OPTIMAL INTEGRATION OF STEAM TURBINES IN INDUSTRIAL PROCESS PLANTS

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Outline

- Definitions: CHP and Efficiency
- Thermodynamics Review
- Energy integration theory
- CHP models

DEFINITIONS: CHP & EFFICIENCY

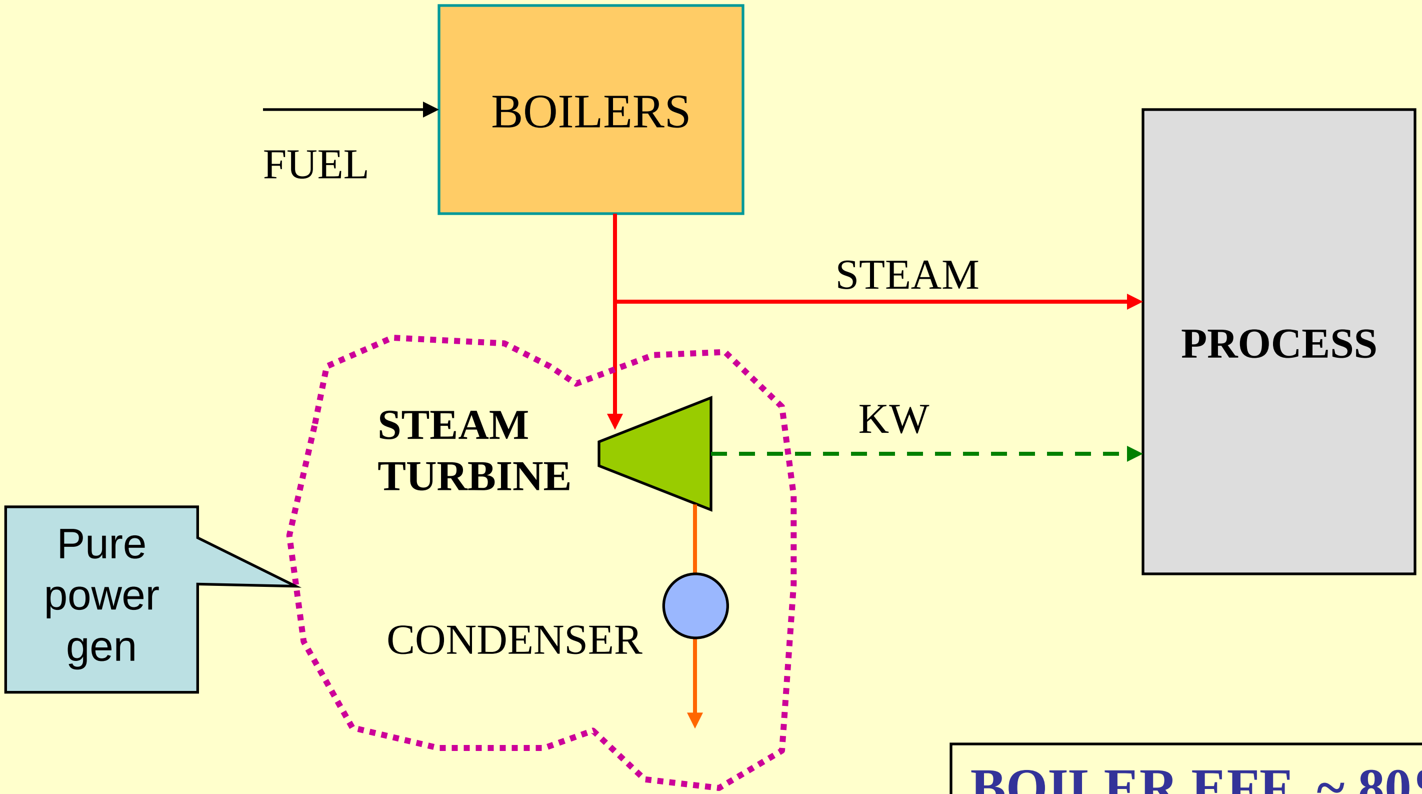
- CHP = **C**ombined **H**eat and **P**ower (= energy utility system for the plant site)
- Steam Turbines are Heat Engines that operate on the Rankine cycle. They convert ΔP into Shaftwork; a generator then converts Shaftwork into Elec power
- Thermodynamic Efficiency is defined as

$$\frac{\text{Useful Energy Output}}{\text{Energy Input}}$$

- For Generation, 1 useful output = Power only. Machine eff = ~20%, System Eff = ~35%
- For Cogeneration, 2 useful outputs = Power + Process Heat, Machine eff = ~20%, but System Eff ~75-80%

This is CHP, but <u>not</u> Cogeneration

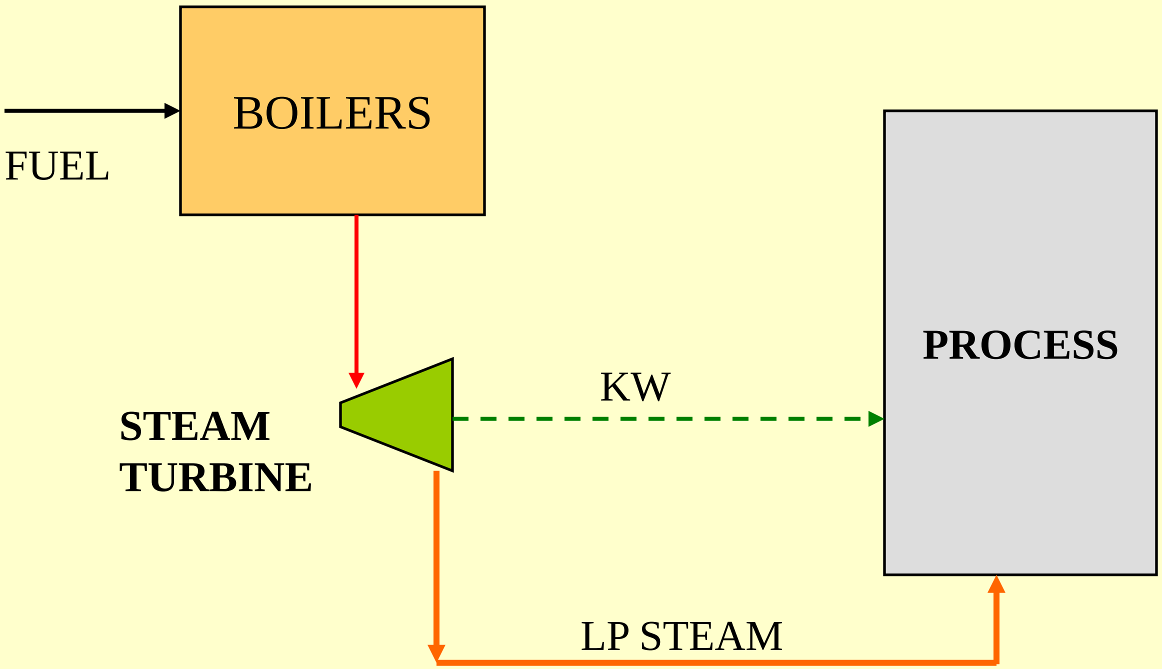
LATENT HEAT OF ST EXHAUST IS WASTED



BOILER EFF ~ 80%
POWER GEN EFF < 25%

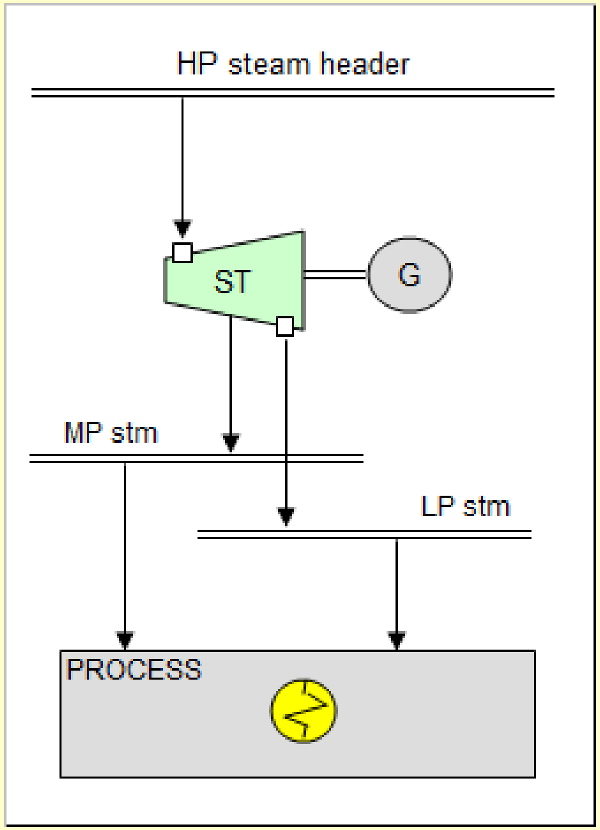
This is both CHP and "Co-Generation"

LAT HT OF EXHAUST STM IS USED IN THE PROCESS

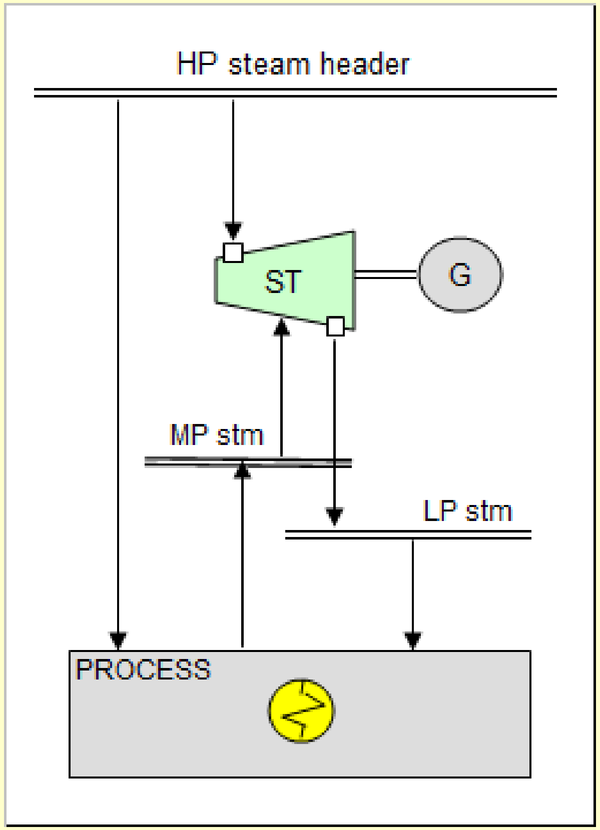


OVERALL EFF ~ 75%

Alternative Cogen configurations

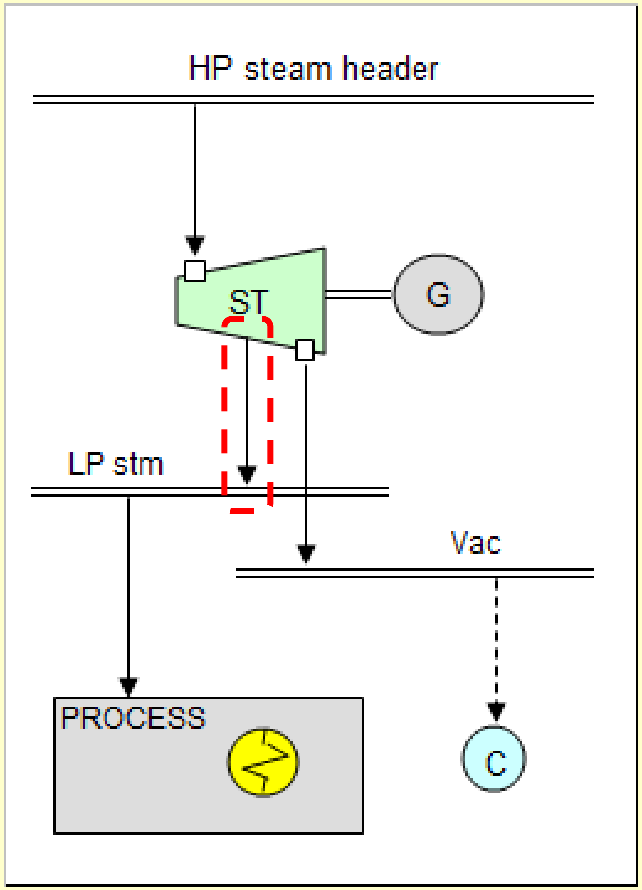


Extraction Turbine

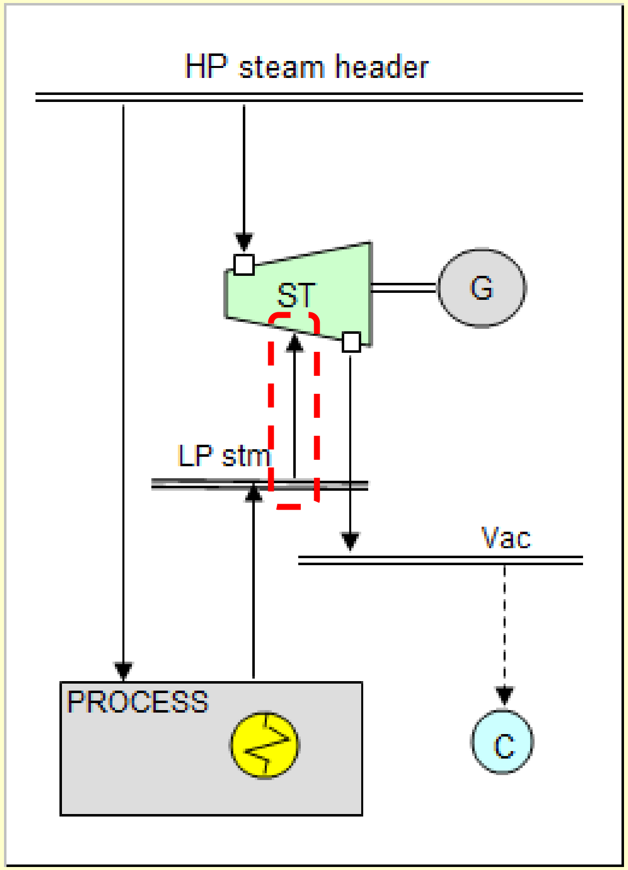


Induction Turbine

Variations – hybrid Cogen and Condensing

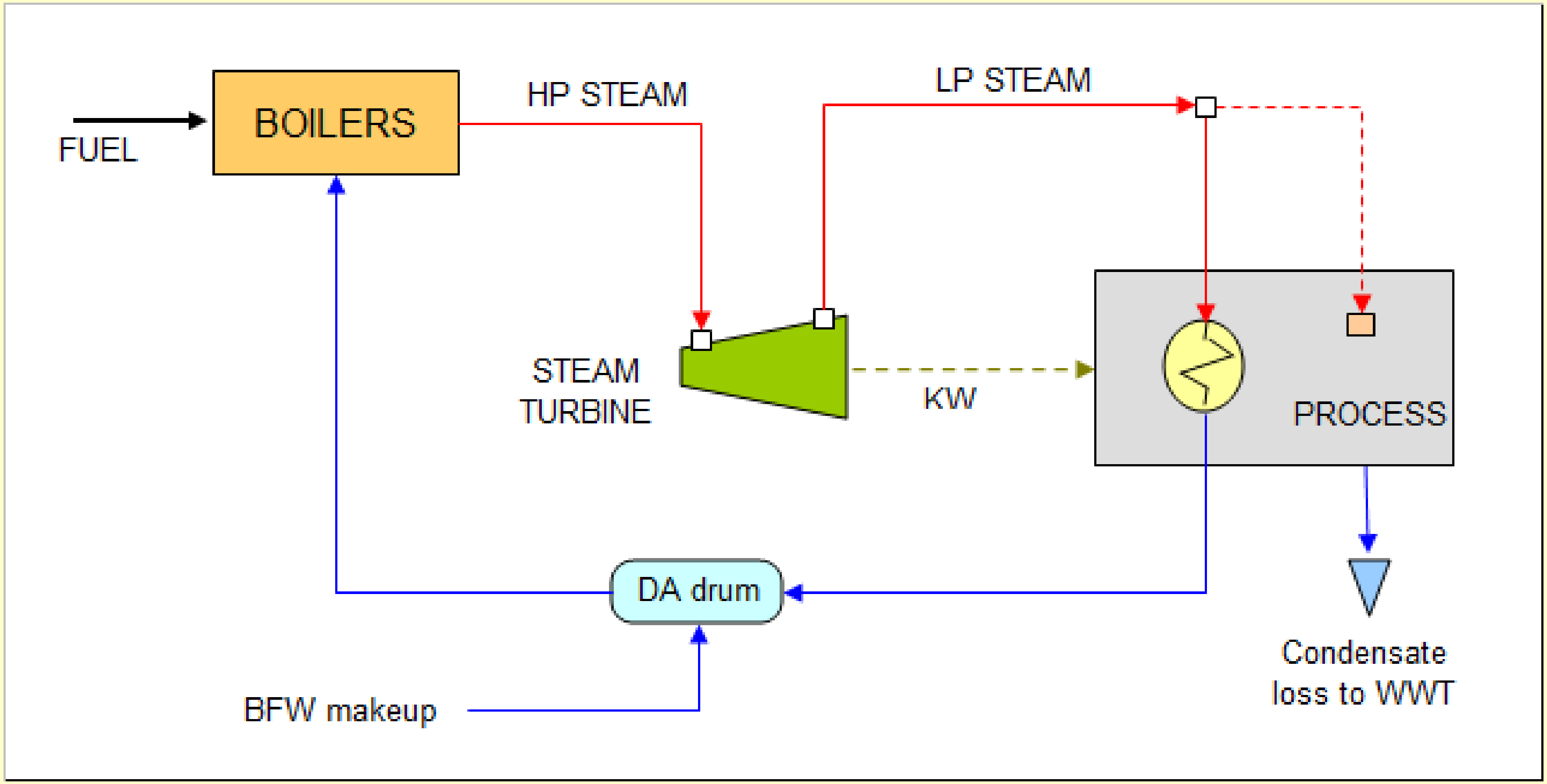


Extraction turbine



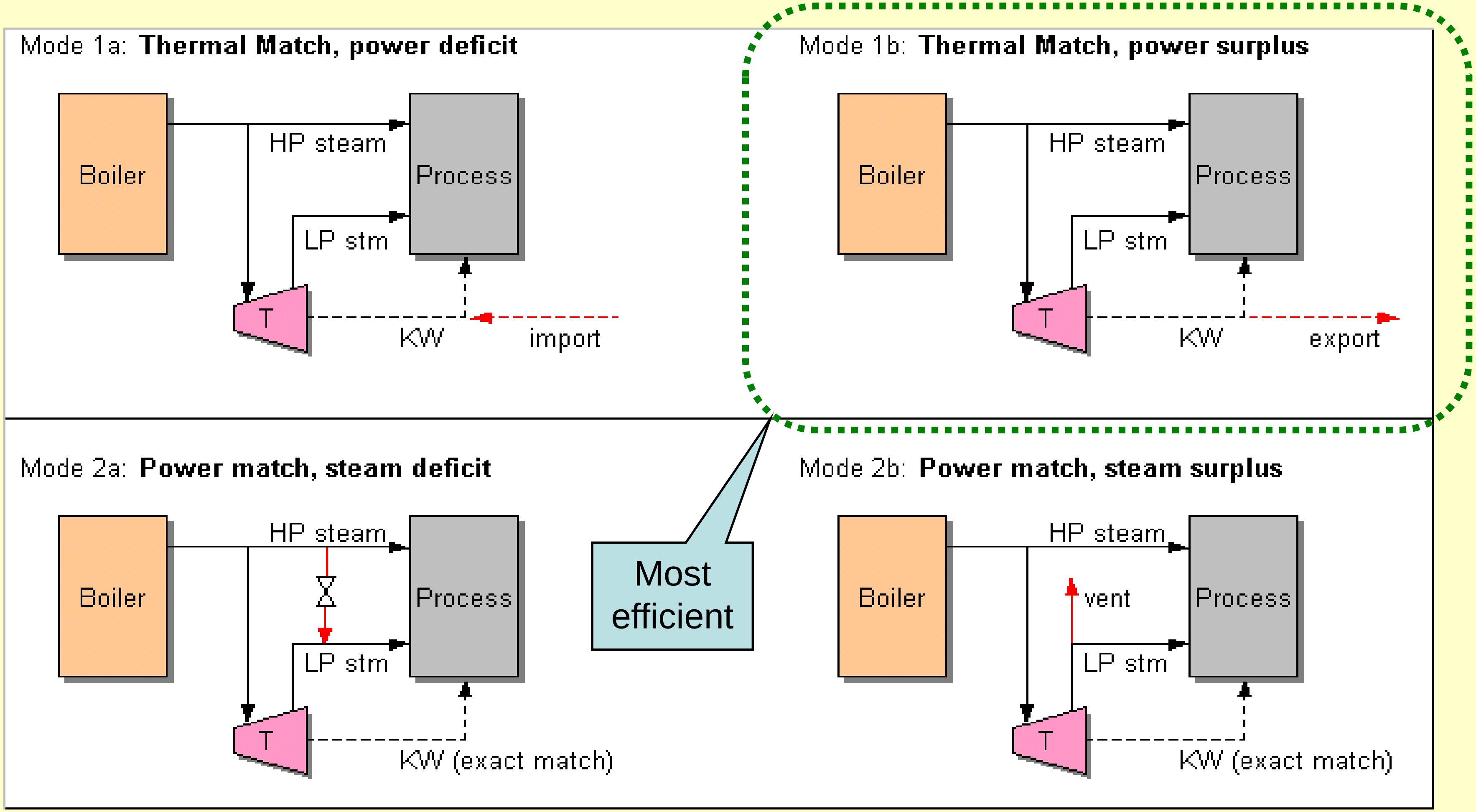
Induction turbine

Simple Rankine Cycle flowsheet



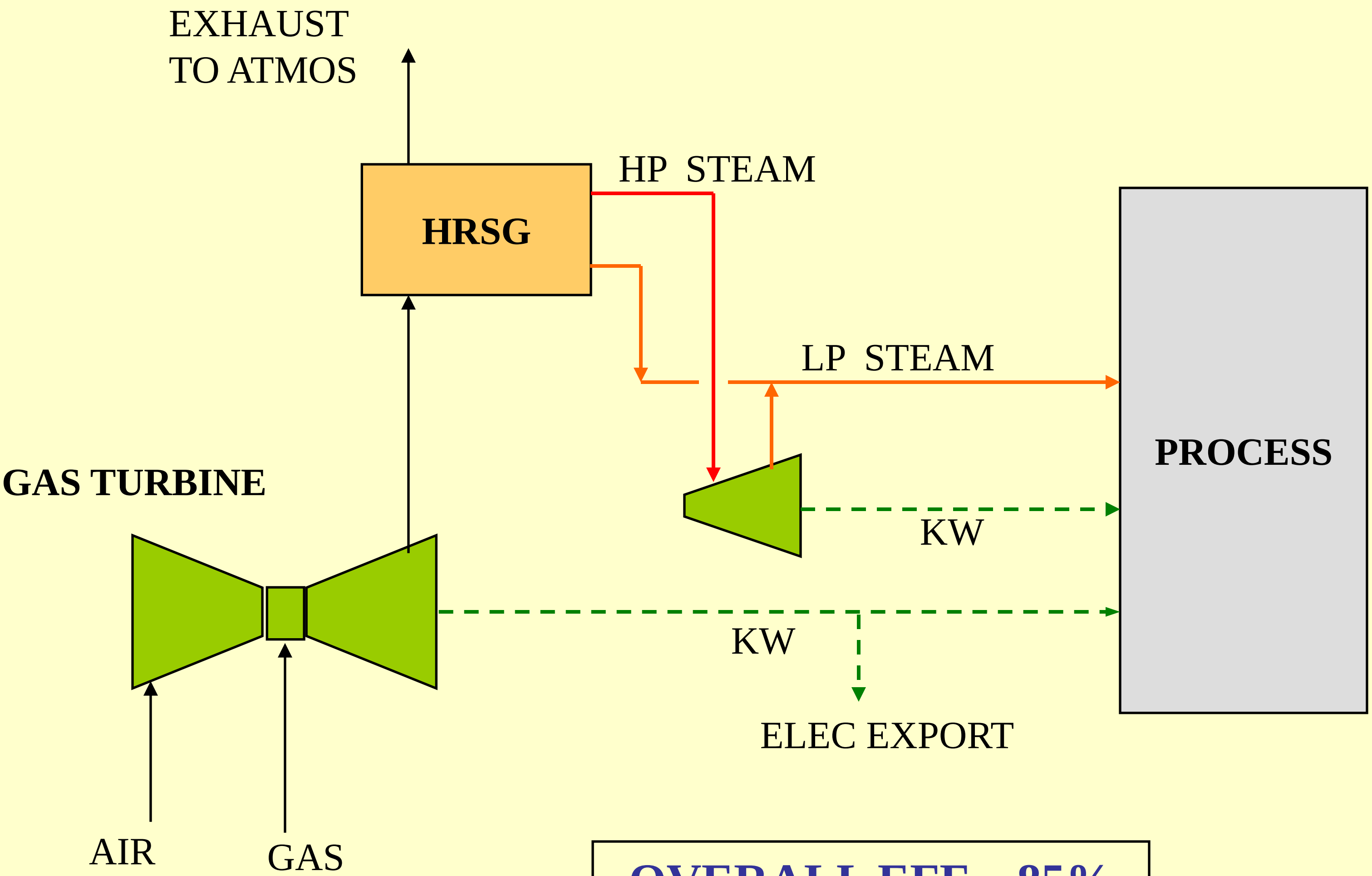
Schematic shown is for cogeneration mode

Difficult to match Heat:Power ratio of process



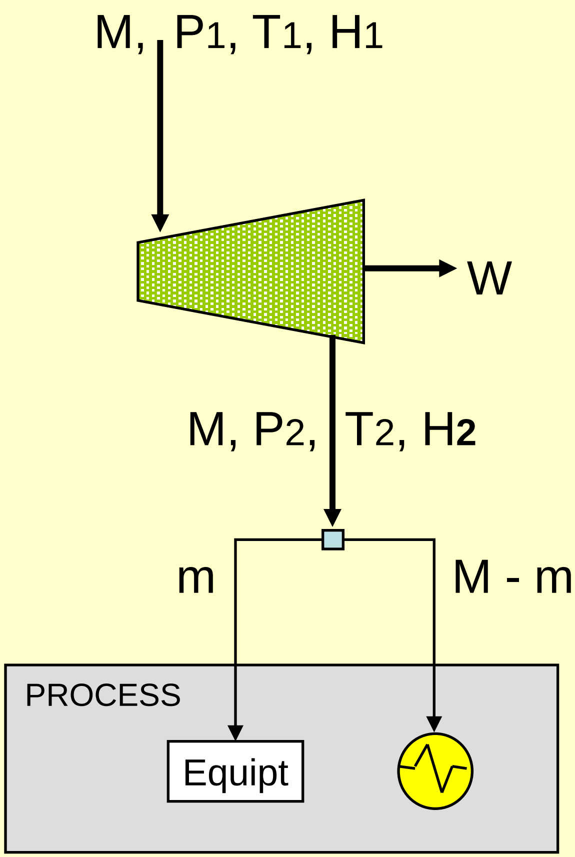
4 Basic Configs – which do you think is most efficient?

The ultimate Combined-cycle Cogen scheme



OVERALL EFF ~ 85%

Different types of ST Efficiency

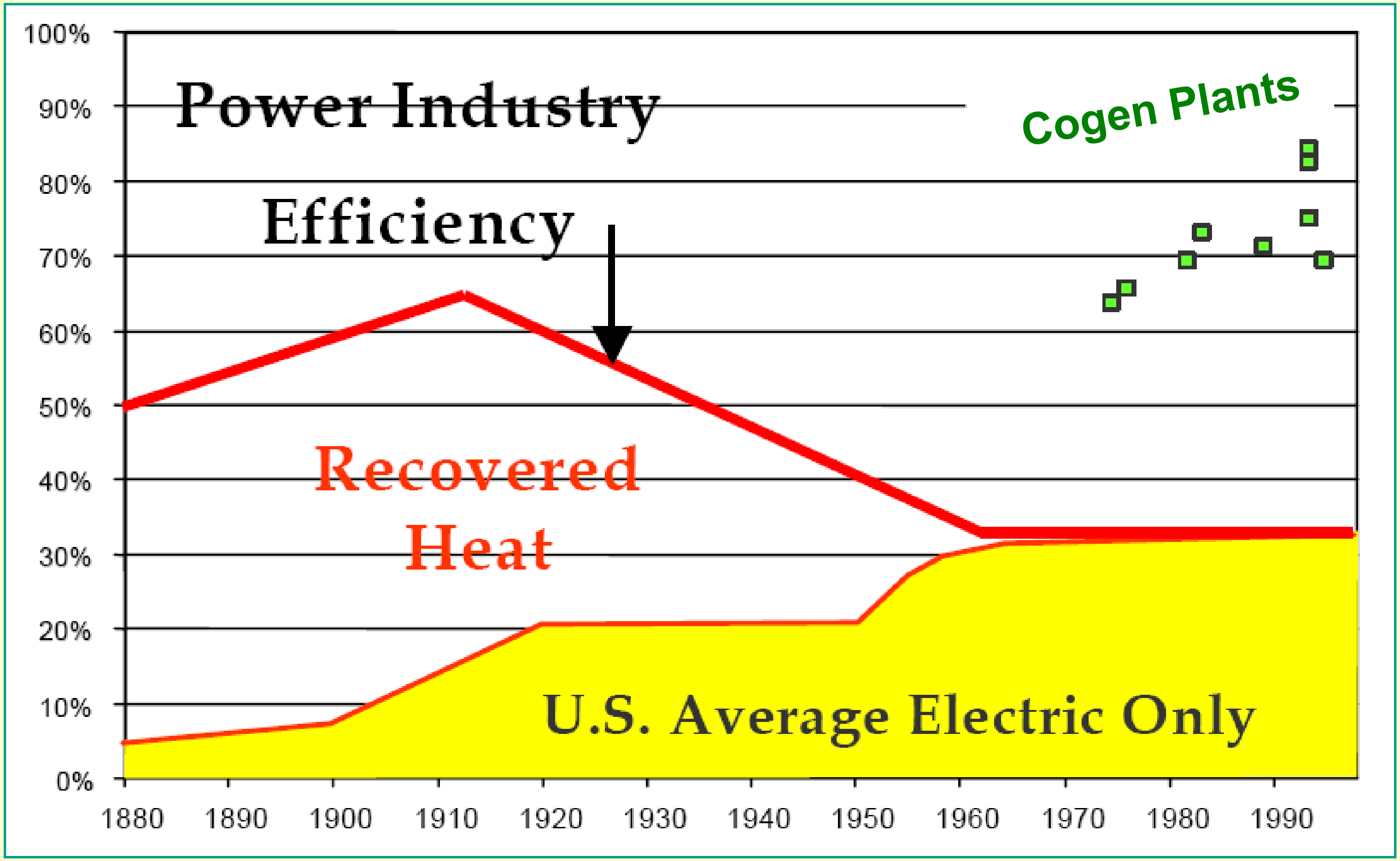


- Machine Efficiency = $W/Q_{in} = (H_1\text{-}H_2)/H_1$
- Isentropic Efficiency $= W/[M.(H_1 - H_2)_{max}]$ $= (H_1\text{-}H_2)/(H_1\text{-}H'_2)$
- System efficiency

$$\eta = \frac{3413.kW + (M - m).\lambda_2 + m.H_2}{M.H_1}$$

H'_2 = exhaust vapor enthalpy IF the expansion were isentropic (which it is not, and can never be)

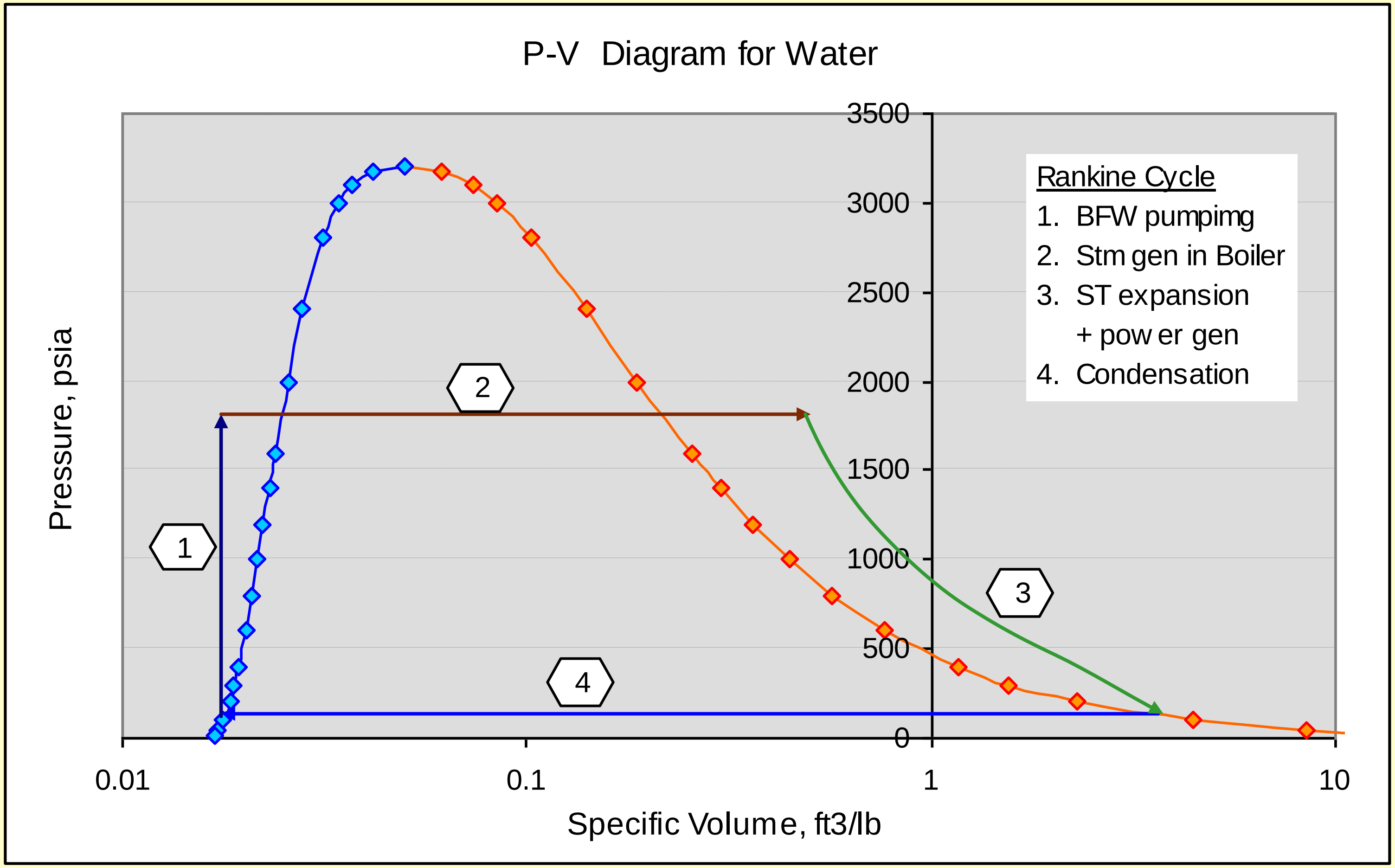
A Bit of History …



US Power plants stopped cogenerating ~1960

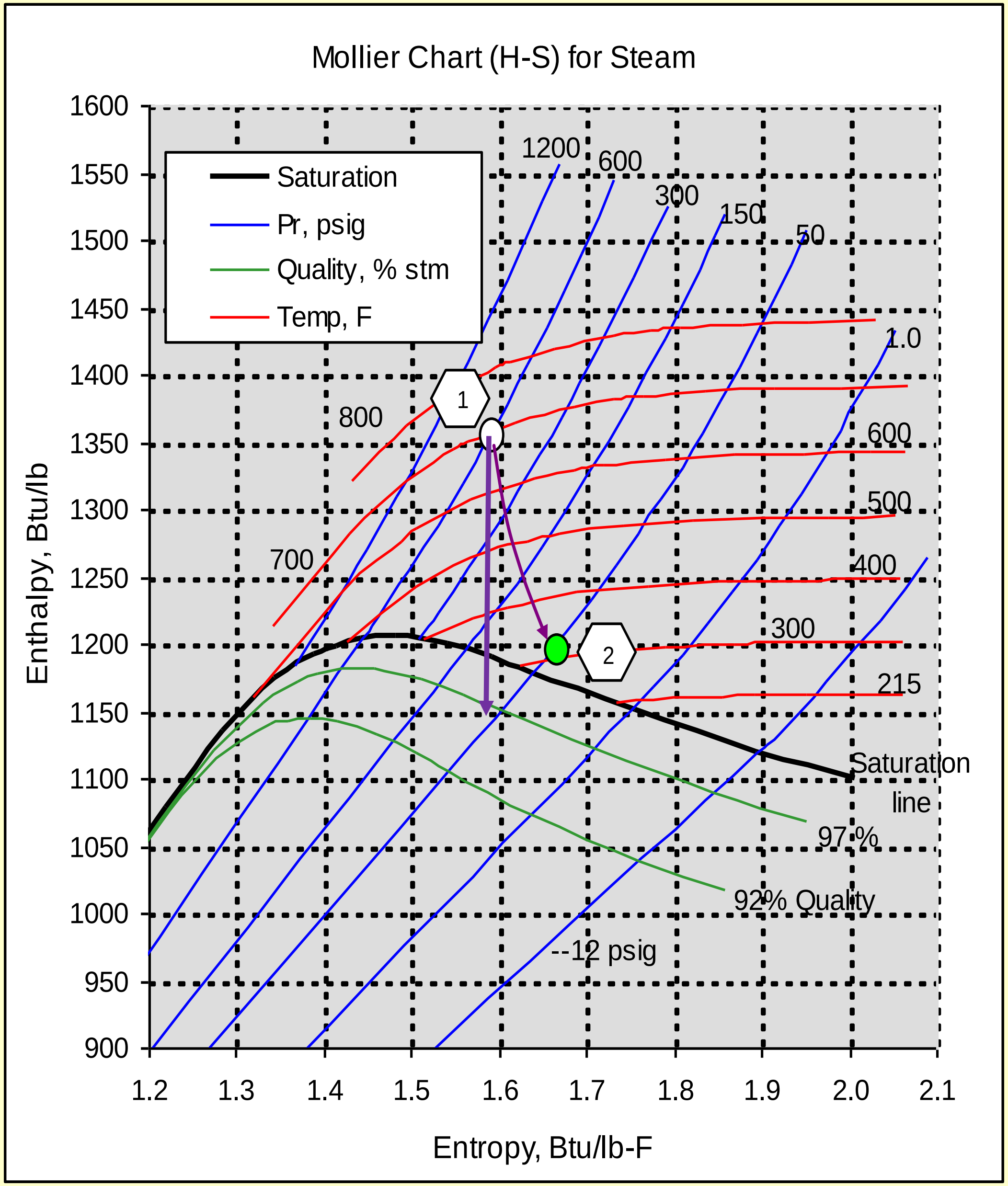
THERMODYNAMICS REVIEW

Rankine cycle on the P-V diagram



Power generation step (#3) on Mollier Chart

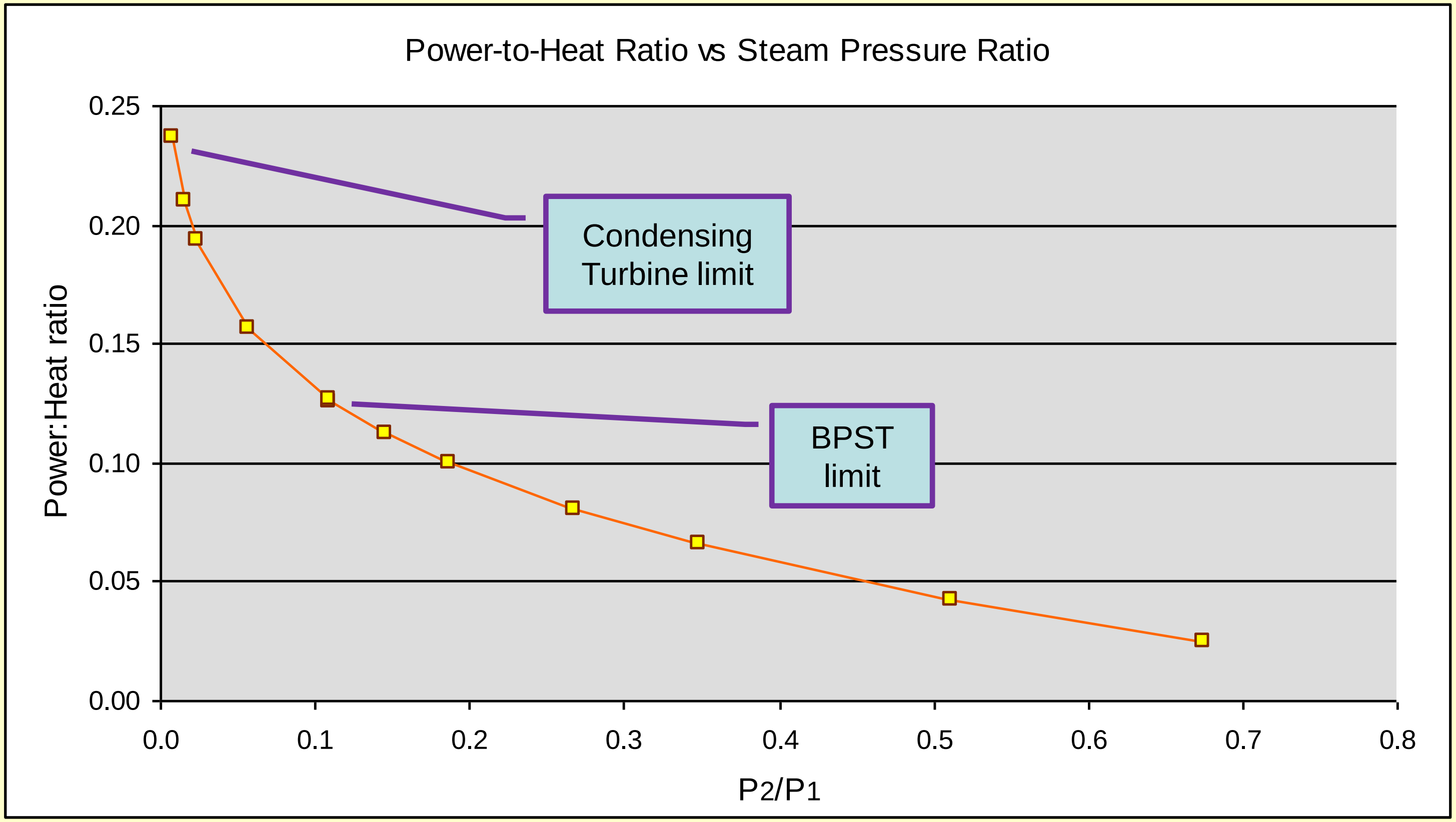
- Adiabatic expansion
  (from 600 psig, 700ºF to 50 psig)
- Isentropic efficiency



Effect of P_2/P_1 on Machine Efficiency (W/Q_{in})

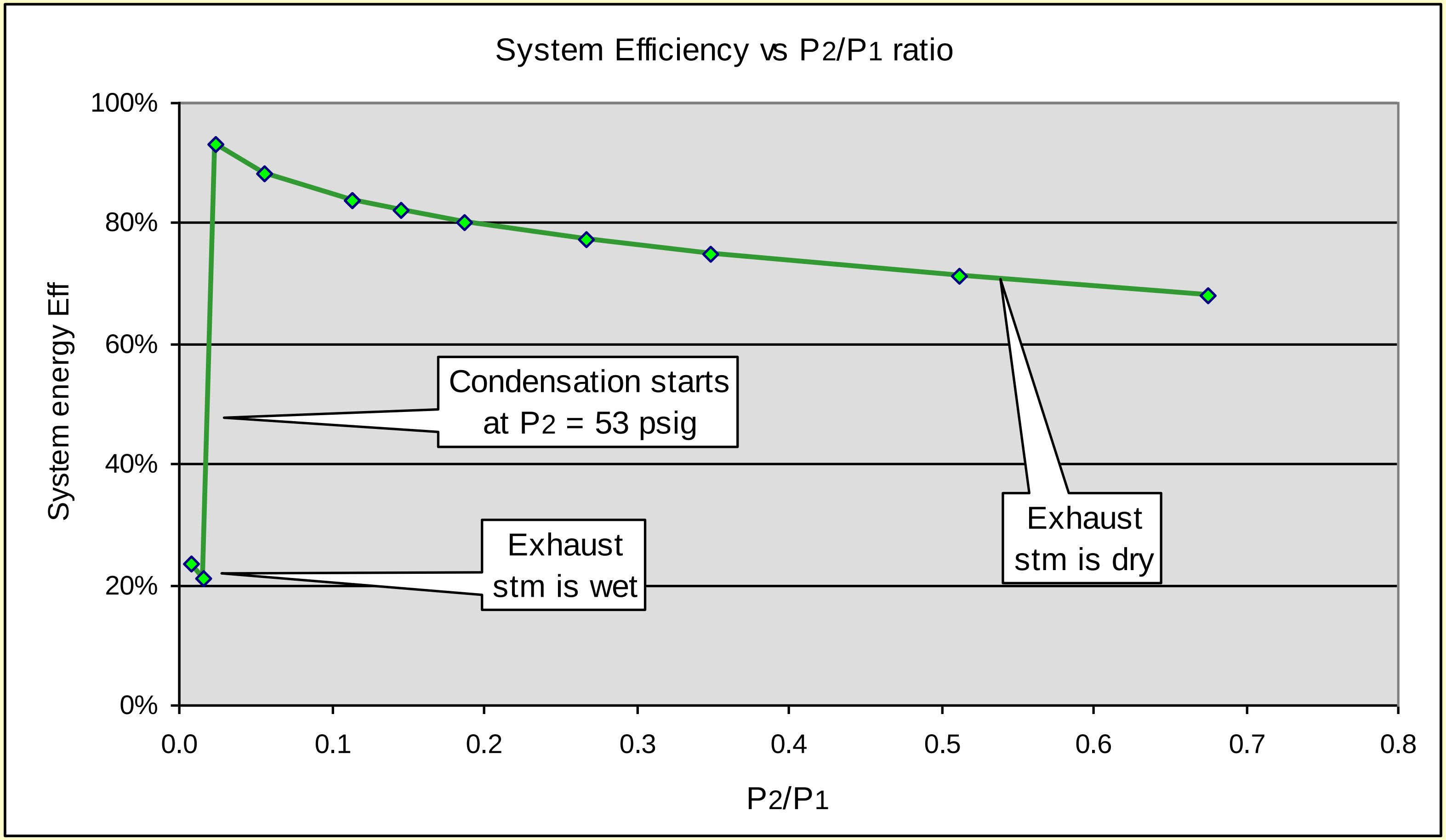
Near-optimal Inlet Conditions for industrial cogen systems

Inlet steam	
flow, lb/h	100,000
psig	600
psia	614.7
sat T	489
actual T	700
superheat	211
H, Btu/lb	1350
S, Btu/lb-F	1.5844



Theoretical Machine Efficiency tops out at ~13% for BPST and 24% for CST before moisture content in turbine reaches dangerous levels.

Effect of P_2/P_1 on System Efficiency



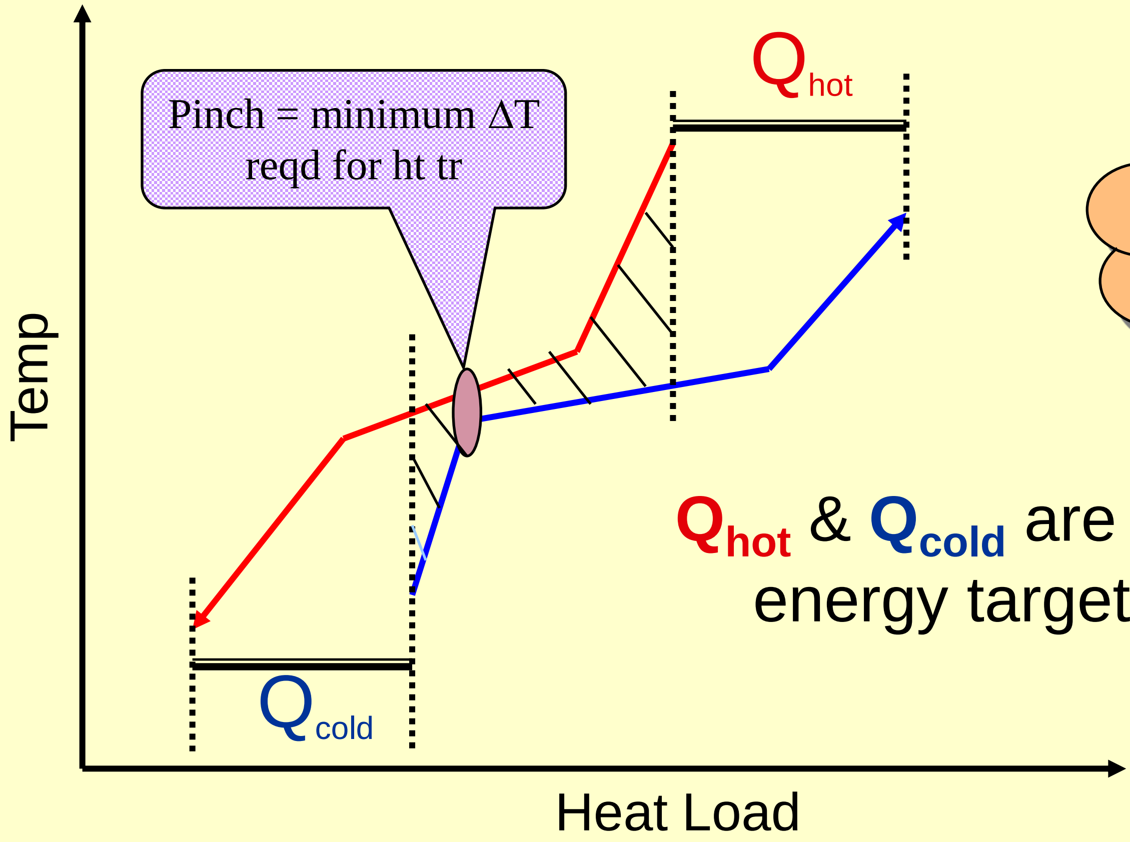
System Efficiency peaks when exhaust steam is saturated, drops rapidly as P_2/P_1 is falls, slowly as P_2/P_1 rises

Next: What is the Optimum Exhaust Pressure?

- P_2 should be at a high enough pressure that it can be used for process heating
- If there are multiple steam levels in the process, an extraction type turbine should be considered, with both exhaust pressures above ambient.
- The amounts should match the process steam requirements (→ “thermal match”)
- For higher P_2 or W/Q_{in} → increase P_1 and T_1

PINCH ANALYIS provides the ANSWER

OPTIMUM TURBINE INTEGRATION

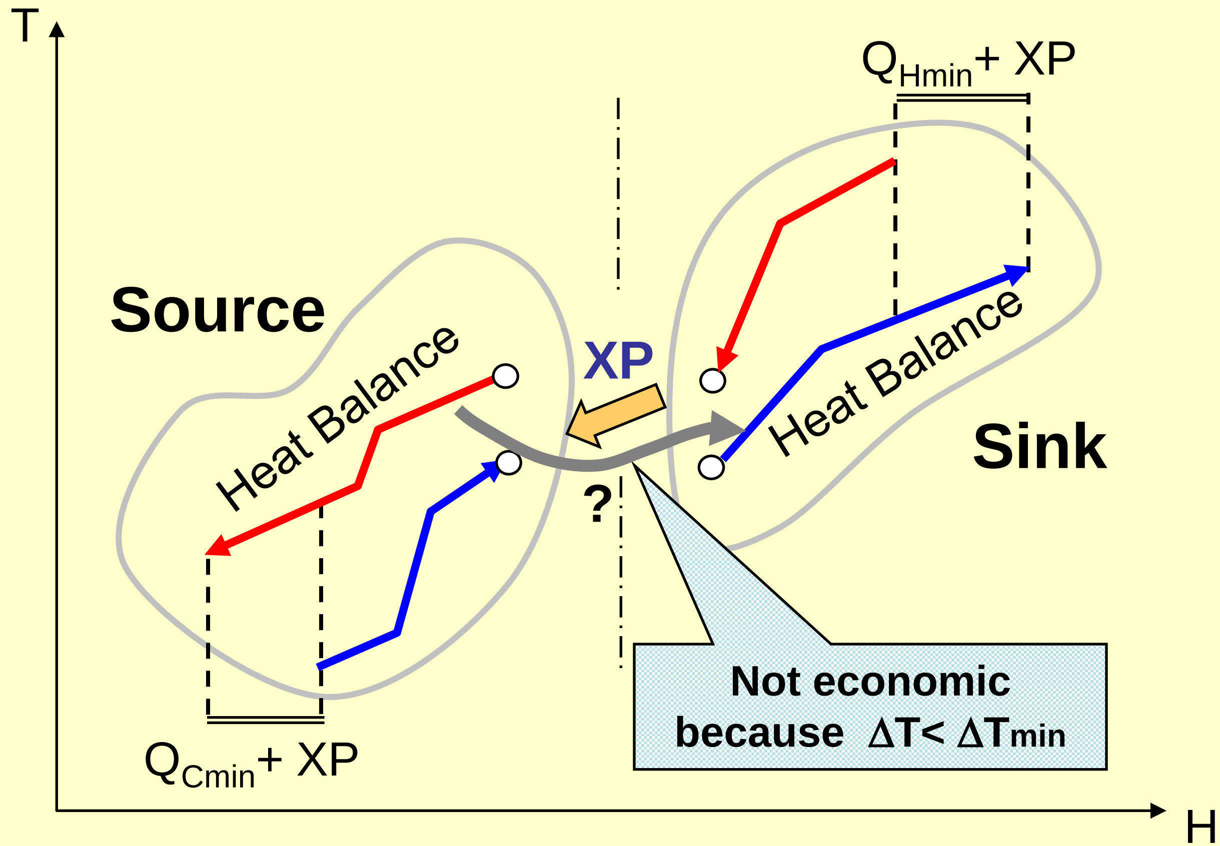


“Pinch Analysis”

Q_{hot} & Q_{cold} are the energy targets

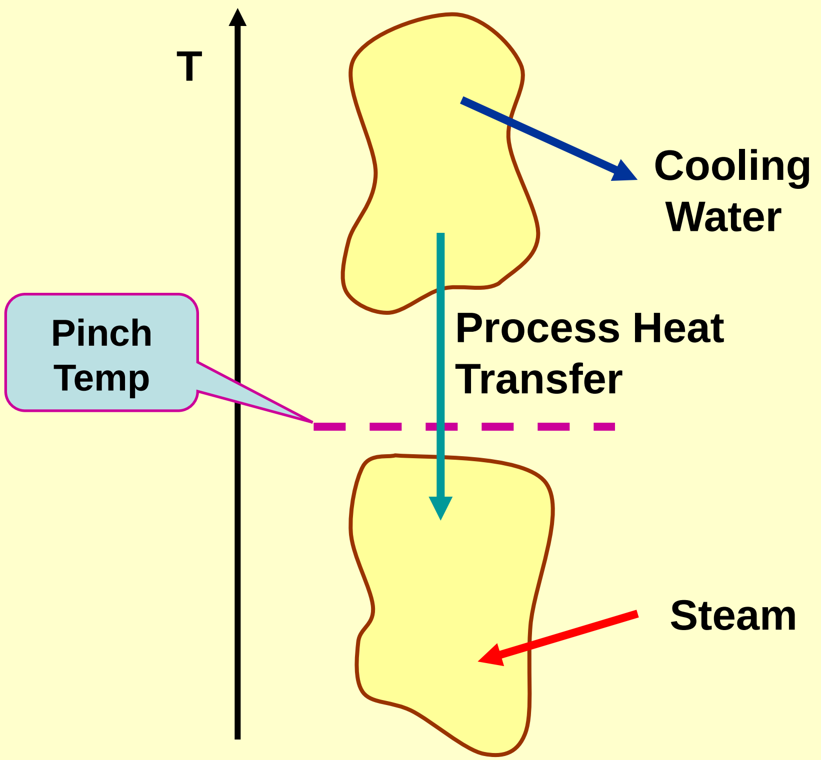
It is possible to consolidate ALL the heating and cooling duties in the process into two **Composite Curves** that show the enthalpy change requirements between the entire temperature range over which the process operates

The Pinch Principle - 1



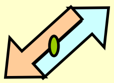
If we allow **XP** heat transfer, Q**h** and Q**c** both increase by **XP**

The Pinch Principle - 2

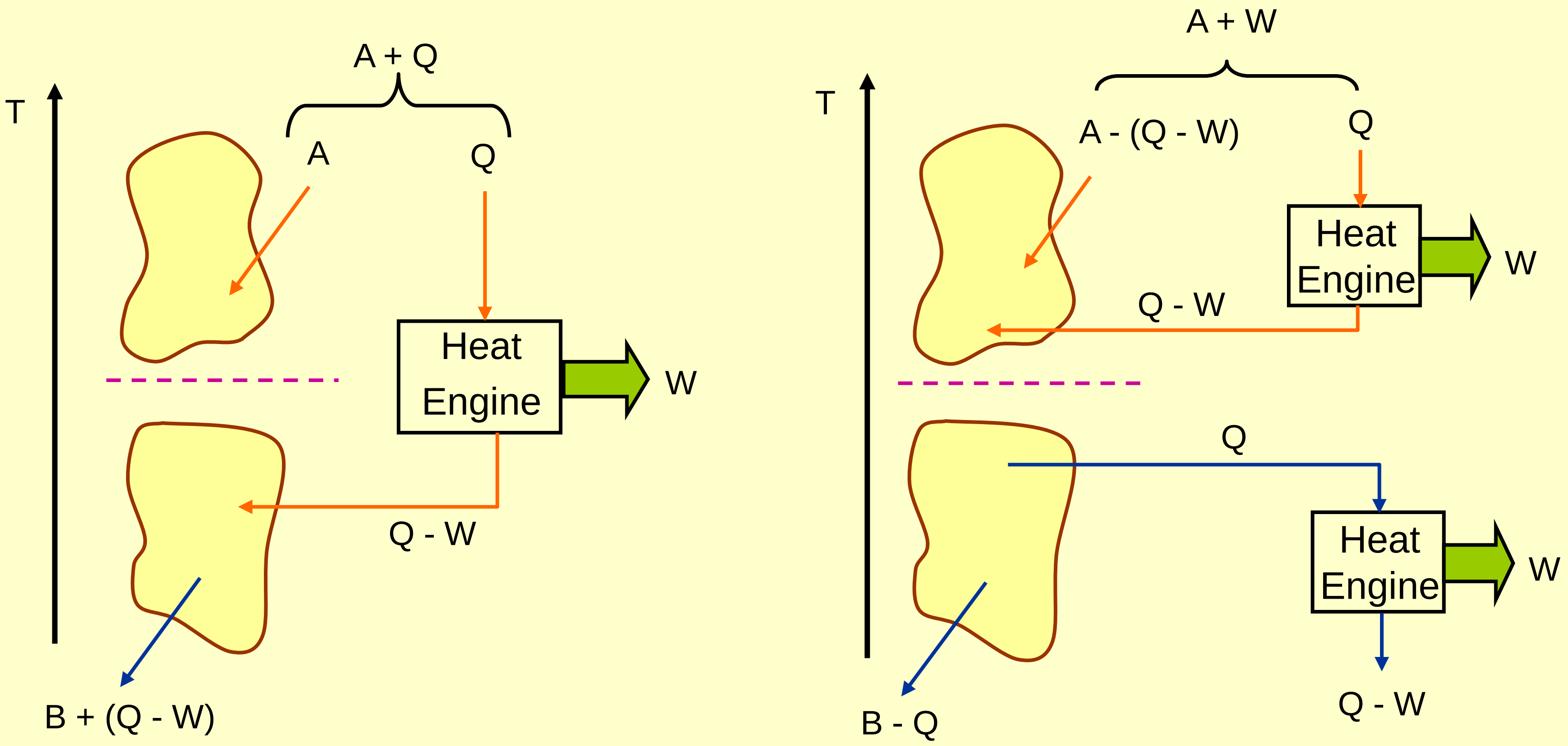


To achieve the Energy Targets, **DO NOT**

- use Steam below Pinch
- use CW above Pinch
- transfer heat from process streams above Pinch to process streams below Pinch



Steam Turbine Integration options



No improvement in system η

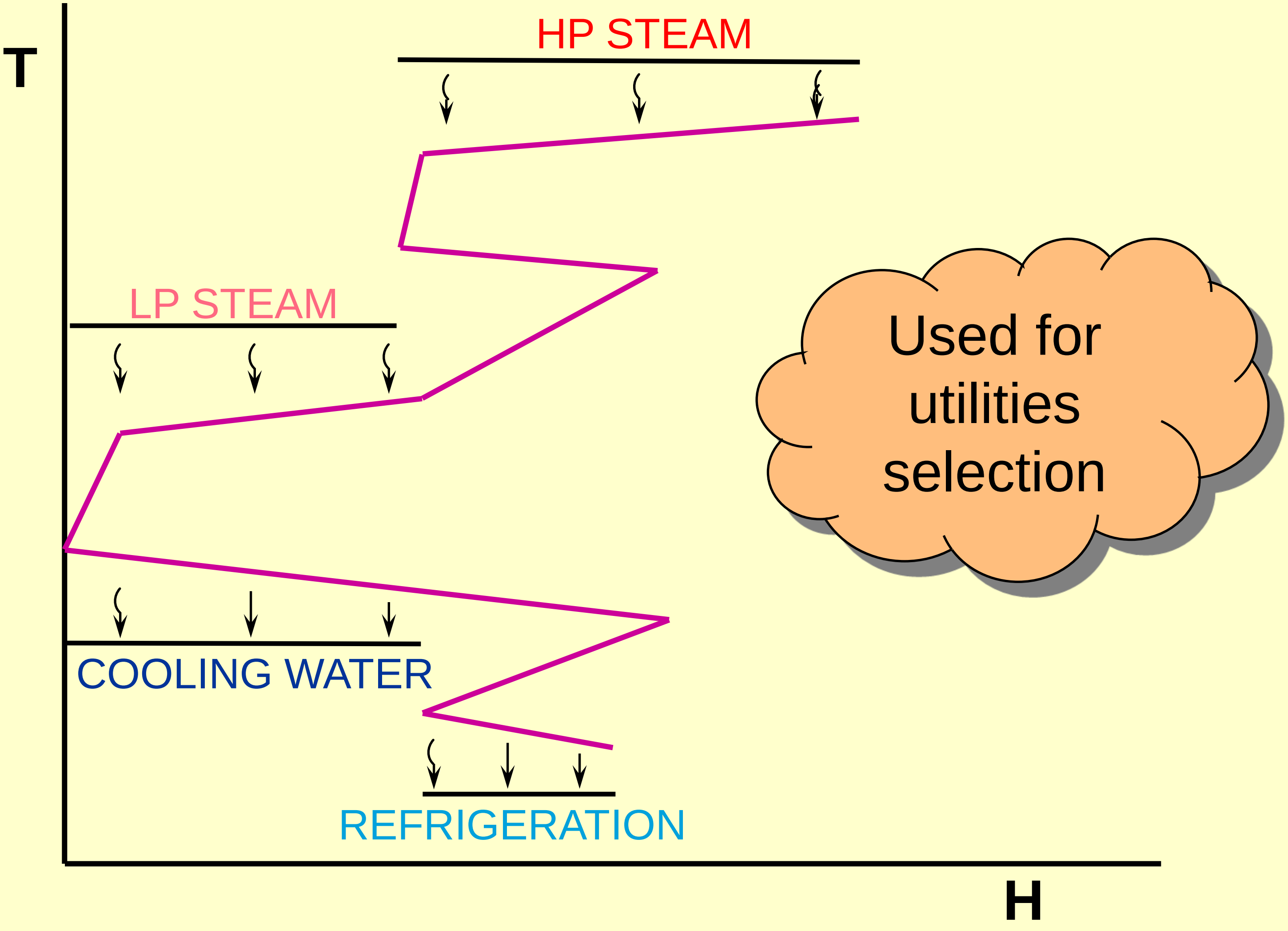
100% conversion of Q → W

Summary of Energy Balances

Parameter	Integrate Across PP	Integrate Above PP	Integrate Below PP
Process steam from fired boiler	A	A	A
Turbine steam from fired boiler	Q	Q	0
Turbine steam from WHB below Pinch	0	0	Q
Turbine exhaust vapor	Q – W	Q – W	Q – W
Net HP steam required	A + Q	A+W	A
Net Total Cooling Duty	B + (Q-W)	B	B – W
System energy efficiency	~ 20%	~ 95%	free power

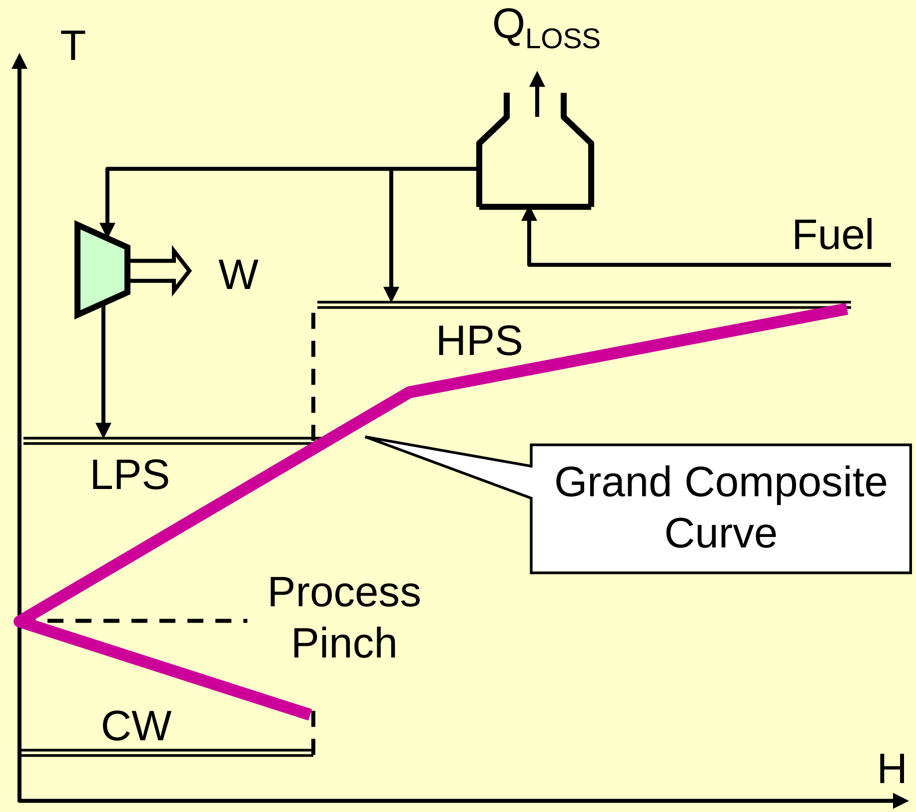
= Machine efficiency

Grand Composite Curve - GCC



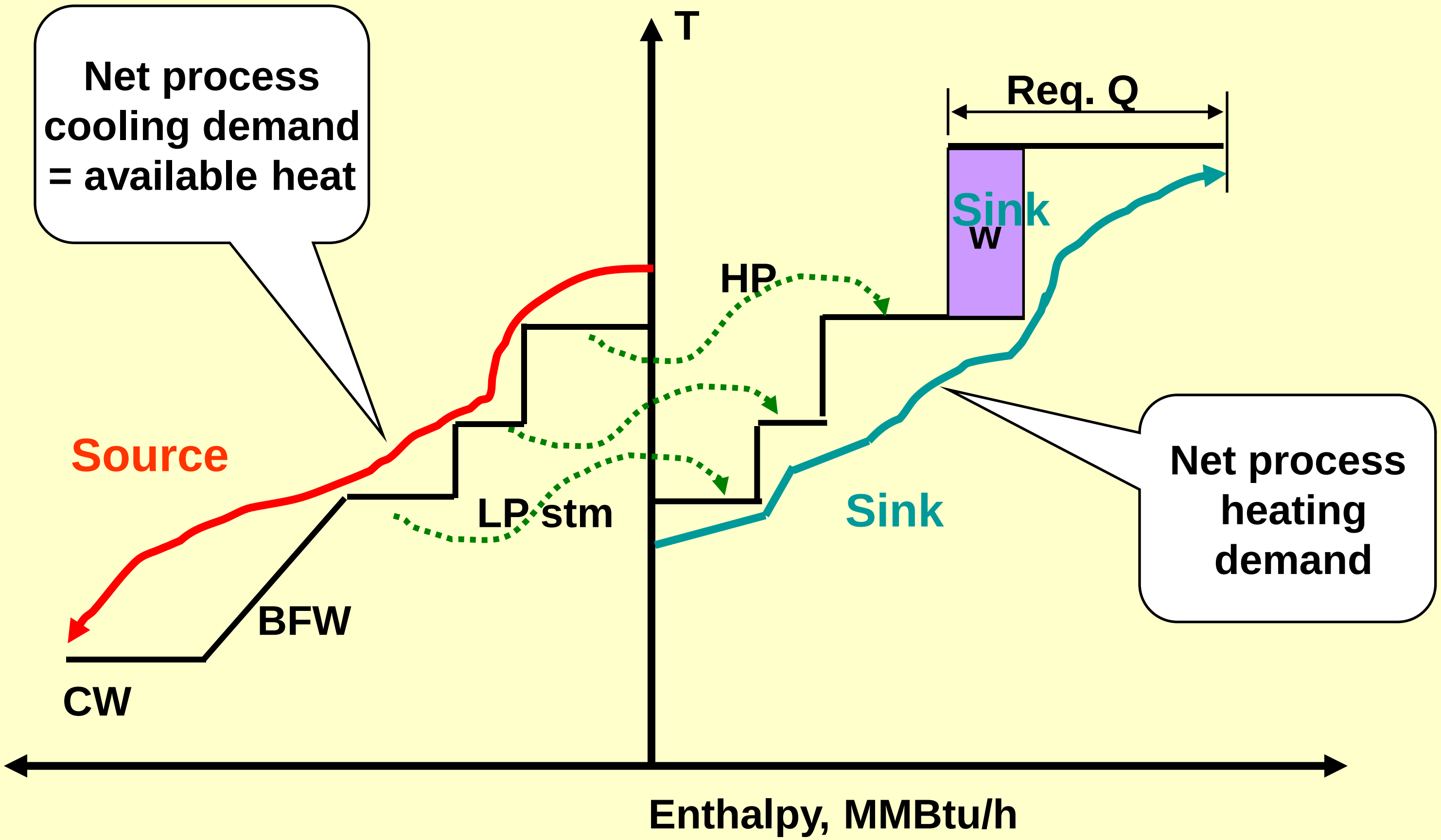
Correct Integration of Steam Turbine

- GCC shows us exactly how much HP and LP steam is needed, and the right P/T levels
- ST must <u>always</u> exhaust ABOVE the Process Pinch
- When designed this way, payback is very good, typically 3-4 yrs

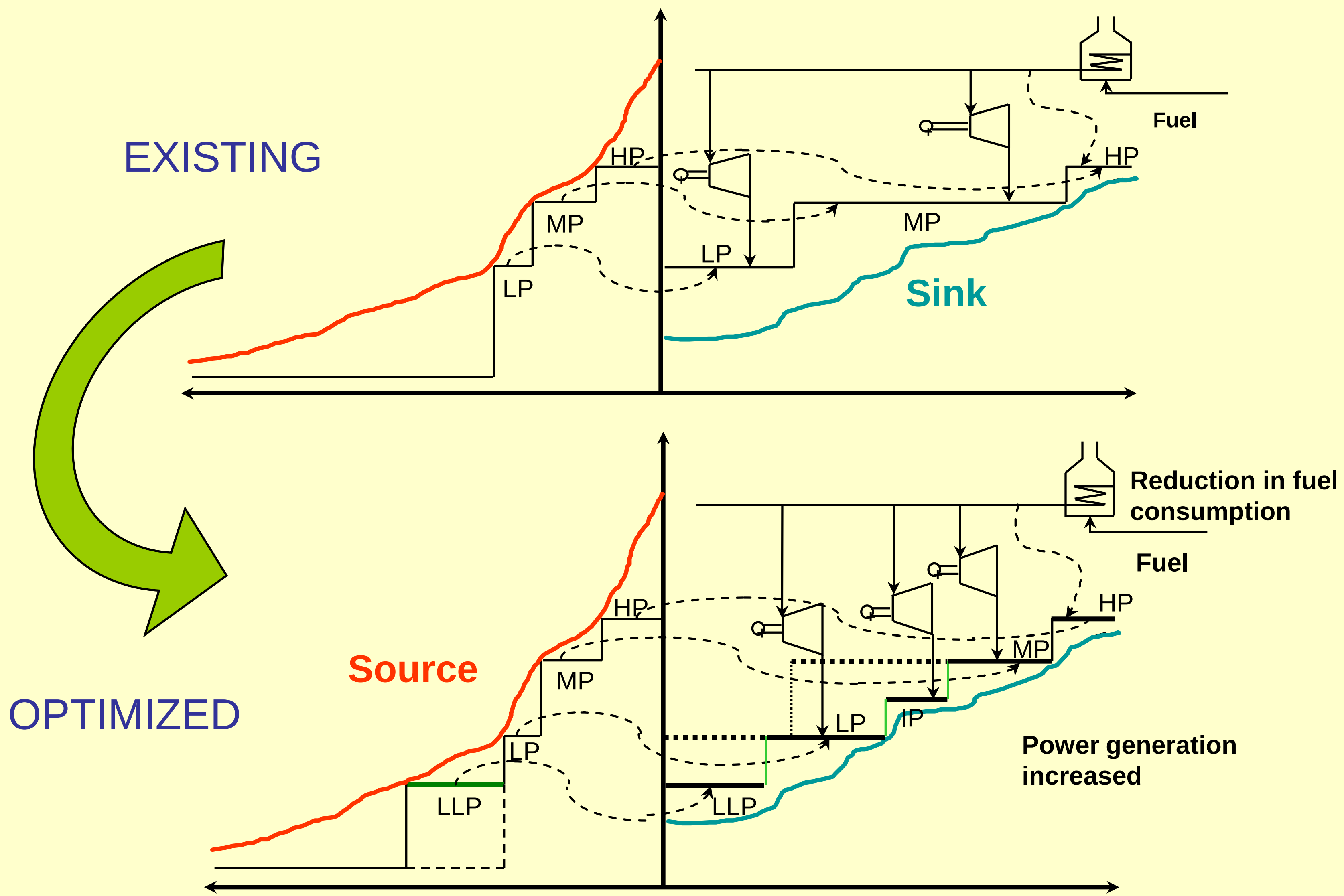


$$\text{Fuel} = \text{HPS} + \text{LPS} + \text{W} + Q_{loss}$$

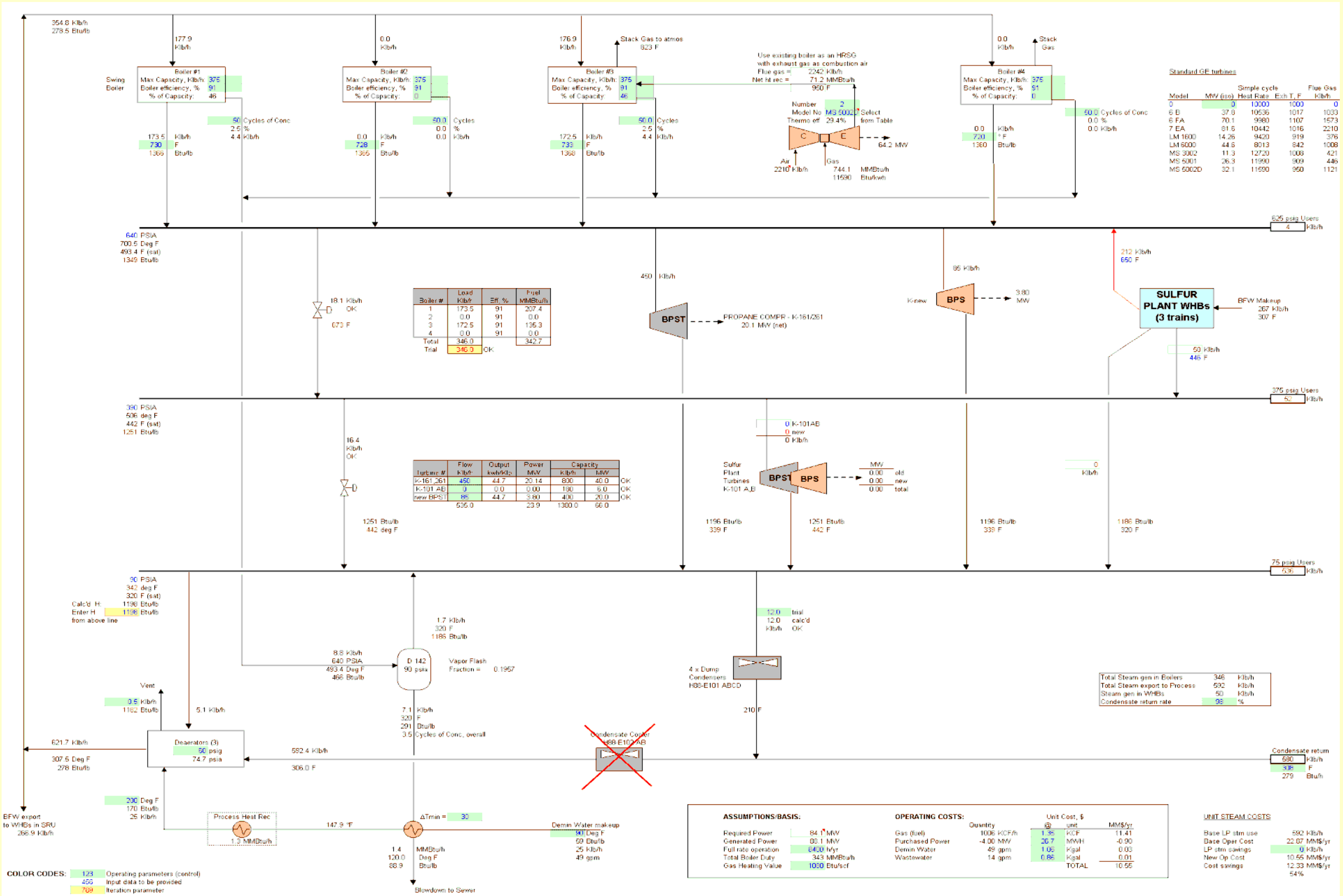
Total Site Source-Sink curves



Optimize Configuration



CHP SIMULATION MODELS



Excellent Tool for Analysis

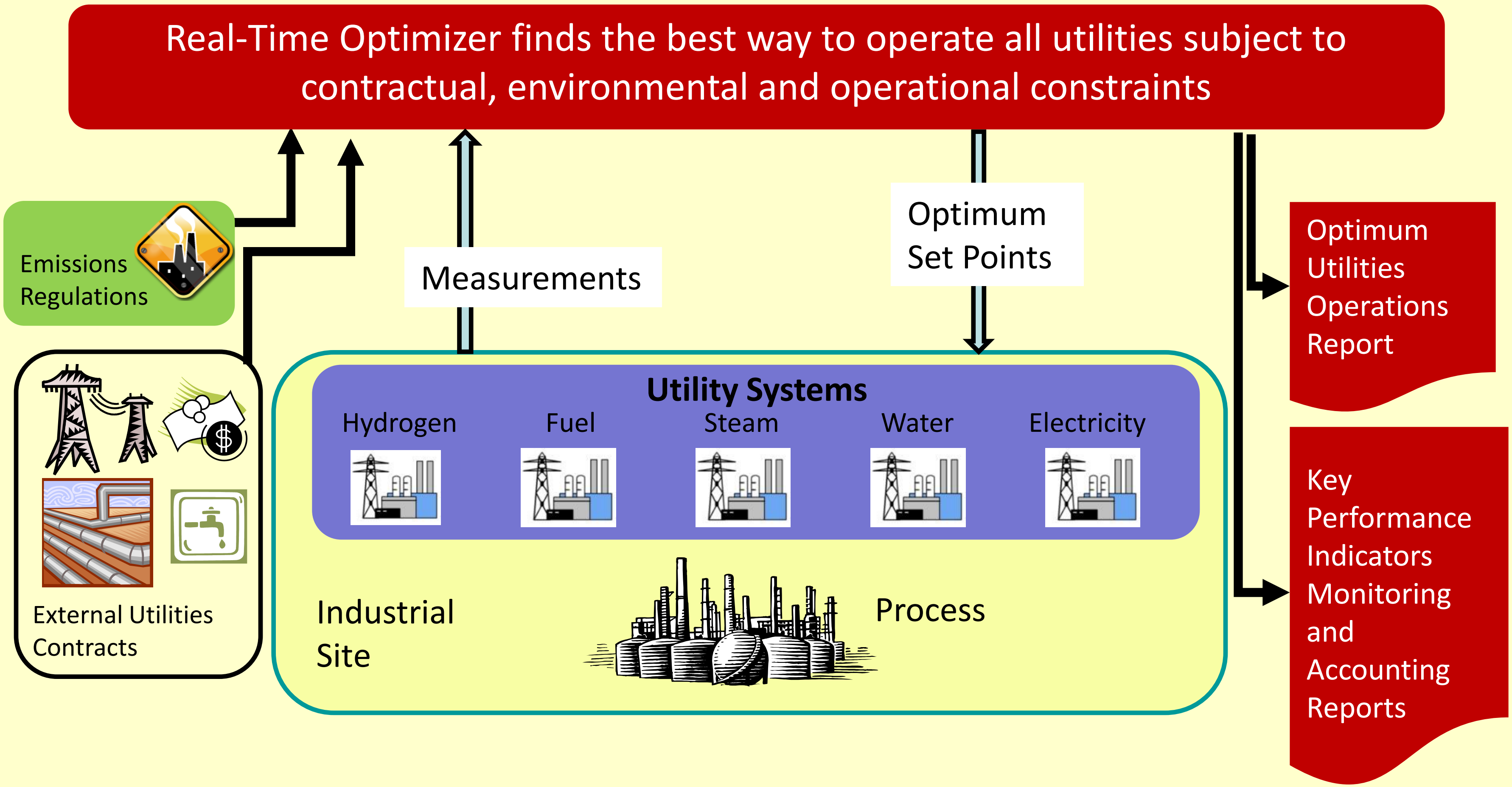
Model should include all Key System Features:

- Multiple steam levels
- Multiple boilers (with eff. curves)
- Process WHBs
- Steam and Gas turbines (incl HRSG)
- PRVs, Desuperheaters
- Condensate recovery (by steam pr level)
- Boiler blowdown flash & HX
- Deaerators (could be > 1)
- “Dump condenser”, if needed
- Economizer for BFW preheat
- BFW integration with process
- Process power demand

CHP Optimization Guidelines

- Set BPST exhaust pressures based on process steam headers (from GCC)
- Set steam flows through BPSTs based on process heating duties at each Pr level
- Condensing Turbines invariably a BAD idea
- Minimize flows through PRVs
- Use highest feasible DeAerator pressure(s)
- Maximize condensate recovery
- Preheat cold BFW makeup water by using it as a cooling medium in the process

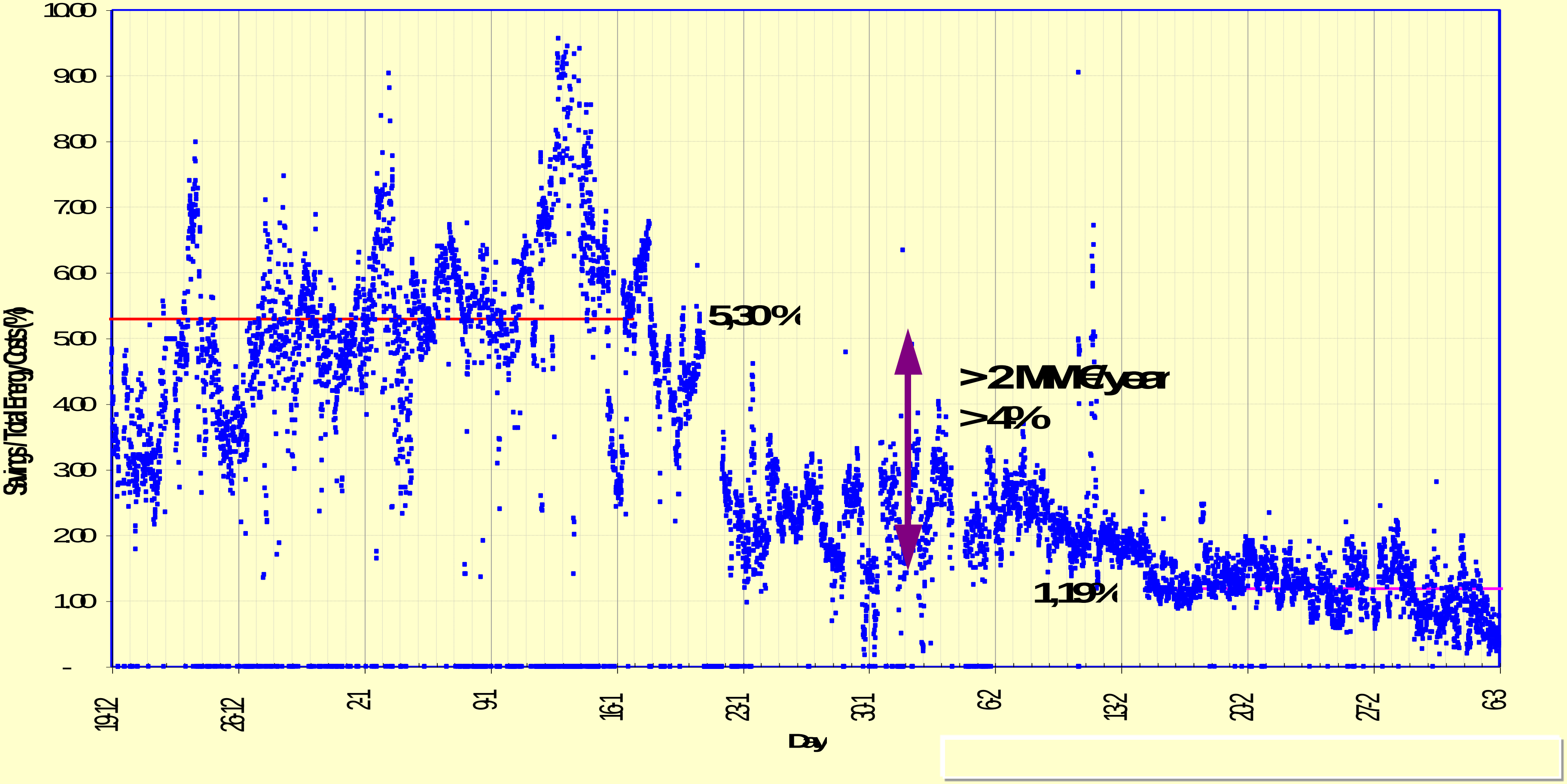
On-line Utilities Optimization



Expected Benefits and Costs

- Typical savings = 3-5% of baseline (operator-optimized) energy costs
- Typical installed cost = $500-900K
- Typical Payback << 1 yr
- Proven in dozens of Oil refineries, Chemical plants, Pulp/Paper mills (can be deemed a Best Practice)

Case Study – Operate closer to Optimum



Y axis = Deviation from Optimum = Remaining Savings Opportunity

IN CONCLUSION

- Use GCC to choose Stm Levels and Loads
- Use BPSTs in cogen mode when possible
- Condensing steam turbines are Invariably Bad*
- Use TSSS to identify optimum CHP structure
- Use CHP models to optimize parameters
- Always optimize process demand before trying to design/optimize the CHP system
- Ability to export excess power to the Grid at a fair price is critical to optimizing energy efficiency at National scale, and minimizing global GHG emissions

✡ with a few rare exceptions

Optimum Process Integration

It's like a jig-saw puzzle, but well worth the effort