System Considerations in Waste Heat Recovery

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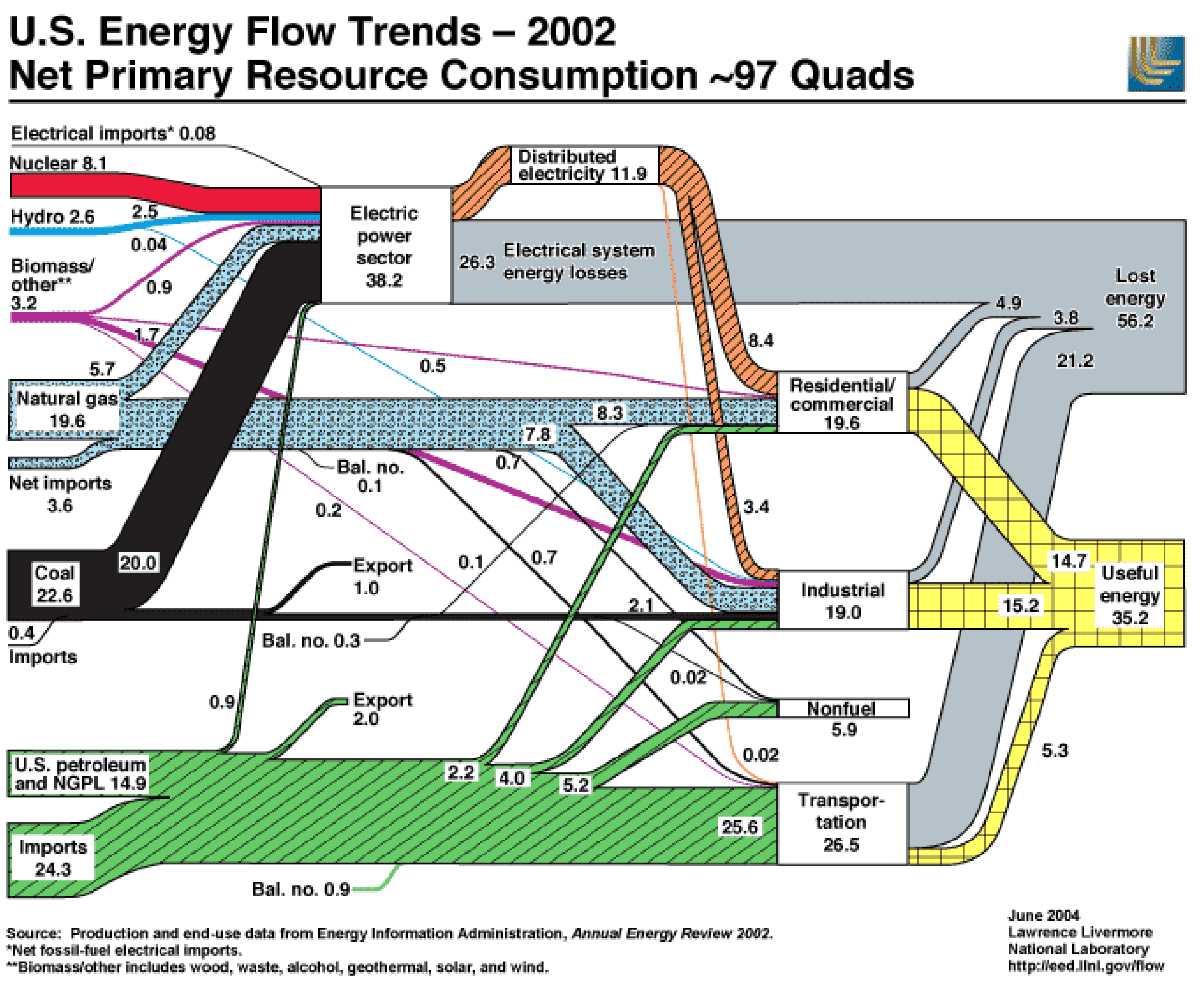
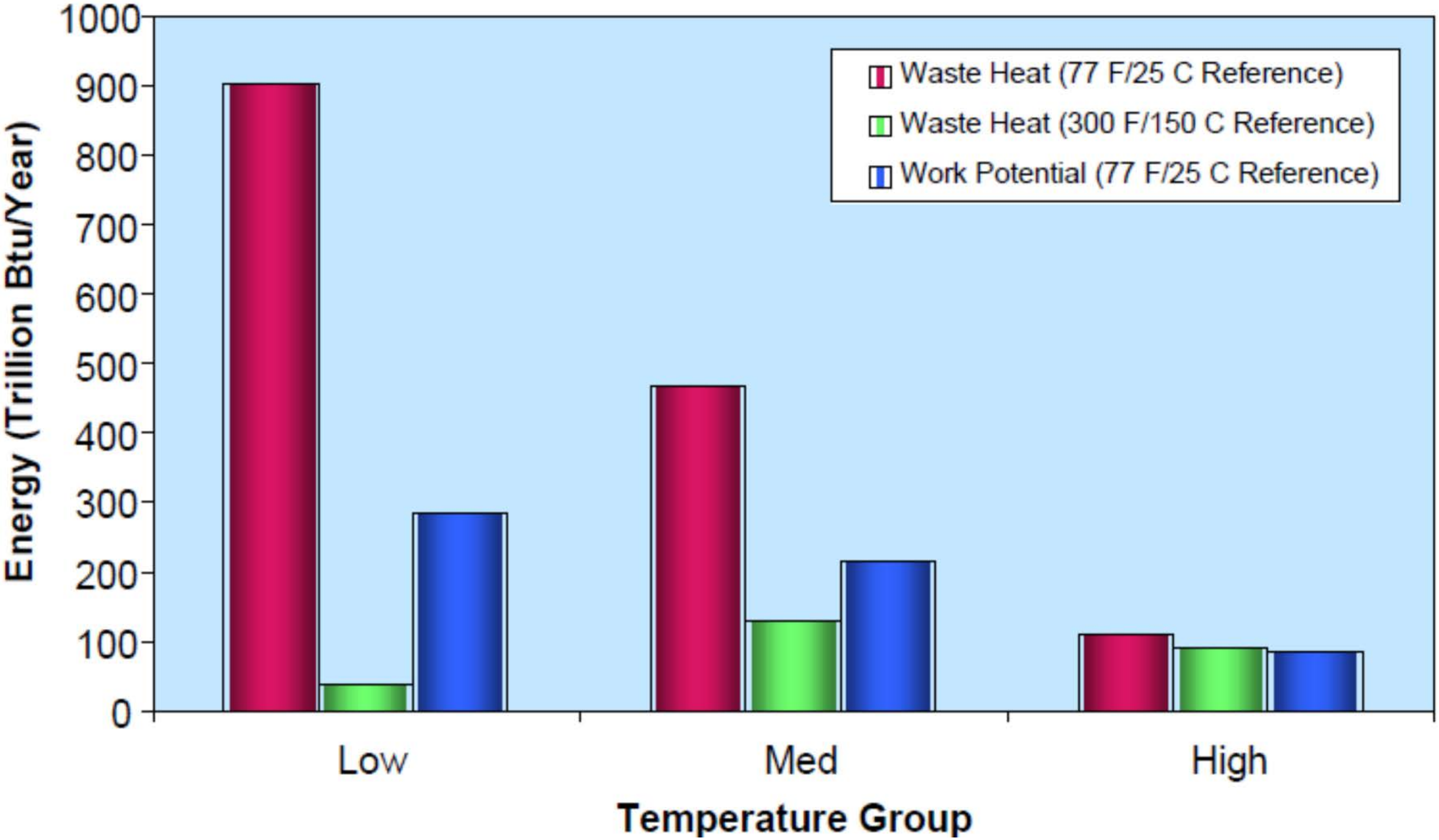
Energy Usage in US

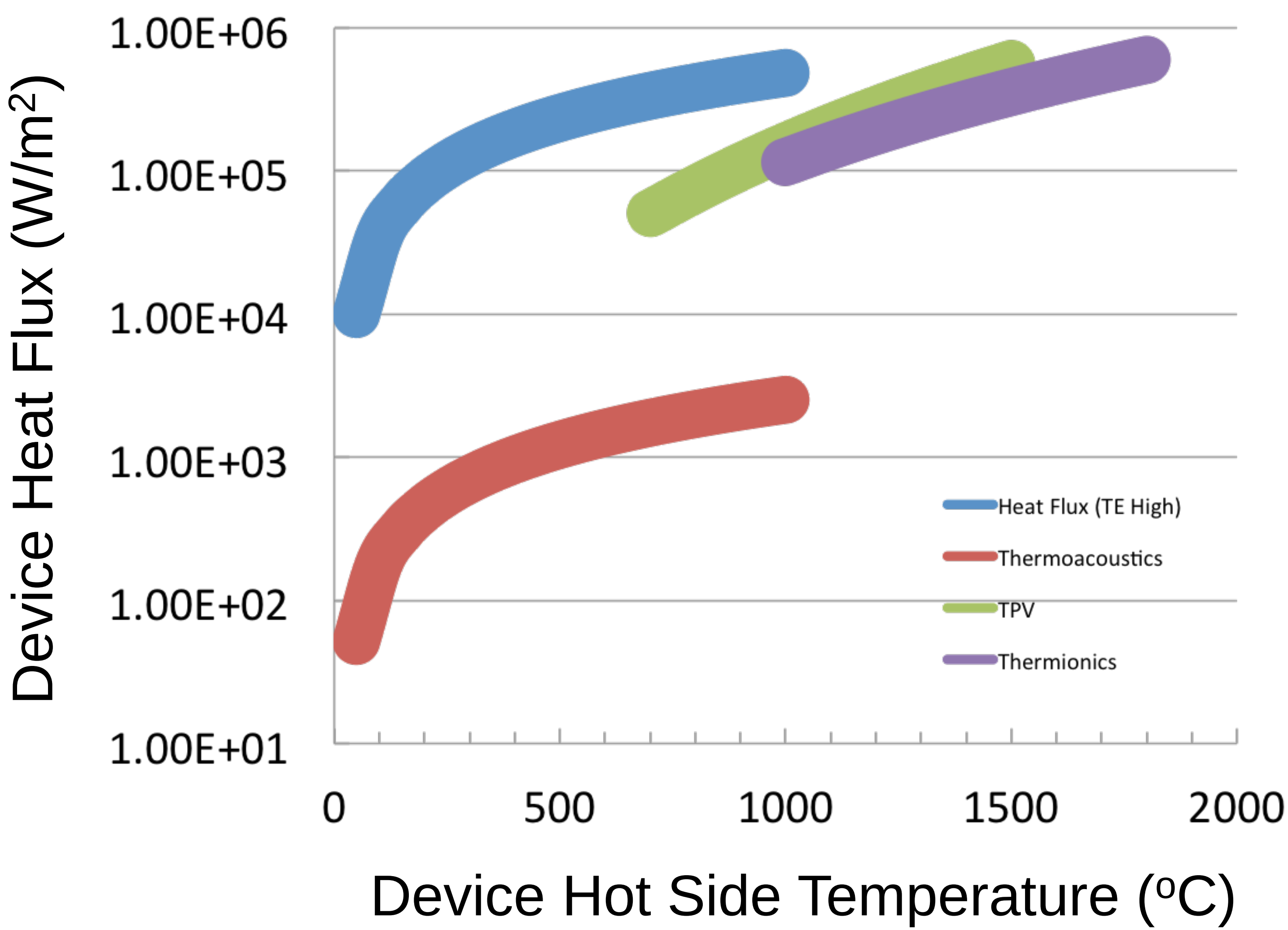


Waste Heat Source Temperature

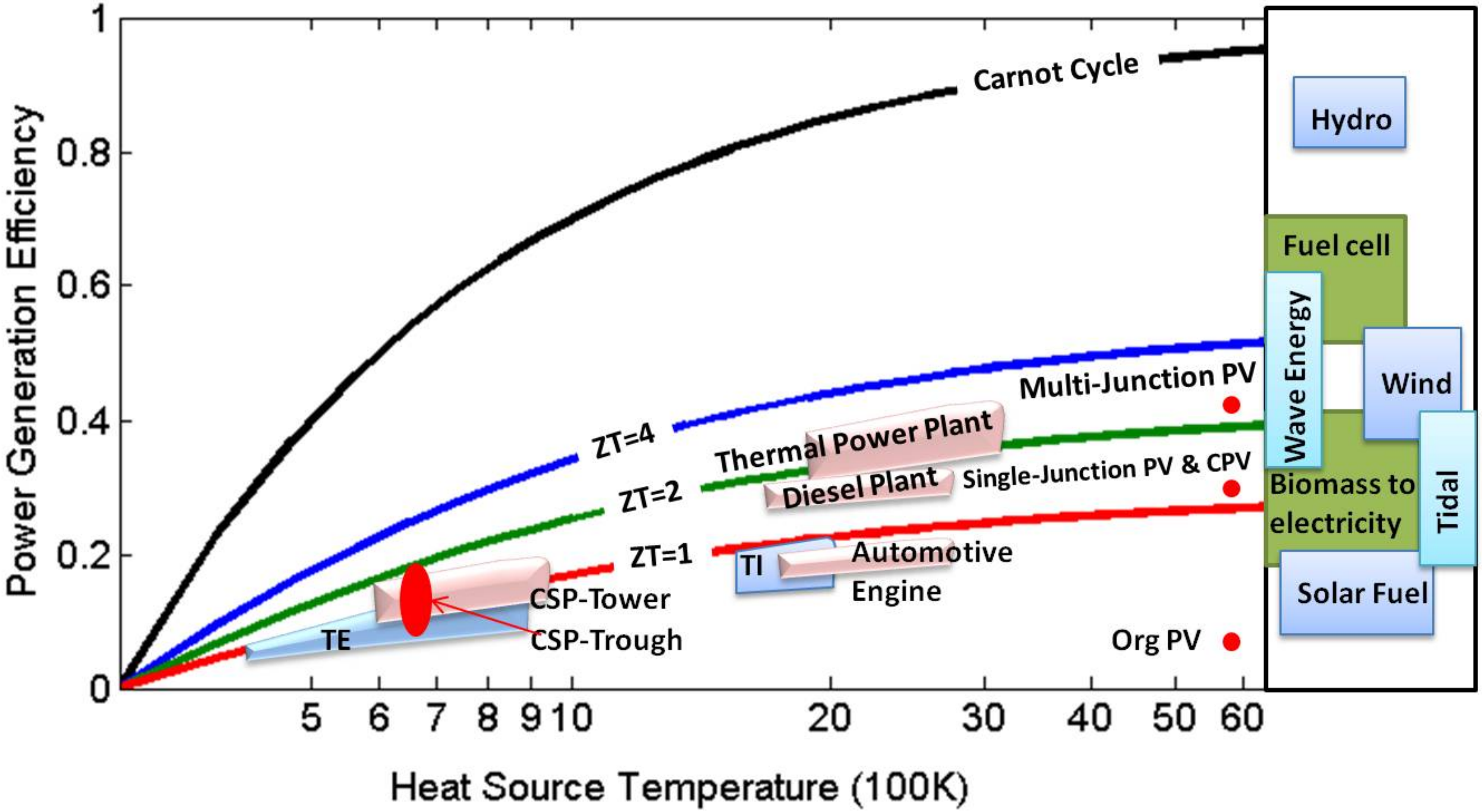


Waste Heat Recovery- Technology and Opportunities for U.S. Industry BCS, Incorporated — Energy Efficiency and Renewable Energy Office, DOE (2008).

Direct Energy Conversion Device Working Range (Back of Envelope)



Energy Conversion Efficiency

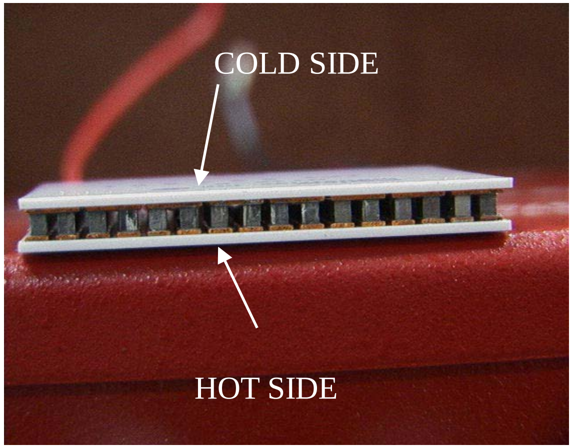


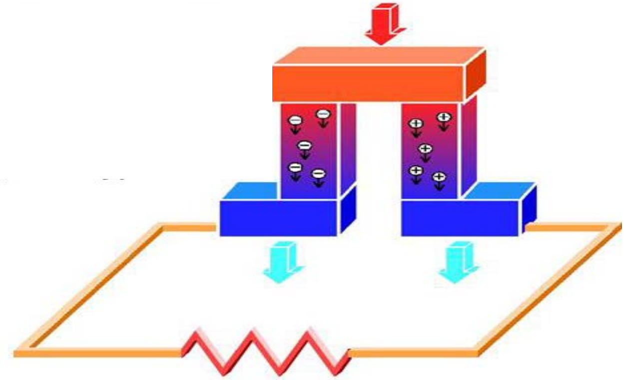
Zebarjadi et al., Energy & Env. Sci., 5, 5147,2012

System Consideration

- How to collect heat?
- How to reject heat?
- What is system cost?

Thermoelectric Devices





Nondimensional Figure of Merit

Joule Heating

Seebeck Coeff. Electron Cooling

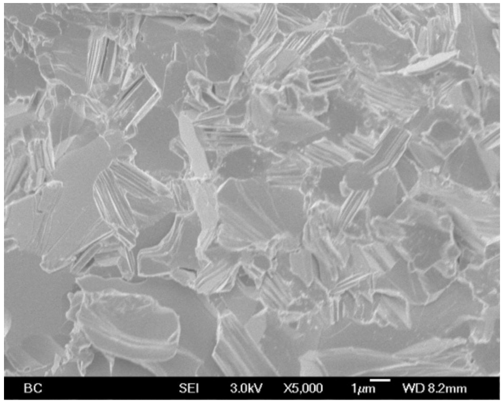
$$ZT = \frac{\sigma S^2 T}{k}$$

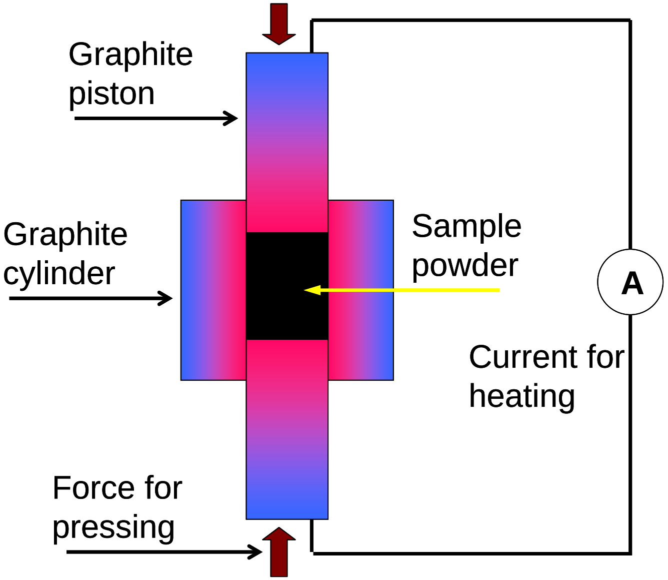
Reverse Heat Leakage Through Heat Conduction

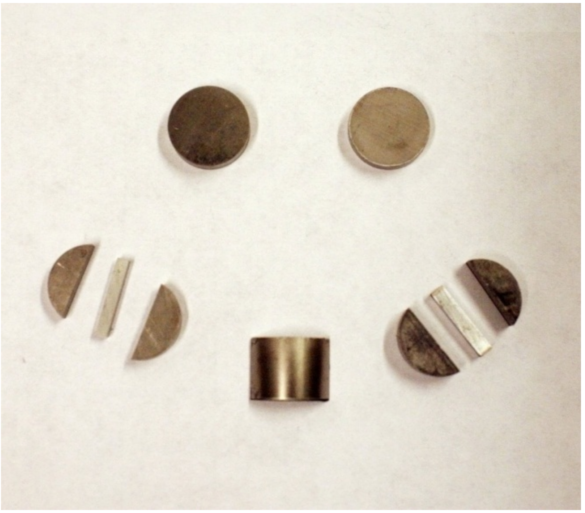
Nanocomposite Synthesis

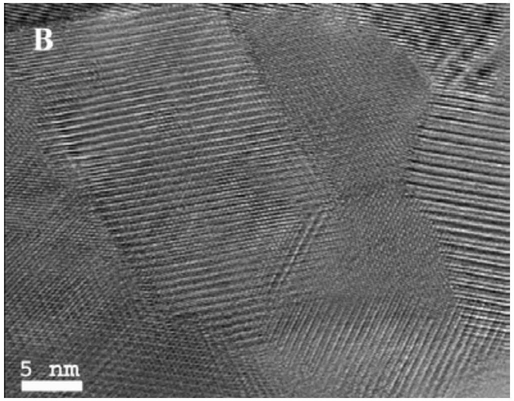
Increase interfacial scattering by mixing nano-sized particles.

Batch fabrication for large scale application.





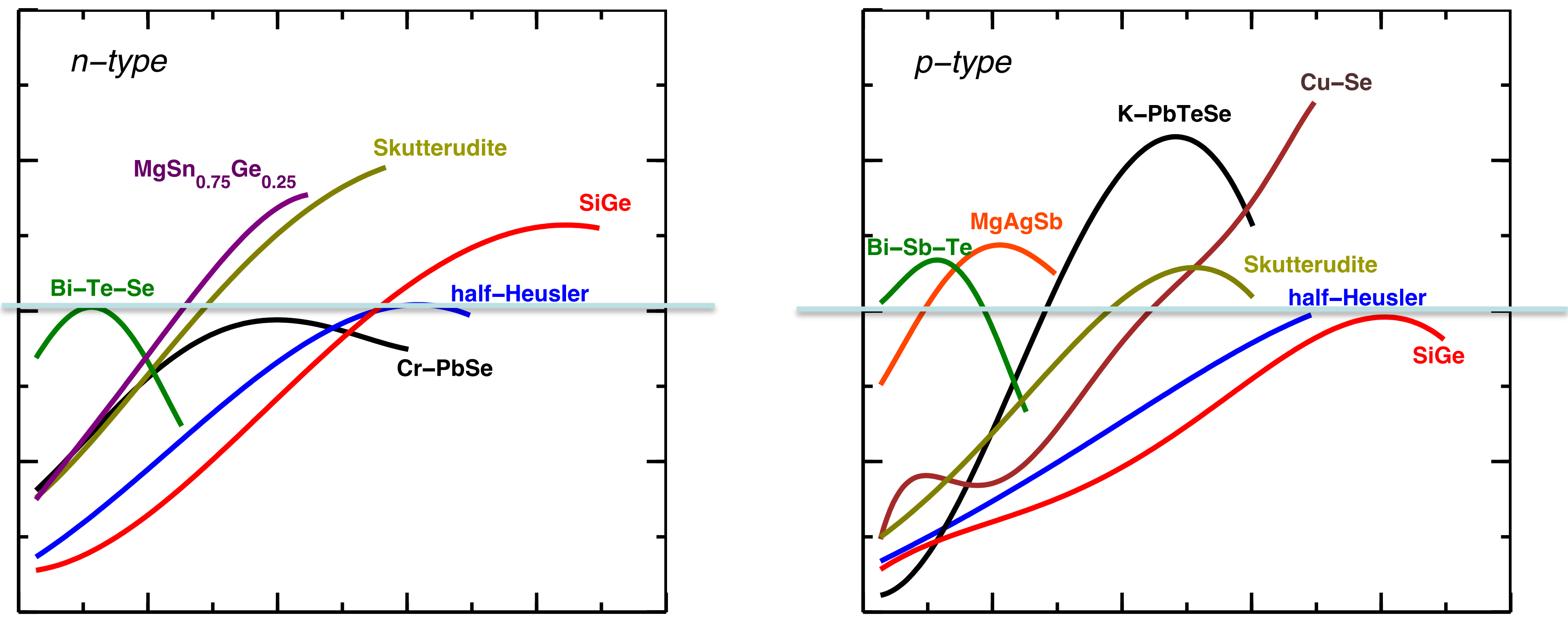




Nano Bi_2Te_3

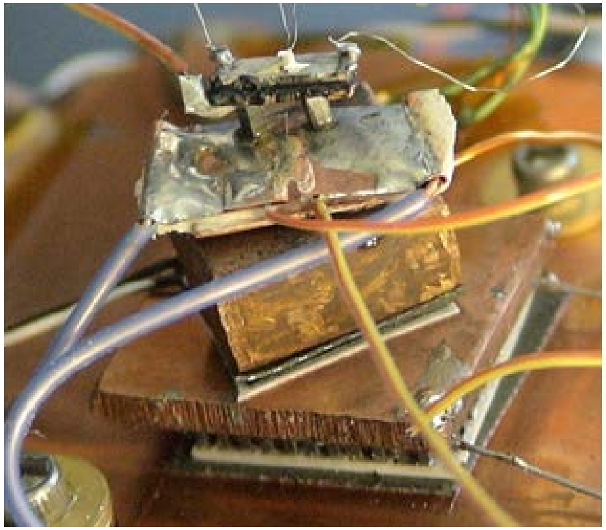
Poudel et al. Science, v. 320, p. 634, 2008

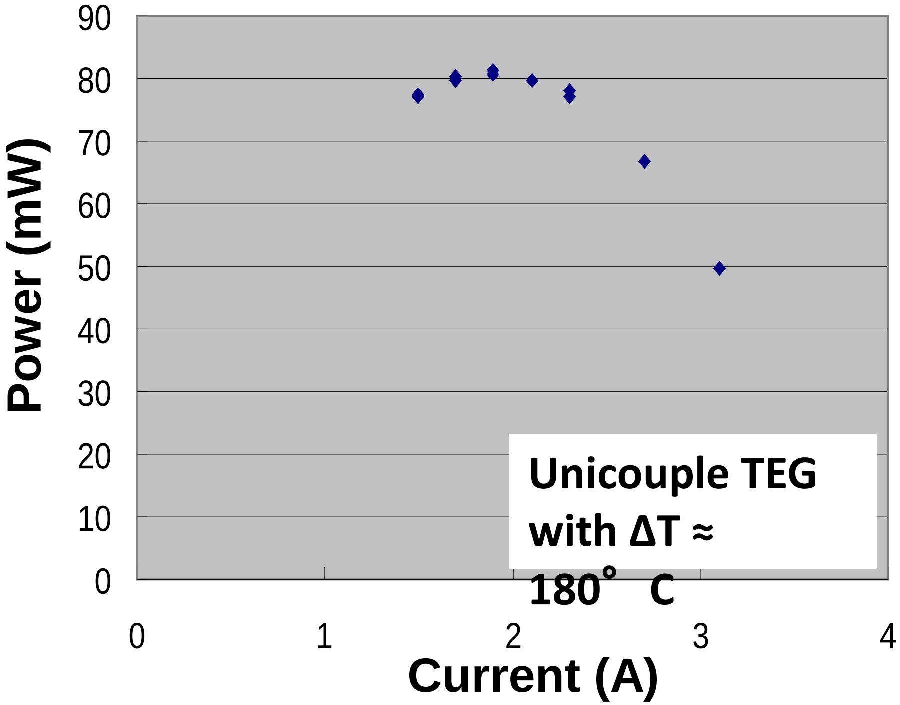
Materials ZT Improvements



From Z.F. Ren

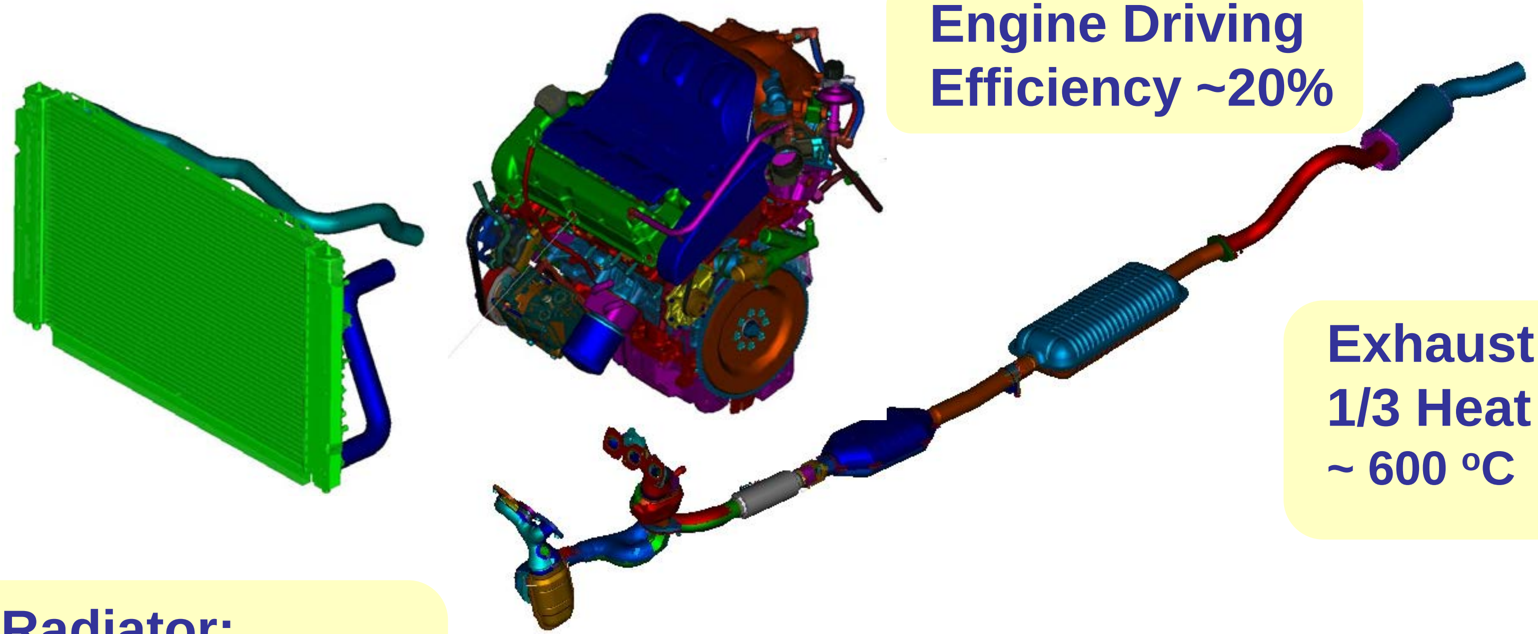
Power and Cost Example





- Dimensions of TE elements: 1.5mm x 1.5 mm x 1.6 mm
- Material cost per power output ≈ 0.1 $/Watt
- Cost of TE material can be small relative to total system cost!

Vehicle Waste Heat Recovery



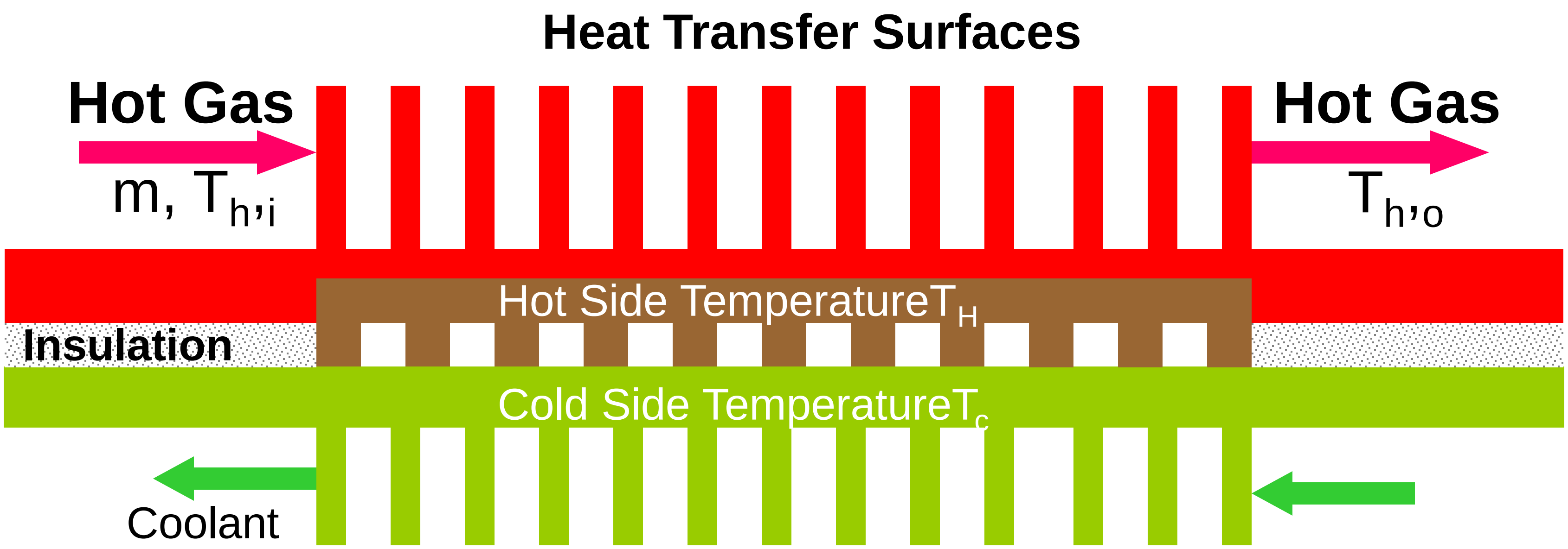
Engine Driving Efficiency ~20%

Exhaust:
1/3 Heat Wasted
~ 600 °C

Radiator:
1/3 Heat Wasted
T_{hot} ~ 80 °C

How Much We Can Really Recover?
What Temperature Range?

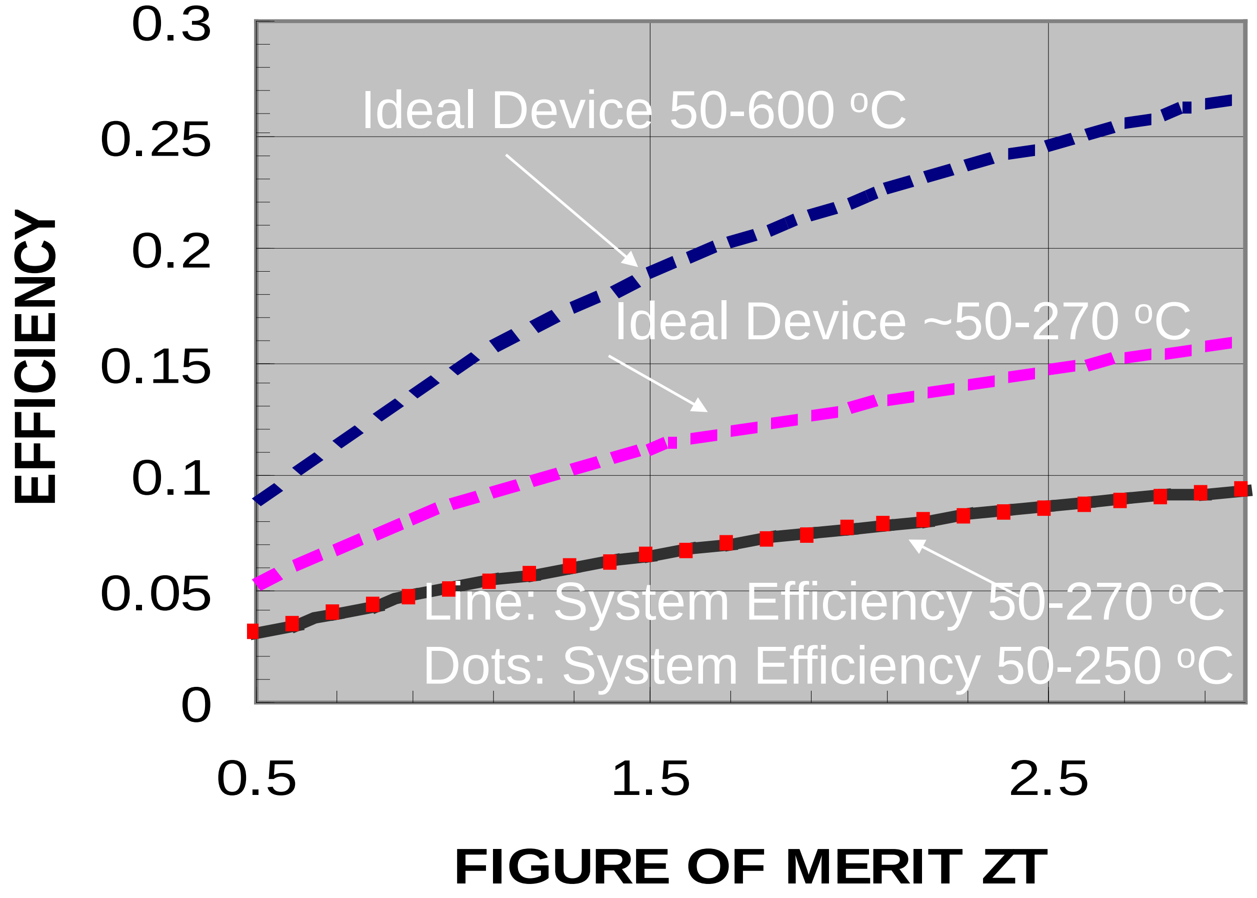
Heat to Electricity Recovery from Gas Stream



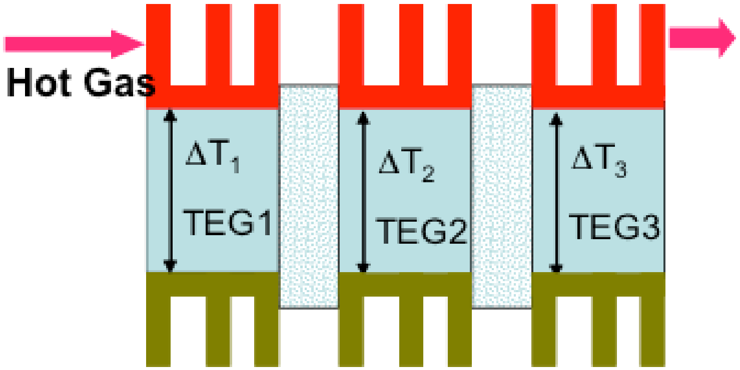
- **For thermoelectric devices, T_H higher is better**
- **However, maximum heat intercepted from hot gas stream, $mc_p(T_{h,i}-T_H)$, decreases with T_H**

Efficiency Expectations

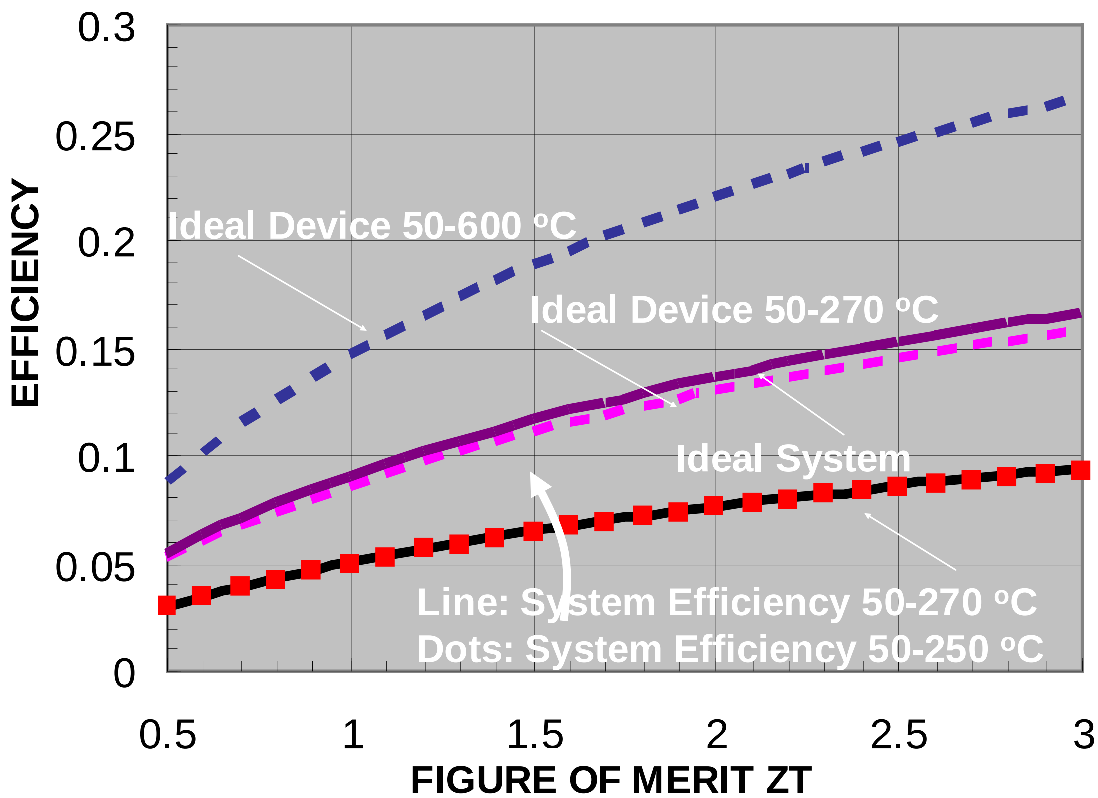
- $T_{h,i}$=600 °C, T_c=50 °C
- Optimal Hot Side Temperature ~ 270 °C



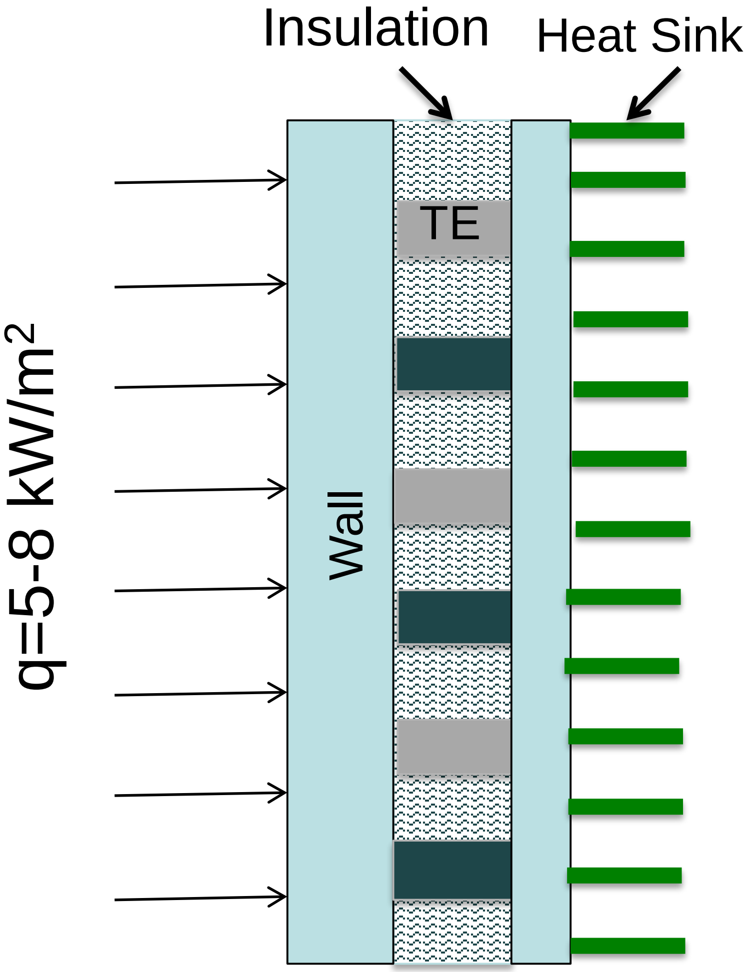
Locally Optimized Systems



- 1-3% Absolute Efficiency
- 5-20% Fuel Saving
- Engineering Room
- Materials Development
- 10% Cogeneration System



Heat Rejection



Current: T_{air}=25 ^{o}C
T_{hot}~400 ^{o}C

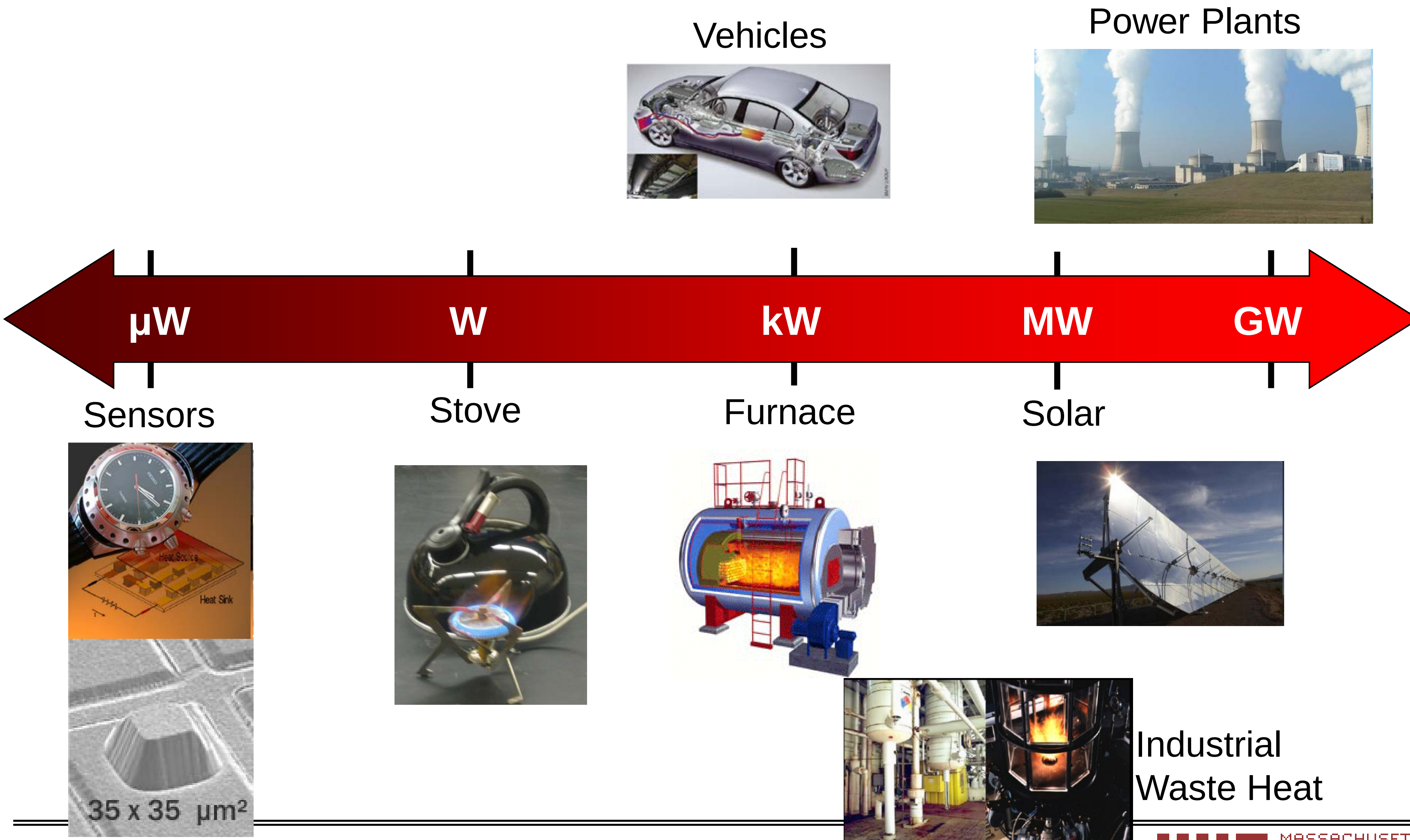
$$q = k\frac{\Delta T}{L} \approx 1\frac{\mathrm{W}}{\mathrm{m} * \mathrm{K}}\frac{100\,\mathrm{K}}{\mathrm{L}}$$

q=5000 W/m^2 ; L=20 mm

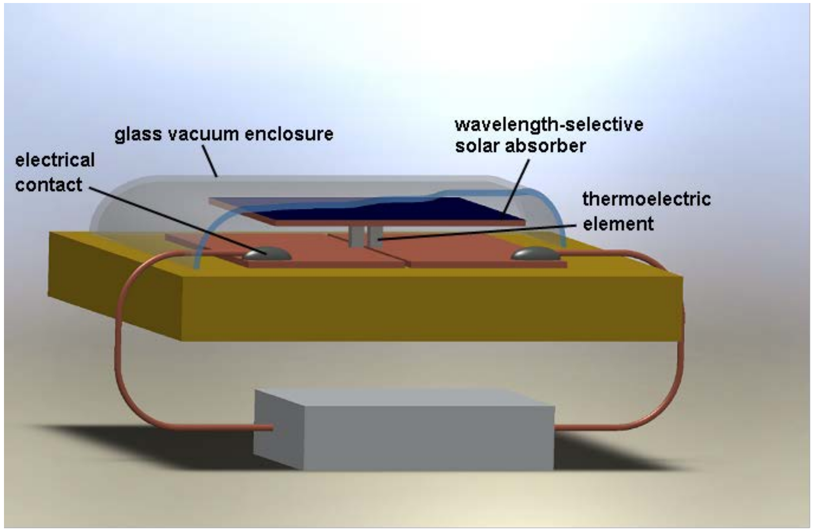
- Too expensive!

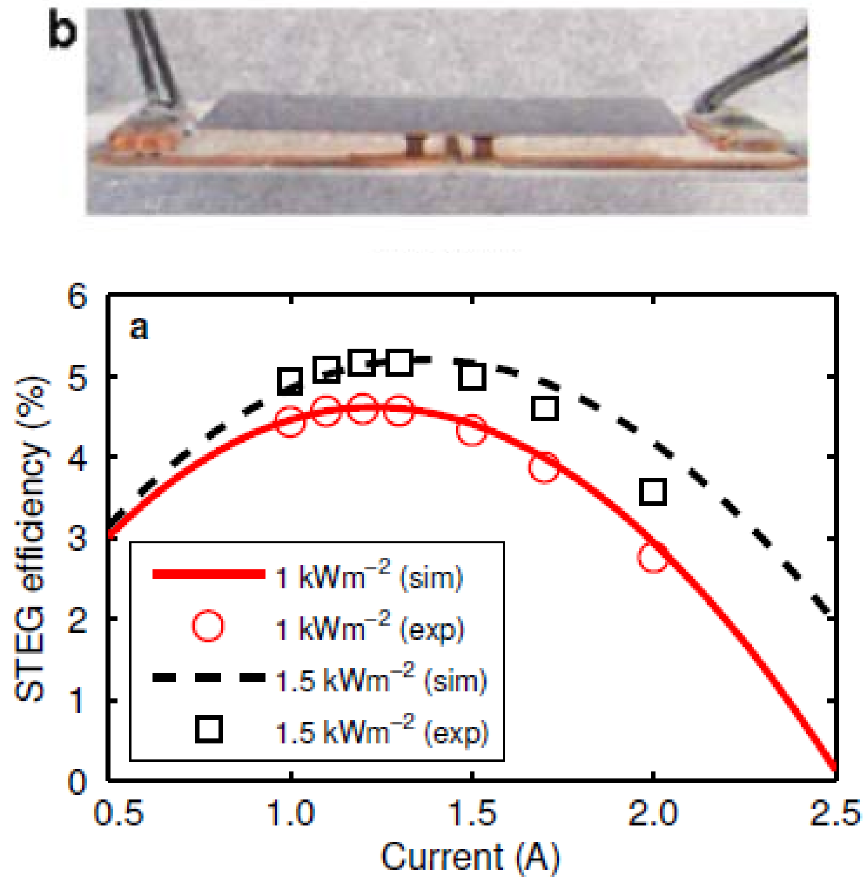
- What are TE filling fractions
- What are insulation requirement
- What are heat sink requirement
- What are system cost

From Micro Watts to Giga Watts



Solar Thermoelectric Power Generator (STEG)





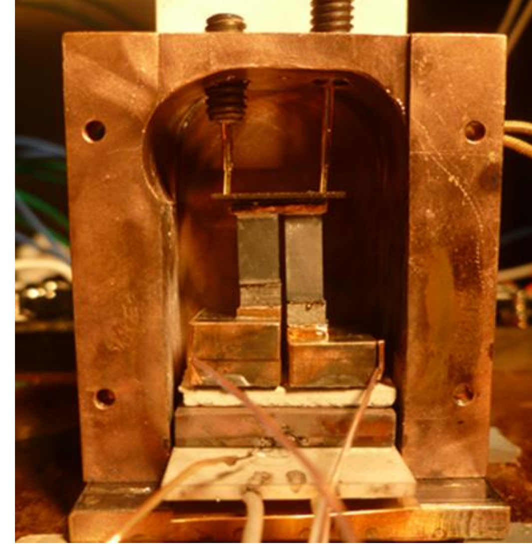
$$q = k\frac{\Delta T}{L} \approx 1\frac{\mathrm{W}}{\mathrm{m} * \mathrm{K}}\frac{100\,\mathrm{K}}{\mathrm{L}}$$

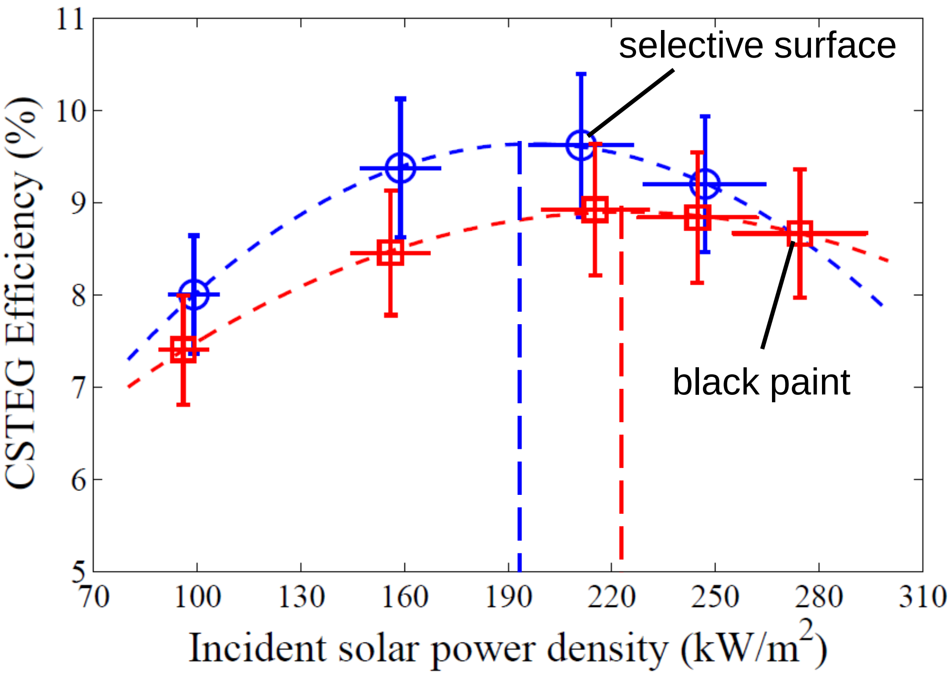
q=1000 W/m^2 (1 Sun); L=100 mm

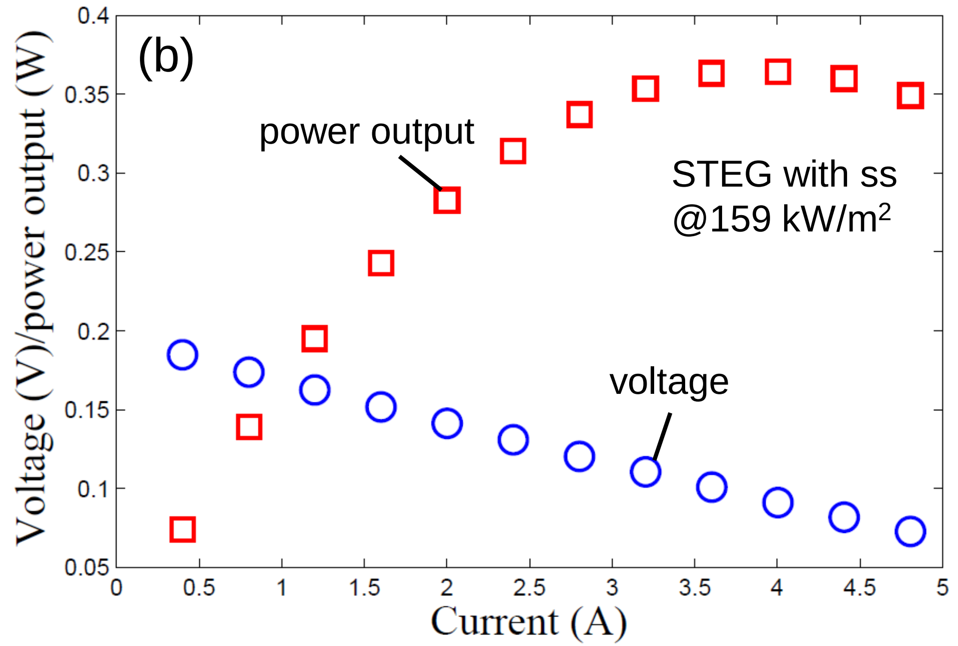
q=100,000 W/m^2 (100 Sun); L=1 mm

Kraemer et al., Nature Materials, 10, 523, 2011

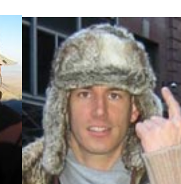
Segmented TE Device







Kraemer et al., Nature Energy, 1, 16153, 2016.



Summary

- Waste heat is everywhere.
- System thinking is crucial, heat collection and rejection subsystems should be considered for successful deployment.
- Applications could also be where large entropy is generated.
- Excellent progress in materials, challenges are taking materials to devices and systems that can penetrate market.