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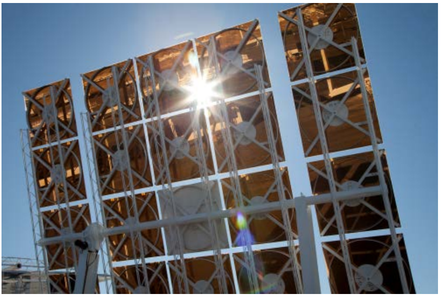

RESEARCH GUIDED BY TECHNOECONOMIC ANALYSIS

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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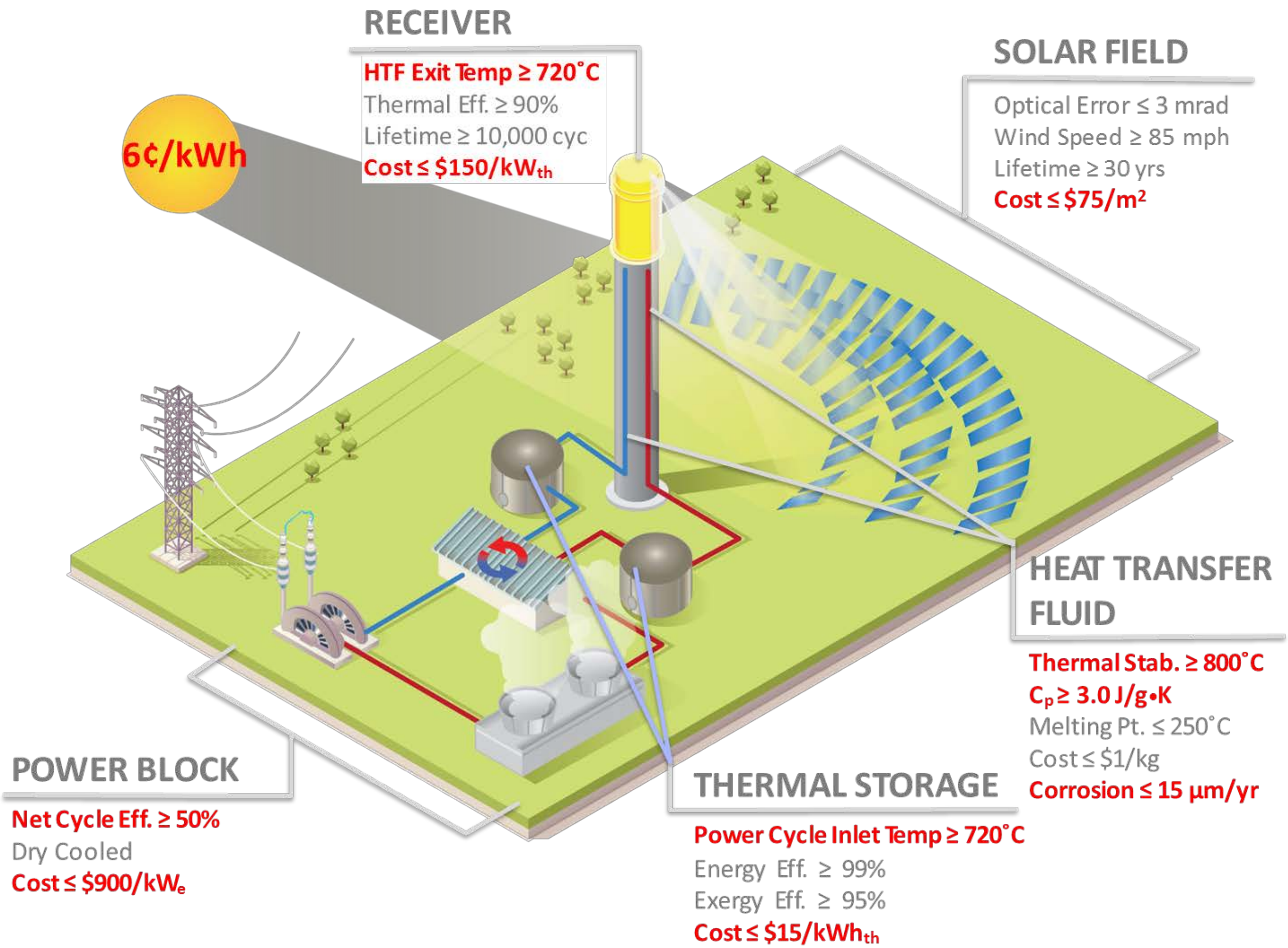
SunShot CSP Tower Targets



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.

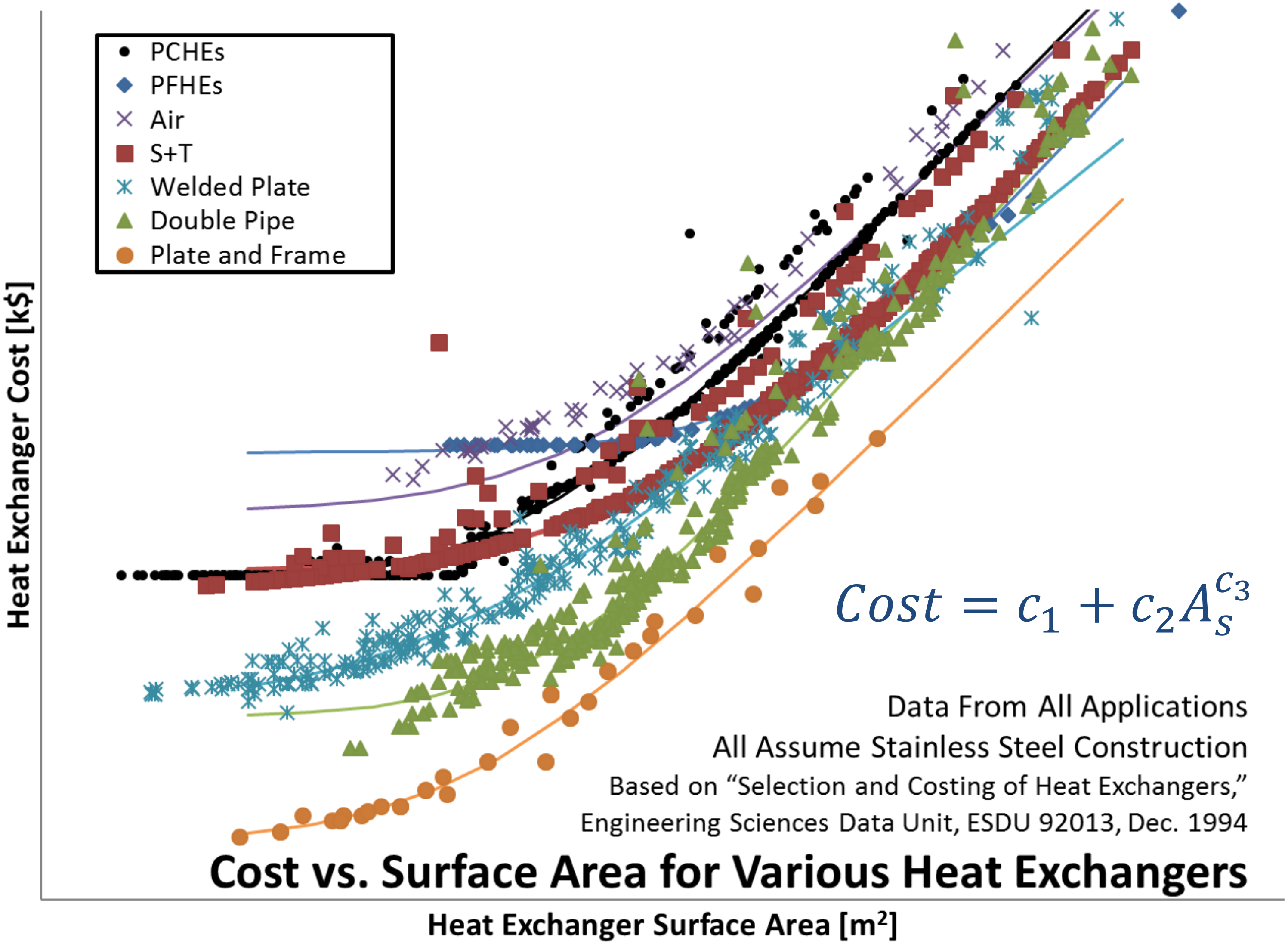
Reference Cycle Cost Analysis

- **Purpose**
  - Develop a cost metric for the particle/sCO2 heat exchanger using the SunShot power block cost of 900 $/kWe

- **Approach**
  1. Collect literature-based cost models for the major components
  2. Collect sCO2 Brayton cycle layout options, including CSP-optimized

     For 1 and 2 see 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.
  3. Fit cost model trends to available and obtained vendor estimates
  4. Approximate the uncertainty in cost model estimates
  5. Develop a confidence range for the particle/sCO2 Hxer cost

Cost Scaling with Surface Area



$$Cost = c_1 + c_2 A_s^{c_3}$$

Data From All Applications

All Assume Stainless Steel Construction

Based on "Selection and Costing of Heat Exchangers," Engineering Sciences Data Unit, ESDU 92013, Dec. 1994

Cost vs. Surface Area for Various Heat Exchangers

Heat Exchanger Cost Models

Overall Heat Transfer Coefficient

Heat Transfer Rate

Heat Transfer Surface Area

Temperature Differential

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

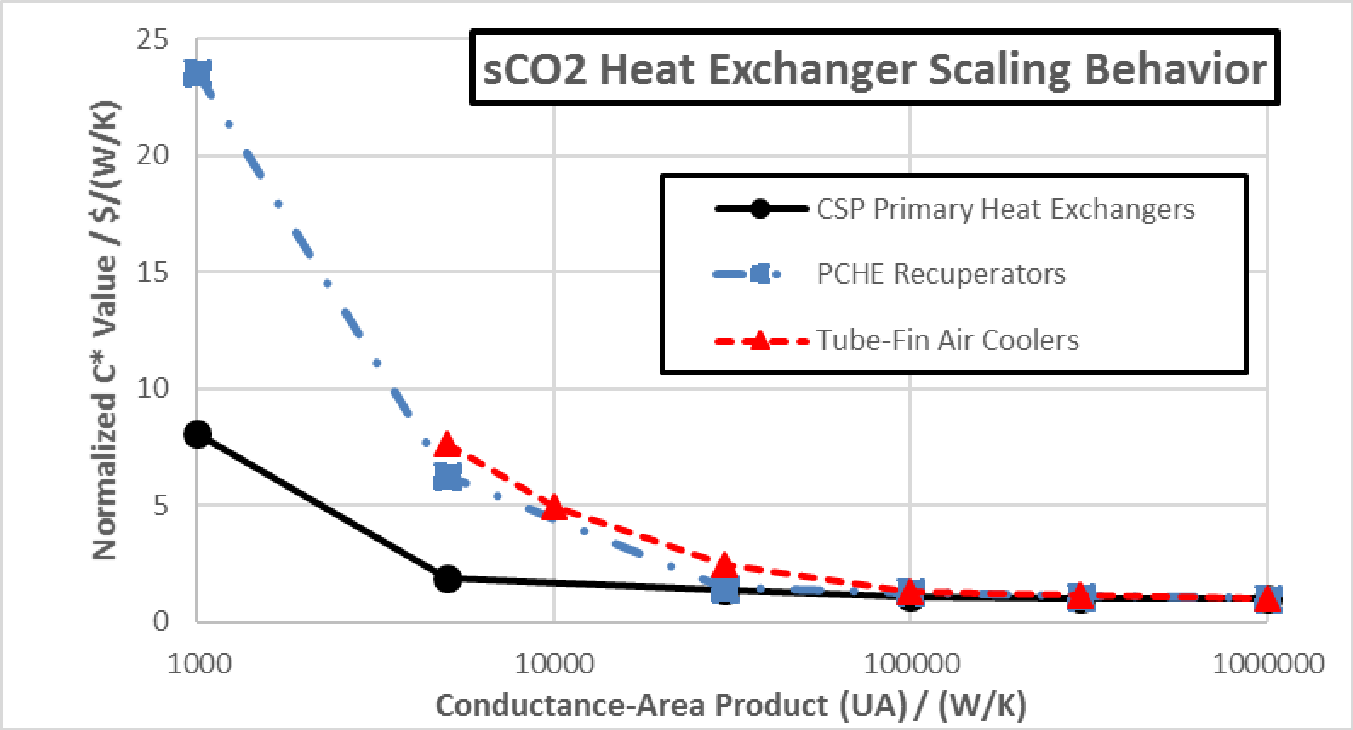
$$\frac{Cost(\dot{q}_2)}{Cost(\dot{q}_1)} = \frac{A_2}{A_1}\frac{U_2\Delta T_{m,2}}{U_1\Delta T_{m,1}}$$

Requires scaling related to heat transfer and thermodynamic variables

$$\frac{Cost(U_2A_2)}{Cost(U_1A_1)} = \frac{\dot{q}_2}{\Delta T_{m,2}}\frac{\Delta T_{m,1}}{\dot{q}_1}$$

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

Turbomachinery Cost Models

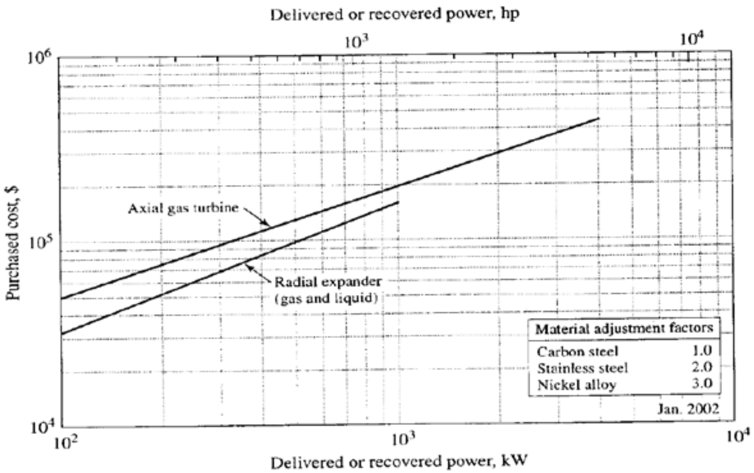


Figure 12-34
Purchased cost of turbines and expanders

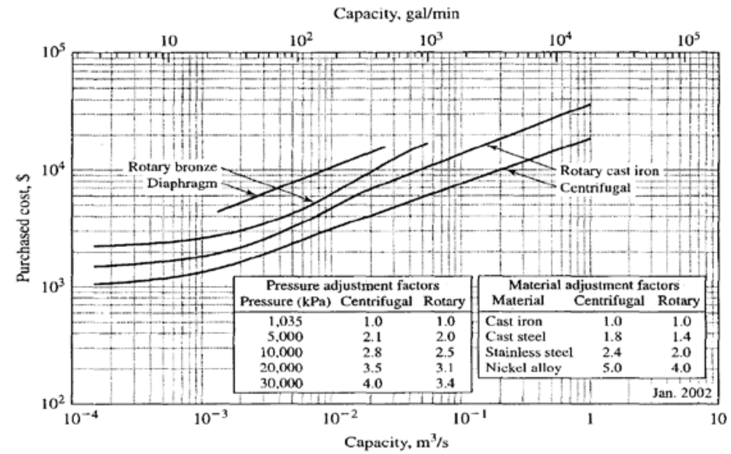


Figure 12-23
Purchased cost of diaphragm, centrifugal, and rotary pumps

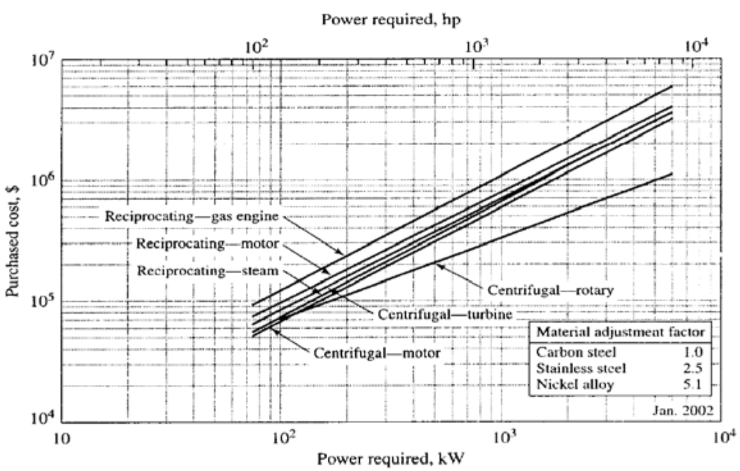


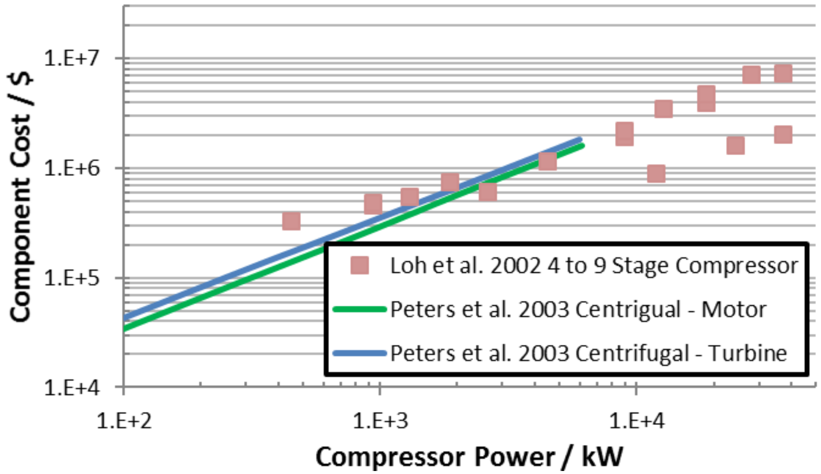
Figure 12-28
Purchased cost of compressors. Price includes drive, gear mounting, baseplate, and normal auxiliary equipment; operating pressure to 7000 kPa (1000 psig).

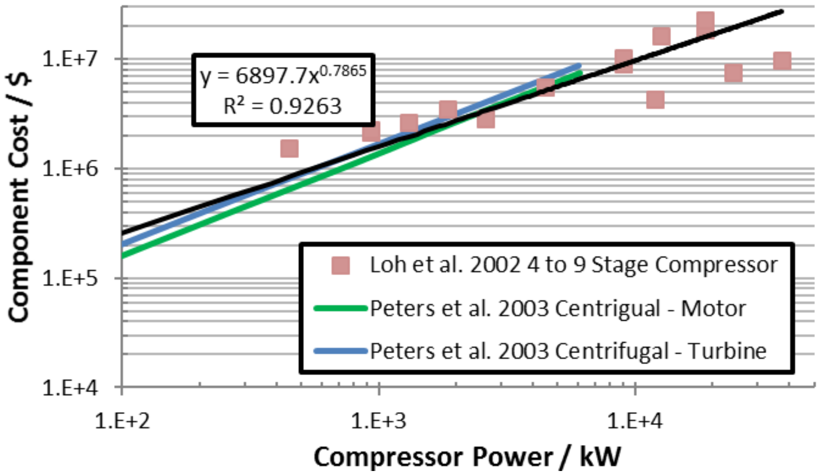
	Power-law Cost Scaling
Motor-Driven Compressor ($)*	$461.91(\dot{W}/kW)^{0.9339}$
Turbine-Driven Compressor ($)*	$643.15(\dot{W}/kW)^{0.9142}$
Radial Expander ($)**	$4001.4(\dot{W}/kW)^{0.6897}$
Axial Gas Turbine ($)**	$9923.7(\dot{W}/kW)^{0.5886}$
Centrifugal Pump ($)***	$124427\left(\dot{V}/\frac{m^3}{s}\right)^{0.3895}$

*Includes factors of 2.5 and 0.2 for stainless steel construction and density ratio of air and CO_2 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.

Compressor Cost Baselining

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

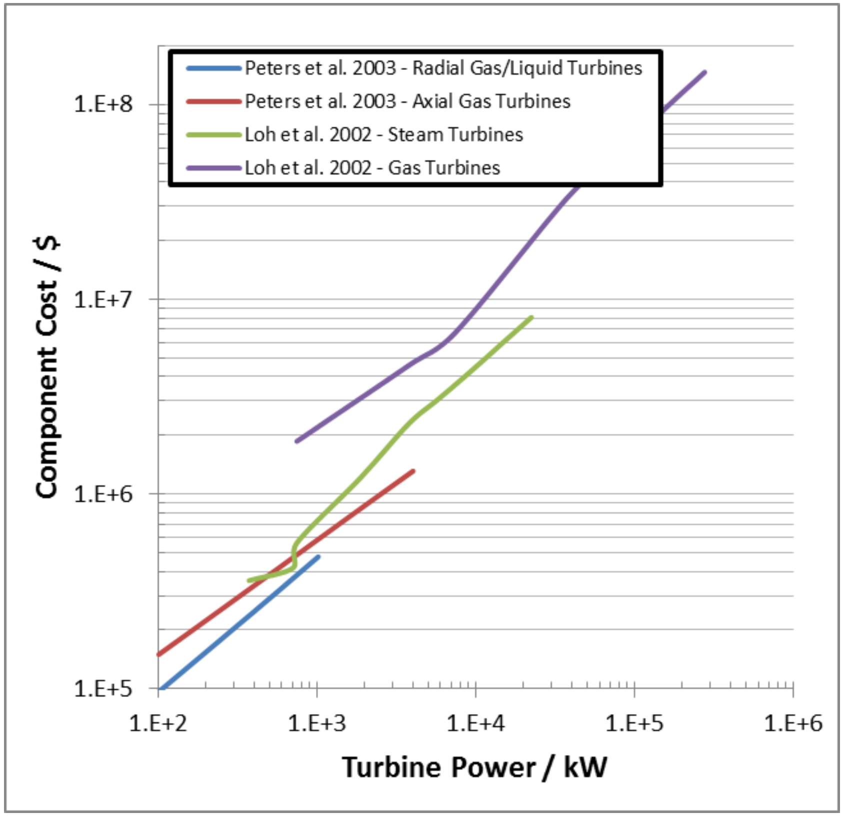


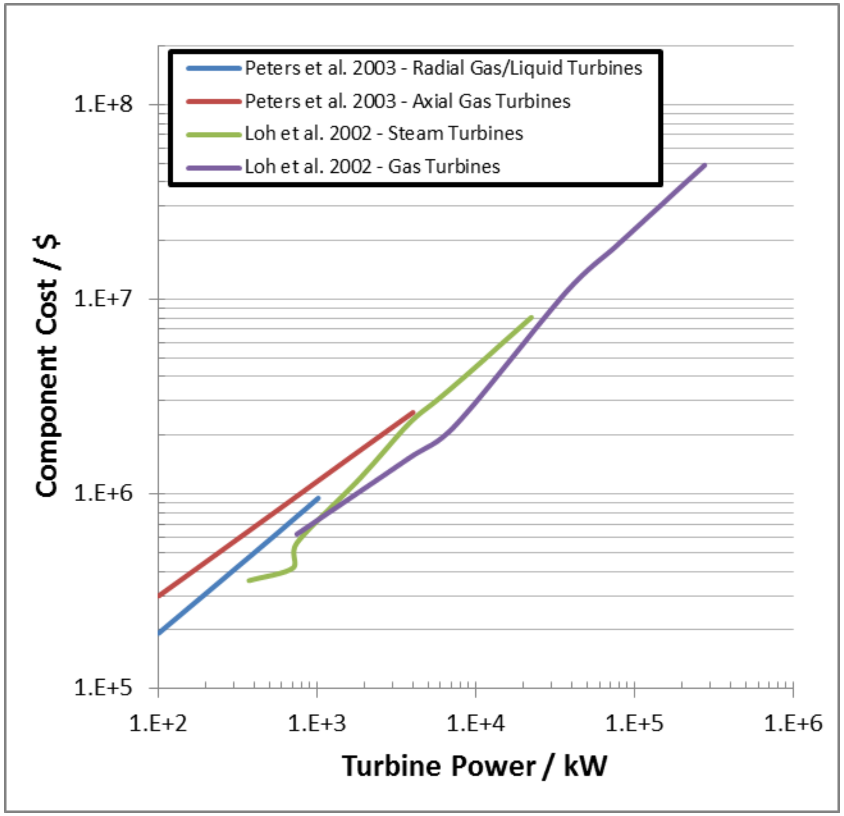


$$Cost/\$ = 6898\left(\dot{W}/kW\right)^{0.7865}$$

Turbine Cost Baselining

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



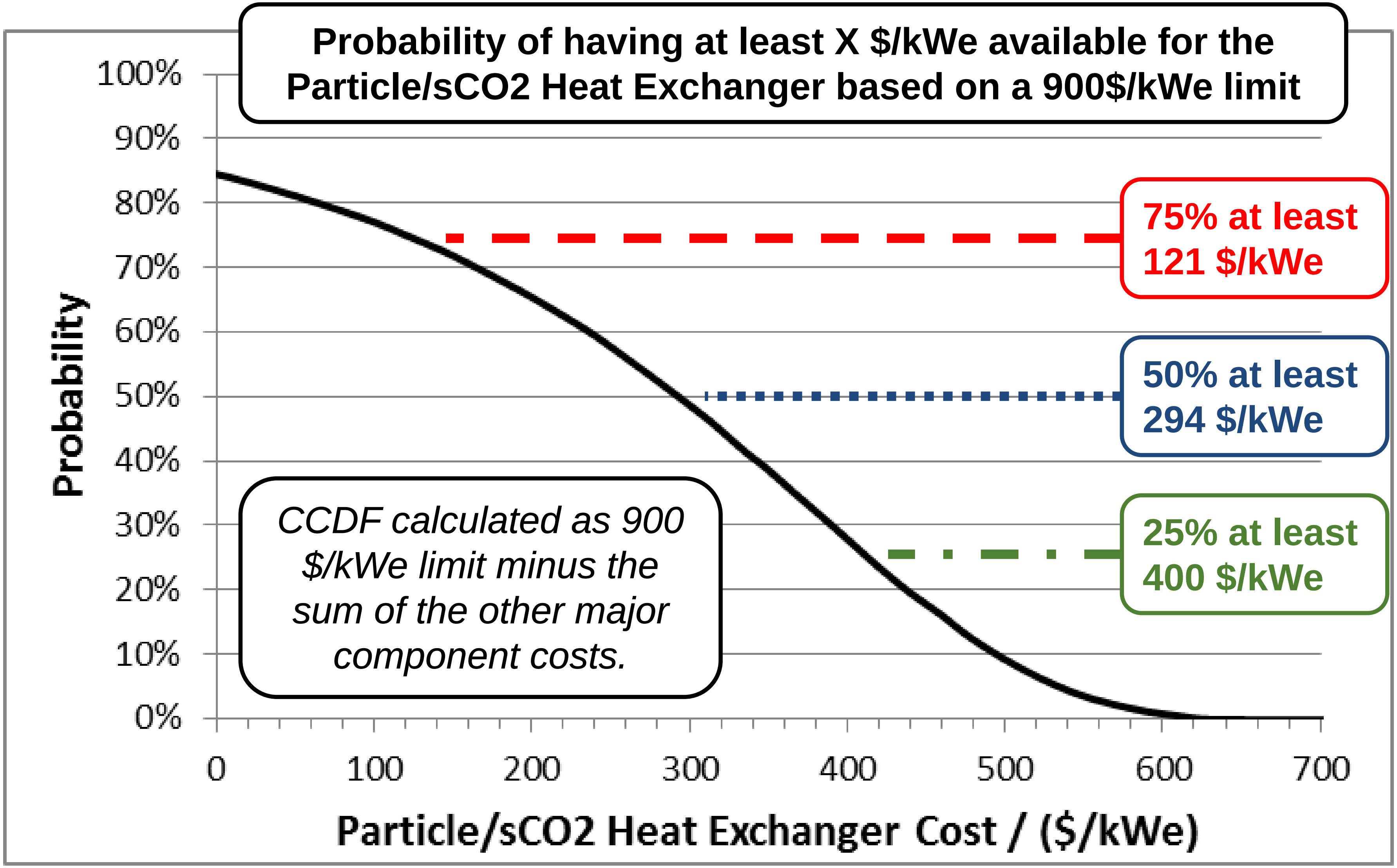


$$Cost/\$ = 7790\left(\dot{W}/kW\right)^{0.6842}$$

Cost Confidence with Minimal Data

- Approaches to cycle cost estimation
  - Use specific literature cost models or vendor estimates
    - ✗ Assigning uncertainty to specific data is somewhat arbitrary
  - Weighted average of available cost data (Ho et al. 2015)
    - ✗ Propagated uncertainty still relies on assigned uncertainty data
  - Bayesian analysis of component cost data (SuNLaMP)
    - ➢ Only assumes the functional form and fit parameter distributions
- Assumption of the hierarchical Bayesian approach
  - Component cost will follow a log-normal distribution
  - Cost vs. size functional form (i.e. power-law, $Cost = \alpha_0 Capacity^{\alpha_1}$)
  - Fitting parameters are normally-distributed
  - Prior precision is described by a gamma distribution
  - See P. R. Garvey, S. A. Book, and R. P. Covert, *Probability methods for cost uncertainty analysis: a systems engineering perspective*. 2016.

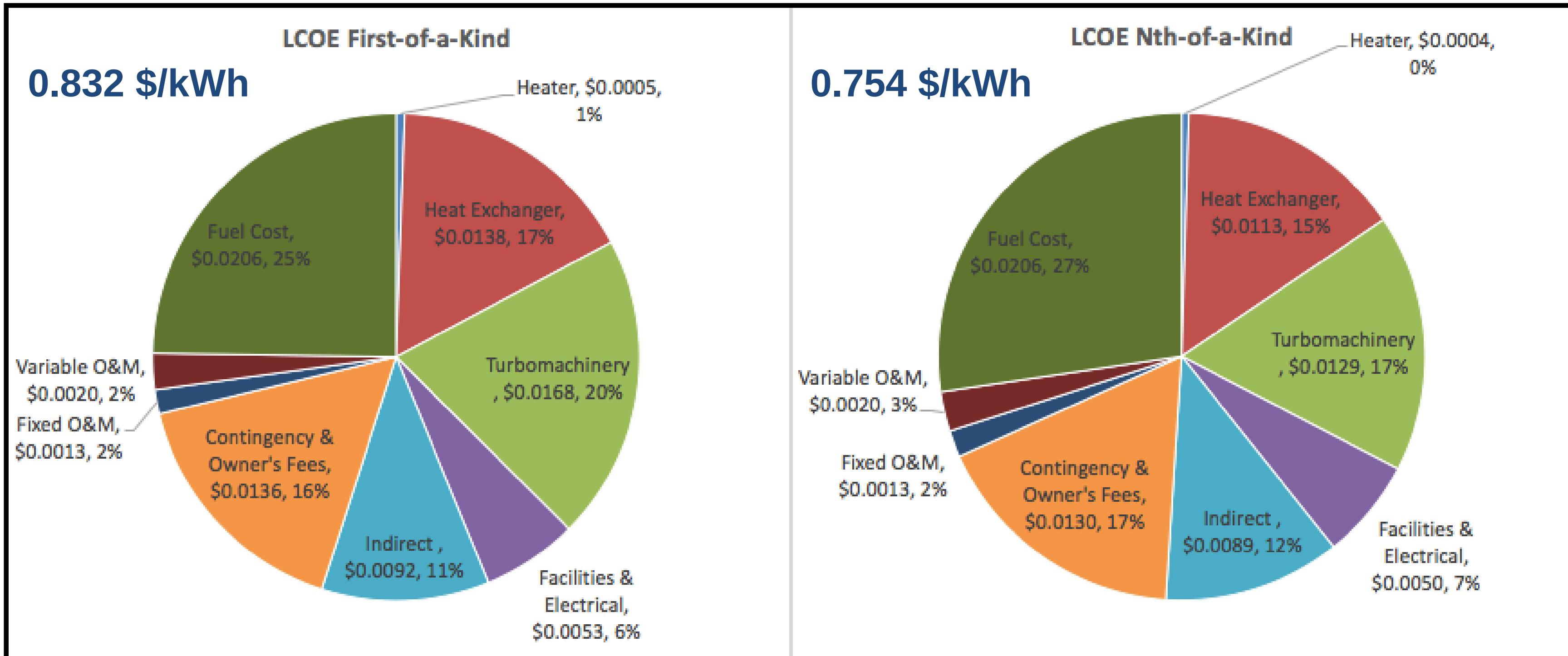
Heat Exchanger Cost Confidence



Brayton Cycle Economic Tool

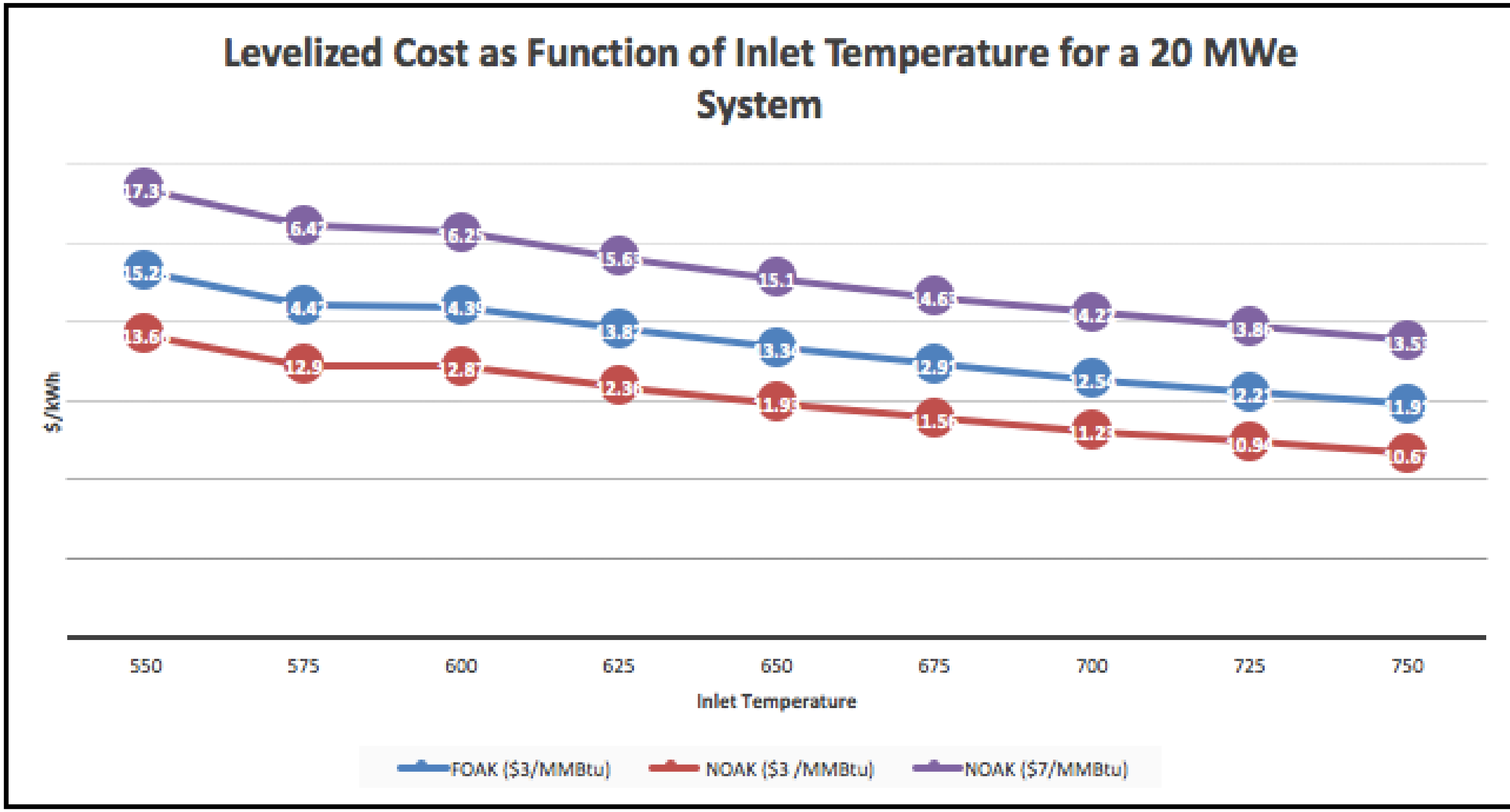
- Recompression closed Brayton cycle (RCBC) Evaluation and Trade Studies tool (RETS)
  - Pasch, J. 2016. The RCBC Evaluation and Trade Studies Tool (RETS). Sandia National Laboratories
- Supercritical CO2 (sCO2) cycle component cost models
  - Carlson, M., B. Middleton, and C. Ho. "Techno-economic comparison of solar-driven SCO2 Brayton Cycles using component cost models baselined with vendor data", PowerEnergy2017-3590, Proceedings of the ASME 2017 Power and Energy Conference, Charlotte, NC.
- Levelized cost of energy methodology
  - Drennen, T. and J. Andruski, 2012. Power Systems Life Cycle Analysis Tool (Power LCAT), SAND2012-0617, May.
- First- / Nth-of-a-kind (FOAK / NOAK) methodology
  - National Energy Technology Laboratory (NETL), 2013. Technology Learning Curve (FOAK to NOAK), DOE/NETL-341/081213, August.
- **Enables exploration of LCOE sensitivities with configuration**

100 MWe Fossil, 700 °C, Dry-cooled



For the 100 MWe facility, the various heat exchangers and turbomachinery account for 15% and 17% of the total costs for the nth-of-a-kind plant, respectively. The non-component costs, ranging from fuel costs, project indirect, owner’s costs, and contingency costs account for the majority of costs.

Higher alloy costs offset by efficiency



As turbine inlet temperature increases, certain individual system components require higher-quality alloys. The results (above) show that the higher costs are offset by the increase in overall system efficiency.