Tool Documentation

INDUSTRIAL DECARBONIZATION TOOLKIT

https://industrialdecarb.lbl.gov/

USER GUIDE FOR PINCH HEAT INTEGRATION TOOL

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Introduction

Industrial processes often use energy for both heating and cooling to make products. For instance, in milk production, milk is heated up to 195°F for pasteurization and then cooled to 40°F for storage. This concurrent need for both heating and cooling presents an opportunity for energy optimization through heat integration between ‘needs heating’ and ‘needs cooling’ streams.

Pinch Analysis is a methodology designed to optimize processes by maximizing heat exchange while minimizing utility cooling and heating loads (Townsend & Linnhoff, 1983). It also offers insights into the optimal placement and sizing of heat pumps between process streams. For a deeper understanding of Pinch Analysis, refer to the Department of Energy (DOE) tip sheet titled “Minimize Heating and Cooling Energy Use through Process Integration”.

This Pinch Heat Integration Tool (PHIT) facilitates this optimization process by generating a pinch diagram (shifted composite curve) based on inputs for all streams requiring heating and cooling at a facility (see Fig. 1). The blue lines represent processes that need cooling, and the red lines represent processes that need heating. The overlapping region between the blue and red lines represents where heat can be effectively transferred from the processes that need cooling to the processes that need heating. The region to the left of the overlap shows the potential heat source for a heat pump. The region to the right of the overlap shows the potential heat sink for a heat pump.

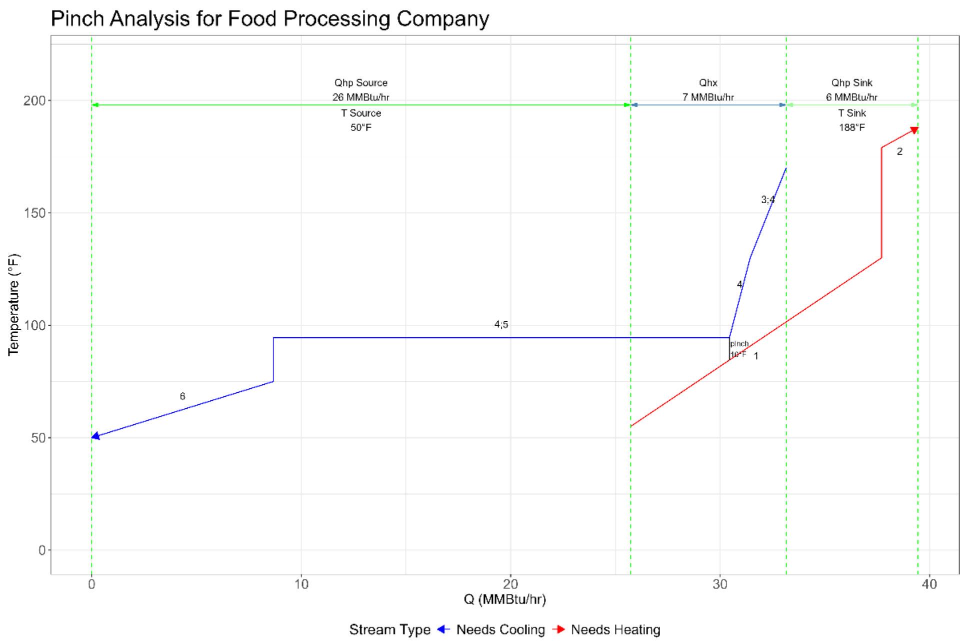


Figure 1: Facility CO_2e flow for a representative facility (MT CO_2e/yr)

In addition to producing the shifted composite curve, the tool enables simulation of heat exchangers and heat pumps between different process streams.

This guide outlines the tool's working principles and provides step-by-step guidelines on how to use it.

How to Use the Tool

The tool is split into two components:

1. Input Sheet (Excel-based)
2. Visualization and Simulation (Web-based)

The Input Sheet takes data on the streams which require heating or cooling and can be downloaded from the tool website, while the Visualization Application converts this quantitative data into a Shifted Composite Curve and allows for further analysis of heat pump and heat exchanger system integration. This section outlines how to navigate and use each of the two components.

PHIT – Input Sheet

The following inputs are required for each stream:

1. Stream Number: An indexing number for each stream.
2. Stream Name: Name for each stream (e.g. Hot Water, Milk, etc.)
3. Inlet Temperature (T_{in}): The inlet temperature for each stream.
4. Required Outlet Temperature (T_{out}): The required outlet temperature for each stream.
5. Required Energy (Q): The total heating or cooling energy required for each stream to achieve the required outlet temperature. It can be calculated for non-condensing streams using Eqn. 1 and for condensing streams using Eqn.2.

$$\text{Eqn. 1: } Q = \dot{m}C_p(T_{out} - T_{in})$$

$$\text{Eqn. 2 } Q = \dot{m}\left(h_{fg}\right)$$

6. Stream Type: Specifies if the stream requires heating or cooling.

The inputs are entered in the table as shown in Fig 2.

Stream No.	Stream Name	Tin °F	Tout °F	Q MMBtu/hr	Stream Type
1	Hot Water	55	130	11.98	Needs Heating

Figure 2: Input Sheet

Note: The units for temperature and thermal load can be modified using a dropdown menu or specified explicitly.

PHIT – Visualization and Simulation

The Visualization and Simulation components of the tool is hosted online and can be accessed here. The online tool has three sections:

1. Main Pinch
2. Heat Exchanger
3. Heat Pump

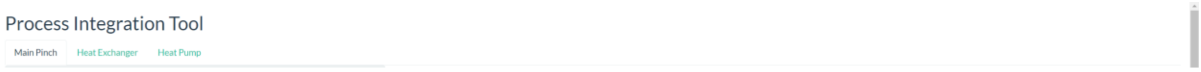


Figure 3: PHIT Visualization Application

Section 1: Main Pinch

Figure 4 shows the layout for the 'Main Pinch' page of the tool. This page takes the excel sheet filled earlier to generate a pinch diagram (Shifted Composite Curve).

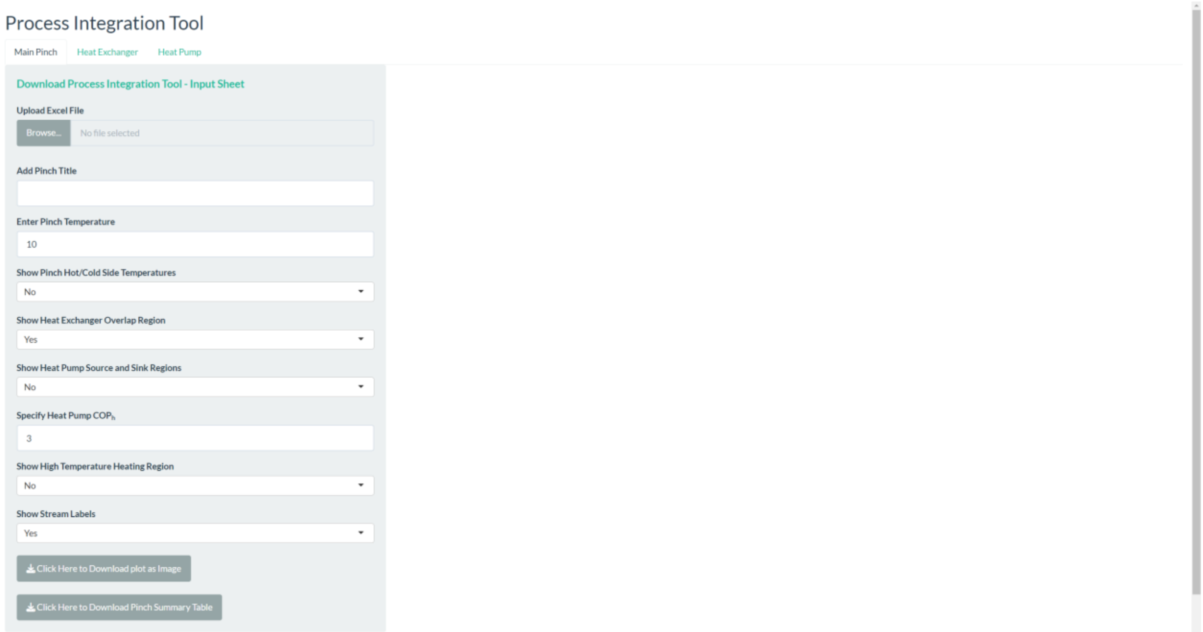
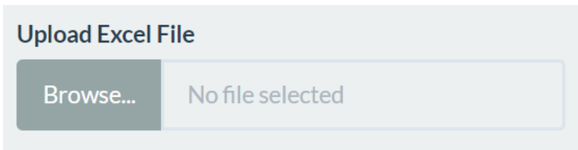


Figure 4: PHIT Main Screen

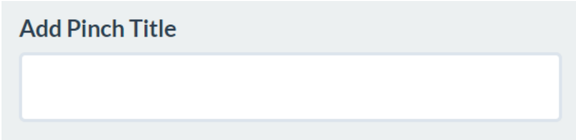
Inputs

1. **Upload 'PHIT – Input Sheet' Excel file**



Click the "Browse" button next to the "Upload Excel File" label to upload the filled out 'PHIT Input Sheet' to the web tool.

2. **Add Pinch Title**



Enter the title for the Pinch Diagram in the text box. This input is used to formulate the caption for the Pinch Diagram.

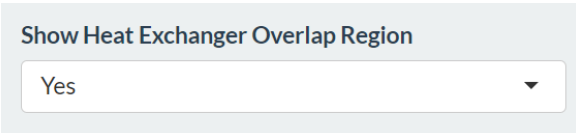
3. **Enter Pinch Temperature**

Specify the pinch temperature for the integration.

4. **Show Pinch Hot/Cold Side Temperatures**

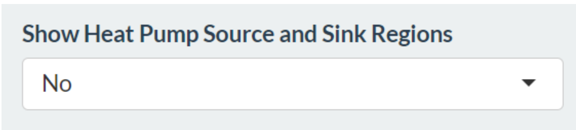
Toggle on/off the overlay for hot and cold side temperatures for the pinch diagram.

5. **Show Heat Exchanger Overlap Region**



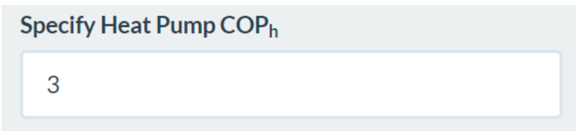
Toggle on/off the overlay for pinch overlap region which shows the heat exchange potential.

6. **Show Heat Pump Source and Sink Regions**



Toggle on/off the overlay for source and sink region for heat pump integration.

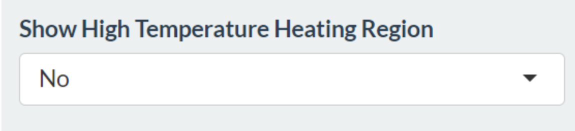
7. **Specify Heat Pump COP_h**



Enter heating Coefficient of Performance (COP_h) for the heat pump. This is used to calculate the heat pump sink potential.

$$COP_h = \frac{Heat\ Output\ (Q_h)}{Input\ Power\ (W_{in})}$$

8. **Show High Temperature Heating Region**

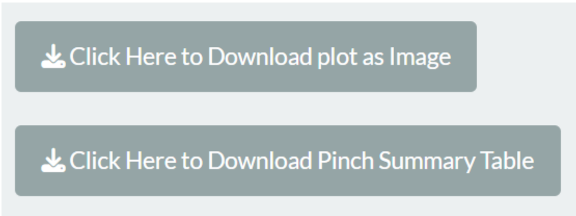


Toggle on/off the overlay for high temperature heating region which can not be serviced by a heat pump.

9. **Show Stream Labels**

Toggle on/off the overlay for stream numbers on the composite curves.

10. **Download Pinch Analysis Diagram and Summary Results**



To download the Pinch Diagram as an image, click the "Click Here to Download as Image" button. Additionally, to download the summary results as a .csv, click the "Click Here to Download Pinch Summary Table."

Outputs

1. **Shifted Composite Curve**

This diagram shows the Shifted Composite Curve for the specified streams. It displays all the needs heating and needs cooling streams on a single diagram with the specified pinch temperature.

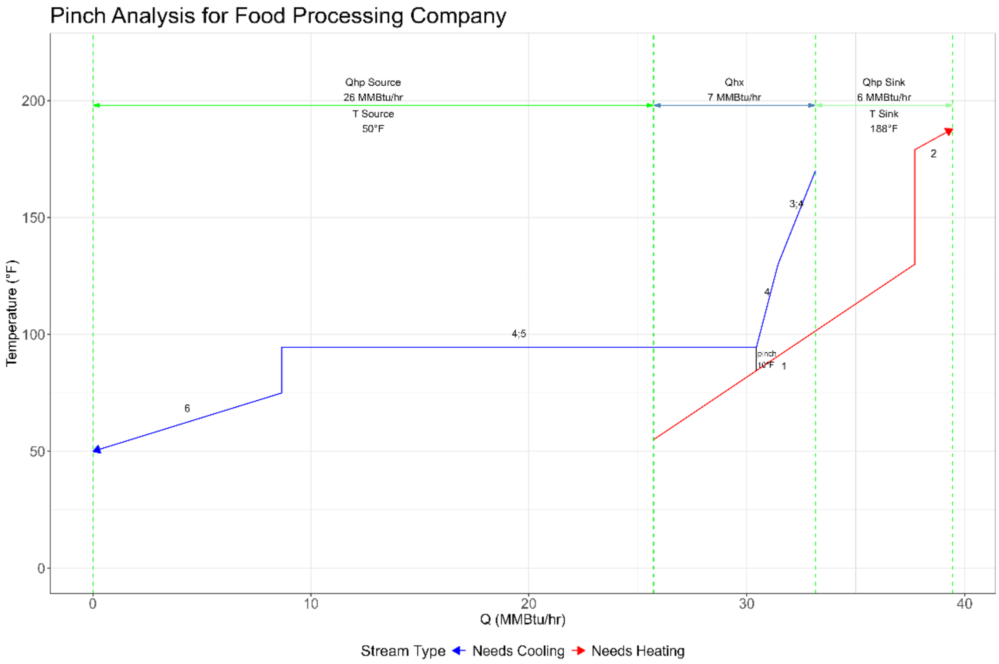


Figure 5: Shifted Composite Curve

2. Summary Table – Results

This table provides all the useful results from the pinch diagram.

Pinch Heat Integration Tool - Summary Table

Title	Value	Units
Heat Exchange Potential	7.4	MMBtu/hr
Heat Pump - Source Potential	25.7	MMBtu/hr
Heat Pump - Source Temperature	50	°F
Heat Pump - Sink Potential	6.3	MMBtu/hr
Heat Pump - Sink Temperature	188	°F
High Temperature Heating Requirement	0	MMBtu/hr
Heat Pump Source Streams	6;4;5	
Heat Exchange Streams - Needs Cooling	4;5;3	
Heat Exchange Streams - Needs Heating	1	
Heat Pump Sink Streams	1;2	
High Temperature Heating Streams	2	

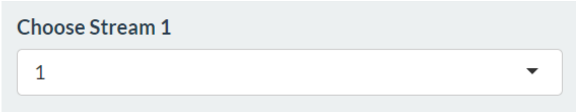
Figure 6: Summary of Results

Section 2: Heat Exchanger

This section works in conjunction with Section 1. After uploading the input sheet in Section 1, this use can simulate the heat exchange potential between two streams using a specified heat exchanger effectiveness.

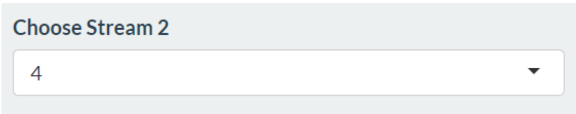
Inputs

1. **Choose Stream 1**



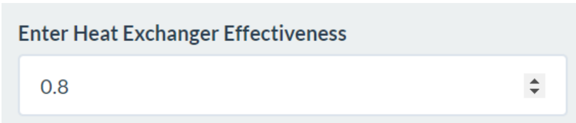
Choose the first stream for the heat exchanger. It can be a needs heating or a needs cooling stream.

2. **Choose Stream 2**



Choose the second stream for the heat exchanger. It can be a needs heating or a needs cooling stream but it must be opposite of the first stream.

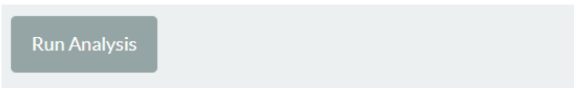
3. **Enter Heat Exchanger Effectiveness**



Specify heat exchanger effectiveness. Effectiveness is defined as the ratio between actual and maximum heat exchange.

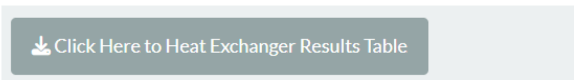
$$eff = \frac{mc_{p,hot}(T_{h,in} - T_{h,out})}{mc_{p,min}(T_{h,in} - T_{c,in})} = \frac{mc_{p,cold}(T_{c,out} - T_{c,in})}{mc_{p,min}(T_{h,in} - T_{c,in})}$$

4. **Run Analysis**



After entering the inputs, press this button to run the calculation.

5. **Download Results**



Click this button to download the results from the heat exchanger calculation as a .csv file.

Outputs

1. Visual Output

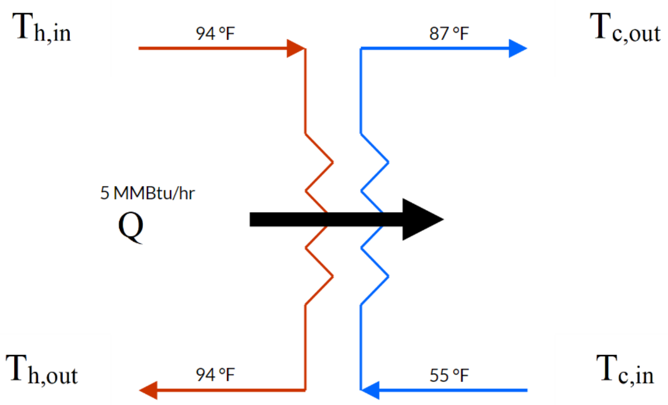


Figure 7: Heat Exchanger Results

This visual output shows the temperatures for the hold and cold streams and the total heat exchange.

2. Summary Table – Inputs & Results

Streams Data (Inputs)

S.No.	Stream Name	Temp,in	Temp,out	Q	Stream Type	Mass Capacitance
(-)	(-)	(°F)	(°F)	(MMBtu/hr)	(-)	(MMBtu/hr °F)
1	Hot Water	55	130	11.98	Needs Heating	0.16
5	Ammonia Condensing	94	94	21.77	Needs Cooling	Inf

Results Table

Title	Value	Units
Th,in	94.5	°F
Th,out	94.5	°F
Tc,in	55	°F
Tc,out	86.6	°F
Q,hx	5.04	MMBtu/hr

Figure 8: Heat Exchanger stream inputs and results

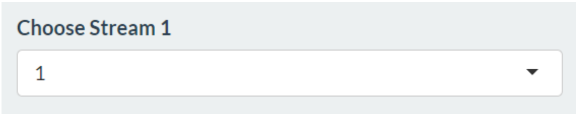
The summary table is split in two sections. First the ‘Streams Data (Inputs)’ shows the required temperature and heating power for the selected streams. The second section, ‘Results Table’, shows the temperatures and heating power with the use of the heat exchanger.

Section 3: Heat Pump

This section works in conjunction with Section 1. After uploading the input sheet in Section 1, this use can simulate the heat pump potential between two streams.

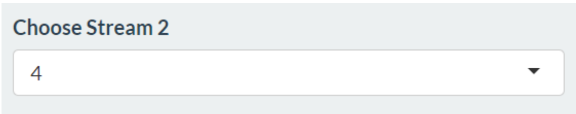
Inputs

1. **Choose Stream 1**



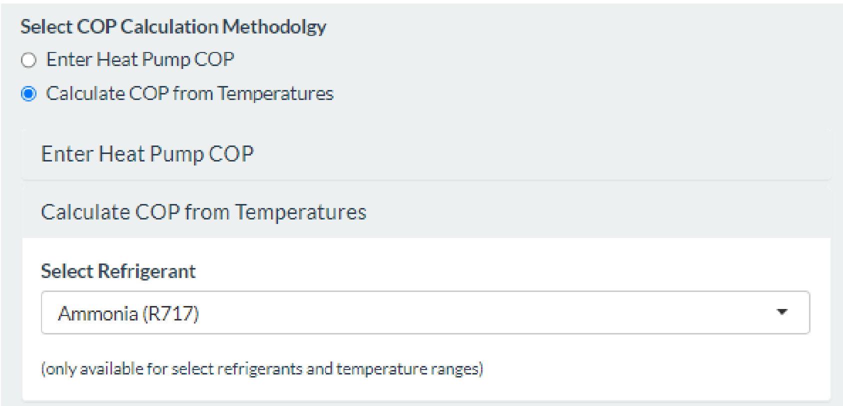
Choose the first stream for the heat pump. It can be a needs heating or a needs cooling stream.

2. **Choose Stream 2**



Choose the second stream for the heat pump. It can be a needs heating or a needs cooling stream but must be the opposite of the first stream.

3. **Select COP Calculation Methodology**



To simulate the performance of the heat pump between the two specified streams, the COP for the heat pump must be specified. This can be done explicitly by entering a COP value or calculated automatically using relationship described by Oluleye et al. (Oluleye et al., 2016). The relationship uses the temperature lift and refrigerant information to calculate the actual COP from ideal COP using the following methodology:

$$COP_{h,ideal} = \frac{T_{cond}}{T_{cond} - T_{evap}}$$

$$COP_{h,actual} = \eta \times COP_{ideal}$$

The Carnot factor (η) is calculated as a function of the condenser (T_{cond}) and evaporator (T_{evap}) temperature using the following relationship:

$$\eta = \beta_0 + \beta_1 T_{cond} + \beta_2 T_{evap} + \beta_3 T_{cond} T_{evap} + \beta_4 T_{cond}^2 + \beta_5 T_{evap}^2$$

The regression relationship is based on the data provided by Oluleye et al. (Oluleye et al., 2016). β values for this relationship for each refrigerant are provided in Table 1.

Refrigerant	Ammonia (R717)	Water (R-718)	Propane (R-290)	Propylene (R-1270)	n-Butane (R600)	isoButane (R600a)
β_0	6.36E-01	7.00E-01	6.03E-01	5.53E-01	6.50E-01	6.56E-01
β_1	9.01E-04	-1.16E-03	3.02E-03	4.54E-03	1.41E-03	1.27E-03
β_2	3.06E-03	1.77E-03	2.23E-03	2.77E-03	1.59E-03	1.69E-03
β_3	-2.90E-05	-4.08E-06	-1.06E-05	-2.51E-05	2.21E-06	4.40E-06
β_4	-1.56E-05	2.01E-06	-6.20E-05	-7.25E-05	-3.11E-05	-3.65E-05
β_5	3.64E-06	-2.64E-09	-2.78E-07	-6.49E-19	1.68E-06	-1.10E-07

The relationship calculates the heating COP for the heat pump, whereas the cooling COP is calculated using:

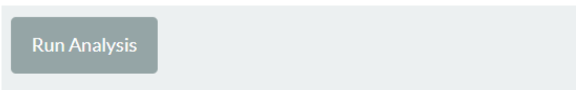
$$COP_{c,actual} = COP_{h,actual} - 1$$

T_{cond} and T_{evap} are assumed at ΔT = 10 °F from the leaving fluid temperature.

It can be run for the following refrigerants:

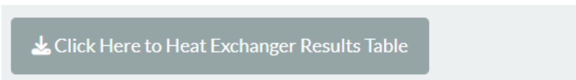
- Ammonia (R717)
- Water (R-718)
- Propane (R-290)
- Propylene (R-1270)
- n-Butane (R600)
- isoButane (r600a)

4. Run Analysis



After entering the inputs, press this button to run the calculation.

5. Download Results



Click this button to download the results from the heat pump calculation as a .csv file.

Outputs

1. **Visual Output**

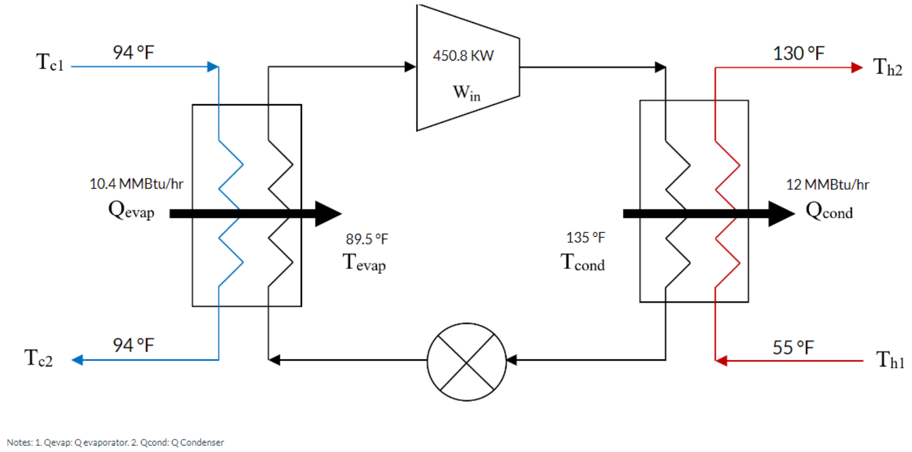


Figure 9: Heat Pump Results

This visual output shows the temperatures for the hot and cold streams and the compressor power input for the heat pump.

2. Summary Table – Inputs & Results

Streams Data (Inputs)

S.No.	Stream Name	Temp,in	Temp,out	Q	Stream Type	Mass Capacitance
(-)	(-)	(°F)	(°F)	(MMBtu/hr)	(-)	(MMBtu/hr °F)
1	Hot Water	55	130	12	Needs Heating	0.2
5	Ammonia Condensing	94	94	21.8	Needs Cooling	Inf

Results Table

Title	Value	Units
Tc,1	94.5	°F
Tc,2	94.5	°F
Th,1	55	°F
Th,2	130	°F
Q,evap	10.4	MMBtu/hr
Q,cond	12	MMBtu/hr
W,in	1.54	MMBtu/hr
COP	7.79	

Figure 10: Heat Pump stream inputs and results

The summary table is split in two sections. First the 'Streams Data (Inputs)' shows the required temperature and heating power for the selected streams. The second section, 'Results Table', shows the temperatures, heating, cooling, and compressor power for the heat pump.

Worked Example

This section outlines how to perform and interpret the Pinch Analysis using a worked example. The procedure can be split into three steps:

1. Collect Data
2. Create Pinch Diagram
3. Interpret Results

Collect Data

The required data to conduct Pinch Analysis includes the inlet (T_{in}) and outlet (T_{out}) temperature for each stream, the heating load (Q) and the stream type. For non-process streams, such as wastewater, the T_{out} can be taken as ambient temperature. Table 1 shows the streams at a representative food processing plant.

Stream No.	Stream Name	Tin °F	Tout °F	Q MMBtu/hr	Stream Type
1	Hot Water	55	130	11.98	Needs Heating
2	Scalding Water	179	188	1.75	Needs Heating
3	Compressor Oil	170	130	0.60	Needs Cooling
4	Ammonia Desuperheating	170	94	2.11	Needs Cooling
5	Ammonia Condensing	94	94	21.77	Needs Cooling
6	Waste-Water	75	50	8.67	Needs Cooling

Table 1: Stream data

Create Pinch Diagram

Figure 11 shows the Pinch diagram for the heat loads specified earlier. The blue lines represent processes that need cooling, and the red lines represent processes that need heating. The overlapping region between the blue and red lines represents where heat can be effectively transferred from the processes that need cooling to the processes that need heating. The region to the left of the overlap shows the potential heat source for a heat pump. The region to the right of the overlap shows the potential heat sink for a heat pump.

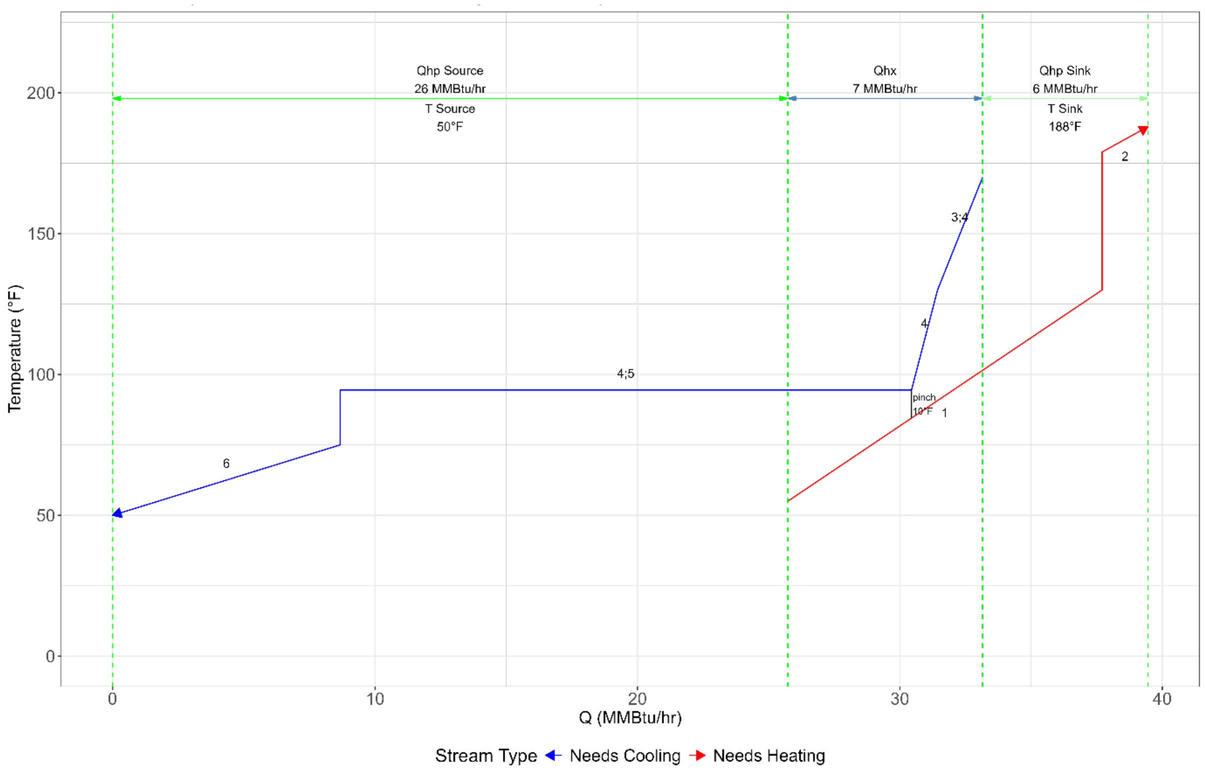


Figure 11: Pinch Diagram - Food Processing Plant

Interpret Results

The overlap region suggests that there is an opportunity for heat exchange for the Hot Water stream with the Ammonia Condensing, Ammonia Desuperheating and Compressor Oil streams. A total of 7 MMBtu/hr of heat exchange is possible through this integration.

For heat pump integration, the pinch suggests the availability of a total of 26 MMBtu of available source for heat pump. A source temperature of 50 F is required to obtain all of this heat. Here, engineering judgment is required to select the source temperature which results in maximum possible heat reclaim at the lowest cost. Decreasing source temperature results in a reduction in heat pump COP, therefore there is a tradeoff between source heat quantity and the heat pump COP. The required sink heat for the heat pump is 6 MMBtu, since this temperature is required at different temperature levels, 130 F for the hot water stream and 188 F for the scalding water stream, multi-stage heat pumps can be used to reduce electricity usage.

Through an integrated heat pump design, with heat reclaim and heat pump, the facility can reduce its Natural Gas consumption by about 13 MMBTu/hr. The integration also eliminates 7 MMBtu/hr of cooling requirement. On an annual basis with 8000 operating hours, this would reduce 104,000 MMBtu of Natural Gas and 16,408,000 kWh of electricity consumption.

Appendix 1 – Computational Method

(Adapted from DOE tip sheet, "Minimize Heating and Cooling Energy Use through Process Integration". Complete code available at: https://github.com/IACDecarb/IAC-Decarb-Tools)

The thermal energy requirements of each process can be visualized by plotting them on temperature versus thermal energy demand axes. Using this method, Table 2 shows three processes that need cooling and three processes that need heating. These processes are then plotted in Figure 12. Further, *Table 2* also contains a column termed "mass capacitance" which is a product of a stream's mass flow rate (ṁ) and specific heat (C_p); mass capacitance of a stream is later utilized to determine the feasibility of heat transfer between two streams in a heat exchanger network.

Table 2: Process streams, their mass capacitance, inlet and outlet temperatures, and heat loads

Stream Type	Process	Mass Capacitance (MMBtu/hr-°F)	Inlet Temperature (°F)	Outlet Temperature (°F)	Stream Heat Load (MMBtu/hr)
Needs Cooling	Pc1	0.4	70	35	14
	Pc2	0.5	105	95	5
	Pc3	0.6	160	35	75
Needs Heating	Ph1	0.5	70	90	10
	Ph2	0.6	60	160	60
	Ph3	0.2	70	270	40

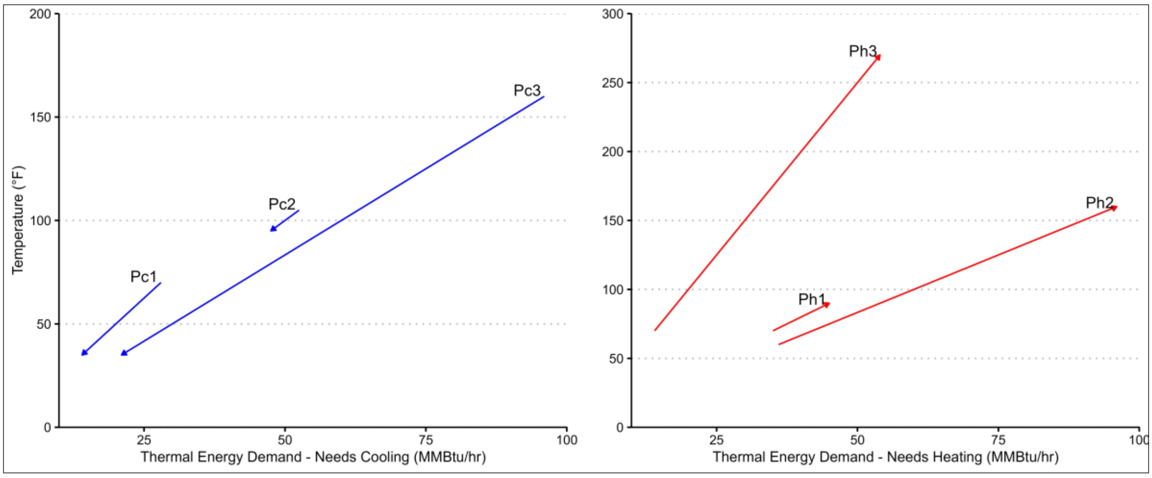


Figure 12: Process curves for the processes in Table 2. Note that the horizontal width of each process stream is fixed by the thermal energy demand of the stream. However, the horizontal position of each process curve is not fixed; thus, these curves could be shifted right or left

Next, composite curves for the 'processes that need cooling' and 'processes that need heating' are constructed. To do so, temperature points are sorted in ascending order and the thermal energy requirement of each interval is calculated. For example, the 'processes that need cooling' temperature intervals are shown in Figure 2. The energy requirements of the first two temperature intervals are then calculated as:

Heat $Load_{70\text{-}35}$ (Pc1, Pc3) $= m_1 C_{pPc1} \times \Delta t_{70\text{-}35} + m_3 C_{pPc3} \times \Delta t_{70\text{-}35}$

$= 0.4 \times (70\text{-}35) + 0.6 \times (70\text{-}35)$

= 35 MMBtu/hr

Heat $Load_{95\text{-}70}$(Pc3) $= m_3 C_{pPc3} \times \Delta t_{95\text{-}70}$

$= 0.6 \times (95\text{-}70)$

= 15 MMBtu/hr

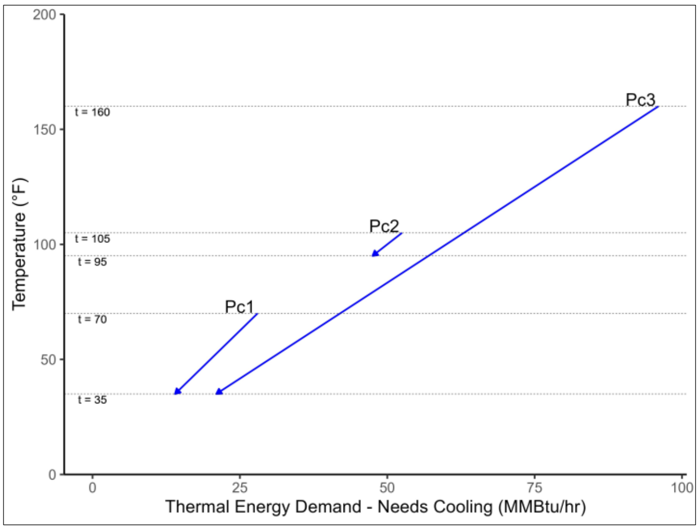


Figure 13: Temperature steps in the 'processes that need cooling' streams.

This process is then repeated for all the temperature intervals in the 'processes that need cooling' curves. This results in a single "processes that need cooling' composite curve. The process is repeated for all the temperature intervals in the 'processes that need heating' curves. This results in a single "processes that need heating' composite curves. The results are shown in Table 2 and Figure 3. In *Table 3*, the temperatures are sorted in descending order for "processes that need cooling" and in ascending order for "processes that need heating" for better clarity.

Table 3: Stream heat loads for composite curves

Stream	Process	Mass Capacitance (MMBtu/hr-°F)	Inlet Temperature (°F)	Outlet Temperature (°F)	Stream Heat Load (MMBtu/hr)
Needs Cooling	Pc3	0.6	105	160	33
	Pc2, Pc3	1.1	95	105	11
	Pc3	0.6	70	95	15
	Pc1, Pc3	1	35	70	35
Needs Heating	Ph2	0.6	60	70	6
	Ph1, Ph2, Ph3	1.3	70	90	26
	Ph2, Ph3	0.8	90	160	56
	Ph3	0.2	160	270	22

Total	-	-	-	**204**

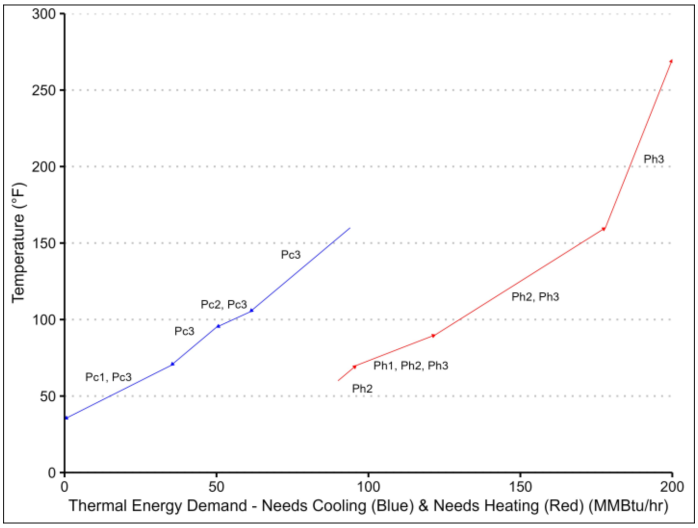


Figure 14: Processes that 'need cooling' and processes that 'need heating' composite curves. Note, as before, the horizontal positions of these composite curves are not fixed; the curves could be shifted right or left.

After plotting the heating and cooling curves on a single diagram, the 'needs heating' composite curve is shifted horizontally until the minimum difference between the two curves is the minimum temperature (t_{min}) difference identified for cost-effective heat transfer. *Figure 15* shows the shifted "needs heating' composite curve (in solid red) based on a minimum temperature difference of 20°F. The original 'needs heating' curve is shown in dotted red. The quantity and location of the minimum temperature difference are called the "pinch point". Larger minimum temperature differences (for example, 40°F) result in smaller, less-expensive heat exchangers, but reduce the energy that can be transferred.

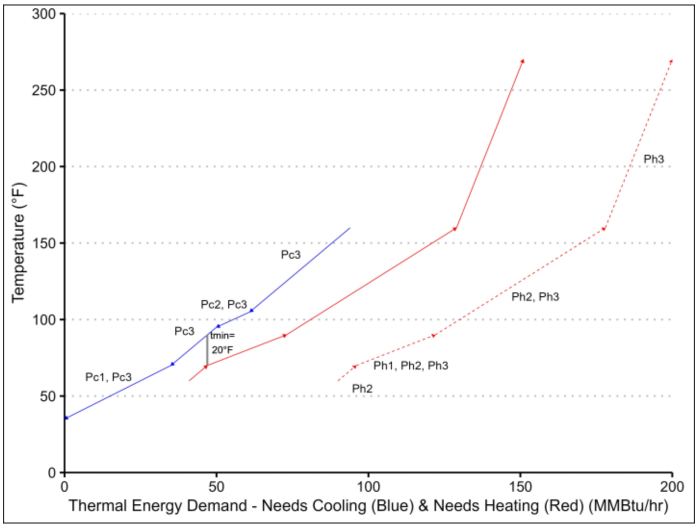


Figure 15: Shifted Composite Curves

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