Estimated Cost and Performance of a Novel sCO_2 Natural Convection Cycle for Low-Grade Waste Heat Recover

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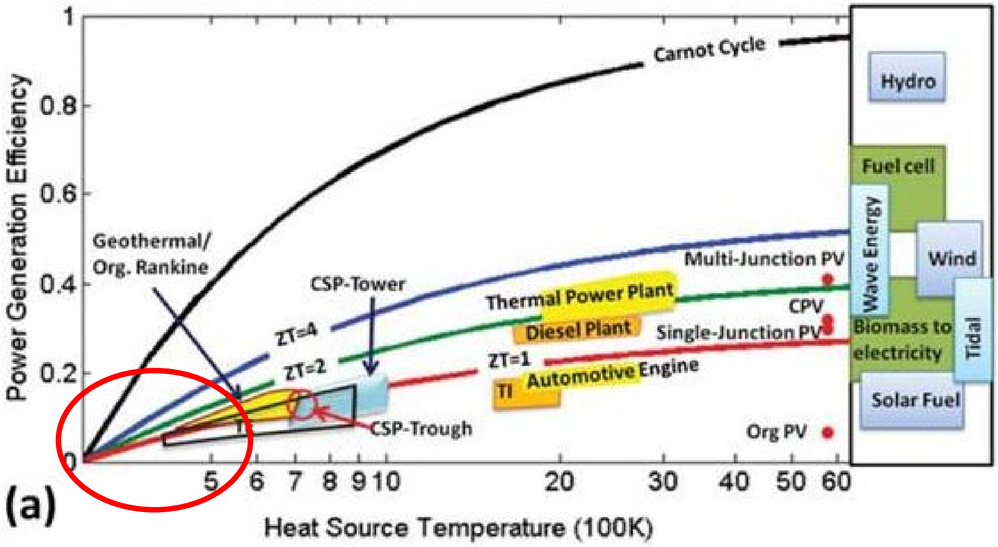
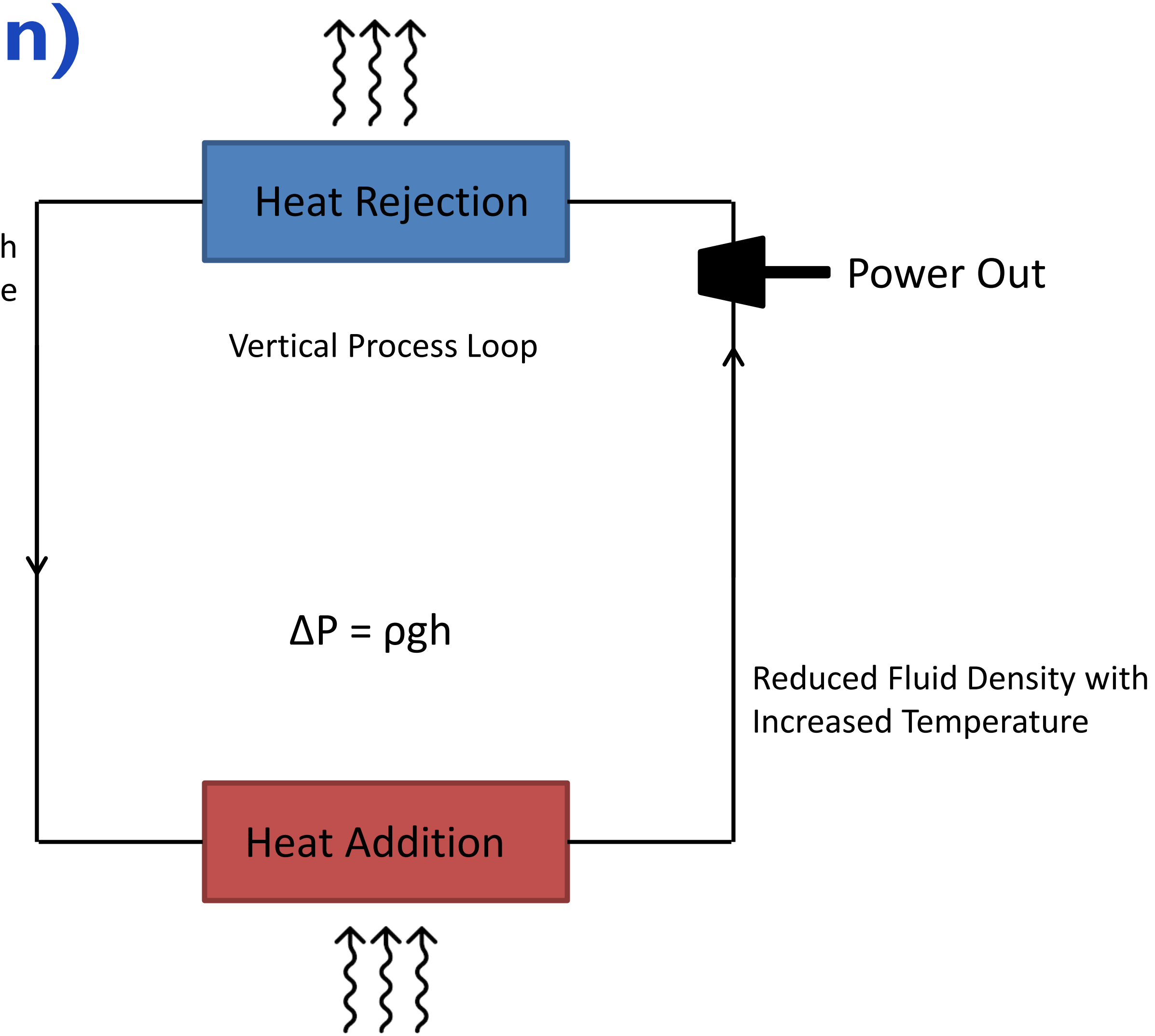
Low-grade Heat Rejection

- <100-300°C [<212-572°F]
- Accounts for as much as 80% of available waste heat
- Inherently low thermal efficiencies result in prohibitively high cost of electricity
- Existing technologies in this space: Organic Rankine Cycles (ORC) or Kalina cycles relying on multiple pumps and expanders for power generation
- Capital cost of installed processes must be reduced to make low-grade WHR commercially viable



R. Kishore and S. Priya, "A Review on Low-Grade Thermal Energy Harvesting: Materials, Methods, and Devices," Materials, 2018.

Proposed Technology: Natural Convection Power Cycle (Thermosiphon)



Heat Rejection

Increased Fluid Density with
Decreased Temperature

Power Out

Vertical Process Loop

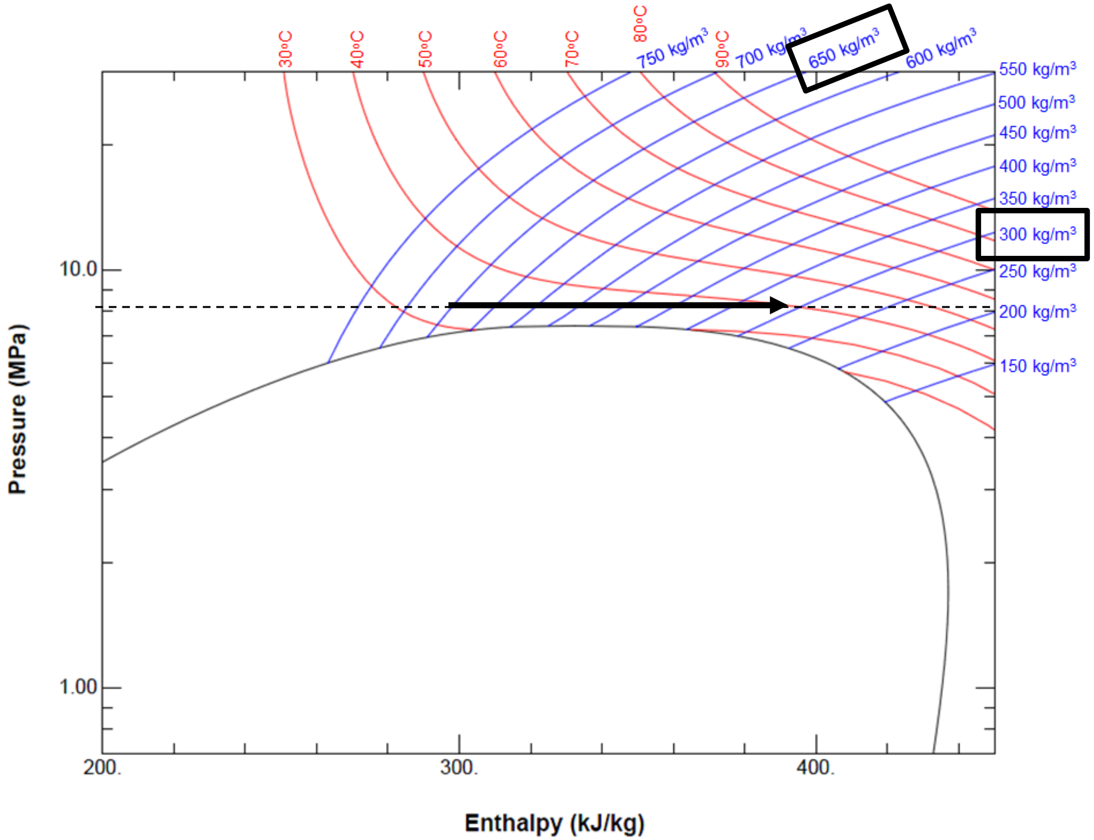
$\Delta P = \rho g h$

Reduced Fluid Density with
Increased Temperature

Heat Addition

- Relatively constant pressure throughout loop
- No pump or compressor required to drive mass flow
- Employing a sealed power-conversion concept minimizes the need for auxiliary systems

Supercritical CO_2

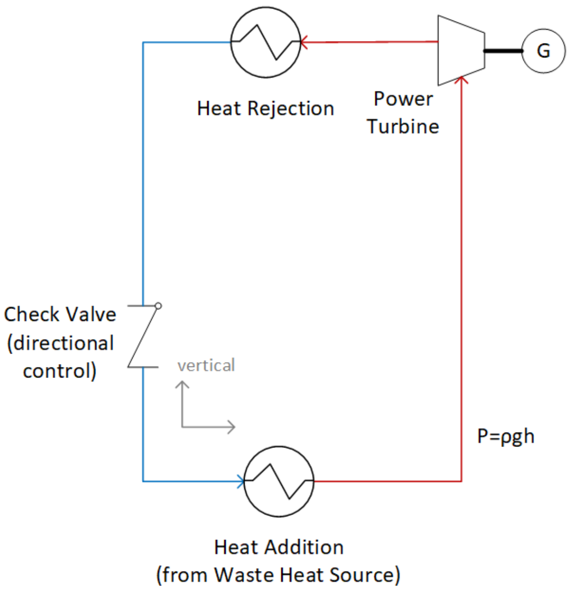


Inherently large density swings near the critical point

Temperature change from 32°C to 40°C at 8.25 MPa yields 54% reduction in density

High fluid density and low viscosity provide a large mass flow potential

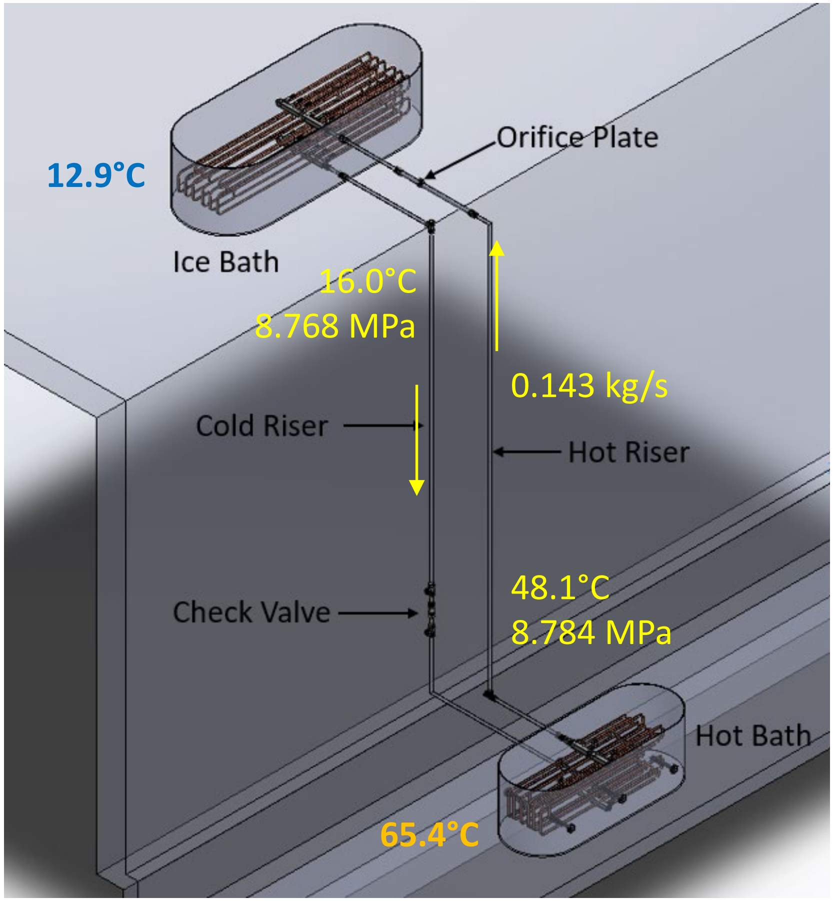
Natural Convection Model Validation



Model Setup and Assumptions

- Discretized flow loop
- Pressure change between nodes
  - major losses
  - minor losses
  - hydrostatic pressure change
- Isothermal vertical pipes (insulated)
- Simplified heat exchangers, defined by the outlet temperature
- Iterative solver used to determine mass flow and cycle pressure for maximizing power output

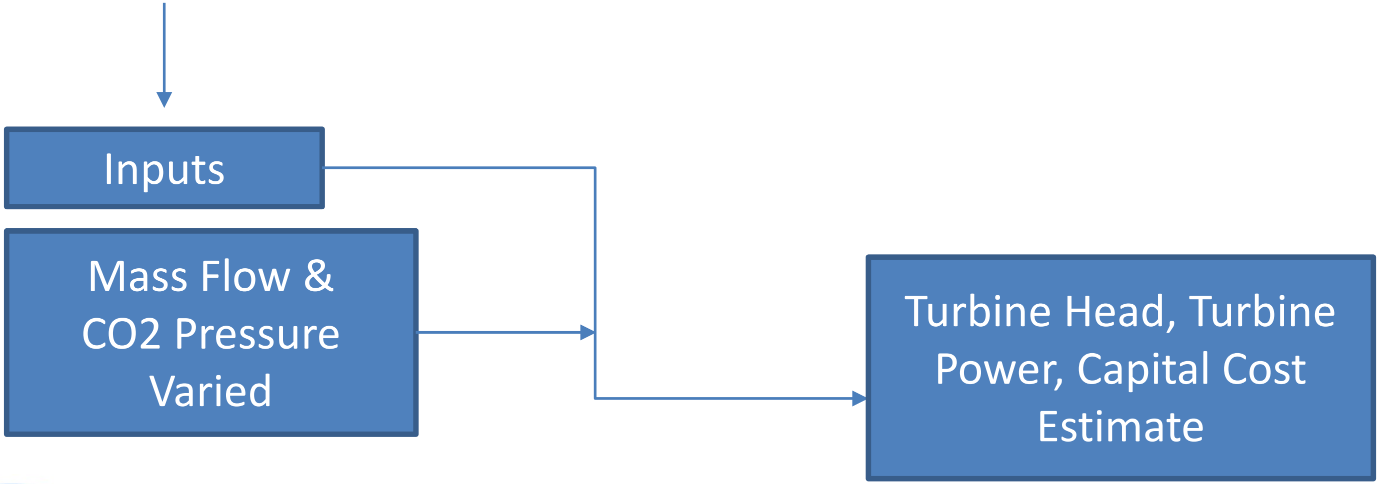
Model Validation



- Predicted P within 1%, T within 10%, and $\dot{m}$ within 5%.
- Phase change did not disrupt circulation

Thermosiphon Scales Considered

Application	Thermal Scale (MW-th)	CO2 Temperature Range (°C)	Pipe Diameter Range (mm)	Loop Height (m)
Data Center	2	30-67	154-254	15-25
Data Center	4	30-70	203-429	20
Industrial Waste Heat	10	32-200	219-406	25
Geothermal	80	25-240	381-829	2300



Inputs

Mass Flow & CO2 Pressure Varied

Turbine Head, Turbine Power, Capital Cost Estimate

Cost Functions: Turbine Cost

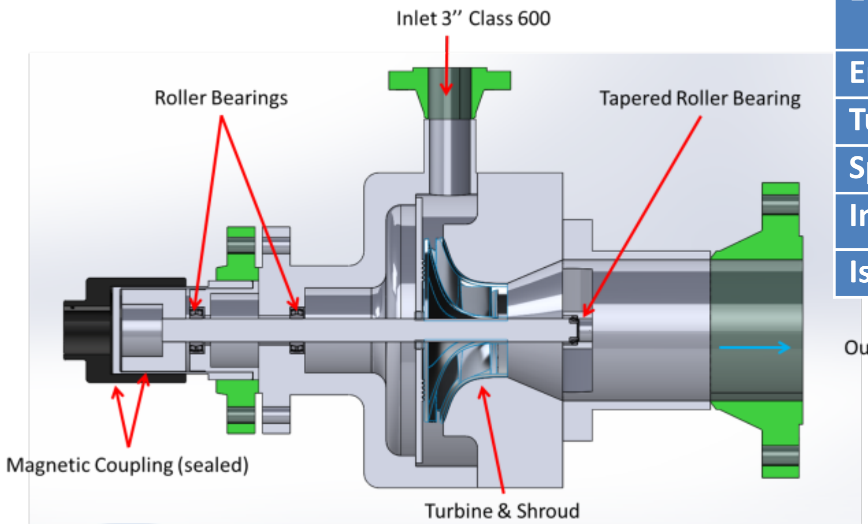
- Conceptual radial turbine design was developed for the 4 MW-th data center application
- Design and fabrication cost was estimated
- This cost was then scaled

$$\text{Cost (USD)} = 227.10 * P + 23{,}288.47$$

where P is isentropic power.

Conditions predicted using cycle model

Application	2MW-th	4MW-th	10MW-th	80MW-th
Mass Flow (kg/s)	12.65	18.00	28.94	230.0
Inlet				
Temperature (°C)	66.6	76.3	200.0	210.0
Pressure (MPa)	8.70	8.55	8.37	20.00
Enthalpy (kJ/kg)	461.22	480.14	638.31	611.51
Entropy (kJ/kg-K)	1.83	1.89	2.28	2.08
Exit				
Temperature (°C)	65.9	75.8	198.7	133.7
Pressure (MPa)	8.619	8.50	8.24	8.50
Enthalpy (kJ/kg)	490.92	479.93	637.33	559.71
Entropy (kJ/kg-K)	1.83	1.89	2.28	2.08
Turbine Sizing				
Speed (RPM)	2,500	1,100	3,000	20,000
Impeller Diam. (mm)	138.0	316.7	206.9	210.0
Isentropic Efficiency	76.2%	95.0%	78.9%	95.6%



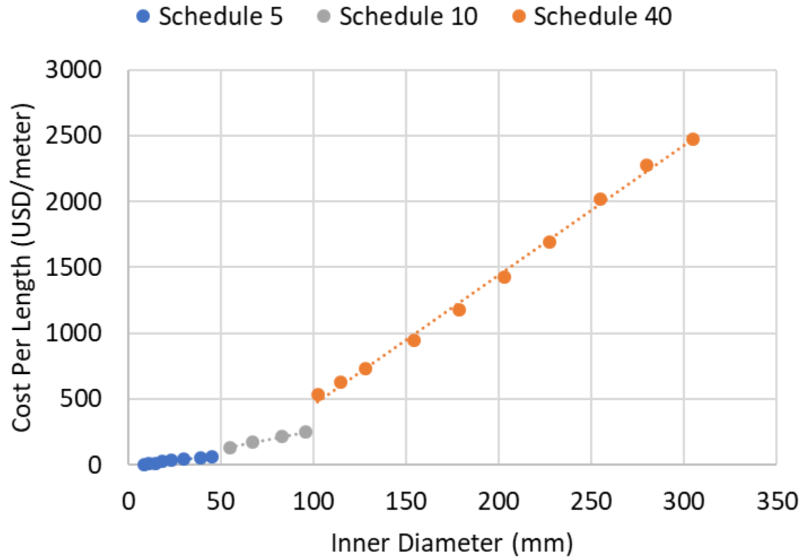
Outlet 10'' Class 600

Cost Functions: Piping

Linear Pipe

- Design pressure of 12 MPa with ASME B31.1 Power Piping Code
- Stainless steel

<1.5 inch NPS	Schedule 5
<3.5 inch NPS	Schedule 10
<12 inch NPS	Schedule 40



ANSI Flanges

<1.5 inch NPS 383.33 USD

>1.5 inch NPS

Cost (USD) = 0.049 * ID2 - 0.65 * ID + 312.82

where ID is the inner pipe diameter in millimeters.

This assumes 900# ANSI raised-face flange

Pipe Elbow Cost

<1.5 inch NPS

Cost (USD) = 0.40 * ID + 11.19

>1.5 inch NPS

Cost (USD) = 0.038* ID2 – 2.14 * ID + 23.00

where ID is the inner pipe diameter in millimeters.

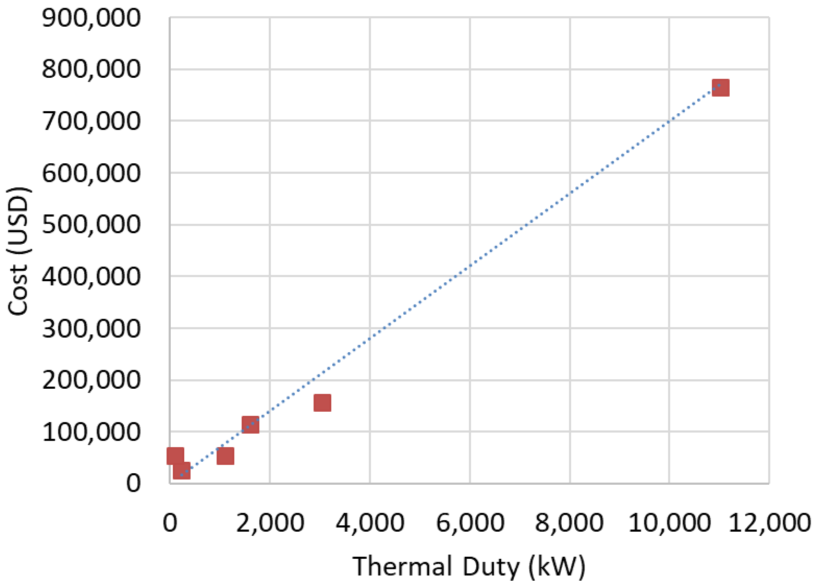
Cost Functions

Heat Exchangers

Developed using vendor quotes for sCO2 heat exchangers, with opposing stream of Air or Water.

$$\text{Cost (USD)} = 70 * Q$$

where Q is the rated thermal duty of the heat exchanger in kilowatts.



Power Generation/Conversion

- Generator quotes for multiple sizes from three vendors.
- Vendor quotes for power conversion (rectifier, capacitors, inverter module, and a DC/DC module). Note that each setup will have a unique power conversion setup.

$$\text{Cost (USD)} = 0.106 * P + 3407.70$$

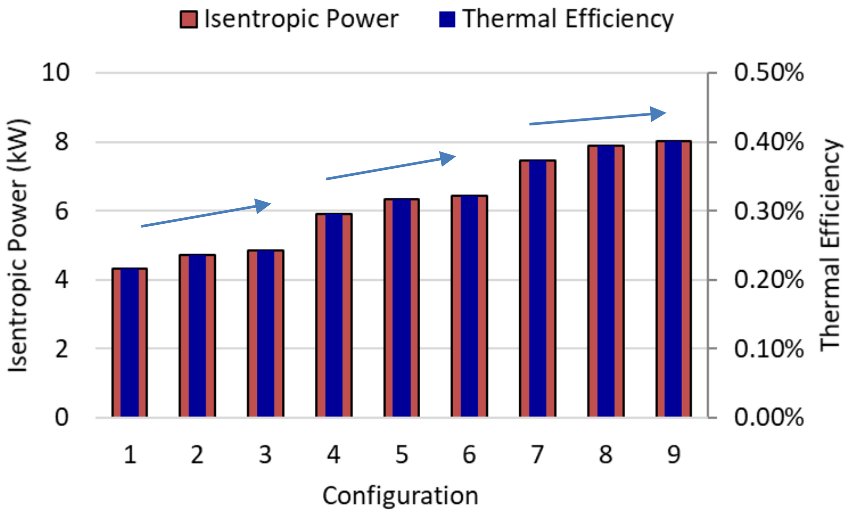
where P is the turbine power output in watts.

Geothermal Cost

- +20% additional cost.
  - Higher pressure, higher speed turbine
  - Drilling and casing the well

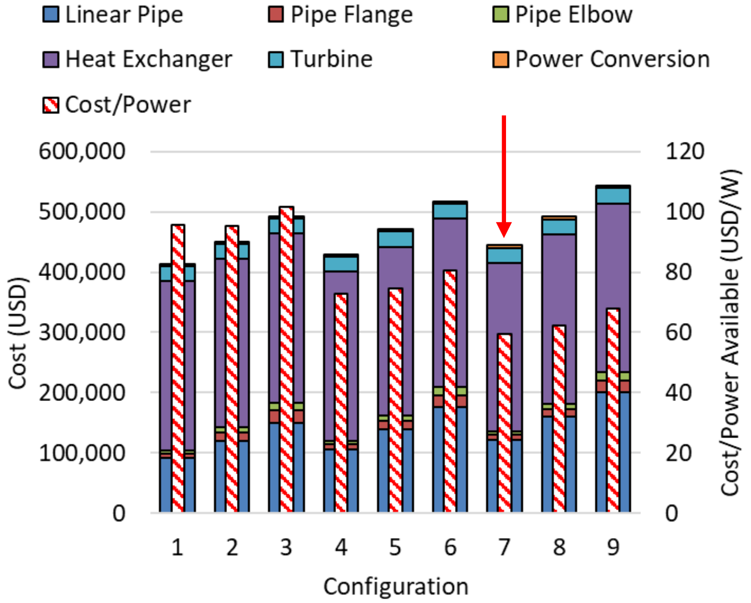
2 MW-th Data Center

Config.	T-cold (°C)	T-hot (°C)	Pipe ID (mm)	Height (m)
1	30.0	66.6	154.1	15
2	30.0	66.6	202.8	15
3	30.0	66.6	254.3	15
4	30.0	66.6	154.1	20
5	30.0	66.6	202.8	20
6	30.0	66.6	254.3	20
7	30.0	66.6	154.1	25
8	30.0	66.6	202.8	25
9	30.0	66.6	254.3	25



Findings:

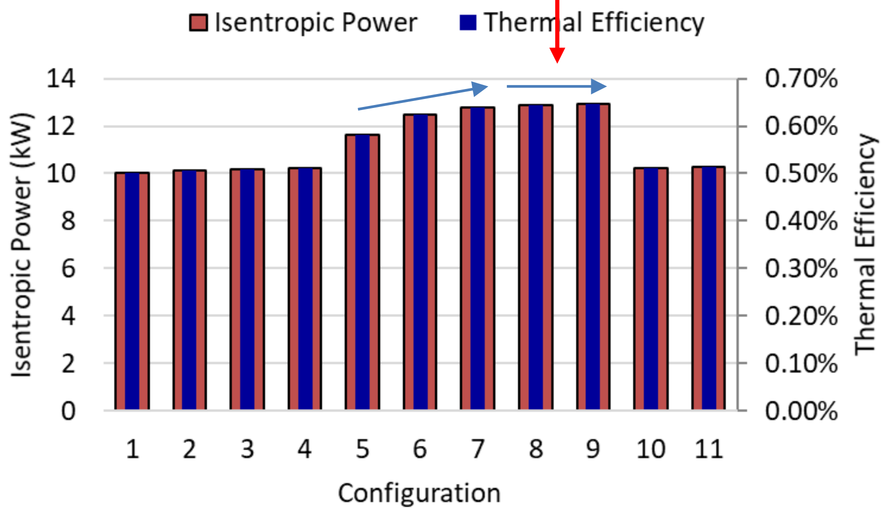
- Power increases with Loop Height and Pipe Size
- Cost per power is minimized for a large Loop Height but small Pipe Size (Configuration 7)
- Most significant cost elements are Heat Exchangers and Piping

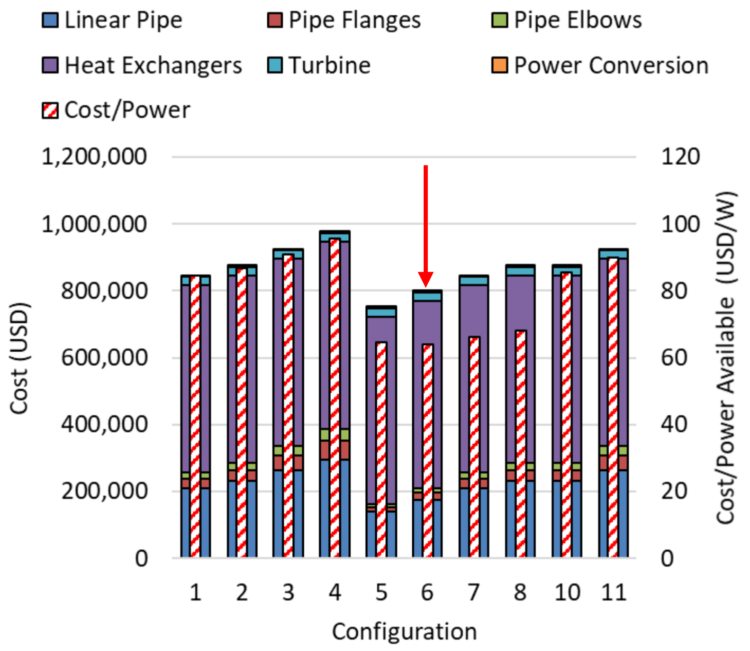


4 MW-th Data Center

Config.	T-cold (°C)	T-hot (°C)	Pipe ID (mm)	Height (m)
1	35.0	66.6	303.0	20
2	35.0	66.6	333.2	20
3	35.0	66.6	381.0	20
4	35.0	66.6	428.8	20
5	30.0	66.6	202.8	20
6	30.0	66.6	254.3	20
7	30.0	66.6	303.0	20
8	30.0	66.6	333.5	20
9	30.0	66.6	381.0	20
10	35.0	70.0	333.3	20
11	35.0	70.0	381.0	20

Frictional losses minimized



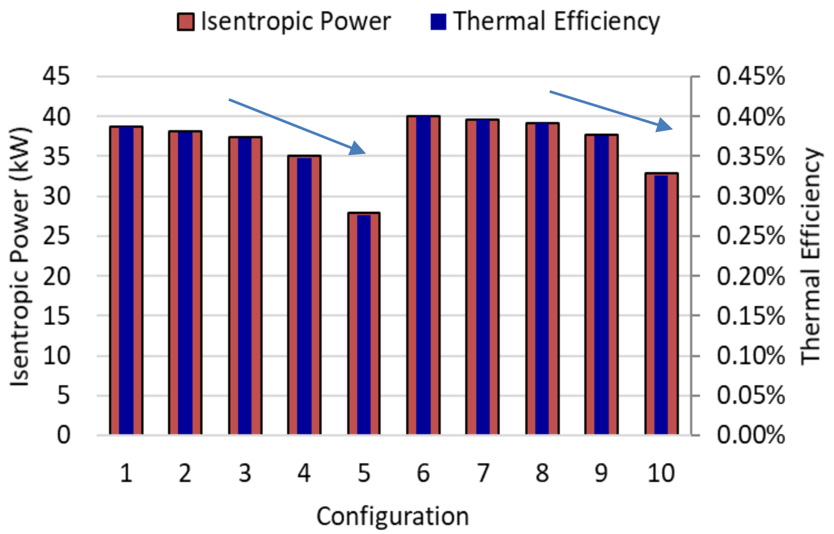


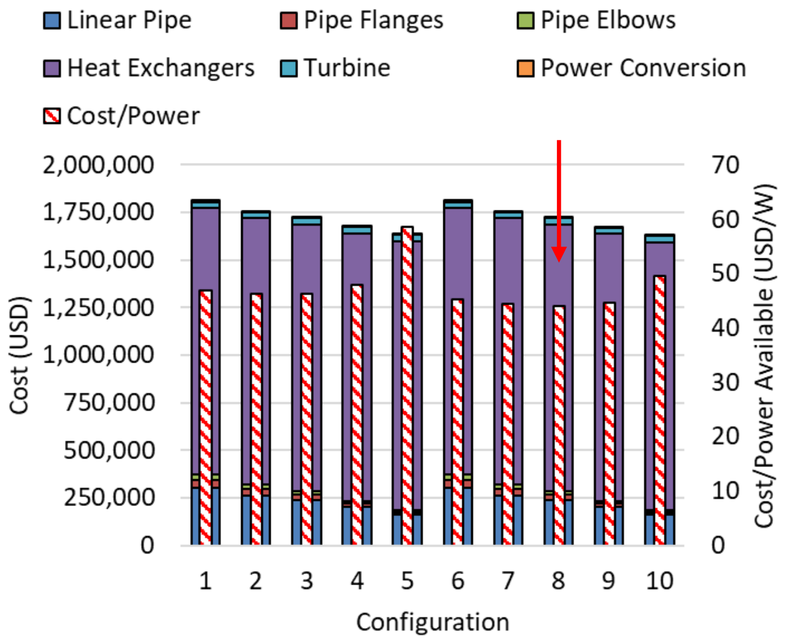
Findings:

- Power increases with reduced CO_2 Cold-Side Temperature (25% increase with 5°C delta)
- An optimum Pipe Size can be found to minimize specific cost (Configuration 6)
- At the same Loop Height, the specific cost is lower for the larger thermal resource

10 MW-th Industrial Waste Heat

Config.	T-cold (°C)	T-hot (°C)	Pipe ID (mm)	Height (m)
1	32.0	120.0	406.4	25
2	32.0	120.0	355.6	25
3	32.0	120.0	323.9	25
4	32.0	120.0	273.1	25
5	32.0	120.0	219.1	25
6	32.0	200.0	406.4	25
7	32.0	200.0	355.6	25
8	32.0	200.0	323.9	25
9	32.0	200.0	273.1	25
10	32.0	200.0	219.1	25



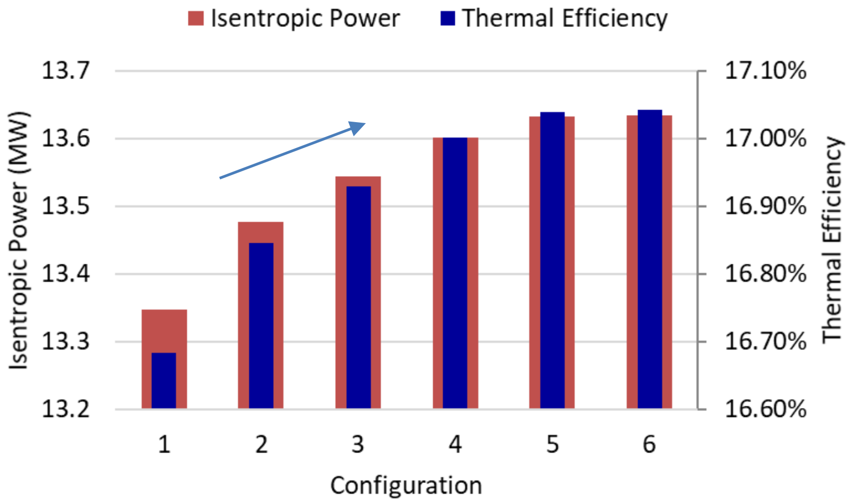


Findings:

- Power increases with CO_2 Hot-Side Temperature (6% increase with 80°C delta)
- Over-restrictive Pipe Size significantly reduced power production
- Again, reduced specific cost with increased thermal load

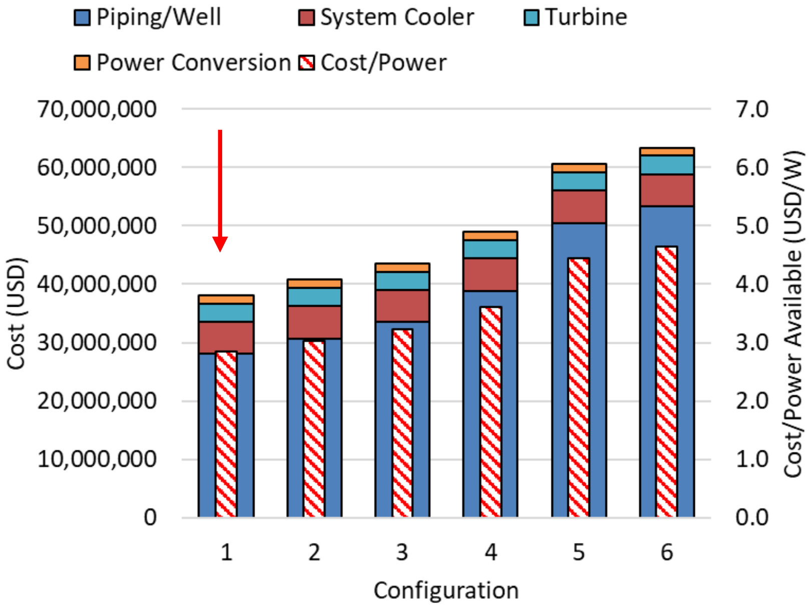
80 MW-th Geothermal

Config.	T-cold (°C)	T-hot (°C)	Pipe ID (mm)	Height (m)
1	25.0	240.0	381.0	2300
2	25.0	240.0	428.8	2300
3	25.0	240.0	478.0	2300
4	25.0	240.0	574.5	2300
5	25.0	240.0	777.8	2300
6	25.0	240.0	828.6	2300



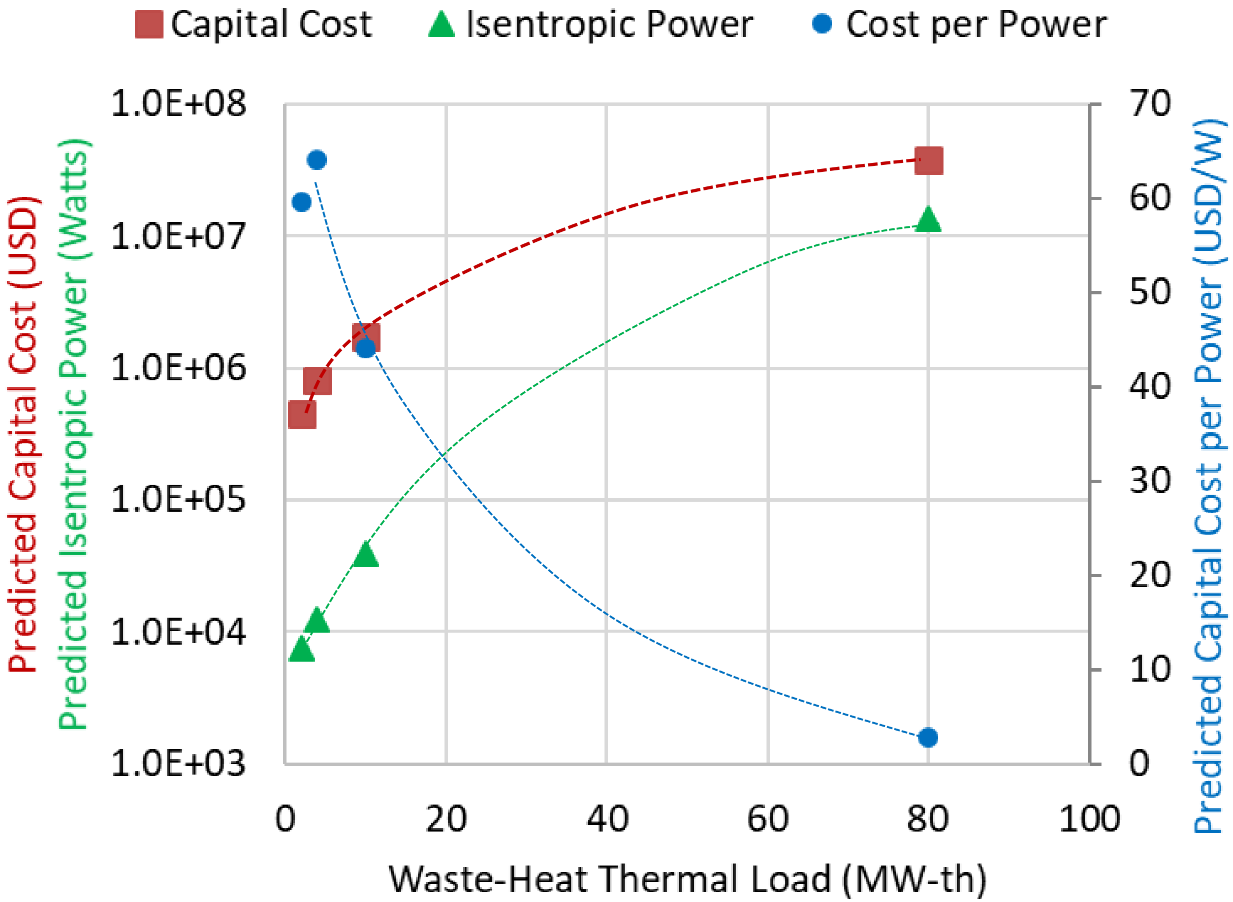
Findings:

- Power and efficiency increase with pipe size
- Specific power is lowest for the smallest pipe size



Thermal Scale Comparisons

- ➢ Capital cost increases with thermal duty
- ➢ Specific cost per power decreases with thermal duty
- ➢ Recoverable power increases with thermal duty



Conclusions

- A natural convection cycle can produce significant levels of power utilizing only waste heat and a single turbomachine at waste heat temperatures well below 100°C
- The most significant performance improvements are achieved by increasing loop height and decreasing CO_2 cold side temperature (to slightly below critical temperature)
  - Separating this cycle from the existing technologies which target the higher source temperatures
- Capital cost follows the trends of cycle power, increasing with pipe size, loop height, and CO_2 temperature delta
- Specific cost per power decreases with increased loop height, optimized pipe size, and increased thermal duty
- Thermal efficiency also improves with scale
- In general, the installation cost is still considered high but the cycle simplicity and compactness make it a viable option for low-grade waste heat recovery

Questions?

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