Efficiency, Cost and Weight Trade-off in TE Power Generation System for Vehicle Exhaust Applications

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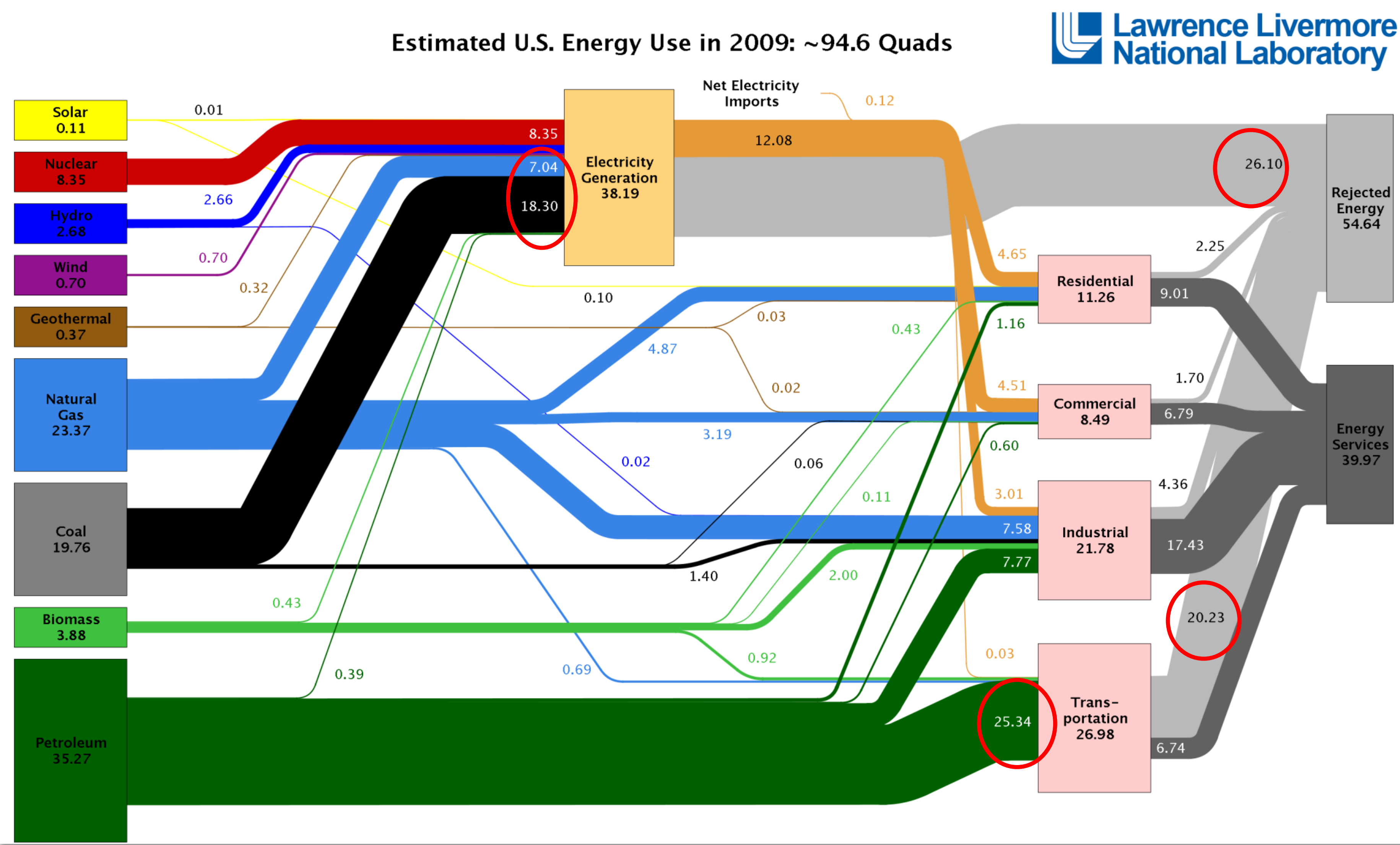
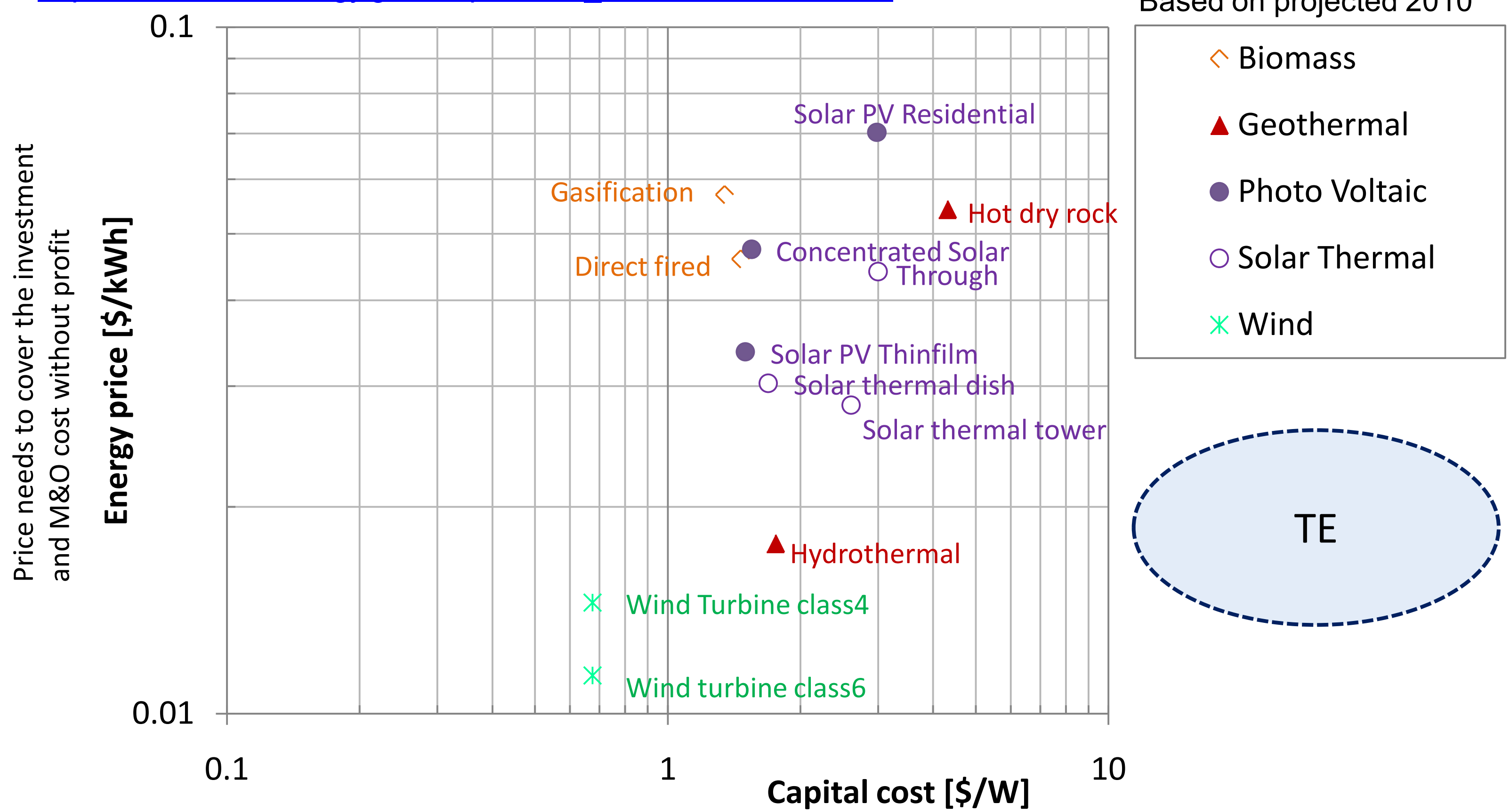
Background



Estimated U.S. Energy Use in 2009: ~94.6 Quads
Lawrence Livermore National Laboratory
Solar 0.11
Nuclear 8.35
Hydro 2.68
Wind 0.70
Geothermal 0.37
Natural Gas 23.37
Coal 19.76
Biomass 3.88
Petroleum 35.27
0.01
8.35
2.66
0.70
0.32
7.04
18.30
Electricity Generation 38.19
Net Electricity Imports
0.12
12.08
26.10
Rejected Energy 54.64
2.25
4.65
Residential 11.26
9.01
0.10
0.03
4.87
0.43
1.16
0.02
4.51
1.70
Commercial 8.49
6.79
Energy Services 39.97
3.19
0.02
0.06
0.60
0.11
3.01
4.36
Industrial 21.78
7.58
17.43
1.40
2.00
7.77
0.43
0.92
20.23
0.39
0.69
0.03
25.34
Trans-portation 26.98
6.74

Renewable energy sources

Reference: E.A. DeMeo and J.F. Galdo, 'Renewable Energy Technology Characterizations' , *DOE report TR-109496*, December, 1997
http://www1.eere.energy.gov/ba/pba/tech_characterizations.html



Investment (or Overnight cost to build a system) including materials, fixture and additional equipments

Performance/Cost in Applications

Wrist watch SEIKO

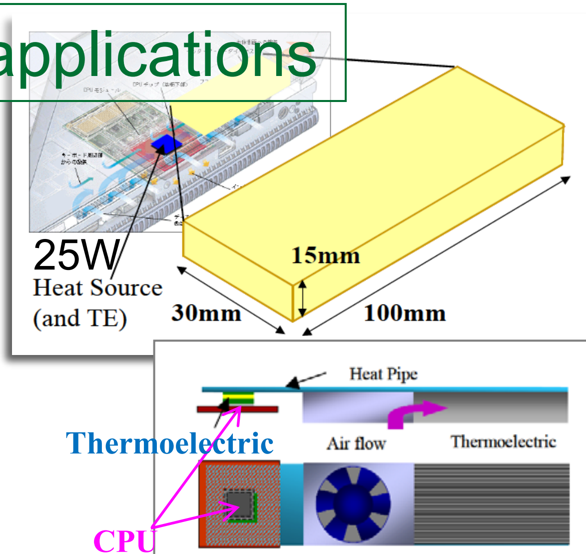
Extraterrestrial

Thermoelectric Power generation

Performance $\propto$? Efficiency

Specialized applications

Vehicle exhaust BMW-BSST



Fan drive by self heat in Laptop PC Yazawa et al

Body sensors Leonov et al

Material efficiency

$$\eta_{max} = \left[\frac{T_h - T_c}{T_h}\right] \cdot \left[\frac{(1+Z^*\overline{T})^{1/2} - 1}{(1+Z^*\overline{T})^{1/2} + 1}\right]$$

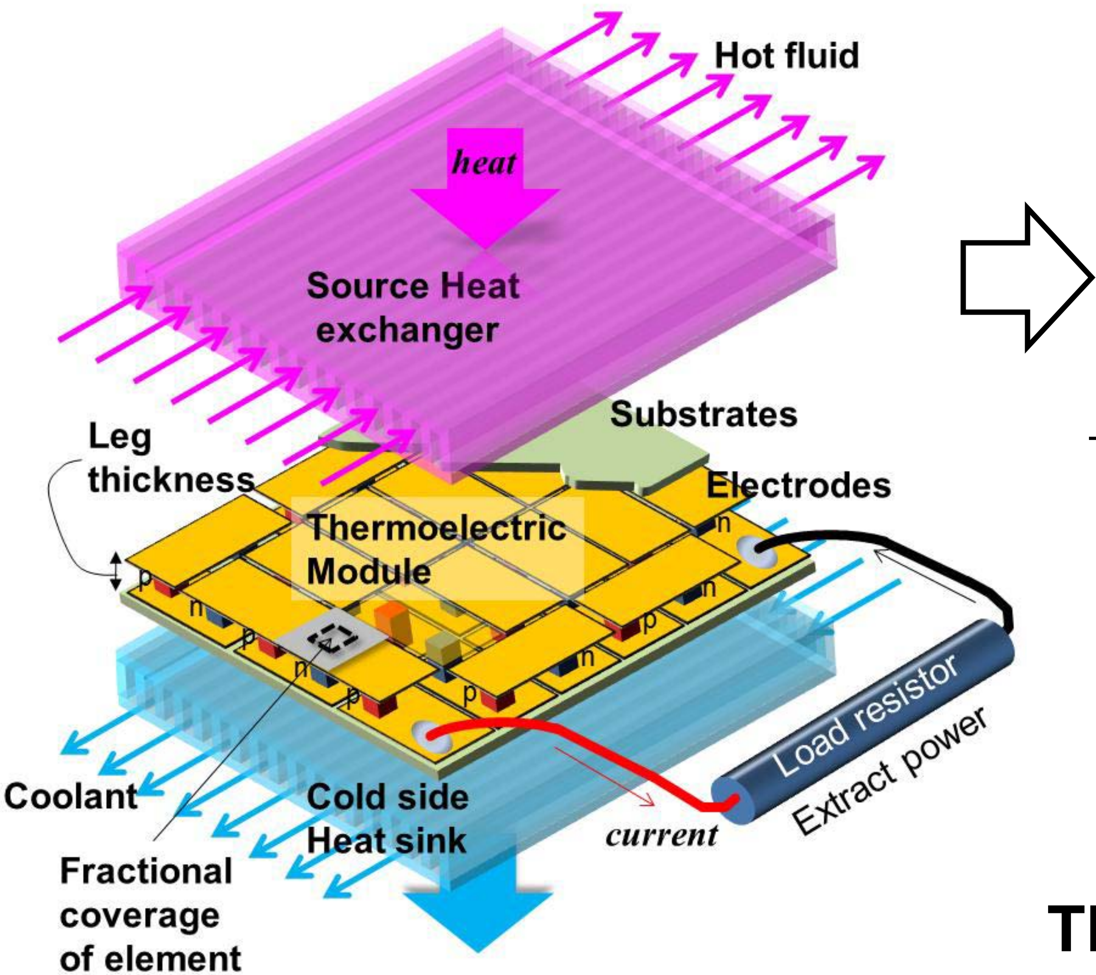
How?

Cost/Power [$/W]

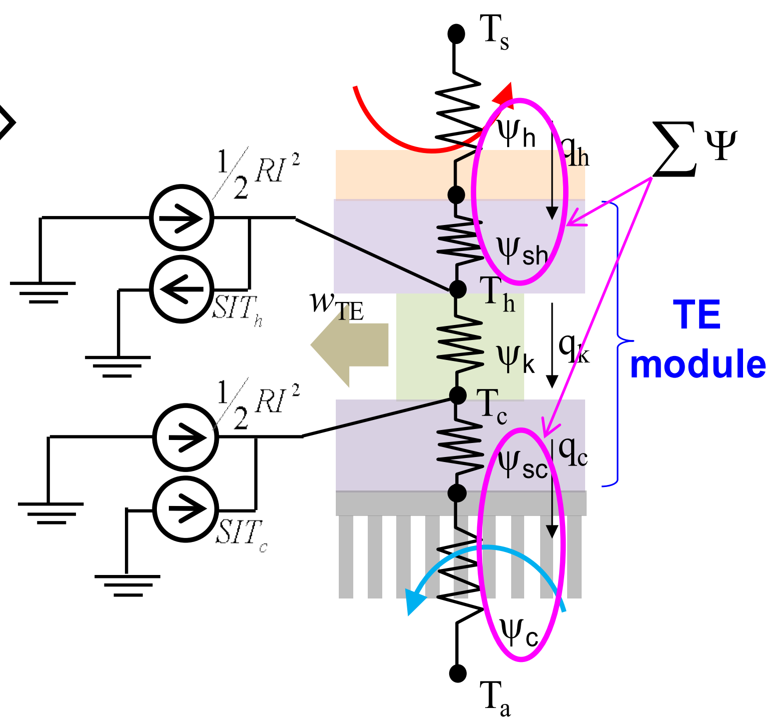
Energy Price

As a system

TE module and cold side



1D scalable model



Thermal network circuit

$\sum \Psi$ can include interface resistance

Model

Energy balance at each nodes,

$$(T_s - T_h) = \psi_h q_h = \psi_h \left(q_k + \frac{Z}{(1+m)^2} \frac{\beta}{2d} \left((2m+1) T_h + T_c \right) (T_h - T_c) \right)$$

$$(T_h - T_c) = \psi_k q_k$$

$$(T_c - T_a) = \psi_c q_c = \psi_c \left(q_k + \frac{Z}{(1+m)^2} \frac{\beta}{2d} \left(T_h + (2m+1) T_c \right) (T_h - T_c) \right)$$

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

d: leg length

Yields power density w

$$w = \frac{mZ}{(1+m)^2} \frac{d\beta}{\left(d + \beta \sum \psi X\right)^2} (T_s - T_a)^2$$

where,

$$X = \left(1 + \frac{Z}{2(1+m)^2} \left((2m+1) T_h + T_c \right) \right) \frac{\psi_h}{\sum \psi} + \left(1 + \frac{Z}{2(1+m)^2} \left(T_h + (2m+1) T_c \right) \right) \frac{\psi_c}{\sum \psi}$$

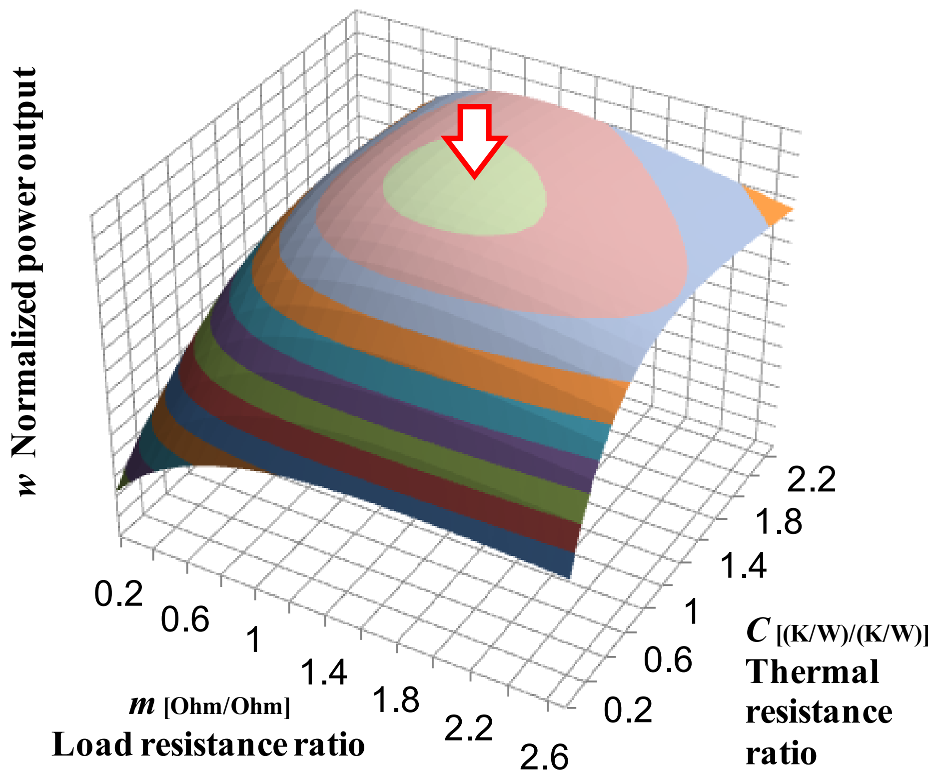
X is dimensionless factor

For special case $\psi_h = \psi_c$,

$$X = \left(1 + \frac{Z\bar{T}}{(1+m)} \right)$$

Maximum power output

Thermal-electrical co-optimization



Full optimization of parameters m and C.
Peak is found at m=1.414 & C=1.414 for ZT=1

Impedance match
(Electrical and Thermal)

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

Maximum power output

$$w = \frac{Z}{4(1+m)^2} \frac{1}{A\sum\Psi}(T_s - T_a)^2$$

Optimum leg length

$$d = m\beta A\sum\Psi$$

Smaller $\sum\Psi$ yields thinner element

K. Yazawa and A. Shakouri, 2010, “Energy Payback Optimization of Thermoelectric Power Generator Systems”, *Proceedings of ASME IMECE2010*, IMECE2010-37957

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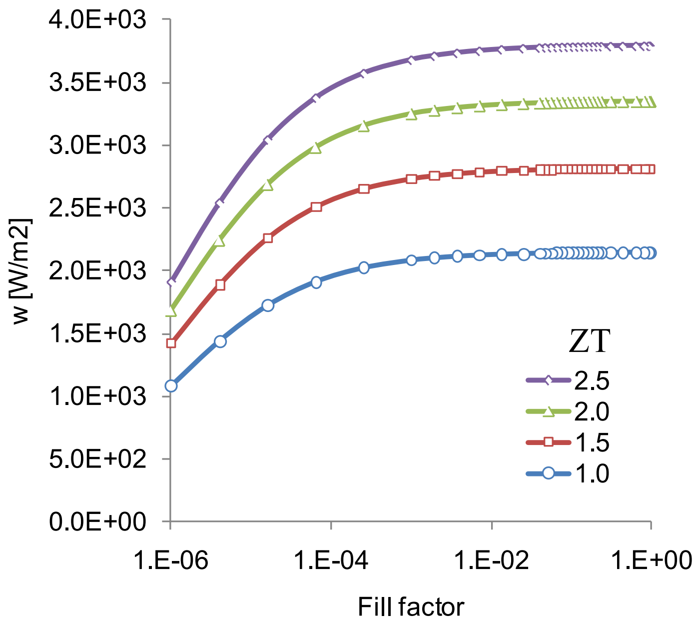
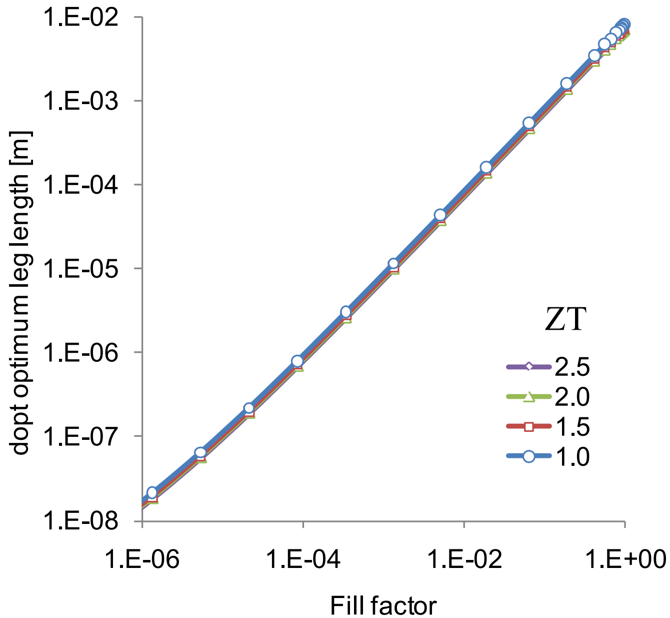
Fill factor impact on power

Power per unit substrate area doesn't change much, but volume of TE decreases a lot at low fill factors.



Power density vs fill factor



Optimum leg length vs fill factor

T_s=600 [K], T_a=300 [K], β_s=140 [W/mK],
d_s=0.2e-3 [m], U_h, U_c= 500 [W/m^{2}K]

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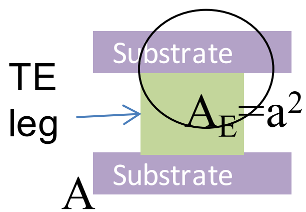
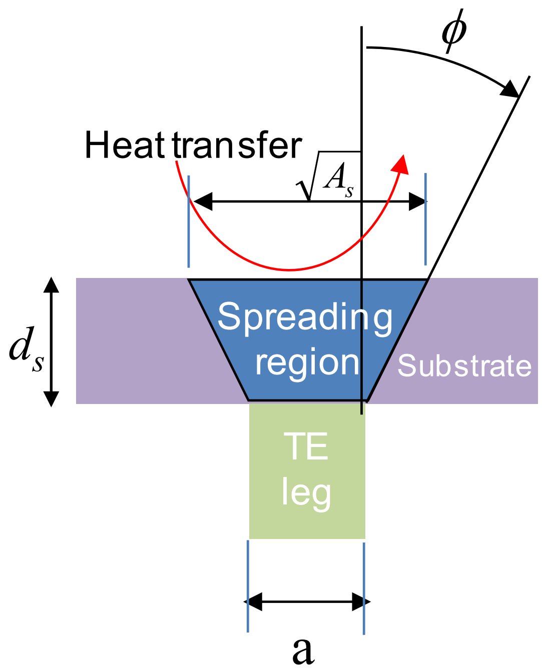
Fractional area factor

Trade-off impact of the TE element coverage area factor





Spreading thermal resistance,

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

where angle ϕ is,

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

Vermeersch et al, J of HT, 2008

and substrate thickness impact λ is,

$$\lambda = d_s / a$$

At Maximum square array packing,

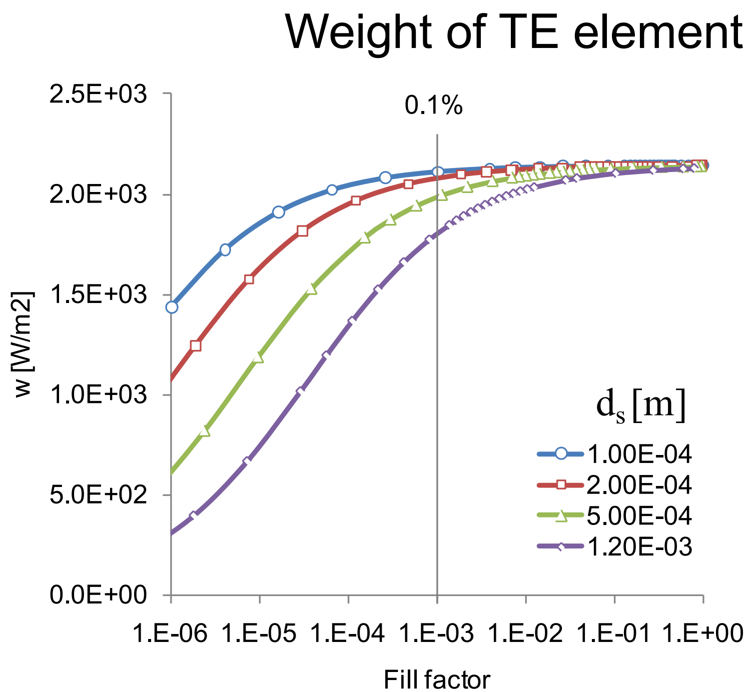
$$F = \left(1 - \frac{2d_s \tan\phi}{a}\right)^2$$

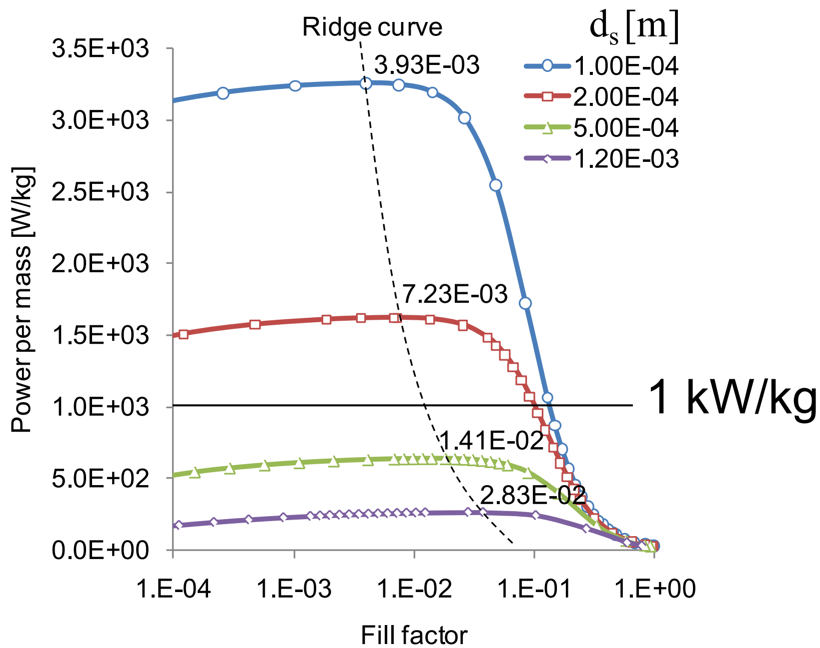
F: fractional area factor (Fill factor)

$$\sum \Psi = \Psi_h + \Psi_c + \frac{2\lambda}{\beta_s a(1 + 2\lambda \tan\phi)}$$

Design to optimize energy per unit mass

Optimum weight ratio is found for small fraction < 10% area





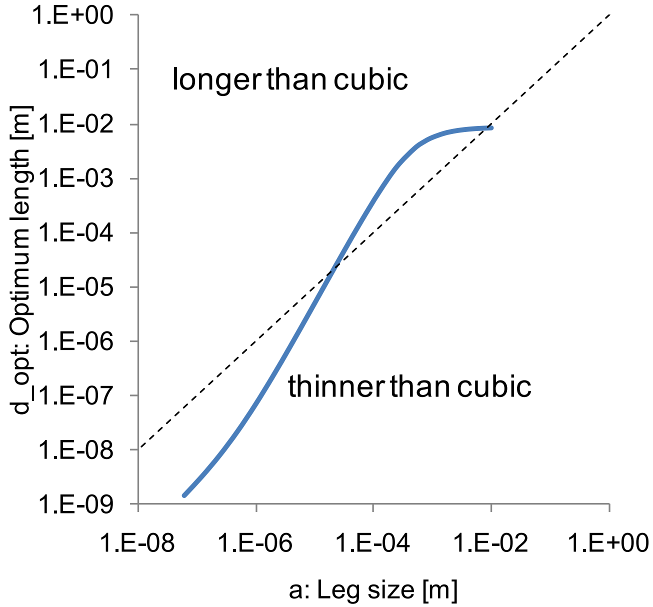
Power density vs fill factor

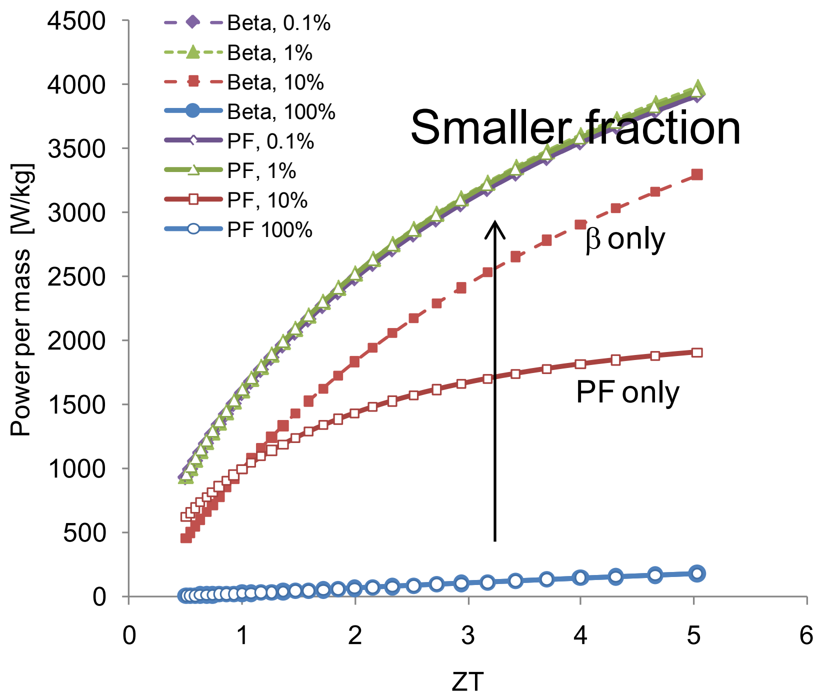
Power output per unit mass vs fill factor

$ZT=1$, $T_s=600$ [K], $T_a=300$ [K], $\beta_s=140$ [W/mK], U_h, $U_c= 500$ [W/m^{2}K],
$\rho_{TE}=9.78$ [kg/m2], $\rho_{sub}= 3.26$ [kg/m2]

At the optimum design

1. Optimum aspect ratio changes as function of fill factor.
2. In practical fill factors, thermal conductivity reduction is rather important.





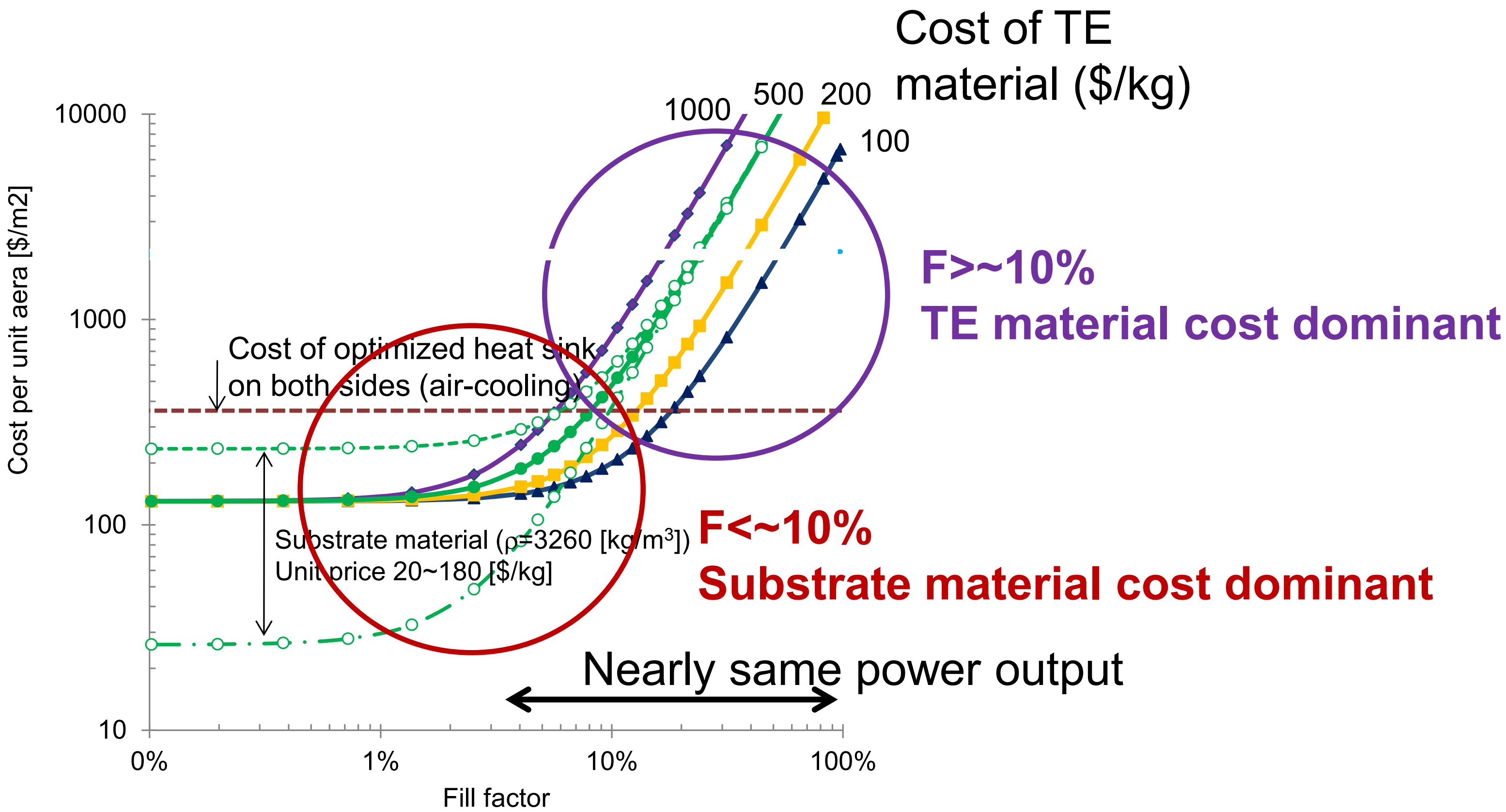
Aspect ratio of the TE leg

optimized by changing fill factor

Power per mass vs. ZT

ZT=1, T_s=600 [K], T_a=300 [K], b_s=140 [W/mK], d_s=0.2e-3 [m], U_h, U_c= 500 [W/m^{2}K]

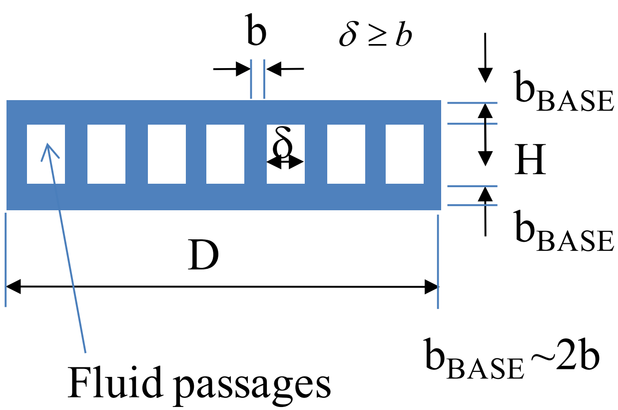
TE module cost analysis



Cost performance of thermoelectric power generation versus the fill factor. Different prices for the TE material and the substrate are assumed.

Pumping power penalty

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

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

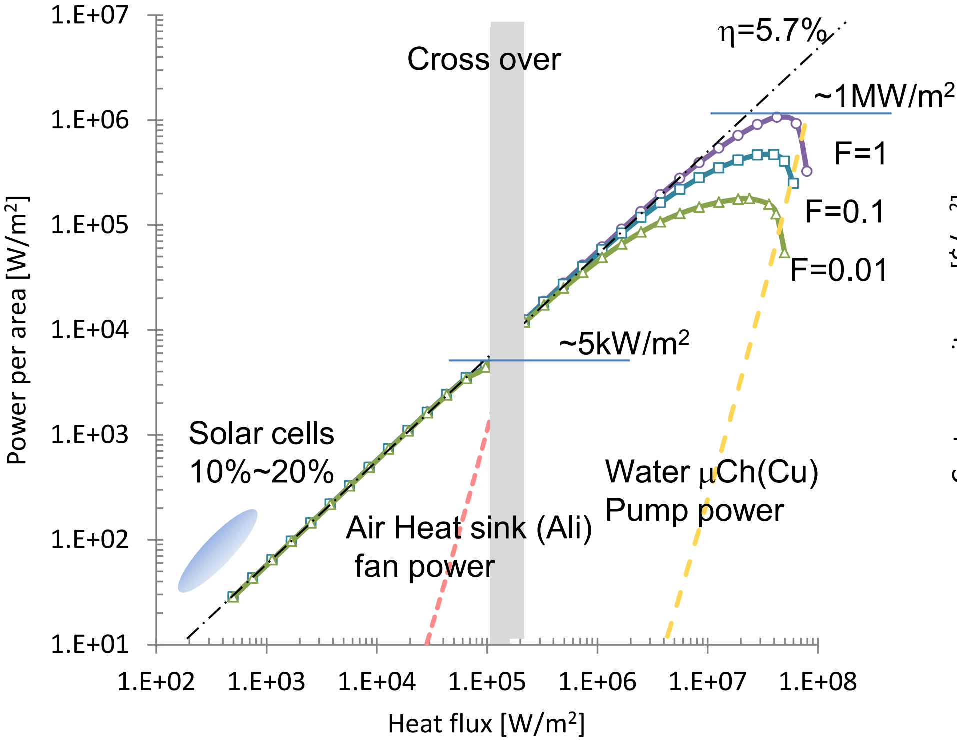
Nusselt number

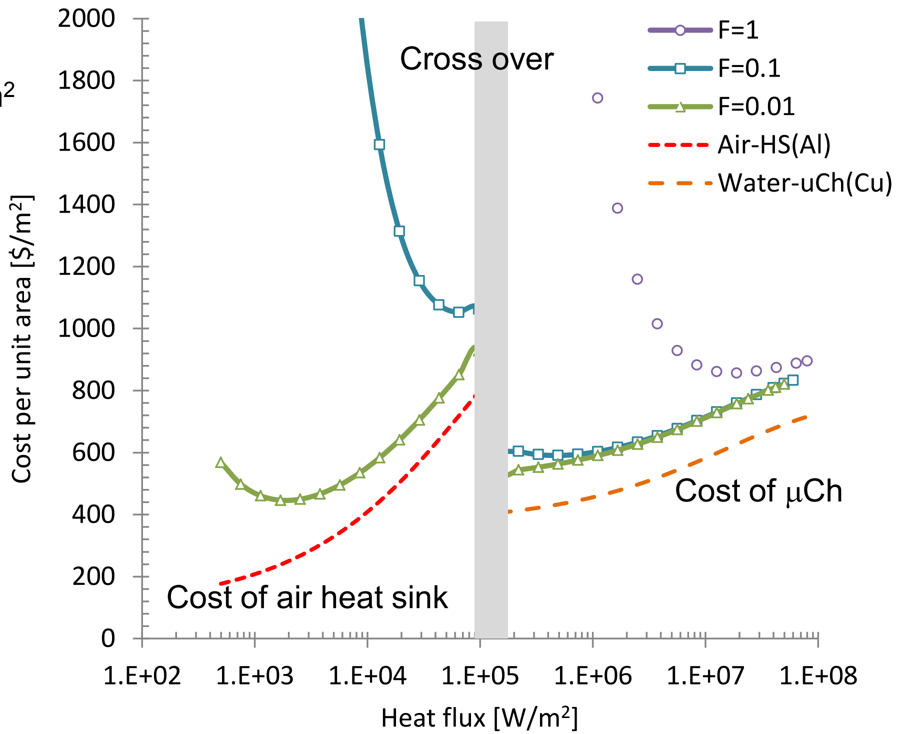
$$Nu = 4.52 * (1 - \delta / H)^{3.78} + 2.98$$

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

Heat flux dependency

At the optimum TE design



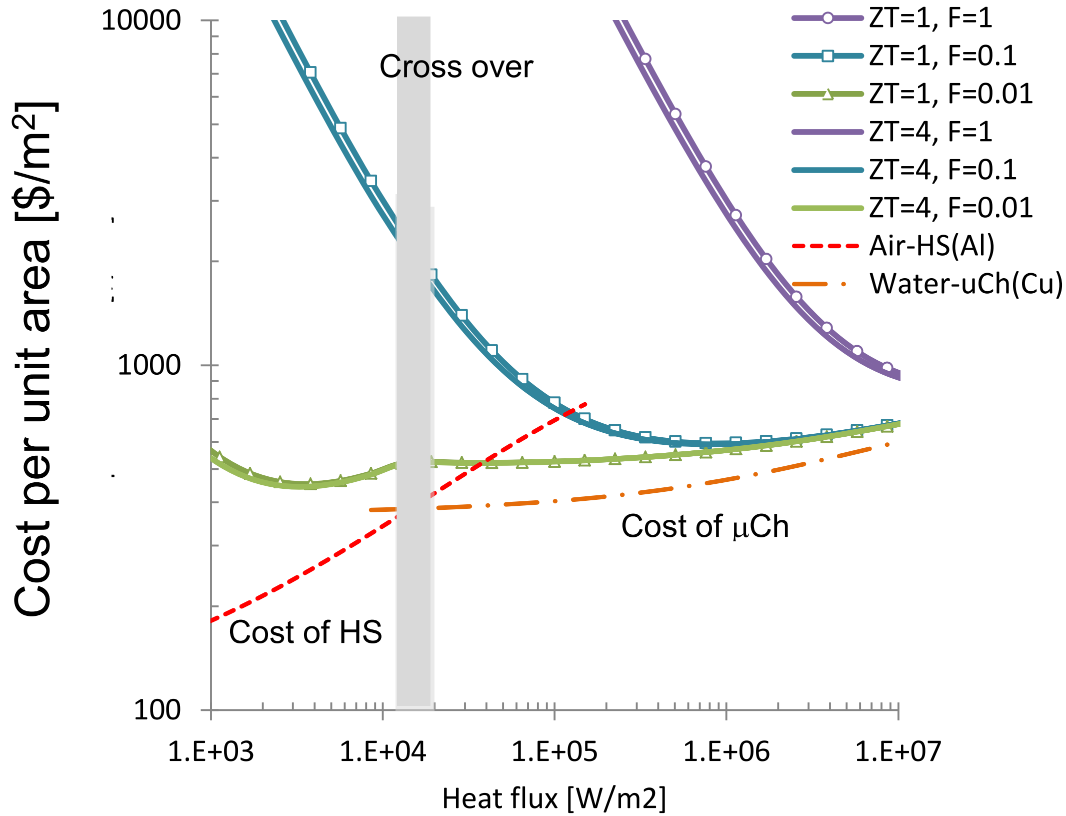


Conditions: ZT=1, β=1.5[W/mK] T_s=600K, T_a=300K, Fan efficiency 30%, TE $500/kg, Substrate-AIN: $100/kg, Aluminum heat sink: $8/kg, copper microchannel: $20/kg

F: Fractional area coverage ratio of thermoelement to substrate

Cost per unit area for vehicle exhaust

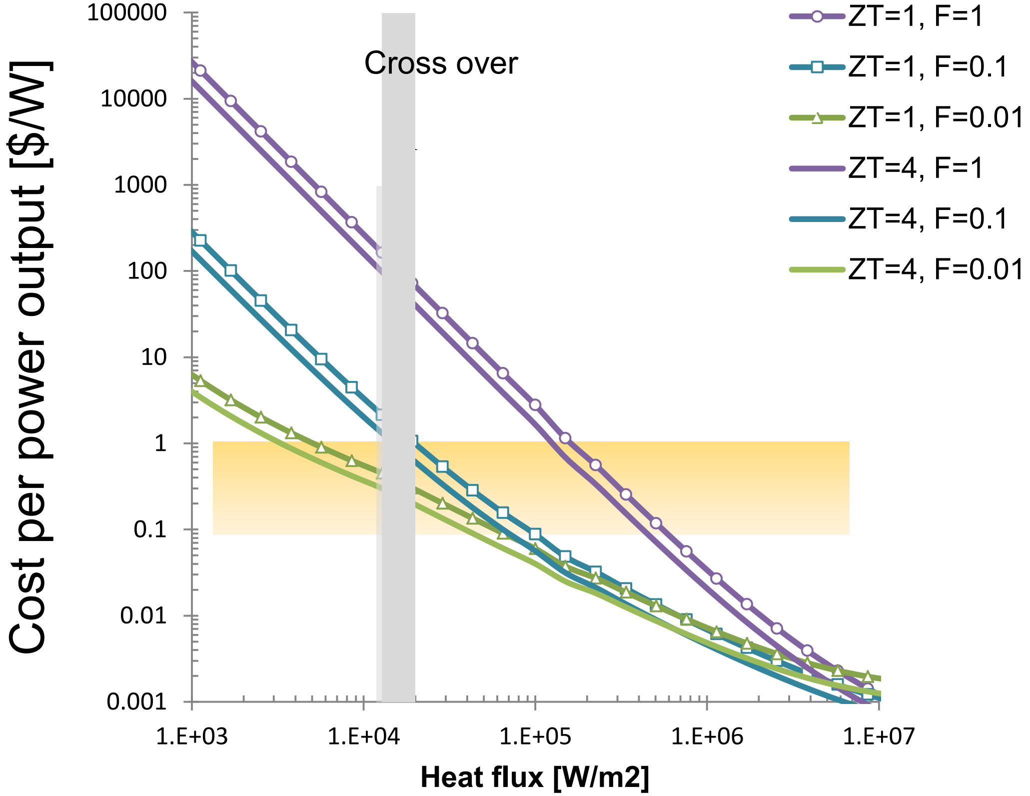
Power output per unit area (exhaust gas heat exchanger)



Conditions: ZT=1, β=1.5[W/mK] and ZT=4, β=0.75[W/mK] β_{sub}=100 W/mK, t_{sub}=0.2mm,
T_s=900K, T_a=370K, Fan efficiency 30%,
TE $500/kg, Substrate-AlN: $100/kg, aluminum heat sink: $8/kg, copper ($\mu$Ch): $20/kg

Cost per power output

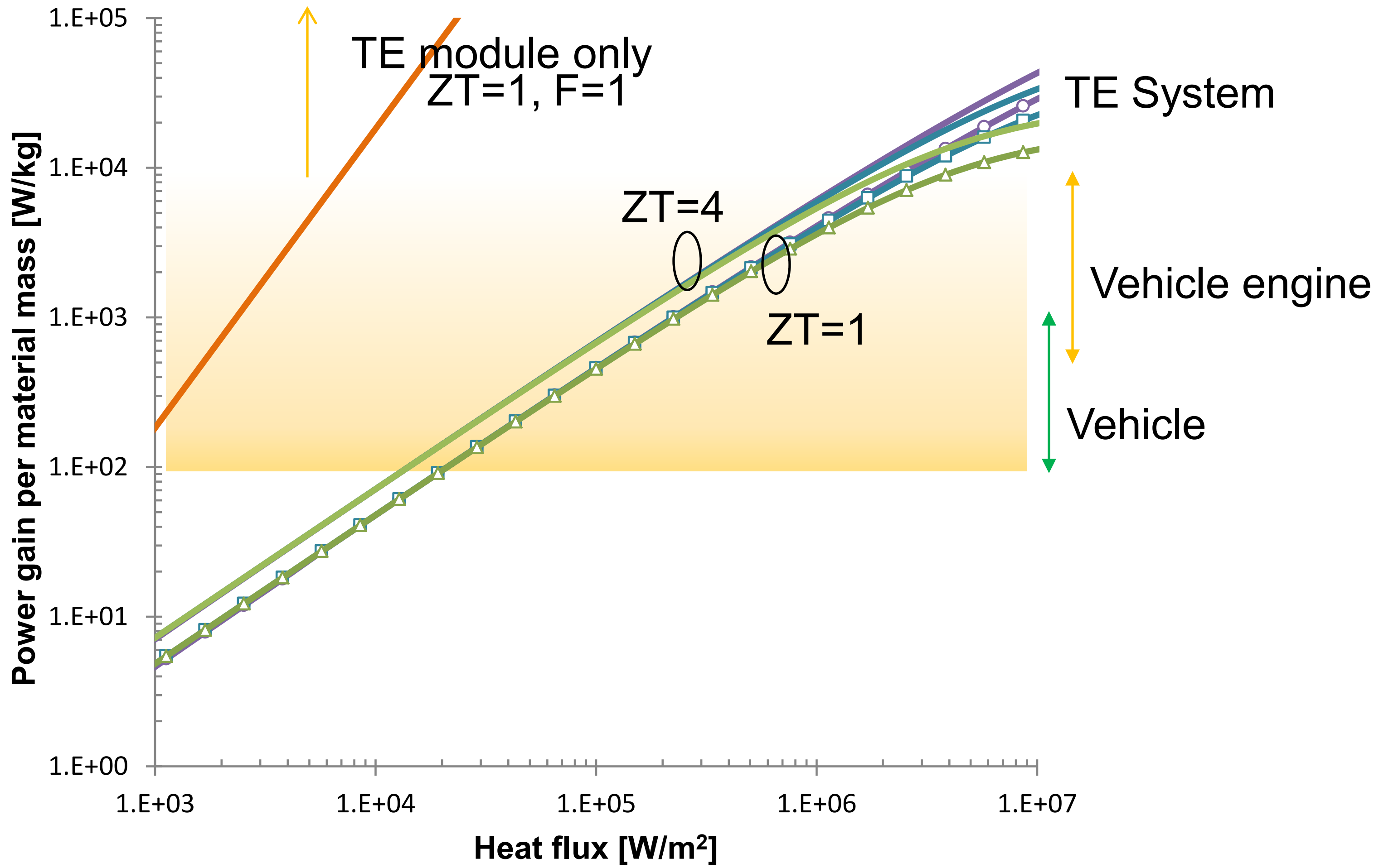
System [TE + Heat sink]



Conditions: ZT=1, β=1.5[W/mK] and ZT=4, β=0.75[W/mK] β_{sub}=100 W/mK, t_{sub}=0.2mm,
T_s=900K, T_a=370K, Fan efficiency 30%,
TE $500/kg, Substrate-AlN: $100/kg, aluminum heat sink: $8/kg, copper ($\mu$Ch): $20/kg

Power per weight (Watt/kg)

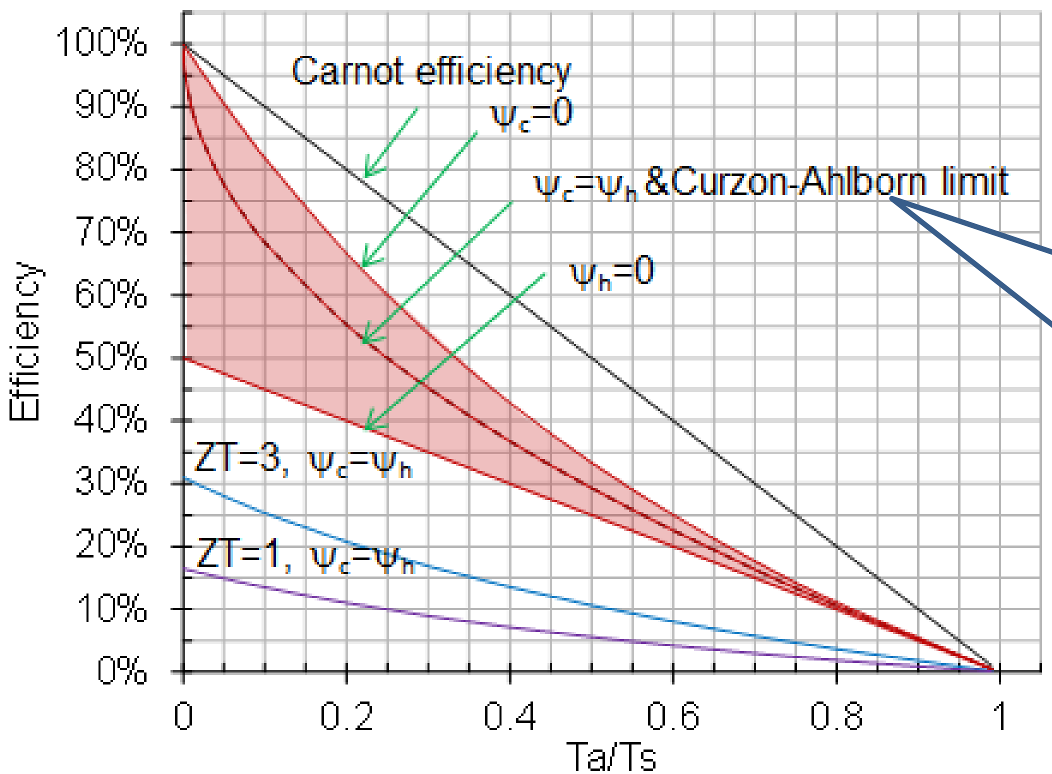
As a system, heat sink dominates weight performance



Same condition as previous

Efficiency at optimum

1. System never reach Carnot but Curzon-Ahlborn as limit.
2. “smaller ψ_c” works better for large ΔT, higher ZT.



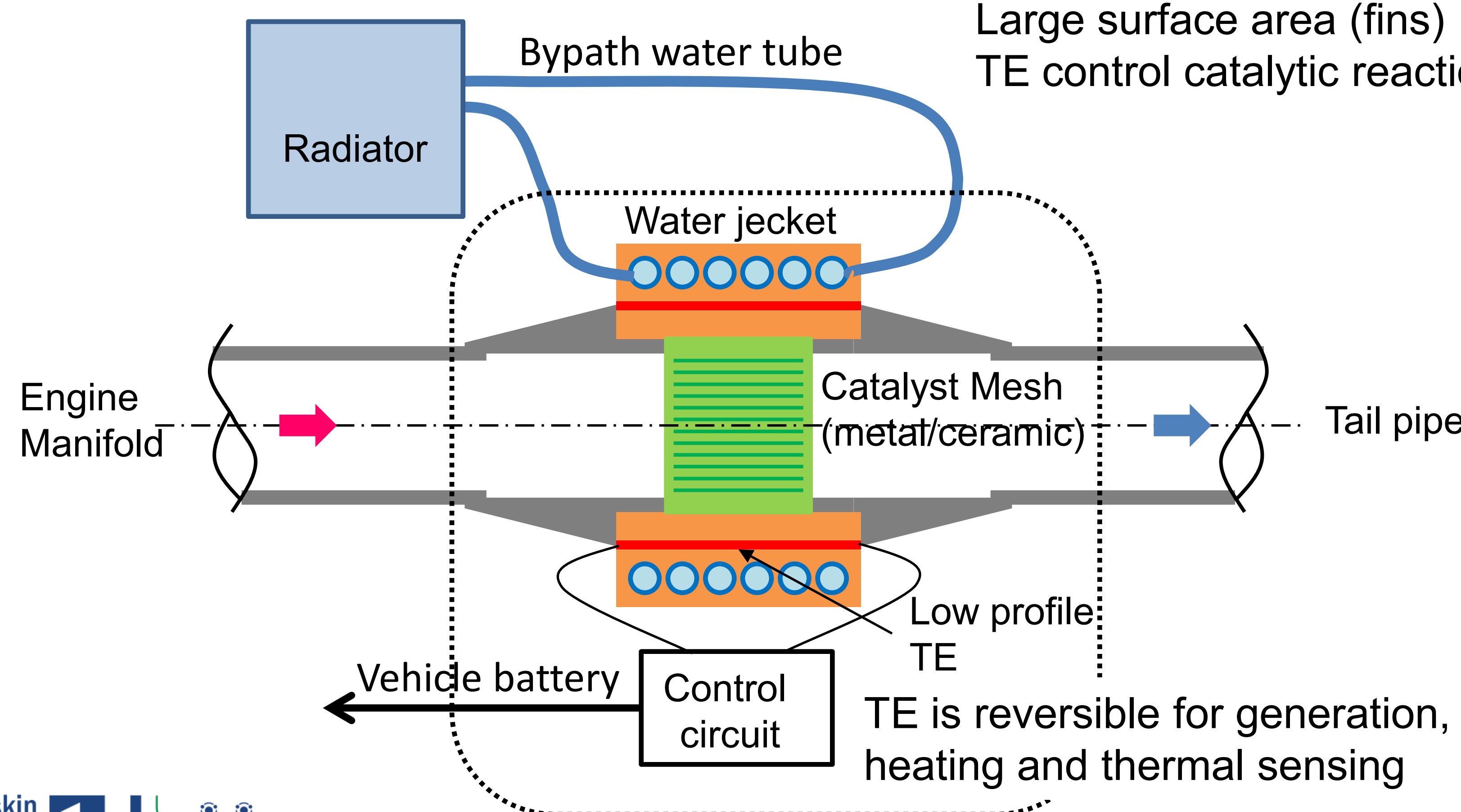
$$\eta_{\text{limit}} \rightarrow 1 - \sqrt{\frac{T_s}{T_a}}$$

T_s: heat source
T_a: cold reservoir

Vehicle waste heat recovery

Potential implementation

Minimum additional ΔP
Large surface area (fins)
TE control catalytic reaction



TE is reversible for generation, heating and thermal sensing

Summary

- A general formalism is developed for TE power generation system.
- Optimum design for the TE module with heat sink is identified.
- Output power density per mass is found to have a peak around few % fractional coverage. Considering parasitic impacts of contact resistance and heat leak, fractional coverage area ratio few% - 10% seems to be practical, and still cost effective.
- Efficiency at maximum power output is determined to vary by external thermal resistances. Cold side heat sink has more impact.
- Energy payback, cost, power-to-weight at optimum are highly depends on heat flux condition.

Thank you for your kind attention!