Thermoelectricity: From Atoms to Systems

Week 4: Thermoelectric Systems

Lecture 4.2: Thermoelectric cost/efficiency Trade off

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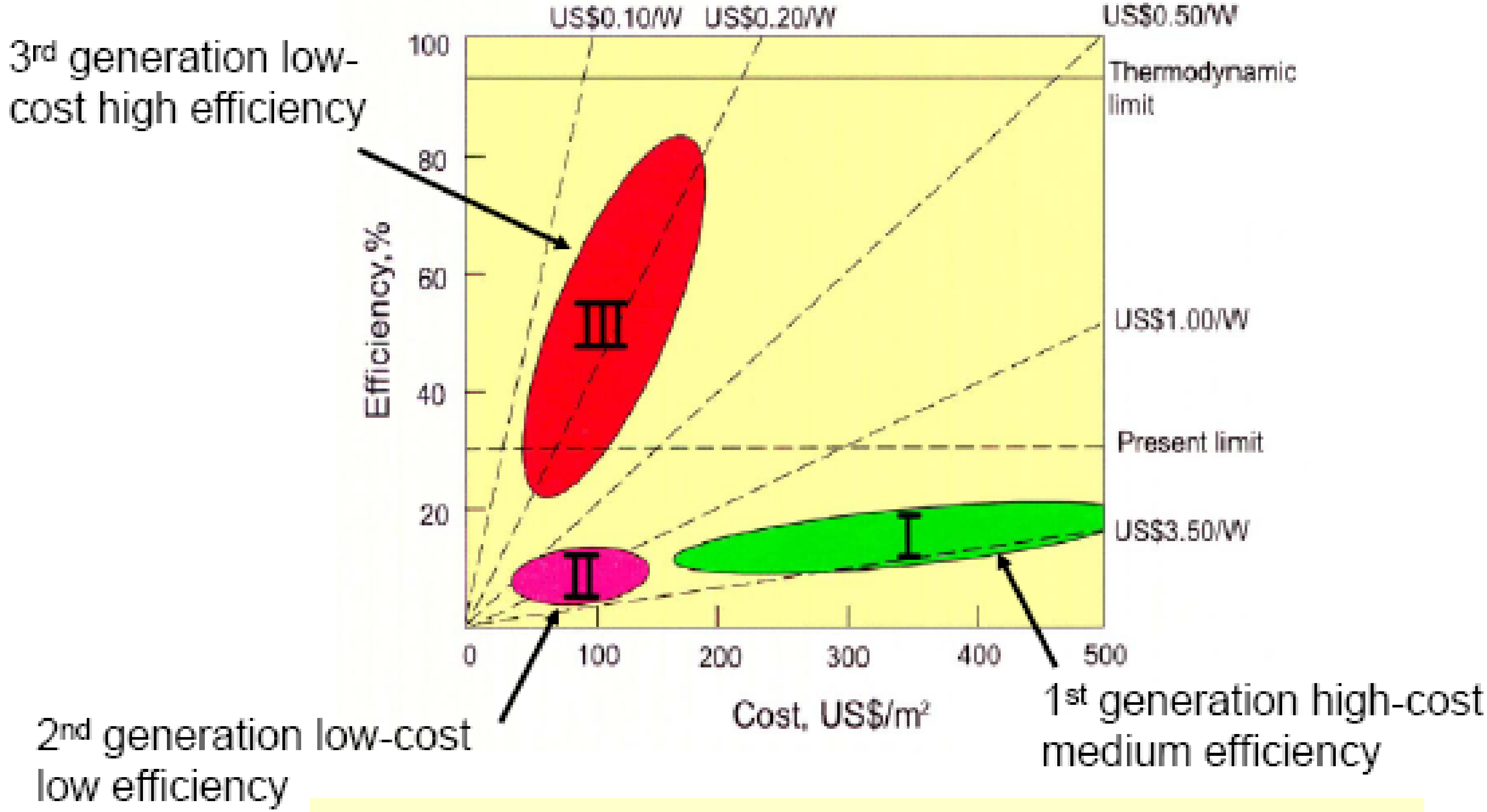
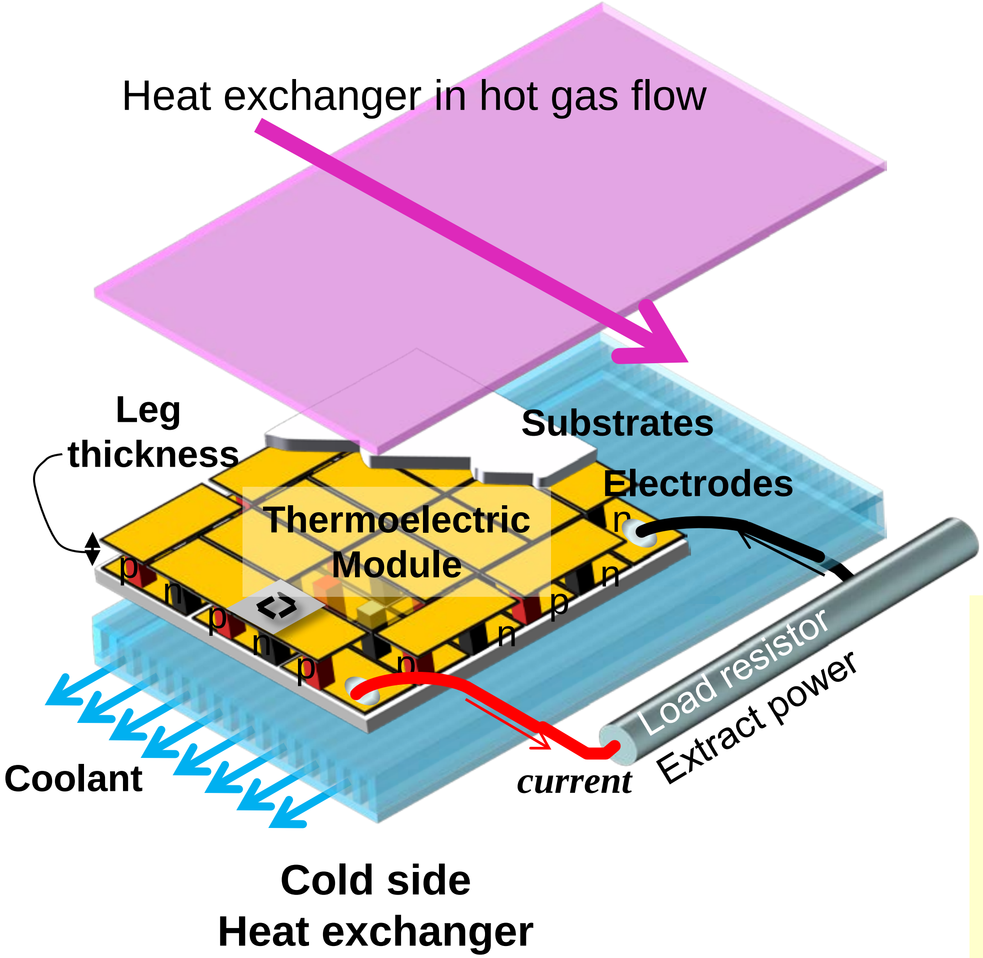
Solar Cells

(Efficiency+ Cost → $/W)



We need to estimate the cost of TE system per surface area of the heat source ($/m^2)

Model of TE module + heat exchanger for cost/efficiency trade off analysis



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K. Yazawa and A. Shakouri, Env. Science and Technology (July 2011)

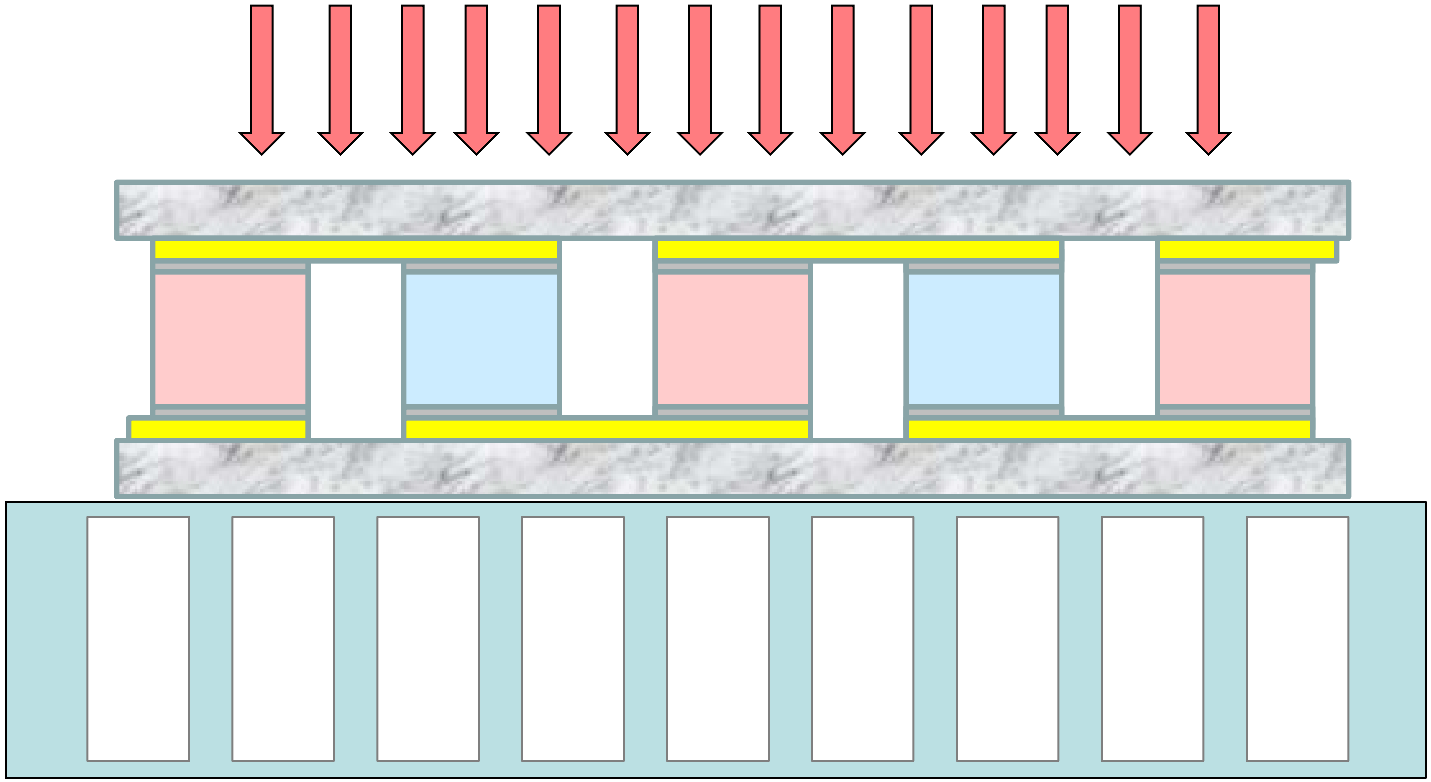
J. Appl. Phys. 111, 024509 (2012)

TE module and the heat sink need to be co-optimized to get the highest output power (thermal impedance matching).

TE module & cold side heat exchanger for waste heat recovery

T_{source} , Input heat flux

TE Module

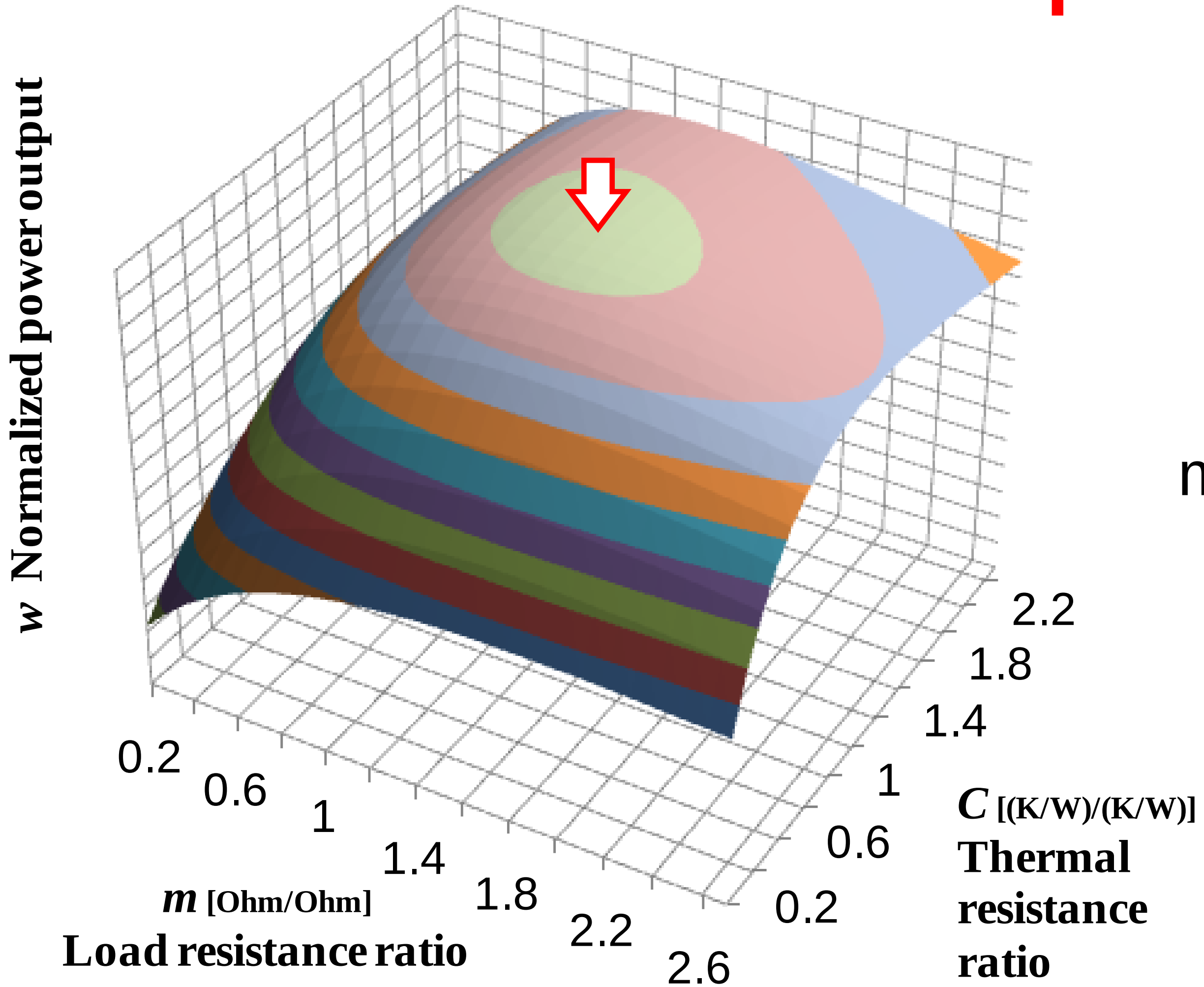


Heat Sink
(e.g. microchannel)

$T_{ambiant}$

Yazawa and Shakouri, Env. Science and Technology (July 2011)

Thermal-electrical co-optimization



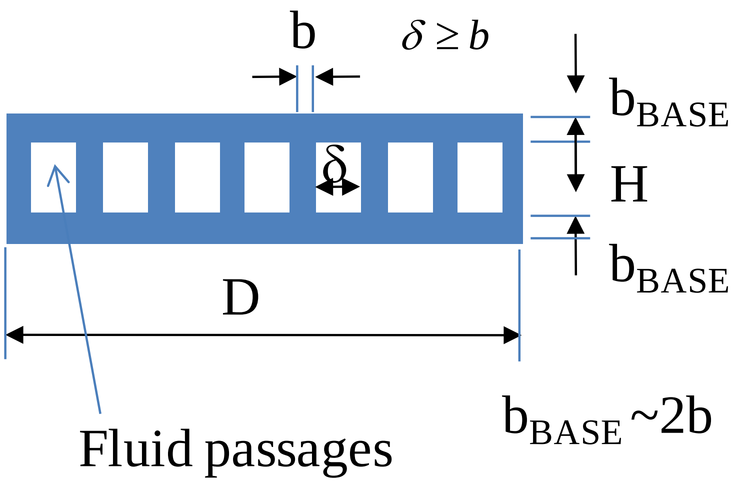
$$m = \sqrt{1 + Z\overline{T}}$$

Peak is found at m=1.4 & C=1.4 for ZT=1

K. Yazawa and A. Shakouri, Env. Science and Technology (July 2011)

Heat sink optimization

Micro-channel heat sinks



L:length of channel

$$U_{BASE} A_{BASE} = 1/\left(\frac{1}{2\rho C_p G} + \frac{1}{U_{fin} A_{fin}}\right)$$

Matched pumping power

$$w_{pp} = 3\mu\left(\frac{N_u k_f}{\rho C_p}\right)^2 \frac{(H+\delta)^6}{(b+\delta)(H\delta)^5} L^2$$

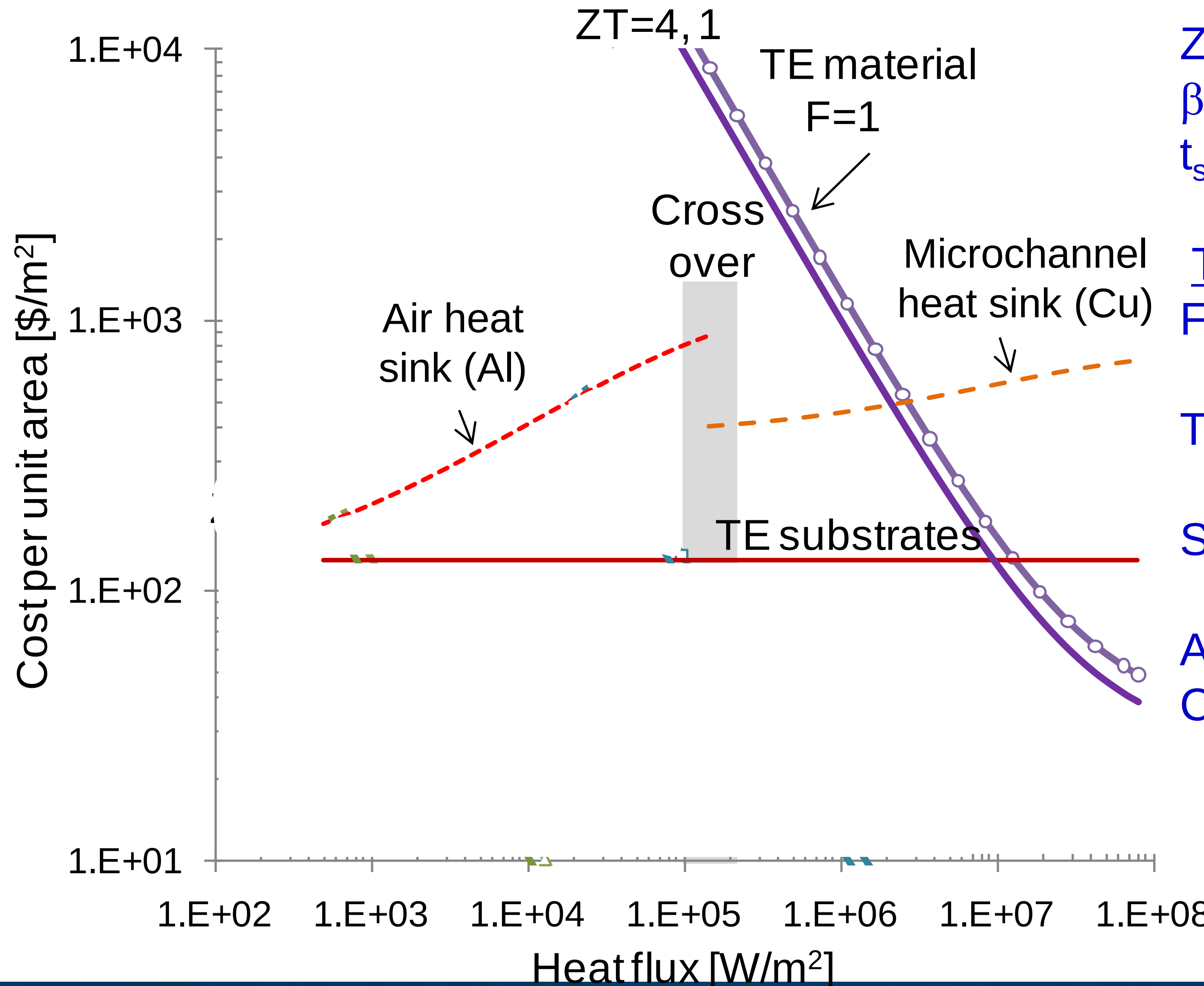
Nusselt number

$$Nu = 4.52 * (1 - \delta / H)^{3.78} + 2.98$$

Optimum design: matched resistance based on convection from fin surface and sensitive heat of fluid.

Yazawa and Shakouri, Env. Science and Technology (July 2011)

Components of TE system (cost per unit area)



ZT=1, β=1.5 W/mK
β_{sub}=100 W/mK
t_{sub}=0.2mm

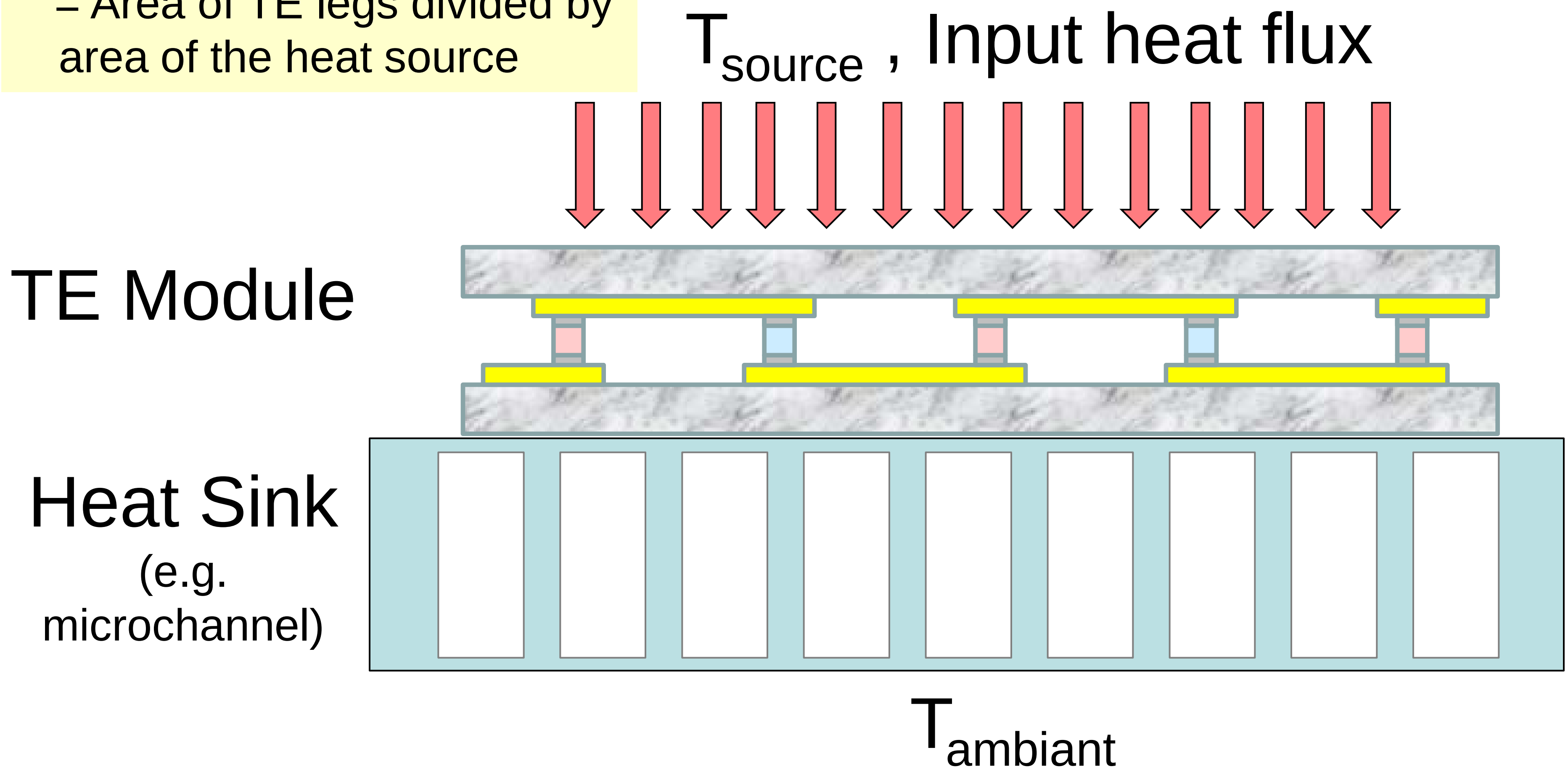
T_s=600K, T_a=300K
Fan efficiency 30%

TE (BiTe or PbTe): $500/kg
Substrate-AlN: $100/kg
Al: $8/kg
Cu: $20/kg

K. Yazawa and A. Shakouri, Env. Science & Technology (July 2011)

Use of heat spreading inside TE module (thermal concentration)

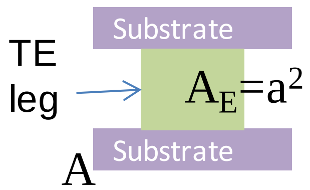
F= Fractional area coverage
= Area of TE legs divided by area of the heat source

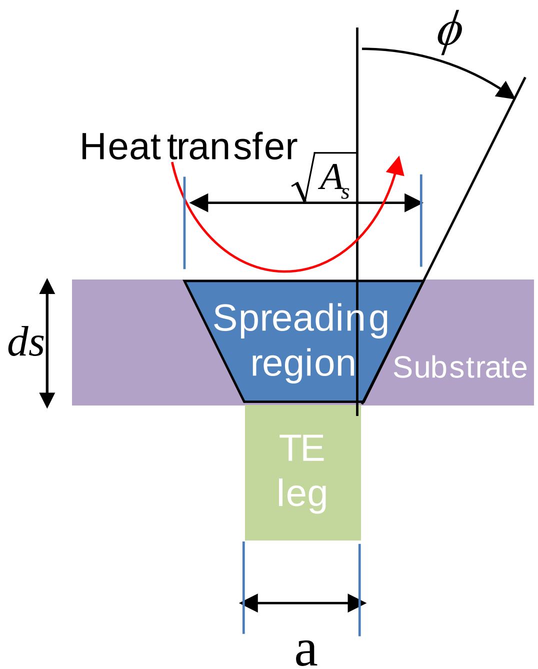


Yazawa and Shakouri, Env. Science and Technology (July 2011)

Fractional area factor

Heat concentration => Less TE material use





Spreading thermal resistance,

$$\psi_{sh} = \psi_{sc} = \frac{\lambda}{\beta_s a(1 + 2\lambda \tan\phi)}$$

where angle ϕ is,

$$\begin{cases} \phi = 5.86 \ln(\lambda) + 40.4 & 0.0011 < \lambda \le 1 \\ \phi = 46.45 - 6.048\lambda^{-0.969} & \lambda \ge 1 \end{cases}$$

$$\lambda = d_s / a$$

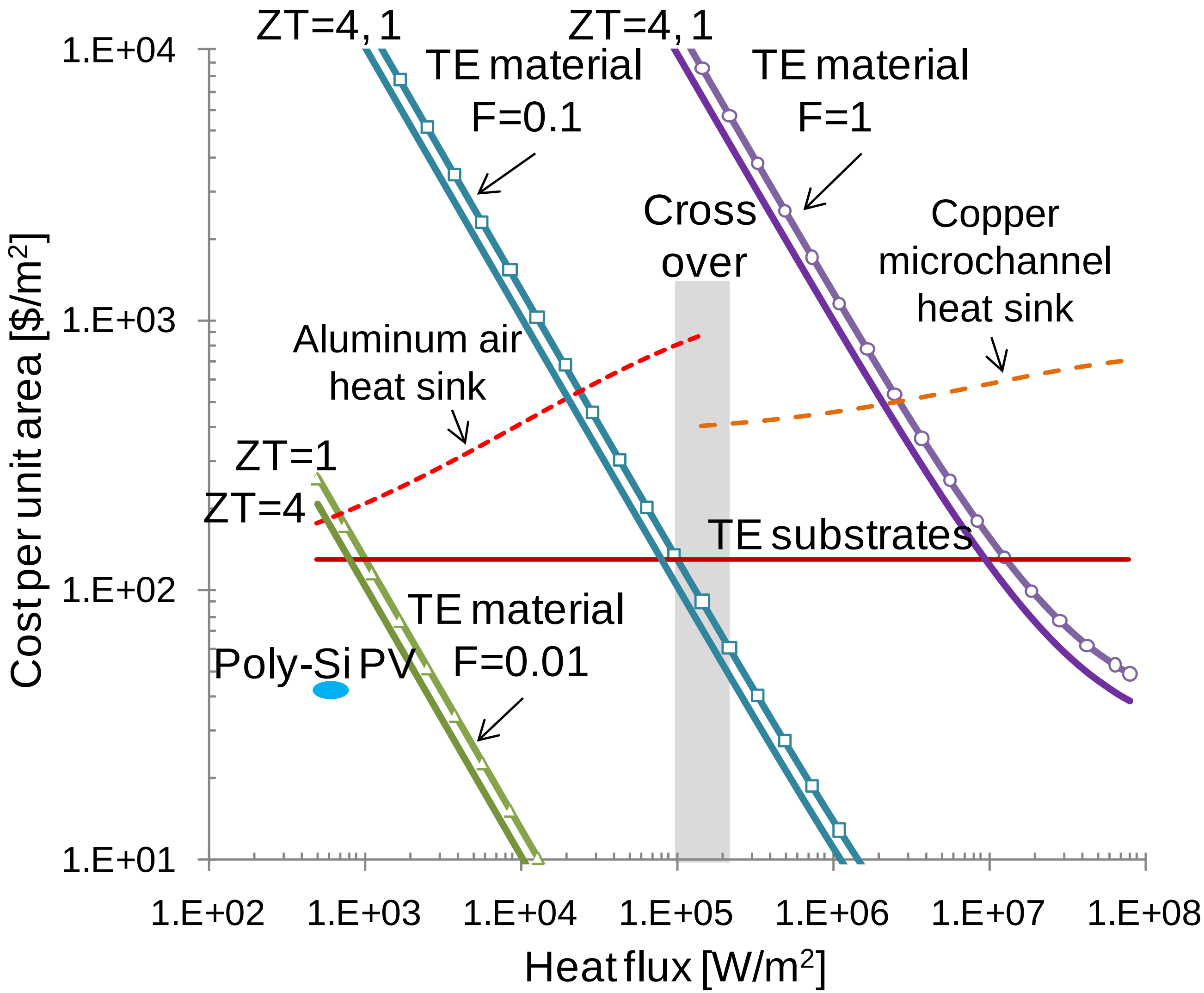
Vermeersch et al, J of HT, 2008

$$F = \left(1 - \frac{2d_s \tan\phi}{a}\right)^2$$

F: fractional area factor (Fill factor)

Yazawa and Shakouri, Env. Science and Technology (July 2011)

Cost per unit area for TE bottom cycle waste heat recovery (TE module + heat sink)



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K. Yazawa and A. Shakouri, Env. Science & Technology (July 2011)

- Fractional area coverage in TE module plays a big role to reduce the overall cost.
- High input heat fluxes require much less TE material (thermal impedance matching)

TE Module/Heat Sink Material Cost per Watt (car exhaust application)

Yazawa & Shakouri; Journal of Material Research 2012

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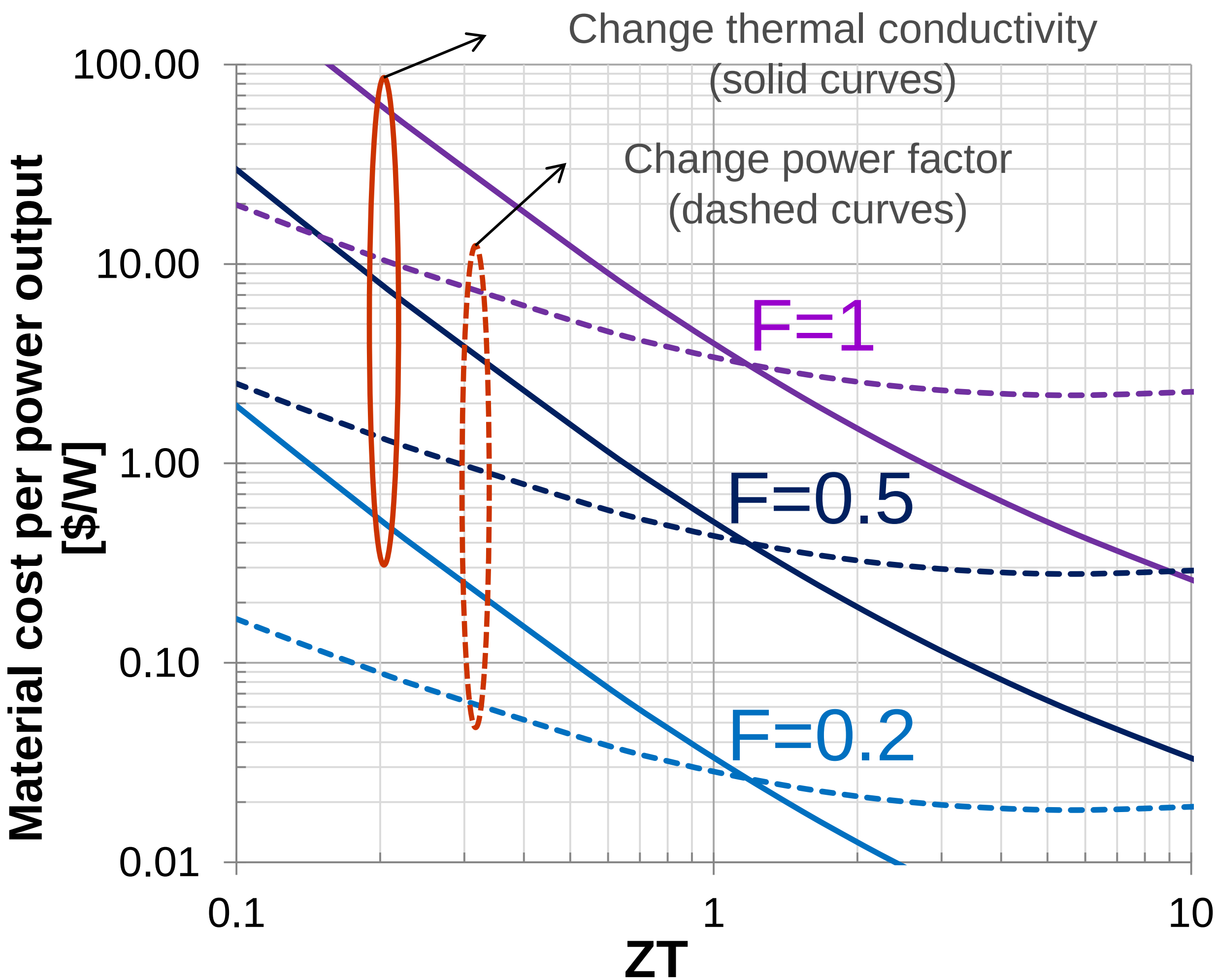


ZT=1, β=1.5 W/mK,
β_{sub} =23 W/mK,
t_{sub} =0.2mm,

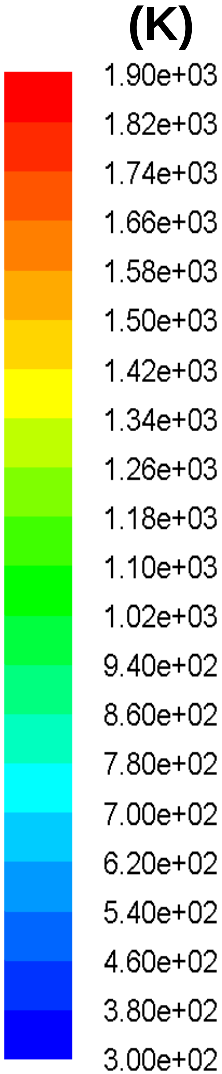
Ts=900K, Ta=330K,
Pump efficiency 30%

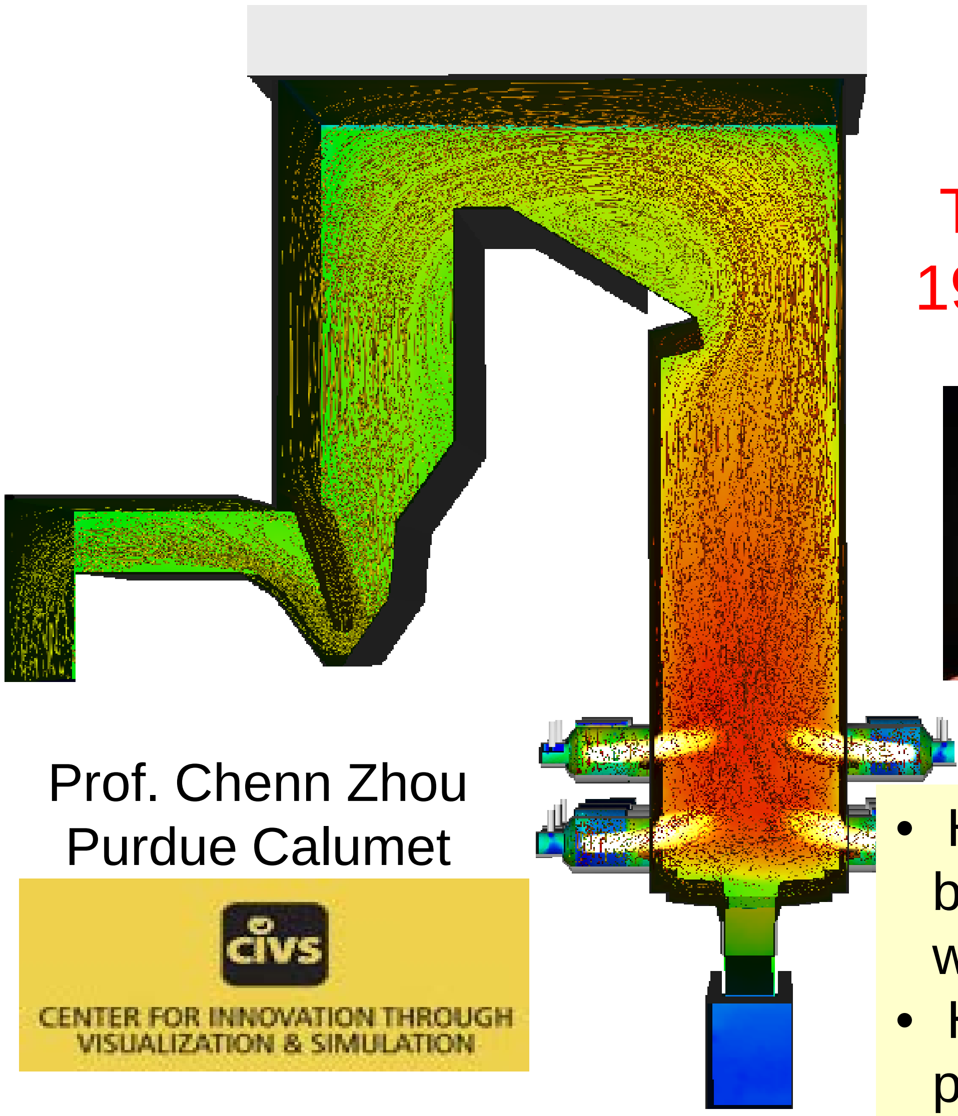
TE: $500/kg,
Alumina substrate: $ 5/kg,
Copper heat sink: $ 20/kg

U_h=4.6x10^{2}W/m^{2}K
U_c=1.5x10^{3}W/m^{2}K (U_c/U_h=0.3)

- TE material with ZT=0.5-1 can have a big impact in high heat flux waste heat recovery applications if the source of heat is free (neglect impact on the topping cycle).

TE for topping cycle applications





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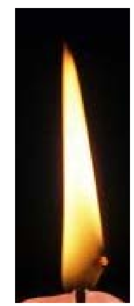
Coal Power Plant

T_{hot}= 1900K

$T_{interface}$

$T_{ambient}$

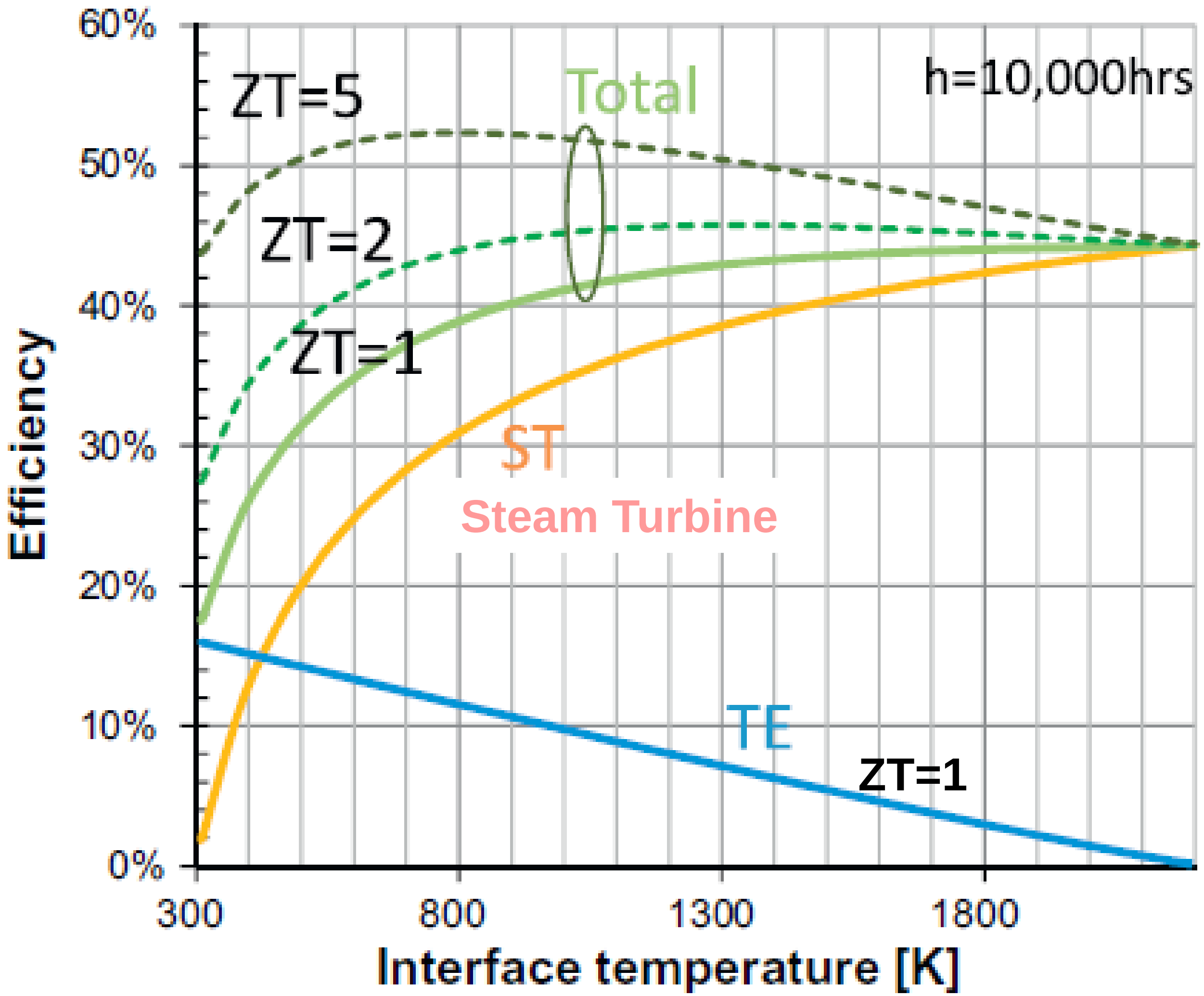


TE System

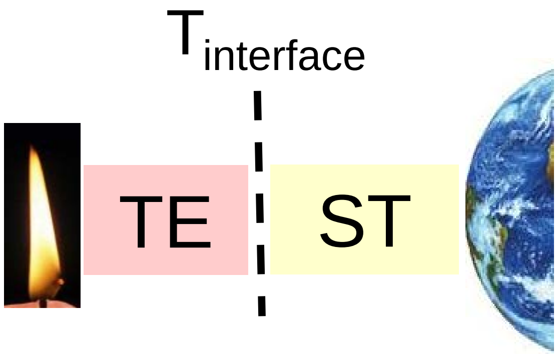
Rankine cycle

- Highest exergy lost is between the flame and the working fluid (steam).
- Highest steam temperatures/ pressures are limited by the turbine materials.

TE / Steam Turbine combined cycle



Yazawa & Shakouri,
***Applied Energy*, 2013**

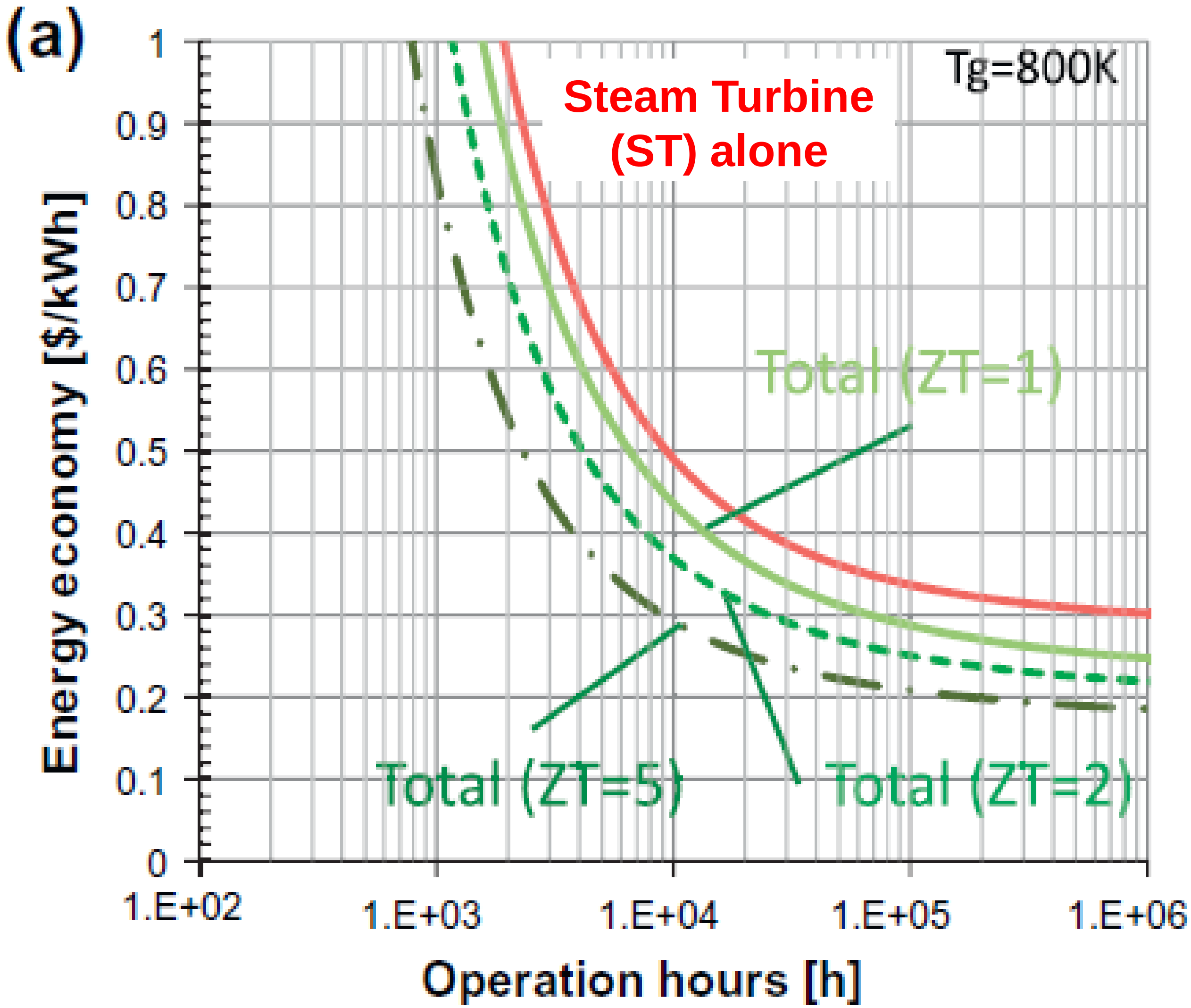


Simplified Steam Turbine Model

Assuming baseline performance for steam turbines.

- With today's steam temperatures (775-825K), material with ZT=0.3-1 can have a big impact to increase the overall power plant efficiency (+2.6% to +8.2%).

TE/Steam Turbine Energy Cost

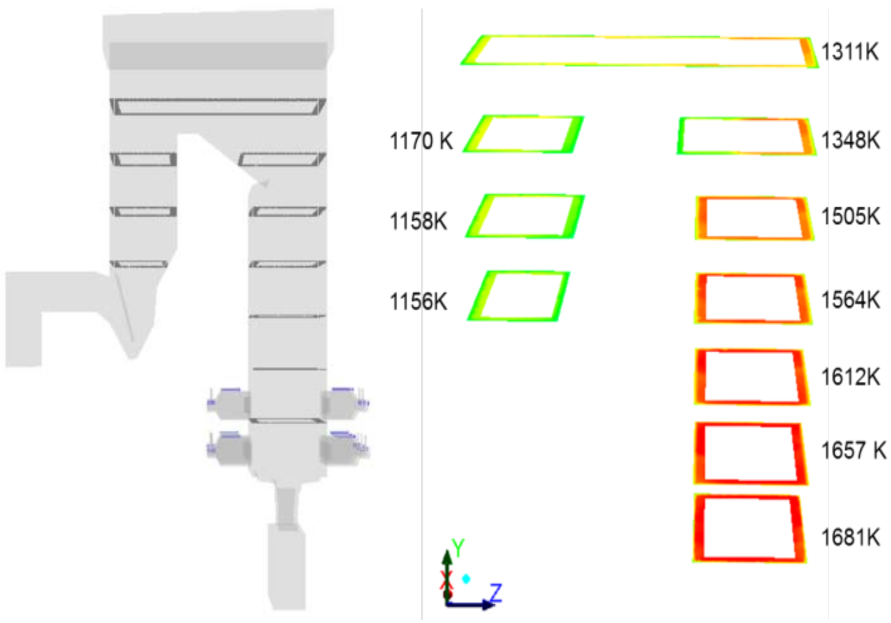


Yazawa & Shakouri, *Applied Energy*, 2013

Simplified Steam Turbine Model

Material with ZT=0.3-1 (even at a cost of $500/kg) can have a big impact to improve the energy economy of the TE topping cycle power plants.

Detailed Coal-Fired Power Plant Model



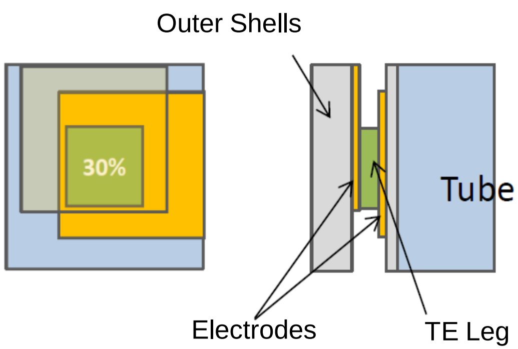
Supercritical steam turbine with 520 MW_e power output, efficiency ~40-42%

A. Silaen et al.

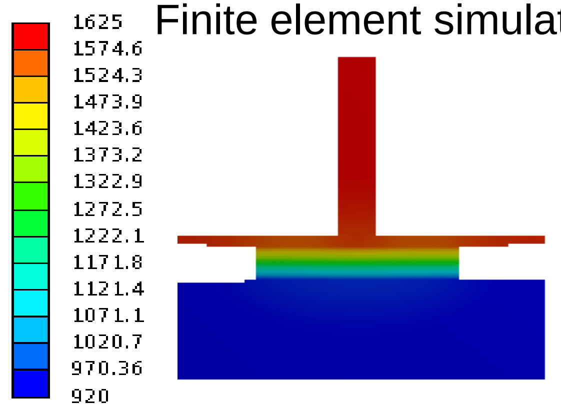
To be published in **Proceedings of the ASME 2013 4th Micro/Nanoscale Heat & Mass Transfer International Conference**

December 11-14, 2013, Hong Kong

TE integration on boiler tubes



Finite element simulation



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- TE module optimized based on temperature and heat flux at each location on the wall of the boiler.

Topping Cycle TE Coal-Fired Power Plant

	Gas Temperature (K)			
	1680	1500	1300	1150
Leg thickness (mm)	0.3	0.4	0.5	0.55
Fin height (mm)	4.3	4.4	3.8	3.4
T_h (K)	1439.8	1284.4	1104.1	977.1
T_c (K)	1213.4	1067.6	927.2	842.8
ZT	0.88	0.78	0.73	0.61
$w_{TE,leg}$ (W/m^2)	4.17×10^4	2.88×10^4	1.54×10^4	8.08×10^3
w_{TE} (W/m^2)	1.65×10^4	1.14×10^4	6.10×10^3	3.21×10^3
η_{TE}	3.5%	3.4%	2.8%	2.1%
w_{steam} (W/m^2)	2.26×10^5	1.62×10^5	1.07×10^5	7.36×10^4
w_o (W/m^2)	2.26×10^5	1.62×10^5	1.07×10^5	7.36×10^4
w_{total} (W/m^2)	2.42×10^5	1.74×10^5	1.13×10^5	7.68×10^4
Δw	7.1%	7.0%	5.6%	4.4%

TE leg thermal conductivity (β)	1.5	W/m-K
TE leg electric conductivity (σ)	25000	1/Ω-m
TE density (ρ)	8200	kg/m^3
TE leg Seebeck coefficient (S)	2×10^{-4}	V/K

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- TE with today's bulk material can increase power generated in different areas of the boiler by 4.4-7.1%. **The overall efficiency of the power plant can increase by ~7%.**

Lecture 4.2: Summary

- Cost/efficiency trade off:
  - Importance of heat sink and load resistance co-optimization
- New TE module designs can lower the cost significantly
  - Fractional area coverage of TE elements => heat concentration inside the module)
- High temperature topping cycle thermoelectrics with moderate ZT~0.3-1 can improve power plant efficiency by 2-8%