Annexes

Industrial Heat Pumps: Electrifying Industry’s Process Heat Supply

Contents

Section 1. Pinch Methodology

DATA COLLECTION

The first step is to obtain credible process flow data that include supply temperature (°C), target temperature (°C), and the heat duty (kW) of each of the process streams. These data were obtained from studies done during the Annex 21 of several industries where actual process stream data was collected by Chalmers University, Sweden.

DEVELOPING BASE MODEL

The data of the specific unit operation are then fed into a pinch with the final selected model being the IChemE Pinch Analysis software (IChemE Model, Kemp and Lim 2020). Additional information of the Excel-based spreadsheet model is presented in Appendix 1 for reference. Many thanks are due to Ian Kemp for his support and help in the initial stages as the team was getting up to speed in working with the model. Additionally, Mr. Kemp played a role in overcoming some technical issues with the spreadsheet tool so that it could be used to model complex processes such as ethylene.

Figure A1 shows the potato-processing data in the IChemE model. This would be considered the starting point of any pinch analysis (base model).

1. Select Input Method from the Dropdown list: Heat Duty

2. Input Global dTmin & select input temperature units: 10 °C

3. Select appropriate units for the input data from the drop down lists below (E15/F15).

4. Input data: Stream Name, Temperatures & Heat/Flow Data (max 50 streams).

Requires Input -
Optional Input -
Calculation cell -

5. Select desired output unit set: SI-based (kW/K)

Stream Name	Supply Temperature	Target Temperature	dT Min Contrib	Heat Duty		Heat Flow	Stream Type	Supply Shift	Target Shift
	°C	°C	°C	kW		kW		°C	°C
Product.	43.3	29.4		9		8.7922	HOT	38.3	24.4
Exhaust air.	71.1	48.9		321		320.621	HOT	66.1	43.9
Exhaust air.	48.9	35.0		1,936		1935.742	HOT	43.9	30.0
Process water.	18.3	82.2		253		252.6299	COLD	23.3	87.2
Dryer air.	47.8	218.9		3,306		3306.182	COLD	52.8	223.9
Sec. dryer air.	35.0	121.1		514		513.7703	COLD	40.0	126.1
Final dryer air.	35.0	102.2		46		45.7208	COLD	40.0	107.2
Steam1	370.6	371.1		-		0.0	COLD	375.6	376.1
Steam2	181.1	181.7		-		0.0	COLD	186.1	186.7
Cooling water.	25.0	35.0		-		0.0	COLD	30.0	40.0

Figure A1. Base model for potato processing in IChemE model

Figure A2 represents the problem table and the pinch analysis results for the base operations of potato processing. There are several important parameters to note as one evaluates the pinch analysis model results:

- Pinch temperature: this is where pinch occurs and limits the heat transfer

- Hot utility: amount of external process heat (fossil-fuel based) needed at the hot end (right side)
- Cold utility: amount of external cooling (process cooling, cooling tower water) needed at the cold end (left side)
- Temperature intervals and heat surplus or demand in that interval

Problem Table & Cascade

Shift Temperatur	Interv al	$T_{i+1}-T_i$	mCp_{net}	dH			Infeasible Cascade		Feasible Cascade	
°C		°C	kW/K	kW						
376.1111								0		3725
	1	0.5555	0.0	0.0	deman		0		0	
375.5556								0		3725
	2	151.6667	0.0	0.0	deman		0		0	
223.8889								0		3725
	3	37.2222	-19.3218	-719.2015	deman		-719.202		-719.202	
186.6667								-719.2		3005
	4	0.5556	-19.3218	-10.7352	deman		-10.7352		-10.7352	
186.1111								-729.9		2995
	5	60	-19.3218	-1159.3106	deman		-1159.31		-1159.31	
126.1111								-1889		1835
	6	18.8889	-25.2882	-477.6665	deman		-477.666		-477.666	
107.2222								-2367		1358
	7	20	-25.9684	-519.3671	deman		-519.367		-519.367	
87.2222								-2886		838.3
	8	21.1111	-29.9226	-631.6982	deman		-631.698		-631.698	
66.1111								-3518		206.6
	9	13.3333	-15.4946	-206.5942	deman		-206.594		-206.594	
52.7778						PINCH		-3725		0
	10	8.8889	3.8272	34.02	surplus		34.01998		34.01998	
43.8889								-3691		34.02
	11	3.8889	128.7726	500.7837	surplus		500.7837		500.7837	
40								-3190		534.8
	12	1.6667	135.4191	225.703	surplus		225.703		225.703	
38.3333								-2964		760.5
	13	8.3333	136.0521	1133.7633	surplus		1133.763		1133.763	
30								-1830		1894
	14	5.5556	-3.3212	-18.4511	deman		-18.4511		-18.4511	
24.4444								-1849		1876
	15	1.1111	-3.9542	-4.3935	deman		-4.39352		-4.39352	
23.3333								-1853		1871

Hot Pinch	57.7778	°C
Cold Pinch	47.7778	°C
Min Hot Utilit	3724.57	kW
Min Cold Utili	1871.43	kW

SINGLE PINCH PROBLEM

Figure A2. Problem table for base model for potato processing in IChemE model

As shown in figure A2, all the temperature intervals above the pinch temperature indicate a heat demand (negative numbers in the infeasible and feasible cascade columns) and four temperature intervals below the pinch temperature indicate a surplus of heat available. This model also indicates that ~3,725 kW of minimum process heat (fossil-fuel based) will be needed and additionally ~1,871 kW of minimum external cooling (chilled water, cooling tower), as noted at the bottom of the feasible cascade column, will be required for this potato-processing facility.

Figure A3 represents the hot and cold composite curves and provides a visual perspective into how much heat recovery is happening (or is possible) in the process and defines the hot (red line) and cold (blue line) utilities.

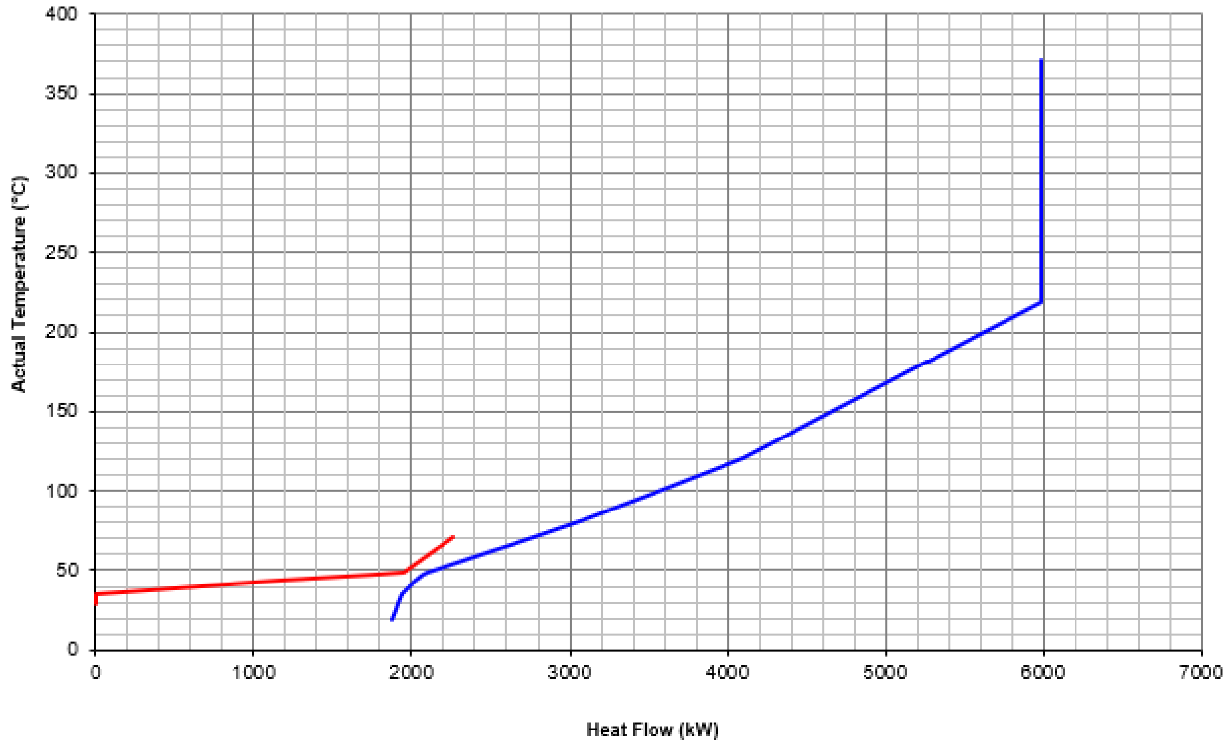

Figure A3. Hot and cold composite curves for base model for potato processing in IChemE model

Figure A4 represents the grand composite curve, which looks at the net heat requirement (supply and demand) at each temperature level and provides a strong indication where pinch occurs (NO heat exchange possible).

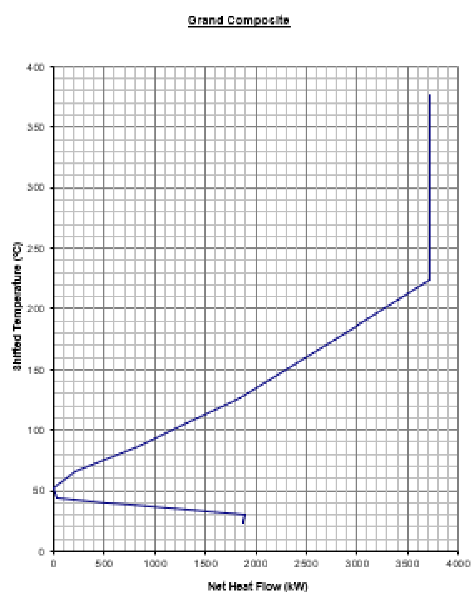

Figure A4. Grand composite curve for base model for potato processing in IChemE model

DEVELOPING THE IHP WITH ECONOMIC POTENTIAL

The next step is to determine the application of an IHP in the unit operation. Looking at the temperature intervals that have a SURPLUS below the pinch temperature and DEMAND above the pinch temperature (figure A2) is extremely important in determining those intervals and the IChemE pinch analysis model was selected for its clarity in defining these intervals and the pinch point.

The characteristics of the economic potential have been described elsewhere in the report, but the main characteristics and constraints are:

- Temperature lift of IHP < 35°C
- Maximum heat sink temperature of 160°C
- Existing IHP technology should be available in the market to implement the IHP
- For a mechanical vapor compression system, it should represent a single-stage of compression
- There should be a significant heat content (which relates to the size of the IHP) – look for at least 5% compared to the minimum HOT utility
- Preferably source and sink streams should be at constant temperatures (in other words, they should be condensing or evaporating streams)
- Preferably source and sink streams shouldn't be split; if split, they should be split into no more than two streams

Looking at the figure 2 (problem table), one can see that there is not a small temperature interval (0.5°C) until we get to interval 4 (temperature level of 186°C). Given that our pinch temperature is 52.8°C, we have to pump heat from below that temperature to 186°C—that is clearly impossible since it violates several of the economic IHP heat constraints. Hence, in the potato-processing case, both the source and sink streams will have a temperature glide,[1] which is okay. Temperature interval 11 and temperature interval 8 seem to be well matched, as shown in figure A5. Nevertheless, they may not meet the maximum temperature lift for the economic IHP implementation. That may mean that the source and/or sink stream may need to be split. Lastly, figure A6 provides the actual details of which streams would be the source and sink streams for this IHP.

[1] Temperature glide = the difference between the inlet and outlet temperature of the heat source or sink. This is generally associated with sensible cooling (heat source) and heating (heat sink)

87.2222							▼	-2886	▼	838.3
	8	21.1111	-29.9226	-631.6982	deman		-631.698		-631.698	
66.1111							▼	-3518	▼	206.6
	9	13.3333	-15.4946	-206.5942	deman		-206.594		-206.594	
52.7778						PINCH	▼	-3725	▼	0
	10	8.8889	3.8272	34.02	surplus		34.01998		34.01998	
43.8889							▼	-3691	▼	34.02
	11	3.8889	128.7726	500.7837	surplus		500.7837		500.7837	
40							▼	-3190	▼	534.8

Figure A5. Identifying temperature intervals for IHP in base model for potato processing

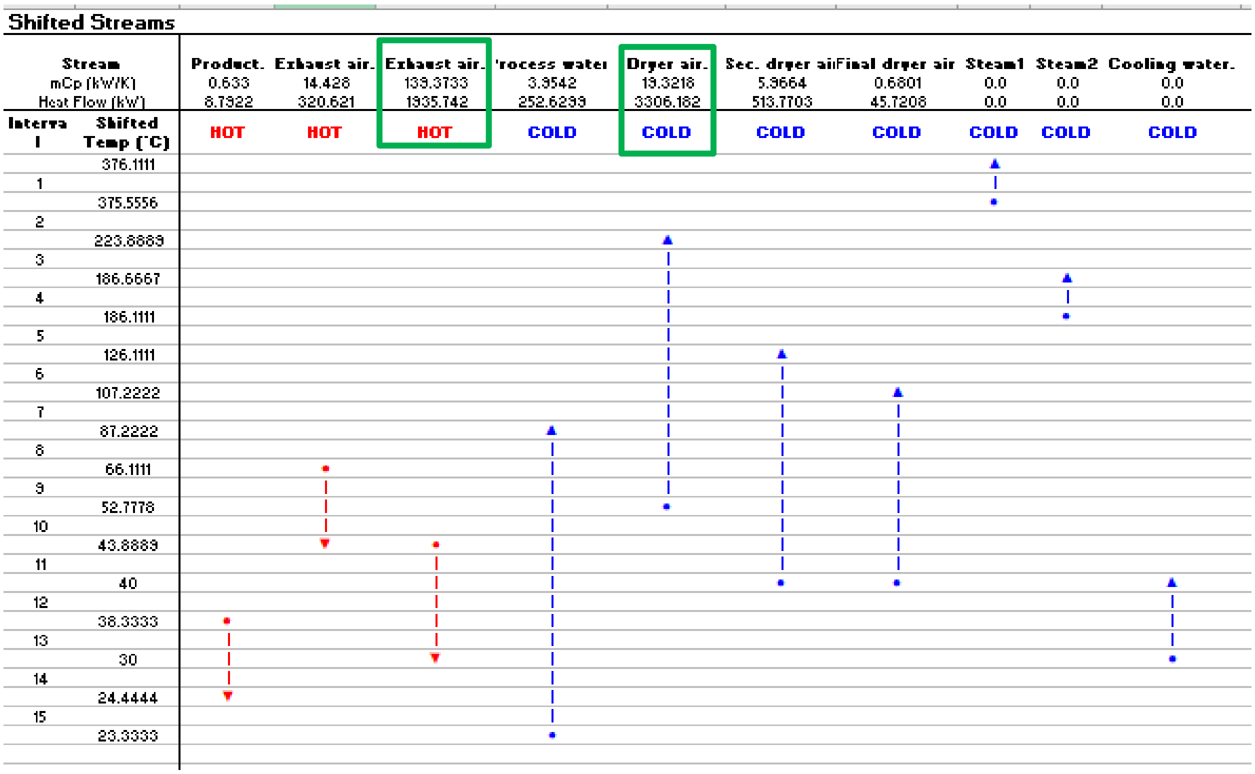

Figure A6. Identifying specific streams for IHP in base model for potato processing

Further mass and energy balances are done on the process streams to fix the size of the heat pump, temperature lift, COP, and then to determine the energy and GHG emission savings for the IHP application in the unit operation. This results in new process stream information (supply temperature, target temperature, and heat duty). This is presented in figure A7 as the new INPUT data (or new base model after economic IHP application). Note the yellow highlighted cells. They specifically are the streams and their supply/target temperatures and heat duties which changed due to the economic IHP application. Comparing these data points with figure A1 can provide the reader with a better understanding of the detailed changes.

Input Data

1. Select Input Method from the Dropdown list: Heat Duty
2. Input Global dTmin & select input temperature units: 10 °C
3. Select appropriate units for the input data from the drop down lists below (E15/F15).
4. Input data: Stream Name, Temperatures & Heat/Flow Data (max 50 streams).
5. Select desired output unit set: SI-based (kW/K)

Requires Input -
Optional Input -
Calculation cell -

Stream Name	Supply Temperature	Target Temperature	dT Min Contrib	Heat Duty		Heat Flow	Stream Type	Supply Shift	Target Shift
	°C	°C	°C	kW		kW		°C	°C
Product.	43.3	29.4		9		8.7922	HOT	38.3	24.4
Exhaust air.	71.1	48.9		321		320.621	HOT	66.1	43.9
Exhaust air.	46.3	35.0		1,574		1573.742	HOT	41.3	30.0
Process water.	18.3	82.2		253		252.6299	COLD	23.3	87.2
Dryer air.	70.0	218.9		2,877		2877.2092	COLD	75.0	223.9
Sec. dryer air.	35.0	121.1		514		513.7703	COLD	40.0	126.1
Final dryer air.	35.0	102.2		46		45.7208	COLD	40.0	107.2
Steam1	370.6	371.1		-		0.0	COLD	375.6	376.1
Steam2	181.1	181.7		-		0.0	COLD	186.1	186.7
Cooling water.	25.0	35.0		-		0.0	COLD	30.0	40.0

Figure A7. New base model after implementation of economic IHP in potato processing

Figure A8 represents the details of the economic IHP implementation along with information as it relates to energy savings, new pinch temperature and the new HOT and COLD utilities that will be required for the potato processing facility after the economic IHP application. Note that the pinch temperature changed after the economic IHP application (went higher). The HOT utility reduced thereby providing energy savings of ~10.2%.

Base Case (Current Operations)			After Heat Pump Application											
Pinch Temp	Hot Utility	Cold Utility	Source Stream	Sink Stream	Sink Temp	Source Temp	Lift	Source Q	Sink Q	New Pinch Temp	Hot Utility	Cold Utility	Energy Savings	
°C	kW	kW			°C	°C	°C	kW	kW	°C	kW	kW	kW	%
52.8	3,725	1,871	Exhaust Air	Dryer Air	70.0	46.0	24.0	362	430	66.1	3,347	1,561	378	10.2

Figure A8. Summary of base model and comparison after implementation of economic IHP in potato processing

Section 2. Using the IChemE Pinch Analysis spreadsheet software

ENTERING THE DATA

When the spreadsheet is opened, it takes you directly to the INPUT tab (worksheet), where the data is entered.[2]

On the INPUT tab, choose from the dropdown menu in cell F4 whether to enter the data as specific heat capacity and mass flowrate, heat capacity flowrate (*CP*), or heat flow. Then enter the global DT_{min} (DTMIN) chosen for the problem in cell F6, followed by the stream data. Note that the data must be in compatible units, as described in Section 10.4.5. The default spreadsheet display assumes that SI-based metric units are in use, but you can use your own units and alter the cell headings in E15 and, if required, F15. (Note: correct operation is not guaranteed if non-SI sets of units are used).

Enter the stream data line by line. As you begin each line, cells requiring input are highlighted in yellow. Streams can be numbered, named or both. If a stream changes heat capacity significantly over the temperature range, enter each segment separately (e.g., as 3a, 3b, 3c, etc.). Enter latent heat streams by assigning them a small temperature difference, say 0.1°C.

RESULTS OUTPUT

As data are entered, the spreadsheet automatically calculates the full stream data, which can be seen on the right-hand side of the first tab and on other “results” tabs. The program calculates whether a stream is hot or cold depending on the difference between the supply and target temperatures. All heat capacity flowrates (*CP*) should be entered as positive, never negative.

The furthest left-hand tab, INDEX, gives a list of all the results tabs, with hyperlinks. The results worksheets are as follows:

PT – Problem table, energy targets, pinch temperature and type of problem (pinch, threshold, multiple pinch or pinch region)

CC – Hot and cold composite curves

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[2] The Microsoft Excel spreadsheet for pinch calculations may be downloaded from the Companion Materials section of the Elsevier website, at www.elsevier.com/books-and-journals/book-companion/9780081025369

SCC – Shifted composite curves

GCC – Grand composite curve

GRID – Network grid diagram, shifted temperatures

AS – Stream data plot, actual temperatures

AT – Interval tables (heat loads and temperatures), actual temperatures

SS – Stream data plot, shifted temperatures

ST – Interval tables (heat loads and temperatures), shifted temperatures

DTMIN – Variation of hot and cold utility targets and pinch temperature with DT_{min}

A1 – Calculation basis and conversions between different sets of units

A2 – Tables of plotting points for hot and cold composite curves, shifted hot and cold composite curves, and grand composite curves.

The DTMIN calculation, for varying DT_{min} over a range, uses a macro and will not work if your spreadsheet security levels are set to high; therefore, on the spreadsheet menu go to Tools | Macro | Security and set to medium (recommended) or low. To obtain the plots, enter the maximum and minimum value of the required range and the program will then calculate over the range in 20 equal steps of ΔT_{min}.

The spreadsheet is protected to prevent inadvertent alteration of the cell formulae. Numerical results, e.g., the problem table and the tables in sheet A2, can be cut-and-pasted into other spreadsheets or documents. The plots of the composite and grand composite curves cannot be cut and pasted directly; instead, take a screenshot, paste it into your document and crop the picture. Alternatively, generate your own plot by cutting and pasting the plotting points (sheet A2) into Excel.

Section 3. Input Sources for IHP Analysis

PULP AND PAPER

KRAFT PULP DIGESTER

Sector	Paper- Kraft Pulp Production	
Unit Operation Evalutated	Digester	
Total production for sector	78460	1,000 tons per year
Amount of production with unit operation	42786	1,000 tons per year
Total facilities in sector	166	Mills
Number of Facilities with Unit Operation	166	Mills
Benchmark Energy Consumption for Unit Operation	2.07	MMBtu/ton
Total sector energy consumption	88.6	

Figure A11. Inputs for paper – Kraft Pulp Digester

References

- From DOE Bandwidth Study Paper Industry – 2015. www.energy.gov/eere/amo/downloads/bandwidth-study-us-pulp-and-paper-manufacturing
- MECS Table 5.2 End Uses of Fuel Consumption, 2018; EIA file "Table5_2_2018"
- MECS Table 1.4 Number of Establishments 2018
- AF&PA 2020 production data provided by Jesse Levine, AF&PA October 12, 2021

MECS Table 5.2, Sector 322 - Paper

- TOTAL FUEL CONSUMPTION = 2039 TBtu/yr
- TOTAL FUEL CONSUMPTION, Natural Gas = 572 TBtu/yr
- Indirect Uses-Boiler Fuel, Natural Gas = 386 TBtu/yr
- Process Heating, Natural Gas = 143 TBtu/yr

DOE Paper Bandwidth study, June 2015, Appendix A1: Summary of Pulp and Paper Table

Table A1. U.S. Production Volume of Six Pulp and Paper Processes in 2010 with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

Process	2010 Production (1,000 tons)	Average Onsite Energy Intensity (MMBtu/ton)				Calculated Onsite Energy Consumption (TBtu/year)			
		CT	SOA	PM Lower Limit	TM	CT	SOA	PM Lower Limit	TM
Liquor Evaporation	50,255	3.55	3.04	2.27	2.11	178.2	152.7	114.0	106.2
Pulping Chemical Prep	50,255	2.07	1.62	1.43	0.90	104.0	81.4	72.0	45.1
Wood Cooking	50,255	2.56	2.06	1.89	1.89	128.8	103.4	95.0	95.0
Bleaching	54,344	1.32	0.91	0.91	0.57	71.7	49.5	49.5	30.9
Paper Drying	91,728	4.68	3.47	2.77	1.44	429.7	318.7	254.3	132.3
Paper Machine Wet End	91,728	2.07	1.35	1.35	0.93	190.3	123.5	123.5	87.9

The four bandwidth measures are current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM).

Figure A12. Summary pulp and paper table. Source: DOE Bandwidth Study, June 2015.

Assume energy intensity for Unit Operation related to Digester is Pulping Chemical Prep = **2.07** MMBtu/ton pulp

Total pulp production from Kraft mills from AF&PA 2020 data. Total production = 12,378+8,691+21,717 = **42,786** thousand tons/yr

Table A1. Wood pulp production

Type of Wood Pulp	Production (1,000 tons)
Sulfite	151
Bleached Kraft – Softwood (SW)	12,378
Bleached Kraft – Hardwood (HW)	8,691
Unbleached Kraft	21,717
Stone Ground Wood (SGW)	292
Thermo – Mechanical Pulp (TMP)	915
Neutral Sulfite Semi – Chemical (NSSC)	2,926
Total Wood Pulp Production	47,070

Total number of Kraft Pulp mills with Digester in US = **166**. Reference MECS 2018 energy consumption data for Paper sector and the MECS facility count for Pulp only mills and Paper Mills. Used MECS “other fuel” data which is assumed to be biomass to estimate the number of Paper Mills that were integrated mills and had a Digester.

KRAFT PULP MULTI-EFFECT EVAPORATOR

Sector	Paper- Kraft Pulp Production	
Unit Operation Evalutated	Multi Effect Evaporator	
Total production for sector	78460	1,000 tons per year
Amount of production with unit operation	42786	1,000 tons per year
Total facilities in sector	166	Mills
Number of Facilities with Unit Operation	166	Mills
Benchmark Energy Consumption for Unit Operation	3.55	MMBtu/ton
Total sector energy consumption	151.9	

Figure A13. Inputs for paper – Kraft Pulp Multi Effect Evaporator

References

- From DOE Bandwidth Study Paper Industry – 2015 www.energy.gov/eere/amo/downloads/bandwidth-study-us-pulp-and-paper-manufacturing
- MECS Table 5.2 End Uses of Fuel Consumption, 2018; EIA file "Table5_2_2018"
- MECS Table 1.4 Number of Establishments 2018
- AF&PA 2020 production data provided by Jesse Levine, AF&PA October 12, 2021

MECS Table 5.2, Sector 322 - Paper

- TOTAL FUEL CONSUMPTION = 2039 TBtu/yr
- TOTAL FUEL CONSUMPTION, Natural Gas = 572 TBtu/yr
- Indirect Uses-Boiler Fuel, Natural Gas = 386 TBtu/yr
- Process Heating, Natural Gas = 143 TBtu/yr

DOE Paper Bandwidth study, June 2015, Appendix A1: Summary of Pulp and Paper Table

Table A1. U.S. Production Volume of Six Pulp and Paper Processes in 2010 with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

Process	2010 Production (1,000 tons)	Average Onsite Energy Intensity (MMBtu/ton)				Calculated Onsite Energy Consumption (TBtu/year)			
		CT	SOA	PM Lower Limit	TM	CT	SOA	PM Lower Limit	TM
Liquor Evaporation	50,255	3.55	3.04	2.27	2.11	178.2	152.7	114.0	106.2
Pulping Chemical Prep	50,255	2.07	1.62	1.43	0.90	104.0	81.4	72.0	45.1
Wood Cooking	50,255	2.56	2.06	1.89	1.89	128.8	103.4	95.0	95.0
Bleaching	54,344	1.32	0.91	0.91	0.57	71.7	49.5	49.5	30.9
Paper Drying	91,728	4.68	3.47	2.77	1.44	429.7	318.7	254.3	132.3
Paper Machine Wet End	91,728	2.07	1.35	1.35	0.93	190.3	123.5	123.5	87.9

The four bandwidth measures are current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM).

Figure A12 (repeated): Summary pulp and paper table. Source: DOE Bandwidth Study 2015.

Assume energy intensity for Unit Operation related to Digester is Pulping Chemical Prep = **3.55** MMBtu/ton pulp

Total pulp production from Kraft mills from AF&PA 2020 data. Total production = 12,378+8,691+21,717 = **42,786** thousand tons/yr

Table A1 (repeated). Wood pulp production

Type of Wood Pulp	Production (1,000 tons)
Sulfite	151
Bleached Kraft – Softwood (SW)	12,378
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Thermo – Mechanical Pulp (TMP)	915
Neutral Sulfite Semi – Chemical (NSSC)	2,926
Total Wood Pulp Production	47,070

Total number of Kraft Pulp mills with Digester in US = **166**. Reference MECS 2018 energy consumption data for paper sector and the MECS facility count for pulp only mills and paper mills. Used MECS "other fuel" data which is assumed to be biomass to estimate the number of paper mills that were integrated mills and had a digester.

PAPER MILL, NON-INTEGRATED MILLS PULPER

Sector	Paper Mills - Non-integrated Mills	
Unit Operation Evalutated	Pulper	
Total production for sector	72828.9	1,000 tons per year
Amount of production with unit operation	25758.9	1,000 tons per year
Total facilities in sector	172	Mills
Number of Facilities with Unit Operation	172	Mills
Benchmark Energy Consumption for Unit Operation	1.035	MMBtu per ton pulp
Total sector energy consumption	26.7	

Figure A14. Inputs for paper mills (non-integrated) pulper

References

- From DOE Bandwidth Study Paper Industry – 2015 www.energy.gov/eere/amo/downloads/bandwidth-study-us-pulp-and-paper-manufacturing
- MECS Table 5.2 End Uses of Fuel Consumption, 2018; EIA file "Table5_2_2018"
- MECS Table 1.4 Number of Establishments 2018
- AF&PA 2020 production data provided by Jesse Levine, AF&PA October 12, 2021

MECS Table 5.2, Sector 322 - Paper

- TOTAL FUEL CONSUMPTION = 2039 TBtu/yr
- TOTAL FUEL CONSUMPTION, Natural Gas = 572 TBtu/yr
- Indirect Uses-Boiler Fuel, Natural Gas = 386 TBtu/yr
- Process Heating, Natural Gas = 143 TBtu/yr

DOE Paper Bandwidth study, June 2015
Appendix A1: Summary of Pulp and Paper Table

Table A1. U.S. Production Volume of Six Pulp and Paper Processes in 2010 with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

Process	2010 Production (1,000 tons)	Average Onsite Energy Intensity (MMBtu/ton)				Calculated Onsite Energy Consumption (TBtu/year)			
		CT	SOA	PM Lower Limit	TM	CT	SOA	PM Lower Limit	TM
Liquor Evaporation	50,255	3.55	3.04	2.27	2.11	178.2	152.7	114.0	106.2
Pulping Chemical Prep	50,255	2.07	1.62	1.43	0.90	104.0	81.4	72.0	45.1
Wood Cooking	50,255	2.56	2.06	1.89	1.89	128.8	103.4	95.0	95.0
Bleaching	54,344	1.32	0.91	0.91	0.57	71.7	49.5	49.5	30.9
Paper Drying	91,728	4.68	3.47	2.77	1.44	429.7	318.7	254.3	132.3
Paper Machine Wet End	91,728	2.07	1.35	1.35	0.93	190.3	123.5	123.5	87.9

The four bandwidth measures are current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM).

Figure A12 (repeated). Summary pulp and paper table. Source: DOE Bandwidth Study.

Assume energy intensity for unit operation related to pulper in non-integrated paper mill. Assume 50% of energy in paper machine wet end goes to pulper = 50% of **2.07** = 1.035 MMBtu/ton pulp

Total paper mill production in non-integrated mills is assumed to be the proportion of the number of (non-integrated mills / total mills) * total production of paper products = 172/338 * 72,829 thousand tons/yr = **37,060** thousand tons/yr

Table A2. Paper, paperboard, and market pulp production

	Production/Shipments (1,000 tons)
Paper & Paperboard	
Corrugating Material	11,455
Linerboard	26,501
Recycled Board	4,192
Folding Boxboard + Gypsum Board	3,954
Bleached Folding Boxboard / Milk & Food	4,954
Other Paperboard	170
Unbleached Packaging Papers	1,842
Bleached Packaging Papers	845
Special Industrial	1,445
Newsprint	485
Uncoated Mechanical	471
Coated Mechanical	928
Uncoated Freesheet	5,246
Bleached Bristol	N/A
Other Specialties	N/A
Coated Freesheet	2,386
Tissue	7,955
Subtotal Paper and Paperboard	72,829
Market Pulp	
Kraft Pulp, Bleached & Semi-bleached	8,905
Kraft Pulp, Unbleached (included in subtotal)	N/A
Sulfite Pulp (included in subtotal)	N/A
Recycled Pulp	N/A
Other Pulp / Dissolving Pulp	N/A
Subtotal Market Pulp	9,312
Total Paper, Paperboard, and Market Pulp	82,141

Pulper will be in only non-integrated mills. Total number of paper mills in non-integrated mills is difference of total mills (338) minus integrated mills (166) = **172** mills. Reference MECS 2018 energy consumption data for paper sector and the MECS facility count for pulp only mills and paper mills. Used MECS “other fuel” data which is assumed to be biomass to estimate the number of paper mills that were integrated mills.

FOOD

Wet Corn Milling, Steepwater Evaporator

Sector	Wet Corn Milling	
Unit Operation Evalutated	Steepwater Evaporator	
Total production for sector	13178	1,000 tons corn per year
Amount of production with unit operation	13178	1,000 tons corn per year
Total facilities in sector	28	Mills
Number of Facilities with Unit Operation	28	Mills
Benchmark Energy Consumption for Unit Operation	0.6	MMBtu/ton
Tons per hr per plant	53.7	1000 Tons/hr per plant
Total sector energy consumption	7.9	

Figure A15. Inputs for wet corn milling steepwater evaporator

References

- Assume 56 lbs. of corn per bushel
- Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry: An ENERGY STAR® Guide for Energy and Plant Managers; Christina Galitsky, Ernst Worrell and Michael Ruth, July 2003. https://www.osti.gov/servlets/purl/816536
- USDA Grain Crushings and Co-Products Production 2020 – Summary March 2021 https://usda.library.cornell.edu/concern/publications/v979v304g

Top of page 5 of USDA Grain Crushings report, the following table:

Dry and Wet Mill, Corn Consumed – United States: 2020 (continued)

Purpose	August 2020	September 2020	October 2020	November 2020	December 2020	Total 2020
	(1,000 bushels)	(1,000 bushels)	(1,000 bushels)	(1,000 bushels)	(1,000 bushels)	(1,000 bushels)
Consumed for alcohol production						
Beverage alcohol	3,201	3,862	3,301	3,952	3,716	42,418
Fuel alcohol	411,109	402,407	434,167	431,661	431,731	4,775,966
Dry mill	372,657	363,353	391,203	390,774	388,228	4,286,207
Wet mill	38,452	39,054	42,964	40,887	43,503	489,759
Industrial alcohol	8,904	6,405	7,053	5,911	6,331	98,499
Consumed for other purposes						
Total wet mill products other than fuel	38,750	38,753	38,286	39,121	37,948	470,635

Figure A16. Dry and wet mill, corn consumed. Source: USDA.

Assume "Consumed for other purposes, Total wet mill products other than fuel" or 470,635 thousand bushels Total 2020 is the amount processed for Corn Starch.

470,635 * 10^3 bushels corn * 56 lbs/bushel / (2000 lbs/ton) = **13,178** thousand tons

On page 5 the table gives a breakdown of what is produced in the wet mill

Use the MECS Table 5.2 End Uses of Fuel Consumption, 2018; EIA file "Table5_2_2018"

MECS Table 5.2, Sector 311221 – Wet Corn Milling

- TOTAL FUEL CONSUMPTION, Natural Gas = 111 TBtu/yr
- TOTAL FUEL CONSUMPTION, End use not reported = 18 TBtu/yr (some goes to Process Heating)
- TOTAL FUEL CONSUMPTION, Natural Gas = 61 TBtu/yr
- Indirect Uses-Boiler Fuel, Natural Gas = 44 TBtu/yr
- Process Heating, Natural Gas = 16 TBtu/yr
- Percentage of total energy to Boiler and Process Heating > 61/111 = 55%

Total number of wet corn mills in US = 28 [This is from the "Corn Refiners Association" website for listing of Wet Corn Mills - https://corn.org/about-cra/member-company-locations/

From Worrell reference above, on page 14, Table 5:

Table 5: Estimated energy consumption for processes in corn wet milling operations, based on a 100,000 bushel/day facility.[1]

Process	Electricity (HP)[5]	Electricity (kWh)[5]	Electricity (Btu/bu)[5]	Steam (Lb/bu)[5]	Steam (Btu/bu)[5]	Fuel (Btu/bu)[5]	Primary Energy[2] (Btu/bu)[5]
Corn receiving	695	12443	425				1,308
Steeping	350	6266	214	2.52	3,150		3,809
Steepwater evaporation	860	15397	525	15.61	19,513		21,131
Germ recovery (1st grind)	1,115	19963	681				2,098
Germ recovery (2nd grind)	570	10205	348				1,072
Germ recovery (germ washing)	40	716	24				75
Germ dewatering and drying	720	12891	440	2.74	3,425	3,355	8,135
Fiber recovery[3]	3,530	63201	2156				6,642
Fiber dewatering	620	11100	379				1,167
Protein (gluten) recovery[4]	1,635	29273	999				3,076
Gluten thickening and drying	840	15039	513			3,557	5,137
Starch washing	785	14055	480				1,477
Starch dewatering and drying	4,375	78330	2673			27,000	35,232
Gluten feed dryer	1,595	28557	974			22,418	25,419
Total	**17,730**	**317,438**	**10,831**	**20.87**	**26,088**	**56,330**	**115,777**

Figure A17. Estimated energy consumption in corn wet milling operations. Source: ENERGY STAR.

Assume steepwater evaporation energy consumption above is the unit operation or 21,131 Btu/bushel or 377 Btu/lb or 754,678 Btu/ton or .75 MMBtu/ton. Assume 0.6 MMBtu/ton since process has probably improved since 2003.

WET CORN MILLING, HIGH FRUCTOSE CORN SYRUP

Sector	Wet Corn Milling	
Unit Operation Evalutated	High Fructose Corn Syrup	
Total production for sector	13178	1,000 tons corn per year
Amount of production with unit operation	13178	1,000 tons corn per year
Total facilities in sector	28	Mills
Number of Facilities with Unit Operation	28	Mills
Benchmark Energy Consumption for Unit Operation	0.25	MMBtu/ton
Tons per hr per plant	53.7	1000 Tons/hr per plant
Total sector energy consumption	3.3	

Figure A18. Inputs for wet corn milling high fructose corn syrup

References

- Assume 56 lbs of corn per bushel
- Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry: An ENERGY STAR® Guide for Energy and Plant Managers; Christina Galitsky, Ernst Worrell and Michael Ruth, July 2003. www.osti.gov/servlets/purl/816536
- Grain Crushings and Co-Products Production 2020 – Summary March 2021 usda.library.cornell.edu/concern/publications/v979v304g
- USDA Economic Research Service website www.ers.usda.gov/topics/crops/sugar-sweeteners/background.aspx#hfcs
- Measuring Improvement in the Energy Performance of the U.S. Corn Refining Industry, July 2012. citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.365.2013&rep=rep1&type=pdf
- Energy Analysis of 108 Industrial Processes, Harry L. Brown, et al, pages 30-33

Top of page 5 of the Grain Crushings and Co-Products Production 2020 report has the following table:

Dry and Wet Mill, Corn Consumed – United States: 2020 (continued)

Purpose	August 2020	September 2020	October 2020	November 2020	December 2020	Total 2020
	(1,000 bushels)	(1,000 bushels)	(1,000 bushels)	(1,000 bushels)	(1,000 bushels)	(1,000 bushels)
Consumed for alcohol production						
Beverage alcohol	3,201	3,862	3,301	3,952	3,716	42,418
Fuel alcohol	411,109	402,407	434,167	431,661	431,731	4,775,966
Dry mill	372,657	363,353	391,203	390,774	388,228	4,286,207
Wet mill	38,452	39,054	42,964	40,887	43,503	489,759
Industrial alcohol	8,904	6,405	7,053	5,911	6,331	98,499
Consumed for other purposes						
Total wet mill products other than fuel	38,750	38,753	38,286	39,121	37,948	470,635

Figure A16 (repeated). Dry and wet mill, corn consumed. Source: USDA.

Assume “Consumed for other purposes, Total wet mill products other than fuel” or 470,635 thousand bushels total 2020 is the amount processed for corn starch.

470,635 * 10^3 bushels corn * 56 lbs/bushel / (2000 lbs/ton) = 13,178 thousand tons corn consumed for non-fuel purposes. We will assume that a portion of this amount of corn produces High Fructose Corn Syrup. From the USDA Economic Research Service website they quote the 2019 HFCS production at 7.9 million tons which is 60% of total corn consumption in wet mills making corn products.

The IHP is supplementing the process heat for the Starch Conversion unit operation which is the beginning of the refining section for the sugars including HFCS. The “Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry: An ENERGY STAR® Guide for Energy and Plant Managers; Christina Galitsky, Ernst Worrell and Michael Ruth, July 2003” on page 14, Table 5 quotes 115,577 Btu/bushel.

Table 5: Estimated energy consumption for processes in corn wet milling operations, based on a 100,000 bushel/day facility.[1]

Process	Electricity (HP)[5]	Electricity (kWh)[5]	Electricity (Btu/bu)[5]	Steam (Lb/bu)[5]	Steam (Btu/bu)[5]	Fuel (Btu/bu)[5]	Primary Energy[2] (Btu/bu)[5]
Corn receiving	695	12443	425				1,308
Steeping	350	6266	214	2.52	3,150		3,809
Steepwater evaporation	860	15397	525	15.61	19,513		21,131
Germ recovery (1st grind)	1,115	19963	681				2,098
Germ recovery (2nd grind)	570	10205	348				1,072
Germ recovery (germ washing)	40	716	24				75
Germ dewatering and drying	720	12891	440	2.74	3,425	3,355	8,135
Fiber recovery[3]	3,530	63201	2156				6,642
Fiber dewatering	620	11100	379				1,167
Protein (gluten) recovery[4]	1,635	29273	999				3,076
Gluten thickening and drying	840	15039	513			3,557	5,137
Starch washing	785	14055	480				1,477
Starch dewatering and drying	4,375	78330	2673			27,000	35,232
Gluten feed dryer	1,595	28557	974			22,418	25,419
Total	**17,730**	**317,438**	**10,831**	**20.87**	**26,088**	**56,330**	**115,777**

Figure A17 (repeated). Estimated energy consumption in corn wet milling operations. Source: ENERGY STAR.

Likewise, the “Measuring Improvement in the Energy Performance of the U.S. Corn Refining Industry” report quotes HFCS (20-55%) and HFCS (55+%) at 108,278 and 111,032 BTU/bushel corn, respectively.

Using the Energy Analysis of 108 Industrial Processes book and adding up the total steam consumption for all the unit operations requiring steam we can estimate the amount of steam for the starch conversion unit operation where the IHP is applied. The steam consumption by unit operation is as follows:

2 – Steep Tank 95 Btu; 3 – Steep Water Evap 350 Btu; 5 – Germ Dryer 175 Btu; 6 – Oil extractor 75 Btu; 7 Filter Separ Refiner. 50 Btu; 11 Feed Dryer 350 Btu; 13 Starch Drying 250 Btu; 14 Dextrin Rcaster 100 Btu; 15 Starch Conversion 100 Btu; 17 Light Refining 125

Btu; 18 Evaporators. 125 Btu; 19 Heavy Refining 75 Btu; 20 Evaporator. 100 Btu; 22 Dryer 15 Btu

Total heat = 1985 for 1 lb of corn processed. Starch conversion is 100 Btu/1985 Btu or 5.0% of total process heat.

And the "Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry: An ENERGY STAR® Guide for Energy and Plant Managers" report; on page 14, Table 5 shows the process heating is (26,088 + 56,330) / 115,577 Btu/bushel or 71% of total energy intensity.

Therefore, energy intensity starch conversion unit operation = 5% * 71% of average of [108,278 and 111,032] BTU/bushel corn = 3,892 Btu/bushel * (bushel/56 lbs) * (2000 lbs/ton) / (10^6 Btu/MMBtu) = 0.14 MMBtu/ton corn – make **<u>0.25 MMBtu/ton corn</u>** to account for boiler losses and other losses (see 108 Industrial Processes book boiler losses)

Therefore, we'll assume same corn throughput as steep water = **<u>13,178 thousand tons per year</u>**

Use the MECS Table 5.2 End Uses of Fuel Consumption, 2018; EIA file "Table5_2_2018"

MECS Table 5.2, Sector 311221 – Wet Corn Milling

- TOTAL FUEL CONSUMPTION, Natural Gas = 111 TBtu/yr
- TOTAL FUEL CONSUMPTION, End use not reported = 18 TBtu/yr (some goes to Process Heating)
- TOTAL FUEL CONSUMPTION, Natural Gas = 61 TBtu/yr
- Indirect Uses-Boiler Fuel, Natural Gas = 44 TBtu/yr
- Process Heating, Natural Gas = 16 TBtu/yr
- Percentage of total energy to Boiler and Process Heating > 61/111 = 55%

Total number of wet corn mills in US = 28 [This is from the "Corn Refiners Association" website for listing of Wet Corn Mills - https://corn.org/about-cra/member-company-locations/

13,178 x 10^3 tons corn * .25 MMBtu per ton corn /1012 = 3.3 TBtu/yr. The amount of energy is 3.3 / 61 TBtu natural gas for 311221 NAECS sector = **<u>5.4%</u>** of natural gas from MECS natural gas consumption for wet corn milling sector which agrees with 5% assumed for starch conversion assumption of percentage of total process heating energy.

Grain Alcohol, Ethanol Fuel

Sector	Grain Alcohol, Dry Mill, Ethanol fuel	
Unit Operation Evalutated	Distillation of ethanol (15%) - water (85%)	
Total production for sector	43875	1,000 tons ethanol per year
Amount of production with unit operation	43875	1,000 tons ethanol per year
Total facilities in sector	180	Mills
Number of Facilities with Unit Operation	180	Mills
Benchmark Energy Consumption for Unit Operation	5.0	MMBtu/ton
Tons per hr per plant	27.8	1000 Tons/hr per plant
Total sector energy consumption	219.4	

Figure A19. Inputs for grain alcohol, dry mill, ethanol fuel

References

- Assume 56 lbs of corn per bushel
- Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry: An ENERGY STAR® Guide for Energy and Plant Managers; Christina Galitsky, Ernst Worrell and Michael Ruth, July 2003. www.osti.gov/servlets/purl/816536
- Grain Crushings and Co-Products Production 2020 – Summary March 2021 usda.library.cornell.edu/concern/publications/v979v304g
- USDA Economic Research Service website www.ers.usda.gov/topics/crops/sugar-sweeteners/background.aspx#hfcs
- Measuring Improvement in the Energy Performance of the U.S. Corn Refining Industry, July 2012. citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.365.2013&rep=rep1&type=pdf
- US DOE Biomass program fact sheet on ethanol, ethyl alcohol afdc.energy.gov/fuels/ethanol_fuel_basics.html
- Grain alcohol is also call ethyl alcohol, 95% of grain alcohol from corn grain
- USDA report www.usda.gov/sites/default/files/documents/LCA_of_Corn_Ethanol_2018_Report.pdf A Life-Cycle Analysis of the Greenhouse Gas Emissions from Corn-Based Ethanol; ICF September 5, 2018
- Penn State report on ethanol production www.e-education.psu.edu/egee439/node/673
    - Distillation process brings 15% ethanol – 85% water mixture to 95% ethanol – 5% water mixture
- Paper with MVR applied to ethanol-water distillation process cdn.intechopen.com/pdfs/33754/InTech-

Energy_conservation_in_ethanol_water_distillation_column_with_vapour_recompression_heat_pump.pdf

From Penn State reference:

Distillation and Increase of Ethanol Concentration

The last phase of ethanol production is the processing of ethanol to increase the ethanol concentration. Downstream from the fermenters, the ethanol concentration is 12-15% ethanol in water (which means you have 85-88% water in your solution!). Distillation was mentioned in an earlier lesson; crude oil must be distilled into various boiling fractions to separate the oil into useable products. Distillation is a process to separate components using heat and specially designed towers to keep the liquid flowing downward and the vapors being generated to flow upwards. Water boils at 100°C, while ethanol boils at 78°C. However, because water and ethanol evaporate at a lower temperature than their boiling points, and because they both have OH functional groups that are attracted to each other, ethanol and water molecules are strongly bound to each other and form an azeotrope together. That just means that you cannot completely separate ethanol from water – the ethanol fraction will contain about 5% water and 95% ethanol when you get to the end of the distillation process. Figure 7.15 shows a schematic of a distillation unit. You don't want water in gasoline as you drive because it prevents efficient combustion. Do you want water in your ethanol if you use it as a fuel?

Top of page 5 of the Grain Crushings and Co-Products Production 2020 report has the following table:

Dry and Wet Mill, Corn Consumed – United States: 2020 (continued)

Purpose	August 2020	September 2020	October 2020	November 2020	December 2020	Total 2020
	(1,000 bushels)	(1,000 bushels)	(1,000 bushels)	(1,000 bushels)	(1,000 bushels)	(1,000 bushels)
Consumed for alcohol production						
Beverage alcohol	3,201	3,862	3,301	3,952	3,716	42,418
Fuel alcohol	411,109	402,407	434,167	431,661	431,731	4,775,966
Dry mill	372,657	363,353	391,203	390,774	388,228	4,286,207
Wet mill	38,452	39,054	42,964	40,887	43,503	489,759
Industrial alcohol	8,904	6,405	7,053	5,911	6,331	98,499
Consumed for other purposes						
Total wet mill products other than fuel	38,750	38,753	38,286	39,121	37,948	470,635

Figure A16 (repeated): Dry and wet mill, corn consumed. Source: USDA.

- For ethanol analysis assumed "Fuel alcohol, Dry Mill" or 4,286,207 thousand bushels Total 2020 is the amount processed for producing ethanol fuel
- 4,286,207 * 10^3 bushels corn * 56 lbs/bushel / (2000 lbs/ton) = 120,000 thousand tons corn consumed in Ethanol fuel dry mills.

- The IHP is applied to the distillation process, diagram below. The IHP waste heat source is the condenser heat assumed to be at 78°C and the IHP heat sink is the Reboiler at 100°C.

Using the below reference:

https://cdn.intechopen.com/pdfs/33754/InTech-Energy_conservation_in_ethanol_water_distillation_column_with_vapour_recompression_heat_pump.pdf

See page 36, energy requirements in ethanol distillation:

Ethanol distillation, like any other distillation process, requires a high amount of thermal energy. Studies carried out by several authors reveal that the distillation process in ethanol distilleries consumers more than half of the total energy used at the distiller (Pfeffer et al. 2007). It has been estimated that distillation takes up about 70-85% of total energy consumed in ethanol production. Pfeffer et al. (2007) estimates that distillation consumes half of the total production energy 5.6 MJ/Liter out of 11.1 – 12.5 MJ/Liter.

The energy requirements for ethanol production have improved markedly during the past decade due to a variety of technology and plant design improvements. The energy needed to produce a liter of ethanol has decreased nearly 50% over the past decade and that trend is likely to continue as process technology improves (Braisher et al. 2006).

5.6 MJ/Liter * 947 BTU/MJ * (1 liter/0.264 gal) = 20,000 Btu/gal

20,000 Btu/gal / (6.5 lbs/gal) = 3076 Btu/lb (assume per lb of ethanol only not water plus ethanol)

3076 Btu/lb ethanol * 2000 lbs/ton / 10^6 (Btu/MMBtu) = 6.2 MMBtu/ton ethanol. Assume 5 MMBtu/ton ethanol since processes have improved since 2006.

Assume 90% of 15 billion gallons Ethanol fuel from Dry Mills. Or .90 * 15 x 10^9 gallons * 6.5 lbs ethanol/gallon / 2000 lbs/ton = 43,875 thousand tons ethanol

Assuming 15 billion gallons ethanol produced each year then 0.9 * 15 x 10^9 gallons * 6.5 lb/gal * 3,076 Btu/lb = 270 TBtu/yr—this amount makes sense since the total MECS energy consumption is 359 TBtu/yr of natural gas. This is 75% of natural gas consumption.

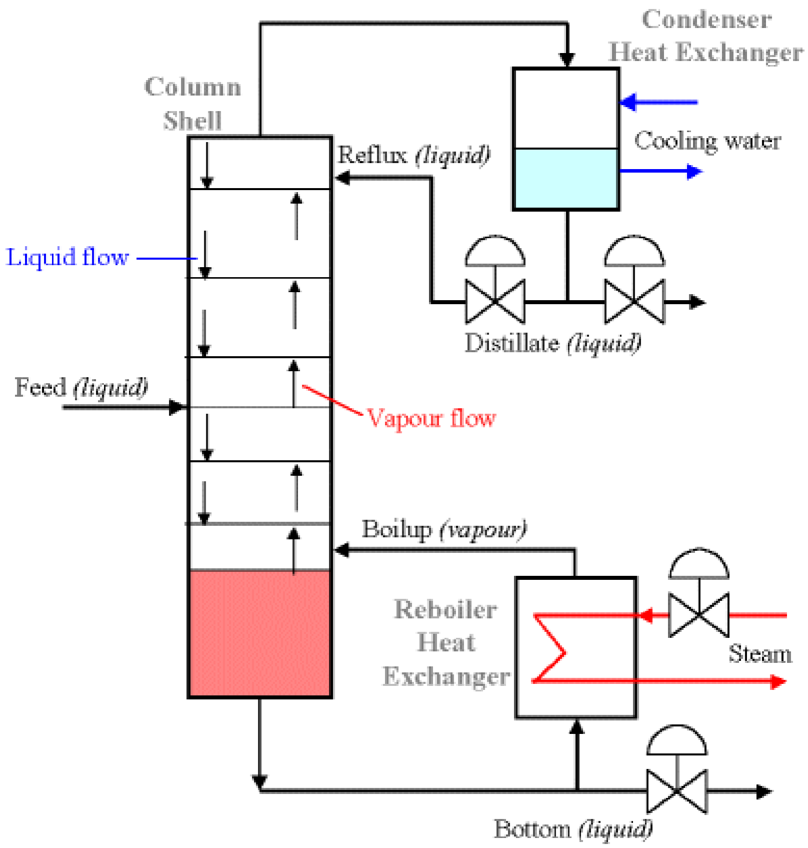

Figure A20. Distillation unit for increasing concentration of ethanol. Credit: Newcastle (link is external)

MECS Table 5.2, Sector 325193 – Ethyl Alcohol:

- TOTAL FUEL CONSUMPTION, Natural Gas = 359 TBtu/yr
- Indirect Uses-Boiler Fuel, Natural Gas = 205 TBtu/yr
- Process Heating, Natural Gas = 157 TBtu/yr
- Total number of dry corn mills for ethanol production in US ~ 180 [This is from the "Renewable Fuels Association" website for listing https://ethanolrfa.org/resources/ethanol-biorefinery-locations

Potato Drying

Sector	Potato	
Unit Operation Evalutated	Potato Drying	
Total production for sector	2514	1,000 tons potatoes per year
Amount of production with unit operation	2514	1,000 tons potatoes per year
Total facilities in sector	22	Mills
Number of Facilities with Unit Operation	22	Mills
Benchmark Energy Consumption for Unit Operation	3.4	MMBtu/ton
Total sector energy consumption	5.0	

Figure A21. Inputs for potato drying

References

- Note: Reference USDA report www.nass.usda.gov/Statistics_by_State/Washington/Publications/Potatoes/index.php
- www.linkedin.com/pulse/efficiency-data-better-can-potato-processing-industry-steven-tsirakos/
- MECS Table 5.2 End Uses of Fuel Consumption, 2018; EIA file "Table5_2_2018"

MECS Table 5.2, Sector 3114

- TOTAL FUEL CONSUMPTION, Natural Gas = 129 TBtu/yr
- TOTAL FUEL CONSUMPTION, Natural Gas = 92 TBtu/yr
- Indirect Uses-Boiler Fuel, Natural Gas = 59 TBtu/yr
- Process Heating, Natural Gas = 22 TBtu/yr

USDA report shows annual potato production as below

Processing — United States: 2019-2020

Utilization items	Crop year 2019 (1,000 cwt)	Crop year 2020 (1,000 cwt)
Processing		
Chips and shoestrings	59,639	59,217
All dehydrated (including starch and flour)	41,621	44,893
Frozen french fries	162,394	155,623
Other frozen products	11,848	10,968
Canned products	898	1,429
Other canned products (hash, stews, soups)	836	1,172
Other (including fresh pack, potato salad, vodka, etc.)	6,031	6,490
Total	283,267	279,792

Hot air drying is applicable in "Chips and Shoestrings, all dehydrated (including starch and flour), Frozen french fries, and other frozen products" = 270,701 thousand CWT $=270.701*10^6*112/2000/1000$ = 15,159 thousand tons

1 hundred weight (CWT) = 112 lbs

Found on Internet the following: www.linkedin.com/pulse/efficiency-data-better-can-potato-processing-industry-steven-tsirakos/

Energy intensity of potato processing is 2.1 to 6.1 MegaJoules/kg and 23.24 MegaJoules/kg = 10,000 Btu/lb. Assume 4 MG/KgTotal process heat targetable by IHP.

Total number of ethylene plants in US = 26 (estimate by Don Strickler, JR Simplot)

For our analysis we assumed:

- 75% of potatoes go through hot air dryer. This would amount to Or 11,369 thousand tons per year
- energy intensity of potato processing is 2.1 to 6.1 MG/kg and 23.24 MG/kg = 10,000 Btu/lb. Assume 3 MG/Kg which is =3*948/2.2*2000/1000000 = 2.6 MMBtu/ton
- 11,369 thousand tons * 2.6 MMBtu/ton = 36.7 TBtu/yr

www.nass.usda.gov/Statistics_by_State/Washington/Publications/Potatoes/index.php which shows 270,701 thousand CWT for chips and shoestrings, all dehydrated, frozen french fries, other frozen products potatoes 2020 processing of potatoes. One CWT = 112 lbs

CHEMICALS

ETHYLENE

Sector	Ethylene	
Unit Operation Evalutated	Ethylene - Debutanizer	
Total production for sector	44040.0	1,000 tons per year
Amount of production with unit operation	44040.0	1,000 tons per year
Total facilities in sector	38	
Number of Facilities with Unit Operation	38	
Benchmark Energy Consumption for Unit Operation	0.495	MMBtu per ton ethylene
Average production rate per facility	1158.9	1,000 tons per year
Unit Operation Energy Consumption per Facility	0.57	TBtu per year
Total energy consumption for Unit Operation for Sec	21.8	TBtu per year

Figure A9. Inputs for ethylene debutanizer

References

- DOE Chemicals Bandwidth study June 2015 www.energy.gov/sites/prod/files/2015/08/f26/chemical_bandwidth_report.pdf
- MECS Table 5.2 End Uses of Fuel Consumption, 2018; EIA file "Table5_2_2018"
- EIA fact sheet on petrochemicals sector www.eia.gov/todayinenergy/detail.php?id=48056 May 21, 2021

MECS Table 5.2, Sector 325110 - Petrochemicals (some portion of this energy goes to ethylene production)

- TOTAL FUEL CONSUMPTION, Natural Gas = 569 TBtu/yr
- TOTAL FUEL CONSUMPTION, End use not reported = 240 TBtu/yr (some goes to Process Heating)
- TOTAL FUEL CONSUMPTION, Natural Gas = 304 TBtu/yr
- Indirect Uses-Boiler Fuel, Natural Gas = 125 TBtu/yr
- Process Heating, Natural Gas = 145 TBtu/yr
- Percentage of total energy to Boiler and Process Heating > 270/569 = 47.5% (note that the percentage to Boiler/Process Heating is greater since some of the End user not reported goes to Boiler/Process heating). Assume 70% of ethylene energy goes to Process Heating or 0.70

DOE Chemicals Bandwidth study, June 2015

- See page 28, Table 4-5. Calculated U.S. Onsite Current Typical Energy Consumption for 74 Chemicals in 2010:
- Ethylene energy intensity = 7,071 Btu/lb (DOE, 2010);

- Production = 40 million metric tons/year (EIA 2020) = 40 x 10^6 * 2202 lbs/metric ton / (2000 lbs/ton)/ 10^3 = **44,040** thousand tons/yr;
- Estimate of 373 TBtu/yr (DOE, 2010) to ethylene out of 569 TBtu/yr (MECS 2018) for total petrochemicals;
- Process heating energy intensity = 70% of 7,071 Btu/lb * 2000 lbs/ton /10^6 = 14,142 Btu/ton
- Estimate for energy intensity for Debutanizer unit operation. Estimate is that 5% of the total process heating goes to Debutanizer process.

Therefore, total process heat targetable by IHP for ethylene debutanizer unit operation for ethylene production= 14,142 Btu/ton * 70% * 5% = **.495** MMBtu/ton

Total number of ethylene plants in US = **38** [Map on EIA fact sheet 2020]

Sector	Ethylene	
Unit Operation Evalutated	Ethylene - Process Water Stripper Reboiler	
Total production for sector	44040.0	1,000 tons per year
Amount of production with unit operation	44040.0	1,000 tons per year
Total facilities in sector	38	
Number of Facilities with Unit Operation	38	
Benchmark Energy Consumption for Unit Operation	0.228	MMBtu per ton ethylene
Average production rate per facility	1158.9	1,000 tons per year
Unit Operation Energy Consumption per Facility	0.26	TBtu per year

Figure A10. Inputs for ethylene process water stripper reboiler

References

- DOE Chemicals Bandwidth study June 2015 www.energy.gov/sites/prod/files/2015/08/f26/chemical_bandwidth_report.pdf
- MECS Table 5.2 End Uses of Fuel Consumption, 2018; EIA file "Table5_2_2018"
- EIA fact sheet on petrochemicals sector www.eia.gov/todayinenergy/detail.php?id=48056 May 21, 2021

MECS Table 5.2, Sector 325110 - Petrochemicals (some portion of this energy goes to ethylene production)

- TOTAL FUEL CONSUMPTION, Natural Gas = 569 TBtu/yr
- TOTAL FUEL CONSUMPTION, End use not reported = 240 TBtu/yr (some goes to Process Heating)
- TOTAL FUEL CONSUMPTION, Natural Gas = 304 TBtu/yr
- Indirect Uses-Boiler Fuel, Natural Gas = 125 TBtu/yr

- Process Heating, Natural Gas = 145 TBtu/yr
- Percentage of total energy to Boiler and Process Heating > 270/569 = 47.5% (note that the percentage to Boiler/Process Heating is greater since some of the End user not reported goes to Boiler/Process heating). Assume 70% of ethylene energy goes to Process Heating or 0.70

DOE Chemicals Bandwidth study, June 2015

- See page 28, Table 4-5. Calculated U.S. Onsite Current Typical Energy Consumption for 74 Chemicals in 2010:
- Ethylene energy intensity = 7,071 Btu/lb (DOE, 2010);
- Production = 40 million metric tons/year (EIA, 2020) = 40 x 10^6 * 2202 lbs/metric ton / (2000 lbs/ton)/ 10^3 = **44,040** thousand tons/yr;
- Estimate of 373 TBtu/yr (DOE, 2010) to ethylene out of 569 TBtu/yr (MECS, 2018) for total petrochemicals;
- Process heating energy intensity = 70% of 7,071 Btu/lb * 2000 lbs/ton /10^6 = 14,142 Btu/ton
- Estimate for energy intensity for Debutanizer unit operation. Estimate is that 5% of the total process heating goes to Debutanizer process.

Therefore, total process heat targetable by IHP for ethylene debutanizer unit operation for ethylene production= 14,142 Btu/ton * 70% * 2.3%[3] = **0.228** MMBtu/ton

Total number of ethylene plants in US = **38** [Map on EIA fact sheet, 2020]

[3] From the pinch model of ethylene based on Chalmers data is:

Hot utility is ~65,000 kW

Cold utility is ~260,000 kW

The energy required in refrigeration is very high and at the temperatures at which the ethylene process runs (-150/-160F), the coefficient of performance of the refrigeration machine is very low. I figured a conservative number of a COP=2.0 based on my experiences in cryogenic units and the 108 Processes book (which assumes a steam turbine mechanical device and not an electric motor). Hence, the total process demand = 65,000 + 260,000/2 = ~200,000 kW

The debutanizer heat duty is 10,500 kW (Chalmers data) and so that translates to ~5%.

The process water stripper heat duty is 4,525 kW (Chalmers data) and so that translates to 2.3%.

Section 4. Raw Process Data for Unit Operations

PULP & PAPER (DIGESTER)

In this unit, the wood is cooked with white liquor and then taken away for refining and washing. The liquor is then concentrated in an evaporator section.

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Chips	299.8	385.9	10,023.3
White liquor	355.4	385.9	4,044.4
Chips + white liquor + condensed steam	385.9	434.8	13,100.2
Chips + white liquor + condensed steam	434.8	427.6	1,934.3
Flash steam (17 psig)	395.9	395.9	15,124.0
Flash steam (17 psig)	395.9	385.9	293.1
Weak black liquor	377.6	368.2	4,220.2
2.5 psig steam	377.6	377.5	8,324.1
Wash water	333.2	427.6	23,797.6
Pulp	427.6	333.2	1,875.8

PULP & PAPER (MULTI-EFFECT EVAPORATOR)

There are three parallel trains of evaporators which receive all the weak black liquor from the decker washers. The first train: The weak black liquor containing about 16% solids, enters bottom of the fourth and fifth effects. The liquor is the pumped to the six effects. The liquid product after the last flashing which contains about 50% solids is sent to a sweetening tank. The product vapor from the first effect is then used in the next effect and this process is continued until the sixth effect.

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Effect 1 vapors	383.2	382.6	11,019.5
Effect 2 vapors	374.3	373.7	10,075.8
Effect 3 vapors	362.0	361.5	10,726.4
Effect 4 vapors	350.9	350.4	11,488.4
Effect 5 vapors	342.6	342.0	14,155.4
Effect 6 vapors	335.4	334.8	14,738.6

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Effect 6 vapors	334.8	310.9	618.4
Effect 6 liquid	336.5	337.0	14,155.4
Effect 5 liquid	343.7	344.3	11,488.4
Effect 4 liquid	352.0	352.6	10,667.8
Effect 3 liquid	352.6	364.3	1,260.4
Effect 3 liquid	364.3	364.8	8,815.6
Effect 2 liquid	364.8	377.0	1,084.5
Effect 2 liquid	377.0	377.6	9,891.2
Effect 1 liquid	377.6	386.5	615.2
Effect 1 liquid	386.5	387.0	10,667.8

There are three parallel trains of evaporators which receive all the weak black liquor from the decker washers. The third train: this is a six-effect evaporator and uses a falling film technique. The weak black liquor containing 16% solids is fed to the top of the fifth and sixth effects. The liquid is then pumped to the other effects.

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
3-eff 1a1b vapor	384.3	383.7	18,079.6
3-eff 2 vapor	367.0	366.5	18,167.6
3-eff 3 vapor	355.4	354.8	17,666.4
3-eff 4 vapor	345.4	344.8	17,408.5
3-eff 5 vapor	336.5	335.9	19,506.9
3-eff 6 vapor	328.2	327.6	22,135.7
3-eff 6 vapor	327.6	310.9	650.6
3-eff 1a1b liquid	375.4	394.3	2,494.1
3-eff 1a1b liquid	394.3	399.3	18,078.5
3-eff 2 liquid	360.9	372.0	1,588.5
3-eff 2 liquid	372.0	375.4	16,490.6
3-eff 3 liquid	348.7	358.2	1,272.0
3-eff 3 liquid	358.2	360.9	16,895.6

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
3-eff 4 liquid	339.3	347.0	1,260.0
3-eff 4 liquid	347.0	348.7	16,406.2
3-eff 5 liquid	338.7	339.3	17,373.3
3-eff 6 liquid	329.3	329.8	19,506.9

PULP & PAPER (NON-INTEGRATED PULPER)

The mill is an integrated paper mill with production of mechanical pulp of two kinds, Thermo Mechanical Pulp (TMP) and Stone Ground WOOD (SGW). Furthermore, pulp of waste paper is produced. This study considers two TMP units and four paper machines. The raw material to TMP is whitewood. TMP is produced by refining of wood chips. The wood is based with steam and then washed. The wood chips are then preheated with steam under pressure. The refining is done in two steps. After the second step the pulp is dissolved in a dissolver and then pumped to a latency tank where the fiber is relaxed. After that the pulp is sent to a filter. The accept from the filter is then washed and dewatered. Some of the pulp is sent to a bleach plant where it is bleached. Some chemicals are added to the bleached pulp. The pulp is then sent to a paper machine.

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Refining condensate, TMP2	384.4	347.2	3,984.1
Reject steam flow	384.5	384.4	6,900.3
Reject steam condensate	384.4	347.2	485.5
Process water	347.2	308.2	9,773.4
Process water cooling	347.2	342.2	3,715.0
Process water cooling	333.2	330.2	2,128.5
Reject steam	384.5	384.4	713.0
Reject steam condensate	384.4	328.2	75.3
Process water outlet	319.2	308.2	1,454.2
Process water outlet	330.2	308.2	1,071.6
Process water outlet	319.2	308.2	841.9
Exhaust air from PM2	335.7	316.2	325.3
Exhaust air from PM2	316.2	313.2	376.2

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Exhaust air from PM2	345.6	324.2	1,132.7
Exhaust air from PM2	324.2	323.2	610.7
Exhaust air from PM11	345.2	324.8	1,939.6
Exhaust air from PM11	324.8	323.2	1,916.8
Exhaust air from PM12	353.2	329.7	2,079.8
Exhaust air from PM12	329.7	323.2	7,676.5
Exhaust air from PM3	357.4	328.7	2,515.6
Exhaust air from PM3	328.7	323.2	5,945.5
Exhaust air from all PM	323.2	313.2	29,270.0
Exhaust air from all PM	313.2	303.2	18,960.0
Exhaust air from all PM	303.2	293.2	12,060.0
Exhaust air from all PM	293.2	283.2	8,000.0
Process water, PM2	321.2	331.2	6,000.0
Process water, PM1	332.2	342.6	8,000.2
Process water, PM3	320.2	328.2	2,305.6
Condensate from paper mill, (115t/h)	343.2	403.2	8,100.0
Water to chemical cleaning	274.2	293.2	18,796.7
Warm water	293.2	328.2	20,468.0
Water to the refinery	347.2	363.2	2,824.0
Air used for drying, PM2	298.2	373.2	630.6
Air used for drying, PM2	298.2	381.2	637.4
Air used for drying, PM2	298.2	351.2	365.4
Air used for drying, PM11	307.2	373.2	1,636.8
Air used for drying, PM11	307.2	383.2	1,884.8
Air used for drying, PM3	306.2	373.2	1,667.0
Air used for drying, PM3	306.2	381.2	2,084.3
Ventilation air, PM11	253.2	306.2	9,762.6
Ventilation air, PM3	253.2	306.2	8,167.3
Ventilation air, PM2	253.2	298.2	5,526.0

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Compensation of process water	293.2	343.2	1,169.5
Water from scrubber	353.2	308.2	3,132.0
Outlet, TMP1	333.2	308.2	1,740.0
Outlet, PM12	320.2	308.2	2,088.0
ventilation air, PM12	253.2	299.2	10,276.4
Air used for drying, PM12	299.2	390.2	1,528.8
Air used for drying, PM12	299.2	396.2	1,823.6
Compensation of process water	293.2	403.2	2,572.9

The plant produces a wide range of fine and brown papers. The plant as a whole operates continuously, although production on individual machines is frequently interrupted according to the grade of paper produced and for maintenance. There are five paper machines in use. The process for a typical machine is this: Raw pulp is fed to a 'pulper' to produce a thick slurry of pulp in water. After blending, the pulp is 'refined' to convert the fibers to a form suitable for paper making. The cleaned hood base fiber slurry flows from the head box base onto a moving wire mesh where it is first drained by gravity and then, in the later stages, by suction. The paper web is now capable of supporting itself and more water is removed in a pair of presses prior to entering the first dryer. The pre-dryer comprises of a number of steam heated cylinders and drying is carried out by the application of heat via direct contact with the cylinders. The paper emerging from the pre-dryer is almost dry and it passes to a 'size press' where starch is added to seal the sheet. Drying is completed in the after dryer, and the finished paper is fed to a reel. The end product is scanned continuously to measure moisture content, thickness, and so on, and adjustments are made to the machine, via a microprocessor control loop, to maintain product quality.

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Cold 1.1	288.7	358.2	83.7
Cold 1.2	358.2	358.7	587.3
Cold 2	283.2	333.2	228.6
Cold 3	283.2	311.0	91.6
Cold 4	288.2	399.9	8.0
Hot 5.1	333.2	322.1	53.7
Hot 5.2	322.1	313.2	43.3
Hot 5.3	313.2	311.0	79.7

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Hot 5.4	311.0	305.4	156.5
Hot 5.5	305.4	297.1	173.5

The paper mill is a modern news print paper plant. The plant utilizes waste paper and pulp as raw materials. The plant consists of two lines of de-inking plant (DIP) for converting waste paper to pulp stock, one pulping plant to convert raw pulp to pulp stock (CTMP) and three paper machines to convert pulp stock to finished paper. It also has an effluent treatment (ET) and broke recovery plant. The PI study divides the paper mill process in four parts, the three paper mills and the remaining plant. Here is stream data for the first paper machine.

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Vent 1	341.4	323.2	2.7
Vent 1c	323.2	293.2	27.4
Vent 2	340.8	322.2	2.8
Vent 2c	322.2	293.2	26.7
Vent 3	339.3	321.2	2.7
Vent 3c	321.2	293.2	25.3
Vent 4	337.0	320.2	2.5
Vent 4c	320.2	293.2	24.9
Sulzer air	419.2	320.2	8.8
Sulzer air circulator	320.2	293.2	14.5
Paper cooling	363.2	303.2	3.1
Basement air	281.2	326.5	9.1
Pv 1	314.2	358.2	8.8
Pv 2	314.2	363.2	9.8
Pulp stock	323.2	362.2	8.1
Paper drying	362.2	363.2	78.8
Roof air	281.2	323.0	14.5
Roof circulator 1	316.7	336.2	4.0
Roof circulator 2	313.7	319.2	1.7

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Silo	321.2	323.2	23.5
Vacuum condenser water	283.2	341.2	35.9
Boiler feed water	283.2	313.2	29.7

The paper mill is a modern news print paper plant. The plant utilizes waste paper and pulp as raw materials. The plant consists of two lines of de-inking plant (DIP) for converting waste paper to pulp stock, one pulping plant to convert raw pulp to pulp stock (CTMP) and three paper machines to convert pulp stock to finished paper. It also has an effluent treatment (ET) and broke recovery plant. The PI study divides the paper mill process in four parts, the three paper mills and the remaining plant. Here is stream data for the second paper machine.

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Vent 1	342.2	326.2	2.2
Vent 1c	326.2	293.2	31.4
Vent 2	343.6	326.2	2.4
Vent 2c	326.2	293.2	30.6
Vent 3	343.4	323.2	2.8
Vent 3c	323.2	293.2	25.5
Vent 4	340.2	321.2	2.6
Vent 4c	321.2	293.2	23.6
Sulzer air	424.2	323.2	6.6
Sulzer air circulator	323.2	293.2	12.1
Paper cooling	363.2	303.2	3.0
Basement air	281.2	324.2	9.5
Pv 1	313.7	358.2	8.4
Pv 2	313.7	363.2	9.3
Roof air	281.2	321.2	9.0
Pulp stock	323.2	362.2	7.9
Paper drying	362.2	363.2	76.5
Roof circulator 1	316.7	329.7	3.0
Roof circulator 2	314.7	328.5	3.5

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Silo	321.2	323.2	22.9
Vacuum condenser water	283.2	341.2	35.9

The paper mill is a modern news print paper plant. The plant utilizes waste paper and pulp as raw materials. The plant consists of two lines of de-inking plant (DIP) for converting waste paper to pulp stock, one pulping plant to convert raw pulp to pulp stock (CTMP) and three paper machines to convert pulp stock to finished paper. It also has an effluent treatment (ET) and broke recovery plant. The PI study divides the paper mill process in four parts, the three paper mills and the remaining plant. Here is stream data for the third paper machine.

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Vent 1	338.6	322.2	2.6
Vent 1c	322.2	293.2	28.4
Vent 2	341.4	323.2	2.9
Vent 2c	323.2	293.2	28.0
Vent 3	341.0	315.2	4.2
Vent 3c	315.2	293.2	19.1
Paper cooling	363.2	303.2	1.9
Pv 1	281.2	356.2	6.7
Pv 2	281.2	371.2	6.1
Pulp stock	323.2	362.2	5.2
Paper drying	362.2	363.2	51.4
Silo	321.2	323.2	14.7
Vacuum condenser water	283.2	341.2	16.2

WET CORN MILLING (STEEPWATER EVAPORATION)

The cleaned corn is steeped or soaked for 24 to 48 hours in the steeping tanks. Steeping softens the kernel, disintegrates the starch-binding protein in the kernel, and removes solubles for recovery. Steeping is completed in a series of tanks with a countercurrent flow of steepwater. The steepwater that is drained from the last tank is concentrated in evaporators and can eventually be used in animal feed. After steeping, the corn is sent to germ recovery. The degerminating mill tears apart the soft kernels of the steeped corn thus freeing uncrushed germs. The germs are recovered from the hulls, starch, and gluten in hydrocyclones. The germs are washed, dewatered, and finally dried. The dried germs are then ready for oil recovery. After the hydrocyclones, the remaining corn products, starch gluten and hulls are sent to mills for fine milling. The milling releases the rest of the starch. After milling, the mixture is passed through a series of screens to separate the hulls or fibers from the starch. The fibers are washed to recover additional starch and then dewatered and dried for animal feed. The starch and gluten slurry or starch milk that is produced in the hull washing step is ready to be separated into individual components. The starch milk goes through a several stages of separation. After the gluten has been separated, some of the starch milk is dewatered and dried to the final corn starch product. The other portion of the starch milk is sent to the high fructose corn syrup refinery.

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Cold 1	299.8	324.8	583.8
Hot 1	322.0	310.9	1,371.6
Cold 2	299.8	308.2	641.8
Hot 2	323.7	311.5	1,547.4
Cold 3	322.0	323.7	107.3
Cold 4.1	302.6	458.7	672.9
Cold 4.2	458.7	459.3	2,051.5
Cold 5	302.6	355.4	398.7
Hot 3	344.3	322.0	3,751.3
Hot 4	355.4	310.9	4,736.0
Cold 6	298.7	449.8	2,016.0
Hot 5	344.3	302.6	579.2
Cold 7	298.7	588.7	3,024.5
Hot 6	344.3	330.4	443.1
Hot 7	338.7	310.9	30.5
Cold 8	298.7	677.6	2,320.6
Hot 8	383.2	333.2	344.7
Cold 9	298.7	588.7	6,823.1
Hot 9	374.8	333.2	1,078.6
Hot 10	338.7	310.9	107.9
Cold 10	324.8	365.9	1,080.9

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Cold 11	362.6	363.2	2,344.6
Hot 11	324.8	324.3	2,344.6
Hot 12	374.8	299.8	1,460.7
Hot 13	342.6	299.8	347.1
Cold 12	367.0	367.6	10,550.6
Hot 14	367.6	367.0	10,550.6

WET CORN MILLING (HIGH FRUCTOSE CORN SYRUP REFINERY)

In the refinery, the process begins by thinning the starch. The slurry first passes through the jet cookers. After the jet cookers, the starch slurry passes through a set of thinning coils and into a flash chamber. After the flash chamber, the slurry is transferred to the enzyme liquefaction reactor to continue thinning the starch and is finally flashed again to the desired temperature. The thinned starch slurry is transferred to a series of saccharification reactors. Once the desired dextrose level is reached, the corn syrup is filtered and sent through ion exchange columns. After ion exchange, the corn syrup is concentrated to about 45% solids an evaporator. The corn syrup is then passed through the isomerization columns. The isomerization columns isomerize dextrose to fructose to produce high fructose corn syrup. The high fructose corn syrup is fed to ion exchange columns and then to another evaporator. After the evaporator, the high fructose corn syrup is fructose enriched by chromatographic separation in the fractionation columns. Fructose is retained in a greater degree in the column. Dextrose passes through the column as raffinate. The high fructose corn syrup is washed out of the fractionation columns with water. The final products are blended and then concentrated to about 77% solids in the final evaporators.

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Cold 1	299.8	324.8	265.0
Cold 2	310.9	324.8	572.1
Cold 3.1	299.8	458.7	921.2
Cold 3.2	458.7	459.3	2,754.9
Hot 1.1	365.9	365.4	947.2
Hot 1.2	365.4	305.4	105.5
Hot 2	365.9	337.6	1,808.5

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Hot 3.1	333.2	332.6	886.3
Hot 3.2	332.6	305.4	44.5
Cold 4	322.0	360.4	347.0
Cold 5	322.0	333.2	248.5
Cold 6	329.3	347.0	1,453.6
Cold 7	333.2	347.0	344.7
Cold 8	344.3	365.4	1,626.0
Hot 4	360.9	322.6	2,446.9
Hot 5	372.0	299.8	2,940.1
Cold 9	322.0	330.9	562.7
Cold 10	330.9	360.4	1,941.6
Hot 6	360.9	347.0	682.3
Hot 7	344.3	324.8	982.4
Hot 8	372.0	299.8	1,622.3
Cold 11	333.2	335.9	14.1
Cold 12	324.8	335.9	136.0
Cold 13	299.8	335.9	1,052.7
Cold 14	306.5	333.2	243.8
Cold 15	333.2	347.0	398.6
Hot 9	344.3	322.0	567.4
Hot 10	505.4	366.5	187.6
Hot 11	616.5	366.5	520.5
Cold 16	324.8	369.3	1,943.7
Cold 17	369.3	369.8	4,220.2
Hot 12.1	328.7	328.2	3,798.2
Hot 12.2	328.2	299.8	190.6
Hot 13	360.9	299.8	902.7
Hot 14	333.2	306.5	447.8
Hot 15	360.9	360.4	830.0

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Hot 16	370.4	369.8	567.4
Cold 18	322.0	363.7	1,066.7
Cold 19	363.7	364.3	4,337.5
Hot 17	326.5	325.9	4,243.7
Hot 18	362.0	299.8	471.4
Hot 19	325.9	299.8	194.6
Hot 20	362.0	361.5	478.3
Cold 20	365.4	365.9	21,957.0
Hot 21	365.9	365.4	21,957.0
Cold 21	365.4	365.9	12,116.8
Fructose MR condenser	365.9	365.4	12,116.8
Hot 22	299.8	359.8	304.8
Cold 23	299.8	322.0	1,017.5
Cold 24	299.8	322.0	2,098.4
Cold 25	299.8	322.0	1,641.2

FOOD & BEVERAGE (POTATO DRYING)

The site is a vegetable dehydration plant. The different units in the plant are washing, cooking, mixing, conditioning, drying, cooling, and screening steps. The balance of the heat is used to make hot water for the washing and cooking operations. The cooling requirements are in the conditioning step and after the final dryer where product is cooled with chilled air.

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Product	316.5	302.6	8.8
Exhaust air	344.3	322.0	320.6
Exhaust air	322.0	308.2	1,935.7
Process water	291.5	355.4	252.6
Dryer air	320.9	492.0	3,306.2
Sec. dryer air	308.2	394.3	513.8
Final dryer air	308.2	375.4	45.7

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Steam 1	643.7	644.3	-
Steam 2	454.3	454.8	-
Cooling water	233.2	235.9	-

ETHYLENE (DEBUTANIZER REBOILER AND PROCESS WATER STRIPPER REBOILER)

This is an ethylene manufacturing process. The ethylene process is a typical world scale naphtha cracking plant. The process has been divided into two sections. Only the above ambient part of the process is considered here.

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
Quench oil 1	476.5	450.4	88,258.1
Quench oil 2	450.4	444.3	7,795.8
Quench water 1	354.3	333.2	125,065.6
Quench water 2	333.2	304.8	21,980.6
PFO to store	477.0	349.8	598.0
Proc water strip overheads	381.5	380.9	17,549.2
First stage discharge	353.2	304.8	13,985.5
second stage discharge	349.3	304.8	9,047.3
Third stage discharge	355.9	317.0	5,870.2
Fourth stage discharge	353.2	303.2	13,270.3
Fifth stage discharge	364.3	322.0	7,095.2
Fifth stage discharge	322.0	306.5	4,832.8
Caustic tower overhead	314.8	298.2	1,834.7
DS blowdown	443.2	310.9	3,109.5
C2 hydrogen reactor effluent 1	350.4	305.4	4,598.2
C2 hydrogen interstage cooler	359.8	337.6	2,157.0
Deethanizer bottoms 1	348.7	298.7	1,943.2
C3 hydrogen interstage cooler	358.7	342.0	627.1

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
C3 hydrogen reactor effluent	348.2	342.0	345.8
C3 stripper condenser	325.9	322.6	5,741.3
C3 stripper vent condenser	322.6	316.5	451.3
C3 splitter condenser	323.2	305.4	24,680.0
Debutanizer condenser	323.2	308.7	11,400.9
Debutanizer bottoms	377.6	310.9	1,989.8
Gasoline product	383.2	310.9	2,019.3
Methanator effluent	559.3	300.9	3,041.7
Methane compressor discharge	396.5	306.5	460.1
Meth compressor interstage cooler	390.9	309.3	416.2
Ethylene refrigeration condenser 1	356.5	307.6	2,291.7
Propylene refrigeration condenser 1	348.2	306.5	12,896.4
Propylene refrigeration condenser 1	306.5	305.9	53,005.0
Naphtha preheater	299.8	383.2	13,378.6
Gasoil preheater	299.8	427.6	1,732.4
DS steam generation	443.2	443.7	95,362.8
DS boiler feedwater preheater	379.8	443.2	13,868.3
Gas stripper reboiler	373.2	374.8	1,652.9
Process water strip feed	355.4	381.5	17,548.6
Process water strip reboiler	381.5	382.0	4,525.0
Third stage knockout pot offgas	317.0	319.3	337.0
Condenser stripper reboiler	354.3	355.4	4,598.3
DS superheater	443.2	465.4	2,447.2
Deethanizer overheads 2	295.4	336.5	4,062.0
Deethanizer reboiler	348.7	349.3	12,467.3
Depropanizer reboiler	356.5	358.7	7,370.8
Depropanizer overheads	286.5	329.8	1,943.1
C3 hydrogen feed	329.3	329.8	4,481.1
C3 hydrogen feed	329.8	335.4	316.5

Stream Description	Inlet Temperature (K)	Outlet Temperature (K)	Heat Duty (kW)
C3 splitter reboiler	329.3	329.8	22,777.6
Debutanizer reboiler	373.7	374.3	10,456.8
H2 to methanator	295.9	523.7	3,112.1

Section 5. Summary of Analysis IHP Results for Unit Operations

UNIT OPERATION: PULP & PAPER, DIGESTER

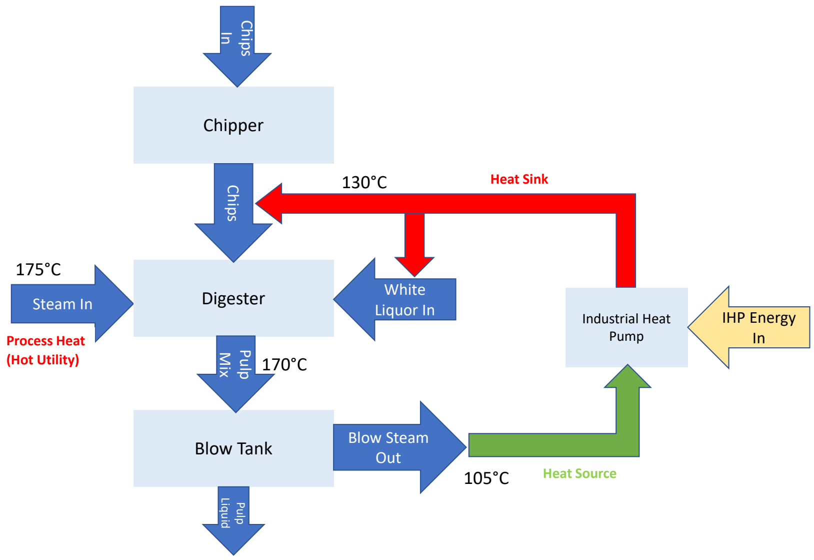

Figure A22. Illustration of IHP location in process heat chain for pulp and paper digester, economic scenario

Table A3. Results of pinch analysis

Parameter	Units	Process Information
Process Heat (Hot Utility)	MMBtu/ton	2.1
Pinch Temperature	°C	117.8
Heat Source Temperature	°C	104.4
Heat Sink Temperature	°C	130.0
Source Heat Available	Percent of Process Heat	9.9
Sink Heat Demand	Percent of Process Heat	11.9

Table A4. Results of IHP application in unit operation

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
COP		5.730	6.585	7.871	1.469	1.639	0.494
Heat Source	MMBtu/ton*	0.205	0.205	0.205	0.079	0.096	0.205
Heat Sink	MMBtu/ton*	0.241	0.236	0.231	0.247	0.247	0.101
IHP Energy In (Electric)	MMBtu/ton*	0.036	0.031	0.026	-	0.010	0.004
IHP Energy In (Thermal)	MMBtu/ton*	-	-	-	0.168	0.151	-
Process Heat Saved	%	11.6	11.4	11.2	11.9	11.9	4.9

*** Ton refers to 2,000 lb. of pulp**

UNIT OPERATION: PULP & PAPER, DIGESTER (IHP - TECHNICAL SCENARIO)

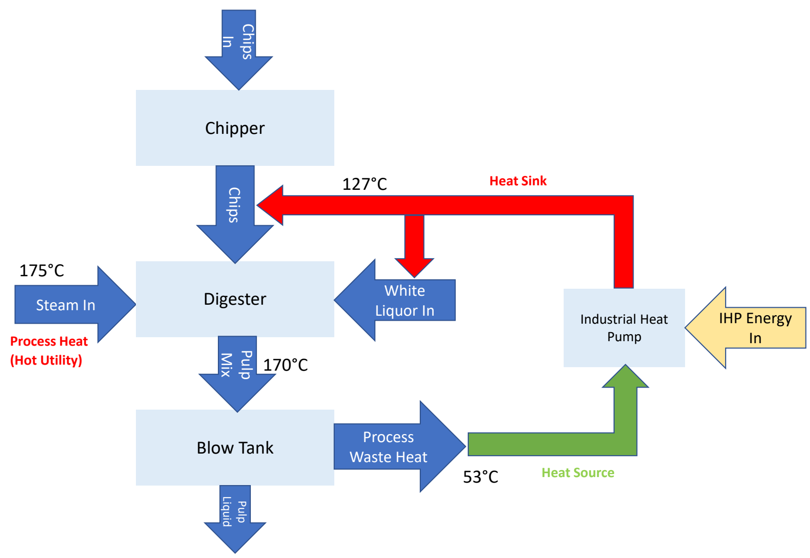

Figure A23. Illustration of IHP location in process heat chain for pulp & paper digester (technical scenario)

Table A5. Results of pinch analysis

Parameter	Units	Process Information
Process Heat (Hot Utility)	MMBtu/ton	2.1
Pinch Temperature	°C	92.8
Heat Source Temperature	°C	53.3
Heat Sink Temperature	°C	127.2
Source Heat Available	Percent of Process Heat	16.4
Sink Heat Demand	Percent of Process Heat	22.7

Table A6. Results of IHP application in unit operation

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
COP		2.415	2.536	2.708	N/A	1.060	0.121
Heat Source	MMBtu/ton*	0.332	0.337	0.339	N/A	0.026	0.339
Heat Sink	MMBtu/ton*	0.469	0.469	0.465	N/A	0.469	0.041
IHP Energy In (Electric)	MMBtu/ton*	0.137	0.133	0.125	N/A	0.020	0.002
IHP Energy In (Thermal)	MMBtu/ton*	-	-	-	N/A	0.443	-
Process Heat Saved	%	22.7	22.7	22.5	N/A	22.7	2.0

*** Ton refers to 2,000 lb. of pulp**

UNIT OPERATION: PULP & PAPER, MULTI-EFFECT EVAPORATOR

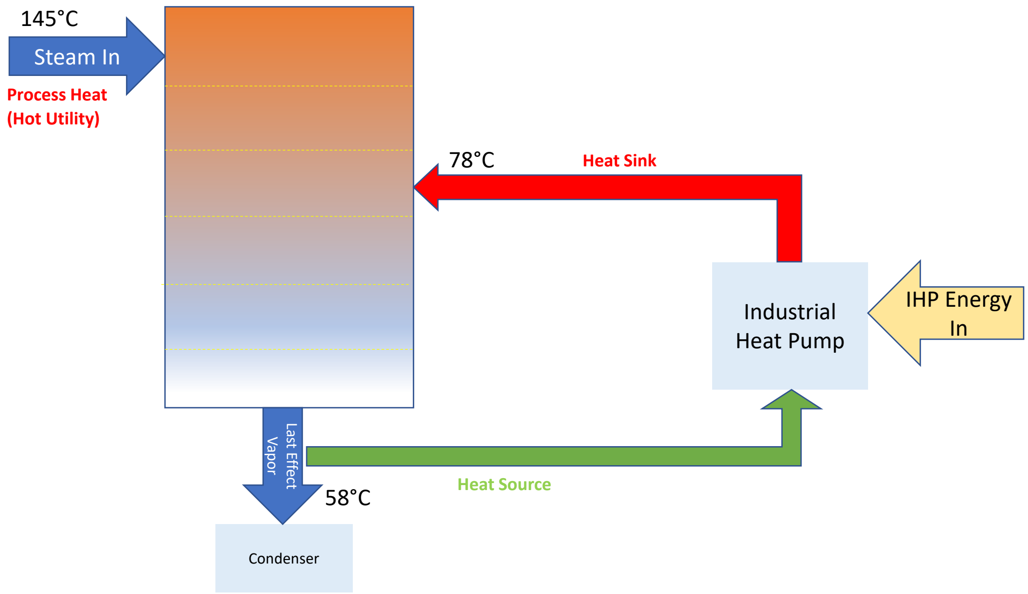

Figure A24. Illustration of IHP location in process heat chain for pulp & paper multi-effect evaporator (economic scenario)

Table A7. Results of pinch analysis

Parameter	Units	Process Information
Process Heat (Hot Utility)	MMBtu/ton	3.6
Pinch Temperature	°C	64.7
Heat Source Temperature	°C	58.4
Heat Sink Temperature	°C	77.5
Source Heat Available	Percent of Process Heat	8.2
Sink Heat Demand	Percent of Process Heat	9.5

Table A8. Results of IHP application in unit operation

		Type of IHP					
Parameter	Units	MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
COP		6.098	7.257	9.151	1.747	2.584	0.295
Heat Source	MMBtu/ton*	0.290	0.290	0.290	0.216	0.208	0.290
Heat Sink	MMBtu/ton*	0.338	0.330	0.322	0.339	0.339	0.086
IHP Energy In (Electric)	MMBtu/ton*	0.048	0.040	0.032	-	0.014	0.004

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
IHP Energy In (Thermal)	MMBtu/ton*	-	-	-	0.123	0.131	-
Process Heat Saved	%	9.5	9.3	9.1	9.5	9.5	2.4

* Ton refers to 2,000 lb. of pulp

UNIT OPERATION: PULP & PAPER, MULTI-EFFECT EVAPORATOR (IHP - TECHNICAL SCENARIO)

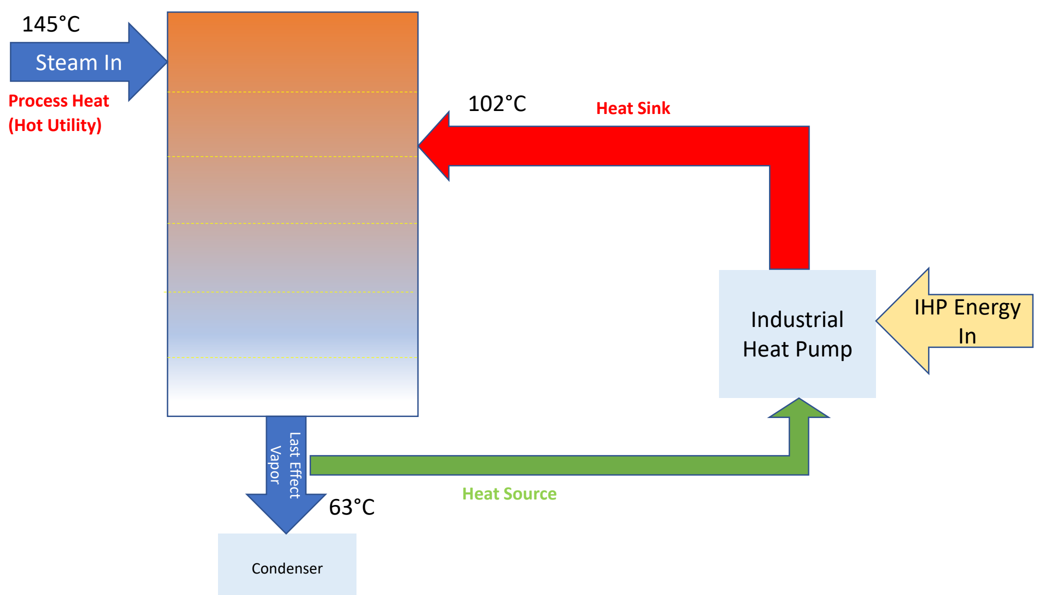

Figure A25. Illustration of IHP location in process heat chain for pulp & paper multi-effect evaporator (technical scenario)

Table A9. Results of pinch analysis

Parameter	Units	Process Information
Process Heat (Hot Utility)	MMBtu/ton	3.6
Pinch Temperature	°C	88.9
Heat Source Temperature	°C	62.8
Heat Sink Temperature	°C	102.1
Source Heat Available	Percent of Process Heat	28.3

Parameter	Units	Process Information
Sink Heat Demand	Percent of Process Heat	36.5

Table A10. Results of IHP application in unit operation

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
COP		3.855	4.234	4.772	N/A	1.582	0.254
Heat Source	MMBtu/ton*	1.003	1.003	1.003		0.477	1.003
Heat Sink	MMBtu/ton*	1.264	1.240	1.214		1.297	0.255
IHP Energy In (Electric)	MMBtu/ton*	0.260	0.237	0.210		0.055	0.011
IHP Energy In (Thermal)	MMBtu/ton*	-	-	-		0.820	-
Process Heat Saved	%	35.6	34.9	34.2		36.5	7.2

*** Ton refers to 2,000 lb. of pulp**

UNIT OPERATION: PULP & PAPER, NON-INTEGRATED PULPER

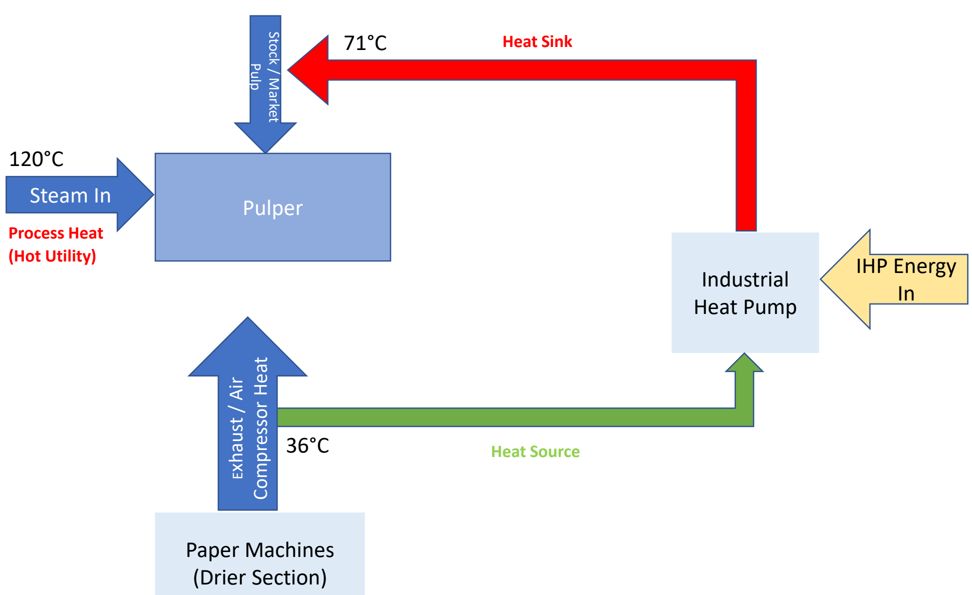

Figure A26. Illustration of IHP location in process heat chain for pulp & paper non-integrated pulper (economic scenario)

Table A11. Results of pinch analysis

Parameter	Units	Process Information
Process Heat (Hot Utility)	MMBtu/ton	1.0
Pinch Temperature	°C	44.2
Heat Source Temperature	°C	35.7
Heat Sink Temperature	°C	70.5
Source Heat Available	Percent of Process Heat	7.4
Sink Heat Demand	Percent of Process Heat	9.3

Table A12. Results of IHP application in unit operation

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
COP		3.886	4.311	4.930	1.072	1.910	N/A
Heat Source	MMBtu/ton*	0.077	0.077	0.077	0.050	0.046	
Heat Sink	MMBtu/ton*	0.096	0.094	0.092	0.096	0.096	
IHP Energy In (Electric)	MMBtu/ton*	0.020	0.018	0.016	-	0.004	
IHP Energy In (Thermal)	MMBtu/ton*	-	-	-	0.047	0.050	
Process Heat Saved	%	9.3	9.1	8.9	9.3	9.3	

*** Ton refers to 2,000 lb. of paper produced**

UNIT OPERATION: WET CORN MILLING, STEEPWATER EVAPORATION

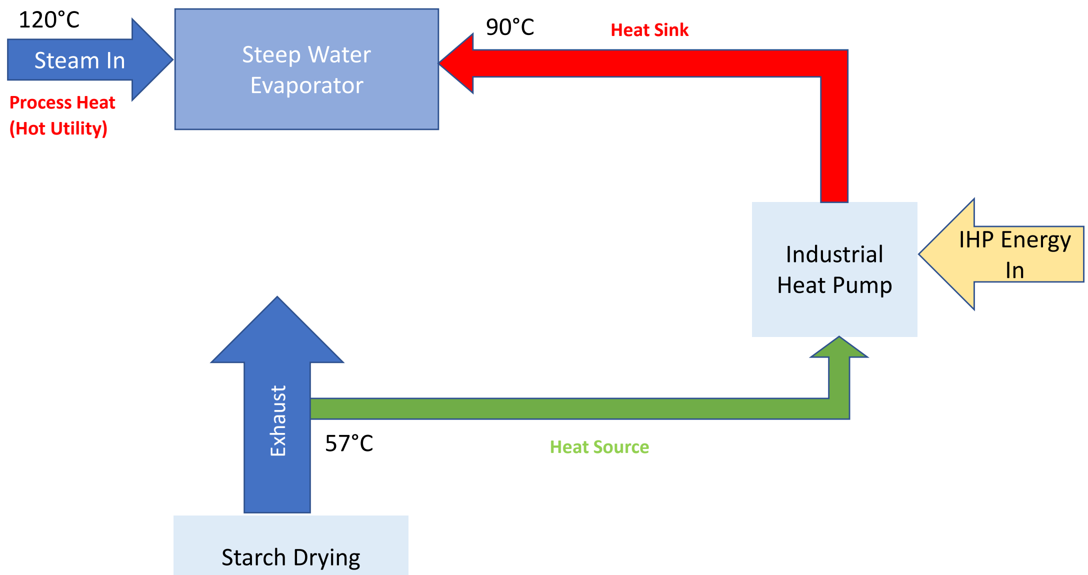

Figure A27. Illustration of IHP location in process heat chain for wet corn milling, steepwater evaporation (economic scenario)

Table A13. Results of pinch analysis

Parameter	Units	Process Information
Process Heat (Hot Utility)	MMBtu/ton	0.6
Pinch Temperature	°C	77.2
Heat Source Temperature	°C	57.0
Heat Sink Temperature	°C	90.0
Source Heat Available	Percent of Process Heat	9.1
Sink Heat Demand	Percent of Process Heat	11.0

Table A14. Results of IHP application in unit operation

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
COP		4.279	4.776	5.500	1.151	1.830	0.225
Heat Source	MMBtu/ton*	0.053	0.055	0.055	0.035	0.030	0.055
Heat Sink	MMBtu/ton*	0.066	0.066	0.065	0.066	0.066	0.012
IHP Energy In (Electric)	MMBtu/ton*	0.013	0.011	0.010	-	0.003	0.001

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
IHP Energy In (Thermal)	MMBtu/ton*	-	-	-	0.031	0.036	-
Process Heat Saved	%	11.0	11.0	10.8	11.0	11.0	2.1

*** Ton refers to 2,000 lb. of corn processed**

UNIT OPERATION: WET CORN MILLING, STEEPWATER EVAPORATION (IHP - TECHNICAL SCENARIO)

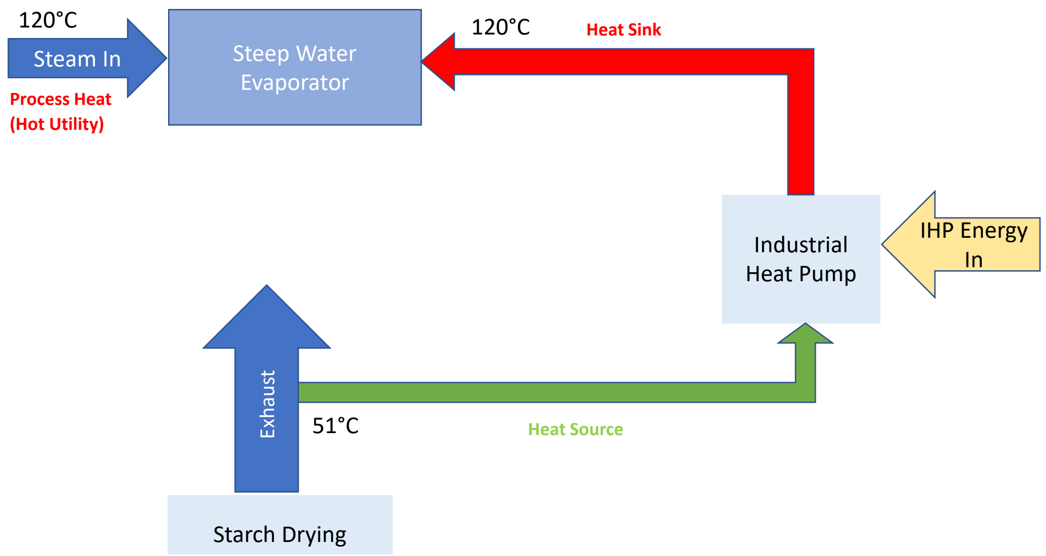

Figure A28. Illustration of IHP location in process heat chain for wet corn milling, steepwater evaporation (technical scenario)

Table A15. Results of pinch analysis

Parameter	Units	Process Information
Process Heat (Hot Utility)	MMBtu/ton	0.6
Pinch Temperature	°C	77.2
Heat Source Temperature	°C	51.0
Heat Sink Temperature	°C	120.0
Source Heat Available	Percent of Process Heat	6.8
Sink Heat Demand	Percent of Process Heat	9.4

Table A16. Results of IHP application in unit operation

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
COP		2.519	2.655	2.848	N/A	1.123	0.107
Heat Source	MMBtu/ton*	0.041	0.041	0.041		0.006	0.041
Heat Sink	MMBtu/ton*	0.057	0.056	0.055		0.057	0.004
IHP Energy In (Electric)	MMBtu/ton*	0.016	0.015	0.014		0.002	-
IHP Energy In (Thermal)	MMBtu/ton*	-	-	-		0.050	-
Process Heat Saved	%	9.4	9.4	9.2		9.4	0.7

* Ton refers to 2,000 lb. of corn processed

UNIT OPERATION: WET CORN MILLING, HIGH FRUCTOSE CORN SYRUP REFINERY

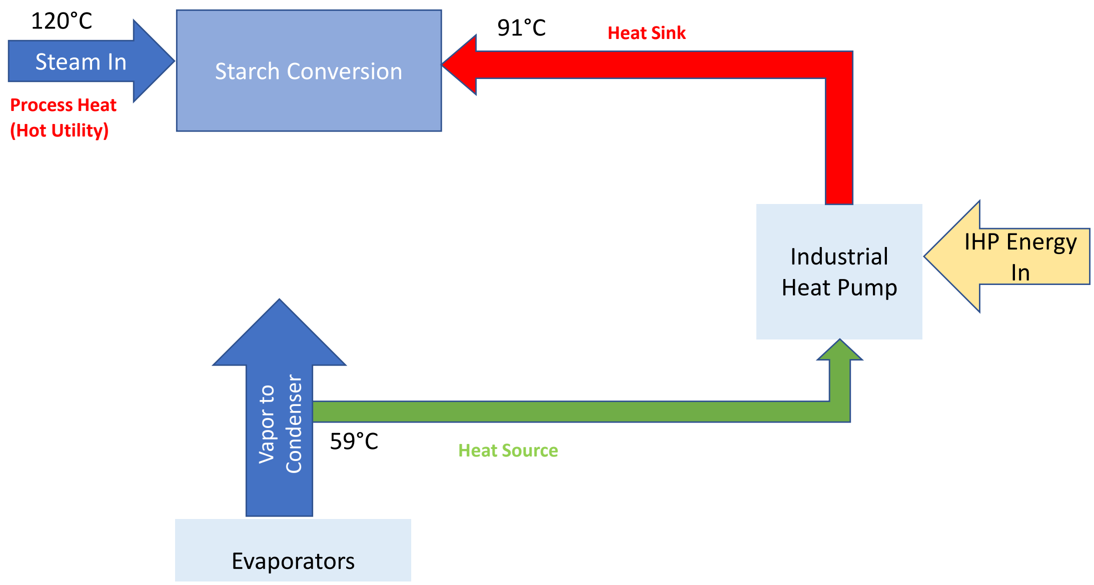

Figure A29. Illustration of IHP location in process heat chain for wet corn milling, high fructose corn syrup refinery (economic scenario)

Table A17. Results of pinch analysis

Parameter	Units	Process Information
Process Heat (Hot Utility)	MMBtu/ton	0.25

Parameter	Units	Process Information
Pinch Temperature	°C	87.7
Heat Source Temperature	°C	59.4
Heat Sink Temperature	°C	91.1
Source Heat Available	Percent of Process Heat	7.3
Sink Heat Demand	Percent of Process Heat	9.1

Table A18. Results of IHP application in unit operation

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
COP		4.426	4.960	5.743	1.207	1.861	0.251
Heat Source	MMBtu/ton*	0.018	0.018	0.018	0.012	0.010	0.018
Heat Sink	MMBtu/ton*	0.022	0.022	0.021	0.023	0.023	0.005
IHP Energy In (Electric)	MMBtu/ton*	0.004	0.004	0.003	-	0.001	-
IHP Energy In (Thermal)	MMBtu/ton*	-	-	-	0.010	0.012	-
Process Heat Saved	%	9.0	8.8	8.6	9.0	9.0	1.8

*** Ton refers to 2,000 lb. of corn processed**

UNIT OPERATION: WET CORN MILLING, HIGH FRUCTOSE CORN SYRUP REFINERY (IHP - TECHNICAL SCENARIO)

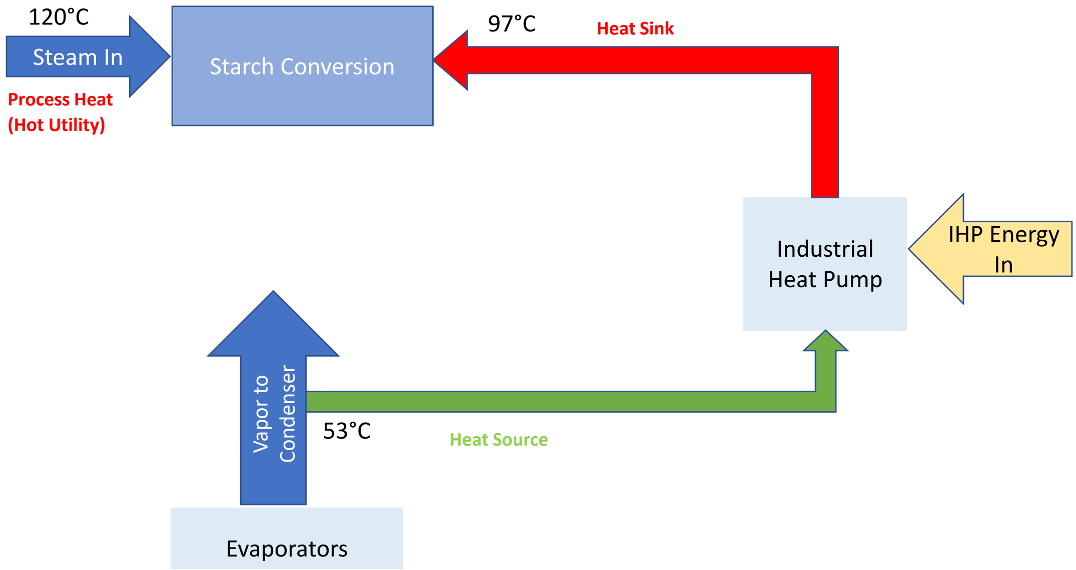

Figure A30. Illustration of IHP location in process heat chain for wet corn milling, high fructose corn syrup refinery (technical scenario)

Table A19. Results of pinch analysis

Parameter	Units	Process Information
Process Heat (Hot Utility)	MMBtu/ton	0.25
Pinch Temperature	°C	87.8
Heat Source Temperature	°C	52.8
Heat Sink Temperature	°C	96.7
Source Heat Available	Percent of Process Heat	51.9
Sink Heat Demand	Percent of Process Heat	67.7

Table A20. Results of IHP application in unit operation

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
COP		3.476	3.780	4.211	N/A	1.531	0.157
Heat Source	MMBtu/ton*	0.130	0.130	0.130		0.059	0.130
Heat Sink	MMBtu/ton*	0.167	0.164	0.161		0.169	0.020

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
IHP Energy In (Electric)	MMBtu/ton*	0.037	0.034	0.031		0.007	0.001
IHP Energy In (Thermal)	MMBtu/ton*	-	-	-		0.111	-
Process Heat Saved	%	66.8	65.6	64.2		67.7	8.1

*** Ton refers to 2,000 lb. of corn processed**

UNIT OPERATION: FOOD & BEVERAGES, POTATO DRYING

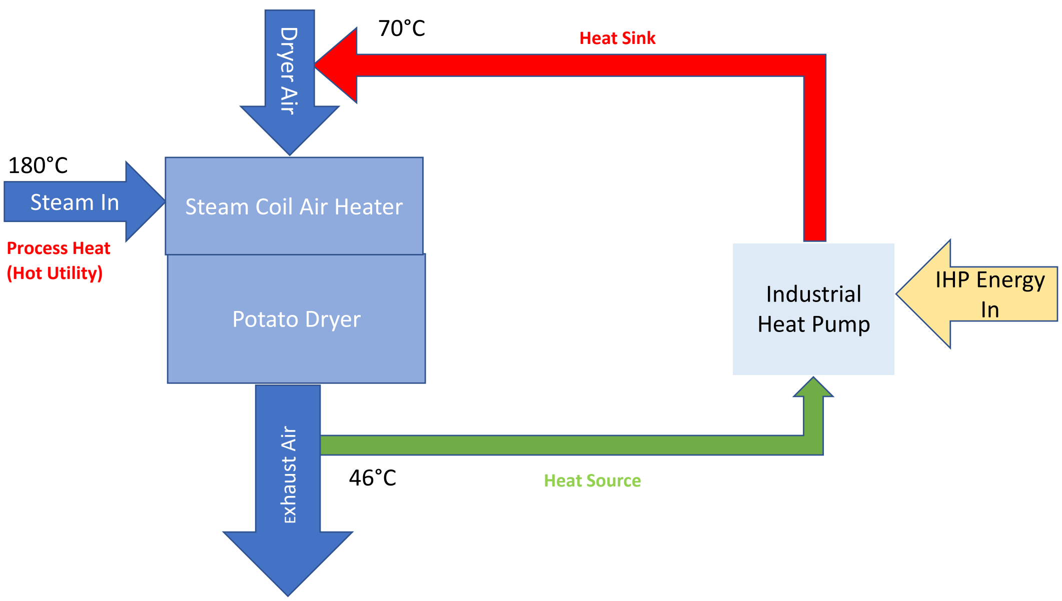

Figure A31. Illustration of IHP location in process heat chain for food and beverage, potato drying (economic scenario)

Table A21. Results of pinch analysis

Parameter	Units	Process Information
Process Heat (Hot Utility)	MMBtu/ton	3.4
Pinch Temperature	°C	52.8
Heat Source Temperature	°C	46.0
Heat Sink Temperature	°C	70.0
Source Heat Available	Percent of Process Heat	9.7

Parameter	Units	Process Information
Sink Heat Demand	Percent of Process Heat	11.5

Table A22. Results of IHP application in unit operation

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
COP		5.118	5.914	7.146	1.538	2.358	0.116
Heat Source	MMBtu/ton*	0.333	0.335	0.335	0.241	0.229	0.335
Heat Sink	MMBtu/ton*	0.398	0.391	0.382	0.398	0.398	0.039
IHP Energy In (Electric)	MMBtu/ton*	0.065	0.057	0.047	-	0.017	0.002
IHP Energy In (Thermal)	MMBtu/ton*	-	-	-	0.157	0.169	-
Process Heat Saved	%	11.5	11.4	11.1	11.5	11.5	1.1

*** Ton refers to 2,000 lb. of potatoes processed**

UNIT OPERATION: FOOD & BEVERAGES, POTATO DRYING (IHP - TECHNICAL SCENARIO)

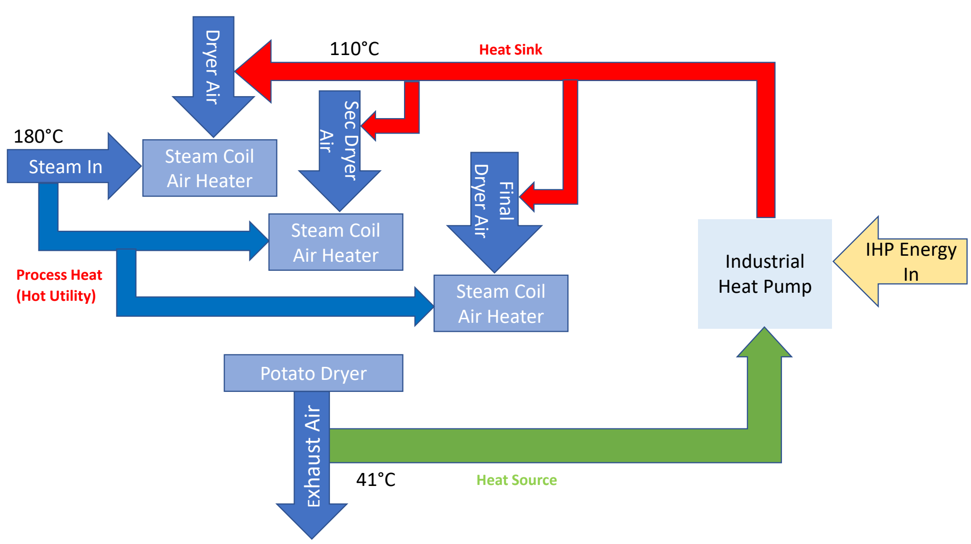

Figure A32. Illustration of IHP location in process heat chain for food and beverage, potato drying (technical scenario)

Table A23. Results of pinch analysis

Parameter	Units	Process Information
Process Heat (Hot Utility)	MMBtu/ton	3.4
Pinch Temperature	°C	66.1
Heat Source Temperature	°C	41.0
Heat Sink Temperature	°C	110.0
Source Heat Available	Percent of Process Heat	20.5
Sink Heat Demand	Percent of Process Heat	31.4

Table A24. Results of IHP application in unit operation

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
COP		2.456	2.588	2.775	N/A	1.168	0.011
Heat Source	MMBtu/ton*	0.708	0.708	0.708		0.156	0.708
Heat Sink	MMBtu/ton*	0.996	0.981	0.962		1.083	0.008
IHP Energy In (Electric)	MMBtu/ton*	0.288	0.273	0.255		0.046	-
IHP Energy In (Thermal)	MMBtu/ton*	-	-	-		0.928	-
Process Heat Saved	%	28.9	28.5	27.9		31.4	0.23

*** Ton refers to 2,000 lb. of potatoes processed**

UNIT OPERATION: ETHYLENE, DEBUTANIZER REBOILER

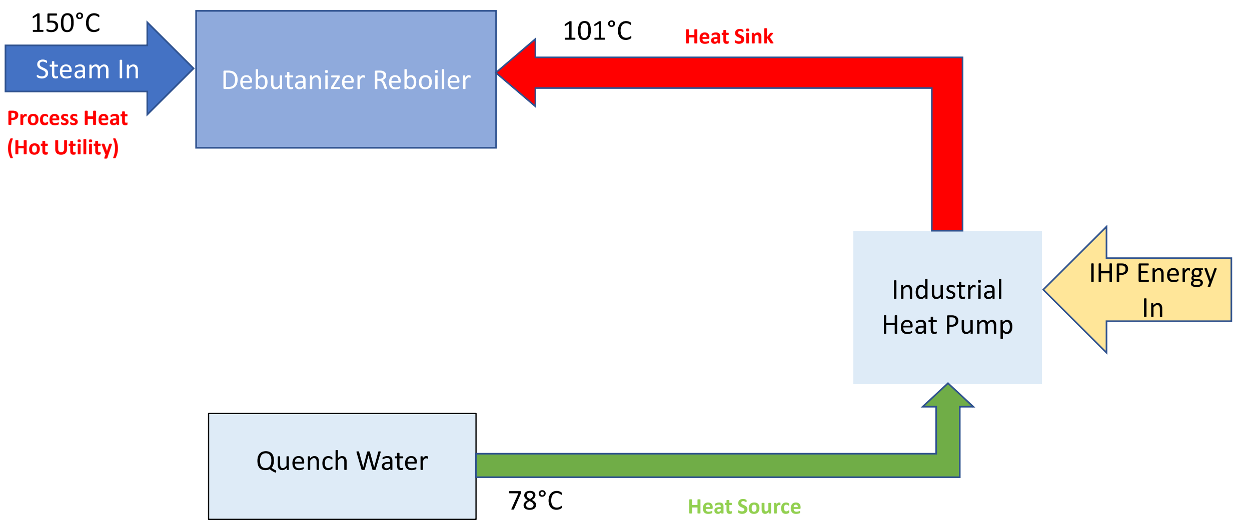

Figure A33. Illustration of IHP location in process heat chain for ethylene debutanizer reboiler (economic scenario)

Table A25. Results of pinch analysis

Parameter	Units	Process Information
Process Heat (Hot Utility)	MMBtu/ton	0.5
Pinch Temperature	°C	80.6
Heat Source Temperature	°C	78.0
Heat Sink Temperature	°C	101.1
Source Heat Available	Percent of Process Heat	15.8
Sink Heat Demand	Percent of Process Heat	18.5

Table A26. Results of IHP application in unit operation

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
COP		5.727	6.657	8.097	1.577	2.090	0.410
Heat Source	MMBtu/ton*	0.078	0.078	0.078	0.056	0.068	0.078
Heat Sink	MMBtu/ton*	0.091	0.090	0.088	0.091	0.130	0.032
IHP Energy In (Electric)	MMBtu/ton*	0.014	0.012	0.010	-	0.004	0.001
IHP Energy In (Thermal)	MMBtu/ton*	-	-	-	0.035	0.044	-

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
Process Heat Saved	%	18.5	18.2	17.8	18.5	18.5	6.5

* Ton refers to 2,000 lb. of ethylene produced

UNIT OPERATION: ETHYLENE, PROCESS WATER STRIPPER REBOILER

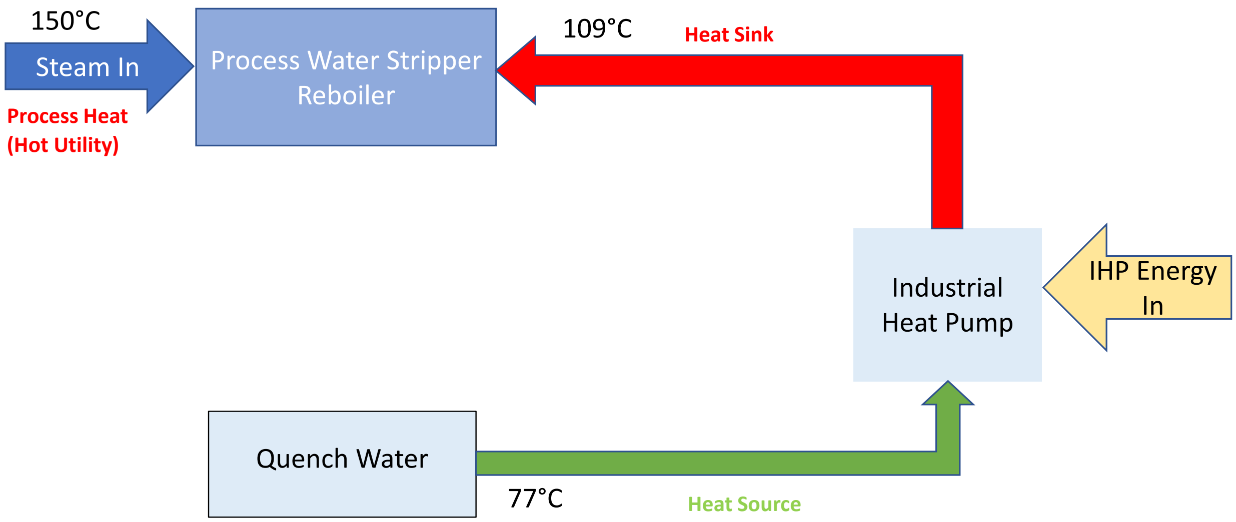

Figure A34. Illustration of IHP location in process heat chain for ethylene, process water stripper reboiler (economic scenario)

Table A27. Results of pinch analysis

Parameter	Units	Process Information
Process Heat (Hot Utility)	MMBtu/ton	0.23
Pinch Temperature	°C	80.6
Heat Source Temperature	°C	77.0
Heat Sink Temperature	°C	108.9
Source Heat Available	Percent of Process Heat	8.0
Sink Heat Demand	Percent of Process Heat	9.8

Table A28. Results of IHP application in unit operation

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
COP		4.617	5.175	5.986	1.198	1.699	0.368
Heat Source	MMBtu/ton*	0.018	0.018	0.018	0.012	0.009	0.018
Heat Sink	MMBtu/ton*	0.022	0.022	0.021	0.022	0.022	0.007
IHP Energy In (Electric)	MMBtu/ton*	0.004	0.004	0.003	-	0.001	-
IHP Energy In (Thermal)	MMBtu/ton*	-	-	-	0.010	0.013	-
Process Heat Saved	%	9.7	9.5	9.3	9.8	9.8	2.9

*** Ton refers to 2,000 lb. of ethylene produced**

UNIT OPERATION: ETHANOL, DRY MILL, DISTILLATION OF 85% WATER/15% ETHYL ALCOHOL

Note: Pinch analysis was not performed on this unit operation. It was treated as a standalone process with waste heat discharged from the condenser heat exchanger and the heat pump delivered heat alternatively to steam heating the reboiler.

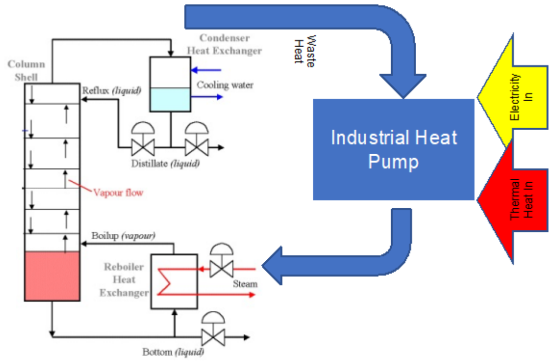

Figure A35. Illustration of IHP location in distillation tower for separation of 85% water/15% ethyl alcohol mixture to 5% water/95% ethyl alcohol mixture (economic scenario only)

Table A3. Results of pinch analysis

Parameter	Units	Process Information
Process Heat (Hot Utility)	MMBtu/ton	5.0
Pinch Temperature	°C	NA
Heat Source Temperature	°C	78
Heat Sink Temperature	°C	100
Source Heat Available	Percent of Process Heat	90
Sink Heat Demand	Percent of Process Heat	90

Table A4. Results of IHP application in unit operation

Parameter	Units	Type of IHP					
		MVC	MVR Semi	MVR Open	TVR	HA Type 1	HA Type 2
COP		5.730	6.585	7.871	1.469	1.639	0.494
Heat Source	MMBtu/ton*	0.205	0.205	0.205	0.079	0.096	0.205
Heat Sink	MMBtu/ton*	0.241	0.236	0.231	0.247	0.247	0.101
IHP Energy In (Electric)	MMBtu/ton*	0.036	0.031	0.026	-	0.010	0.004
IHP Energy In (Thermal)	MMBtu/ton*	-	-	-	0.168	0.151	-
Process Heat Saved	%	11.6	11.4	11.2	11.9	11.9	4.9

*** Ton refers to 2,000 lb. of ethanol**

References

IEA (International Energy Agency). 1995. *Industrial Heat Pumps: Experiences, Potential and Global Environmental Benefits—Final Report, Annex 21*. Sittard, NL: IEA Heat Pump Centre. heatpumpingtechnologies.org/publications/industrial-heat-pumps-experiences-potential-and-global-environmental-benefits-final-report/.

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