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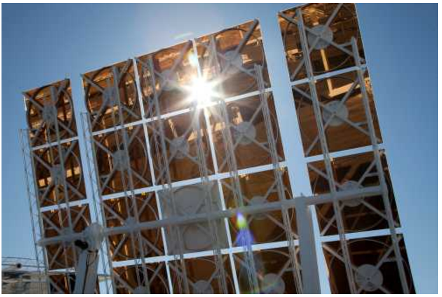

# TECHNO-ECONOMIC COMPARISON OF SOLAR-DRIVEN SCO2 BRAYTON CYCLES USING COMPONENT COST MODELS BASELINED WITH VENDOR DATA AND ESTIMATES

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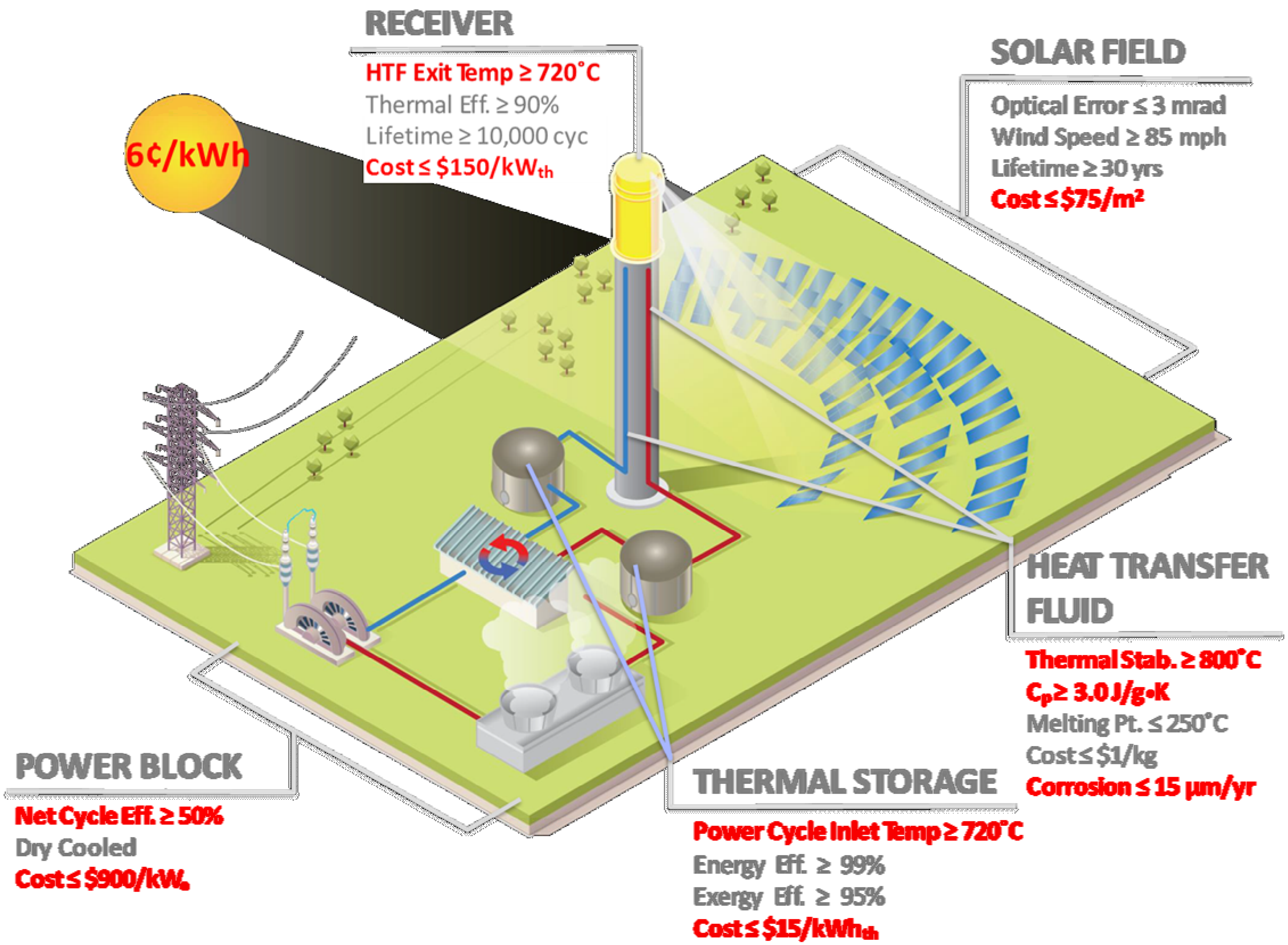
SAND2017-XXXX

# Overview

- Background and Objectives
- Heat Exchanger Costs Models
- Turbomachinery Cost Models
- Baselining and Updated Cycle Comparisons
- Conclusions

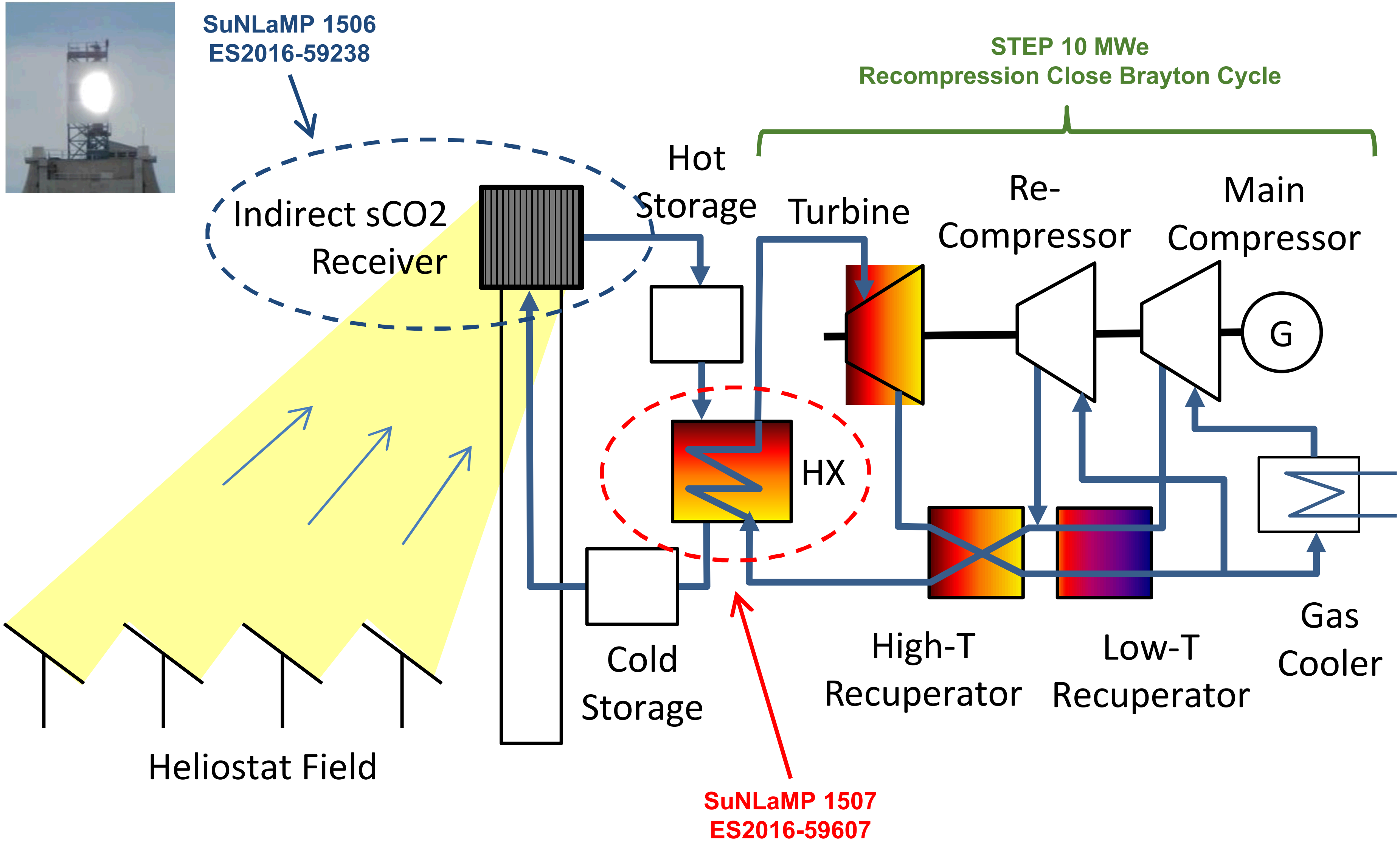
# SunShot CSP Tower Targets

Sandia National Laboratories




M. Bauer, R. Vijaykumar, M. Lausten, J. Stekli, "Pathways to Cost Competitive Concentrated Solar Power Incorporating Supercritical Carbon Dioxide Power Cycles," presented at the 5th International Symposium on Supercritical CO2 Power Cycles,San Antonio, TX, 2016.

# Integration with Sandia Capabilities



# sCO2 Cycle Layout Options

| Application | Size / MWe | Temp / ℃ | Pressure / MPa |
|---|---|---|---|
| Nuclear | 10-300 | 350-700 | 20-35 |
| Fossil (Indirect) | 300-600 | 550-900 | 15-35 |
| Fossil (Direct) | 300-600 | 1100-1500 | 35 |
| Solar | 10-100 | 500-1000 | 20-35 |
| Shipboard | <10-10 | 200-300 | 15-25 |
| Waste Heat | 1-10 | <230-650 | 15-35 |
| Geothermal | 1-50 | 100-300 | 15 |

**Adapted from R. Dennis, "DOE Initiative on SCO2 Power Cycles (STEP) -Heat Exchangers: A Performance and Cost Challenge -," presented at the EPRI-NETL Workshop on Heat Exchangers for SCO2 Power Cycles, San Diego, CA, 2015**

# sCO2 Cycle Cost & Performance

| | SCBC | | RCBC | CCBC | CBI |
|---|---|---|---|---|---|
| Net Power (MWe) | 100 | 100 | 100 | 133 | 100 |
| Efficiency (%) | 16 | 46 | 46 | 28 | 51 |
| $\Delta T_{HTR}$(C) | 540 | 172 | 170 | 518 | 159 |
| $T_{max}$(C) | 700 | 700 | 700 | 600 | 700 |
| $P_{max}$(MPa) | 20 | 20 | 20 | 27.6 | 15 |
| $P_{min}$(MPa) | 6.4 | 8.0 | 7.3 | 8.5 | 2.6 |
| $T_{comp,min}$(C) | 55 | 55 | 55 | 37 | 35 |
| Heater ($/kWe) | 381 | 212 | 322 | 281* | 292 |
| Recuperation ($/kWe) | 0.00 | 243 | 244 | 122* | 259 |
| Cooling ($/kWe) | 545 | 85 | 154 | 574* | 350 |
| Compression ($/kWe) | 423 | 230 | 147 | 80* | 74 |
| Expansion ($/kWe) | 136 | 128 | 135 | 138* | 120 |
| Total ($/kWe) | 1,485 | 898 | 1,002 | 914* | 1,095 |

SCBC=Simple Closed Brayton Cycle
CCBC=Cascaded Closed Brayton Cycle
RCBC=Recompression Closed Brayton Cycle
CBI=Combination Bifurcation with Intercooler

*Corrected from C. K. Ho, M. D. Carlson, P. Garg, and P. Kumar, "Cost and Performance Tradeoffs of Alternative Solar-Driven S-CO2 Brayton Cycle Configurations," in Proceedings of the ASME 2015 Power and Energy Conversion Conference, San Diego, California, 2015, pp. 1–10.

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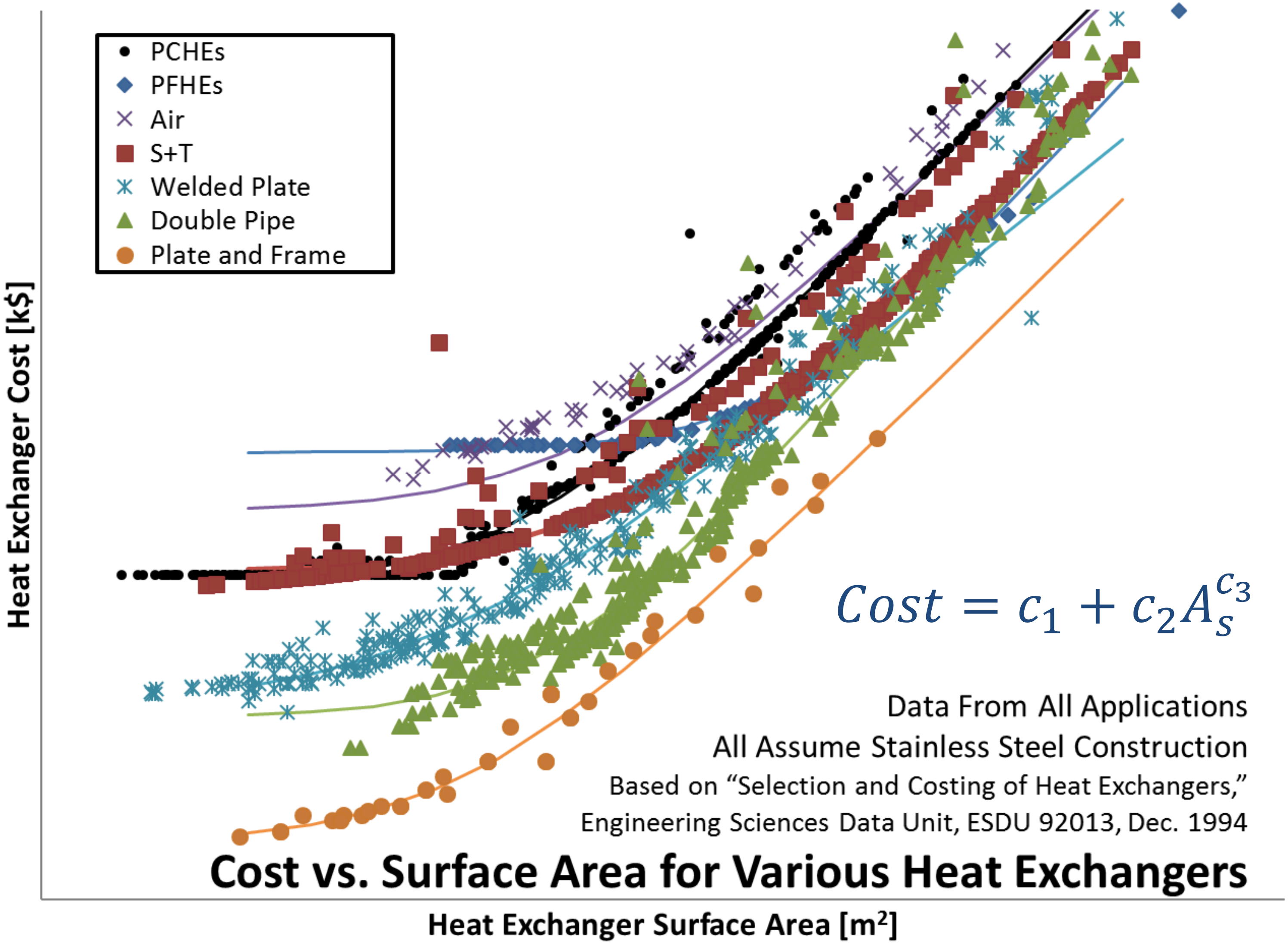
# Cost Scaling with Surface Area



# Heat Exchanger Cost Models

**Overall Heat Transfer Coefficient**

**Heat Transfer Rate**

**Heat Transfer Surface Area**

***Temperature Differential***

$$\dot{q} = UA\Delta T_m$$

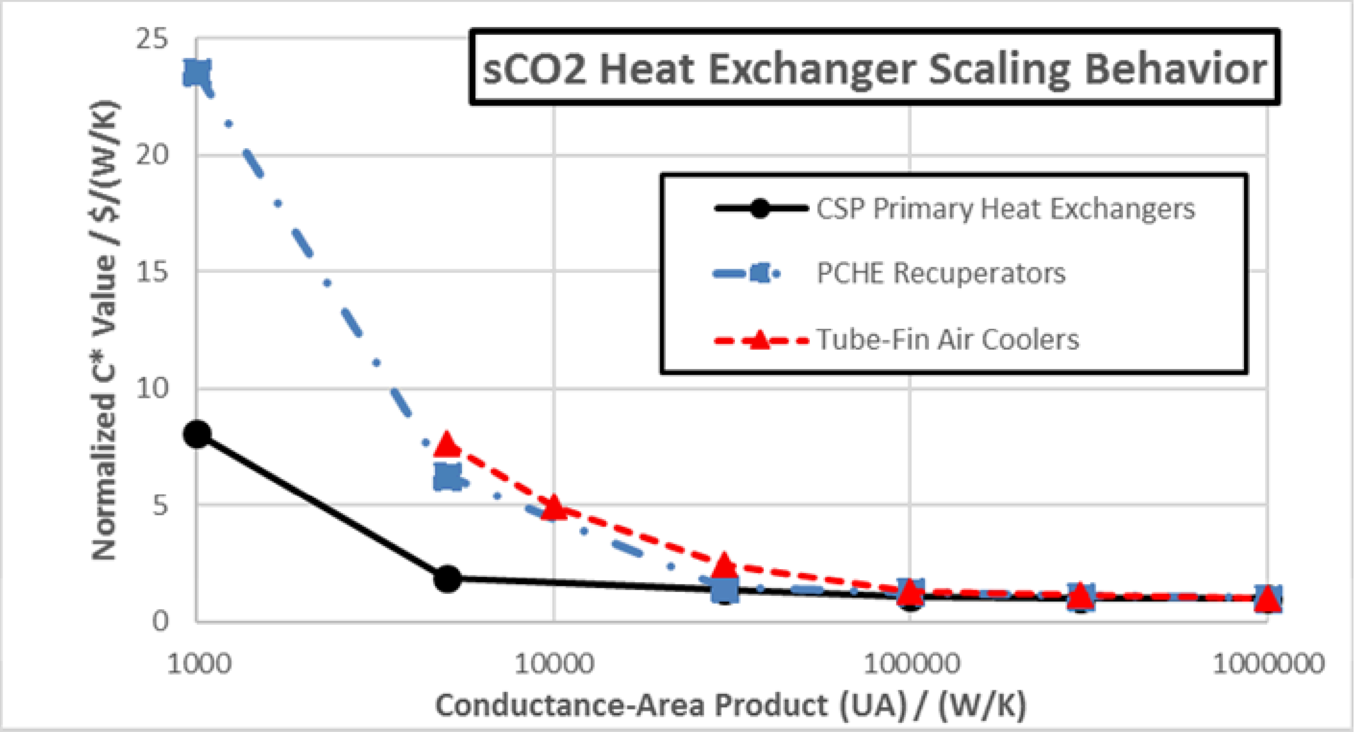
$$\frac{Cost(\dot{q}_2)}{Cost(\dot{q}_1)} = \frac{A_2}{A_1}\frac{U_2 \Delta T_{m,2}}{U_1 \Delta T_{m,1}}$$

**Requires scaling related to heat transfer and thermodynamic variables**

$$\frac{Cost(U_2 A_2)}{Cost(U_1 A_1)} \sim \frac{\dot{q}_2}{\Delta T_{m,2}}\frac{\Delta T_{m,1}}{\dot{q}_1}$$

**Requires scaling only by thermodynamic variables**

# Exchanger Cost Scaling Behavior




| UA (W/K) | $5x10^3$ | $3x10^4$ | $1x10^5$ | $3x10^5$ | $1x10^6$ |
|---|---|---|---|---|---|
| Primary Heat Exchanger ($/(W/K)) | 1.9 | 1.3 | 1.1 | 1.0 | 1.0 |
| Recuperator ($/(W/K)) | 6.3 | 1.4 | 1.3 | 1.1 | 1.0 |
| Air Coolers / Condensers ($/(W/K)) | 7.6 | 2.4 | 1.3 | 1.1 | 1.0 |

# Comparison to ESDU Interpolation

| Category | Model | SCBC | | RCBC | CCBC | CBI |
|---|---|---|---|---|---|---|
| Recuperation ($/kWe) | ESDU | 0 | 243 | 244 | 122 | 259 |
| | Current | 0 | 250 | 251 | 125 | 267 |
| | Change | 0% | 2.9% | 2.9% | 2.5% | 3.1% |
| Cooling ($/kWe) | ESDU | 545 | 85 | 154 | 574 | 350 |
| | Current | 547 | 86 | 155 | 576 | 351 |
| | Change | 0.4% | 1.2% | 0.6% | 0.3% | 0.3% |

- Errors less than 3% between direct interpolation and the proposed fitting method are within the tolerances of rough order of magnitude cost analyses

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# Turbomachinery Cost Models

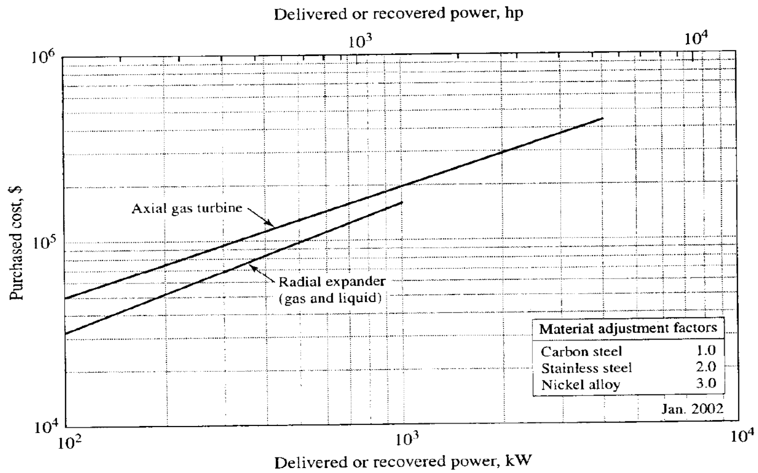


**Figure 12-34**
Purchased cost of turbines and expanders

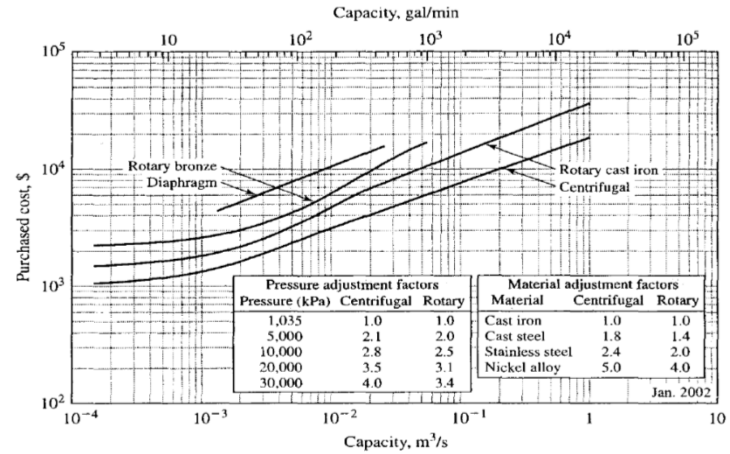


**Figure 12-23**
Purchased cost of diaphragm, centrifugal, and rotary pumps

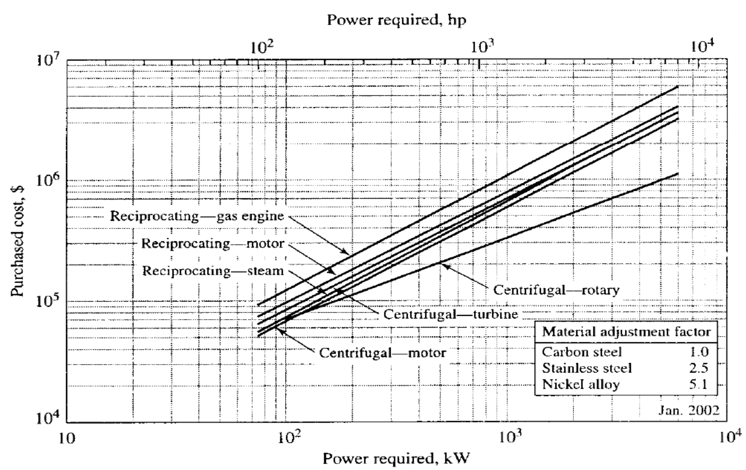


**Figure 12-28**
Purchased cost of compressors. Price includes drive, gear mounting, baseplate, and normal auxiliary equipment; operating pressure to 7000 kPa (1000 psig).

| | Power-law Cost Scaling |
|---|---|
| Motor-Driven Compressor ($)* | $461.91(\dot{W}/kW)^{0.9339}$ |
| Turbine-Driven Compressor ($)* | $643.15(\dot{W}/kW)^{0.9142}$ |
| Radial Expander ($)** | $4001.4(\dot{W}/kW)^{0.6897}$ |
| Axial Gas Turbine ($)** | $9923.7(\dot{W}/kW)^{0.5886}$ |
| Centrifugal Pump ($)*** | $124427\left(\dot{V}/\frac{m^3}{s}\right)^{0.3895}$ |

*Includes factors of 2.5 and 0.2 for stainless steel construction and density ratio of air and CO2 at 8 MPa.
**Includes factor of 3 for nickel alloy construction.
***Includes factors of 2.4 for stainless steel construction and 2.8 for elevator operating pressure.

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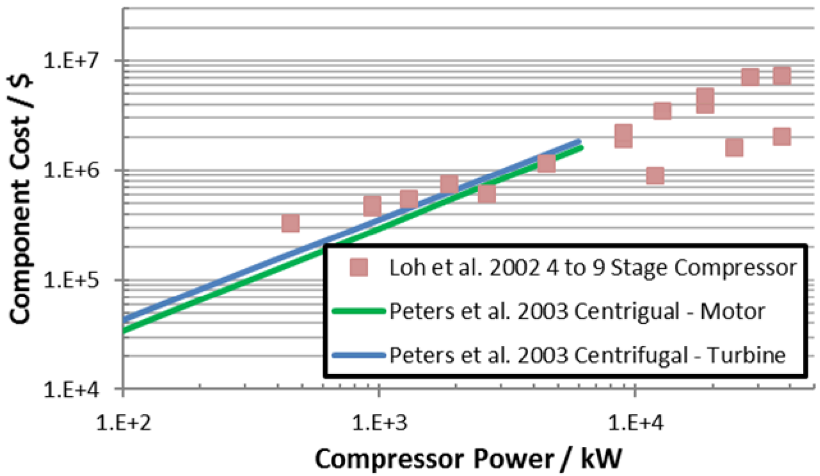
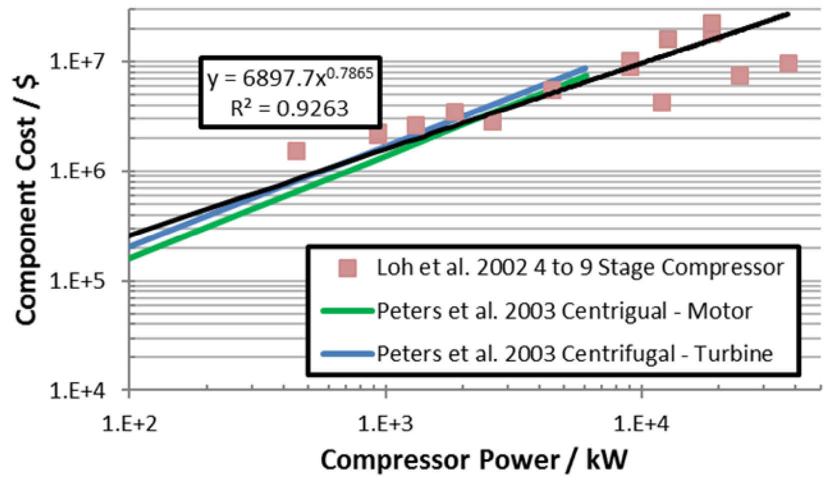
# Compressor Cost Baselining

**Cost models are collapsed to approximately trend with vendor data.**
****Proprietary vendor data not shown****

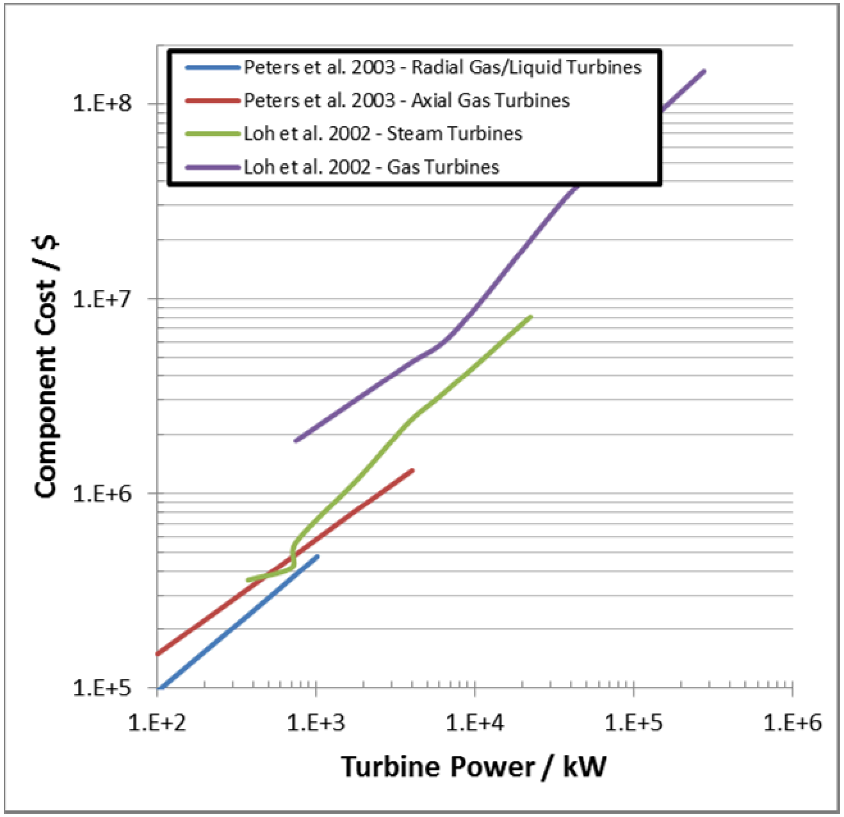


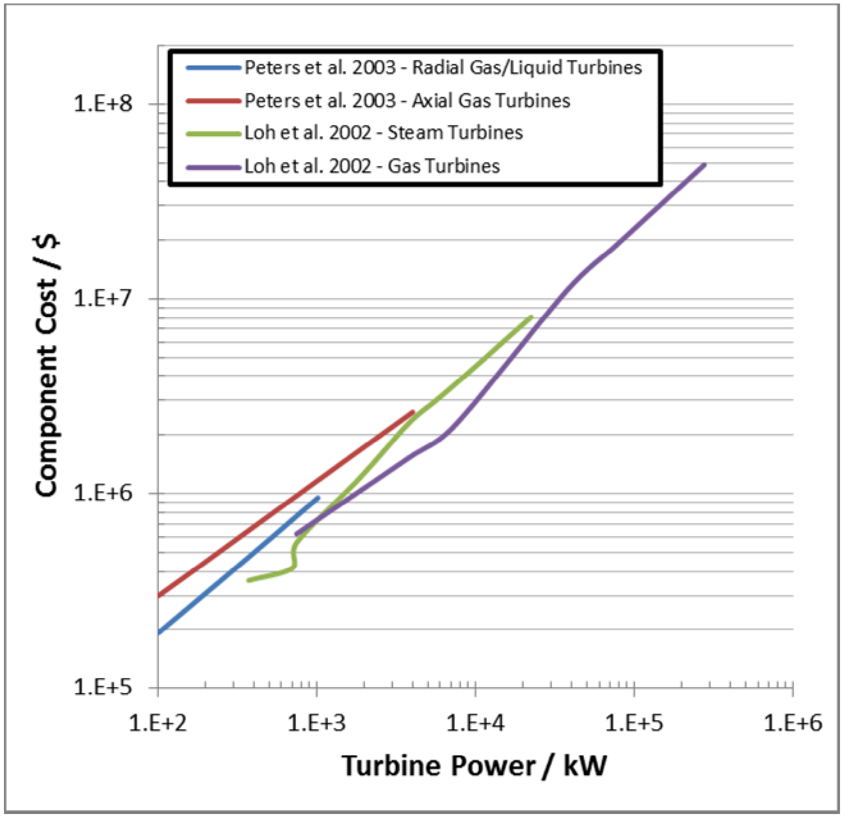




$$Cost/\$ = 6898\left(\dot{W}/kW\right)^{0.7865}$$

# Turbine Cost Baselining

**Cost models are collapsed to approximately trend with vendor data.**
****Proprietary vendor data not shown****




$$Cost/\$ = 7790\left(\dot{W}/kW\right)^{0.6842}$$

# Baselined Heat Exchanger Costs

| UA (W/K) | $5x10^3$ | $3x10^4$ | $1x10^5$ | $3x10^5$ | $1x10^6$ |
|---|---|---|---|---|---|
| Primary Heat Exchanger C* ($/(W/K)) | 1.9 | 1.3 | 1.1 | 1.0 | 1.0 |
| Recuperator C* ($/(W/K)) | 6.3 | 1.4 | 1.3 | 1.1 | 1.0 |
| Air Coolers / Condensers C* ($/(W/K)) | 7.6 | 2.4 | 1.3 | 1.1 | 1.0 |

$$C^* = \exp\left[ ln(C_1^*) + \frac{ln\left(\frac{C_1^*}{C_2^*}\right) ln\left(\frac{UA}{UA_1}\right)}{ln\left(\frac{UA_1}{UA_2}\right)} \right]$$

| $C^*_{1x10^6}$ Values | Naïve | Baselined |
|---|---|---|
| Primary Heat Exchanger | 3.5 | - |
| Recuperator | 1.25 | 1.1 - 4.0 |
| Air Coolers / Condensers | 2.75 | ~2.3 |

$$Cost = C^*_{1x10^6} C^* UA$$

# sCO2 Cycle Cost & Performance

| Category | Model | SCBC | | RCBC | CCBC | CBI |
|---|---|---|---|---|---|---|
| Heater ($/kWe) | Naïve | 375 | 209 | 318 | 277 | 288 |
| Recuperation ($/kWe) | Naïve | 0 | 250 | 251 | 125 | 267 |
| | Baselined | 0 | 220 | 221 | 110 | 235 |
| Cooling ($/kWe) | Naïve | 547 | 86 | 155 | 576 | 351 |
| | Baselined | 458 | 72 | 130 | 482 | 294 |
| Compression ($/kWe) | [6] | 243 | 114 | 147 | 80 | 74 |
| | Baselined | 625 | 328 | 440 | 233 | 311 |
| Expansion ($/kWe) | [6] | 160 | 128 | 135 | 138 | 120 |
| | Baselined | 338 | 268 | 283 | 284 | 250 |
| Total ($/kWe) | Naïve | 1325 | 787 | 1006 | 1196 | 1100 |
| | Baselined | 1796 | 1097 | 1392 | 1386 | 1378 |

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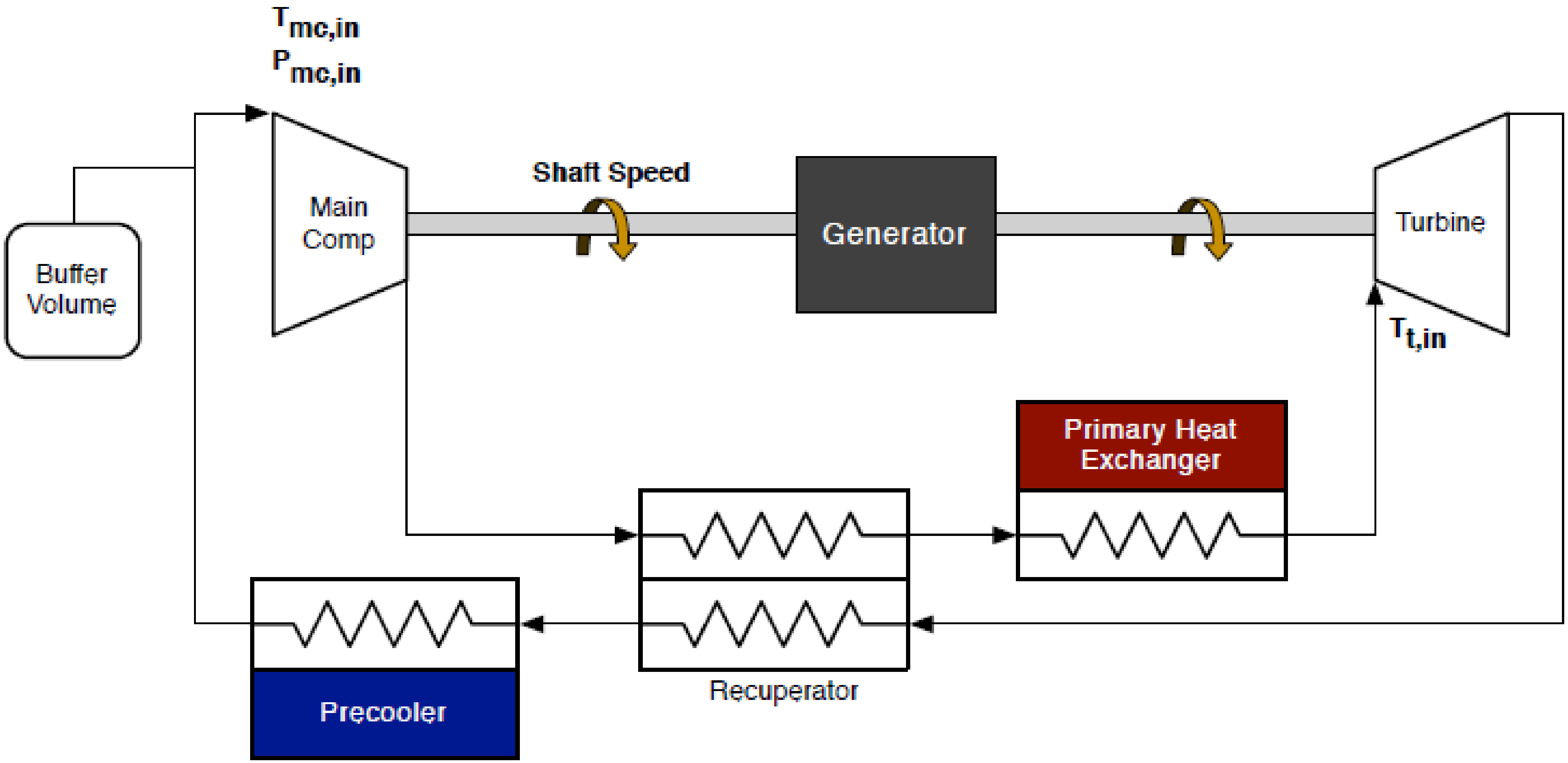
# Conclusions

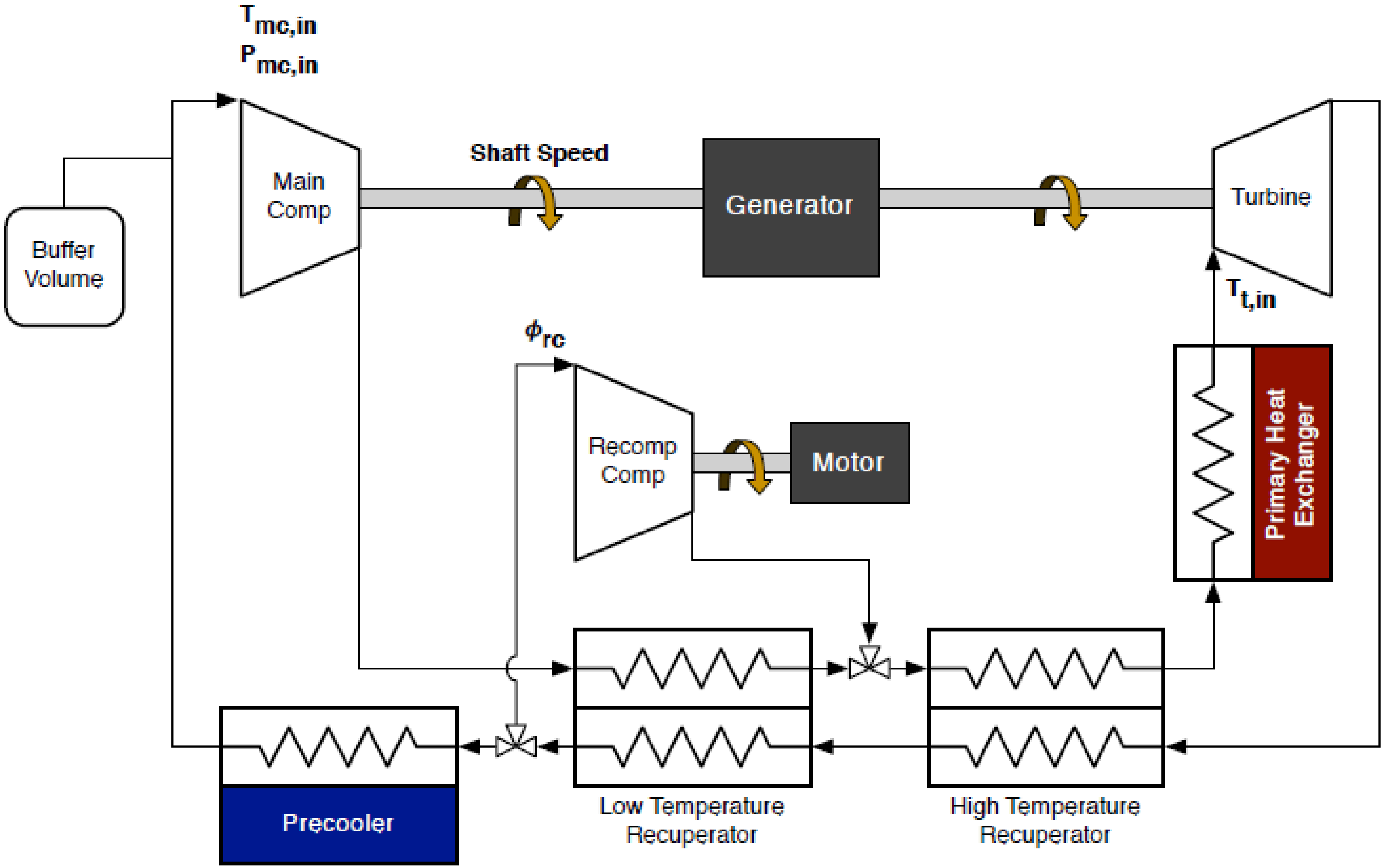
- Logarithmic interpolation and asymptotic extrapolation of heat exchanger cost curves is more accurate the previously-suggested power-law fits
- Naïve cost models
  - Over-predicted heat exchangers by 10% to 20%
  - Under-predicted compressors by 60% to 75%
  - Under-predicted turbines by approximately 50%
- The simple recuperated cycle remains the most promising configuration to achieve SunShot targets
- More cost data should be used to increase the accuracy of turbomachinery cost models

# Backup Slides

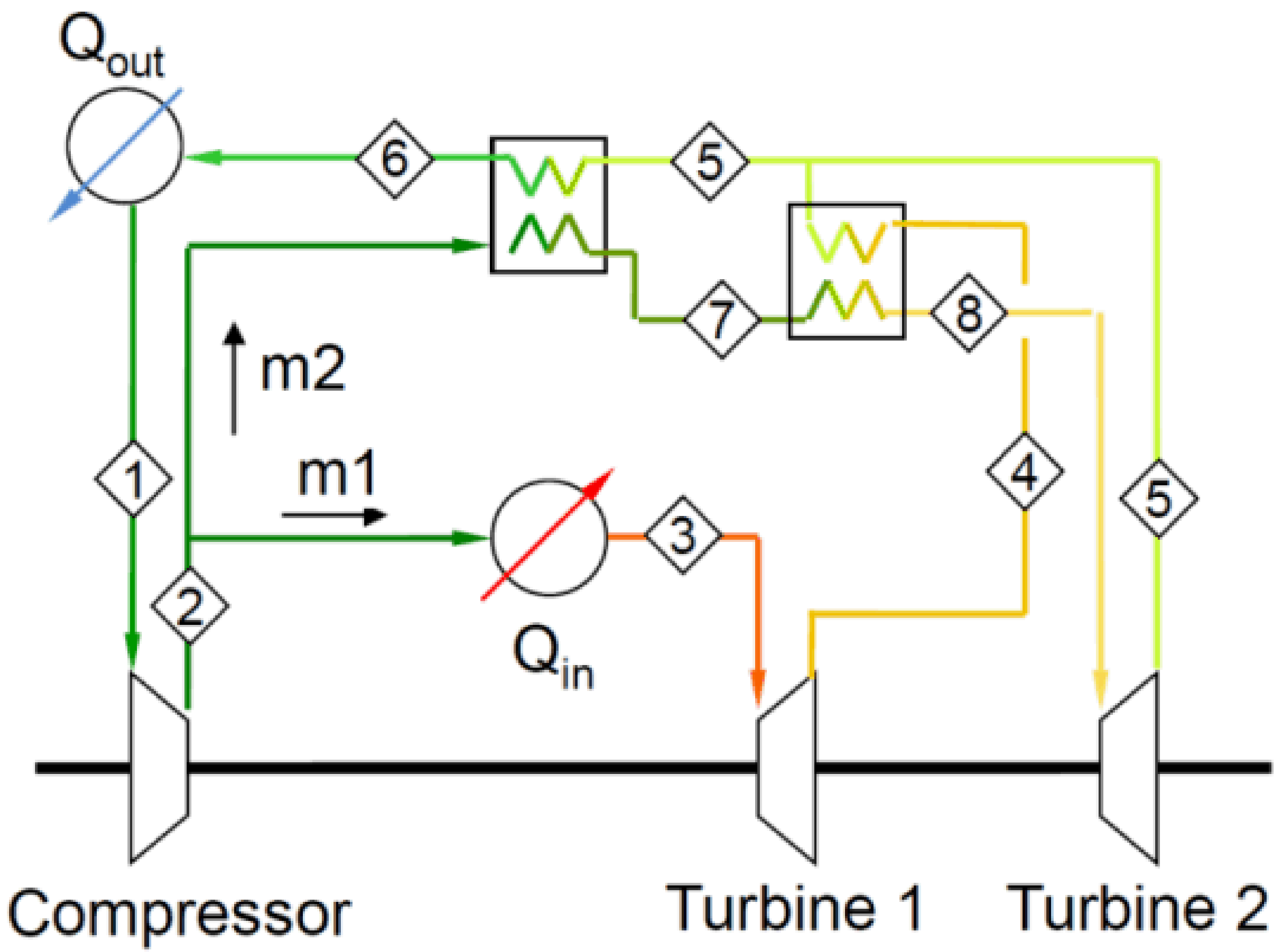
# Simple Closed Brayton Cycle (SCBC)



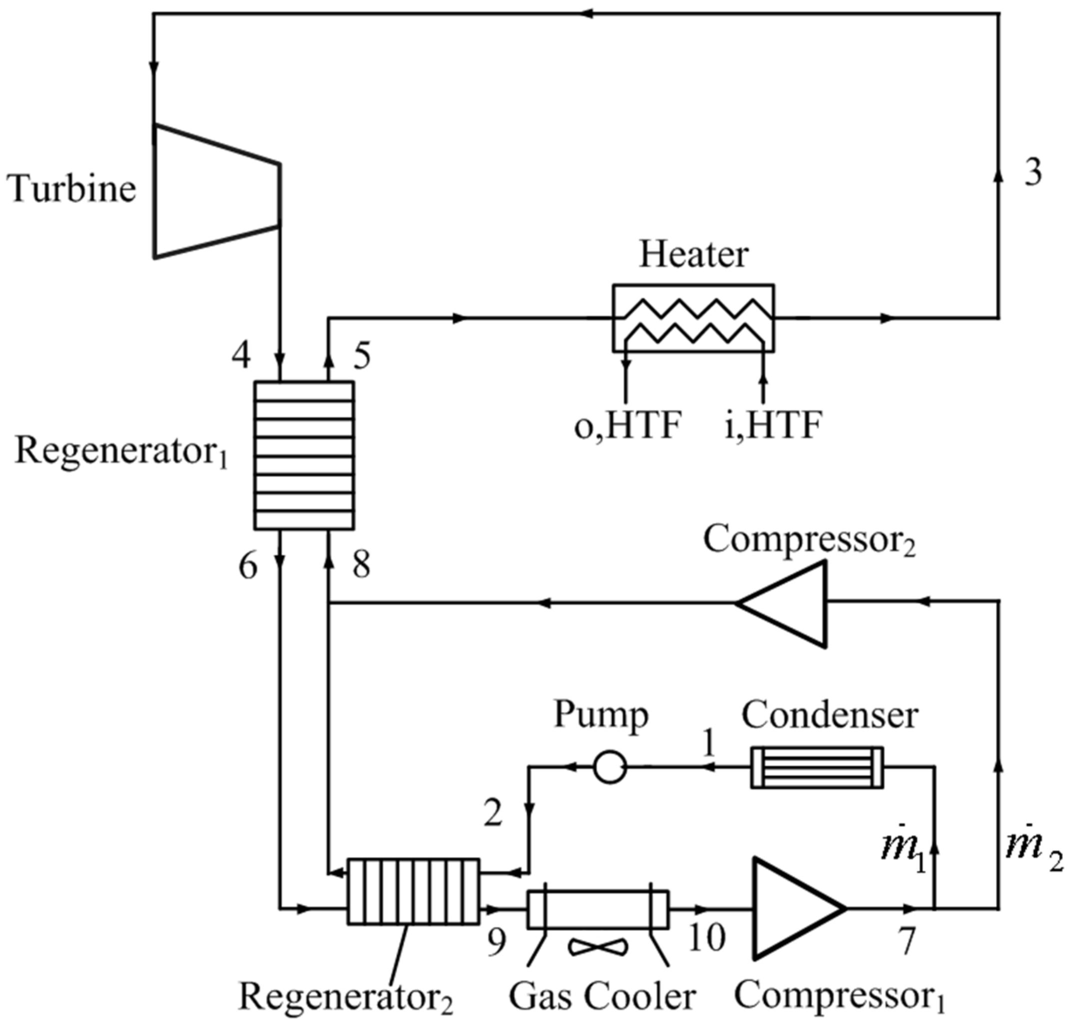
# Recompression Closed Brayton Cycle (RCBC)



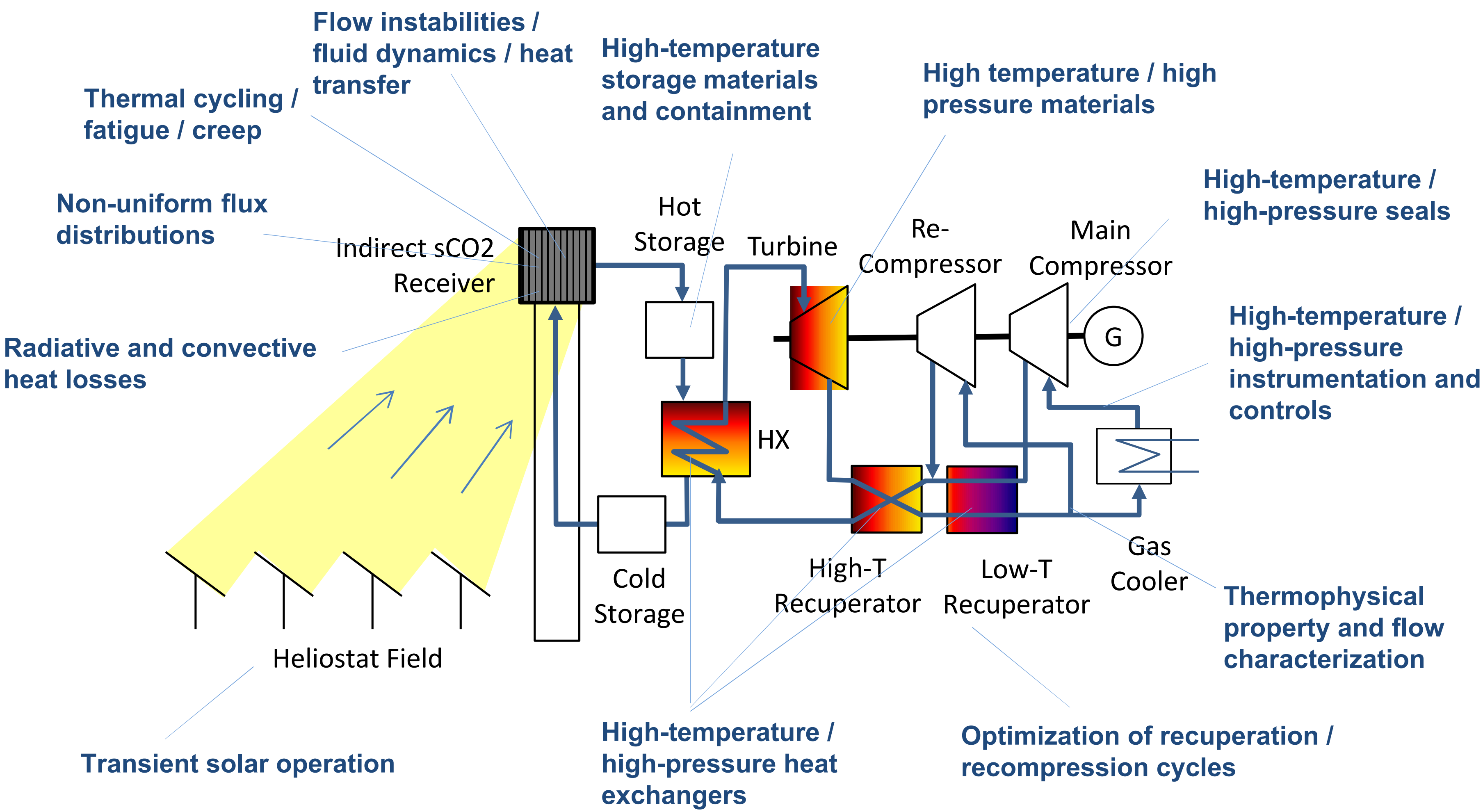
# Cascaded Closed Brayton Cycle



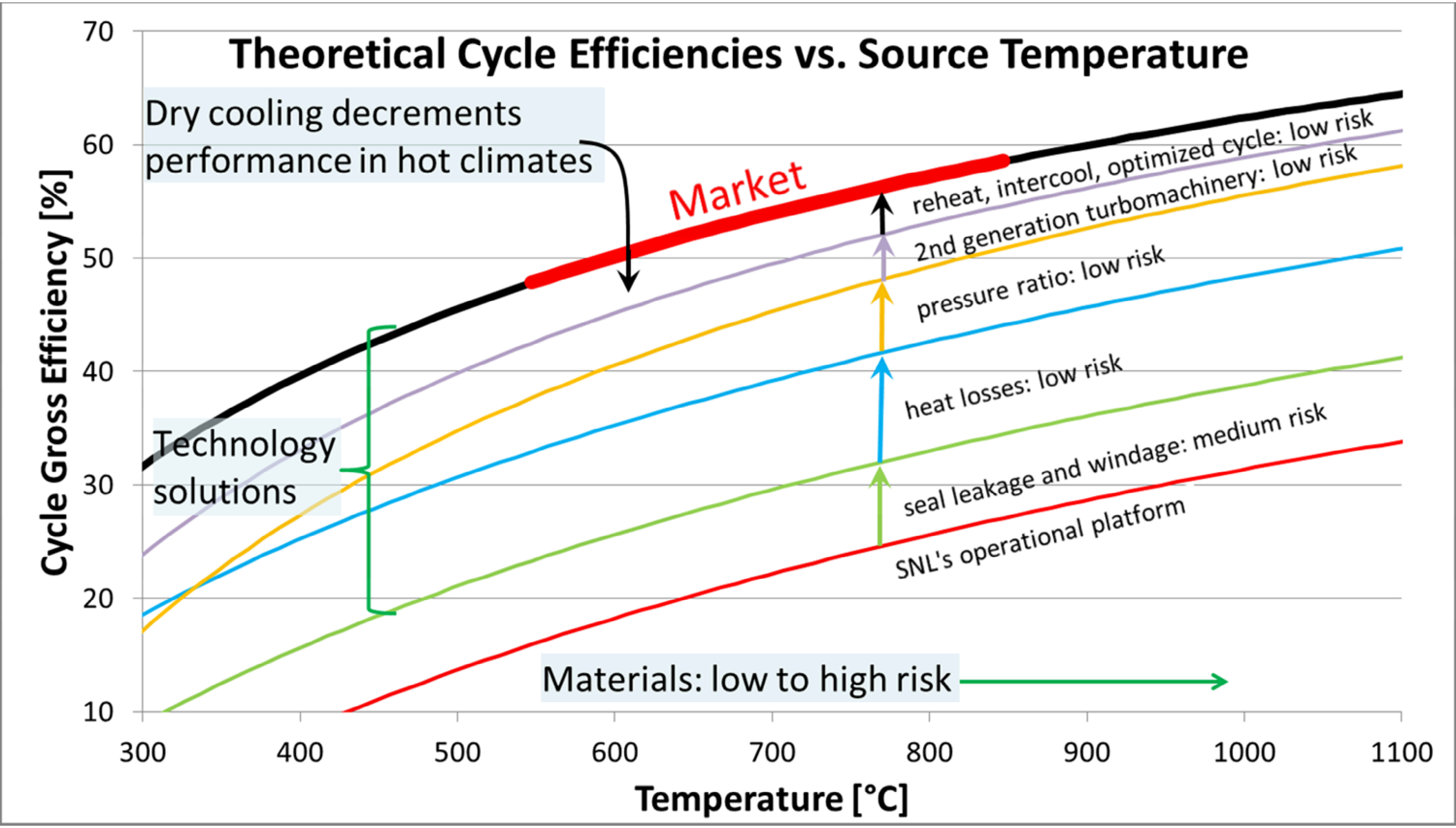
# Combination Bifurcation with Intercooler (CBI)



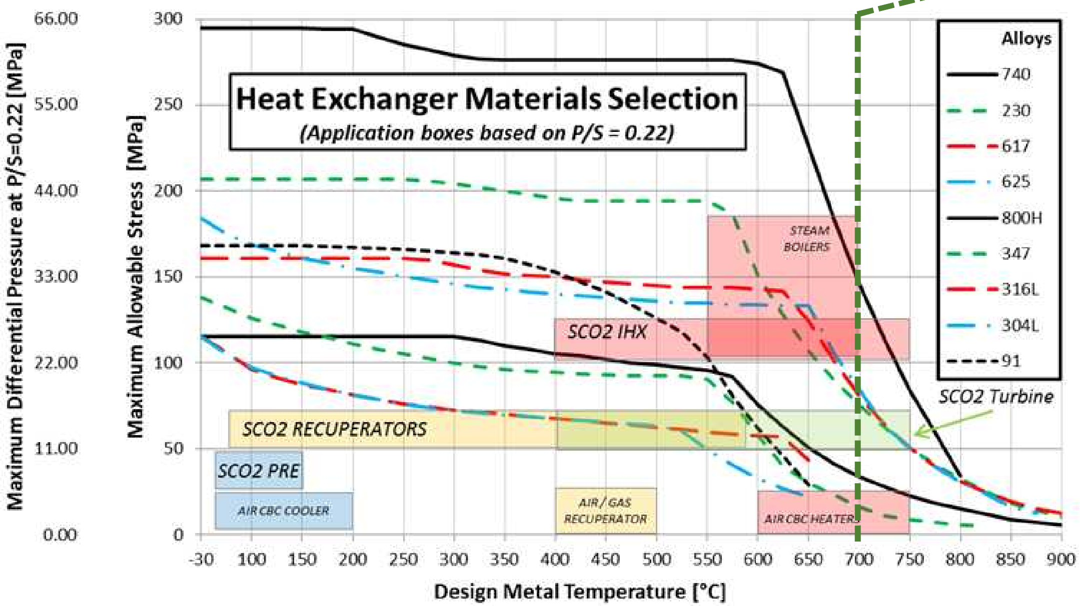
# Technical Challenges

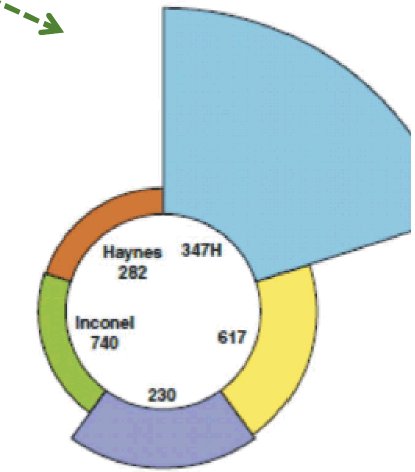


# Path to High Efficiency

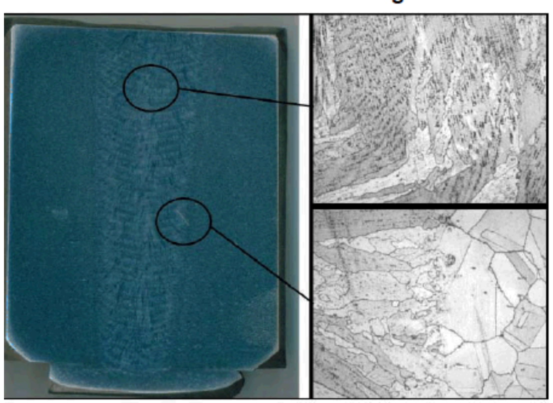


# Materials are limited to ≤700C




**Today: Repeatable 3" (75mm) thick Inconel 740 welds without cracking**



- Advanced Ultrasupercritical (A-USC) research has advanced high temperature materials[1]
- Alloy 617 and 740 are leading candidates for such systems
  - 740 has recently been welded without cracking, more work is still needed to vet any materials issues[1]
- Little industrial experience exists and field testing is sparse.


1. *Shingledecker, Development of Advanced Materials for Advanced Ultrasupercritical (A-USC) Boiler Systems, 2014*
2. M. Carlson, "Options for SCO2 Brayton Cycle Heat Exchangers," presented at the The 4th International Symposium on Supercritical CO2 Power Cycles, Pittsburgh, PA, 2014.