Supercritical CO_2 Carnot Engine for Industrial Waste Heat Recovery and Utilization

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Agenda

Introduction: Issue of Low-Grade Waste Heat

- **<u>Problem</u>**: low-grade waste heat emitted to the environment
  - ~66% waste heat is low-grade (< 200C)
  - difficult to utilize effectively
- **<u>Solution</u>**: supercritical CO_2 Carnot engines
  - Supercritical CO_2 working fluid has a critical temperature of 31.1C
  - "Replace" large cooler duties in process with the Carnot engines

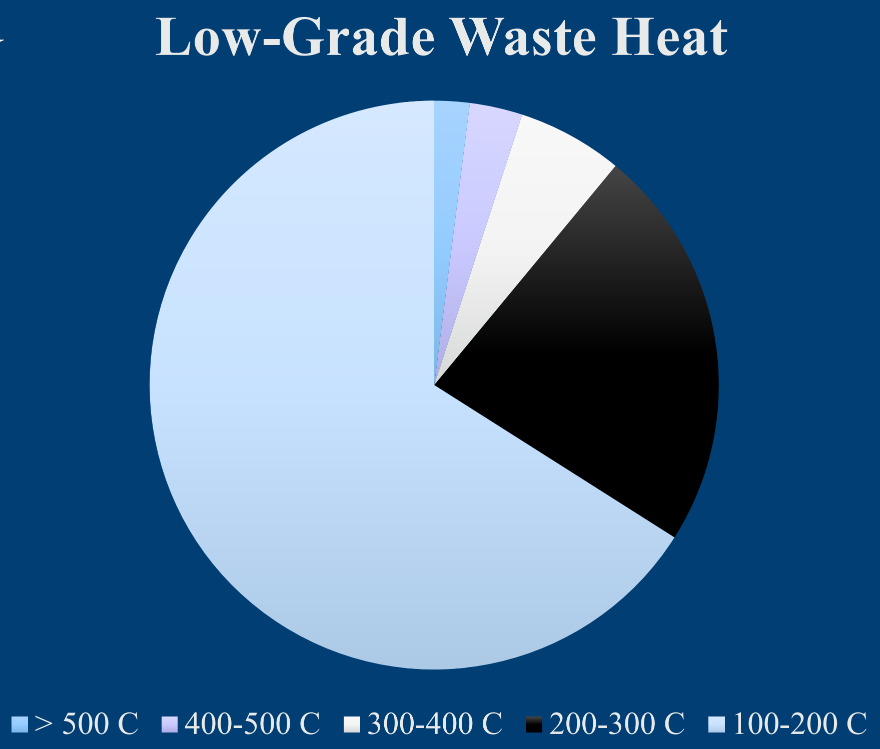


Figure 1: Interreg Central Europe. *Low-grade waste head utilization in the European Union,* June 2017.

Methods: Supercritical CO_2 Carnot Engine

- Lower isotherm at critical temperature of 31.1C
- Upper isotherm at low-grade waste heat temperature
- Straddle critical volume
- Maximize area on P-V plot (available work)

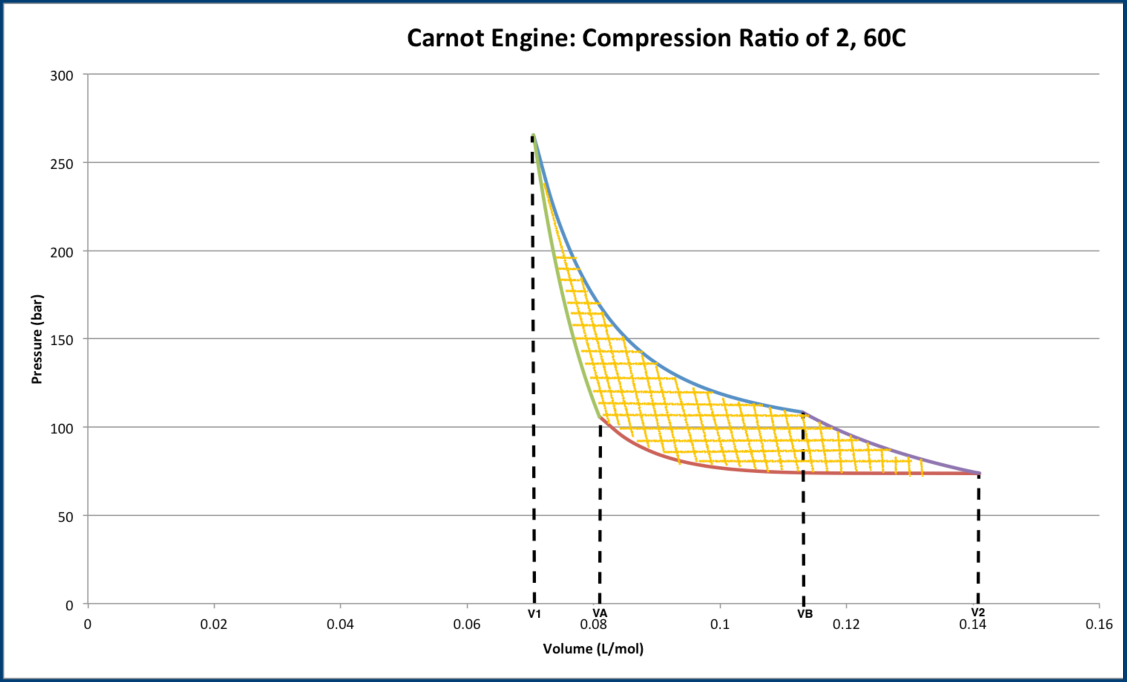


Figure 2: Carnot Cycle on P-V Plot

Methods: Excel Program

Engine Sizing Given Process Inputs

- Analytically calculate work of the Carnot cycle using Van der Waals equations of state

$$Q_H = \int_{V_1}^{V_B} \frac{RT_H}{V-b} = RT_H ln(\frac{V_B-b}{V_1-b})$$

where $b = \frac{1}{8}\frac{RT_c}{P_c}$ Equation 1

$$W = Q_H(1 - \frac{T_C}{T_H})$$ Equation 2

- Reversible adiabatic and isothermal steps assumed
- <1% difference to numerical solution

<u>Inputs</u>

- Compression ratio
- Isotherm temperatures
- Engine size/frequency
- Starting volume
- Cooler size

<u>Outputs</u>

- Work available
- Pressure
- Frequency/engine size required
- Remaining cooler duty

Figure 3: Excel Program Method

Methods: Excel Program

Inputs	
Compression Ratio	2
Critical Volume (L/mol)	0.094
V1 (L/mol)	0.0705
Upper Isotherm T (K)	343
Lower Isotherm T (K)	304.18
Power from Carnot (kW)	135.39
Engine Size (L)	0.25
Outputs	
QH (J/mol)	2328.60491
Work (J/mol)	263.54648
Maximum Pressure (Bar)	295.200354
Frequency (Hz)	289.740011

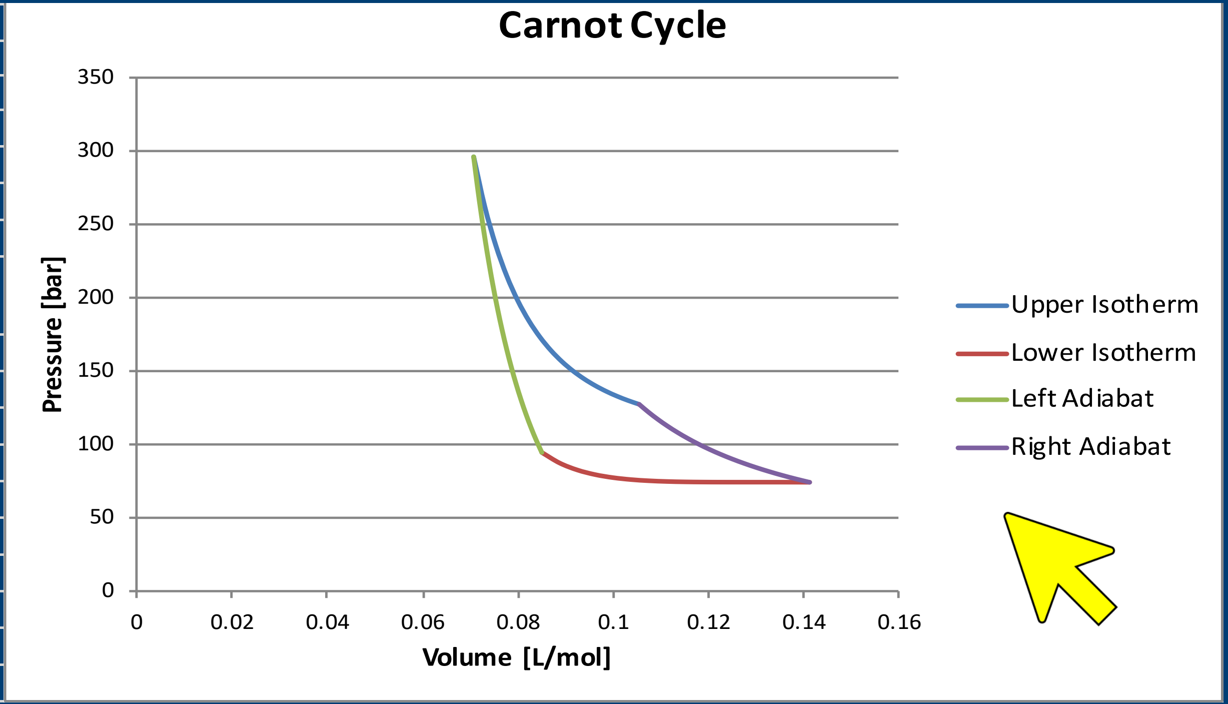
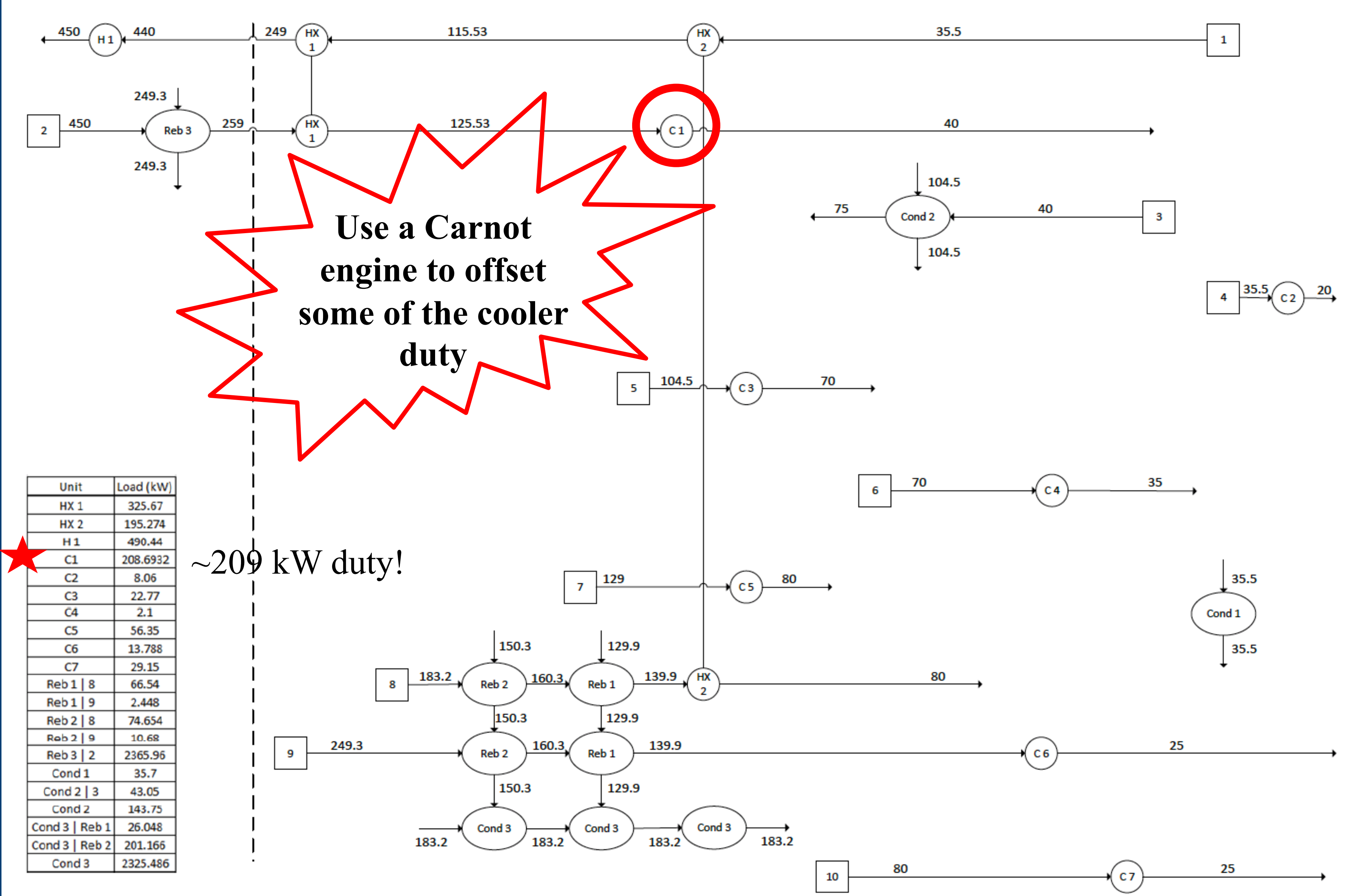


Figure 4: Developed Excel Program

Methods: Example Process Analysis

- Toluene disproportion process (J.T. Banchero B.D. Smith (Ed.) R.J. Hengstebeck. *Disproportionation of toluene*, 1969.)
- Decrease the duty of the major cooler (208.69 kW) of the process
  - Stream with a heat capacity of 2.44 kW/C at 125.53C
- For efficiency purposes, the Carnot cycle would take in a hot stream no cooler than 60C
- In practice, any process could be analyzed in a similar manner



Unit	Load (kW)
HX 1	325.67
HX 2	195.274
H 1	490.44
C1	208.6932
C2	8.06
C3	22.77
C4	2.1
C5	56.35
C6	13.788
C7	29.15
Reb 1 | 8	66.54
Reb 1 | 9	2.448
Reb 2 | 8	74.654
Reb 2 | 9	10.68
Reb 3 | 2	2365.96
Cond 1	35.7
Cond 2 | 3	43.05
Cond 2	143.75
Cond 3 | Reb 1	26.048
Cond 3 | Reb 2	201.166
Cond 3	2325.486

Figure 5: Toluene Process- Streams Diagram

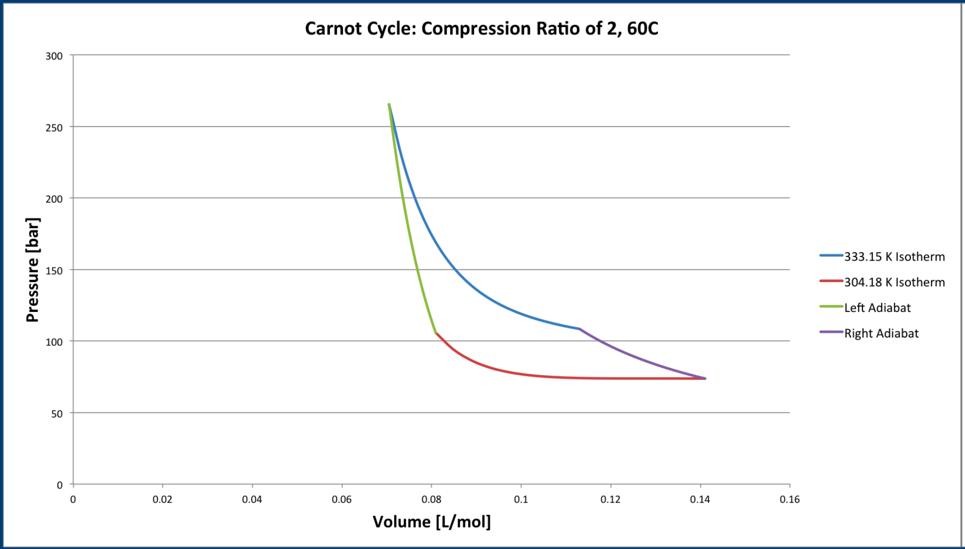


Figure 6: 60C Lower Isotherm

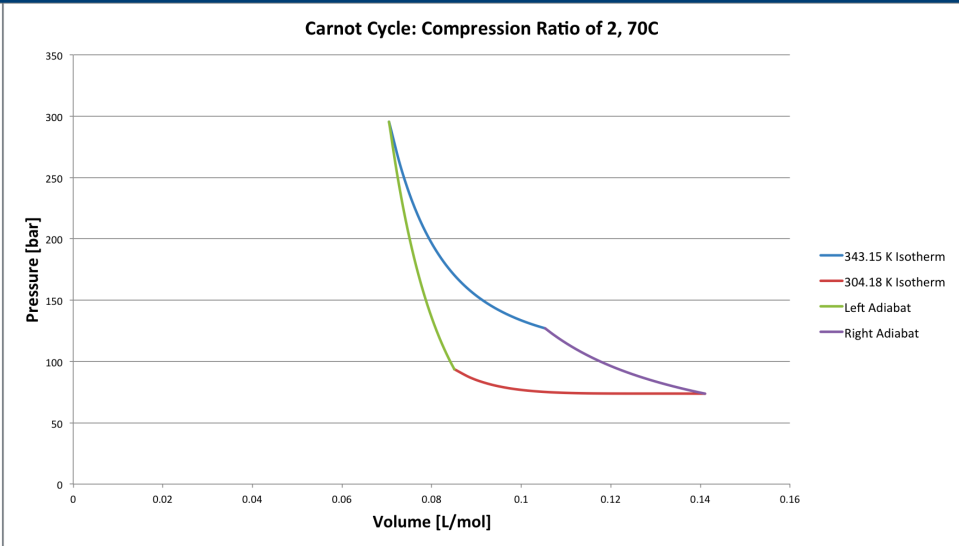


Figure 7: 70C Lower Isotherm

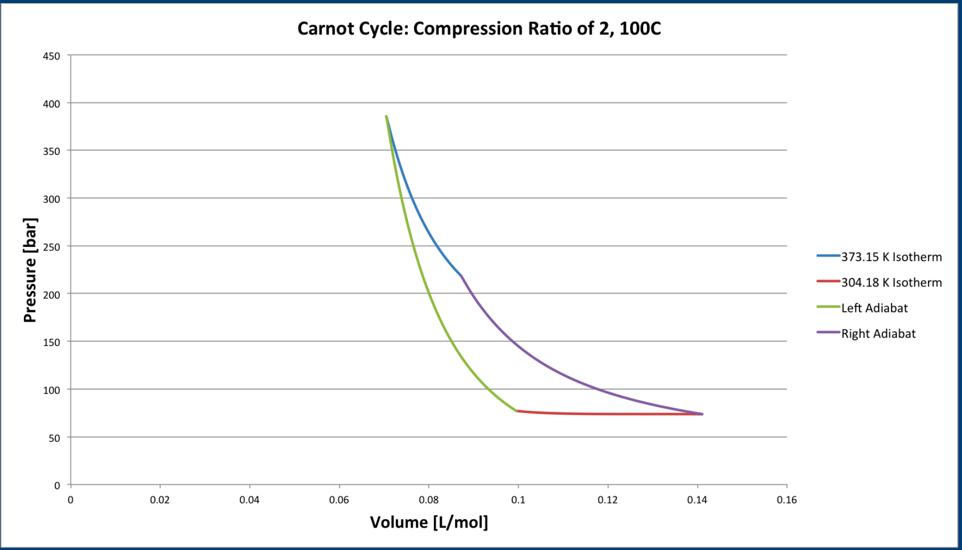


Figure 8: 100C Lower Isotherm

Results: Decreasing 208.69 kW Cooler

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- Compression ratio of 2 and a frequency of 50 Hz:

	Upper Isotherm Temp (C)	Work (J/mol)	Power (kW/mol)	Max Pressure (bar)	Engine Size (L)
	60	224.14	11.21	266	2.01
★	70	264.00	13.20	296	1.45
	100	270.56	13.53	386	0.644

- By increasing the temperature of the input stream there is:
  - roughly a 21% increase in available power
  - **significant** increase in pressure required to go from 70C to 100C (30 bar)
  - **small** increase in available work (2%)
  - Carnot efficiency increases from 9%, to 11%, to 18%

Results: Decreasing 208.69 kW Cooler

- Cooling the stream from 125.53C to 70C releases 135.49 kW
  - P = Heat Capacity * Temperature Change
  - P = (2.44 kW/C) * (125.53-70C) = 135.49 kW

- Cooler still required to decrease the temperature from 70C to the desired final value of 40C
  - P = (2.44 kW/C) * (70-40C) = 73.2 kW

Generate 135.49 kW, <u>Reduce Cooler Duty by 65%</u>

Results: Calculating Required Frequency Given Engine Size

Engine Size (L)	Hz (s^{-1})
0.25	289.7
0.5	144.9
1	72.4
1.5	48.3
2	36.2
4	18.1
6	12.05

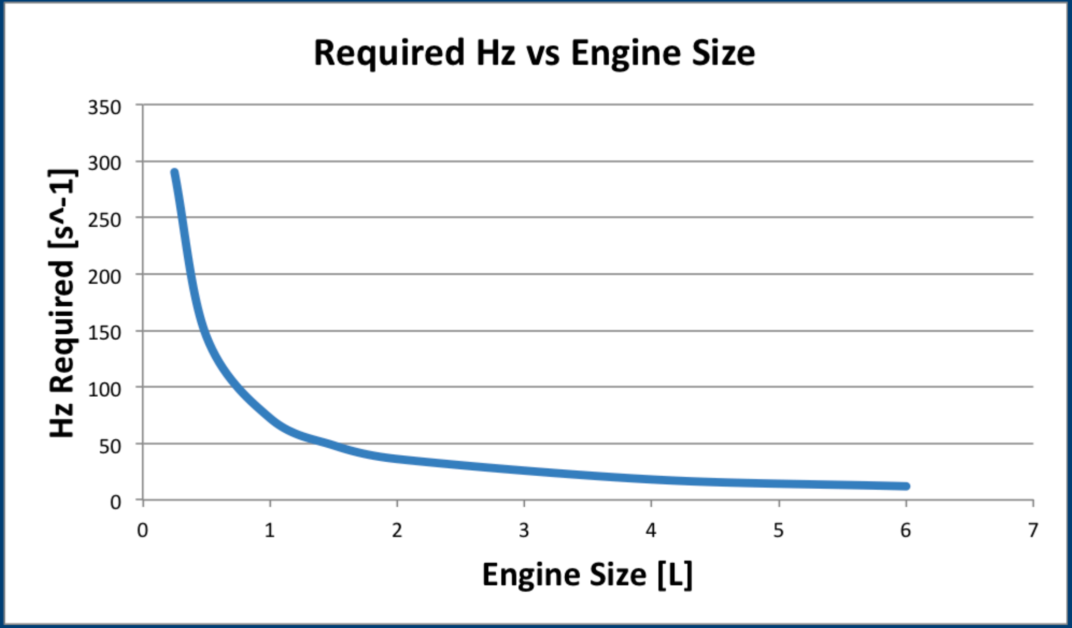


Figure 9: Engine Frequency and Size

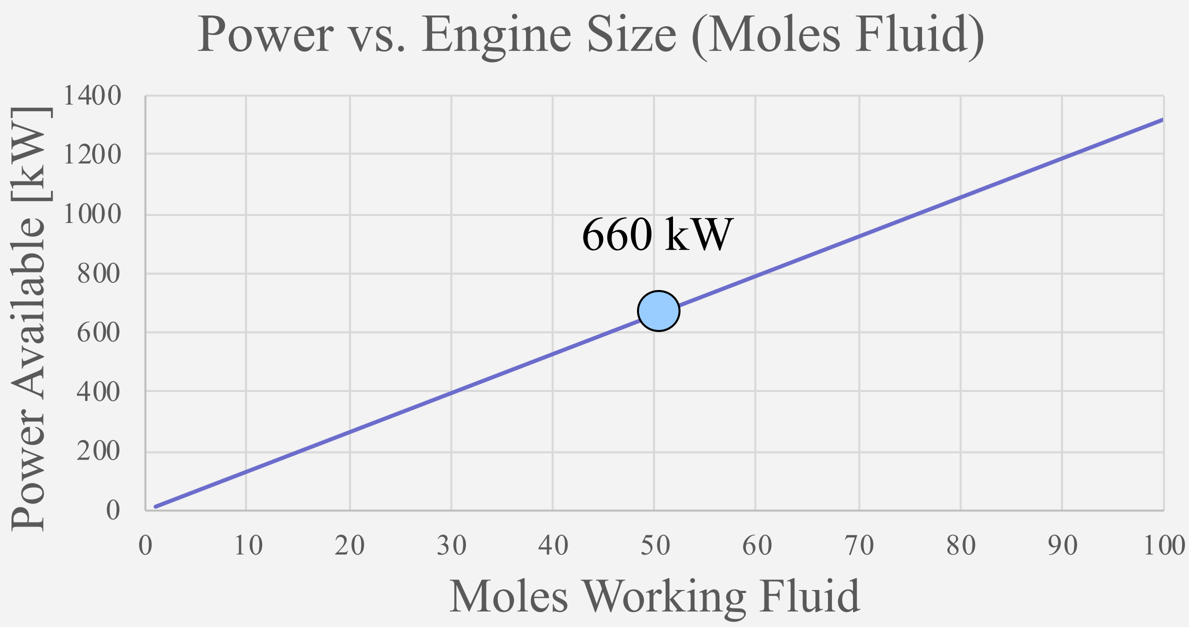
Results: Energy Savings

- 1.45 L engine that provides 135.49 kW, 24 hours a day for 300 days/year amounts to **975,528 kWh/year**

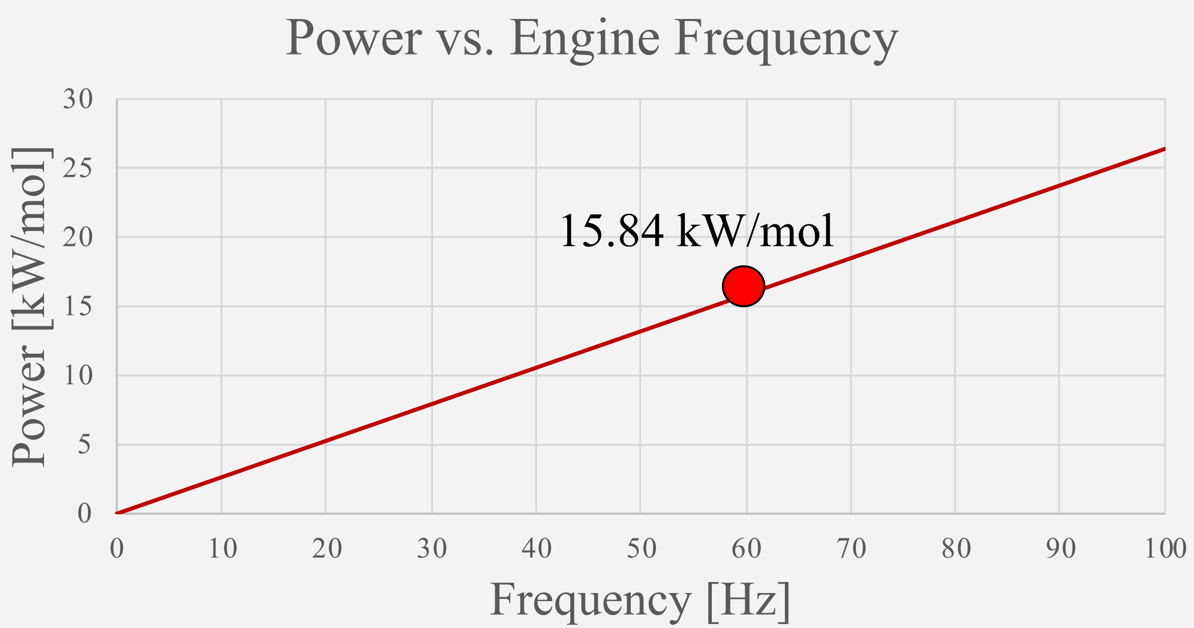
Electricity Source	Price ($/MWh)	Cost Savings per Year ($)
USA National Average	72.4	70,628
Conventional Coal	98.8	96,285
Biomass	95.3	92,968
Onshore Wind	48	48,825
Solar Thermal	126.6	123,502

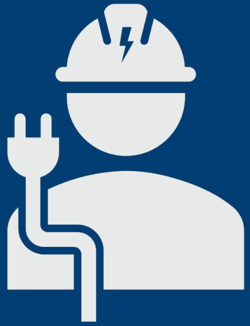
U.S. Energy Information Administration. *Levelized Cost and Avoided Cost of New Generation Resources in the Annual Energy Outlook 2018*, March 2018.

Results: Power Potential



Average household power meters ~5W





Conclusion

- Through the use of supercritical CO_2 Carnot cycles, the ability to recover and utilize a significant portion of the waste is realized
- The developed Excel program includes a simple calculation to determine the engine size and/or frequency required to utilize this waste heat
- Decrease net external energy requirement and environmental emissions

Acknowledgements and Sources

Thank you to the University of Rochester Chemical Engineering Department

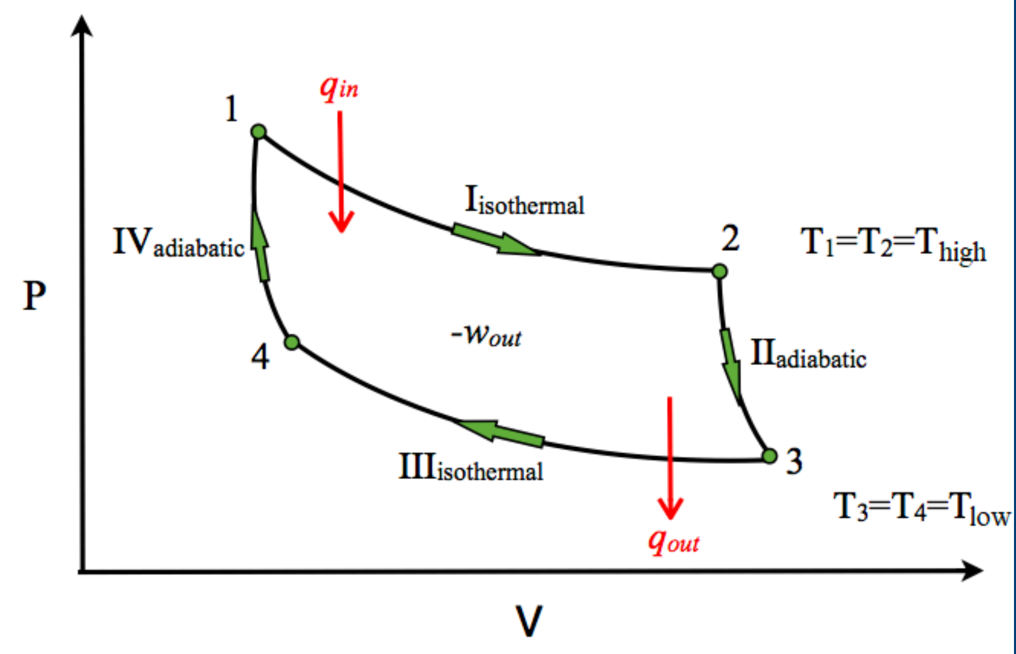
Works Cited

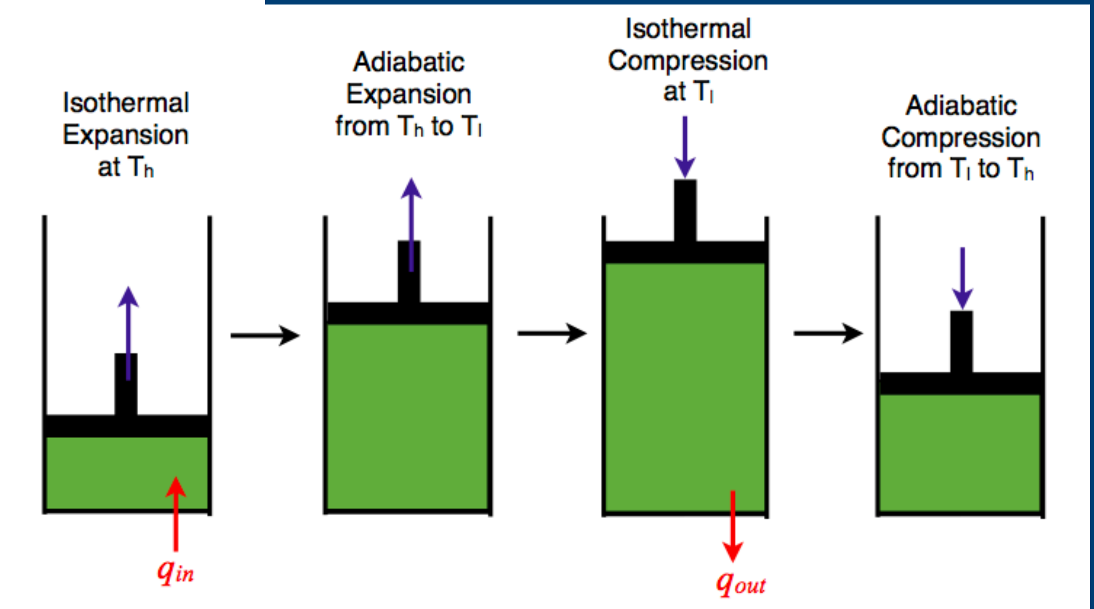
[1] J.T. Banchero B.D. Smith (Ed.) R.J. Hengstebeck. *Disproportionation of toluene*, 1969.

[2] Eldred H. Chimowitz Madeleine R. Laitz, F. Douglas Kelley. *Critical CO_2 Carnot Cycle for Waste Heat Utilization,* 2017.

[3] U.S. Energy Information Administration. *Levelized Cost and Avoided Cost of New Generation Resources in the Annual Energy Outlook 2018*, March 2018.

Visual of the Carnot Engine





Q is supplied from the process streams

Image Credits: chem.libretexts.org