Project Initiation: First Steps

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Waste Heat/Recovered Energy

- Primarily in the form of:
  - Combustion gases
  - Hot air
  - Hot water
- Sometimes:
  - Low pressure steam
  - Non-steam vapors (hydrocarbons)

Prerequisites

- Ample supply of waste heat
  - >200F liquid, >400F gas
  - Clean
  - Accessible
- High cost power (>$.08/kWh)
  - PPA for excess not used internally
- Continuous process (>7000 hr/yr)
- No need for additional process heat
- Upsets tolerated

Goal

- Financial return
  - Project all-in cost of generation < internal
    - $C_T = C_{CR} + \cancel{\text{Fuel}} + C_{OPEX}$
      - No fuel, capital recovery dominates
      - Efficiency is less important than energy utilization
      - Efficiency only matters to the extent that it reduces $/kW
- Reduce emissions
  - Environmental steward, “green” is good
- Energy security
  - Grid independence
  - Less susceptible to higher rates

Total Generation Cost

- All-in cost of generation
  - $C_T = C_{CR} + \cancel{\text{Fuel}} + C_{OPEX}$
    - C_{CR} = Capital Recovery =(C_{RF} x \$/kW)/UTIL
    - C_{RF} = Recovery Factor; 10% +/- for debt; 20% +/- for equity
- Example
  - C_{RF} = 16%, CAPEX = \$2000/kW, UTIL = 8000 h/yr, OPEX = \$.01/kWh
  - C_T = (.16 x 2000)/8000 + .01

    = \$.05/kWh

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Feasibility Criteria

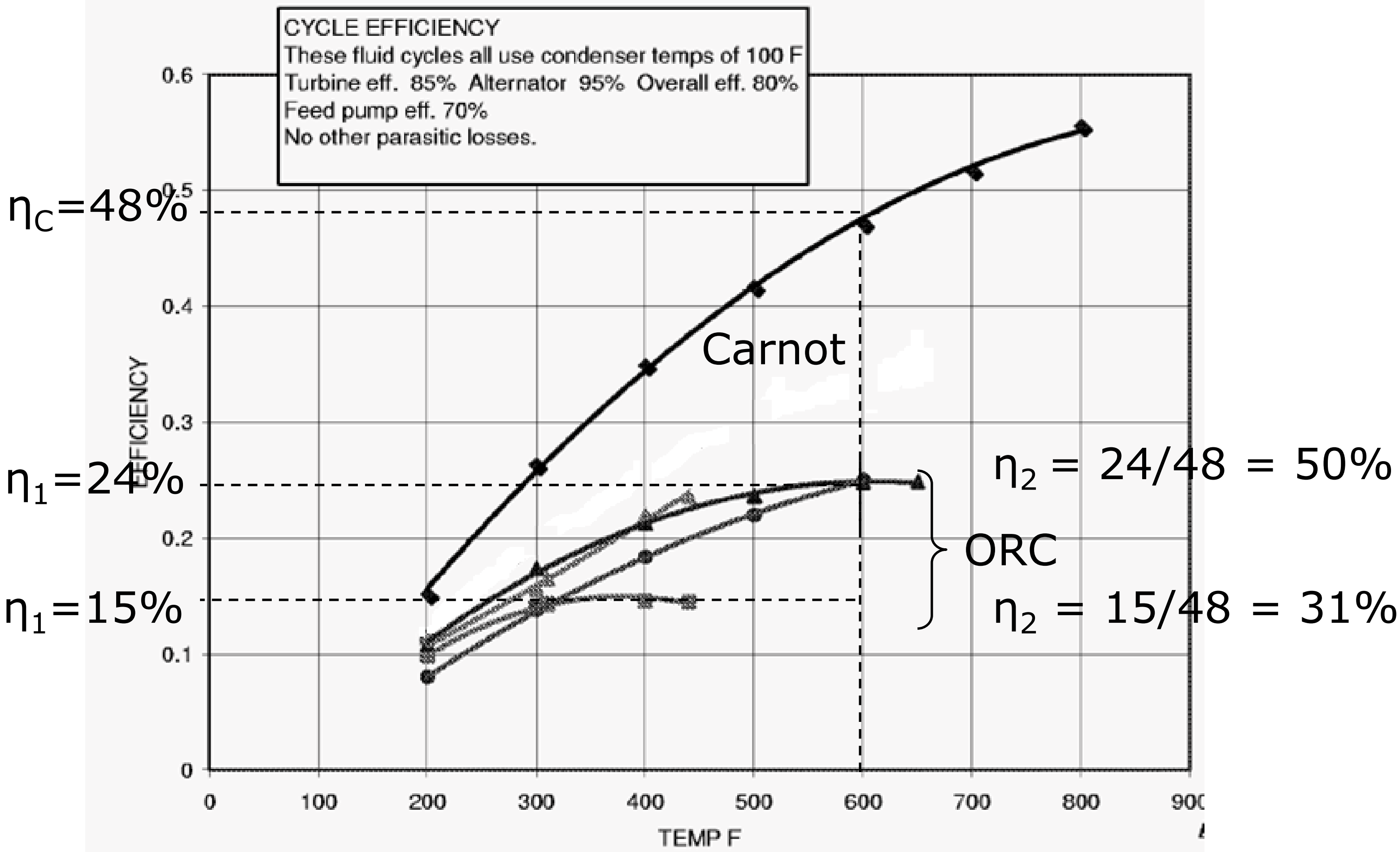
- Project Output ~kW
  - Characterize waste heat
  - Quantity and quality
- Cost
  - CAPEX and OPEX
- Utilization
  - Baseload vs. intermittent
- Risk
  - Source temperature too high?
  - Corrosion/deposition/erosion
  - Interface w/must run process

Project Output

- Output (W) = Energy (ΔH) x η_1
  - *Energy* content (Btu/h or kW thermal) is *quantitative*
  - First Law
  - $\Delta H = m \times c_p \times (T_1 - T_2)$
  - T_1 = initial source temp, T_2 = final source temp
  - Need to find plant (thermal) efficiency, η_1

- Determine *quality* of waste heat to find η_1
  - *Exergy* content
  - Second Law: $E = \Delta H \times [1 - T_0(\ln T_1/T_2)/(T_1 - T_2)]$
    - Assumes T_0 (cooling water) = constant

Cycle Efficiency
ORC vs. Carnot



Source: Barber Nichols

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Output Estimate

Theoretical (Carnot) eff'y:

$\eta_c = [1\text{-}T_0(\ln T_1/T_2)/(T_1\text{-}T_2)]$

Internal eff'y (Second Law):

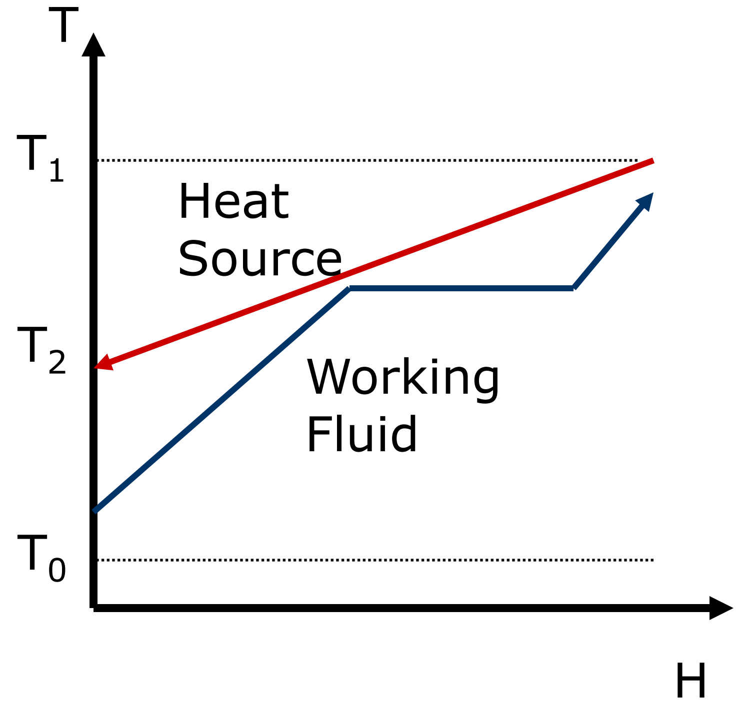
$\eta_2 = \eta_1 / \eta_c$;30%< η_2 <50%

Thermal (First Law) eff'y:

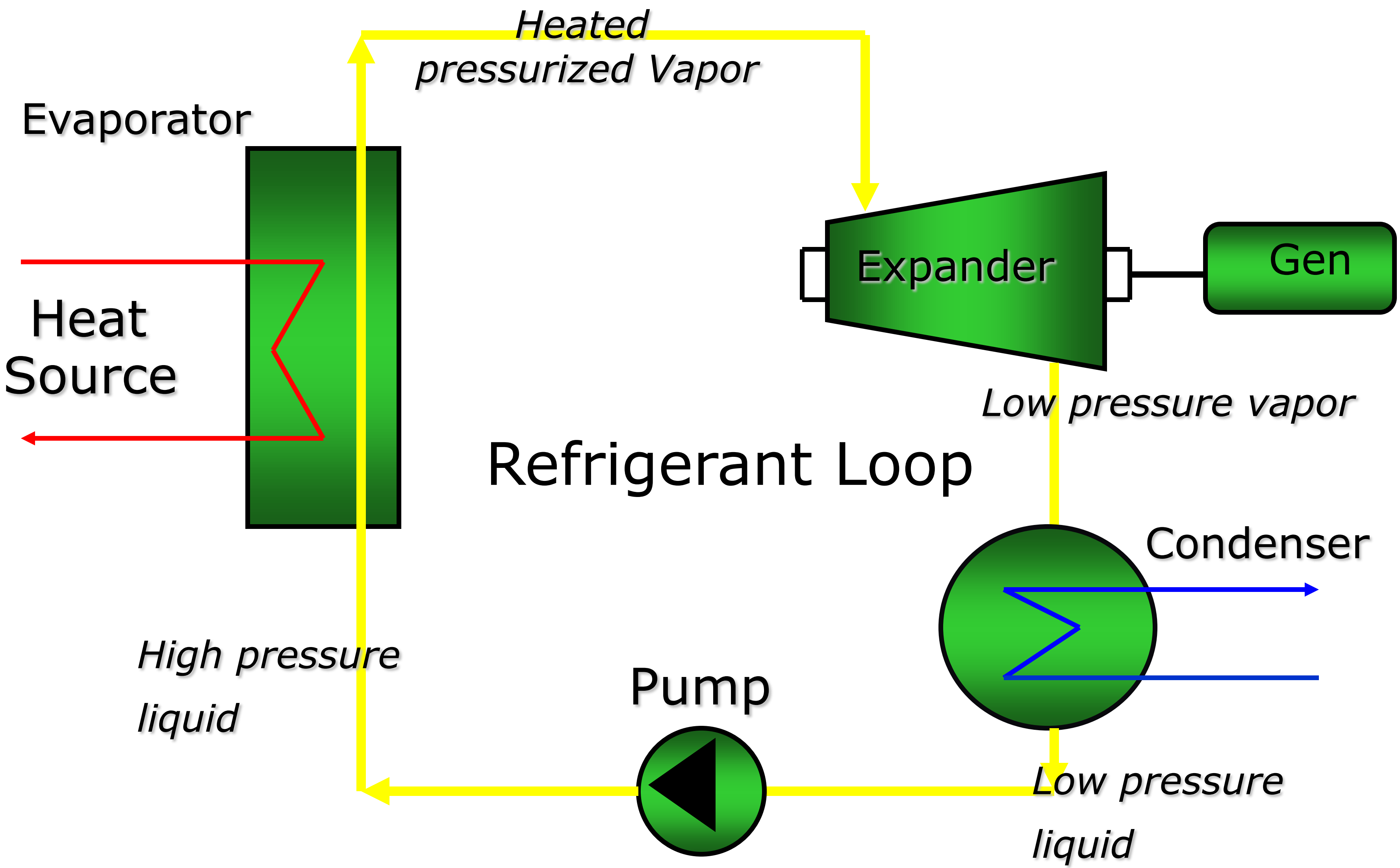
$\eta_1 = \eta_2 / \eta_c$

W = ΔH x η_1

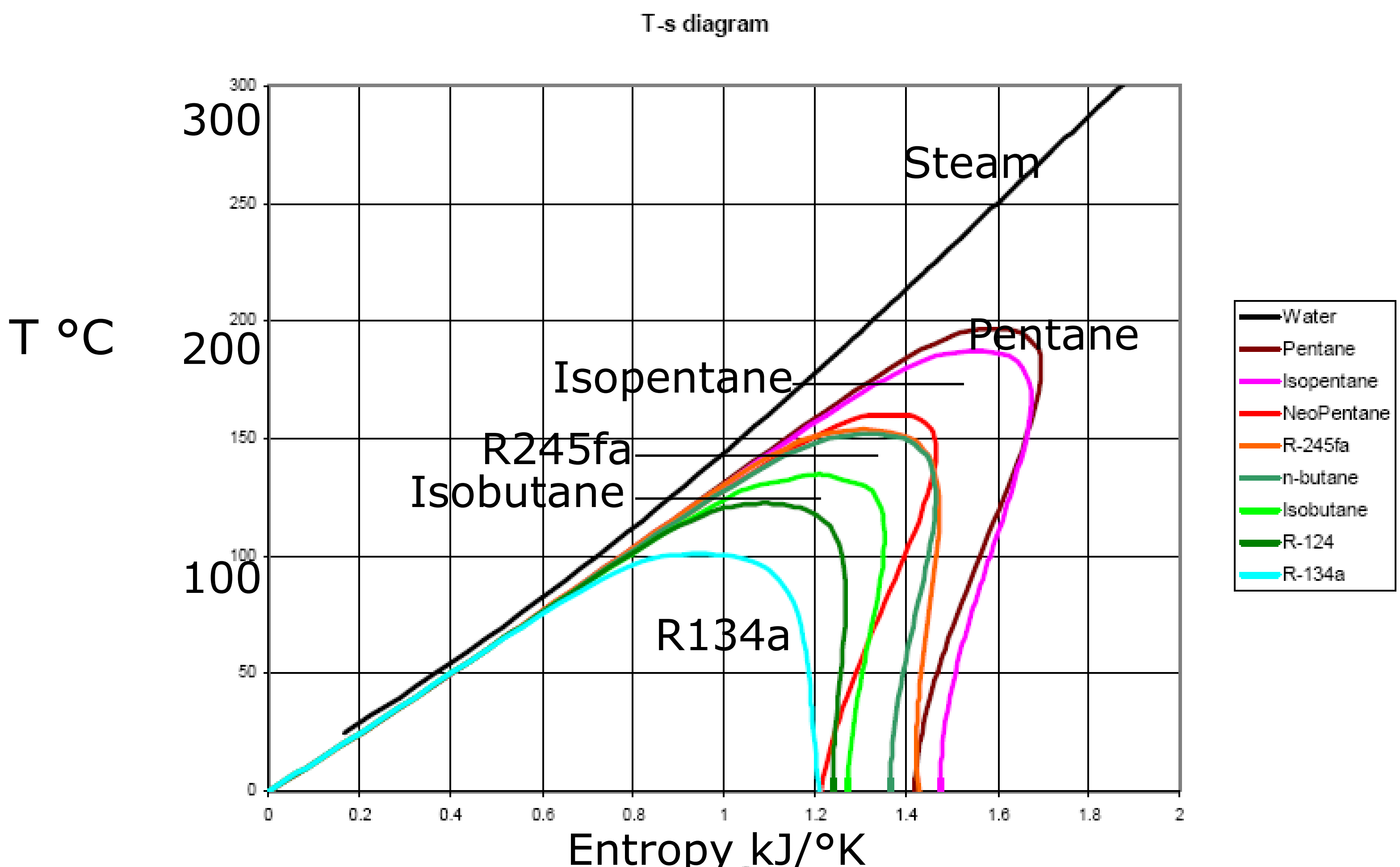
Heat Acquisition Process



Organic Rankine Cycle



Working Fluid Selection



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Cycle and Fluid Selection

- Cycles
  - ORC
  - Ammonia Water (Kalina, Absorption)
- Working Fluids (Refrigerants)
  - Performance (Cycle output)
  - Cost
  - Stability at elevated temperature
  - Safety
  - Reliability
  - Vacuum
  - Operator requirements

Steam vs. ORC

- Steam
  - >700F
  - >10 MW
  - η_1 = 20-30%
  - Water available
  - Licensed operators
  - Complex
    - Vacuum
    - Condensate polish
    - Blow down
- ORC
  - <700F
  - <10 MW
  - η_1 = 10-20%
  - No water
  - Little or no supervision
  - Closed system
    - Above atmospheric
    - No fluid treatment
    - No blow down

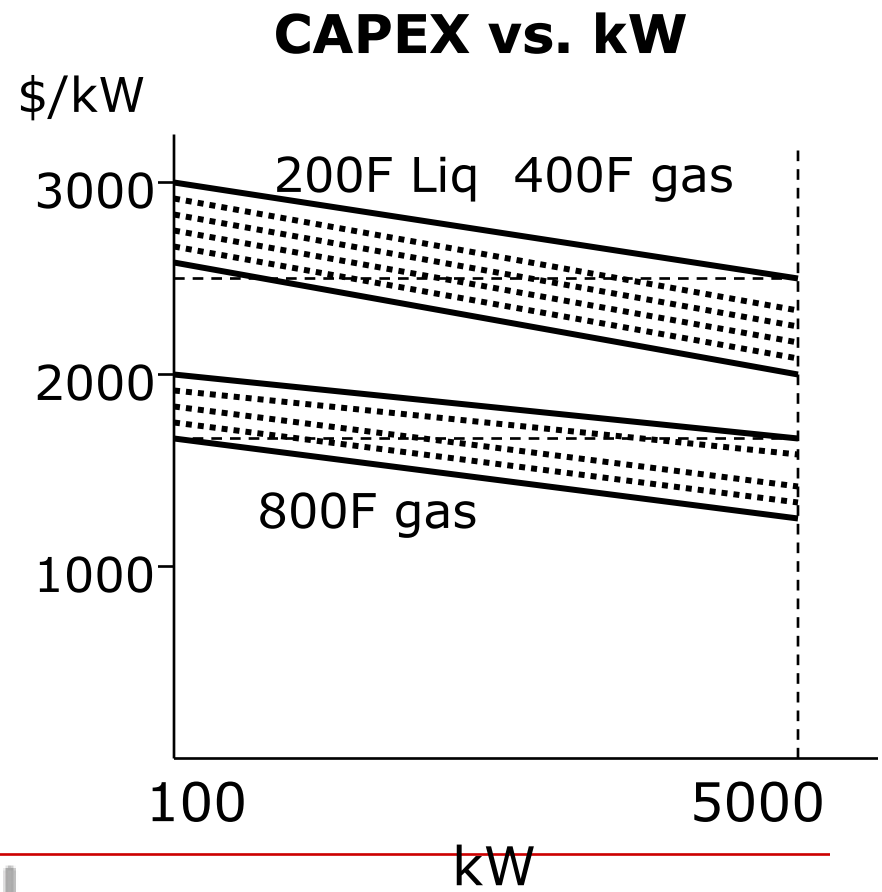
Equipment

- Expander/Generator
  - Expander most expensive by far (25-50% eqp't)
    - Axial turbo (>5MW)
    - Radial turbo (200kW – 5MW
    - Twin Screw (50kW – 500kW)
    - Efficiency (65% - 85%), "right to the bottom line"
- Heat Exchangers
  - Evaporator, preheater, condenser
    - Shell/tube for >~500kW, Plate/fin for <~200kW
- Pump
- BOP (valves, receivers, instruments, etc.)

Focus on Expander

Installed Cost

- Cap cost, \$/kW ~f(kW, ORC temp)
- Installation ~50-100% equipment cost
  - Site specific: height above grade, dist between source and ORC, etc.
  - Modular vs. 'stick built'
  - Air vs. water cooled



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In Conclusion……

- Rules of Thumb
  - Liquid sources below 190F and gas below 400F are too cold
  - Sources below 5 MM Btu/h are too small
  - Stay away from dirty and/or corrosive gases
  - ORC beats steam below 700F and $10MW_e$
  - ORC needs base load source; 7000 h/y
  - Don’t get too excited about efficiency. Focus on $/kW and uptime
  - After selecting the ORC refrigerant the most important item is the expander