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
    - \( C_T = C_{CR} + \text{Fuel} + C_{OPEX} \)
    - 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
  - \( C_T = C_{CR} + \text{Fuel} + C_{OPEX} \)
  - \( C_{CR} = \text{Capital Recovery} = (C_{RF} \times \$/kW)/\text{UTIL} \)
  - \( C_{RF} = \text{Recovery Factor}; 10\% +/- \text{for debt}; 20\% +/- \text{for equity} \)

- Example
  - \( C_{RF} = 16\%, \text{CAPEX} = 2000/\text{kW}, \text{UTIL} = 8000 \text{ h/yr}, \text{OPEX} = .01/\text{kWh} \)
  - \( C_T = (0.16 \times 2000)/8000 + .01 \)
    - \( = .05/\text{kWh} \)
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 \( \Delta H \) \( \times \eta_1 \)
  - *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, \( \eta_1 \)

- Determine *quality* of waste heat to find \( \eta_1 \)
  - *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

\[ \eta_C = 48\% \]
\[ \eta_1 = 24\% \]
\[ \eta_2 = \frac{24}{48} = 50\% \]

Carnot

\[ \eta_2 = \frac{15}{48} = 31\% \]

Source: Barber Nichols
Output Estimate

Theoretical (Carnot) eff'ly:
\[ \eta_c = [1 - T_0(\ln T_1/T_2)/(T_1 - T_2)] \]

Internal eff'ly (Second Law):
\[ \eta_2 = \eta_1 / \eta_c ; 30\% < \eta_2 < 50\% \]

Thermal (First Law) eff'ly:
\[ \eta_1 = \eta_2 / \eta_c \]

\[ W = \Delta H \times \eta_1 \]
Organic Rankine Cycle

Evaporator

Heat Source

Expander

Heated pressurized Vapor

Low pressure vapor

Condenser

Low pressure liquid

High pressure liquid

Pump

Refrigerant Loop
Working Fluid Selection

T-s diagram

T °C

Entropy kJ/°K

Steam

Pentane

Isopentane

R245fa

Isobutane

R134a
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
  - $\eta_1 = 20-30\%$
  - Water available
  - Licensed operators
  - Complex
    - Vacuum
    - Condensate polish
    - Blow down

- **ORC**
  - <700F
  - <10 MW
  - $\eta_1 = 10-20\%$
  - 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

CAPEX vs. kW

- 200F Liq
- 400F gas
- 800F gas

$/kW

100 5000 kW
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