

Exergy Examples for the Chemical Engineering Classroom

Thomas A. Adams II^{a*}

^a Norwegian University of Science and Technology, Department of Energy and Process Engineering, Trondheim, Norway

* Corresponding Author: thomas.a.adams@ntnu.no

ABSTRACT

This work explores several examples of how the thermodynamic concept of exergy can be used in the chemical engineering classroom. Examples include using exergy to determine thermodynamic and monetary value of utilities, to identify better heat exchanger network designs, to aid in work-heat integration applications such as heat pumps and organic Rankine cycles, to scope out realistic energy integration cases, and to assess how well chemical potential is being used and managed. The examples are presented in one connected context that makes it easy to see how exergy analyses can be useful across many aspects of chemical and energy industry supply chains.

Keywords: Exergy, Education, Energy Efficiency, Process Design

INTRODUCTION

Exergy is an interesting thermodynamic property that is especially useful for the design, analysis, and optimization of energy systems. Although there are competing definitions of exergy, I believe the definition of Moran et al. [1] is the most general and the easiest for process systems engineers to understand (emphasis mine):

Definition of Exergy

Exergy is the **maximum** theoretical work obtainable from an overall system consisting of a system and the environment as the system comes into equilibrium with the environment (passes to the dead state).

The text definition can be written mathematically in a form understandable to process systems engineers:

$$e = \max_{\mathcal{P}} w \quad (1)$$

where e is the exergy, \mathcal{P} is a process that brings the system into equilibrium with the environment, and \mathbb{P} is the set of all possible processes such that $\mathcal{P} \in \mathbb{P}$. [2]. Note that “the system” can include a process, device, unit operation, heat, or a substance.

Exergy arises from the ways in which the system differs from the environment, such that some process \mathcal{P} can be made to exploit those differences. For example, if a

fluid has a higher pressure than the environment, a turbine can be used to produce work by passing the fluid through the turbine into the environment (the reverse direction is also possible [2]). If a substance is hotter than the surrounding environment, a Carnot engine can convert the higher temperature heat from the substance into work and use the environment as the sink for the lower-temperature waste heat (or its reverse [3]). Chemical potential, phase differences, concentration differences, gravity, and other forms of energy can all be exploited for some kind of work production [4], and the exergy is the maximum work theoretically possible using a perfect, reversible, frictionless, lossless process. In this form, exergy is both a measure of quantity and quality of energy simultaneously. For example, 1 kJ of heat at 100°C has less exergy than 1 kJ of heat at 200°C, even though they have the same energy.

To the process systems engineer, and especially to the process designer, this property makes exergy useful for process design, optimization, and analysis. Exergy is a good proxy for value. For example, the exergies of utilities are directly correlated with their market prices [4], exergy losses in flowing systems correlate very well system complexity [5], and exergy can also be used as a proxy for capital cost, making it particularly suitable as an objective in optimal process design problems [6]. It is excellent for debottlenecking, benchmarking, and identifying value and thermodynamic limits. It also works in reverse: exergy is also the thermodynamic minimum work

required to take material and energy from the environment and create high value products. This is particularly useful for modern relevant chemical engineering applications such as direct air capture of CO₂, desalination, cryogenic air separation, resource extraction, green hydrogen production from water (“un-combustion of hydrogen”), CO₂ conversion into fuels like synthetic methane (“un-combustion of natural gas”), and environmental remediation.

Despite all these potential uses to the system engineer, exergy is not traditionally taught much in chemical engineering education. It has little to no mention in most major chemical process design textbooks including those by Smith [7], Towler and Sinnott [8], and Peters, Timmerhaus, and West [9]. The 3rd edition of Seider et al. [10] uses the terms “availability” and “2nd law analysis” to express some of the same fundamental concepts, but is relegated to the supplementary material rather than the actual print.

Exergy is a difficult concept for both students and educators. Students need to understand enthalpy and entropy, and many of its benefits to engineering decision making can only be exploited at the senior level or higher. Nevertheless, it can be used at lower levels for analysis purposes, especially when students simply look-up / are given exergy values and skip the difficult computation portion (the book Exergy Tables [4] is simply a compendium of look-up values for students to use, shortcutting the more difficult computational portion). To make this easier, this work provides several examples of how it can be used in the classroom in a variety of contexts.

CLASSROOM EXERGY EXAMPLES

Example 1: Exergy as Proxy for Value

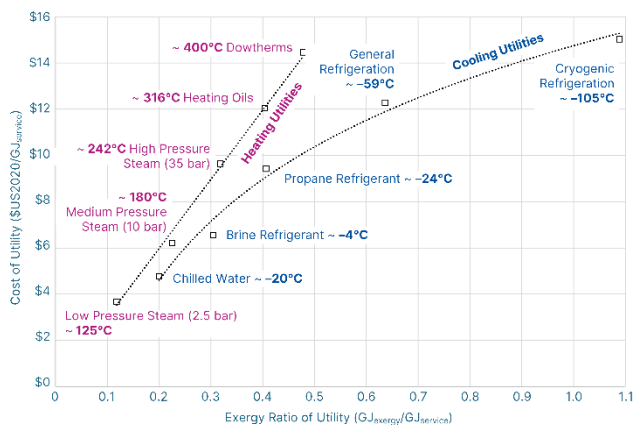


Figure 1: The cost of a utility as a function of its exergy ratio using 78°C as T_{ref} and the assumed average operating temperatures shown. Adapted from [4].

Exergy is an excellent proxy for value and can be used to estimate the market value of cold or hot utilities

at any temperature. This is especially convenient when the designer has enough degrees of freedom to choose the temperature of the desired utility. For example, Deng et al. [4] suggested the existence of a so-called “plant ambient” temperature of 78°C that arises from the statistical cost of utilities presented in Seider et al. [10]. The statistical value/cost of heating and cooling services is effectively zero at 78°C and increases as temperature moves away (up or down) from it. Essentially, 78°C statistically arises as the temperature at which something has zero thermal value on average in chemical plants, and all other deviations from there cost money to achieve. As far as utilities are concerned, 78°C is a better definition of “environmental temperature” for a chemical plant than 25°C. Consequently, Deng et al. [4] showed that the cost of utilities is strongly correlated with exergy using 78°C as the reference temperature (T_{ref}), as shown in Figure 1:

The correlation for the cost of hot utilities C_{heat} is [4]:

$$C_{heat} = 29.9 \text{ USD}_{2020} R_{ex} \quad (1)$$

where R_{ex} is the exergy ratio of the utility at temperature T in °C (sometimes called the exergy quality) which is the amount of exergy of that utility using 78°C as the environmental reference temperature expressed per unit of thermal energy received or delivered by the utility. USD₂₀₂₀ means US dollars in the year 2020. For heat at $T \geq T_{ref}$ this is:

$$R_{ex} = 1 - \frac{273.15 + T_{ref}}{273.15 + T} \quad (2)$$

For example, heating services at 200°C would have an exergy ratio of 0.258 GJ_{exergy} per GJ_{heat} and cost 7.71 USD₂₀₂₀ per GJ_{heat} purchased. For cold, the exergy ratio is the exergy the heat sink (the cooling sink / utility) at temperature T per unit of thermal energy moved from the hot source to the cold utility. The definition of R_{ex} switches for $T \leq T_{ref}$:

$$R_{ex} = \frac{273.15 + T_{ref}}{273.15 + T} - 1 \quad (3)$$

and is expressed in GJ_{exergy} per GJ_{cooling}. The corresponding cost of cooling utilities again applies when R_{ex} is calculated using 78°C for T_{ref} :

$$C_{cool} = 14.75 \text{ USD}_{2020} + 6.31 \text{ USD}_{2020} \ln R_{ex} \quad (4)$$

For example, a cooling sink at -40°C (e.g. refrigeration) has an exergy ratio of 0.506 GJ_{exergy} per GJ_{cooling} and cost 10.5 USD₂₀₂₀ per GJ_{cooling} provided. It is very straightforward for students to quickly connect exergy, temperature, and value with these equations for all sorts of uses.

Example 2: Pinch Analysis & Heat Integration

Consider the balanced composite curves shown for a proposed heat exchanger network (HEN) that meets the minimum energy targets in Figure 2 (left). The red lines indicate the profile of the hot streams of the HEN and the blue lines indicate the cold streams. The heating

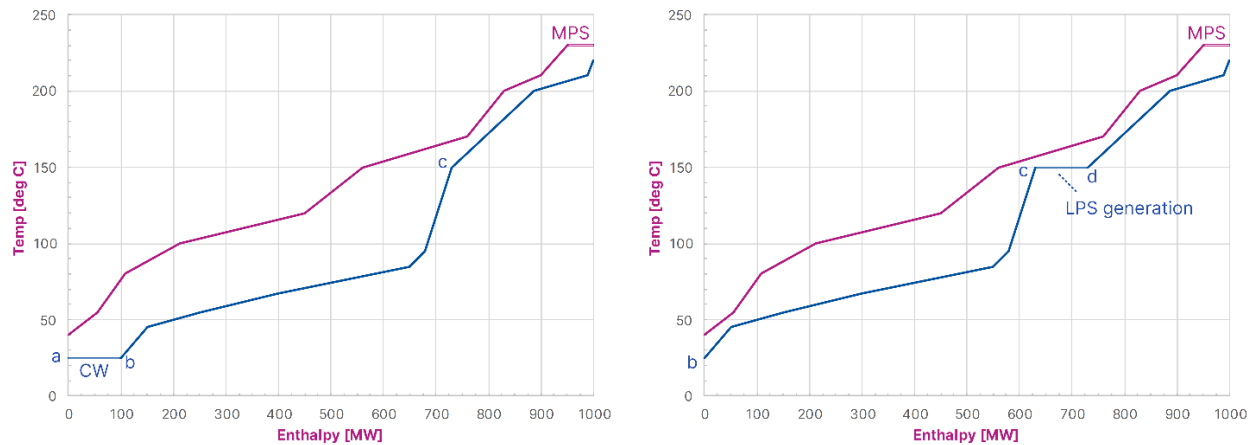


Figure 2: (left) Balanced composite curves of a proposed heat exchanger network resulting from classic methods. (right) A suggested improvement by a student.

utility is medium pressure steam (MPS) as shown, and the cooling utility is cooling water (CW), line segment **ab**. This balanced composite curve is typical of one that would be developed with classic minimum energy targeting methods as described in various popular textbooks [7, 10, 11] and taught in many undergraduate courses.

The student can take another step further and evaluate the exergy value or cost of the utilities. Whether selecting the plant ambient or environmental ambient as the reference case, the exergy of the required utilities can be computed, and their market value approximated from equations (1)–(4). Here, the cost of cooling is about 3.85 USD₂₀₂₀/GJ and at 100 MW (the width of line **ab**) would cost about 12 million USD₂₀₂₀/year. Then the student can identify an improvement to the system which still meets the minimum energy requirements, but has better exergy or monetary value, which are directly correlated.

The general idea is to identify low hanging fruit on the composite curve such that utility loads can shift to places in the HEN with lower cost. For example, a student could suggest that a new HEN could be made with the balanced composite curve shown in Figure 2 (right) by shifting line segment **bc** to the left until a minimum approach temperature other constraint has been reached. In this case, all 100 MW of cooling can be removed, and **bc** shifted all the way to the left. The student can replace the 100 MW of cooling with 100 MW of low-pressure steam (LPS) **generation** at 150°C (segment **cd**). The curves are tighter now for hot-side temperatures around 50°C and 160°C, meaning that the HEN might be more complex and require more heat exchanger area (due to smaller temperature driving forces). But it might be worth it because the utility value improvement is enormous. Instead of spending money on cooling, we can **generate** value up to 16 million USD/year instead of spending 12 million USD/year.

This is simple way to connect many topics relating to energy quantity, quality, economics, thermodynamics, HEN design, and optimization all at once in the classroom. You can immediately see how this can be integrated into the objective functions of optimal heat exchanger network design for more complex class material [6].

Example 3: Work-Heat Integration

Continuing that example, perhaps we do not want to make LPS because we have no need for it or way to sell it, but we could instead use that steam to produce work. A student can immediately estimate the upper bound work production potential of recovering 100 MW at 150°C against our actual environmental temperature (let us choose the common T_{ref} of 25°C). From equation (2), the exergy ratio of that recovered heat is about 0.295, meaning that one could produce a theoretical maximum of 0.295 GJ of work per GJ of heat recovered. For 100 MW of waste heat recovered, this is 29.5 MW of work. That is certainly a large enough potential to considering the idea further.

A student can then use exergy to set a few more benchmarks about how the system could work in practice. First, LPS is generally too weak to produce much work in a steam cycle, so at 150°C we might consider an organic Rankine cycle (ORC). Figure 3 shows an example of how a simple ORC might work using R113 as a working fluid on a Temperature-Enthalpy-Exergy diagram. Thermo-mechanical exergy (e^{tm} , blue lines) is computed using T_{ref} of 25°C and the following equations for thermo-mechanical exergy of a substance [2]:

$$e_1^{tm} = \begin{cases} (h - h_{ref}) - T_{ref}(s - s_{ref}) & p \geq p_{ref} \\ (2h_* - h - h_{ref}) - T_{ref}(s - s_{ref}) & p \leq p_{ref} \end{cases} \quad (5)$$

where h , s , and p are the intensive enthalpy, entropy, and pressure of the point of interest; h_{ref} , s_{ref} , and p_{ref} are the

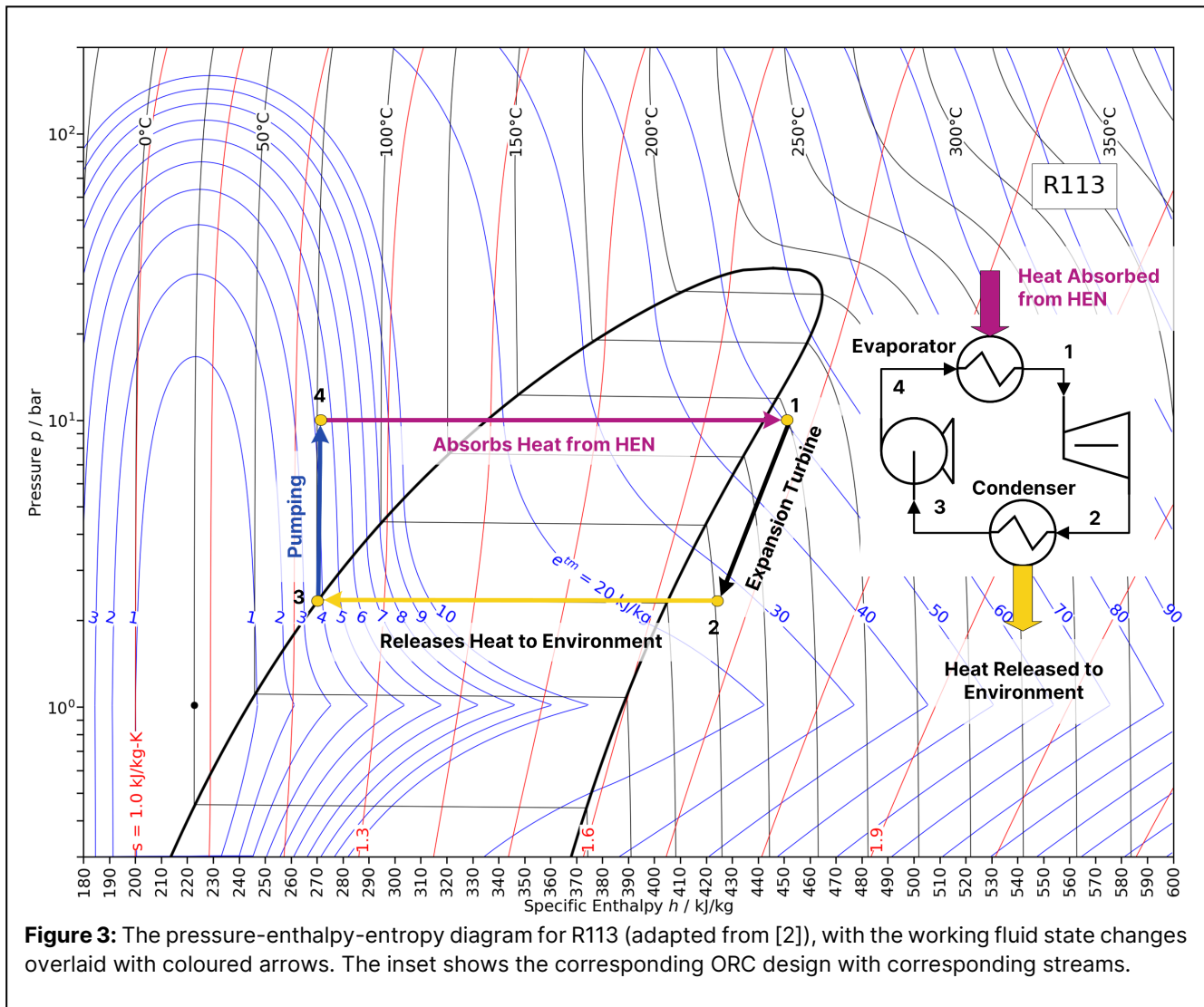


Figure 3: The pressure–enthalpy–entropy diagram for R113 (adapted from [2]), with the working fluid state changes overlaid with coloured arrows. The inset shows the corresponding ORC design with corresponding streams.

intensive enthalpy, entropy, and pressure at the reference conditions (the reference pressure chosen is $p_{\text{ref}} = 1$ atm); and $h_* = h(p_{\text{ref}}, s)$.

Using Figure 3 or equation (5), the student can quickly select some good starting points for an ORC design. The student has chosen point **1** to be the highest pressure that R113 can get while being slightly superheated and at the maximum possible 150°C (about 10 bar, see Table 1 for approximate stream conditions), since this is the temperature of our sink. This student selected the pressure of Point **2** to be the lowest pressure R113 can get along a path of isentropic expansion such that the temperature is still high enough to dump heat to the environment via the condenser. For example, we could decide we want to use cooling towers and so maybe we would pick a temperature of, say, 40°C. The lower the temperature, the more work produced, but then the higher the cost for cooling in the condenser.

Table 1. Approximate stream conditions for the ORC shown in Figure 3.

Stream	1	2	3	4
T °C	150	101	78	78
P bar	10	2.1	2.1	10
h kJ/kg	450	425	272	272
e^{tm} kJ/kg	51	26	4	4
E MW	28.7	14.6		

However, remembering example 2, the point of this was to avoid cooling towers, so the student chose a point at 2.1 bar such that phase change occurs close to the plant ambient temperature so that heat removal in the condenser is basically free. Point **3** is chosen as simply the point at which the R113 is fully condensed. Point **4** is point where the pressure returns to 10 bar isentropically. This line of thinking is simple and quick enough such that points can be chosen by hand and sketched with a pencil on an exam.

The student can quickly determine key several metrics by reading off the diagram or using more rigorous formulas (see Table 1). For example, the flow rate of the working fluid is quickly determined by the enthalpy difference between points 4 and 1 ($h_4 - h_1 = 178$ kJ of heat adsorbed per kg of R113, which at 100 MW absorbed is 562 kg/s of R113).

The exergy at point 1 is about 51 kJ/kg, which at the system flow rate is about 29 MW. This is a good check because it cannot be higher than the theoretical maximum exergy of the 100 MW heat of 29.5 MW exergy we computed earlier. Given the limited precision of Figure 3, it means our choice for point 1 is very good and there is little room for improvement by changing the conditions. Note that for this sketch, the work required by the pump ($h_4 - h_3$) is too small to be considered within the precision of this analysis.

The work produced by the turbine is simply the enthalpy difference between points 1 and 2 ($h_1 - h_2 = 25$ kJ/kg, which for 562 kg/s of R113 is 14 MW). That's a sizeable amount of work and perhaps worth pursuing. Note however, that the work produced by the turbine is also the thermo-mechanical exergy difference between point 1 and point 2 ($e_1^{tm} - e_2^{tm} = 25$ kJ/kg also). We can see immediately since point 2 has a thermo-mechanical exergy of $e_2^{tm} = 26$ kJ/kg that we are not using, we are leaving about half of our potential value on the table with this ORC.

It is instructive for the student to compute some useful metrics such as the energy efficiency (η_{en}) and the exergy efficiency (η_{ex}), noting that work is pure exergy:

$$\eta_{en} = \frac{\text{Power Produced}}{\text{Heat Supplied}} = \frac{14 \text{ MW}}{100 \text{ MW}} = 14\% \quad (6)$$

$$\eta_{ex} = \frac{\text{Exergy Produced}}{\text{Exergy Supplied}} = \frac{14 \text{ MW}}{29.5 \text{ MW}} = 47\% \quad (7)$$

The metrics show that although percentage of the waste we convert to power is relatively small (14%), we recover 47% of the **value**, which is quite good for low quality waste heat! Considering all the metrics together, the student can conclude that (1) the 150°C waste heat is sufficiently large to be meaningful, (2) the ORC design captures about half the value of that heat, which is also meaningful, and (3) there is still much room to improve the design with changes like a lower turbine outlet pressure or an economizer. The process of sketching out design concepts, linking them to thermodynamic states, and then computing and analyzing important metrics relating to energy and exergy is an important take-away skill set for any student approaching any kind of energy engineering problem.

Example 4: MPS Generation by Combustion

Let's continue that example but focus on the MPS utility requirement. Utility steam generation usually requires natural gas or some other fossil fuel combustion to

produce. A student can quickly estimate the cost and exergy value of this steam (50 MW at 230°C) using equations (1) – (4) to be about 14 million USD/yr with an exergy value relative to 25°C of 18.6 MW. Suppose the student should design a boiler process to create this steam from natural gas, and proposes a design shown in Figure 4, with stream conditions in Table 2 determined by Aspen Plus V14 simulation (see end of paper for downloadable link). To deliver heating services by condensing at about 230°C we need steam at 29 bar, and we should make it superheated to 235°C as a safety margin. The steam flow can be determined via the latent heat of vaporization of steam at 29 bar knowing that we need 50 MW of heating service. The rest of the stream rates are determined by other design requirements such as complete combustion of the natural gas, maximum combustion zone temperature, a minimum driving force temperature in the boiler heat exchanger, and assumed conditions about the condensed steam that returns to the boiler in a closed loop.

Table 2. Approximate mass and exergy flows for the boiler process shown in Figure 4.

Stream	F (kg/s)	e^{ch} (MJ/kg)	e^{tm} (MJ/kg)	E (MW)
1	2.68	48.3	-	129
2	2.68	48.3	0.013	129
3	225	-	-	-
4	225	-	0.007	1.6
5	227	0.009	0.063	16.4
6	27.7	0.049	0.207	7.1
7	27.7	0.049	0.209	7.2
8	27.7	0.526	0.964	41.3

Blow. 1	44 kW	0.04
Blow. 2	2.2 MW	2.23
Pump	10 kW	0.01

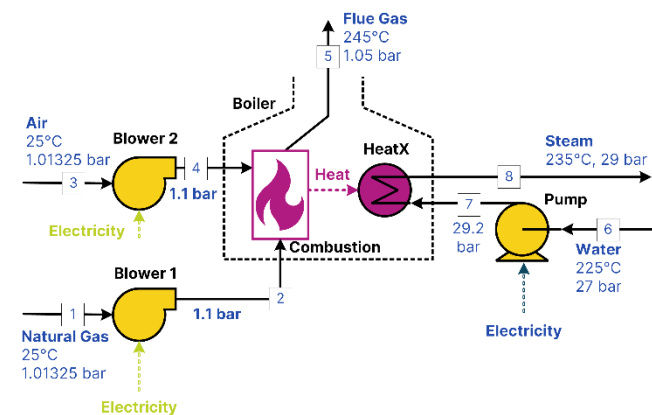


Figure 4. A proposed boiler for generating MPS (29 bar steam slightly superheated to 235°C) which can be used to deliver heat at about 230°C as it condenses.

The thermo-mechanical exergy of the relevant streams can be quickly determined through equation (5) or found in tables such as in the book *Exergy Tables* [4]. Similarly, the chemical exergy (e^{ch}) of the streams (the

work potential associated with chemical bonds, phase, and its chemical composition difference against the environment), can also be found in [Exergy Tables](#) to be 831.7 MJ/kmol (or 48.27 MJ/kg) of US Average Pipeline Natural Gas. From this information, the total exergy flows (E , the sum of thermo-mechanical and chemical exergy) can be computed and shown in a Sankey diagram (Figure 5). Exergy efficiency also can be computed with equation 7 ($\eta_{ex} = 31\%$).

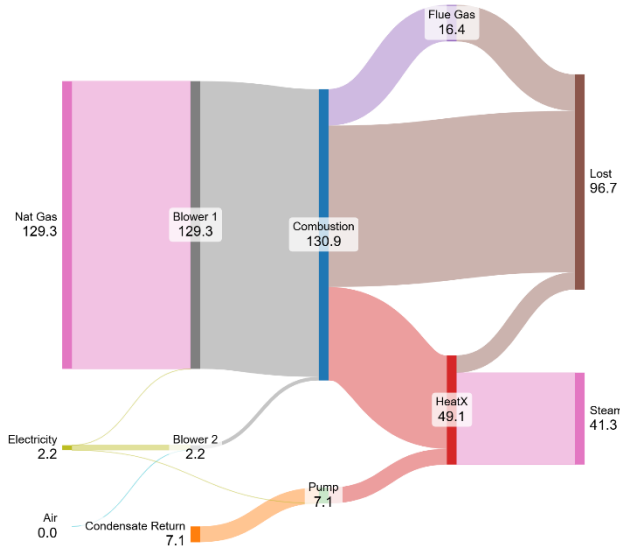


Figure 5. Exergy flows in MW of the boiler process of Figure 4. Generated at Sankeymatic.com.

The Sankey diagram is an excellent teaching tool to visualize the exergy flow (the energetic **value**) through the system. The student can immediately see the relatively small importance of the electricity compared to the chemical exergy of the natural gas. The condensate return (stream 6) matters too. The losses though are the most telling. For example, a sizeable amount of heat is lost in the flue gas, identifying this as a possible place to capture that heat for some purpose and recover a decent amount of value of up to 16.4 MW. Again, the exact values do not matter so much; using different reference conditions or different approximations for exergy will still result in a diagram that looks very much the same with the same analytic usefulness to the engineer.

However, most of the exergy lost is through exergy destruction in the combustion step. In other words, combustion as a process inherently destroys much of the chemical exergy value in the fuel. This has bigger picture concerns in the world of power production in which most transportation mechanical power and municipal electric power is produced from fossil fuels via combustion. Now the student can see the connection between combustion and how well the natural gas is used. This is an opportunity to start larger discussions into sustainability and modern technologies like fuel cells that are not limited by

combustion and therefore can theoretically better use our fossil-fuel resources via non-combustion approaches to heating and power.

Example 5: Heat Pumps

With that note, we can continue the example further by considering whether we can avoid combustion entirely. Looking at the balanced composite curves in Figure 2 (right), we might be able to use a heat pump to take the waste heat from our new 100 MW heat sink at 150°C (with 29.5 MW of exergy) and upgrade it to a heat source at 230°C, potentially replacing the need for some or all of the 50 MW of MPS generation from natural gas.

The student can immediately scope this out with exergy because the 29.5 MW waste heat exergy is higher than the 20.4 MW of exergy needed to provide 50 MW of 230°C heat to our HEN cold streams. In theory, there is more than enough exergy available from the waste heat to convert it to a high temperature heating utility by using **theoretically perfect and fully reversible machines**. In fact, we would only need to recover about $20.4 / 29.5 = 69\%$ of the exergy of our waste heat to replace all MPS needs. Of course, the practical reality can be quite different. Nevertheless, this proposed match is potentially suitable from an exergy perspective and deserving of a closer look.

One option is a chemical heat pump, which uses chemical loop where an endothermic reaction absorbs the low temperature waste heat, and then later the reaction is run in reverse exothermically to release heat at a higher temperature. This process requires relatively little work and is mostly powered by the waste heat [12], so it is a good option when electricity is expensive or has a high carbon footprint. A recent study considered several candidate chemical systems and recommended an optimal design using an isopropanol-acetone-hydrogen chemical heat pump that could take waste heat at 150°C and produce heat at 225°C (very close to this example) with an exergy efficiency (relative to 25°C) of about 33% and a coefficient of performance of about 18% [13]. This is a meaningful amount of exergy recovery for something that is powered almost entirely by waste heat. In other words, instead of using cooling water for this HEN, or instead of building an ORC, this chemical heat pump would convert the 100 MW waste heat at 150°C to about 18 MW at 230°C, reducing the MPS production load by 36% and its associated greenhouse gas emissions from natural gas combustion. The student can then estimate if this concept is worth it by considering the exergy flows and cost as predicted by exergy discussed earlier.

Mechanical heat pumps could be another option, in which a meaningful (but not huge) amount of work is used to upgrade waste heat to higher temperatures. If we had access to low cost and/or low carbon-footprint electricity, this might be a good way to avoid natural gas

combustion for MPS production. However, most so-called “high temperature” mechanical heat pumps operate at ranges well below our targeted application [14] with the next frontier going up to the 200°C range [15]. Unfortunately we need to go to 230°C with an 80°C temperature lift, something that has not been well-proven yet but is under active study.

However, based on some of the highest temperature mechanical heat pumps that have been studied, we can make some estimates using exergy. An ammonia-water absorption-compression heat pump can reach temperatures of 230°C, although perhaps not with this high of a temperature lift. Regardless, based on studies at similar temperatures [16], at best we could expect a coefficient of performance of about 3 in a future system. For a mechanical heat pump, this is:

$$COP = \frac{\text{high temperature heat produced}}{\text{work consumed}} \quad (8)$$

So, for a COP of 3 we would need 16.7 MW_{el} of electric work (which is 16.7 MW of pure exergy) to produce 50 MW of 230°C heat, and by energy balance we would consume 33 MW, or 33% of the 150°C waste heat (so there is ample supply). The student can quickly compute the exergy efficiency of the mechanical heat pump to be:

$$\eta_{ex,mhp} = \frac{20.4 \text{ MW}_{230\text{C,heat}}}{(0.33)29.5 \text{ MW}_{150\text{C,heat}} + 16.7 \text{ MW}_{el}} = 77\% \quad (9)$$

This is a high number and is a good use of high-exergy electricity—much higher than the 31% exergy efficiency from natural gas combustion, and higher than the chemical heat pump to boot. In fact, this is even better than if we used a resistance-type electric heating system (which has 100% energy efficiency!), because the exergy efficiency of that would be only 20.4 MW / 50 MW = 41%. Thus, although the technology has not been well studied yet for this application, there is a real potential value in it.

Other Energy and Sustainability Examples

Some other interesting classroom examples include:

- **Direct Air Capture of CO₂.** Exergy Tables lists the chemical exergy of CO₂ at about 19.8 kJ/mol [4], which is the **maximum** amount of work that could be produced by taking pure CO₂ at 25°C and 1 atm and exploiting the concentration difference with the environment (at hundreds of ppm levels). However, it is also the reverse; it is the thermodynamic **minimum** work required to extract pure CO₂ from the atmosphere at 25°C and 1 atm. Good classroom discussions can follow which compare existing DAC technologies to this bound, or cross-compare against other kinds of CO₂ mitigation or capture technologies.
- **CO₂ Compression for Transport.** CO₂ captured from power plant exhaust or other process

streams is generally high-purity CO₂ near environmental temperature and pressure. The next step usually is compression to supercritical conditions for pipeline transport (often for sequestration). The $e_{\text{CO}_2}^{\text{tm}}$ at common pipeline conditions (120 bar, 30°C) is about 220 kJ/kg [4], meaning that $e_{\text{CO}_2}^{\text{tm}}$ is a great lower bound on the work required to do the compression. Students can use this benchmark to compare quality of compression train designs or for broad-level analyses that place it in a larger picture of CO₂ mitigation technology options for many different supply chains.

- **Liquefied natural gas (LNG) and liquid hydrogen (LH₂).** Exergy Tables [4] lists chemical and thermo-mechanical exergy for many transport fuels. For example, $e_{\text{LNG}}^{\text{tm}}$ is roughly 1.1 MJ/kg, which is about 2% of its chemical exergy. $e_{\text{LH}_2}^{\text{tm}}$ is about 12 MJ/kg, a whopping 10% of its chemical exergy. These are the thermo-dynamic minimum work requirements to liquify each fuel in preparation for transport, highlighting the substantial energy penalty required. It illustrates one major problem with switching from LNG supply chains to LH₂ supply chains since 10% of the chemical value of the H₂ must be spent just to prepare it for transport. This is an interesting, big-picture way of seeing the global problem. It also is a great launch point for discussing cold exergy, since some of that work can be recaptured during regasification.

FINAL NOTES

There is a longstanding debate as to how much importance should be placed on the concept of exergy. Some perhaps place it on too-high of a pedestal with other thermodynamic concepts such as Gibbs or Helmholtz free energies. Thermo-mechanical exergy appears very similar in structure to those fundamental properties, but in the final analysis, exergy lacks the deeper thermo-chemical nuance owing to its dependence on non-arbitrary reference conditions which are very difficult to define and ultimately are always changing [4]. Thus, some argue passionately over the “correct” reference conditions and use cases. Others reject exergy entirely in favour of similar approaches like lost-work analysis (entropy generation), citing the various ambiguities in exergy analysis and the reliance on a subjective determination of what **precisely** constitutes “the environment” [17]. The reader is referred to work by Gößling-Reisemann for a historical overview of this ongoing debate [18].

In my view, the value of exergy is in its usefulness to us process systems engineers. For the examples we have given, it does not truly matter if one person chooses slightly different environmental reference conditions than

another, thus arriving at different actual values of exergy, because differences in the precise values of exergy ultimately do not hinder its usefulness. If I use exergy as a proxy for cost in a design optimization problem, I can get very good optimal design results that will end up being a very good design, regardless of those precise choices. If I use exergy for a thermodynamic bound on my performance, my real performance will never get very close to the perfect theoretical limit anyway, but it remains very helpful in my continual strive to improve my process and approach this bound. It is still very useful for identifying bottlenecks and energy integration opportunities even if the measured size of that opportunity changes a little bit depending on who is doing the asking. The point is in the identification, in the doing, and in the outcomes, not the final metric. My suggestion to the educator is to continually present the material in the context of how it helps the designer make good decisions and focus less on the exact values of the numbers themselves.

DIGITAL SUPPLEMENTARY MATERIAL

The Aspen Plus V14 simulation used in this work is archived in LAPSE and freely downloadable at:

<https://psecommunity.org/LAPSE:2025.0027>

ACKNOWLEDGEMENTS

No funding was received for this work.

REFERENCES

- Moran MJ, Shapiro HN, Boettner DD, Bailey MB. *Fundamentals of Engineering Thermodynamics*, 8th ed.; Wiley: NJ, 2014. ISBN 978-1118412930
- Adams TA II, Gundersen T. Thermo-mechanical exergy of a substance below environmental pressure. *Ind Eng Chem Res* 63:6286-6296 (2024). <https://doi.org/10.1021/acs.iecr.4c00007>
- Adams TA II. Thermo-mechanical exergy of a substance in cold applications approaching absolute zero. *Syst Control Trans* 3:2-9 (2024). <https://doi.org/10.69997/sct.129960>
- Deng L, Adams TA II, Gundersen T. *Exergy Tables*. McGraw-Hill: New York (2023)
- Ibrić N, Adams TA II, Gundersen T. Synthesis of heat-integrated water networks with exergo-economic criteria. *Chem Eng Trans* 103:805-810 (2023). <https://doi.org/10.3303/CET23103135>
- Ibrić N, Adams TA II, Gundersen T. Exergo-economic optimization of heat-integrated water networks. *Thermal Sci Eng Prog* 55:102883 (2024). <https://doi.org/10.1016/j.tsep.2024.102883>
- Smith R. *Chemical Process Design and Integration*, 2nd Edition. Wiley: West Sussex (2016).
- Towler G, Sinnott R. *Chemical Engineering Design*. 6th Edition. Butterworth-Heinemann: Oxford (2020).
- Peters MS, Timmerhaus KD. *Plant Design and Economics for Chemical Engineers*, 5th Edition. McGraw-Hill: New York (2004).
- Seider WD, Seader JD, Lewin DR, Widago S. *Product and Process Design Principles* 3rd Edition. Wiley: New Jersey (2009).
- Kemp, IC. *Pinch Analysis and Process Integration*, 2nd Edition. Elsevier-BH (2006)
- Krishnadoss R, Adams TA II. Integration of a Chemical Heat Pump with a Post-Combustion Carbon Capture Adsorption Unit. *Syst Control Trans* 3: 484-489 (2024). <https://doi.org/10.69997/sct.128149>
- Krishnadoss R, Dyrland IA, Adams TA II. Design and optimization of alcohol-ketone-hydrogen chemical heat pumps. *Submitted to Comput Chem Eng* (2025). <https://psecommunity.org/LAPSE:2025.0009>
- Jiang J, Hu B, Wang RZ, Deng N, Cao F, Wang CC. A review and perspective on industry high-temperature heat pumps. *Renew Sus Energy Rev* 161:112106 (2022). <https://doi.org/10.1016/j.rser.2022.112106>
- Hamid K, Sajjad U, Ahrens MU, Ren S, Ganesan P, Tolstorebrov I, Arshad A, Said Z, Hafner A, Wang CC, Wang R, Eikevik TM. Potential evaluation of integrated high temperature heat pumps: A review of recent advances. *App Thermal Eng* 230:120720 (2023). <https://doi.org/10.1016/j.applthermaleng.2023.120720>
- Jensen JK, Markussen WB, Reinholdt L, Elmegaard B. On the development of high temperature ammonia-water hybrid absorption-compression heat pumps. *Int J Refrig* 58: 79-89 (2015). <https://doi.org/10.1016/j.ijrefrig.2015.06.006>
- Chen D, O'Connell JP, Seider WD. Thermo-economic analyses of sCO₂ power cycles. *AIChE J* 70:e18502 (2024). <https://doi.org/10.1002/aic.18502>
- Göbbling-Reisemann S. Entropy production and resource consumption in life-cycle assessments. Chapter in: *Thermodynamics and the Destruction of Resources*, eds: Bakshi BR, Gutowski TG, Sekulić DP, Cambridge University Press: New York (2011).

© 2025 by the authors. Licensed to PSEcommunity.org and PSE Press. This is an open access article under the creative commons CC-BY-SA licensing terms. Credit must be given to creator and adaptations must be shared under the same terms. See <https://creativecommons.org/licenses/by-sa/4.0/>

