quo

- Change the status quo
    1. Educate our engineers to not rely on the potentially misleading information determined by local 1st law analyses
    2. Encourage broad 1st law analyses as well as 2nd law and economic analyses
    3. Capitalize on energy efficiency opportunities previously hidden by local 1st law analyses such as PRV parallel/CHP

# Questions?

Thank you for your interest!

Want to learn more?
Come see us at booth #22

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