Assignment 4: Pinch analysis

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Subjects and objectives of this assignment

- Setting energy targets for a heat integration problem using graphical and tabular methods
- Techno-economic optimization of heat recovery by calculating the trade-off between capital and energy costs in a heat integration problem
- Factors affecting the application of heat exchanger network designs
- Brief introduction to heat integration in batch processes

Final product
A report of maximum 10 pages

Background literature (on Moodle)
Smith, Robin (2005): Chemical Process: Design and Integration, ISBN: 978-0-471-486817

Further Reading

1. Fesanghary, M., Damangir, E., and Soleimani, I. (2009): Design optimization of shell and tube heat exchangers using global sensitivity analysis and harmony search algorithm. Appl. Therm. Eng. 29, 1026–1031.
2. Kemp, I. C.; Lim, J. S.: Pinch Analysis for Energy and Carbon Footprint Reduction. User Guide to Process Integration for the Efficient Use of Energy. 3rd Edition, 2020.
3. Klemeš, J. (Editor): Handbook of Process Integration (PI), Minimisation of Energy and Water Use, Waste and Emissions. 1st Edition, 2013. Available online in the UNIGE library

Submission date
The report has to be submitted into Moodle on Wednesday 20th March 2024 **at 17:00 at latest**. If you cannot submit on time, please discuss the reasons with the coordinators in advance (not on the day of the submission).

Debriefing
The debriefing of the assignment will take place on Friday 22nd March 2024 at 8:15.

Exercise 1 – Energy targeting (20 points)

In the process flowsheet depicted in Fig.1, a reactant combined with the recycle stream enters the reactor. Product stream and a reaction mixture stream leave the reactor. The Reaction mixture stream is preheated before it is fed to the separator and the Product stream and the Recycling Stream are cooled after leaving the separator.

You will conduct a pinch analysis for the process flow sheet depicted in Figure 1. The temperature difference (ΔTmin) has been set to 10°C. You will thereby apply two different methods (see below, part 1 and part 2).

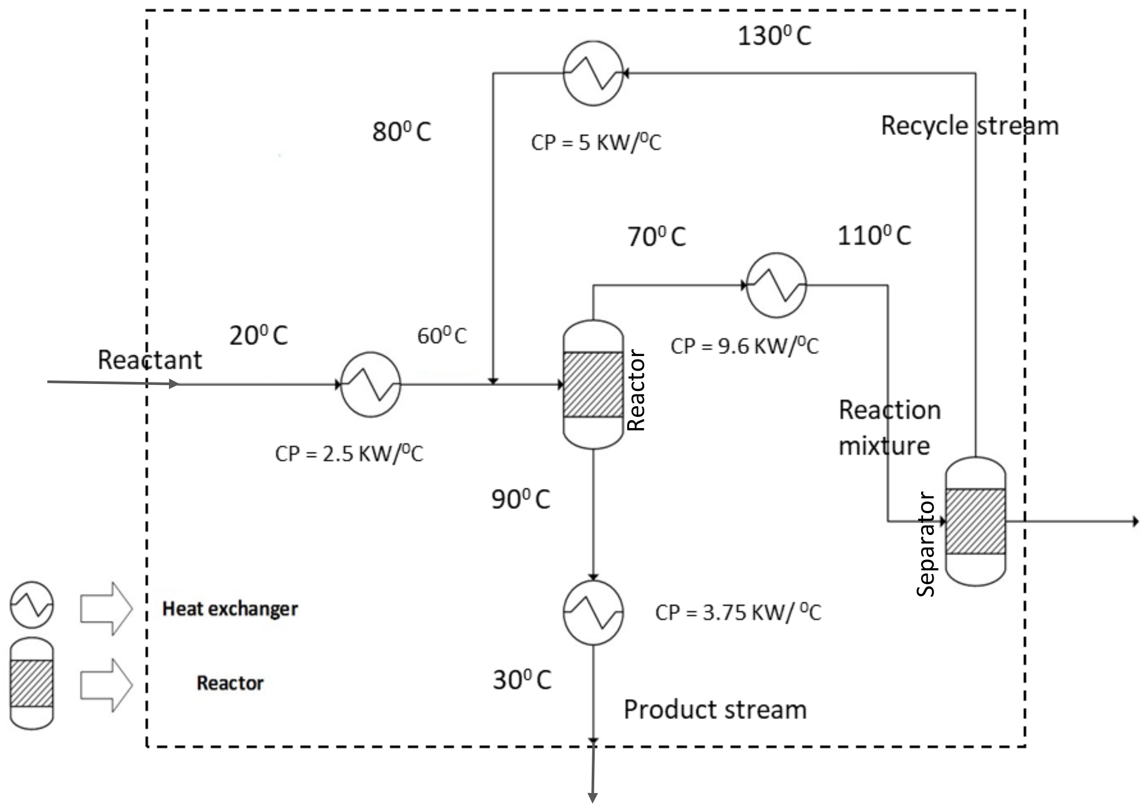


Figure 1 Process flow sheet

1) Composite curve (**7.5 points**)

To obtain an overview of all hot and cold streams, best start by preparing a population stream table.

a) Fill in the stream data table in the Excel file for all hot and cold streams (**1 points**)
b) Draw a table and plot the so-called hot composite curve using the prepared Excel template (**1.5 point**)
Hint: Make a table distinguishing the temperature intervals and insert the flows as arrows (see lecture). Start by writing down the hot streams' temperatures from low to high; we assume that the enthalpy H of the stream of 30ºC is zero.
c) Draw a table and plot the so-called cold composite curve using the prepared Excel template (**1 points**)

Hint: Start by writing down the cold streams' temperatures from low to high. By analogy with the approach chosen for the hot composite curve you can start the cold composite curves at an enthalpy of zero. You will then see that the hot and the cold composite curves cross! Next, try to shift the cold composite curve by increasing the enthalpy of the cold composite curve at its lowest temperature (instead of zero) until you respect the ΔTmin at pinch point! You can do so by trial and error to determine the cold duty that corresponds to ΔTmin=10 °C. The expected cold duty lies between 80 and 90 kW.

Once you have an estimate for the cold utility, the position of both your hot and your cold composite curve are defined in the T-H-diagramme. At this point you can "read" the result of hot utilities from the graph (see slides). Using this insight, please calculate the hot utilities in cell C25 of the template.

d) Draw another table with shifted temperature, (**1 point**) and plot the shifted composite curves for hot and cold streams. (**1 point**). Determine the pinch temperature (**1 points**).
   Determine the minimum hot and cold utility from this curve (you can read the values by hovering over the curve). (**1 point**). (This is an alternative approach to what you have done in section 1-c).

2) Problem table algorithm (**10.5 points**)
   a) Fill in the problem table by dividing the problem into temperature intervals. (**1 points**)
      In each shifted temperature interval, calculate the heat balance. (**2 points**)
      Identify heat surplus or deficit in each interval. (**1.5 points**)
   b) Complete the problem table cascade by cascading any surplus heat from high to low temperature (**1.5 points**)
   c) Heat flows cannot be negative, so add heat to make them at least 0 in a new problem table cascade. (**0.5 points**)
      Plot the Grand composite curve. (**1.5 points**)
   d) Using the table determine the pinch temperature (**1 points**). Determine the minimum hot and cold utility. (**1.5 points**)

3) Compare the results (Pinch point and minimum energy required) from part 1 and part 2. What is the advantage of each method? (**2 points**)

Exercise 2 - The Trade-Off Capital – Energy (20 points)

Suppose you are a process engineer and you are in charge of implementing energy efficiency measures in your plant. Suppose also that you have to deal with a limited budget. Your instinct tells you that the first place to look up is the exothermic reaction process depicted in Figure 2. Your first assessment led to the conclusion that you can save hot utility use (steam) by exchanging heat between the outlet and the inlet of the reactor (i.e., preheat the reactor's feed with the reaction products), as it is shown in Figure 3.

Your task is to find the temperature differential (ΔT_{min}) that minimizes the total cost, using the data available in Table 1. For this purpose, you need plot the total energy and capital costs against ΔT_{min}, knowing that a ΔT_{min}=0 implies infinite heat exchange area, and therefore, infinite capital costs.

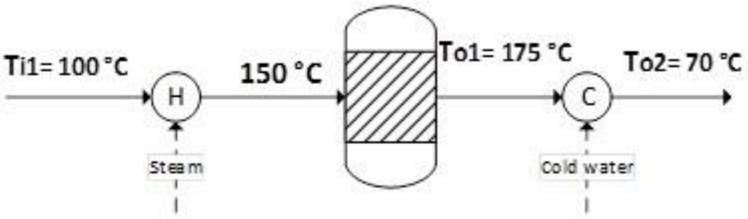


Figure 2 Process without heat integration

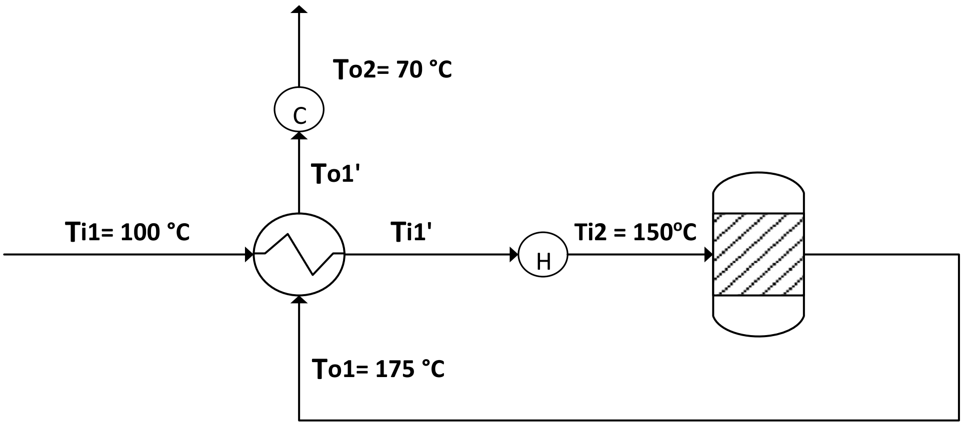


Figure 3 Process with heat integration (i.e., with heat recovery)

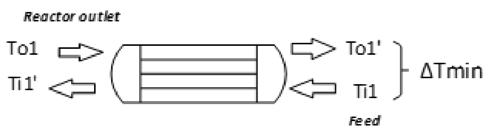


Figure 4 Heat exchanger

Table 1 Parameters

Parameter	Value	Unit	Remarks
A		m^2	Area of heat exchanger
CP_o	3	kW/°C	Outlet heat capacity flow rate
CP_i	5	kW/°C	Inlet heat capacity flow rate
T_{i1}	100	°C	Feed temperature
T_{o1}	175	°C	Reactor outlet temperature
U	0.2	kW/(m^2 °C)	Overall heat transfer coefficient
IF	3.5		Installation factor of heat exchanger
n	20		Number of years / lifetime
r	15	%	Interest rate
OT	8000	h/an	Annual operating time
C_{fuel}	0.08	CHF/kWh	Cost of fuel
ER	1.01	CHF/EUR	Currency exchange rate from EUR to CHF

$$CP_i\,(T_{i1'} - T_{i1}) = CP_0(T_{o1} - T_{o1'}) = Q_{saved}$$

Equation 1 Energy balance – heat savings

$$Q_{no-int} = CP_i(T_{i2} - T_{i1})$$

Equation 2 Utility demand without heat integration

$$T_{o1'} = T_{i1} + \Delta T_{min}$$

Equation 3 Preheat temperature (for a counter-current exchanger)

$$\Delta \boldsymbol{T_{LM}} = \frac{(\boldsymbol{T_{o1}} - \boldsymbol{T_{i1'}}) - (\boldsymbol{T_{o1'}} - \boldsymbol{T_{i1}})}{\boldsymbol{ln}\frac{(\boldsymbol{T_{o1}} - \boldsymbol{T_{i1'}})}{(\boldsymbol{T_{o1'}} - \boldsymbol{T_{i1}})}}$$

Equation 4 Logarithmic mean temperature difference

Note: *The ΔT_{LM} is a logarithmic average of the temperature difference between the hot and cold fluid streams at each end of the heat exchanger. It is used to determine the temperature driving force for heat transfer in flow systems, such as in heat exchangers. The larger the value of ΔT_{LM}, the higher heat is transferred.*

$$Q_{saved} = U.A.\Delta T_{LM}$$

Equation 5 Heat savings

$$Cost_{exch}\,(Euros) = 1957.8 * (A)^{\,0.551}$$

Equation 6 Capital cost of the heat exchanger (in Euros) (Fesanghary et al., 2009)

$$Cost_{capital} = Cost_{exch} * \mathrm{ER} * IF$$

Equation 7 Capital Cost per year (annualized capital cost) of the installed heat exchanger (in CHF)

$$a = \frac{(1+r)^n \times r}{(1+r)^n - 1}$$

Equation 8 Annuity factor

$$Cost_{energy} = Q_{net}(\text{kW}) * OT(\text{h}) * Cost_{fuel}(\text{CHF/kWh})$$

Equation 9 Cost of Energy

Hint: Consider these values for ΔTmin: 0.01, 0.1, 1, 5, 10, 15, 20°C. You can follow these steps in the excel sheet:

2.1) Calculate the Capital Cost (**12 points**)

a) Fill in the heat capacity flow rates. For each considered ΔTmin:
b) Calculate the pre-heat temperature $T_o'{}_1$ (**1.5 points**)
c) Calculate the temperature $T_i'{}_1$ (**1.5 points**)
d) Calculate ΔT_{LM} (**2 points**)
e) Calculate heat savings Q_{saved} (**2 points**)
f) Calculate the heat exchanger area A (**1 points**)
g) Calculate total capital cost in CHF (**1 points**)
h) Calculate the annuity factor (**1 points**)
i) Calculate and plot the total annualized capital cost (of the installed heat exchanger) per year for different ΔTmin (**2 points**)

2.2) Calculate the Energy Cost (**4 points**)

a) Calculate the heat required without heat integration Q_{no-int}(**2 points**)
b) Calculate the cost of energy per year based on the net heat used, Q_{net} (which is the difference between heat used without heat integration and the amount of heat saved Q_{saved}) (**2 points**).

2.3) Calculate the Total Cost (**4 points**)

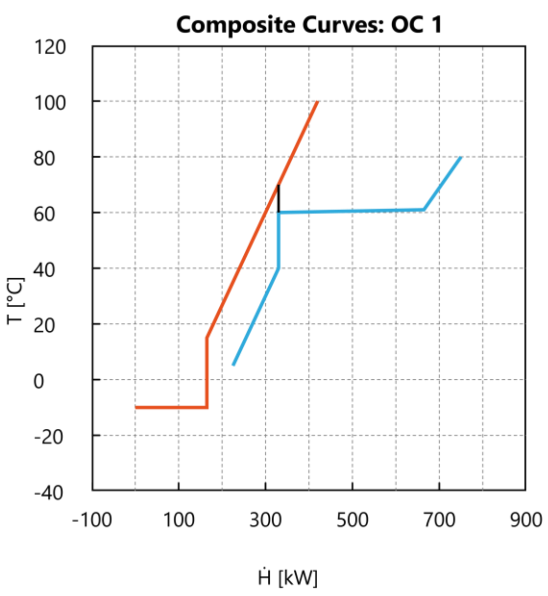
a) Add capital and energy cost per year to find the total cost per year (**2 points**)
b) What is the optimum value of ΔT_{min}? (**2 points**)

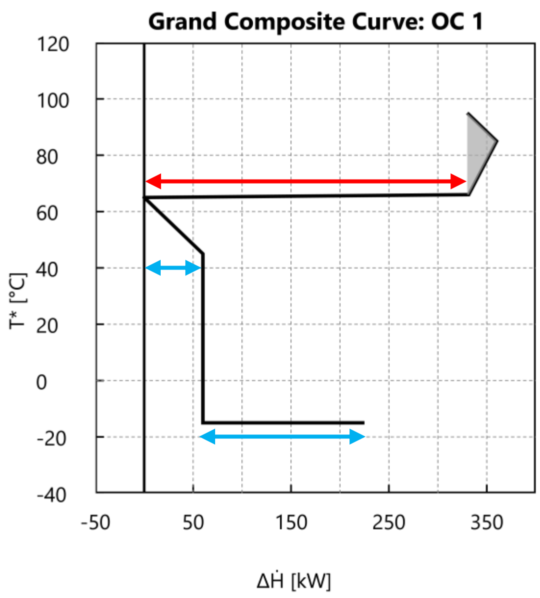
Exercise 3 – Feasibility of HP[1]/RSE[2] integration (6 points)

Pinch analysis is a robust tool that helps engineers evaluate the potential of a processes for residential or industrial applications. Accordingly, maximizing energy recovery would reduce the hot and cold utility requirements which are usually provided by fossil fuels, and consequently result in reduction of CO_2 emissions. However, to achieve net zero emission targets for each sector, further steps must be taken.
Electrification of processes and providing utilities with a clean and sustainable approach are among the vital solutions for the decarbonization of different processes.
Implementing heat pumps and utilization of renewable sources of energy can significantly reduce dependence on fossil fuels by both valorising the excess heat with high efficiencies (200-500% → COP = 2-5) and providing green electricity either for process heat demand or HP/Refrigeration to provide hot and cold utilities.

Below you can find CC/GCC of a process for which we aim to replace the conventional way of supplying hot and cold utility demands by new solutions (we distinguish these options, see below).

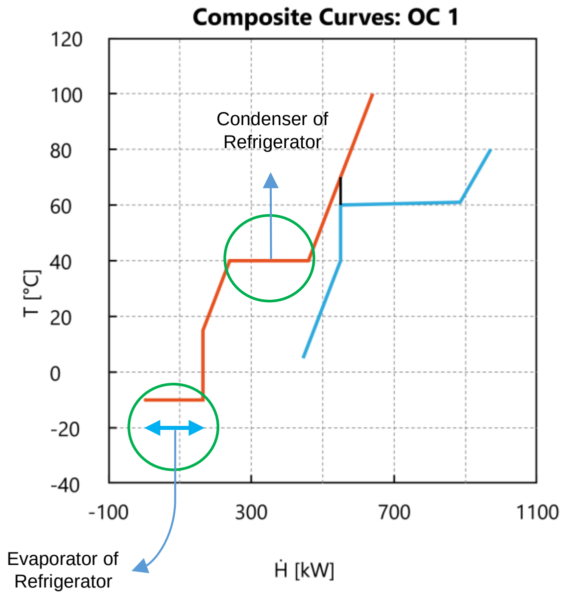
Pinch point temperature (℃) = 65 / ΔT_{min} = 10 / $T_{Ambient}$ = 5℃
Total hot utility demand (kW) = 330
Total cold utility demand (kW) = 225
Total heat recovery (kW) = 195
$COP_{Refrigerator}$ = 4 / $T_{evaporator}$ = -20℃ / $T_{condenser}$ = 40℃
COP_{HP} = 6.6 / $T_{evaporator}$ = 30℃ / $T_{condenser}$ = 70℃
Operating time = 8300 hours/year

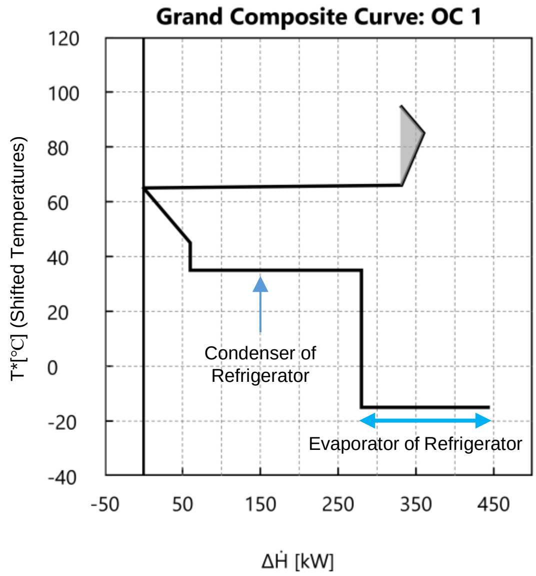




The following graphs represent the profiles after implementation of the Refrigerator (which is essential for supplying cold utility at -20℃):

[1] Heat Pump
[2] Renewable Sources of Energy





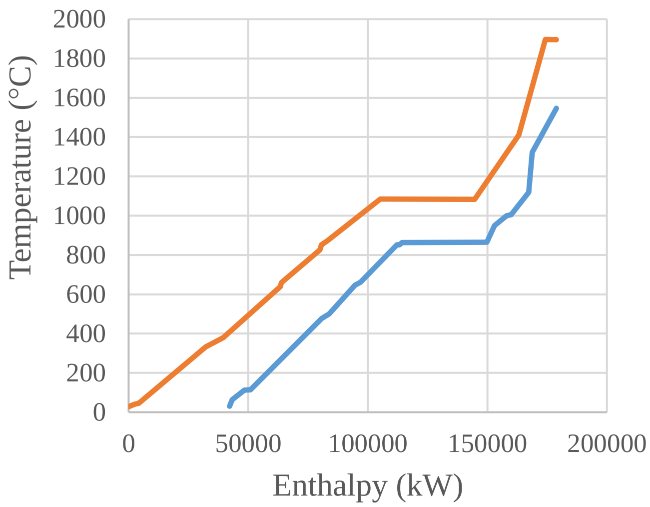
Discuss the advantages and drawbacks of each of the two options below and clarify your reasons for acceptance or rejection of each of them. Which solution seems the most promising?
You also need to consider other profitable solutions (e.g., opportunities for providing heat for district heating or other industries)

1. Cold utility: Cooling down the residual hot streams with the ambient air.
   Hot utility: Solar thermal (temperature is higher than 70℃). (**3 points**)

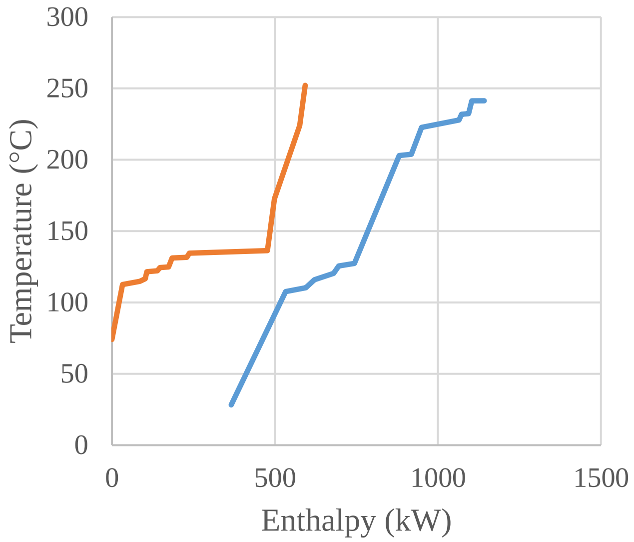
2. Cold utility: Evaporator of heat pump at 30℃ for the residual cooling demand.
   Hot utility: Condenser of heat pump at 70℃ for the heating demand. (**3 points**)

Exercise 4 – Understanding Composite Curves (9 points)

1) Please assign the composite curves below (a, b, c) to one of the following industry sectors (**1.5 points**):
    i. Polymerization: synthetic resin
    ii. Food processing: ice cream factory
    iii. Cement production
2) Compare and contrast the three graphs based on their characteristics. Discuss! (**1.5 points**)
3) For the hot utility requirements of the given CCs, which of the following options would be suitable? Please assign the relevant CC/CCs to each of them. (**3 points**)
    i. Hot water
    ii. Electric heating
    iii. Solar thermal energy
    iv. Geothermal heat
    v. Medium-pressure steam (with 200-300 ˚C)
    vi. Low-pressure steam (with 120-180 ˚C)
    vii. Flue gas or waste heat
    viii. Combustion of biomass
    ix. Thermal oil
4) Which technologies/solutions can be suggested to provide cooling in the given CCs (a to c)? (**3 points**)
    i. Chilled water
    ii. Liquid Nitrogen
    iii. Cryogenic gases (e.g., liquid Oxygen, liquid Argon)
    iv. Cooling towers
    v. Cooling with ambient air
    vi. Deep cooling refrigeration systems
    vii. HVAC systems

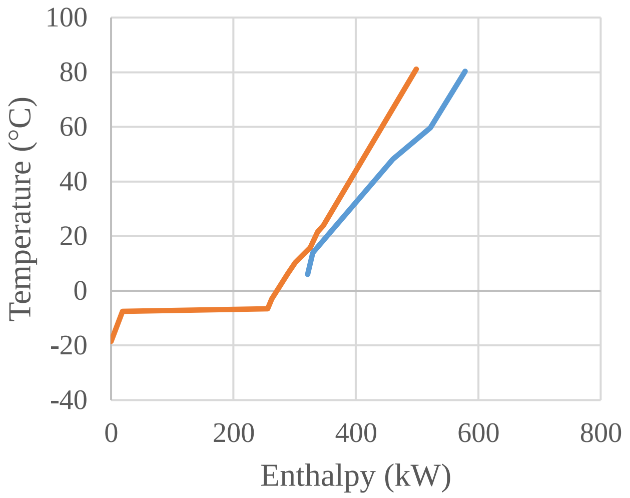


(a)



Temperature (°C)
300
250
200
150
100
50
0
0
500
1000
1500
Enthalpy (kW)

(b)



Temperature (°C)
100
80
60
40
20
0
-20
-40
0
200
400
600
800
Enthalpy (kW)

(c)

Exercise 5 – Understanding Composite Curves (5 points)

In industry, heat is typically supplied to production processes either in the form of flue gasses (for high temperature levels, i.e. above 500 °C) or, alternatively, as steam. For steam, i) low-pressure steam at 4 bar and around 180°C and ii) medium-pressure steam at 10 bar and 280 °C are most commonly used (this steam is nowadays mostly generated by combustion of natural gas). If a manufacturing process requires lower temperature levels (e.g., cooking of food at 130°C), the heat would typically still be provided with the steam system (i.e., at 180°C).

Fig. 1 illustrates the situation in a company of the manufacturing industry. The left of the graph shows the generation of steam at 180°C using flue gas (typically combustion of natural gas). The steam at 180°C is then used for Process 1, 2 and 3 to provide heat at lower temperature levels (e.g., for cooking at 140°C or for washing vessels at 70°C).

Fig. 1. Industrial processes with high-temperature hot utility

The company seeks to replace the steam supply based on natural gas with a heat supply based on renewable energy, which is available at lower temperatures (80°C). Within a consultancy firm, an alternative industrial process has been proposed, which is depicted in Fig. 2.

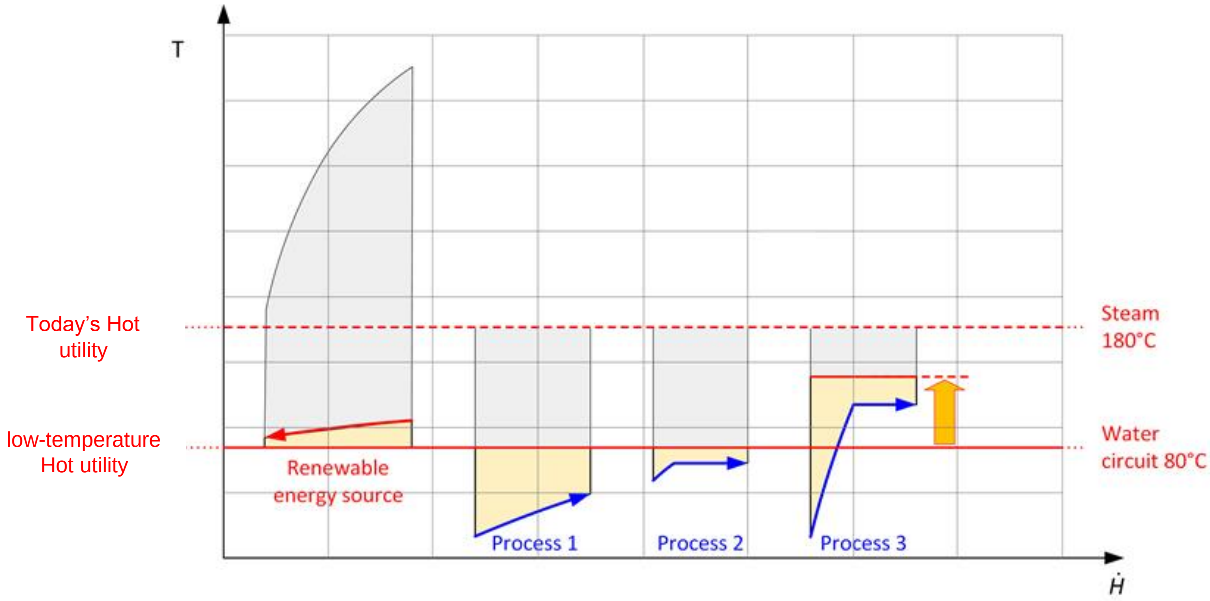


Fig. 2. Industrial processes with low-temperature hot utility

Questions:

1. What types of renewable energies would you suggest for heating water to 80 °C? (**2 points**)
2. Process 3 surpasses 80 °C. How would you provide the heat? (**1 point**)
3. Discuss the advantages and disadvantages of the proposed system. (**2 points**)