

# Exergy Examples for the Chemical Engineering Classroom

A useful systems analysis tool for energy efficiency and energy systems analysis.

Corresponding Paper: *Syst Control Trans* 4:2234-2241 (2025)



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# Exergy Tables

## Out now!

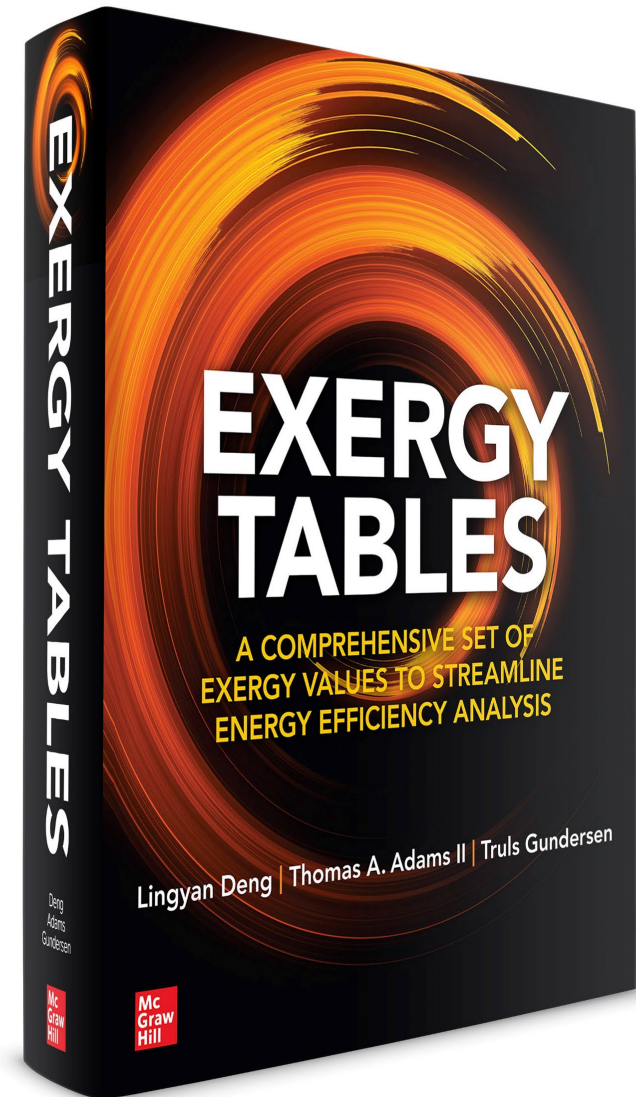
1. Exergy in plain language
2. Exergy from thermodynamics
3. Exergy analyses (how to use it)
4. Reference conditions & substances

*then data tables*

- |                                   |                          |
|-----------------------------------|--------------------------|
| 5. Atmospheric Gases              | 8. Gaseous fuel mixtures |
| 6. Water, Steam, D <sub>2</sub> O | 9. Liquid fuel mixtures  |
| 7. Pure Chemicals                 | 10. Solid fuels          |

<https://PSEcommunity.org/exergy>

Paperback ● E-book ● Access Engineering



# Exergy in a Nutshell

Exergy measures both **quantity** and **quality** of energy:

**Units:** Joules, Calories, etc.

**Quantity:** 1<sup>st</sup> Law of Thermodynamics

**Quality:** 2<sup>nd</sup> Law of Thermodynamics

Water In Olympic-Sized Swimming Pool  
at 28°C (Thermo-Mechanical Energy)

Energy Content: 30 GJ

Exergy Content: 0.15 GJ

**Things you can do with it:**

- Swim in it

8,333 kWh of Electricity

Energy Content: 30 GJ

Exergy Content: 30 GJ

**Things you can do with it:**

- Power a Canadian house for 6 months
- Drive electric car 47,000 km
- Heat up an Olympic sized swimming pool from 25 to 28°C!

Source: Deng, Adams, Gundersen, *Exergy Tables* (2023)

# Exergy Definition

- *Note:* Competing definitions exist.

“ 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).

—Moran, Shapiro, Boettner, and Baley (2014)

We can rewrite this mathematically as:

$$e = \max_{\mathcal{P}} w$$

$\mathcal{P}$  is process that brings the **system into equilibrium with the environment**

$w$  is the work **produced during**  $\mathcal{P}$

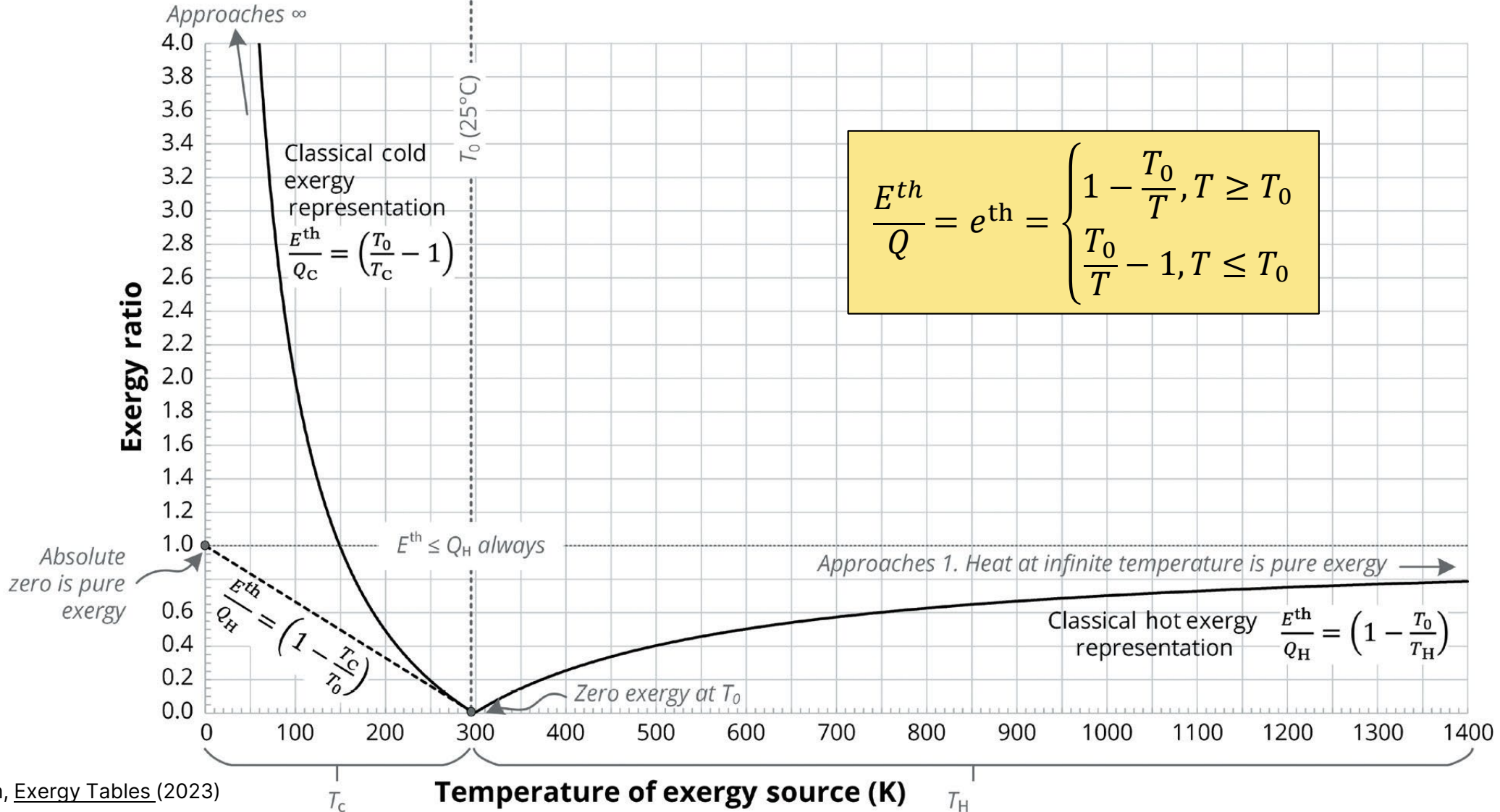
**Source:** Adams TA II, Gundersen T. Thermo-mechanical exergy of a substance below environmental pressure. *Ind Chem Eng Res* 63:6286–6296 (2024)

# Hot Sources and Cold Sinks

Two different mechanisms for  $\mathcal{P}$  means non-smooth behaviour around reference temperature.

Exergy of a cold sink (cold exergy source)  
 $T_C < T_0$

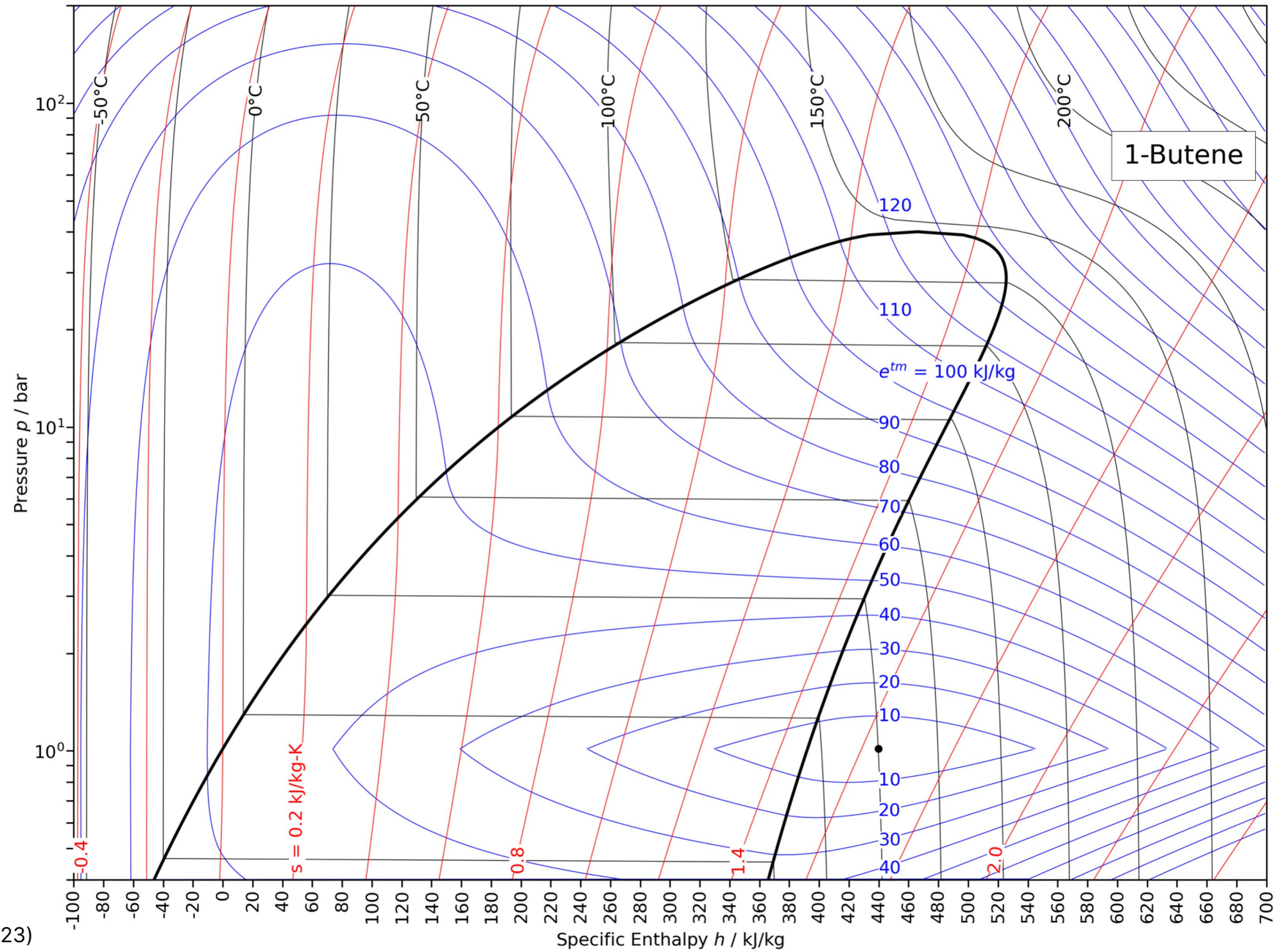
Exergy of a heat stream (hot exergy source)  
 $T_H > T_0$



Source: Deng, Adams, Gundersen, Exergy Tables (2023)

# Example with normal gas

$$e_1^{tm} = \begin{cases} (h_1 - h_0) - T_0(s_1 - s_0) & \text{if } p_1 \geq p_0 \\ (2h_* - h_1 - h_0) - T_0(s_1 - s_0) & \text{if } p_1 \leq p_0 \end{cases}$$



1-Butene

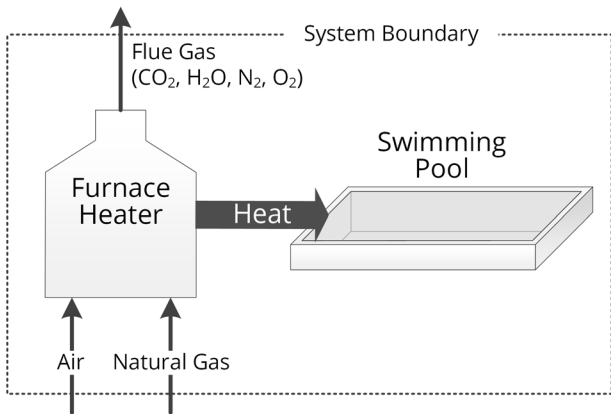
Source: Deng, Adams, Gundersen, Exergy Tables (2023)

# Swimming Pool Again. Example 0.

- **Typical Energy Efficiency** for gas boiler to heat the pool

$$\eta_{sys,HHV} = \frac{\text{Energy of Useful Products}}{\text{Energy of All Inputs}} = \frac{30 \text{ GJ of heat delivered}}{\text{HHV of natural gas}} = \mathbf{86\%}$$

- But with **exergy** it is a very different story.



$$\eta_{sys,ex} = \frac{\text{Exergy of Useful Products}}{\text{Exergy of All Inputs}} = \frac{E_{\text{water}}^{\text{tm}}}{E_{\text{ng}}^{\text{ch}}} = \frac{0.15 \text{ GJ}}{30.8 \text{ GJ}} = \mathbf{0.49\%}$$

- Raises **existential questions for design.**

- Is this something we should be doing at all?
- Is there a “better” way?

| Well                                  |
|---------------------------------------|
| Natural gas from Alberta region       |
| $e_{\text{mix}}^{\text{ch}}$ (kJ/mol) |
| 805.07                                |

| T<br>(°C) | $e^{\text{tm}}$ (kJ/kg) |       |       |
|-----------|-------------------------|-------|-------|
|           | Pressure (bar)          |       |       |
|           | 1.01325                 | 1.084 | 1.154 |

|    |        |        |        |
|----|--------|--------|--------|
| 25 | 0.0000 | 0.0071 | 0.0141 |
| 26 | 0.0070 | 0.0141 | 0.0211 |
| 27 | 0.0279 | 0.0350 | 0.0421 |
| 28 | 0.0627 | 0.0697 | 0.0768 |

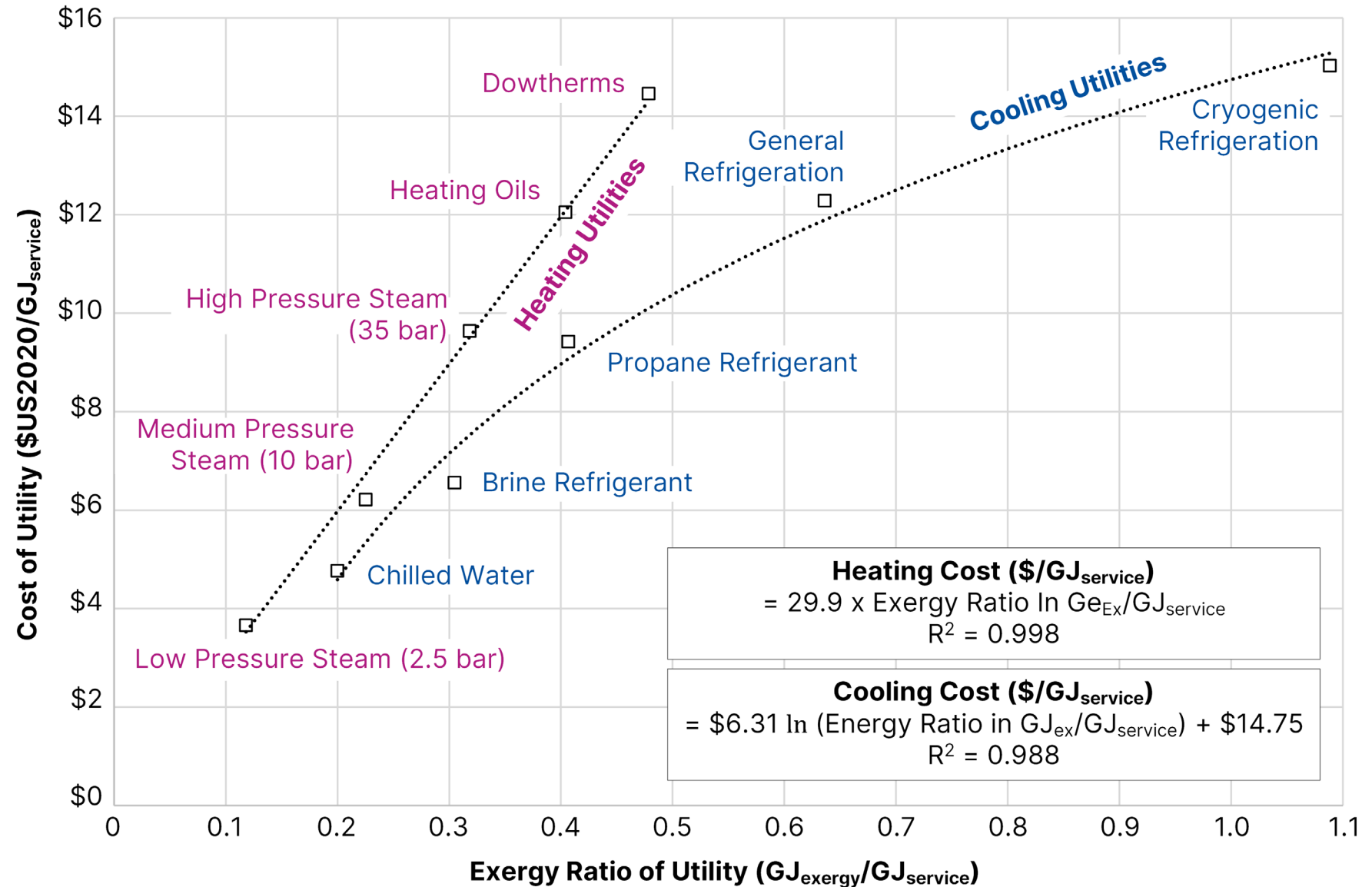
TABLE 6.1 Thermo-mechanical exergy of liquid water and steam (at a mixture of gas and liquid, or a gas).

Source: Deng, Adams, Gundersen, *Exergy Tables* (2023)

# Example 1: Exergy as Proxy for Value

**New:** Exergy values highly correlated with cost

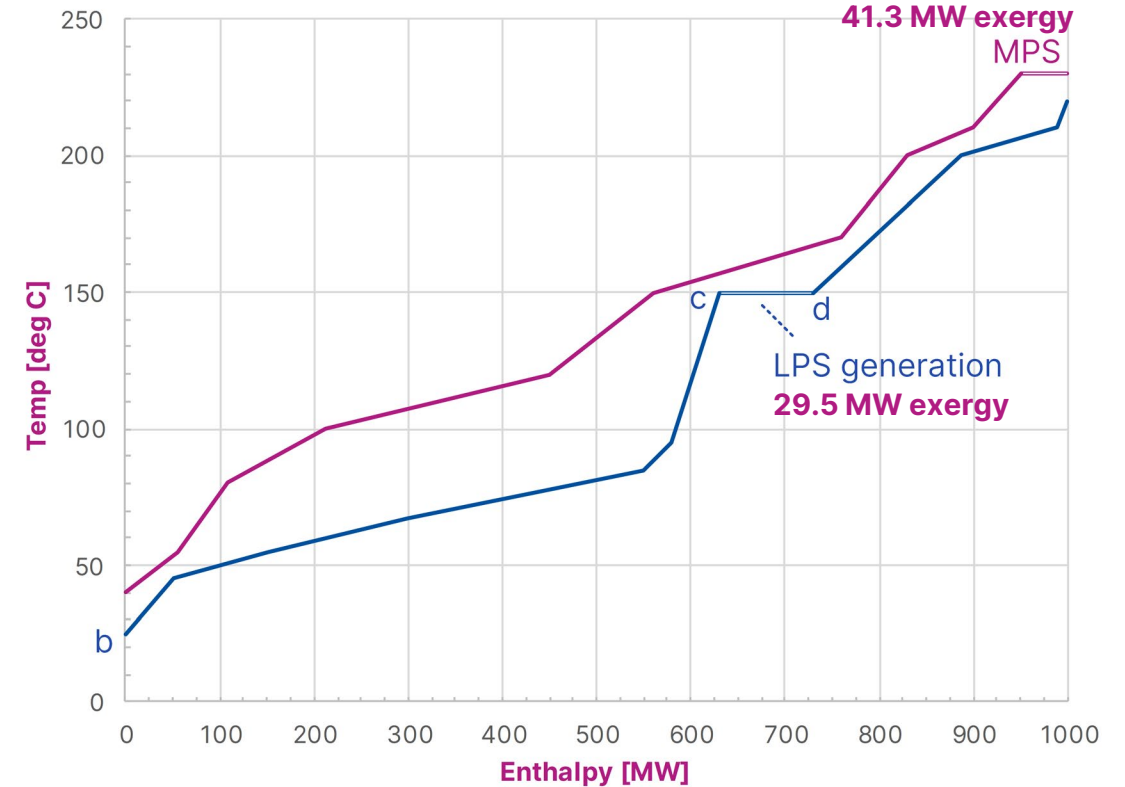
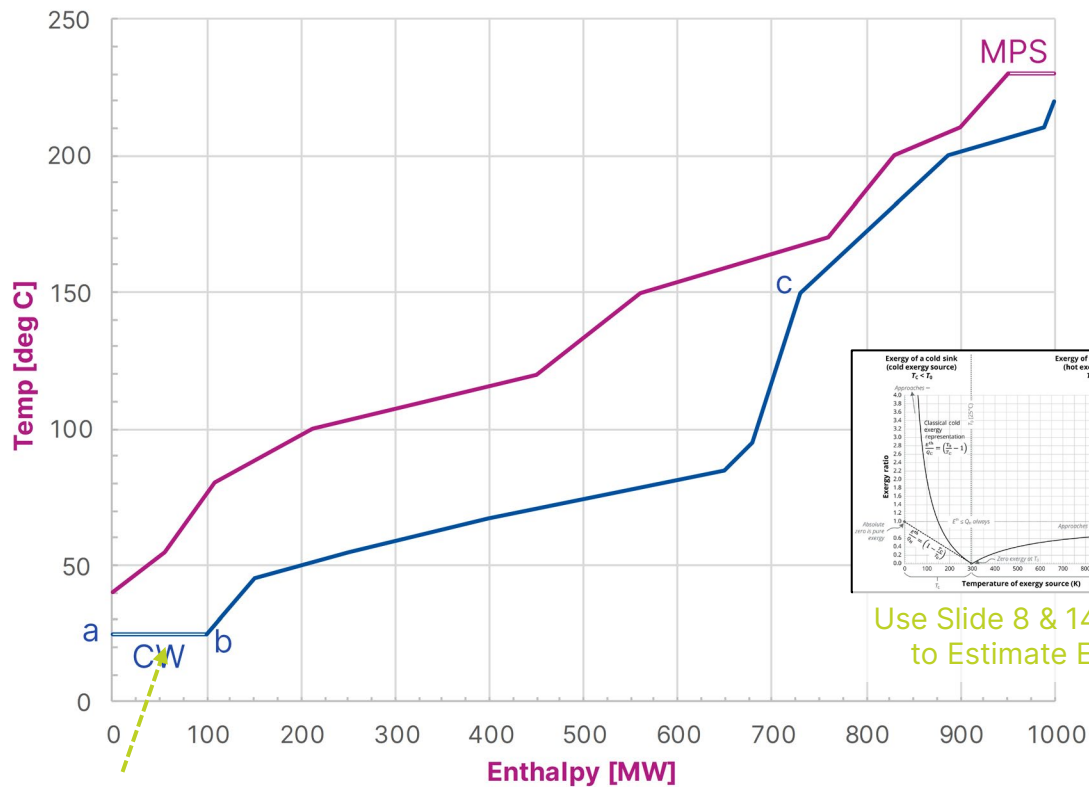
These use “**plant ambient temperature**” of about 78°C.



Source: Deng, Adams, Gundersen, Exergy Tables (2023)

# Example 2: Pinch Analysis

Consider the composite curve on the left. It is possible to improve it by shifting some of the utilities to higher ends. **You can use exergy to value this potential change. Is it worth the effort?**

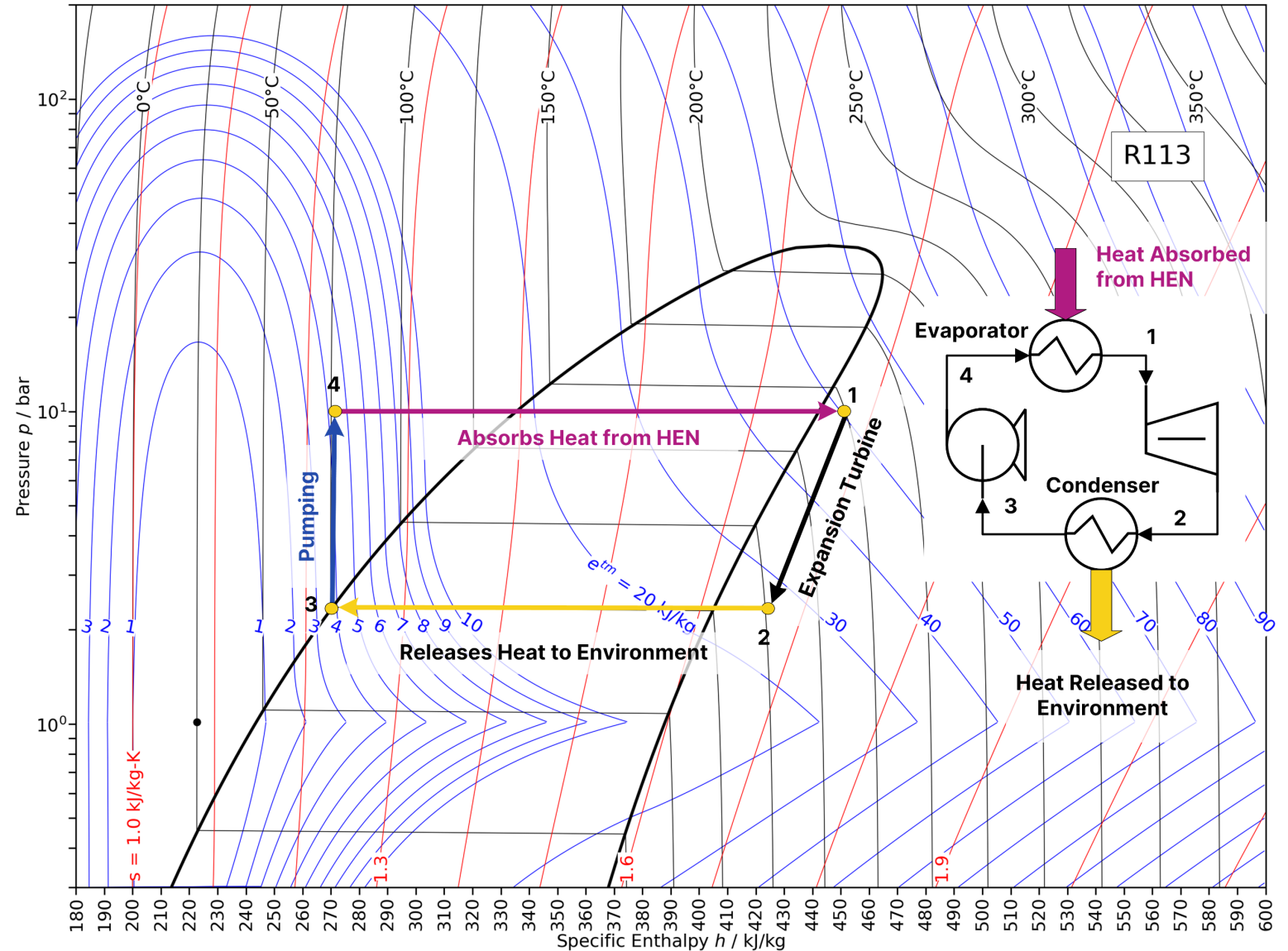


This is removing 100 MW of heat at 25°C. Basically zero exergy. **We can't do useful work with this heat** so we have to pay to dump it via cooling towers.

Great! **Use the exergy cost model** (Ex 1). Estimate quickly that this generates ~\$16 million/yr now instead of costing \$12 million/yr in cooling. Worth it!!!

# Example 3: Work-Heat Integration (ORC)

- **Same case:** Can use 100 MW of waste heat at 150°C
- **Instead:** Max work we could produce? (Chose Point 1,  $e^{tm}$ )
  - About 29 MW (50 kJ/kg)
  - Then how much could this ORC actually produce? (Point 2, 14 MW)
  - Exergy efficiency about 47%. We could do better.
  - See conference paper for worked example



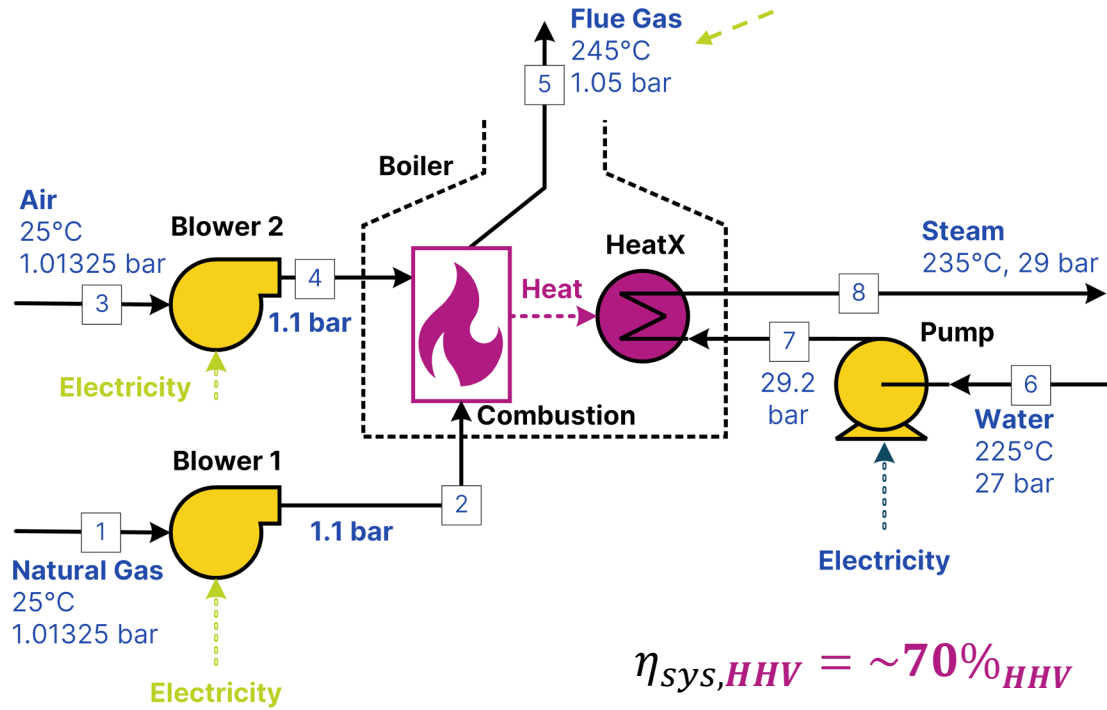
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Source: Adams TA II, Gundersen T. Thermo-mechanical exergy of a substance below environmental pressure. *Ind Chem Eng Res.* 63:6286-6296 (2024)

# Example 4: NG-Fired Steam Generation to produce the MPS utility needed

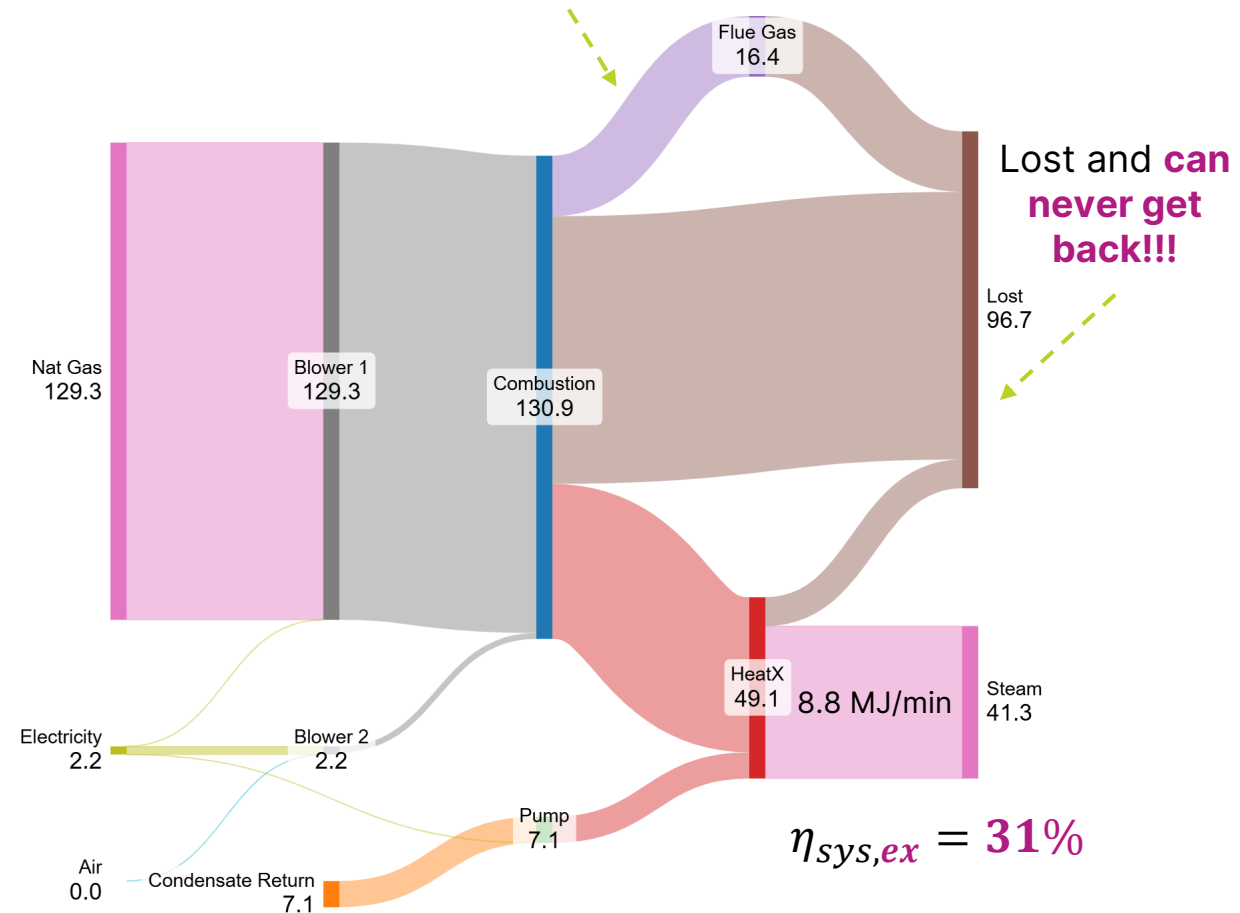
(Make 235°C, 29 bar steam)

Some thermal energy lost out the flue



## Exergy Flows

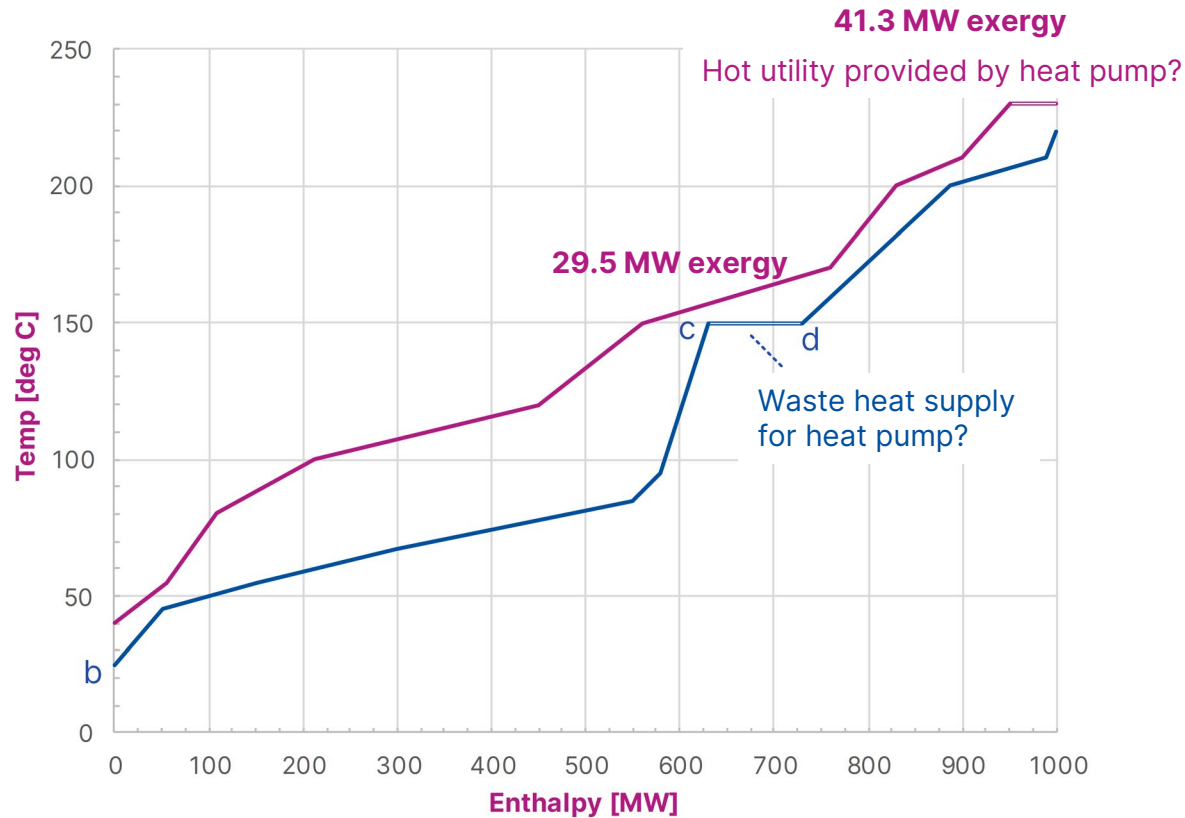
Maybe we can recover this part?



All stream exergies easily looked up from Exergy Tables

See conference paper for worked examples.

# Example 5: Electric Heat Pump Instead?



- **Idea:** Use the waste heat from c-d to generate heat at 230°C
  - **Minimum electricity** is  $41.3 - 29.5 \text{ MW} = \sim 12 \text{ MW}$ .
  - A real COP = 3 heat pump would require  $50 \text{ MW} / 3 \text{ COP} = \sim 17 \text{ MW}$  of electricity.
    - This would be 77% exergy efficient
    - Supply of 150C waste heat is ample!
    - Sounds like we should consider this!
- See conference paper for worked example.

# Example 6: Direct Air Capture

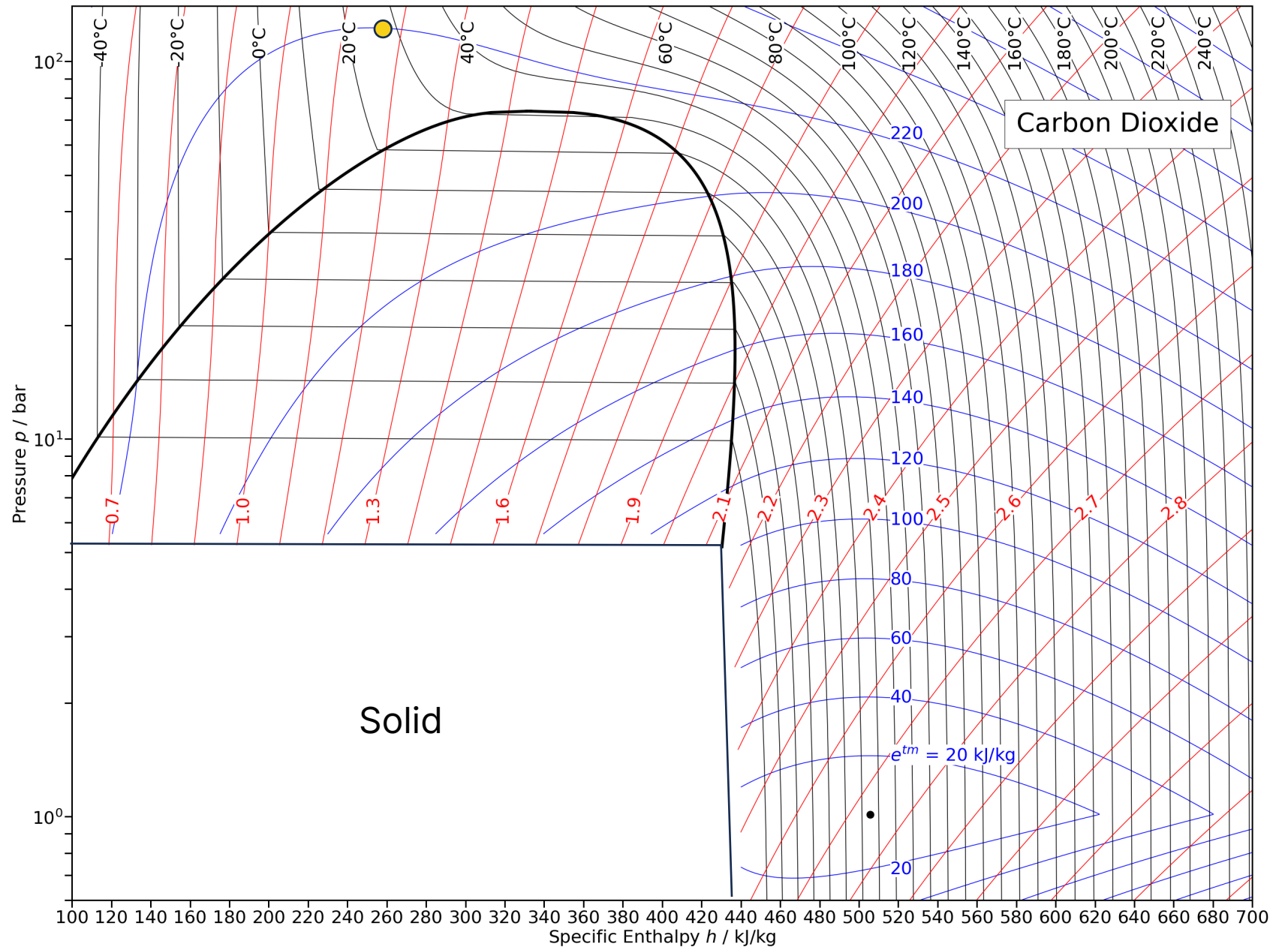
| Chemical Element <i>J</i> |                            | Reference Species <i>I</i>         |                         |                        |                         |                            |
|---------------------------|----------------------------|------------------------------------|-------------------------|------------------------|-------------------------|----------------------------|
| Elements                  | $e_j^{\text{ch}}$ (kJ/mol) | Reference Species Formula <i>I</i> | Mole Percentage $x_i$   | Partial Pressure (kPa) | $\Delta g_i^f$ (kJ/mol) | $e_i^{\text{ch}}$ (kJ/mol) |
| H <sub>2</sub> (g)        | 236.11                     | H <sub>2</sub> O (g)               | 2.1816                  | 2.2106                 | 228.59                  | 9.4822                     |
| N <sub>2</sub> (g)        | 0.66965                    | N <sub>2</sub>                     | 76.328                  | 77.339                 | —                       | 0.66965                    |
| O <sub>2</sub> (g)        | 3.9246                     | O <sub>2</sub>                     | 20.532                  | 20.804                 | —                       | 3.9246                     |
| C (s)                     | 410.27                     | CO <sub>2</sub>                    | 0.0337                  | 0.034194               | 394.38                  | 19.817                     |
| H <sub>2</sub> (g)        | 236.11                     | H <sub>2</sub>                     | 4.89 × 10 <sup>-4</sup> | 0.000496               | —                       | 236.11                     |

- The **chemical exergy** of CO<sub>2</sub> is 19.817 kJ/mol (concentration plus bond exergy)
- Exergy is the maximum amount of work you can get out of something.
  - A perfect machine could produce 19.817 kJ/mol of work from pure CO<sub>2</sub> at 1 atm, 25°C.
- Exergy is also the **minimum amount of work** it takes to make that thing **from the environment!**
  - A perfect machine would require 19.817 kJ/mol of work to make pure CO<sub>2</sub> at 1 atm, 25°C from air
  - a **hard thermodynamic bound**
  - Modern expected DAC using an air-sourced heat pump is about **13.4% exergy efficient**, just to get uncompressed CO<sub>2</sub>. It's a hard problem.

Source: Deng, Adams, Gundersen, Exergy Tables (2023)

# Example 7: CO<sub>2</sub> Compression (1)

- Now I want to take pure captured CO<sub>2</sub> at 25°C and 1 atm to pipeline conditions (120 bar, 28°C)
- **Reading off the chart**, the thermo-mechanical exergy there is **220 kJ/kg** (9.7 kJ/mol)
- **So that's the minimum work required to make it sequestration-ready.**



Source: Deng, Adams, Gundersen, Exergy Tables (2023)



# Thanks!

ESCAPE 35  
Monday, July 7, 2025

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