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New Synthesis Methods for Subambient Processes such as LNG

by

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What is Process "Synthesis"?

Cybernetics
↳ Systems Engineering
↳ Process Systems Engineering
↳ **Process Synthesis**
↳ **Process Integration**

Engineering Insight
- Heuristic Rules

Optimization Methods
- Math Programming
- Stochastic Search

Thermodynamic Methods
- Pinch Analysis
- Exergy Analysis

Motivation (1)

Characteristics of Subambient Processes

- External Cooling provided by **Refrigeration** $\Rightarrow$ Power
- **Pressure** and Fluid **Phase** are important Design Variables (pressurized streams have cooling "stored")
- **Single** Component Refrigerants evaporate at constant Temperature, resulting in large Exergy Losses
- **Multicomponent** Refrigerants provide gliding Temperatures with reduced Exergy Losses, but they also introduce two-phase Flow Distribution Problems
- Extremely tight **Driving Forces** in Heat Exchangers $\Rightarrow$ Rigorous Simulation and Advanced Thermo Packages

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Motivation (2)

- **LNG – The fastest growing Energy Carrier**
  - Our "Test Site" for new Methodologies while trying to develop new Innovative Process Concepts
  - From large Scale Base Load to smaller Scale Plants
  - Floating LNG investigated by several Companies
  - Natural Gas Liquefaction is a mature Process, but there may still be some Scope for Improvements:
    - Thermodynamic Minimum: ≈ 115 kWh/tonne LNG
    - Snøhvit MFC®LNG Process[1]: 234 kWh/tonne LNG
    - Niche with precooling[2]: ≈ 270 kWh/tonne LNG
    - Dual N2 process (BHP)[2]: ≈ 350 kWh/tonne LNG

[1] Roy Scott Heiersted. Presentation at NTNU Alumni, June 2007

[2] Knut Arild Maråk, "Gas Phase Cycles for Liquefaction of Natural Gas – Status and Outlook", Trial Lecture, NTNU, 11 June 2009

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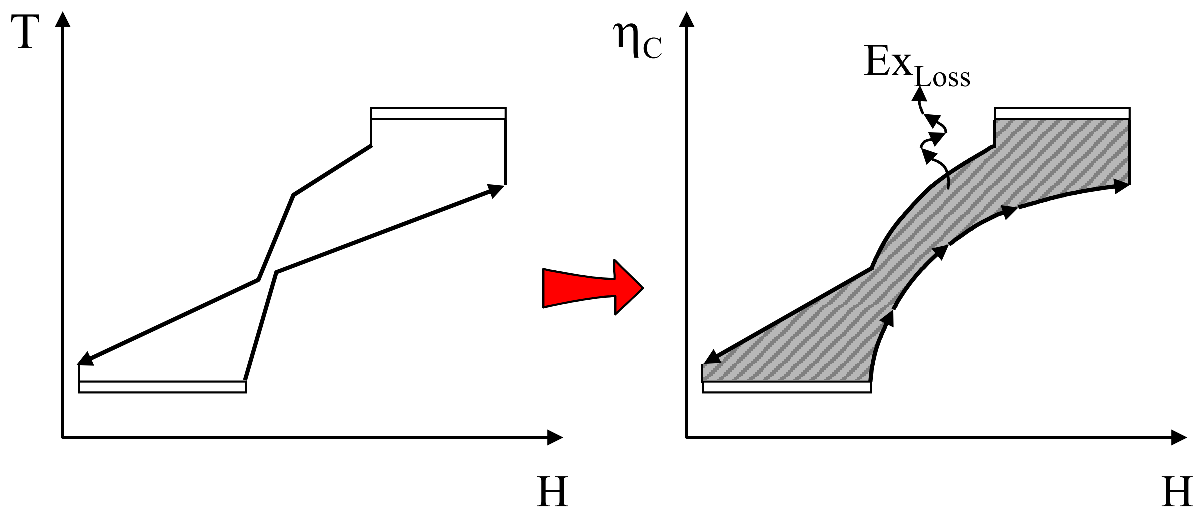
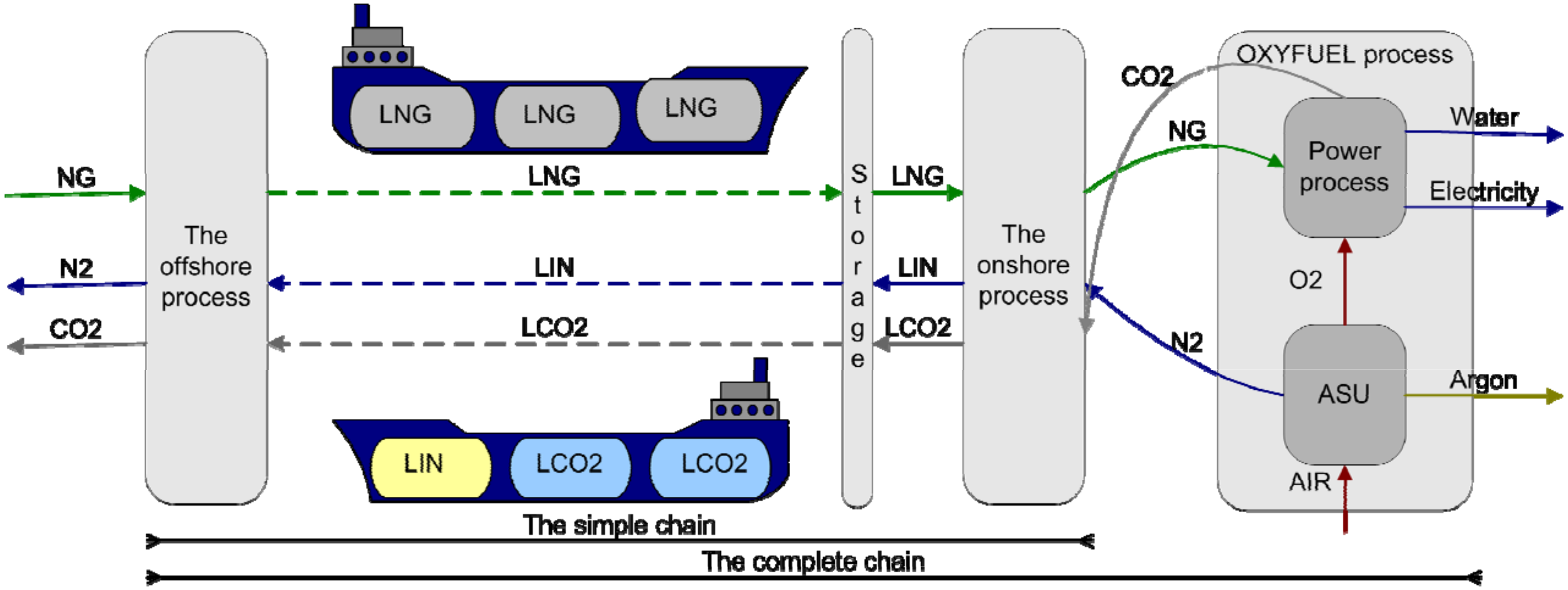
Motivation (3)

- **Limitations in existing Design Methodologies**
  - **Pinch Analysis** has been extensively and successfully applied in a broad Variety of Industries for > 25 years



  - **Exergy** Considerations have been included
  - But: Only **Temperature** is used as Design variable
    - **Pressure**, Composition and Fluid **Phase** <u>not</u> considered

Background: Liquefied Energy Chain



- **Key Features of the "LEC" Concept**
  - Utilization of **Stranded** Natural Gas for Power Production
  - Elegant and Cost Effective solution to the **CCS** Problem
  - CO_2 replaces Natural Gas injection for **EOR**
  - **Combined** Energy Chain (LNG) and Transport Chain (CO_2)

Need for Design Methods identified

- **The Offshore Process was Designed by**
  - Trial & Error
  - Thermodynamic Insight
  - Process Knowledge (LNG)
  - Rigorous Steady-State Simulation
- **The Design Process resulted in Insight**
  - Set of 10 Heuristic Rules were developed for
    - Pressure Manipulations
    - Fluid Phase Considerations
    - Design Actions in General
- **No Systematic Design Method available**
  - Must Consider **Pressure** and Fluid **Phase**

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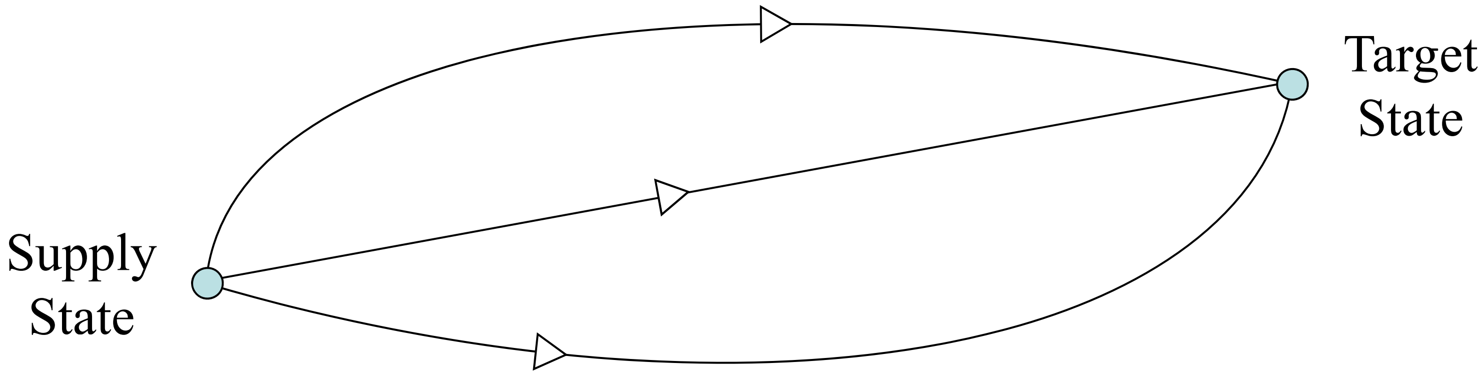
Extended Problem Definition for Heat Recovery Systems



"Given a set of Process Streams with a Supply State (Temperature, Pressure and the resulting Phase) and a Target State, as well as Utilities for Power, Heating and Cooling;
Design a System of Heat Exchangers, Expanders, Pumps and Compressors such that the Irreversibilities (or a Cost related Objective Function such as Total Annualized Cost) is minimized"

The "Path" from Supply to Target State is <u>not</u> fixed

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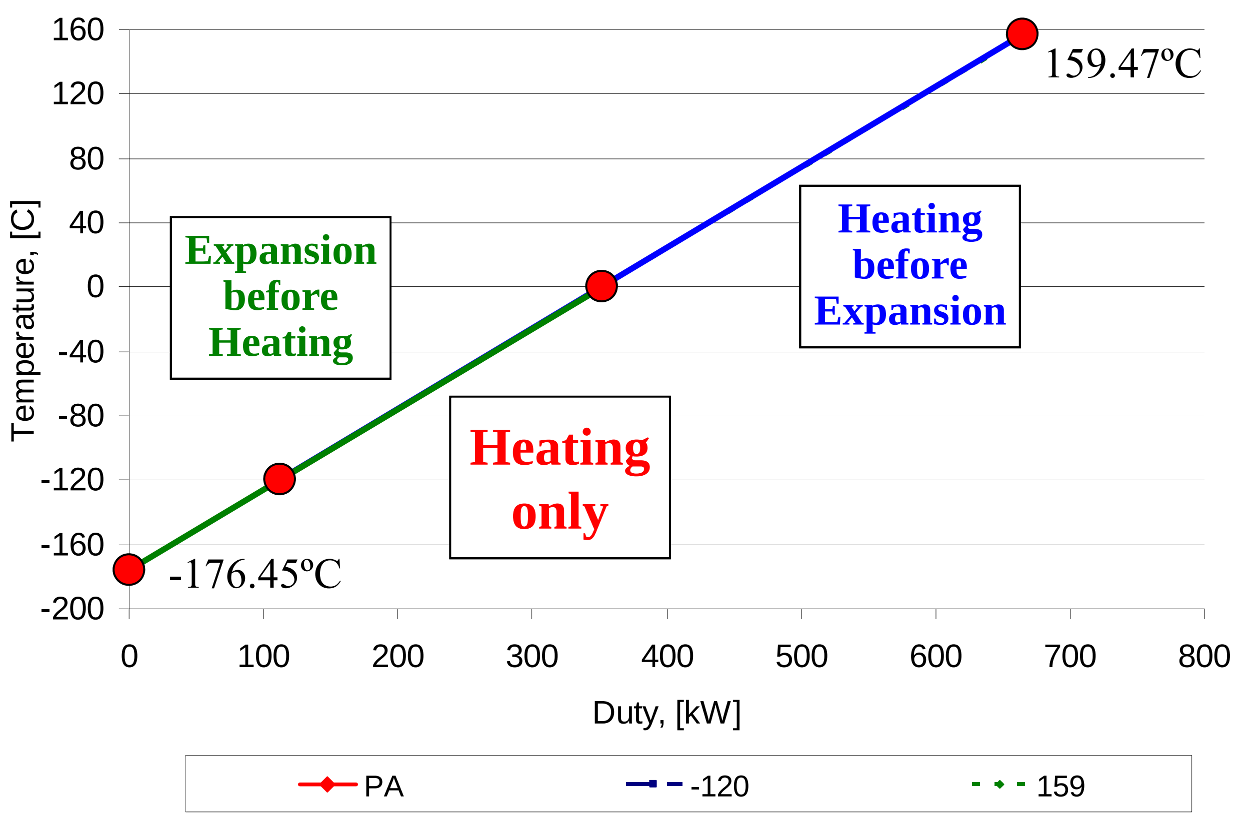
Expanding a pressurized Cold Stream

Given a "Cold" Stream with T_s = - 120ºC, T_t = 0ºC, p_s = 5 bar, p_t = 1 bar

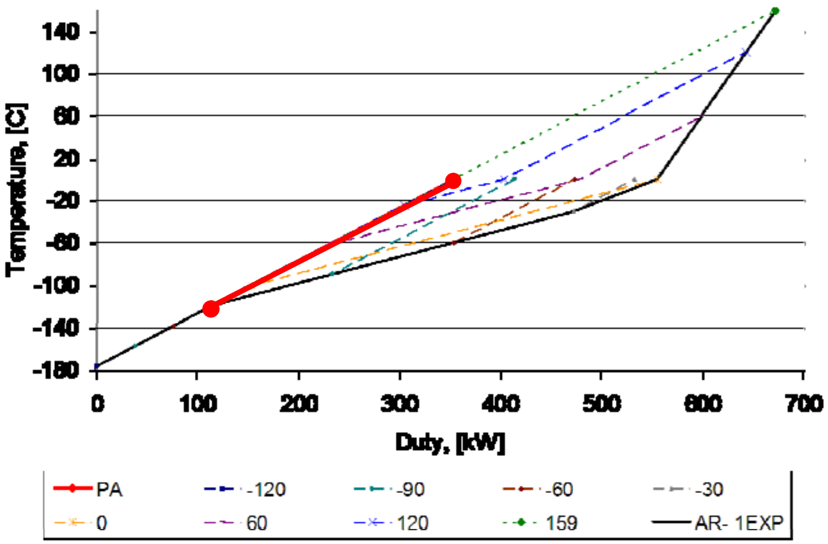
Basic PA and the 2 "extreme" Cases are given below:



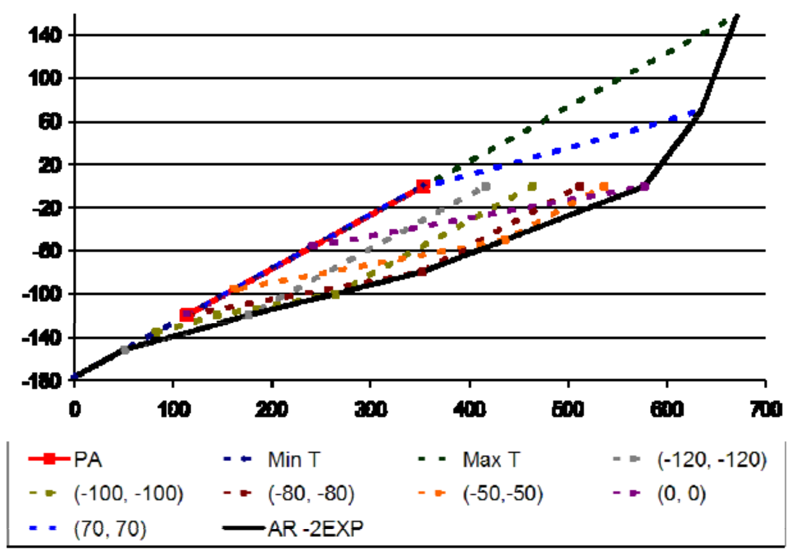
Composite Curves can be manipulated

- **Given a pressurized Cold Stream**
  - ♦ $T_s = -120°C$, $T_t = 0°C$, $p_s = 5$ bar , $p_t = 1$ bar

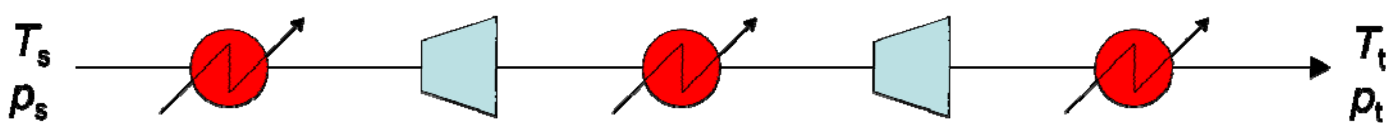
Attainable Region for 1 Stream



Heating Profiles with **1** Expander



Heating Profiles with **2** Expanders



Appropriate Placement Concept of PA revisited for Compressors and Expanders

- **Appropriate Placement (Integration) established for**
  - Chemical Reactors, Distillation Columns and Evaporators
  - Heat Engines, Heat Pumps and Refrigeration Cycles
- **In the "Stand-Alone" Case**
  - **Compressors** should operate at **low** Temperature possibly with interstage Coolers to reduce Power Requirements
  - **Expanders** should operate at **high** Temperature, possibly with reheat to increase Power Production
- **As Part of a Heat Recovery Problem**
  - Compressors provide additional Heat and should be placed **above** the Pinch Temperature (where there is Heat Deficit)
  - Expanders provide additional Cooling and should be placed **below** the Pinch Temperature (where there is Heat Surplus)

Appropriate Placement of Compressors

A very simple "Experimental Setup"

- **Example 1**
  - One Hot, two Cold Streams, H1 to be compressed
  - Key Q: What is the Optimal Compressor inlet Temperature?
  - Objective: Maximize **Exergy** Efficiency
- **Example 2**
  - Two Hot, two Cold Streams, H2 to be compressed
  - Key Q: Effect of $T_{\text{comp,in}}$ on the Process **Pinch**?
- **Assuming Ideal Gases and Isentropic Expansion**

$$\text{Compressor:} \quad \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}$$

$$\Delta \dot{E}_x = \dot{m} \cdot c_p \cdot \left(T_t - T_s - T_0 \cdot \ln \frac{T_t}{T_s} \right) + \dot{m} \cdot c_p \cdot \frac{k-1}{k} \cdot T_0 \cdot \ln \frac{p_t}{p_s}$$

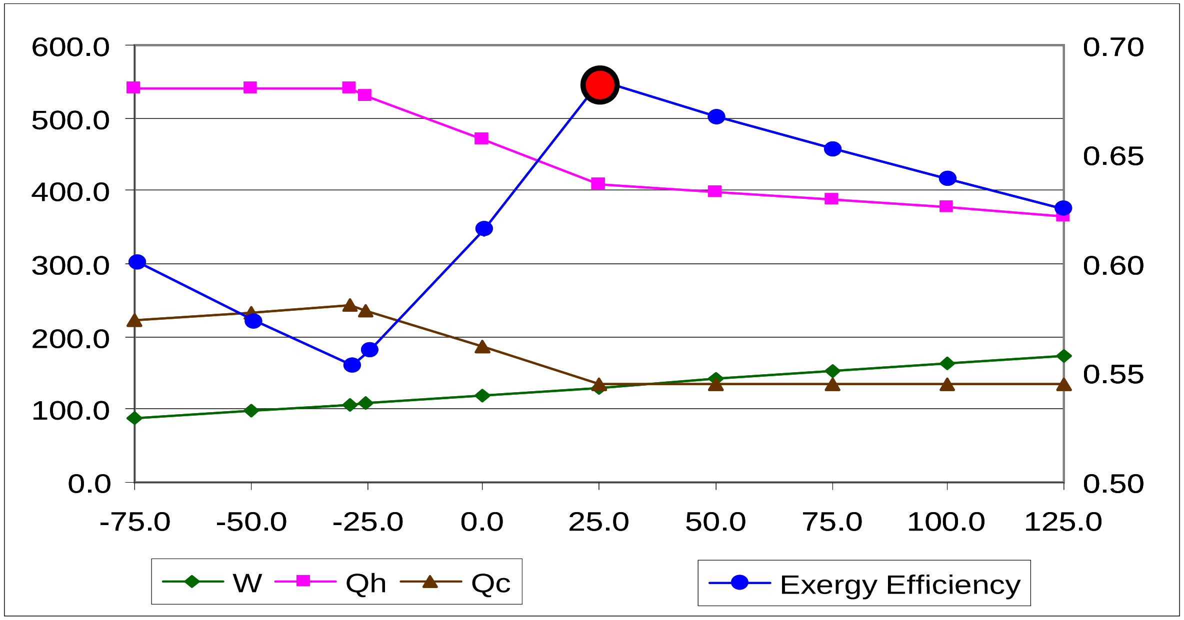
Key Information for Example 1

Table 1 Stream Data for Example 1

Stream	T_s (°C)	T_t (°C)	$\dot{m} \cdot c_p$ (kW/°C)	$\dot{Q}$ (kW)	p_s (bar)	p_t (bar)
H1	130	-75	2.0	410	1.0	2.0
C1	15	140	5.0	625	-	-
C2	-50	140	1.0	190	-	-
LP	150	150	-	-	-	-
R	-85	-85	-	-	-	-

- **Traditional Targeting**
  - $\Delta T_{\text{min}} = 10°\text{C}$, $T_{\text{Pinch}} = 25°\text{C}/15°\text{C}$
  - $Q_{\text{H,min}} = 540$ kW , $Q_{\text{C,min}} = 135$ kW
- **Parameter Values (also for Example 2)**
  - $c_{\text{p}} = 1.0$ kJ/kg°C , $k = c_{\text{p}} / c_{\text{v}} = 1.4$, $T_0 = 298$ K
- **Variation of Compressor inlet Temperature**
  - $T_{\text{comp,in}}$ from -75°C to +125°C

Calculation Results for Example 1



- **Regions for Compressor inlet Temperature**
  - From -75°C to -28.5°C: Compression entirely **below** Pinch
  - From -28.5°C to +25°C: Compression moves gradually into the above Pinch Region
  - From +25°C to +125°C: Compression entirely **above** Pinch
- **Appropriate Placement is exactly at the Pinch**

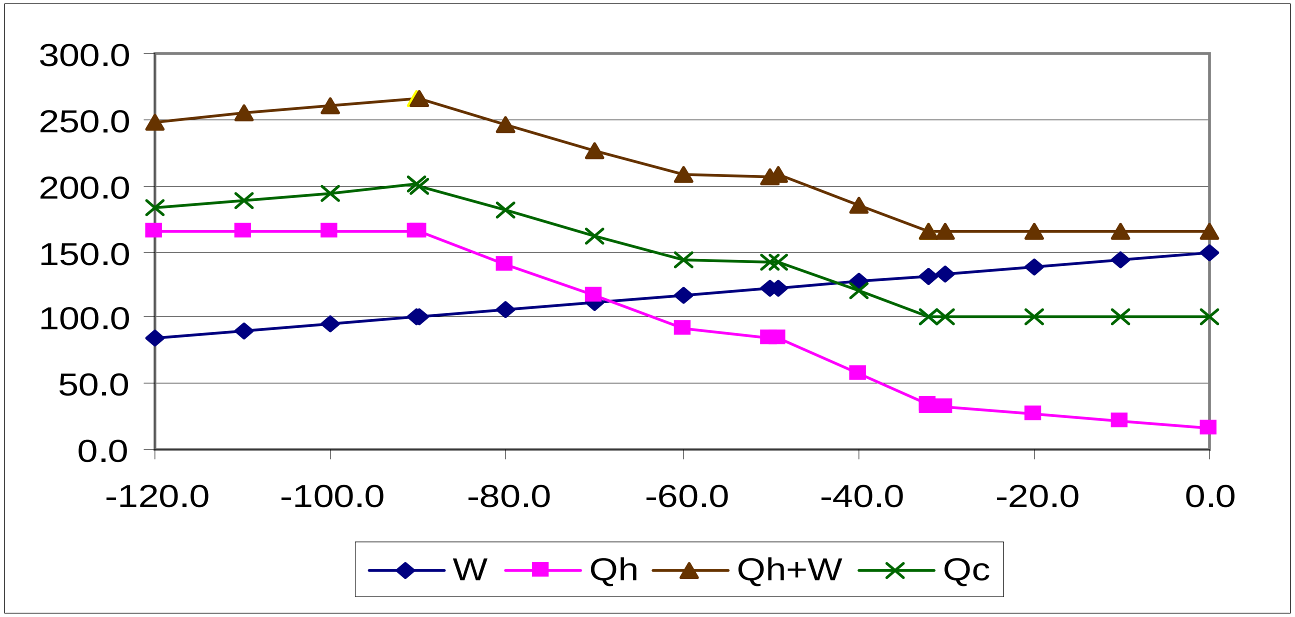
Key Information for Example 2

Table 2 Stream Data for Example 2

Stream	T_s (°C)	T_t (°C)	$\dot{m} \cdot c_p$ (kW/°C)	$\dot{Q}$ (kW)	p_s (bar)	p_t (bar)
H1	50	-160	1.5	315	-	-
H2	0	-120	2.5	300	1.0	2.0
C1	-180	-20	2.0	320	-	-
C2	-60	30	4.0	360	-	-

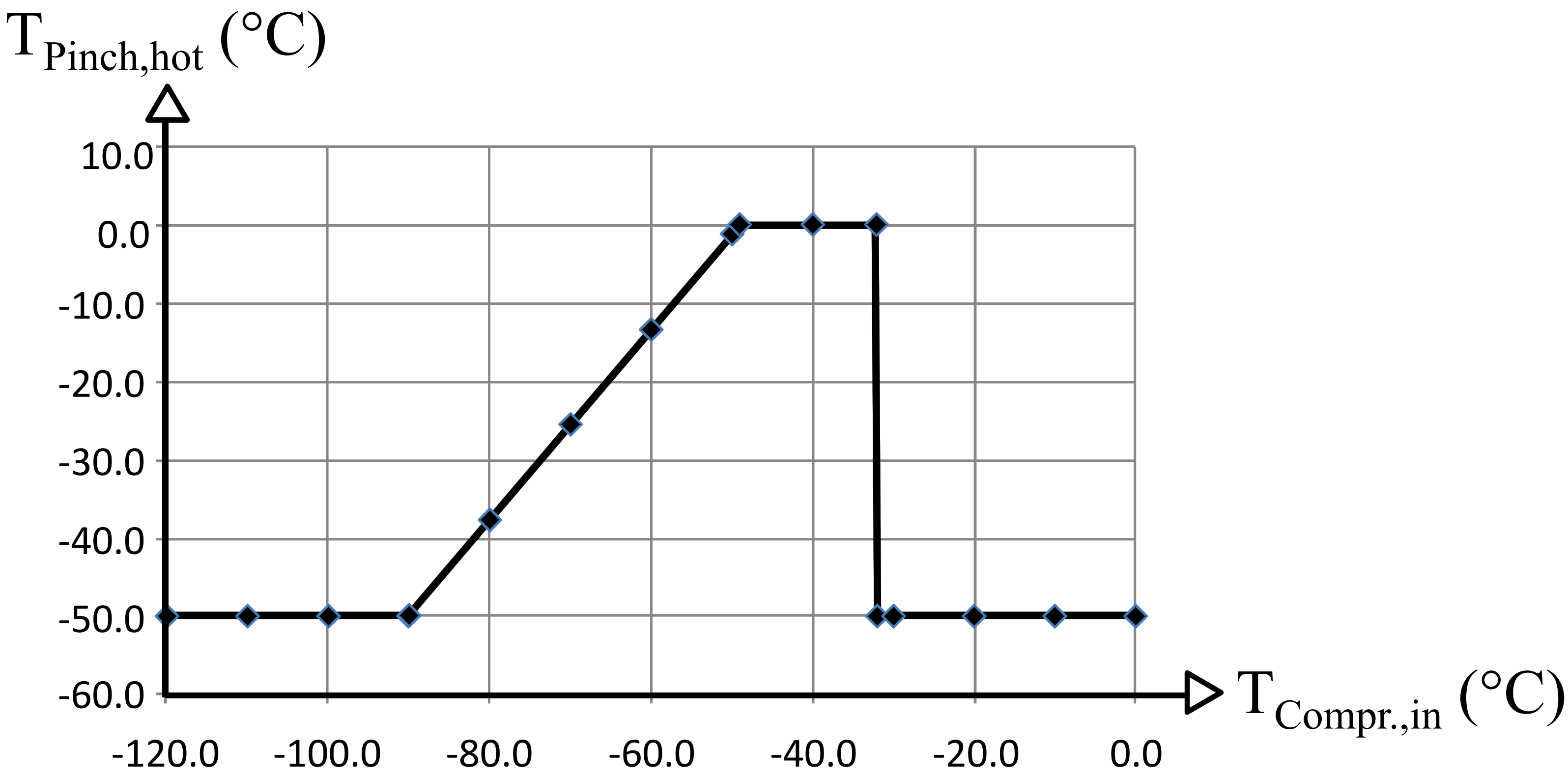
- **No Utility Data provided**
  - Focus is on Pinch Changes
  - No Exergy Calculations
- **Traditional Targeting**
  - $\Delta T_{\text{min}} = 10°\text{C}$, $T_{\text{Pinch}} = -50°\text{C}/-60°\text{C}$
  - $Q_{\text{H,min}} = 165$ kW , $Q_{\text{C,min}} = 100$ kW
- **Variation of Compressor inlet Temperature**
  - $T_{\text{comp,in}}$ from -120°C to 0°C

Calculation Results for Example 2



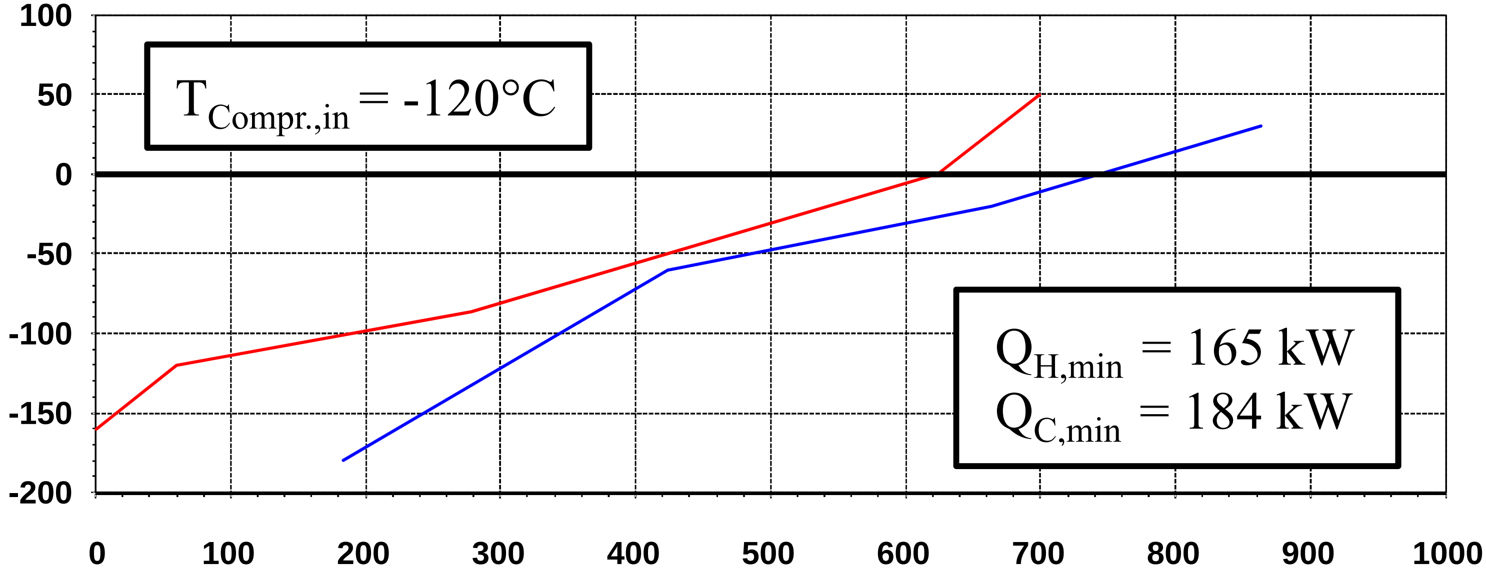
- **Regions for Compressor inlet Temperature**
  - From -120°C to -90.1°C: Compression entirely **below** Pinch
  - For Compressor inlet at -90.1°C, the outlet is -50°C (Pinch)
  - From -90.1°C to about -60°C: Pinch **follows** Compressor outlet Temperature until it reaches 0°C, when the Supply Temperature of H2 (also 0°C) **takes over** as Pinch
  - At $T_{comp,in}$ of about -32°C Pinch **jumps** back to -50°C/-60°C

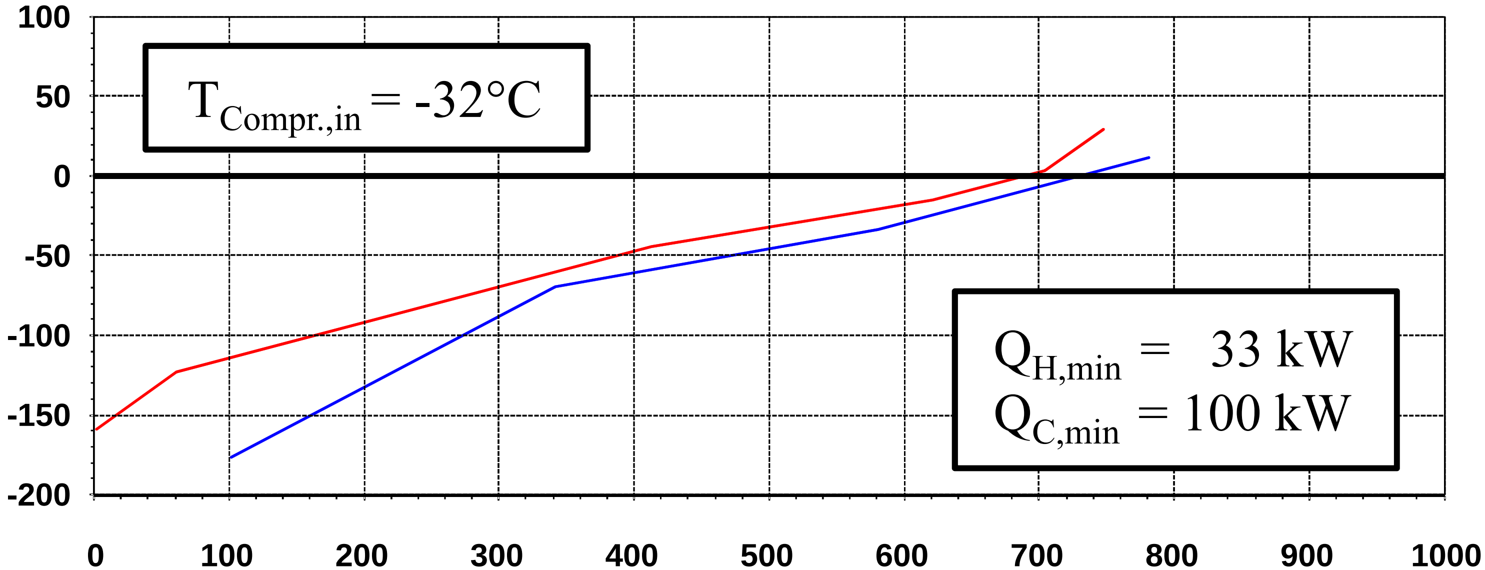
Compressor affects Pinch Temperature



Appropriate Placement vs. a moving Pinch ??

Compressor affects Composite Curves

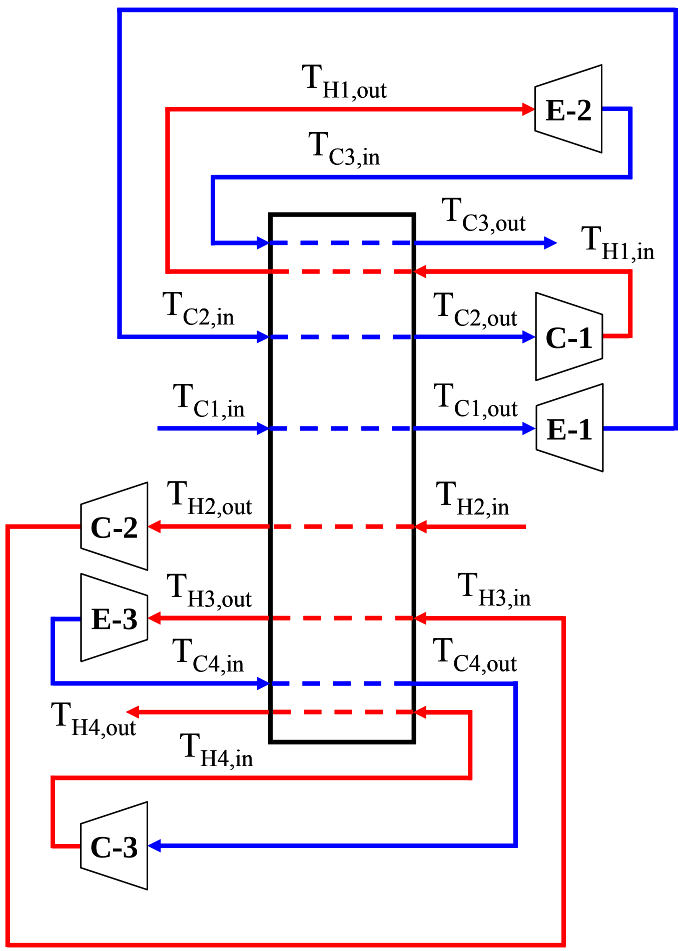




Insights obtained from the Examples

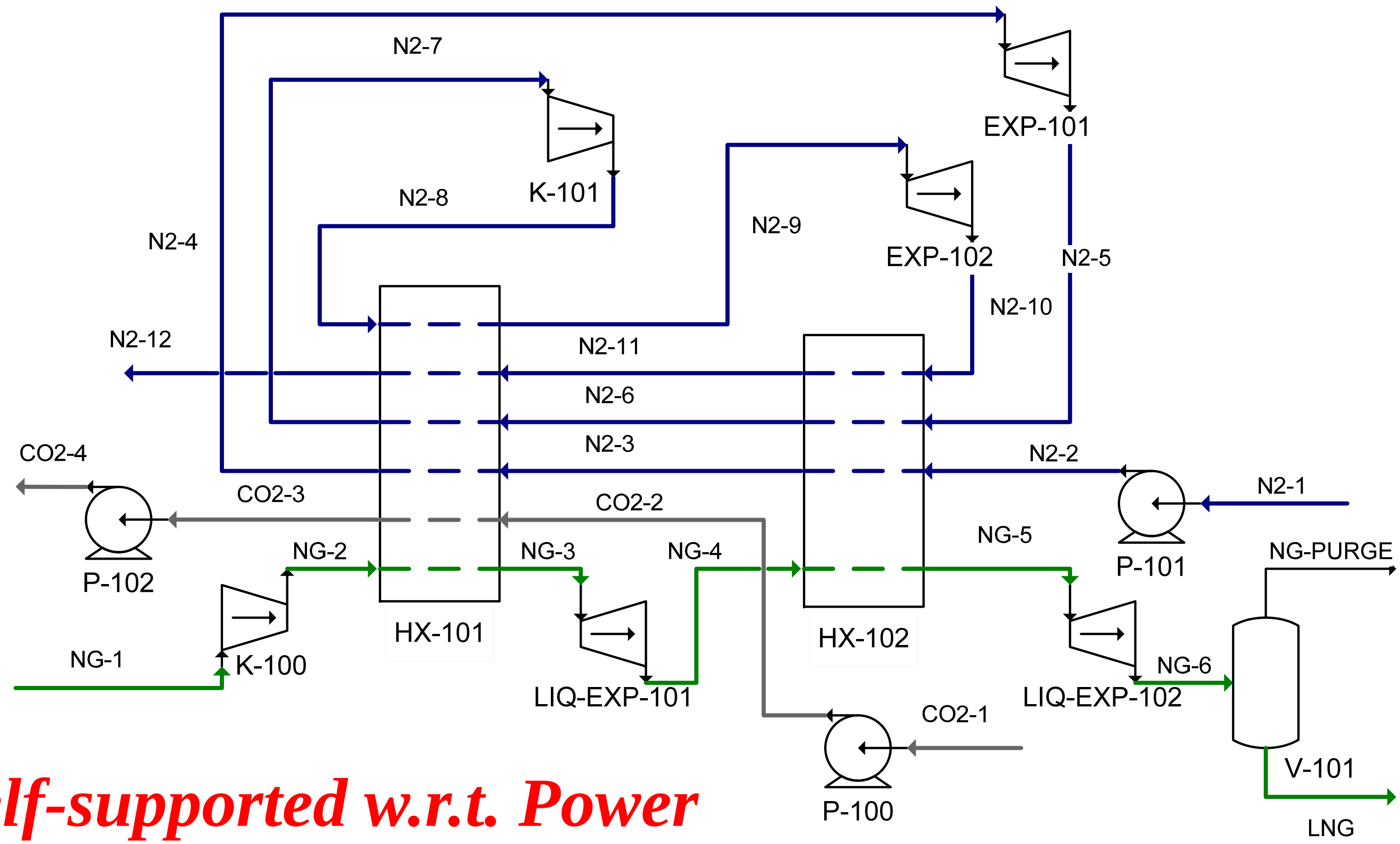
- **From Example 1**
  - Appropriate Placement of a **Compressor** is "at the Pinch", meaning Compressor inlet Temperature at the Pinch Temperature, thus delivering Heat above Pinch
  - Similar (opposite) Conclusions can be made for **Expanders**
- **From Example 2**
  - With multiple Streams some of which are subject to Pressure Changes, Stream Data will be **Floating**, not fixed
  - The **Pinch** (constantly changing) becomes less important, and it is impossible to refer to Appropriate Placement of Compressors and Expanders relative to a moving Pinch
- **The true Value of the new Insight**
  - A new **Superstructure** can be developed for Heat Recovery Problems where Compression and Expansions is included

Superstructure for the Extended Heat Recovery Problem



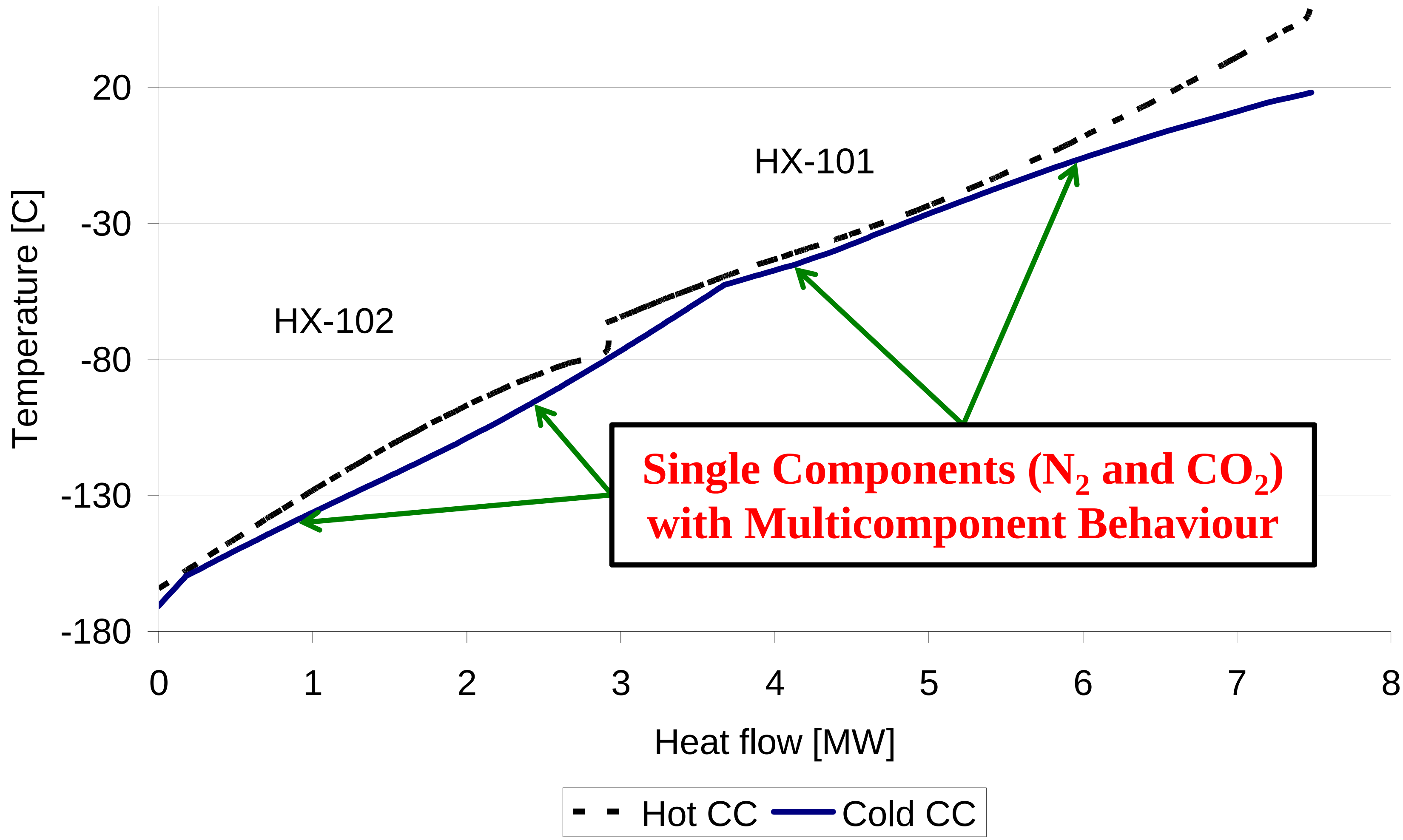
- **Consider a Hot Stream**
  - If the Supply Temperature is above Pinch, it should be **cooled** to Pinch or Target Temperature (if above Pinch)
  - If/when the Stream is at Pinch it should be **compressed** according to the new Insight (outlet Pressure free)
  - Next, it should be **cooled** to Pinch, where the next Option according to the new Insight is to **expand** the Stream (outlet Pressure free)
  - The Stream should then be **heated** to Pinch or the Target Temperature
  - A 2nd and final **compression** can be considered before **cooling** the Hot Stream to Target Temperature

Application of the new Superstructure: A novel Offshore LNG Process

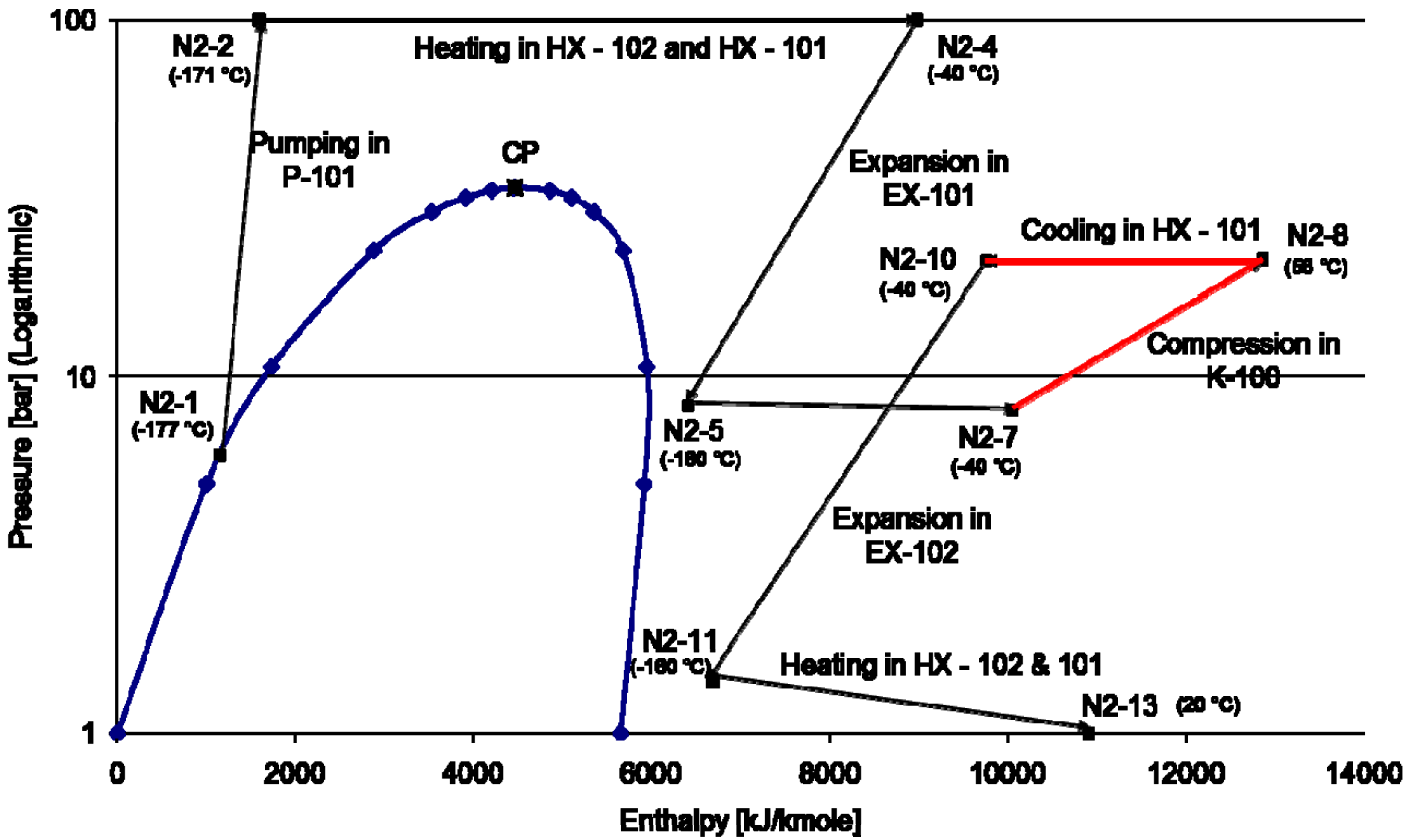


Self-supported w.r.t. Power & no flammable Refrigerants

Resulting Composite Curves



The Nitrogen "Path" Offshore



Concluding Remarks

- **Subambient** Processes have special Characteristics that require new Design Methodologies where **Pressure** and Fluid **Phase** are considered important Design Variables
- In Subambient Processes, external Cooling is provided by **Compression** and **Expansion** (Refrigeration Cycles)
- Not a big Surprise then that Compression and Expansion of **Process Streams** reduce the Need for Refrigeration
- With Compressors & Expanders, Stream Data becomes **Floating**, and the Pinch Concept as well as the Appropriate Placement of Compressors & Expanders are less useful
- A new **Superstructure** for simultaneous Heating, Cooling, Compression and Expansion has been developed
- This new Superstructure has been successfully **applied** to design an Offshore Natural Gas Liquefaction Process

Opportunities for using Optimization

- **Many challenging Tasks**
  - **Structural** Design of Single Process of a Production Chain
  - Optimizing **Operating** Variables in entire Production Chains
  - Optimization of Mixed Refrigerants **Composition**
- **Mathematical Programming ("deterministic")**
  - Strength in **Synthesis** if a clever Superstructure is available
  - Suffers from **Combinatorial Explosion** (binary variables) and **Local Optima** (non-Linearities are often non-Convex)
- **Stochastic Algorithms ("non-deterministic")**
  - Examples are many: Simulated Annealing, Genetic Algorithms, Evolutionary Search, Tabu Search, etc.
  - Can be **combined** with rigorous Process Simulation
  - Successfully applied for **Mixed Refrigerant** Optimization

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