New Energy Recovery Viewpoints & Opportunities: New Paradigm in Defining Optimum Cost Conditions in Thermoelectric Energy Recovery

presented at

Piezoelectric Materials and Applications / 12th Annual Energy Harvesting Workshop / 1st Annual Energy Harvesting Society Meeting

Falls Church, VA

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AGENDA

Motivations

System Cost Modeling & Integration with System-Level Analysis

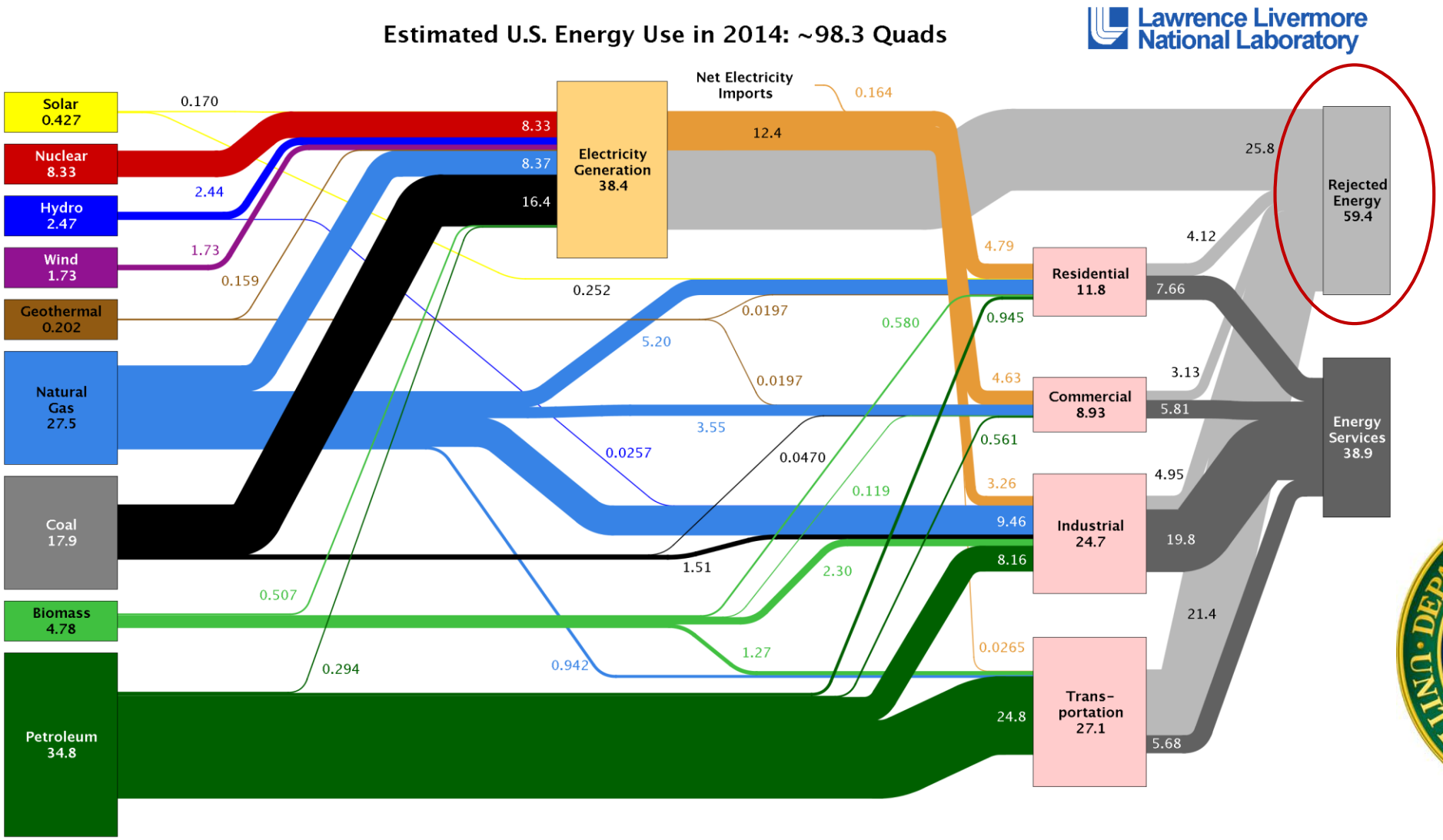
Characteristics of Maximizing Specific Power & Cost Minimization When HEX Rigorously Included

Effects on Optimum Fill Factor & Cost per Power

Case Study & Conclusions

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

United States Energy Flow



Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% [illegible] industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

- Waste Heat To Be "Harvested"

  59.4 Quads

- Up ~ 5 Quads From 2009

Terrestrial Waste Energy Recovery

- Thermoelectric Systems Considered a Prime Energy Recovery Technology Candidate / Option in Many Terrestrial Applications
- Terrestrial Energy Recovery Goals are Often Tied to:
  - Energy Savings
  - Environmental Savings and Impacts
  - Maximizing Conversion Efficiency
  - Maximum Power Output
- However, JPL is Currently Working on System Designs Where the Critical Design Metric is Maximizing Specific Power (W/kg)
  - Knowing Its Relationship to Maximum Power or Efficiency Points is Key
  - T_{exh} = 823 K; T_{amb} = 273 K
- In Additional, Key Barriers Are Not So Much Performance Anymore as System-Level Cost (As Discussed in 2015 ICT, Dresden, Germany)

Cost Modeling and Integrating Cost Modeling With System-Level Performance Modeling is Critical

Must Develop Technologies / Methods to Recover Energy Economically

- Leverage Cost Modeling Work of LeBlanc et al. [1] and Yee et al. [2]
- Combine with System-Level Analysis Work of Hendricks et al. [3]
- Include the Effects of Real-World Heat Exchangers in More Rigorous Cost Analysis Methodology
  - Cost & Performance (Heat Exchanger UA_h)
  - Heat Exchanger Interfacial Heat Flux
  - Rigorously Account for Different Operational Areas
- Hendricks et al. [3] Analysis Modified to Add in Fill Factor, F, and Heat Exchanger Area, A_{HEX}, into System Analysis Techniques
- Fill Factor and Heat Exchanger Area Are No Long "Arbitrarily Selected" Design Parameters – Part of Design Optimization Process

$$F = \frac{A_{TE}}{A_{HEX}}$$

$$\left(\frac{V}{N}\right)^* = f_v(T_h, T_c)$$

$$\left(I \cdot \frac{L}{F \cdot A_{HEX}}\right)^* = f_I(T_h, T_c)$$

$$\eta_{TE}^* = \frac{P}{Q_{h,TE}} = f_{eff}(T_h, T_c)$$

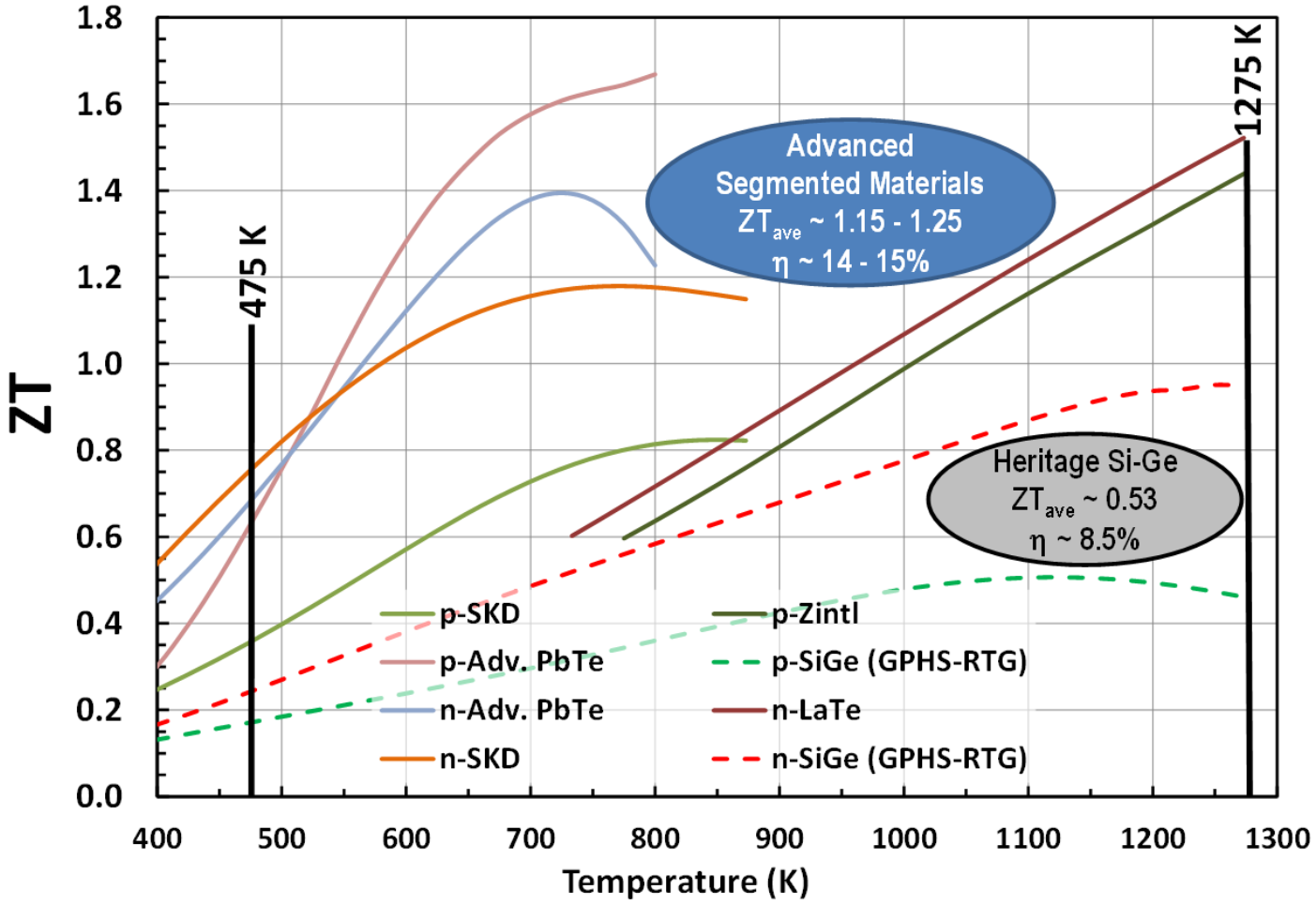
$$\left(\frac{Q_{h,TE} \cdot L}{N \cdot F \cdot A_{HEX}}\right)^* = f_{qh}(T_h, T_c)$$

$$q''_{h,HEX} = F \cdot q''_{h,TE} = \frac{Q_{h,TE} + Q_{loss}}{A_{HEX}} = f_Q(T_{exh}, T_h, T_c)$$

1. S. LeBlanc, S. K. Yee, M. L. Scullin, C. Dames and K. E. Goodson, *Renewable and Sustainable Energy Reviews*, **32**, 313-327, 2014.
2. S. K. Yee, S. LeBlanc, K. E. Goodson and C. Dames, *Energy & Environmental Science*, **6**, 2561-2571, 2013.
3. Hendricks, T.J. and Crane, D. "Thermoelectric Energy Recovery Systems: Thermal, Thermoelectric and Structural Considerations", **CRC Press Handbook of Thermoelectrics & Its Energy Harvesting: Modules, Systems, and Applications in Energy Harvesting**, Book 2, Section 3, Chapter 22, Taylor and Francis Group, Boca Raton, FL, 2012.

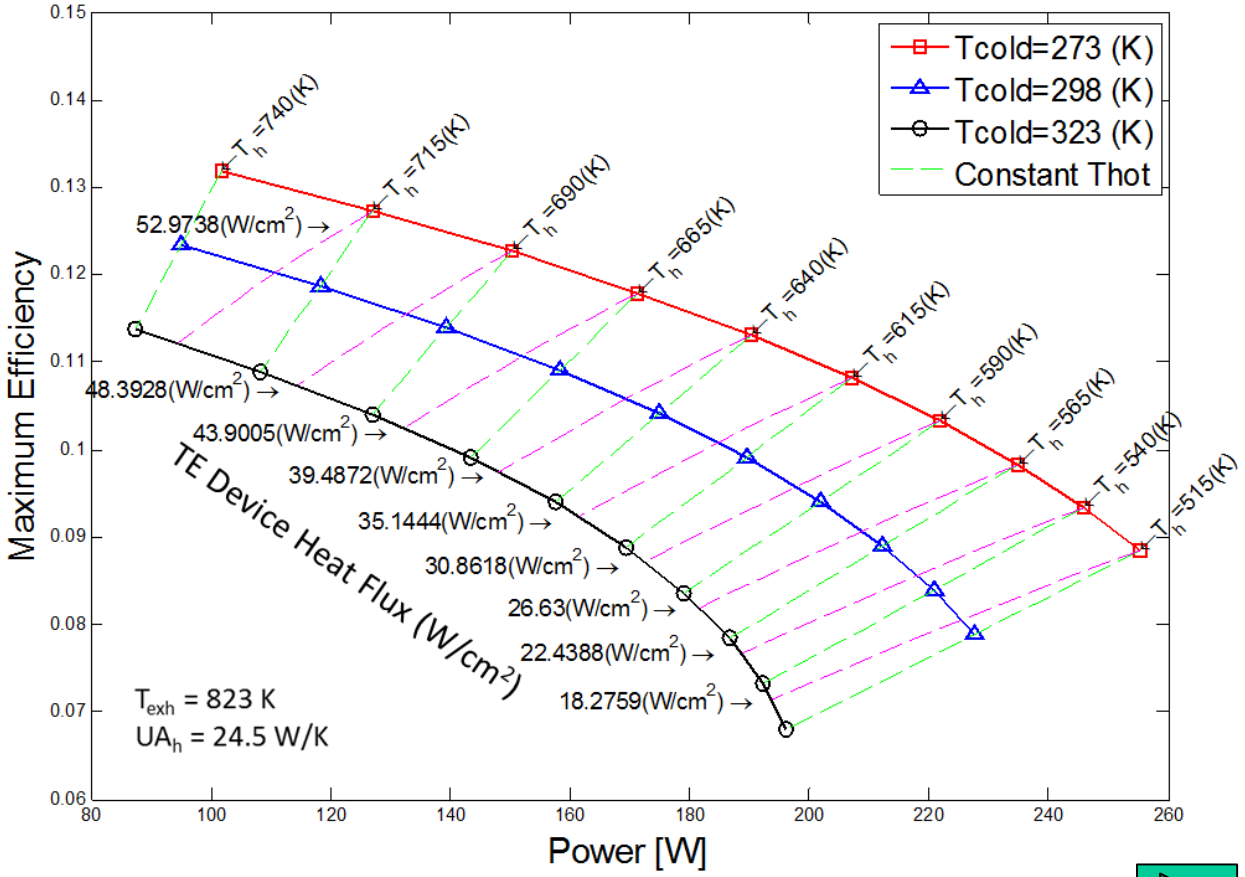
TE Materials Investigated

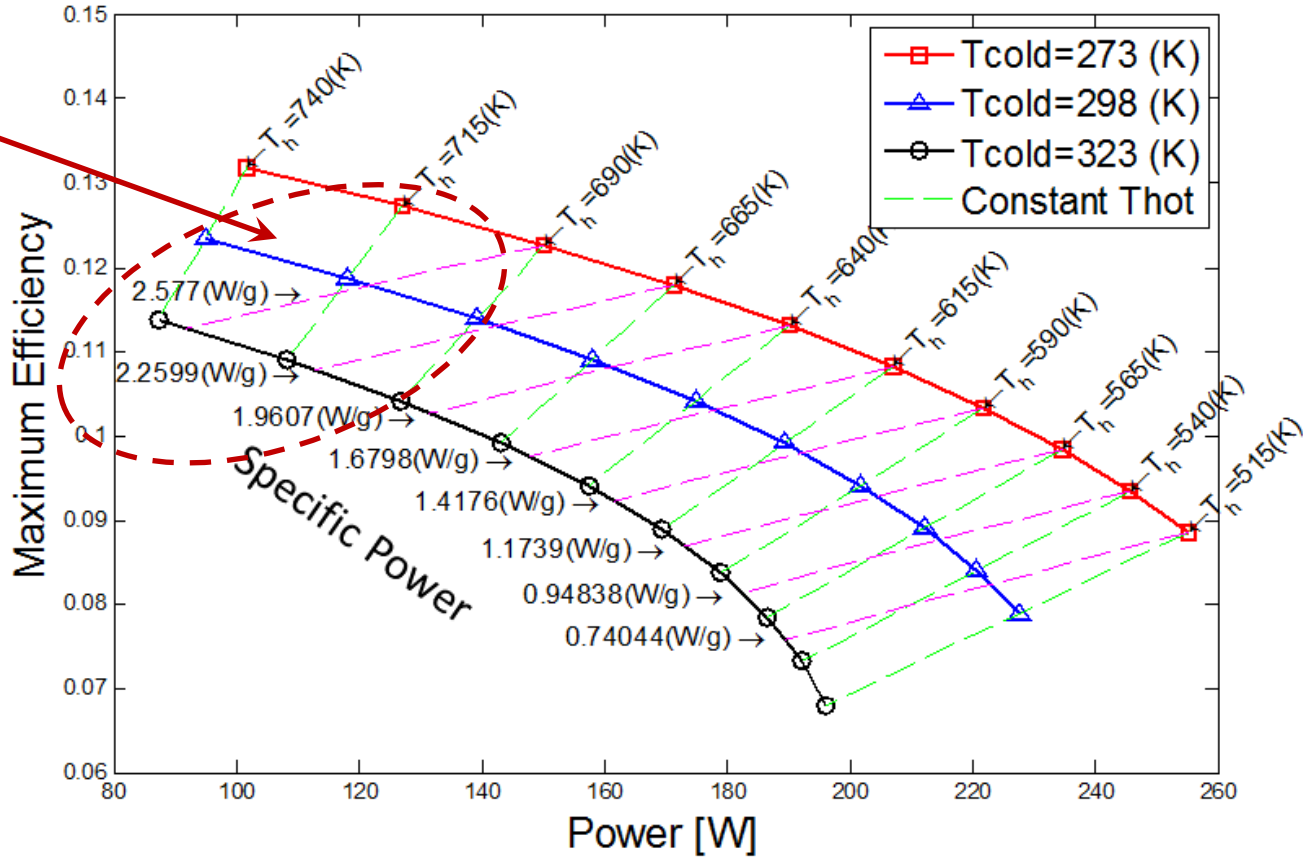
- Focused on JPL Skutterudites Shown Here In This Initial Work
- Currently Developing and Commercializing These Materials
- We Used JPL Raw Cost Data in This Work



TE System Design Regime Results
T_{exh} = 823 K, T_{cold} = 273 – 323 K

- High TE Device Specific Power Regime Identified
  - Coincides with High Efficiency Regimes
  - But Coincides With Low Power Regions





- Also Critical to Identify and Map the Constant TE Device Heat Flux Lines (Regions)
- High TE Device Heat Flux Regions Correspond with High Specific Power Regions
- Design Challenge Associated with High S.P.

Optimum Cost Fill Factor Analysis

- Yee et al.* Originally Looked at this in 2013
- Optimum Cost Fill Factor of Yee et al.* Is Different Type of Analysis
  - Did Not Account for Heat Exchanger Heat Flux Conditions
  - Thermal Matching of the Hot-Side and Cold-Side Heat Exchangers (Very Bad Assumption)
  - $A_u = A_{HEX}$ (Very Bad Assumption)
  - $K_H = UA_{HEX}$ (Very Bad Assumption)
- TE Module Optimum Fill Factor, F_{opt} , Impacted by:
  - Heat Exchanger Interfacial Heat Flux, $q''_{h,HEX}$
  - Heat Exchanger Effectiveness, UA_h
  - Parasitic Thermal Losses, σ
- Latest Results Indicate This Relation* is Not Really Accurate and Was Only Intended to Identify Key Dependences

$$F_{opt} \approx \frac{1}{2} \cdot \sqrt{\frac{C_{HEX,H} + C_{HEX,C}}{C''' \cdot \kappa}} \cdot (U)$$

*Yee, S. K., LeBlanc, S., Goodson, K. E., and Dames, C. *Energy & Environmental Science*, 2013, **6**, 2561-2571.

Cost Modeling Approach

- Costs-per-Watt Relationships Become More Complex When Heat Exchanger Performance, UA_h, Heat Exchanger Heat Flux, $q''_{h,HEX}$, and Different System Areas Accounted For
  - A_{TE}, A_{HEX} , and A_u Are Considered in Rigorous Detail; A_{HEX} and A_u Can Be Very Different in Magnitude
- Yee et al. [1] and LeBlanc et al. [2] Have Shown that Heat Exchanger Costs Can Be Characterized by $C_{HEX,H}$ & $C_{HEX,C}$
  - \$/(W/K) – Basically Cost per UA of the Heat Exchangers
  - Here We Include the Hot-Side and Cold-Side Heat Exchangers Individually
- Started Over With Fundamental Cost and G Relationships of Yee et al.
  - Did NOT Invoke Simplifying Assumptions of Yee et al.

[1] Yee, S. K., LeBlanc, S., Goodson, K. E., and Dames, C. *Energy & Environmental Science*, 2013, **6**, 2561-2571.
[2] LeBlanc, S., Yee, S. K., Scullin, M. L., Dames, C., and Goodson, K. E., *Renewable and Sustainable Energy Reviews, 2014*, **32**, 313-327.

$$C_{TEG}[\$] = \left(C''' \cdot L + C''\right) \cdot F \cdot A_{HEX} + \left(C_{HEX,h} \cdot K_H + C_{HEX,c} \cdot K_C\right)$$

$$G[\$/W] = \frac{\text{Total TEG Costs}}{P} = \frac{\text{Total TEG Cost}}{\eta_{TE} \cdot Q_H} = \frac{\text{Total TEG Cost}}{\eta_{TE} \cdot (1-\sigma) Q}$$

$$G = \frac{4 \cdot (m+1)^2}{S_{pn}^{\ 2} \cdot \sigma \cdot m \cdot (T_{exh} - T_{amb})^2} \cdot \left[\frac{1.1 \cdot \kappa_{TE} \cdot A_{HEX} \cdot F}{K_H} + L\right]^2 \cdot \left[C''' + \frac{C''}{L} + \frac{C_{HEX} \cdot UA_u}{A_{HEX} \cdot L \cdot F}\right]$$

K_C / K_H > 10 to 20 Incorporated this Added Relationship for Maximum Power**

T. J. Hendricks, "Integrated Thermoelectric–Thermal System Resistance Optimization to Maximize Power Output in Thermoelectric Energy Recovery Systems, Mater. Res. Soc. Symp. Proceedings, **1642, Materials Research Society, mrsf13-1642-bb02-04 doi:10.1557/opl.2014.443, 2014.

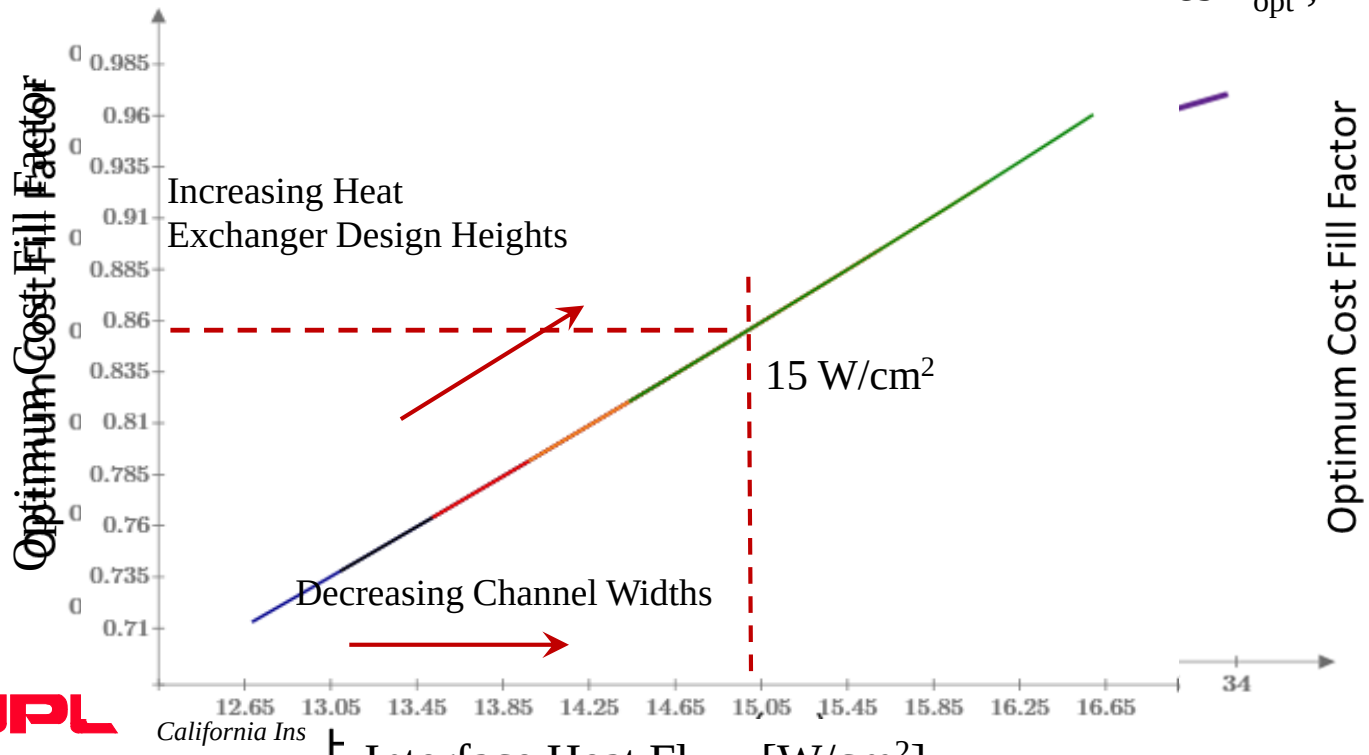
Critical F_{opt} Sensitivities

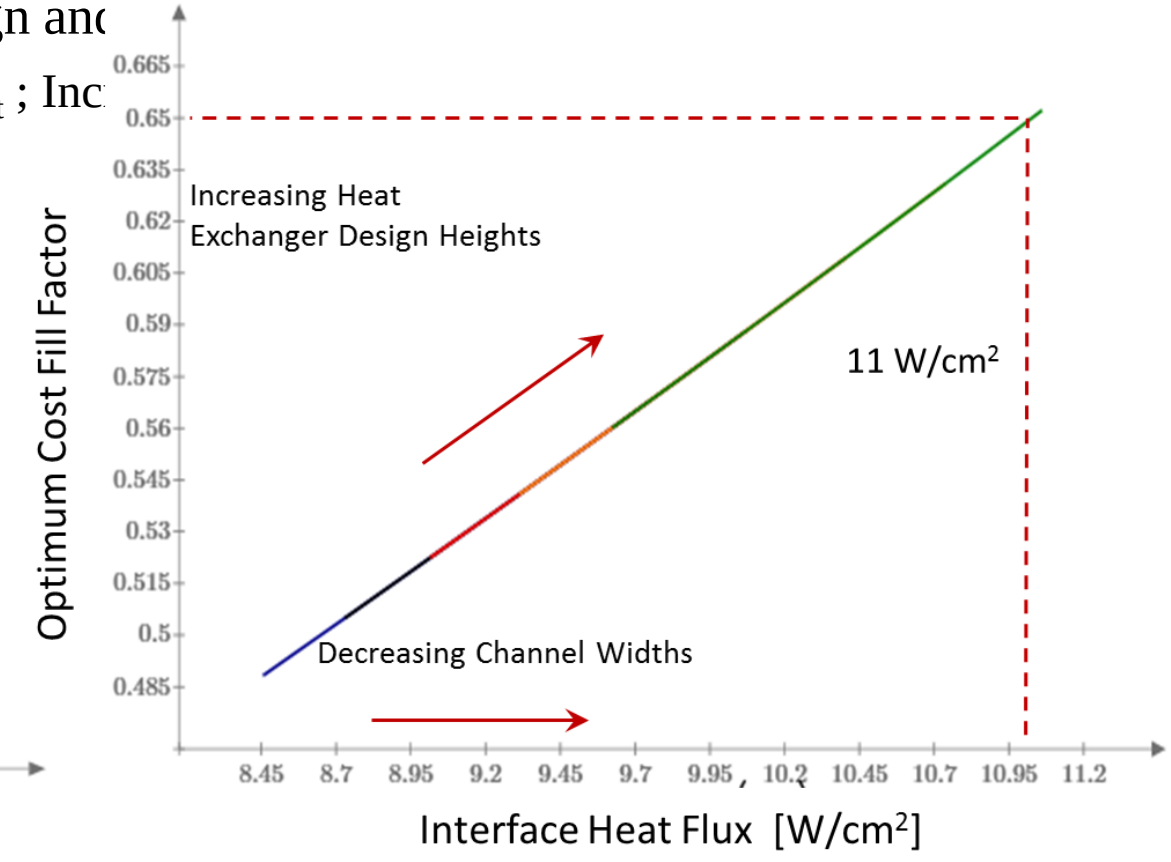
- ∂G/∂F=0 Condition Creates a New, More Accurate, but More Complicated Relationship

$$F_{opt} = \frac{-\left(\frac{\left(C_{HEX,H}+C_{HEX,C}\right)\cdot UA_u}{L_{TE}}\right)\cdot\left(\frac{1.1\cdot\kappa_{TE}}{K_H}\right)+\sqrt{\left(\frac{\left(C_{HEX,H}+C_{HEX,C}\right)\cdot UA_u}{L_{TE}}\right)^2\cdot\left(\frac{1.1\cdot\kappa_{TE}}{K_H}\right)^2+8.8\cdot\left(C'''+C''/L_{TE}\right)\cdot\left(\frac{\kappa_{TE}}{K_H}\right)\left(C_{HEX,H}+C_{HEX,C}\right)\cdot UA_u}}{4.4\cdot\left(C'''+C''/L_{TE}\right)\cdot\left(\frac{\kappa_{TE}\cdot A_{HEX}}{K_H}\right)}$$

- More Accurately Predicts the Optimum Cost Fill Factors Seen Above and Heat Flux Dependency
- Demonstrates Dependencies on Heat Exchanger Design anc

es F_{opt} ; Inc





Optimum Cost Function

- G_{opt} (F_{opt}, κ_{TE}, K_H, L_{TE}, A_{HEX}, Cost Parameters) is a complex function of 5 design parameter groups:
  - [κ_{TE} L_{TE} / K_H] - Non-dimensional – Tied to TE Device/Heat Exchanger interfacial design parameters
  - [F_{opt} A_{HEX} / L_{TE}^2] – Non – Dimensional – TE device design parameters
  - [C_{HEX} UA_U] / [C''' L_{TE}^3 + C'' L_{TE}^2] - Non-dimensional - Ratio of heat exchanger costs to TE device costs
  - [κ_{TE} A_{HEX} / (K_H L_{TE})] – Non-dimensional - Tied directly to interfacial heat flux
  - $1/[(S\Delta T)^2 \cdot \sigma \cdot L_{TE}]$ – Power factor effect
- At least two separate and distinct design areas involved (A_U & A_{HEX}) - Must treat them separately as they are NOT even nearly equal
- G_{opt} is a function of the TE/heat exchanger interfacial heat flux and UA_U – One cannot escape this fact
- Relationship below shows the comprehensive relationship that ties costs to heat exchanger design parameters

$$\frac{G_{opt}\left(\frac{\$}{W}\right)\cdot(S\cdot\Delta T)^2\cdot\sigma\cdot L_{TE}\cdot m}{4\cdot\left(C'''\cdot L_{TE}^3+C''\cdot L_{TE}^2\right)\cdot(m+1)^2}=\left(\frac{1.1\cdot\kappa_{TE}\cdot A_{HEX}\cdot F_{opt}}{K_H\cdot L_{TE}}+1\right)^2\cdot\left[1+\left(\frac{C_{HEX}\cdot UA_u}{C'''\cdot L_{TE}^3+C''\cdot L_{TE}^2}\right)\cdot\left(\frac{L_{TE}^2}{A_{HEX}\cdot F_{opt}}\right)\right]$$

Coupled DIRECTLY to Interfacial Heat Flux

Note: $\Delta T = T_{exhaust} - T_{ambient}$

Cost Critical Relationships

- Two Critical Cost-Determining Factors:

$$\frac{1.1 \cdot \kappa_{TE} \cdot A_{HEX} \cdot F_{opt}}{K_H \cdot L_{TE}} < 0.05 \qquad \left(\frac{C_{HEX} \cdot UA_u}{C''' \cdot L_{TE}^3 + C'' \cdot L_{TE}^2}\right) \cdot \left(\frac{L_{TE}^2}{A_{HEX} \cdot F_{opt}}\right) < 0.05$$

- Which we generally want to minimize (At least we would like to)
- First criteria generally states that we want increased heat fluxes

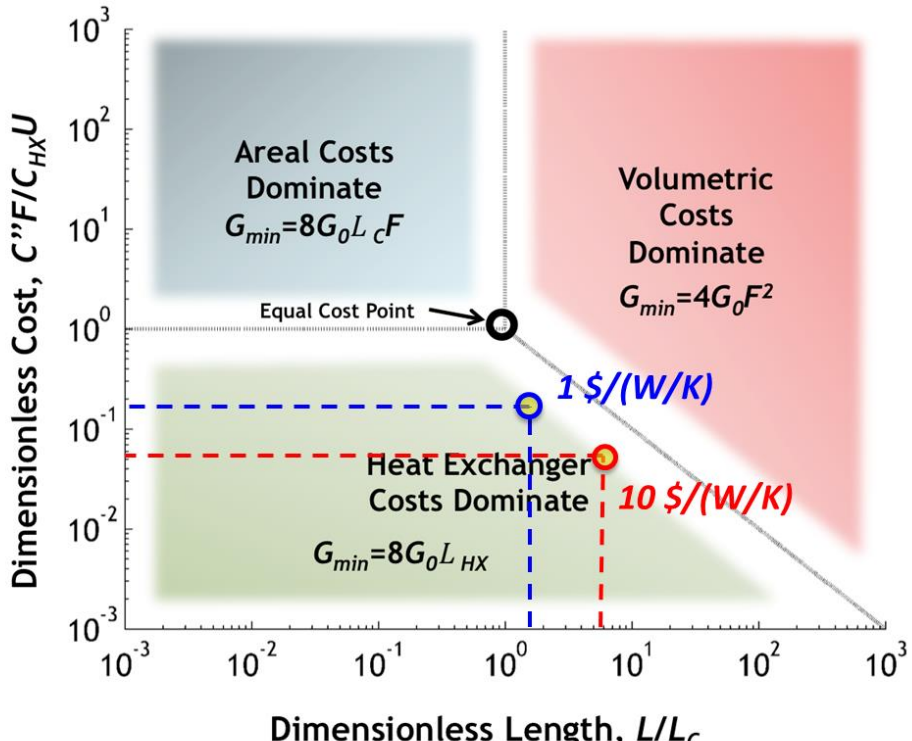
$$\frac{22 \cdot \kappa_{TE} \cdot (T_{exh} - T_{hot}) \cdot F_{opt}}{L_{TE}} < q''_{h,HEX}$$

- But this actually may create a competition/conflict with interfacial energy equation, so there is likely a limit here
  - Goal would be achieve as high a heat flux as possible consistent with interfacial energy equation
- Second criteria generally states that we want low-cost heat exchange systems and defines the heat exchanger dominated regime

TE & Heat Exchanger Costs

	C''' ($/m^3)	C'' ($/m^2)	HEX Costs
Case 1	15 x 8.657x10^4	15 x 168.3	$3/(W/K)
Case 2	10 x 8.657x10^4	10 x 168.3	$2/(W/K)
Case 3	5 x 8.657x10^4	5 x 168.3	$2/(W/K)
Case 4	8.657x10^4	168.3	$1/(W/K)

- Considered 4 TE / Heat Exchanger Cost Conditions In the Cost Domain Map Identified by Yee et al.
  - $1/(W/K) - Aggressive Condition That May Require R&D Investment – Some Believe They Can Get this Now
- The $1-2/(W/K) Condition Still Does Not Escape the Heat Exchanger Cost-Dominated Regime

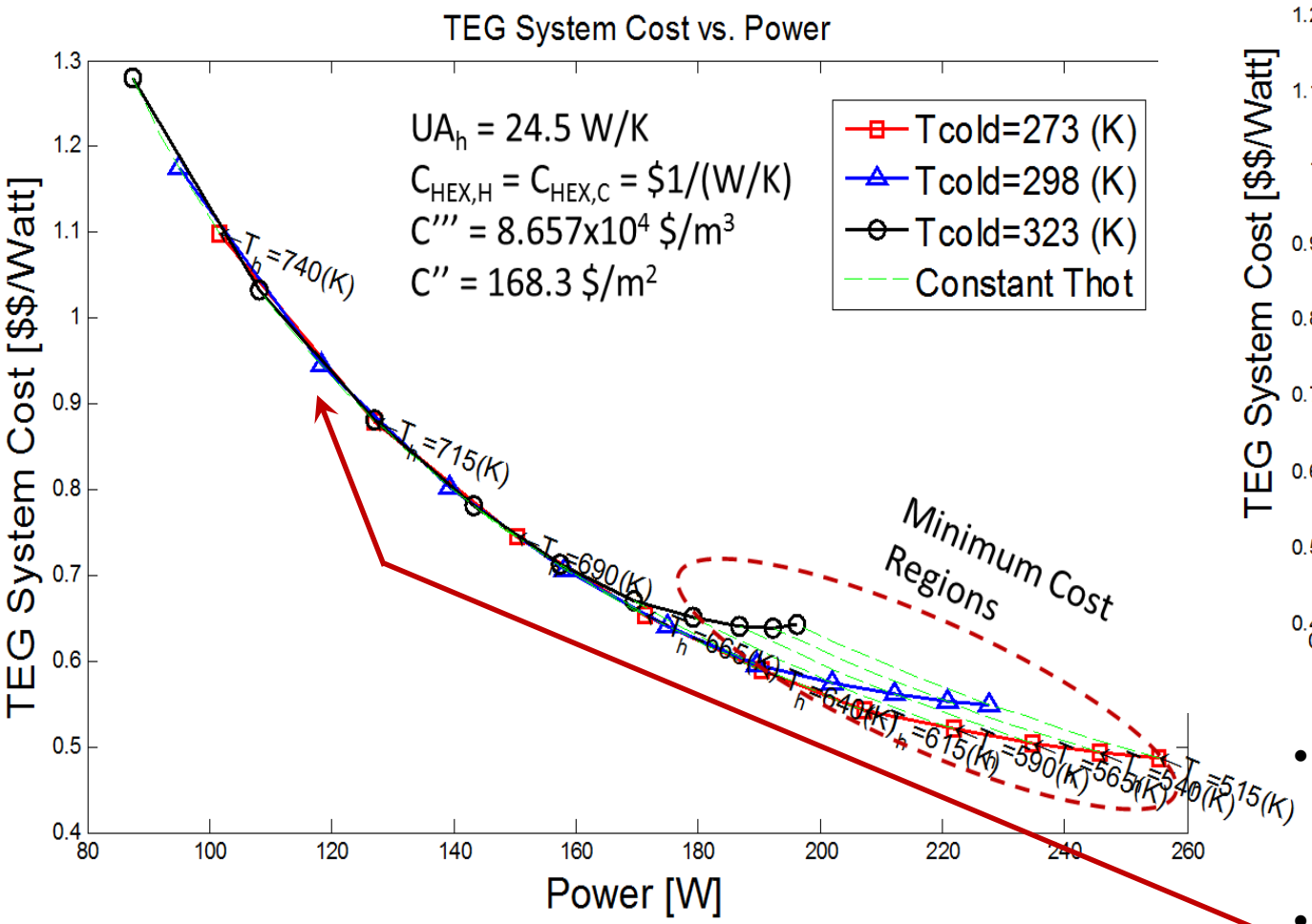


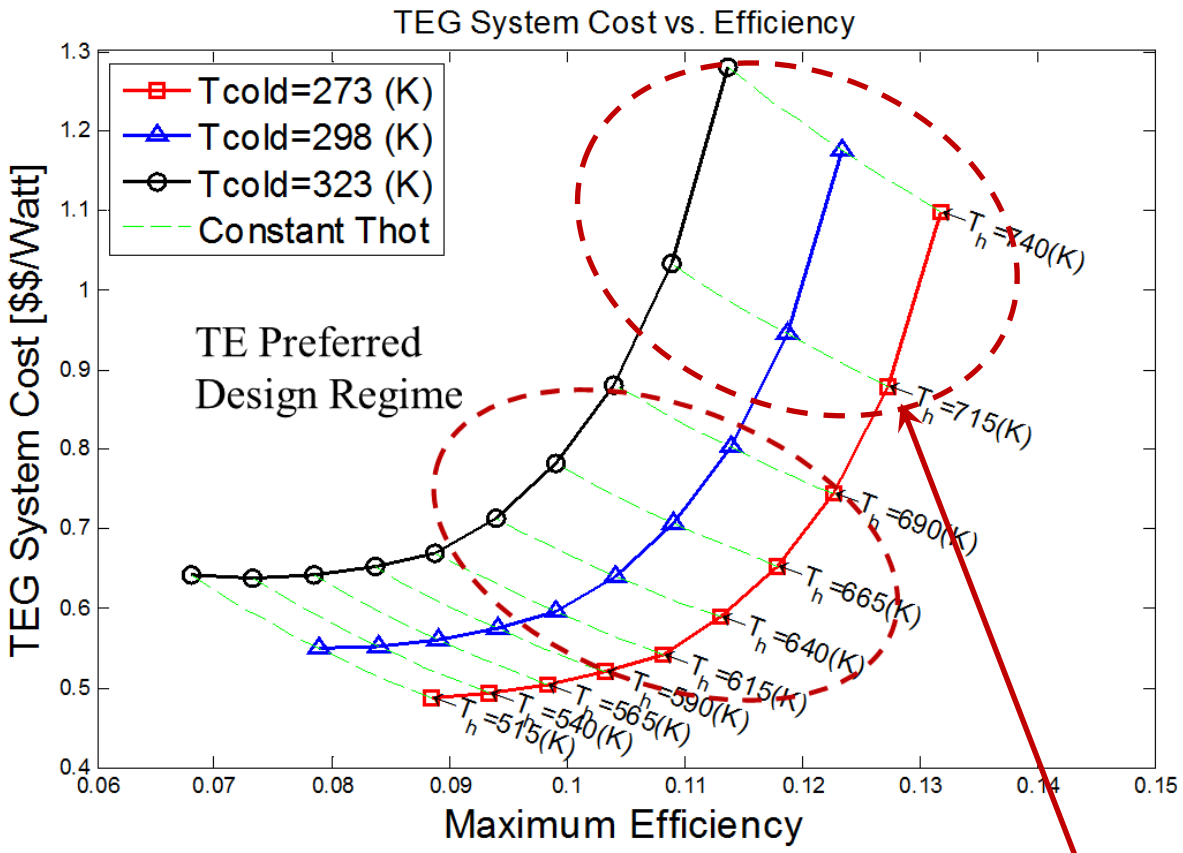
Heat Exchangers Can Dominate The Costs, Even at Low Cost Levels and It is Extremely Difficult to Escape this Regime

Hendricks, T.J., Yee, S., LeBlanc, S., "Cost Scaling of a Real-World Exhaust Waste Heat Recovery Thermoelectric Generator: A Deeper Dive," *Journal of Electronic Materials*, **45**, Issue 3, 1751-1761, DOI 10.1007/s11664-015-4201-y, Springer, New York, 2015.

TE System Design Results
T_{exh} = 823 K, Case 4

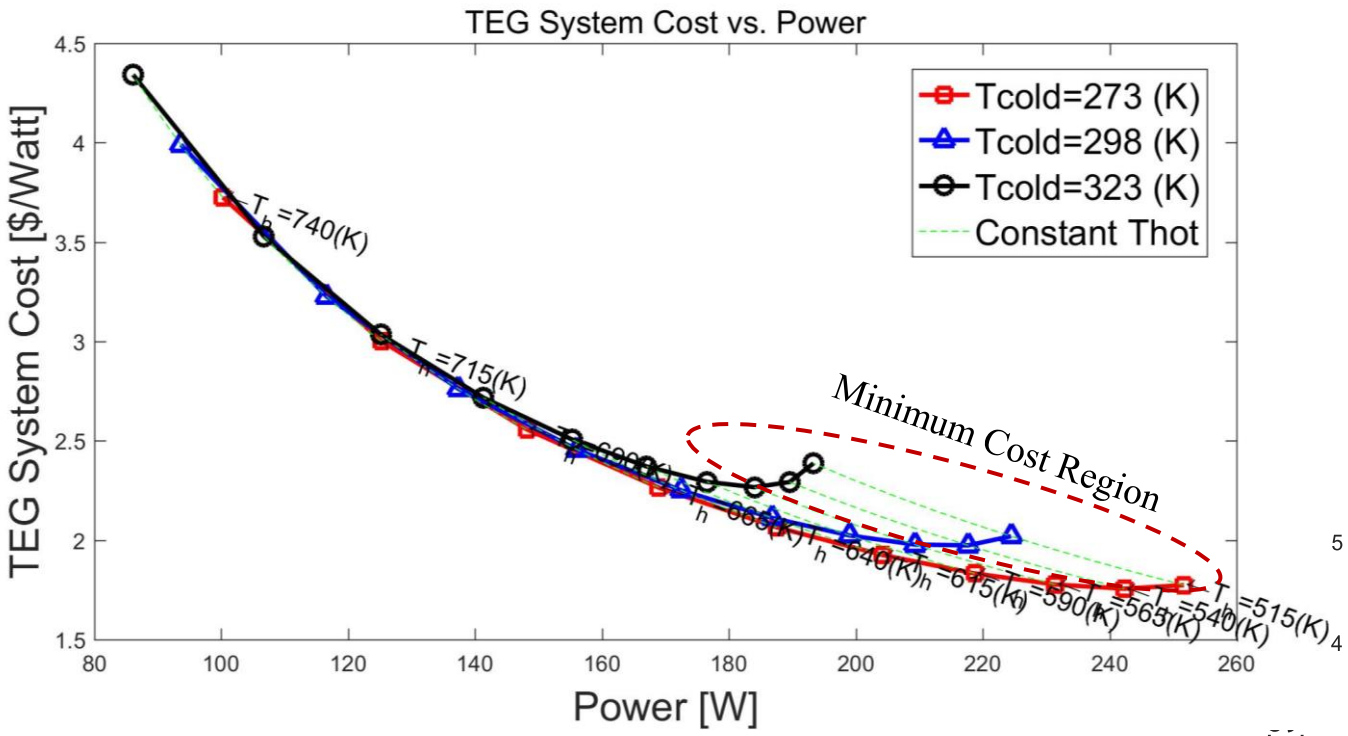
- System Cost is Our Dilemma at the Moment
- But We Now Have the Tools to Work Out of This



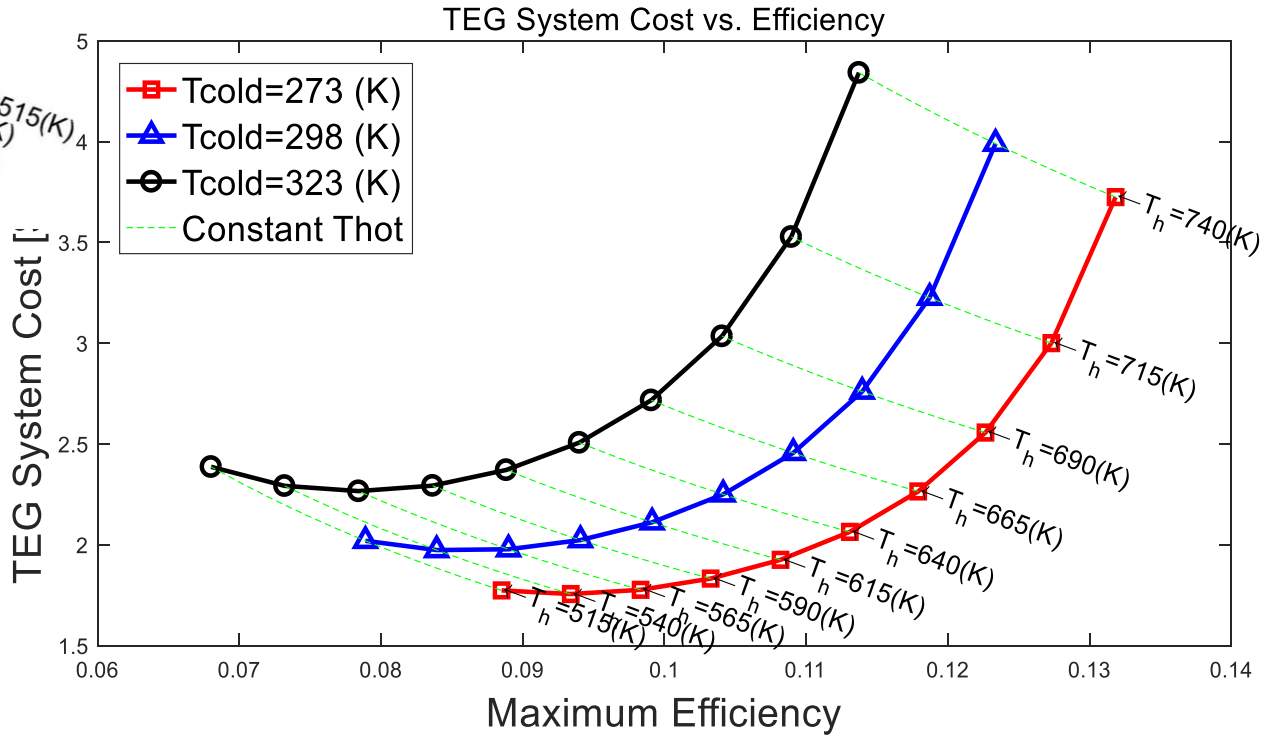


- Dramatically lower TE material and manufacturing costs and sharply lower HEX costs – Cost minimums start to re-appear; System costs quite low
- Higher Cost per Watt Regions Associated with High S.P. Regimes – Appears Penalty Can Small

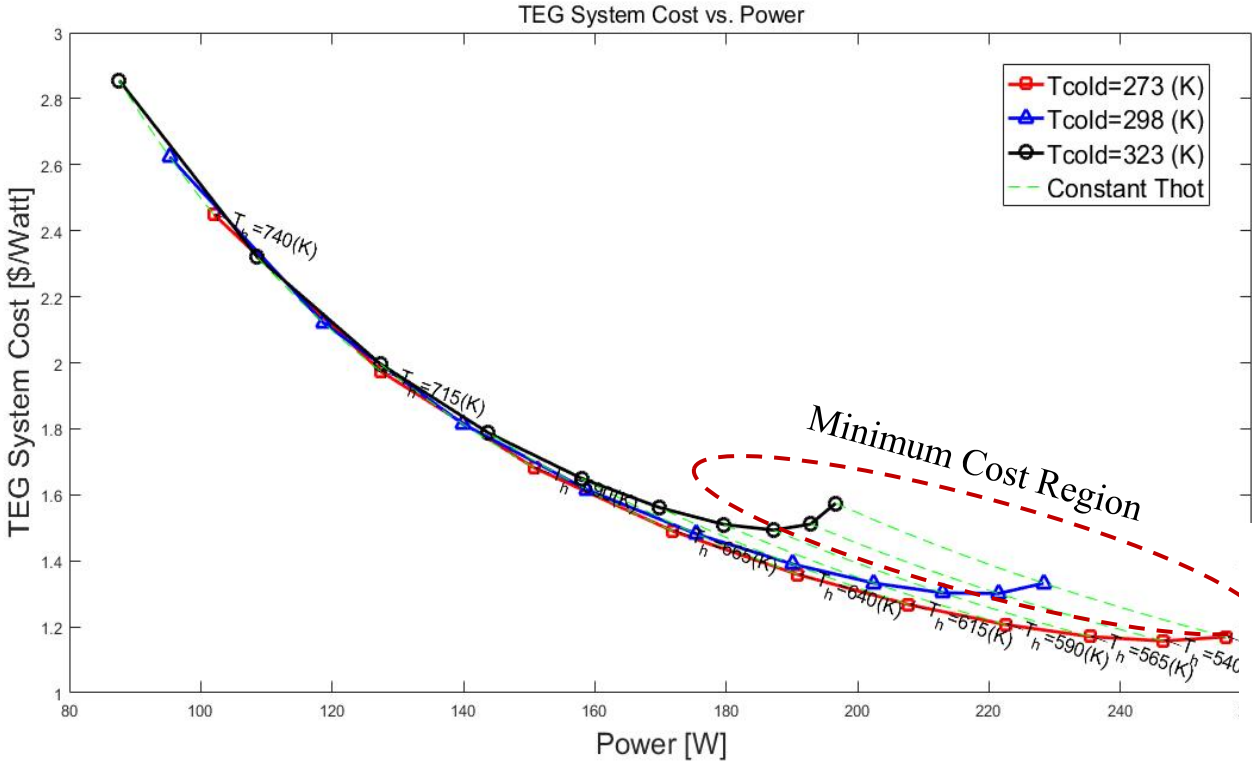
Cost Results – T_{exh} = 823 K, Case 1



- Higher TE material and manufacturing costs drive this away from heat exchanger dominated conditions
- Clearly demonstrated by cost minimum deviating from 1/P relationship – True cost minimum created
- Cost minimum strongly dependent on [T_c / T_h]



Cost Results – T_{exh} = 823 K, Case 2



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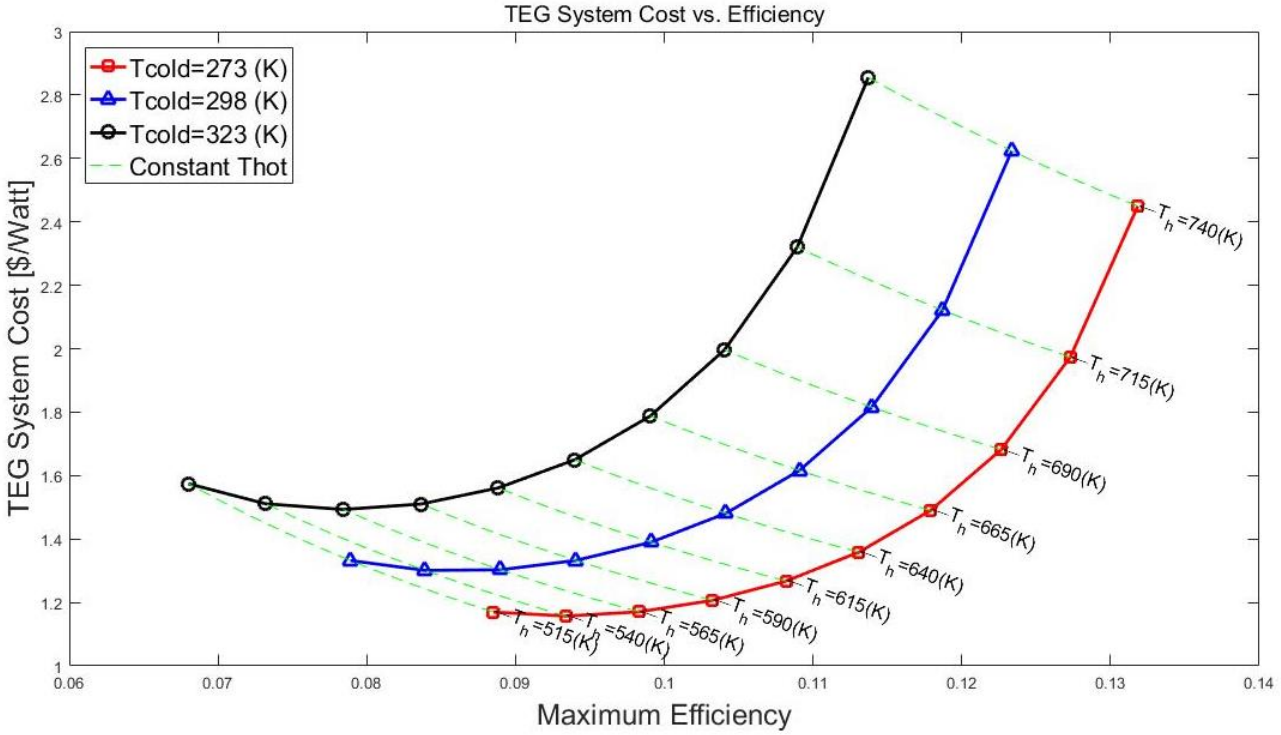
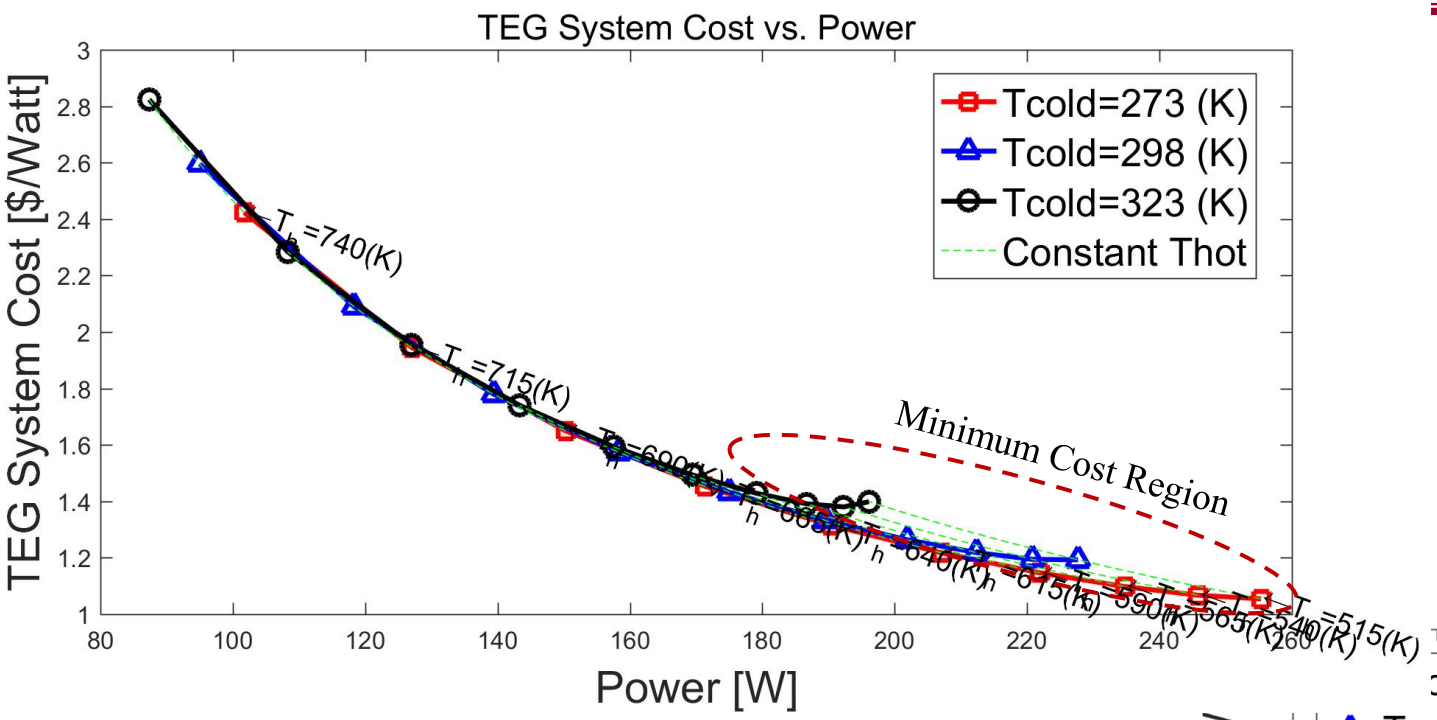
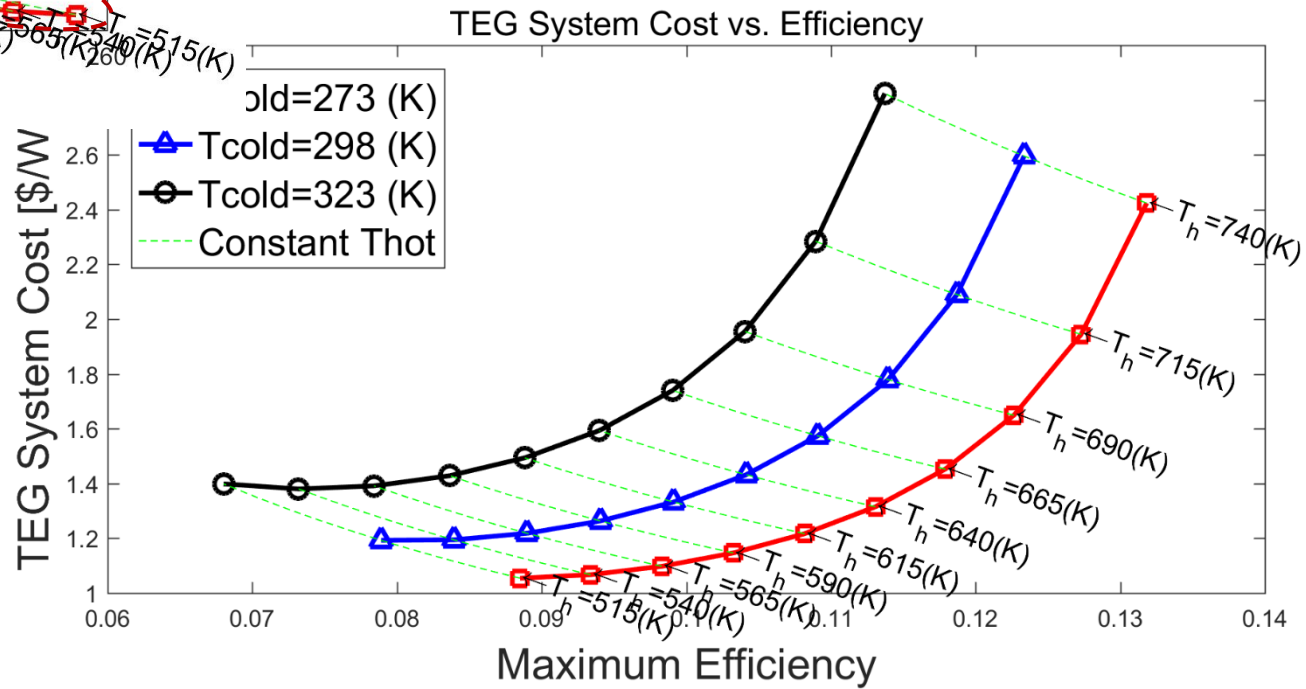


- Cost Relationship Form is Similar in Cases 1 & 2
  - Ratio of Heat Exchanger cost to TE costs is similar

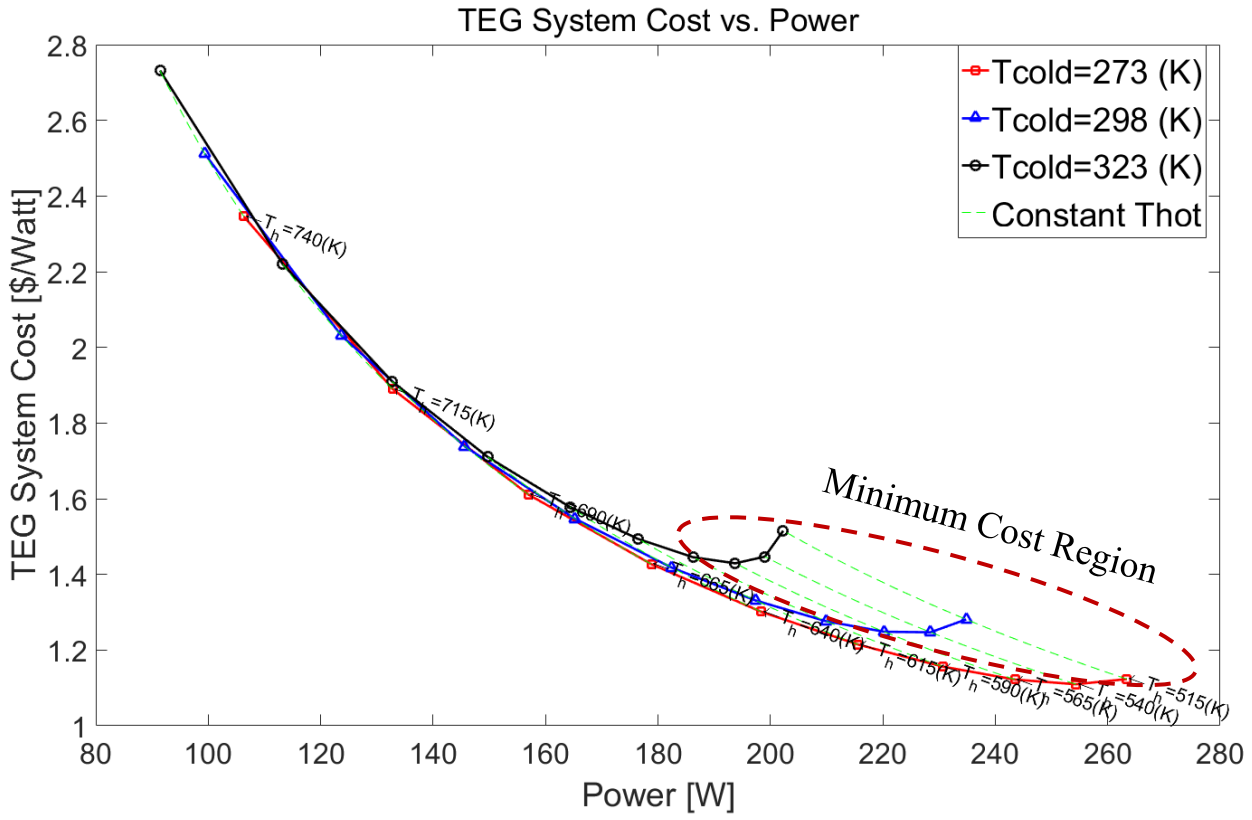
Cost Results – T_{exh} = 823 K, Case 3



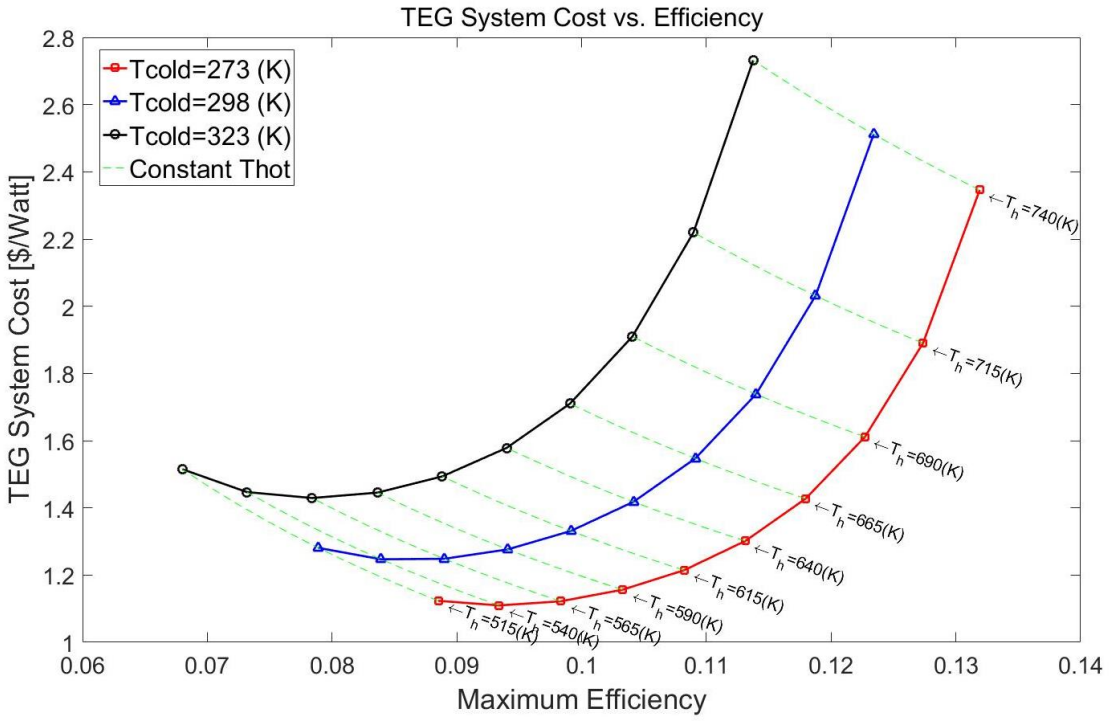
- Lower TE material and manufacturing costs tend to drive system costs toward more heat exchanger dominated
- Cost minimum disappearing and collapsing toward 1/P relationship



Cost Results – T_{exh} = 823 K, Case 3



- 3mm TE height case
- Higher TE material and manufacturing costs tend to drive system costs toward less heat exchanger dominated
- Very distinct cost minimum reappearing and no 1/P relationship
- Minimum cost not changing very much – Yee et al.* first found this, Hendricks et al. # confirmed



*Yee, S. K., LeBlanc, S., Goodson, K. E., and Dames, C. *Energy & Environmental Science*, 2013, **6**, 2561-2571.

#Hendricks, T. J., Yee, S. K., and LeBlanc, S., *Journal of Electronic Materials*, 2015, **45**, No. 3, 1751-1761, The Minerals, Metals, and Materials Society, Springer, DOI: 10.1007/s11664-015-4201-y.

Final Thoughts & Conclusions

- Investigated and Characterized Maximum Specific Power Regimes and Relationships with Maximum Efficiency, Maximum Power, and Low Cost per Watt Regions - Highly Relevant Terrestrial Power System Application
- Leveraged Cost Modeling Methodology of Yee and LeBlanc Combined with TE System-Level Analyses of Hendricks to Develop More Comprehensive Optimum Cost Fill Factor Analysis
  - Fill Factor, F, and Heat Exchanger Mounting Area, A_{HEX}, No Longer Arbitrarily Selected – They are Part of the Optimization
- Hot-Side and Cold-Side Heat Exchanger Performance and Costs More Rigorously & Directly Included
  - Heat Exchanger UA
  - Heat Exchanger Heat Flux,
  - All Relevant Areas (A_{TE}, A_{HEX} , and A_u) Accounted For Separately

Expanding Our Energy Toolbox

- New G_{opt} (F_{opt}) Relationship Developed – More Comprehensive Relationship that More Accurately Accounts for UA and $q''_{h,HEX}$ Effects – New Relationship Allows Us to Investigate Cost-Performance Impacts of Various Heat Exchanger Technologies
- G_{opt} and F_{opt} Inextricably Governed by Heat Exchanger Design Parameters and Heat Flux $q''_{h,HEX}$
  - Increasing Heat Exchanger UA → Increases G_{opt} and F_{opt}
  - Increasing Heat Exchanger Heat Flux → Increases G_{opt} and F_{opt}
  - Characterized Detailed Heat Exchanger Design Parameter Effects (i.e., Channel Widths and Design Heights)
- Goal is to Transition Terrestrial Power Advances Back into NASA Missions & Systems

Terrestrial Power Advances ⟷ NASA Mission Requirements

ACKNOWLEDGMENTS

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Cost Disclaimer:

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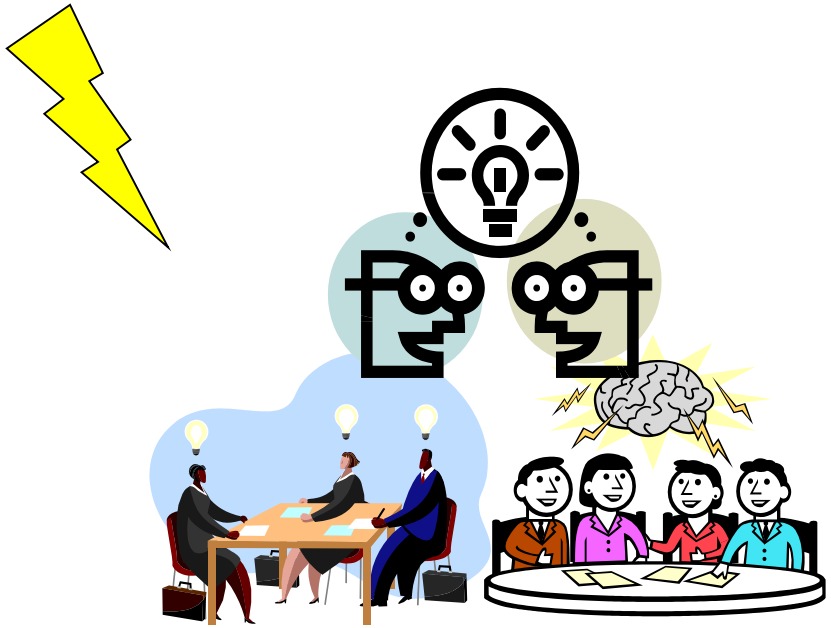
Thank you for your interest and attention

We are What We Repeatedly do. Excellence, Then, is not an Act, But a Habit.

Aristotle

Questions & Discussion



BACKUP

Learn from the mistakes of others. You won't live long enough to make them all yourself.

Yogi Berra

Catch This Wave …… And **Ride** It!!

We Can Do This!! We Have the Tools and Knowledge!

This Too Can Be The Ride of Our Lives!!

AN ENERGY TSUNAMI AHEAD

Heat Exchanger Cost Characterization

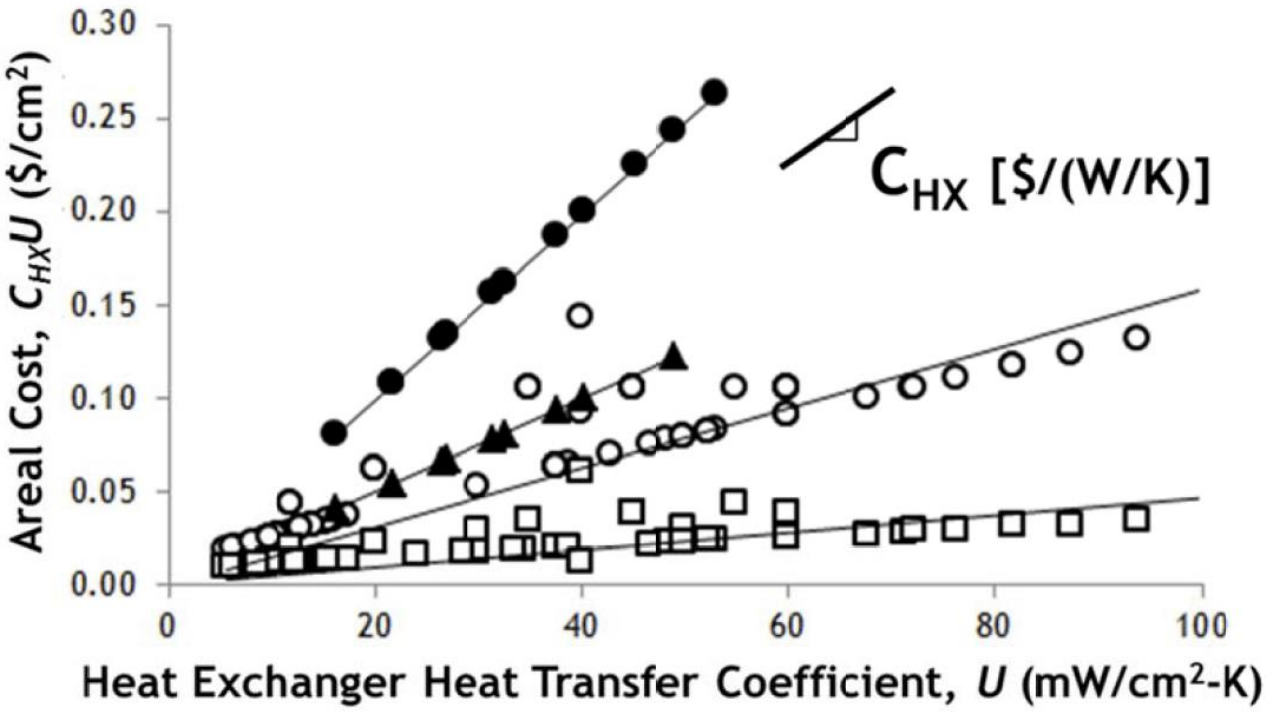


Figure S1: Heat exchanger costs. Typical areal cost as a function of heat transfer coefficient for tube and shell (open points) and plate and fin heat exchangers (solid points). The cost depends on the heat flow Q_H and temperature difference (T_H-T_1). For K_H= Q_H/(T_H-T_1)= 5 kW/K (circles), 10 kW/K (triangles), and 30 kW/K (squares). Data extracted from Ref. 17.

U.S. National Waste Energy Recovery

- **Transportation Sector**
  - 12.5 Quads
  - Light-Duty Passenger Vehicles + Light-Duty Vans/Trucks (SUVs)[1]
  - Medium & Heavy-Duty Vehicles[1]

- **Industrial Process Sector is Another Opportunity**
  - 10 Quads of Waste Energy Flows in Industrial Processes
    - Aluminum, Glass
    - Paper
    - Petroleum
    - Chemical
  - 1.8 Quads Recoverable, Potentially 1.56 GW[2]
  - Wide Range of Temperatures & Heat Sources

- **Europe and Asia Have Similar Challenges**

Waste Energy All Around Us

[1] *Transportation Energy Data Book*, 2010, Edition 29, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Vehicles Technology Program. ORNL-6985, Oak Ridge National Laboratory, Oak Ridge, Tennessee. http://cta.ornl.gov/data/index.shtml.

[2] U.S. Energy Information Agency, 2007 Annual Energy Outlook

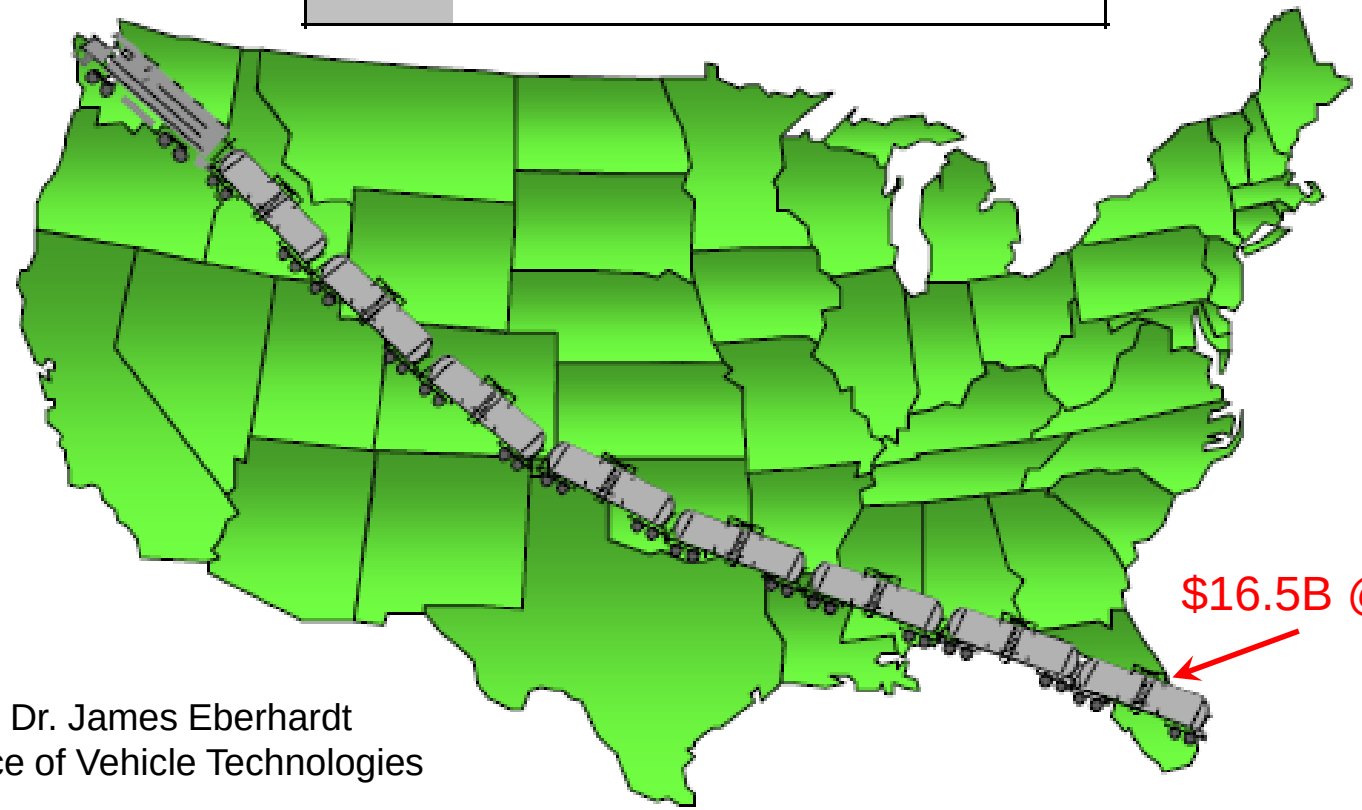
The Magnitude of Our Energy Problem

Office of Heavy Vehicle Technologies

	1973	1997
U.S.	74 Quads	91 Quads
World	225 Quads	365 Quads

2014
~98.3 Quads[1]

[1]U.S. Energy Information Agency



$16.5B @ $50/Barrel

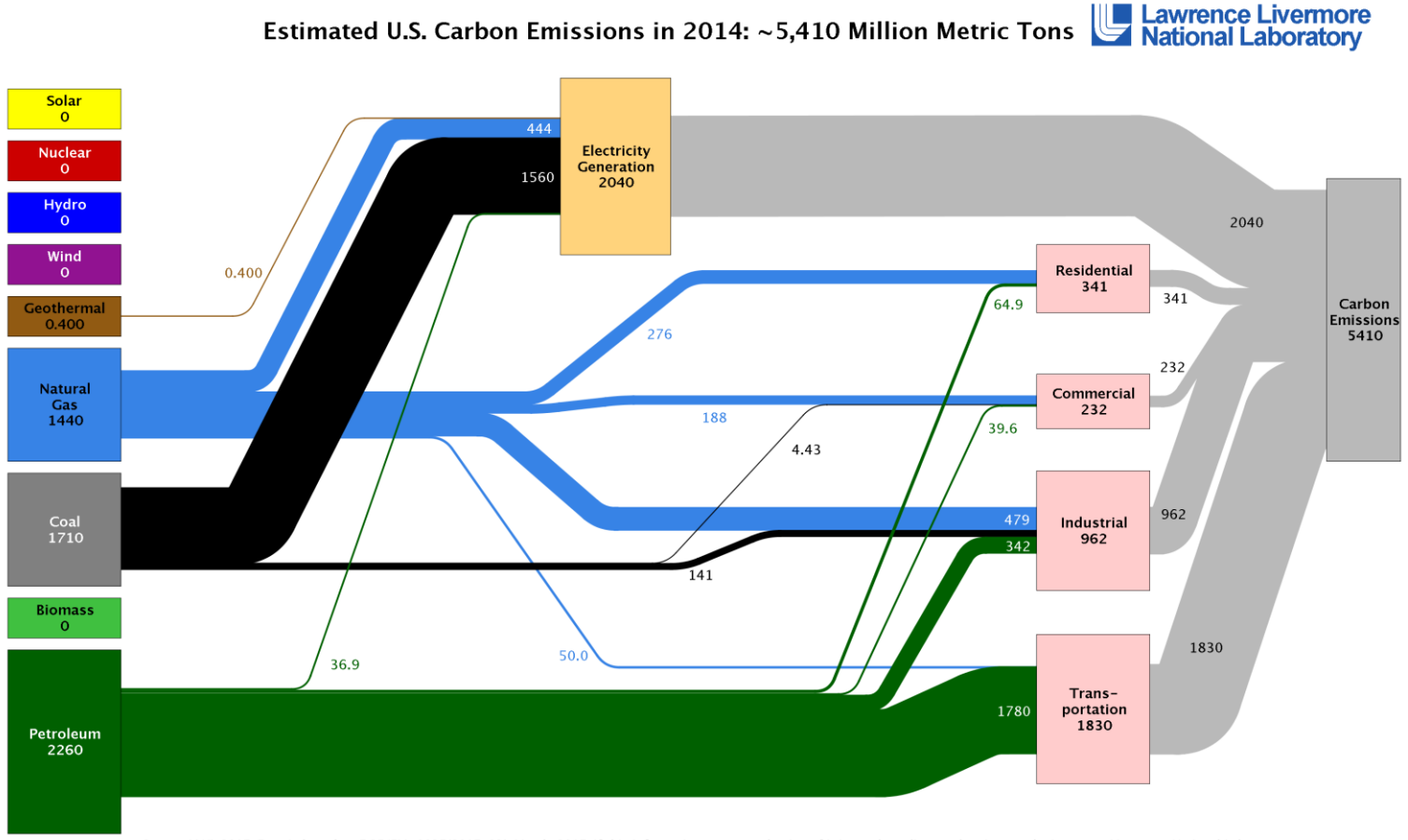
Reference - Dr. James Eberhardt
DOE – Office of Vehicle Technologies

1 Quad of energy is equivalent to 340,000 tank cars of crude oil stretched from Miami to Seattle (3,300 miles).

Environmental Effects Are Strongly Tied to Our Energy Use

- ~1 kg of CO_2 produced per 1 kWhr (Coal Produced Power)
- ~0.5 kg of CO_2 is produced for 1 kWhr (Natural Gas Power)
- Coal Price $52.45 / short ton (28 April) = ~2.62 / Million BTU
- Natural Gas Spot Price $2.5-3.25/Million BTU (U.S. Spot Prices)
  - Has been less than this fairly recently

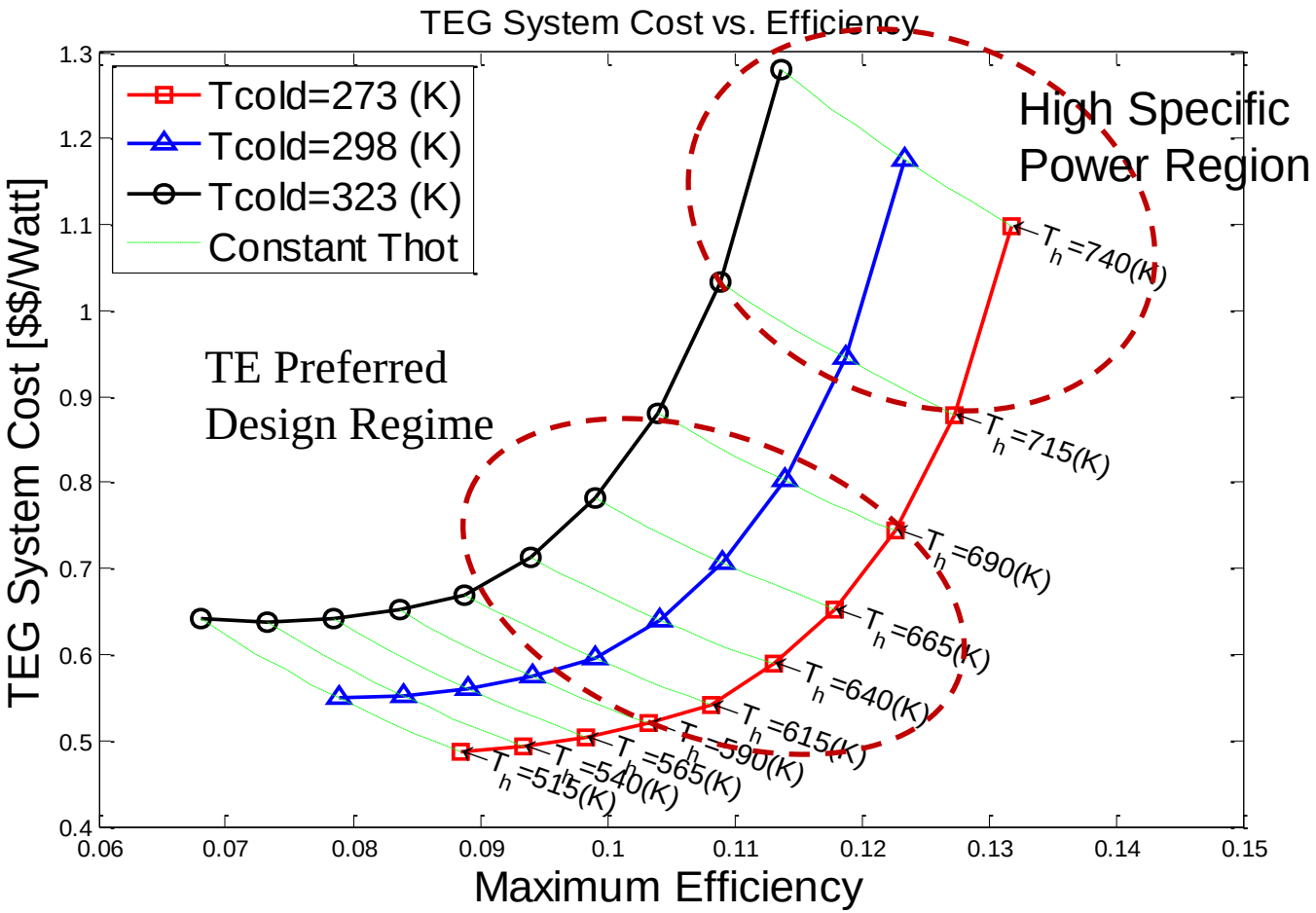
Down ~400 Million Metric Tons From 2008
Mostly from Reduced Coal & Petroleum Use



Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2015. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Carbon emissions are attributed to their physical source, and are not allocated to end use for electricity consumption in the residential, commercial, industrial and transportation sectors. Petroleum consumption in the electric power sector includes the non-renewable portion of municipal solid waste. Combusition of biologically derived fuels is assumed to have zero net carbon emissions – the lifecycle emissions associated with producing biofuels are included in commercial and industrial emissions. Totals may not equal sum of components due to independent rounding errors. LLNL-MI-410527

Results – T_{exh} = 823 K, Case 4, Heat Exchanger Costs $1/(W/K)

- Preferred TE Design Regimes Allow us to Move into Higher Efficiency, Higher Power Densities & Higher Fluxes With Very Little Cost and Power Penalties – "PRETE (Pretty)" Design Regime
- High Specific Power Regions Even Higher in Efficiency Than PRETE Design Regime
- Highly Idealized Case

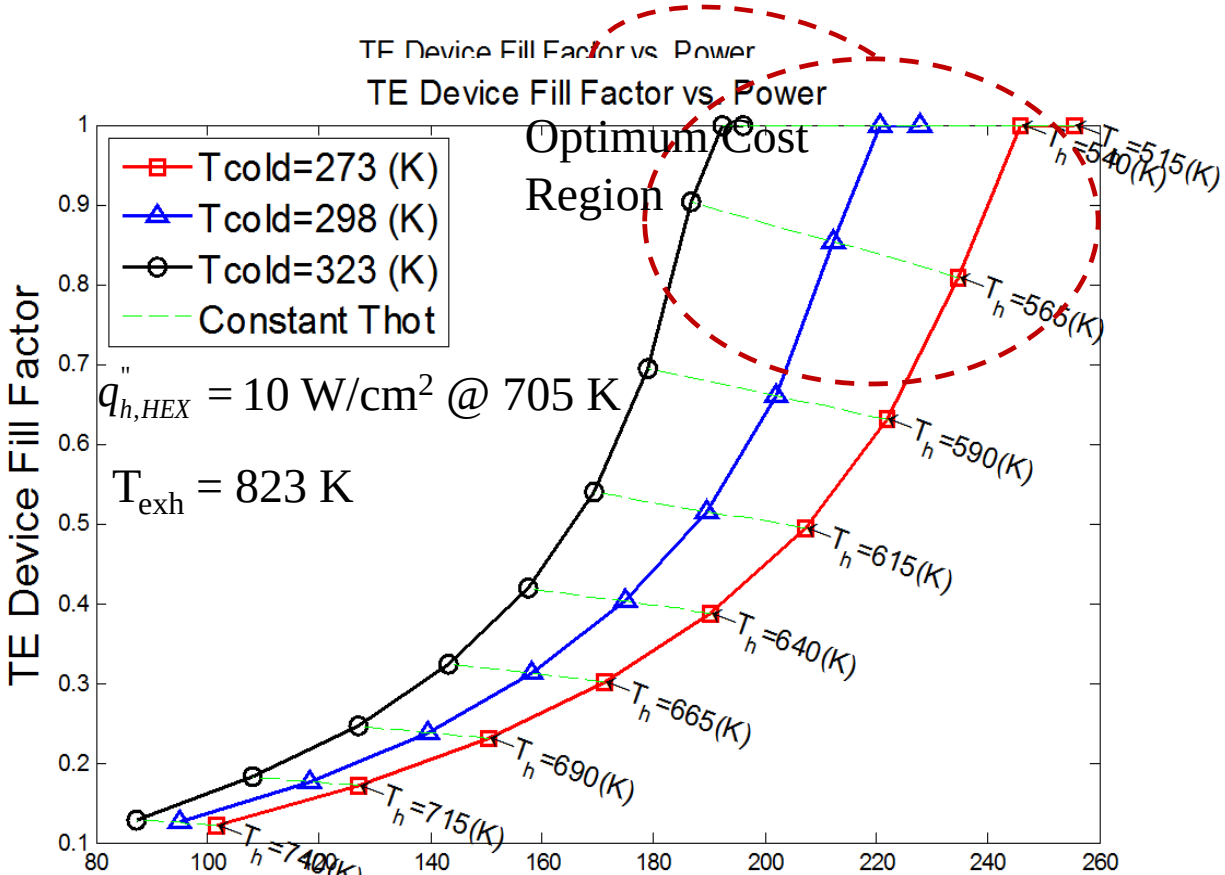


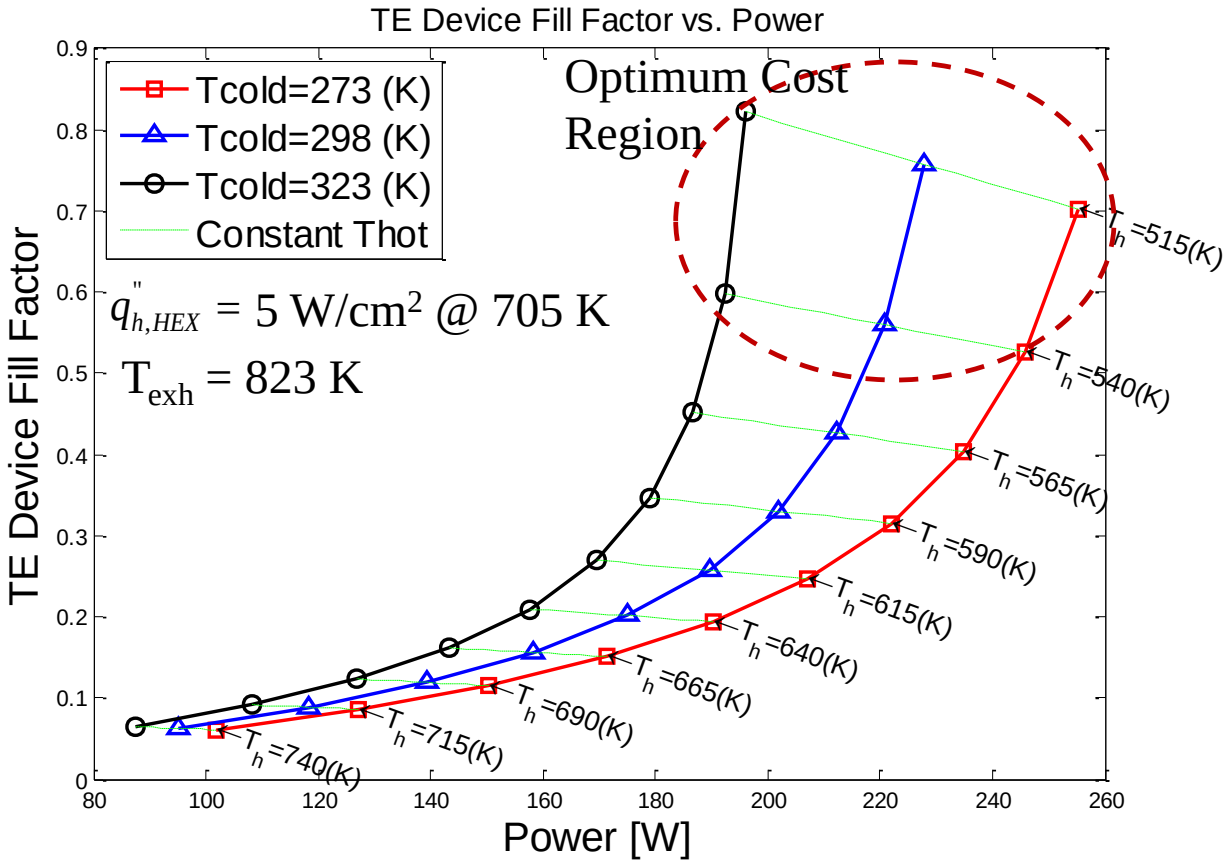
Fill Factor In Various Design Regions

- Required Fill Factor Dependent on TE Device Heat Flux <u>AND</u> Heat Exchanger Heat Flux

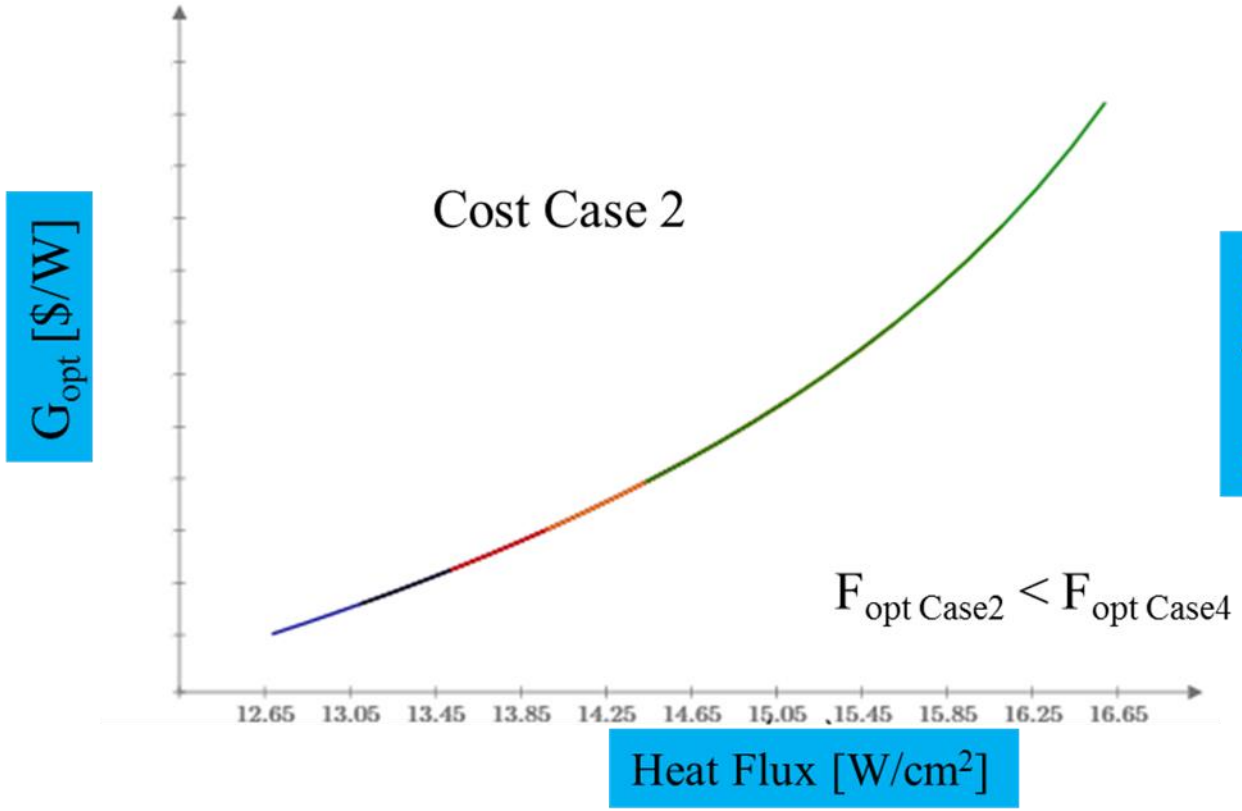
$$F = \frac{A_{TE}}{A_{HEX}} \qquad q''_{h,HEX} = F \cdot q''_{h,TE} = \frac{Q_{h,TE} + Q_{loss}}{A_{HEX}} = f_Q(T_{exh}, T_h, T_c)$$

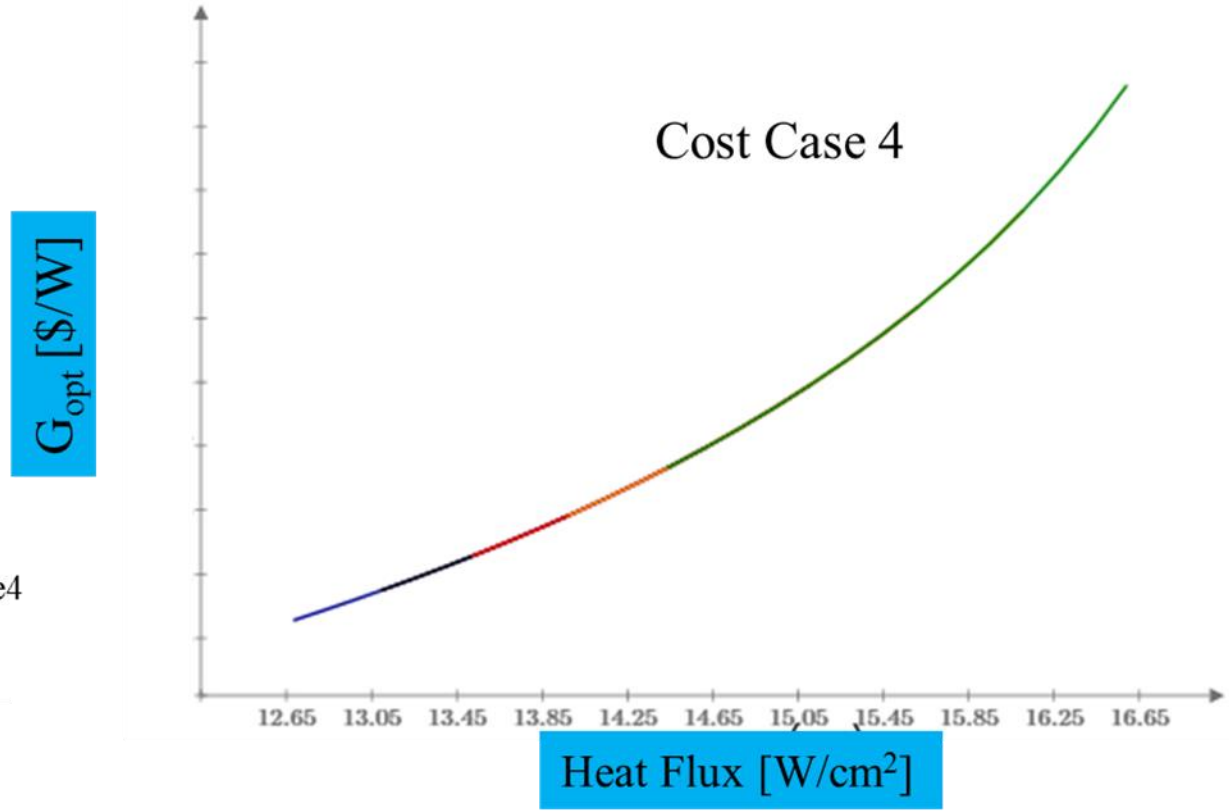
- For Constant UA_h = 24.5 W/K Characteristic F-Behavior Shown Below - F = f ($q''_{h,HEX}$ &)
- High Required Heat Exchanger Heat Fluxes Can "Saturate" the Available Heat Exchanger Area (F=1)



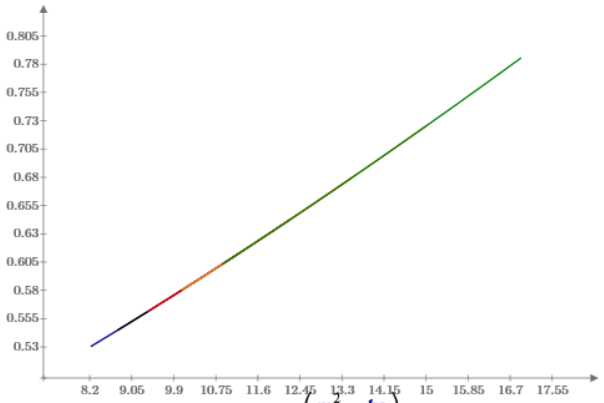


This is what it typically looks like





Optimum Cost Function – Case 1



$UA_{t_{1,j}} \left(\frac{m^2}{K} \cdot \frac{kg}{s^3}\right)$

$UA_{t_{2,j}} \left(\frac{m^2}{K} \cdot \frac{kg}{s^3}\right)$

$UA_{t_{3,j}} \left(\frac{m^2}{K} \cdot \frac{kg}{s^3}\right)$

$UA_{t_{4,j}} \left(\frac{m^2}{K} \cdot \frac{kg}{s^3}\right)$

$UA_{t_{5,j}} \left(\frac{m^2}{K} \cdot \frac{kg}{s^3}\right)$

$G_{opt_{1,j}} \left(\frac{s^3 \cdot ¤}{kg \cdot m^2}\right)$

$G_{opt_{2,j}} \left(\frac{s^3 \cdot ¤}{kg \cdot m^2}\right)$

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$G_{opt_{5,j}} \left(\frac{s^3 \cdot ¤}{kg \cdot m^2}\right)$

$0.75\ qflux_{2,j} \left(\frac{kg}{s^3}\right)$

$0.75\ qflux_{3,j} \left(\frac{kg}{s^3}\right)$

$0.75\ qflux_{4,j} \left(\frac{kg}{s^3}\right)$

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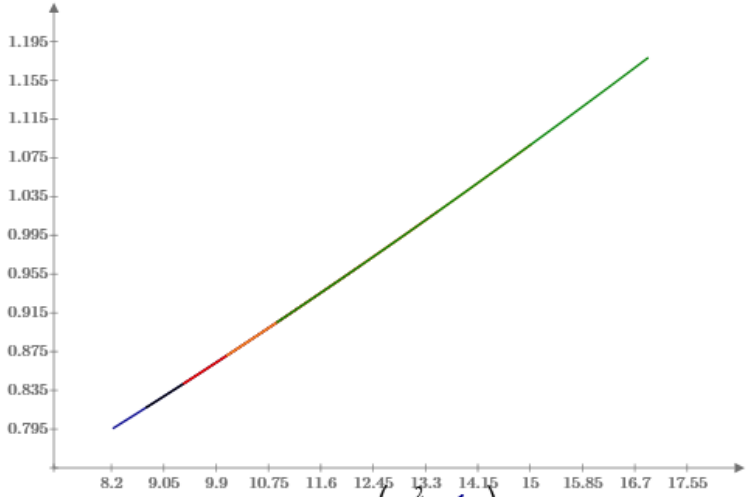

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