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CHANGING WHAT'S POSSIBLE

Putting Hot Air to Work

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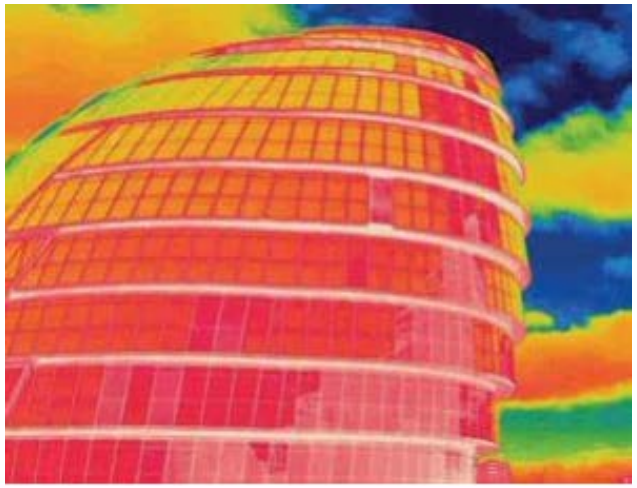
Program Director

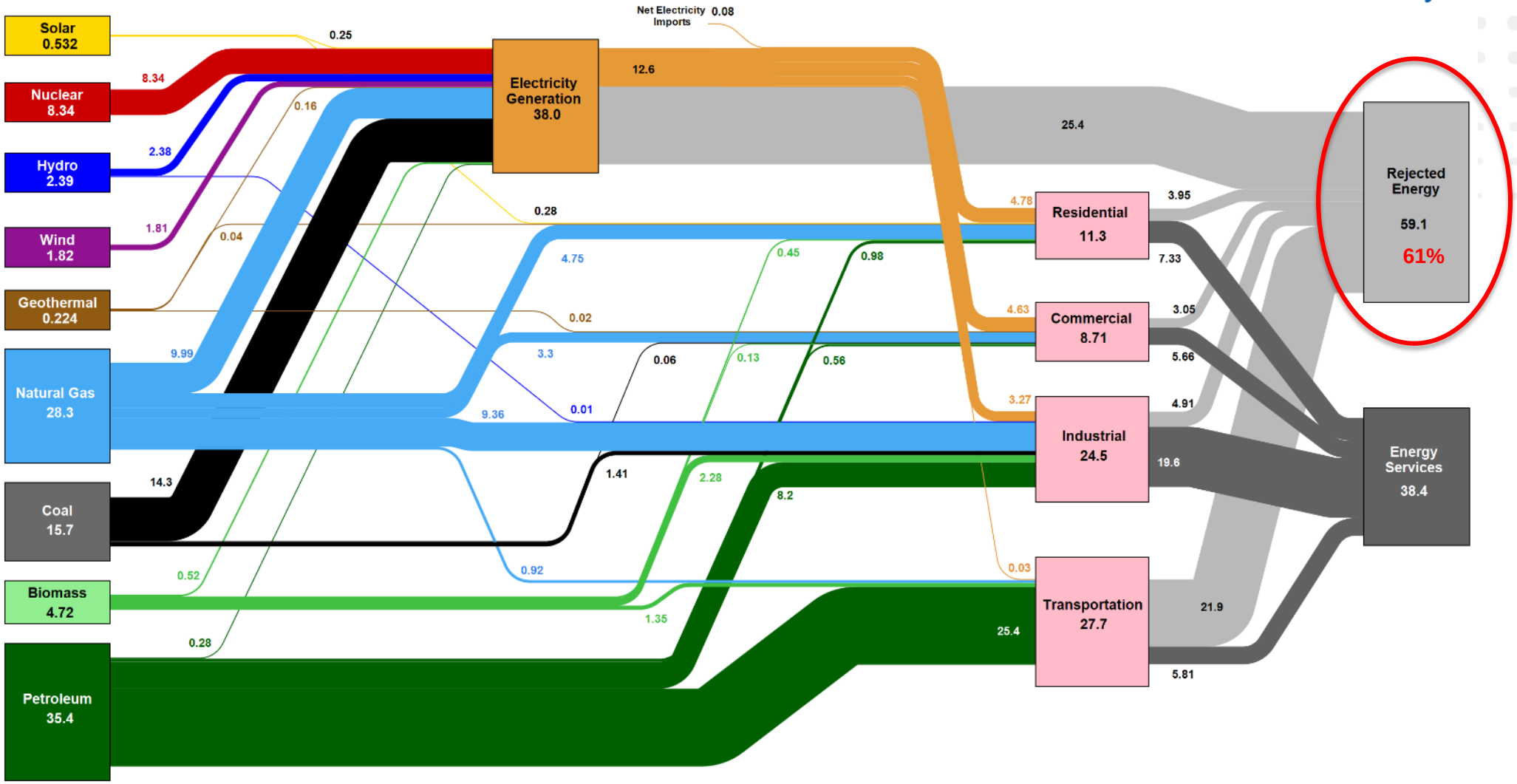
February 27, 2017



The Opportunity

Estimated U.S. Energy Consumption in 2015: 97.5 Quads

Lawrence Livermore National Laboratory



Source: LLNL March, 2016. Data is based on DOE/EIA MER (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. 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 sector, 65% for the commercial sector, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

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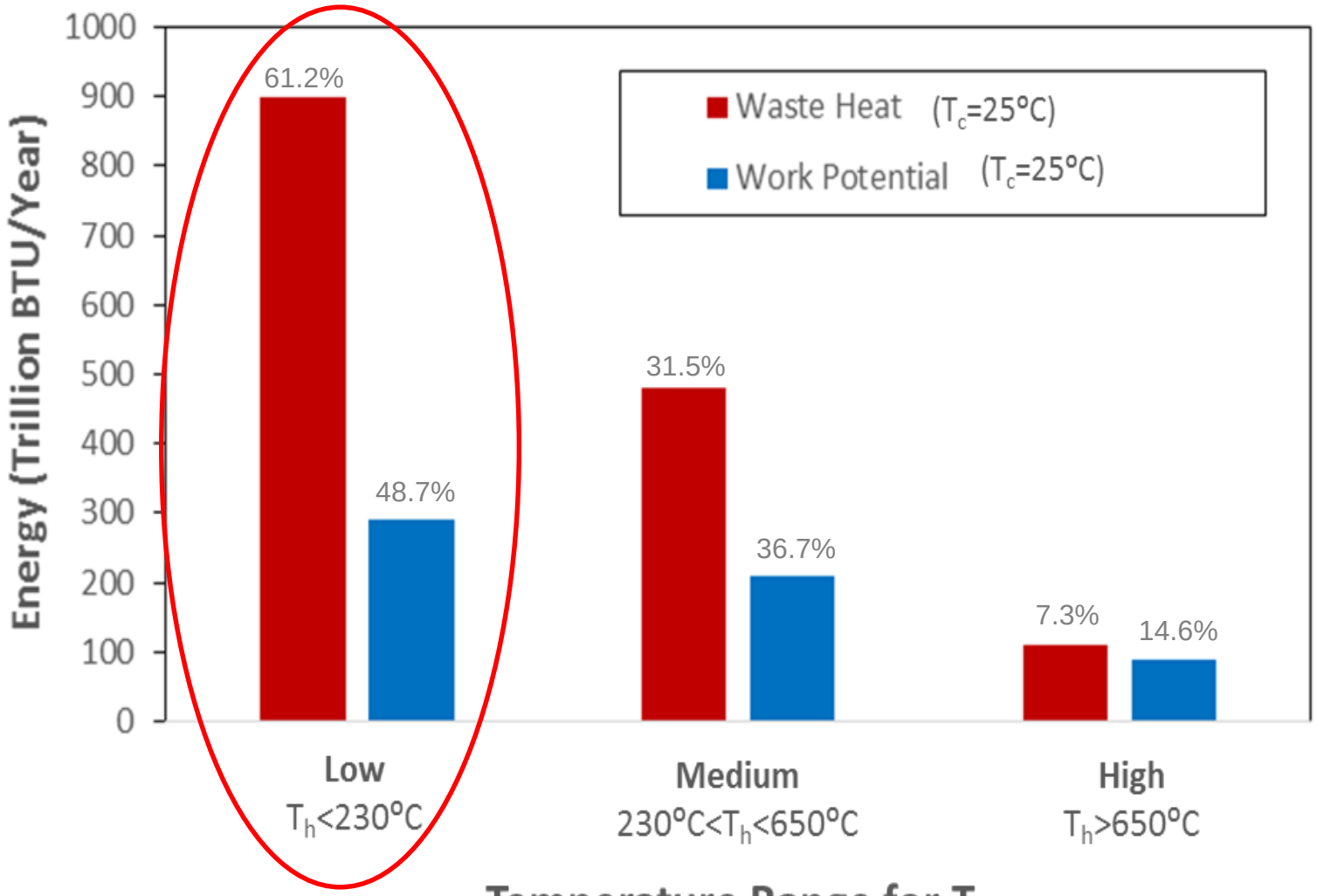
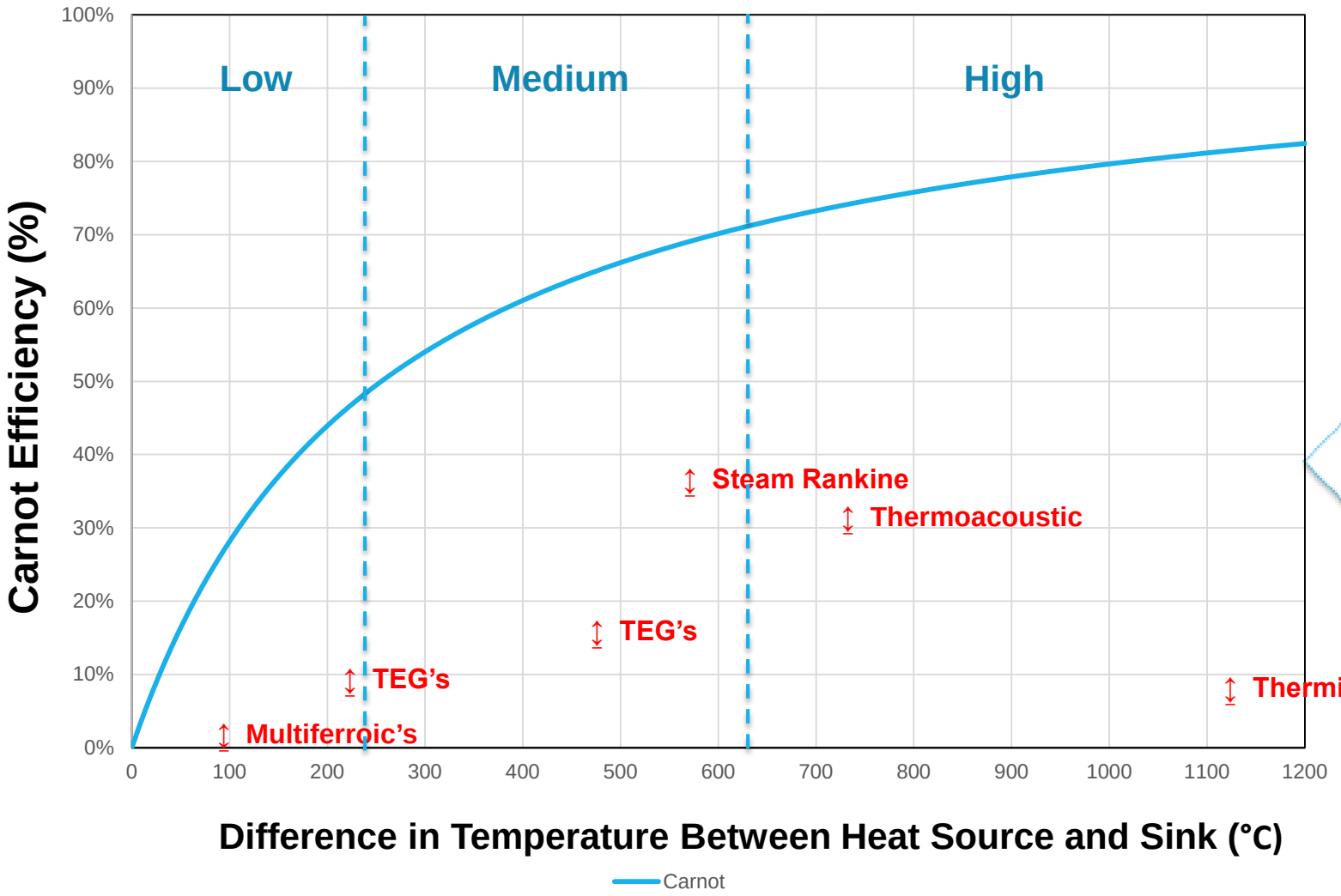
Provocation: Biggest Opportunity Is In “Lower Quality” Heat



Source - U.S. Department of Energy Industrial Technologies Program report: “Waste Heat Recovery – technical and Opportunities in U.S. Industry, prepared by BCS, Inc. March 2008”

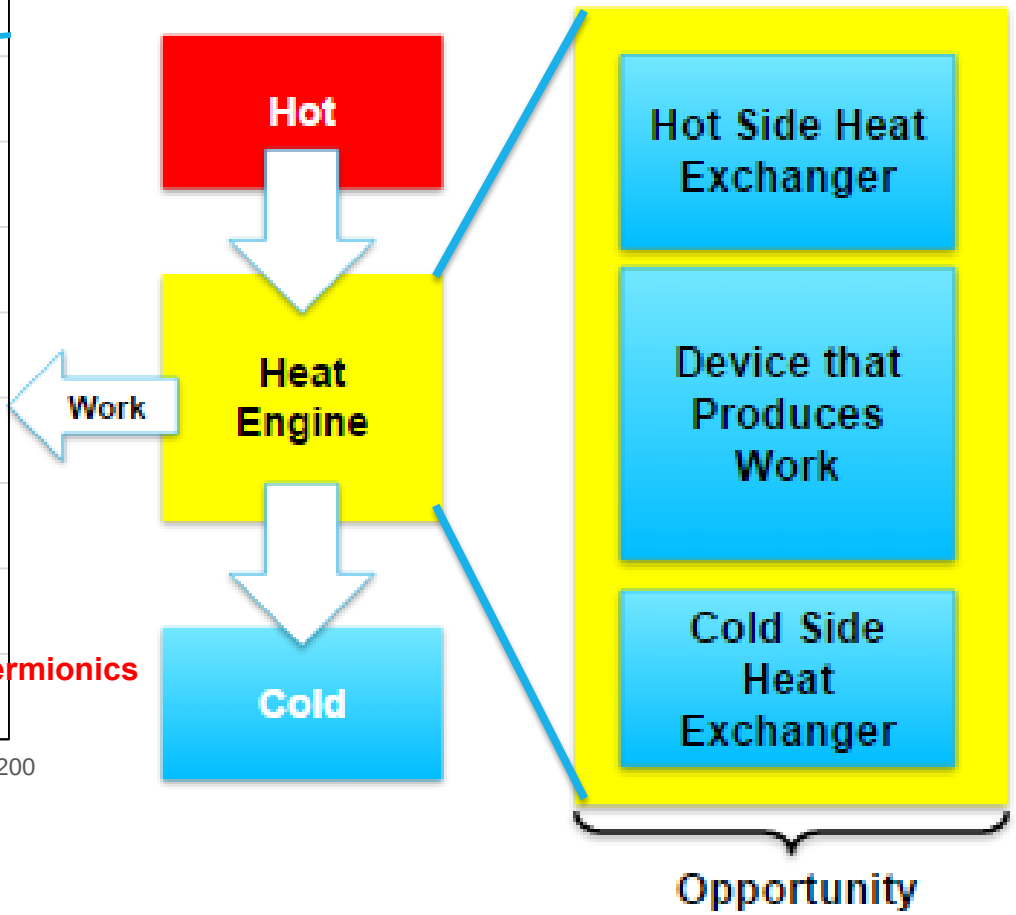
Maximum Speed Limit

Carnot Efficiency of a Heat Engine



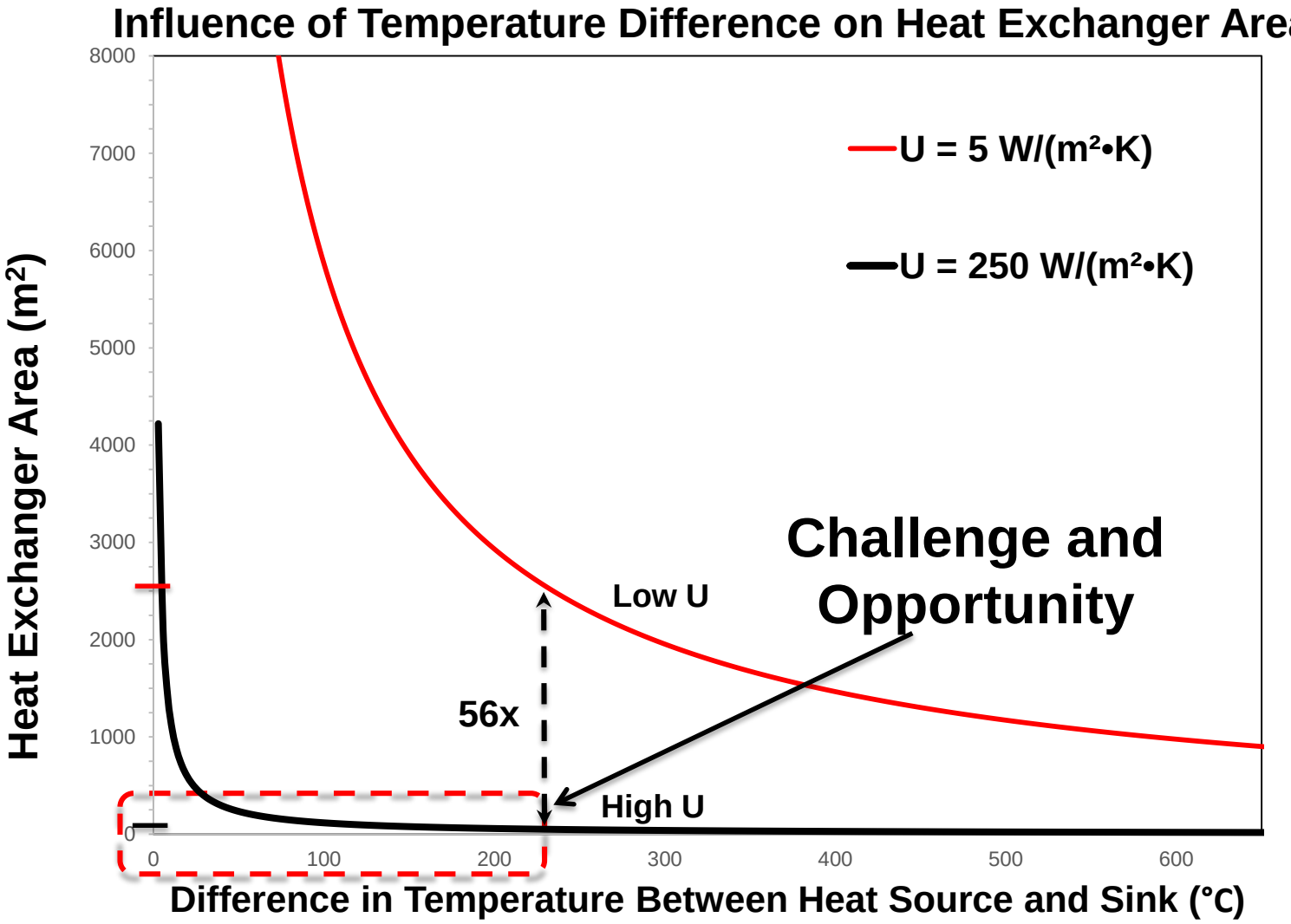
Carnot Equation:

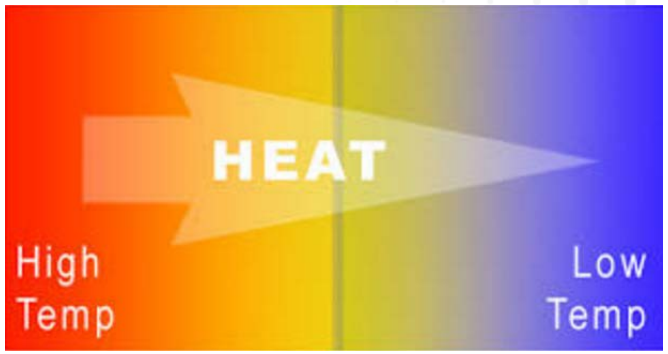
$$\eta = 1 - T_C/T_H$$



Source - *John Murrell (2009). "A Very Brief History of Thermodynamics"*. PDF (142 Archived November 22, 2009, at the Wayback Machine. KB)
Carnot's theorem provides an upper limit on the efficiency that any classical thermodynamic engine can achieve during the conversion of heat into work,

The Real Heat Issue





Heat Transport

Where: $Q = U \bullet A \bullet \Delta T$

(Watts or Btu's)

Q = heat transfer rate

U = heat transfer coefficient

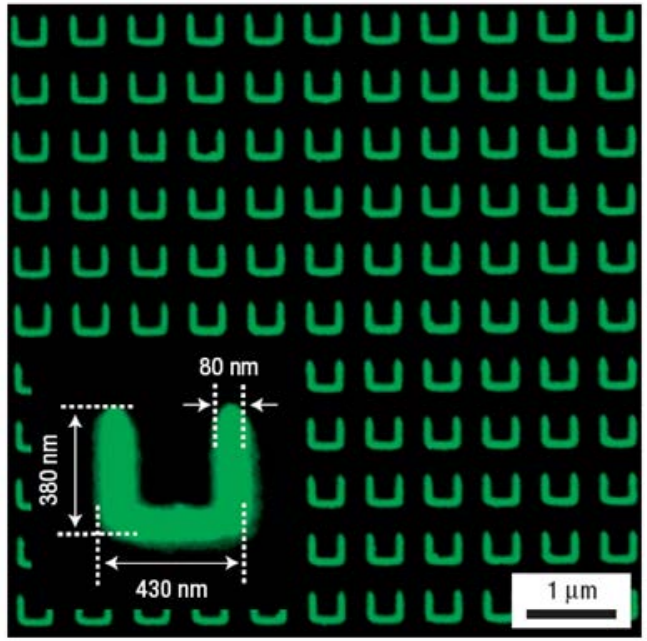
A = surface area of the heat exchanger

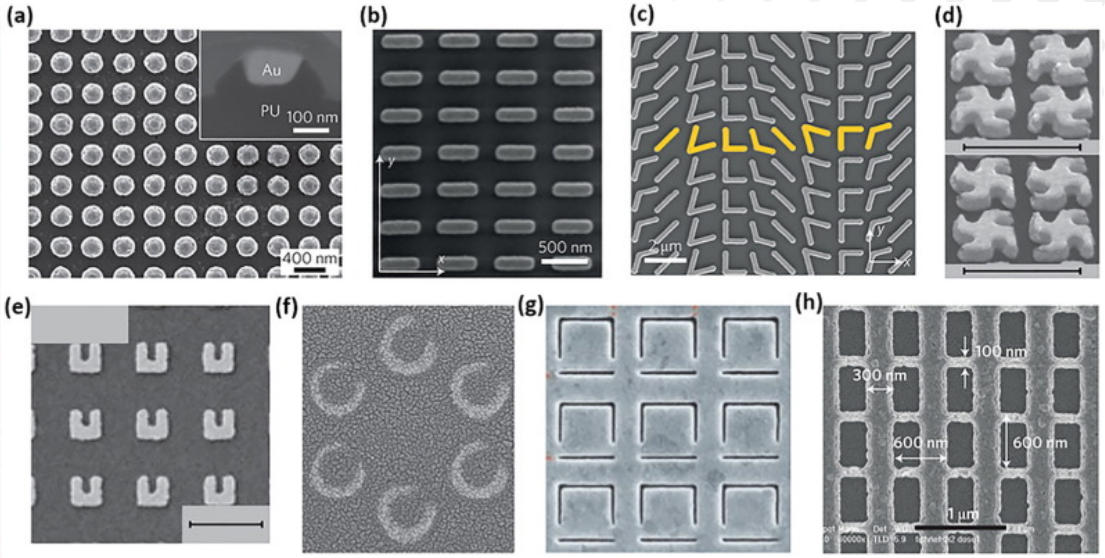
ΔT = temperature difference between the two streams

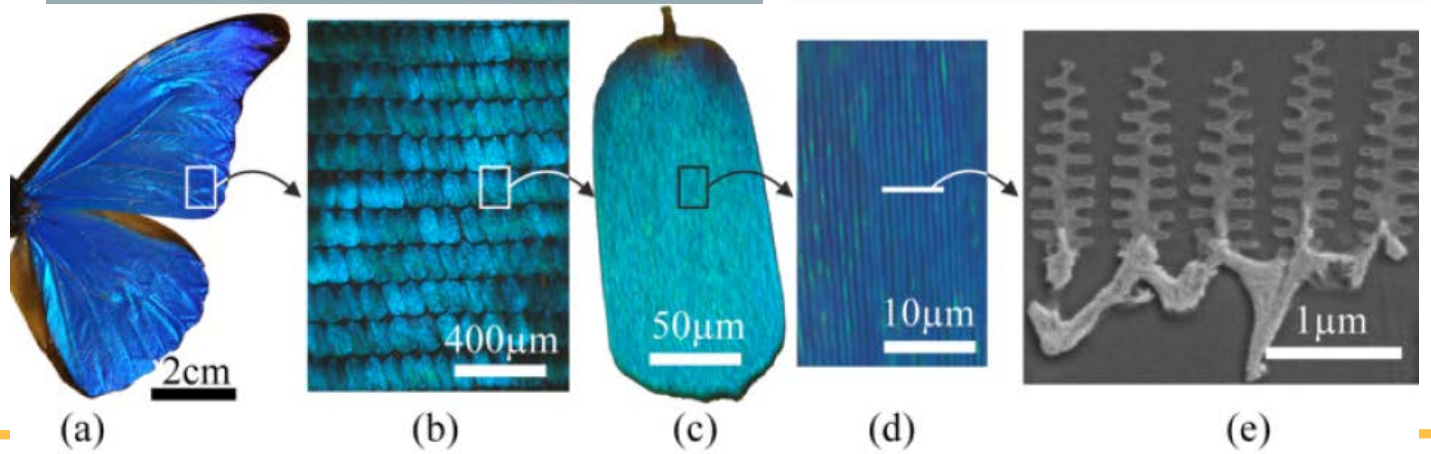
Source - U.S. Department of Energy Industrial Technologies Program report: "Waste Heat Recovery – technical and Opportunities in U.S. Industry, prepared by BCS, Inc. March 2008"

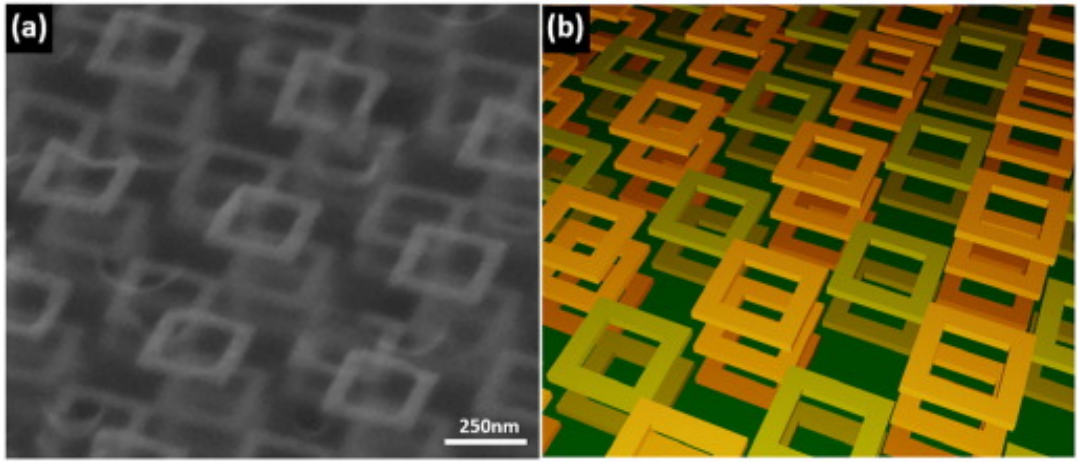
This figure graphs the surface area (m^2) required for recovering 10 million Btu/hr from a gaseous exhaust stream with a mass flow rate of 5 million lbs/hr by transfer to liquid water flowing at 1 ft^3/s. Calculated using estimated log mean temperature difference for ΔT.

Metamaterials Emergence . . . Redux









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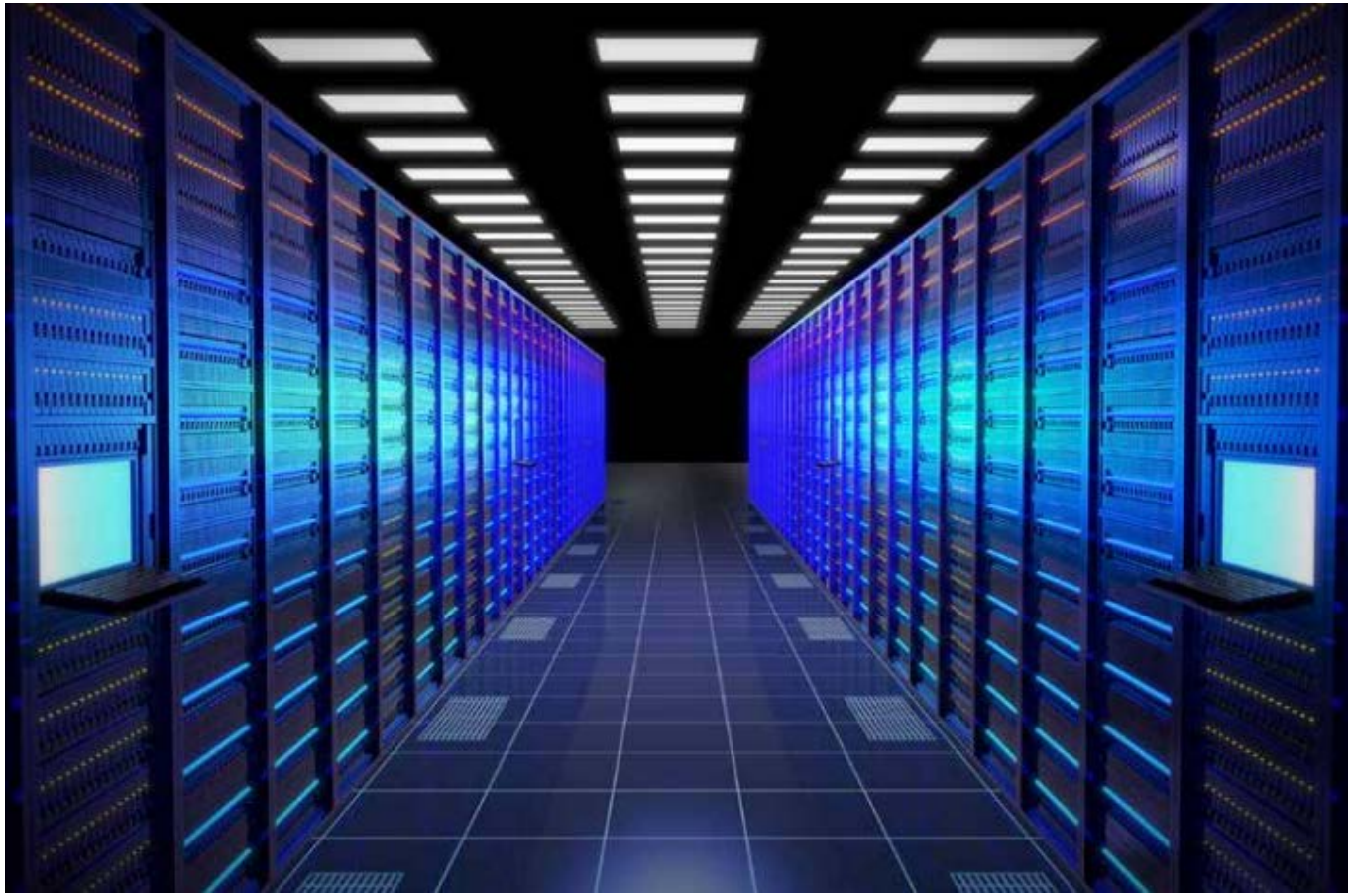
1. AskNature.org; 2. Gwanho Yoon, Inki Kim, Junsuk Rho *Microelectronic Engineering*, **163**, September 2016, pg. 7-20.

Technology Gap For Lower Grade Heat Conversion

- **Systems Integration Challenge - Advanced Heat Transport**
  - Extreme Cost Reduction
  - Next Gen Materials and Designs
  - Novel Working Fluids and Surfaces
- **Conversion Challenge - Next Gen Devices**
  - High Conversion Efficiencies
  - Lower Operational Temperatures
  - Robust Manufacturing
  - Scalability



Thank You

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