Can Thermoelectrics Help Energy Savings and Emission Reduction Goals in the United States?

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2009 Thermoelectrics Applications Workshop - San Diego, CA
29 September 2009

Outline

Introduction

State of Thermoelectrics in the U.S.

- Introduction
- Why thermoelectrics and issues with the present technology
- Recent commercialization initiatives

Prospects for TE Performance Improvements

- Materials
- Cycles
- Material usage

Societal Needs for Thermoelectrics

- Energy conservation/reduction
- Emission reduction
- Fossil fuel importation policies

Actions Needed

Summary/Conclusions

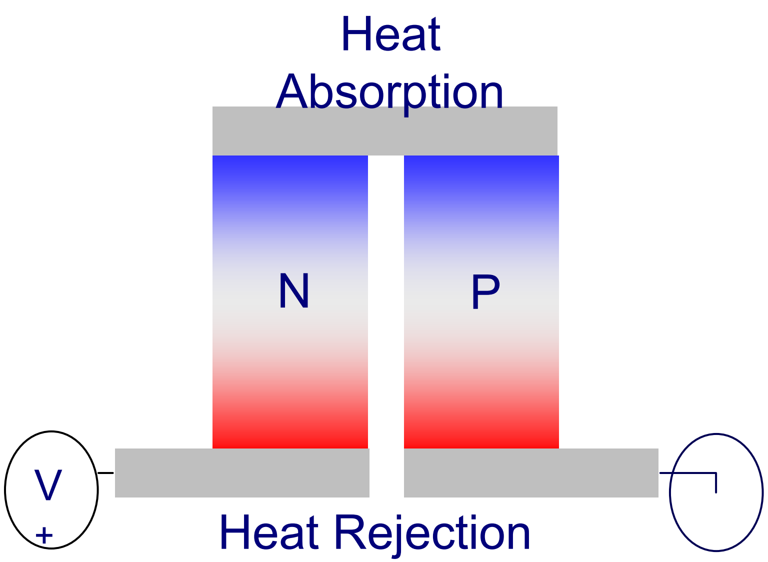
Thermoelectric Heat Engines

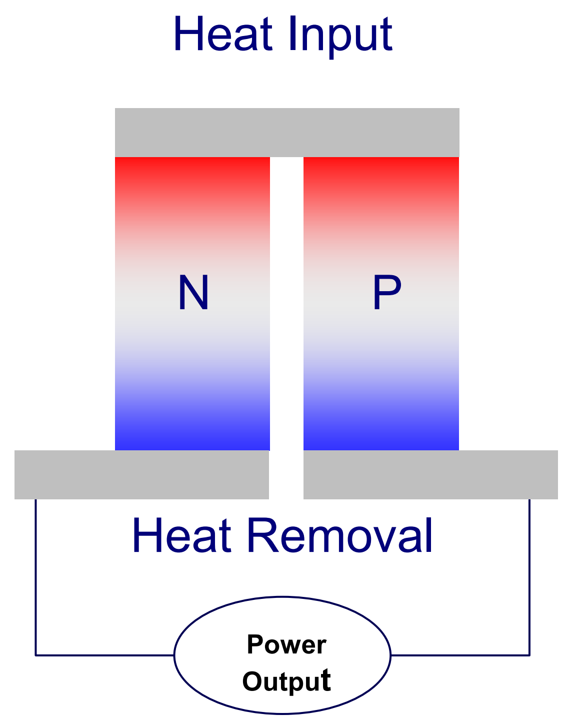
Cooling / Heating

Power Generation

(Peltier Effect)

(Seebeck Effect)





Ideal Governing Equations

Cooling/Heating

$$\beta_c = \frac{T_c}{\Delta T}\left(\frac{M - 1 - \frac{\Delta T}{T_c}}{M + 1}\right)$$

Where β_c = Maximum cooling COP
T_c = Cold side temperature
ΔT = Hot/cold side temperature differential

$$\beta_H = \frac{Q_H}{P_{in}} = 1 + \beta_c$$

Where β_H = Maximum heating COP
Q_H = Hot side heat rejection
P_{in} = Electric power in

$$ZT = \frac{\propto^2 T}{\rho\lambda}$$

Where α= Seebeck coefficient
r = Electric resistivity
λ = Thermal conductivity
T = Absolute temperature

$$M = \sqrt{ZT_A + 1}$$

Where T_A, = Average engine temperature

Power Generation

$$\emptyset = \frac{\Delta T}{T_H}\left(\frac{M - 1}{M + 1 - \frac{\Delta T}{T_H}}\right)$$

Where T_H = Hot side temperature

BSST

Why Use Thermoelectrics?

- Solid-state cooling, heating and power generation
- Small, light-weight. Potentially very reliable and rugged
- Electrically powered with very few (or no) moving parts
- Distributed (and spot) cooling/heating/temperature control/heat pumping
- No gaseous pollutants/CO_2 replacement for cooling/heating applications
- Interfaces well with electrified systems

Limits of Thermoelectrics

Cooling efficiency has been less than 12% of Carnot

- Inadequate for many high-power applications
- Limits usage to low wattage (>200 Watts) applications
- Too inefficient for full automotive HVAC use

Thermal flux density has been low

- Amount and hence cost of TE material too great for broad commercial application at high wattage
- Form factor not readily adaptable to some application needs
- Does not interface well with high capacity thermal media (liquids)

Lack of design knowledge and effective simulation tools

- Performance often poorer than predicted because of limited understanding
- Characteristics and, hence response, can be a strong function of operating conditions

Prospects for TE Performance Improvements

Performance Gain Opportunities

High ZT materials

- Improve efficiency in all applications
- Indirectly lower cost

Alternate thermodynamic cycles

- Improve efficiency in key HVAC, and heat pump applications

Reduced material usage

- Lowers cost
- Indirectly increases efficiency

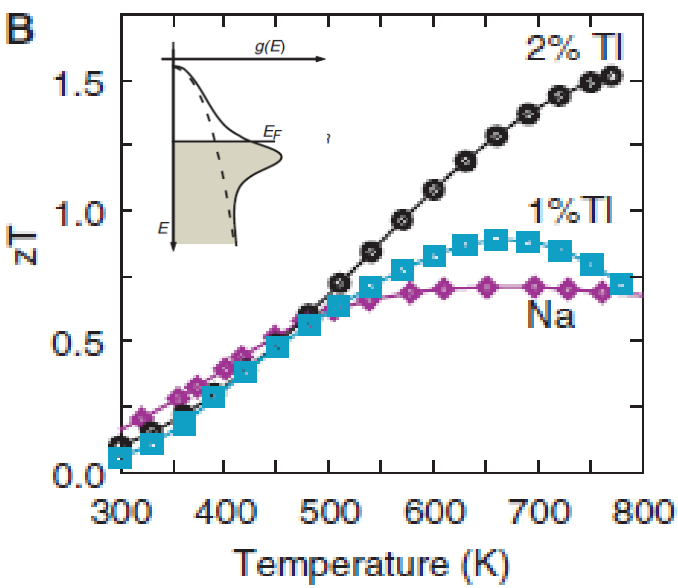
Distributed operation

- Allows zonal control
- Indirectly improves efficiency
- Thermal power when, where needed

Material Improvement

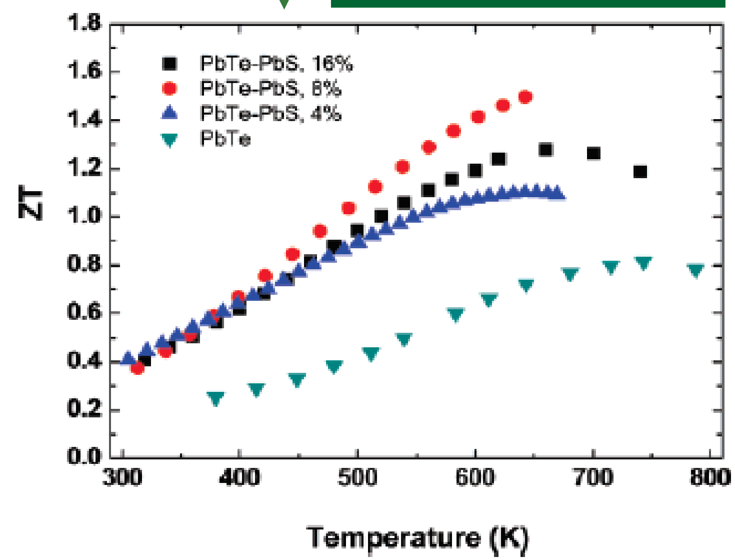
$$ZT = \frac{\boxed{\alpha^2\sigma}}{\left(k_e + \boxed{k_{ph}}\right)}T$$

THE OHIO STATE UNIVERSITY



Enhancement of Thermoelectric Efficiency in PbTe by Distortion of the Electronic Density of States
Joseph P. Heremans, *et al.*
Science **321**, 554 (2008);

MICHIGAN STATE UNIVERSITY



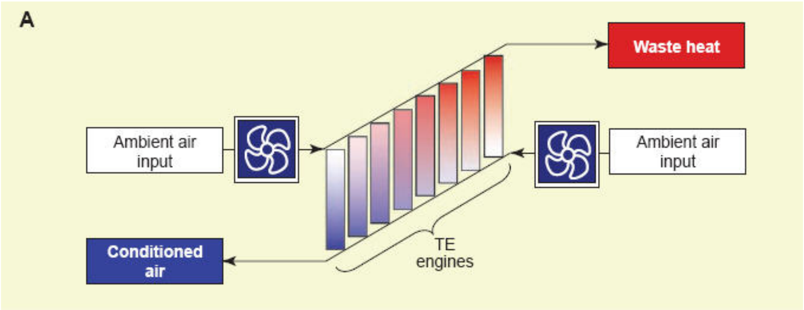
Spinodal Decomposition and Nucleation and Growth as a Means to Bulk Nanostructured Thermoelectrics: Enhanced Performance in $Pb_{1-x}Sn_xTe-PbS$

John Androulakis,† Chia-Her Lin,† Hun-Jin Kong,‡ Ctirad Uher,‡ Chun-I Wu,§ Timothy Hogan,§ Bruce A. Cook,⊥ Thierry Caillat,# Konstantinos M. Paraskevopoulos,£ and Mercouri G. Kanatzidis*,†,¶

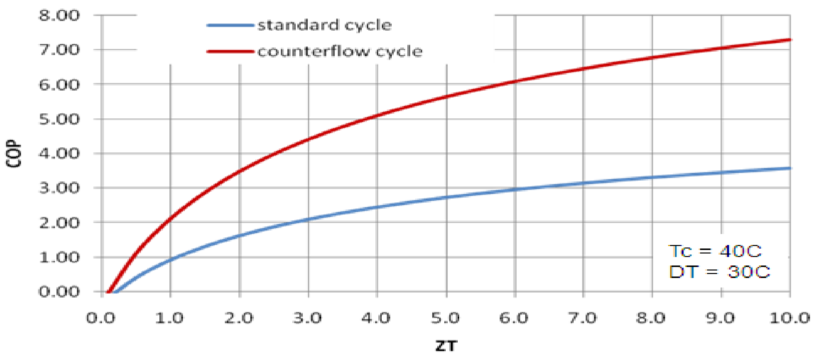
J. AM. CHEM. SOC. 2007, *129*, 9780−9788

Alternative Cycles

Thermodynamic cycles. By optimizing each element along the thermal gradient, the engine resembles a gas turbine engine (the high-efficiency Brayton cycle) rather than the less efficient diesel cycle, in which the temperature and pressure conditions of every element (TE junction or combustion cylinder) are the same.



System efficiency (COP) for standard and counterflow cycles.



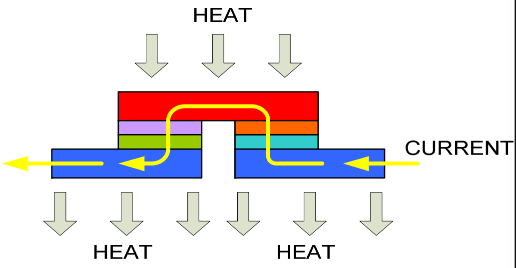
Equivalent material ZT required for performance of standard to equal that of counterflow cycle.

ZT with Counterflow Cycle	Equivalent ZT Required with Standard Cycle	COP
1.00	3.04	2.11
1.25	4.21	2.52
1.50	5.61	2.87
1.75	7.27	3.19
2.00	9.23	3.48

Cost Effective TEG Design

Critical Design Limitations

- Parasitic electrical and thermal resistances require long TE element designs
- Tensile and shear stresses reduce durability in large arrays
- As a result TE material power density is low, requiring large amounts of TE material



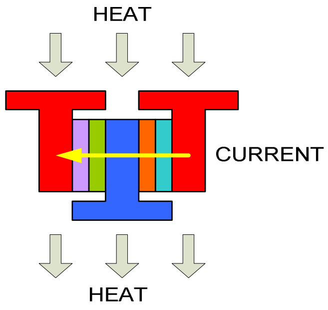
TRADITIONAL CONFIGURATION

Solutions

- Stack design reduces parasitic losses
- Compressive forces independent for low electrical and thermal resistances

Results

- Increased longevity and stability
- 75% - 84% TE material usage reduction
- Reduced impact of CTE mismatch
- However, custom designs are expensive at low volume manufacture and early prototype production



BSST HIGH POWER DENSITY CONFIGURATION

Recent Commercialization Initiatives

- Electron passing/phonon blocking primarily reduces thermal conductivity with some enhancement of electronic properties
- Nanostructure scatters phonons reducing thermal conductivity. Considered broadly applicable process for diverse TE material systems.
- Combination of electronic property enhancement from distortion of the electronic density of states, and separately, thermal conductivity reduction through nanostructure formation of a second phase

Societal Needs for Thermoelectrics

Major Shifts in Global Energy Policies Favor Thermoelectrics

Vehicle electrification requires new heating and cooling solutions

- Heat is no longer free
- Cooling (and heating) must be electrically driven to operate with engines off

Home and industrial heating and cooling have to be weaned of fossil fuels

- Requires efficient electrically powered heating at very low temperatures
- Two phase fluids may not offer broadly attractive solutions because of emissions and safety

Energy must be conserved

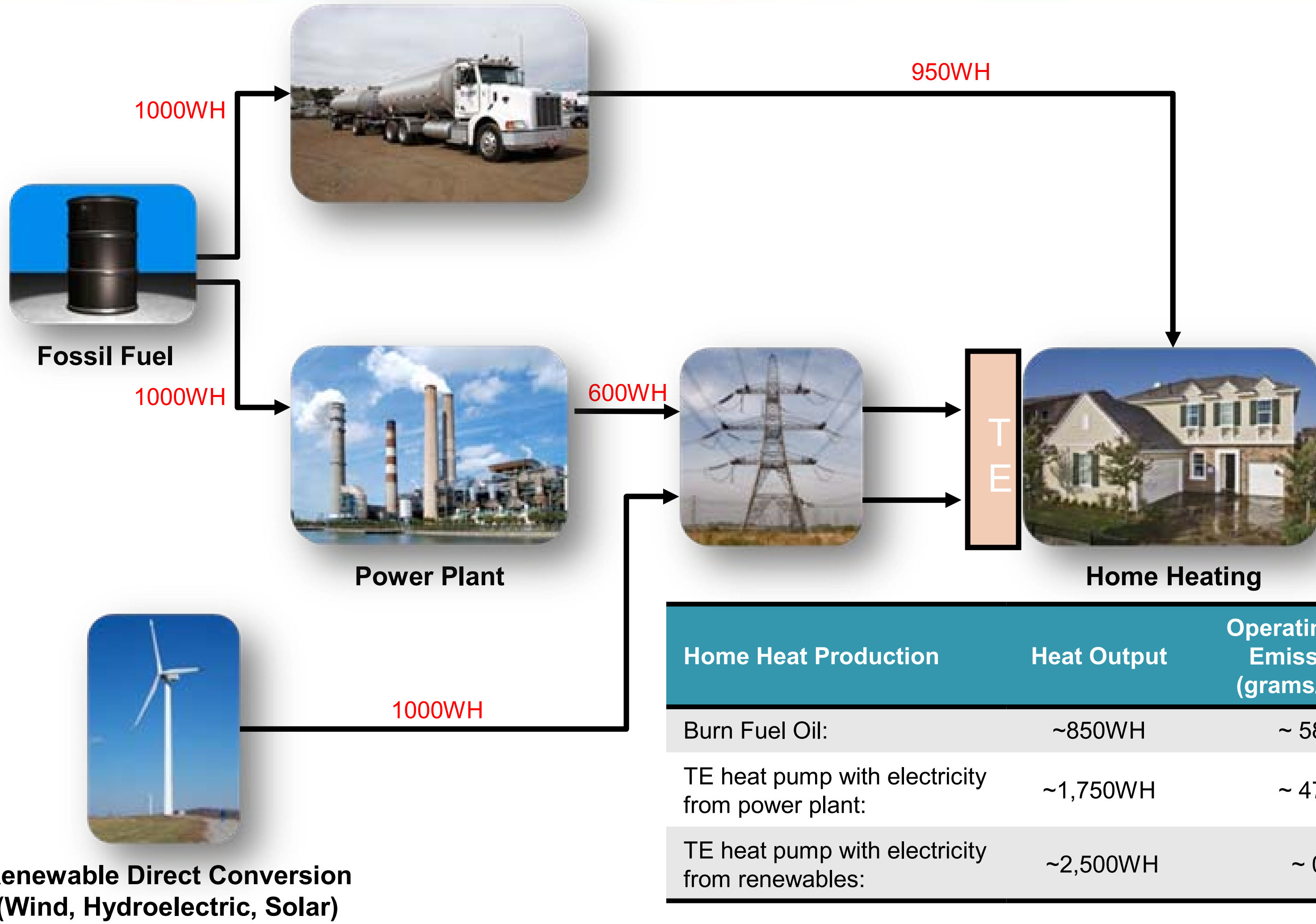
- TE eased zonal on demand HVAC most attractive
- Needs to slow primary resource depletion

Waste heat must be addressed

- Recovery in industrial processes can provide cost savings and energy use reduction
- Vehicle waste heat recovery can reduce CO_2 and may reduce costs

Program Area of Interest	Specific Sub areas of Interest	Projected Impact of Thermoelectric System Advances
Electrification of Transportation	Climate Control in Vehicles	The use of TE systems can reduce by 40-60% the current impact on mileage (up to ~20-30%) in vehicles running on electric power. compared to traditional heat and air conditioning. Additionally, TE systems eliminate the need for R134a, The 1 kg used in cars today has a CO_2 equivalency of 1,300 kg of CO_2.
	Battery Management	The use of TE systems to optimize the thermal environment of batteries in electrified vehicles enables faster, more efficient charging and longer life under both hot >35C and cold <-10C conditions.
Advanced Vehicle Technologies	Disruptive Vehicle Energy Recapture Technologies	For vehicles that are difficult to electrify, such as large trucks, TE systems can increase mileage 8% to 11% through exhaust waste heat recovery.
Efficient End Use of Energy	Home, commercial and industrial HVAC	Solid-state TE cooling systems eliminate the need for R134a and provide very efficient heating, 1 kg of which is equivalent in terms of emissions to 1,300 kg of CO_2.
	Distributed Energy	TE systems enable the efficient distribution of energy by localizing heating and cooling where and when it is needed and at the exact power level needed. Furthermore, waste heat can be harvested and recycled back into the system.
Industrial Efficiency	Low Cost Waste Heat-to-Power Conversion Technologies	Waste heat can be recaptured from industrial processes such as Aluminum smelting, other pyrometallurgical processes, glass production and other applications.

Altlernative Sources for Home Heating

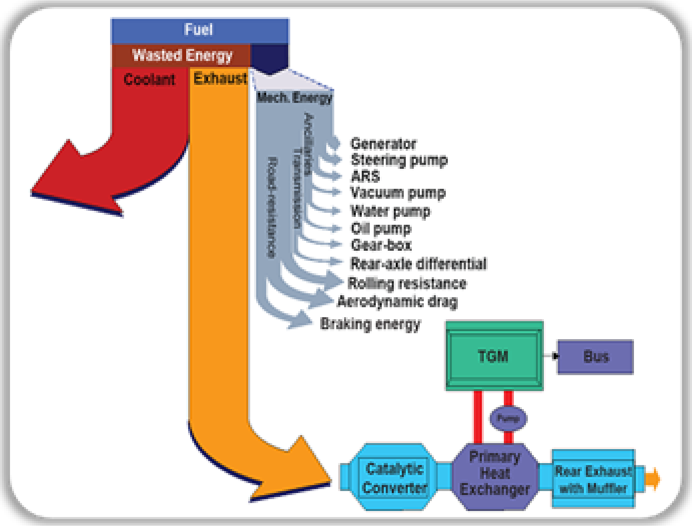


Home Heat Production	Heat Output	Operating CO_2 Emissions (grams/kWh)
Burn Fuel Oil:	~850WH	~ 580
TE heat pump with electricity from power plant:	~1,750WH	~ 470
TE heat pump with electricity from renewables:	~2,500WH	~ 0

In Q4 2004 the US DOE Office of Vehicle Technologies started 4 Thermoelectric Waste Heat Recovery Programs

The Program objectives include:

- 10% fuel efficiency improvement
- Reduced emissions
- A demonstrated path to commercialization and economic feasibility assessment



Press Coverage of the CCS Discussing Efficiency Gains:

Honda FCX Clarity: A glimpse at the future

Sleek fuel-cell vehicle gets 68 mpg on hydrogen and handles like a sports sedan

Super seats

To help move away from petroleum-based resins and other synthetic fibers toward plant-based fabrics.

Heated and cooled seats

Permeable foam
Thermo electric device
Blower
Ventilation ditch
Ventilation ditch

Everyone else may like them too. The heated and cooled seats keep the driver and passenger comfortable as well as help the Clarity use less of its engine to control the car's climate. The second-row bucket seats provide nearly as much as comfort and space as the front ones.

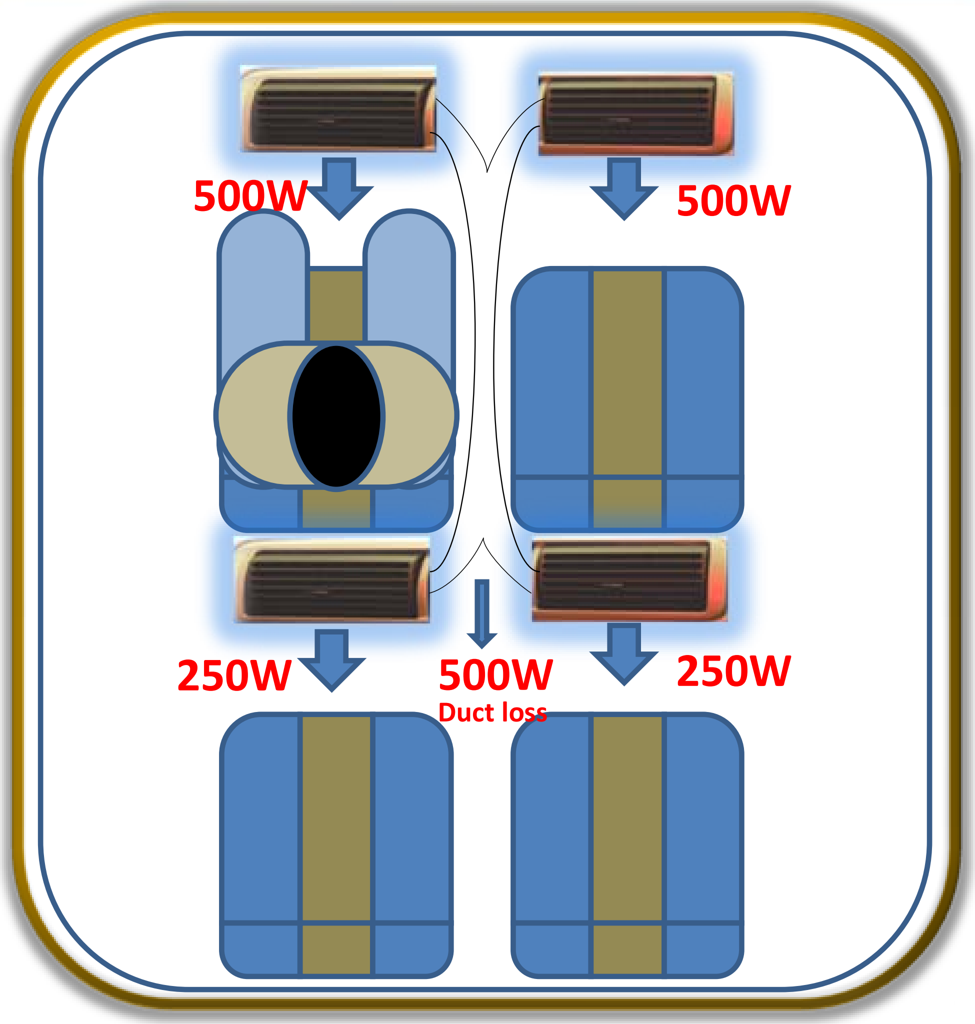
COP Calculations – Traditional PTC Heater in an EV

Heating to driver = 500W

Total PTC heating to vehicle = 2000W

PTC COP = 1

Total power used = 2000W



COP Calculations – TE Central HVAC in an EV + Enhanced CCS + Zonal Devices

Heating to driver = 500W

Total TE central HVAC heating to vehicle = 1200W

TE central HVAC COP = 2.5 (assumed)

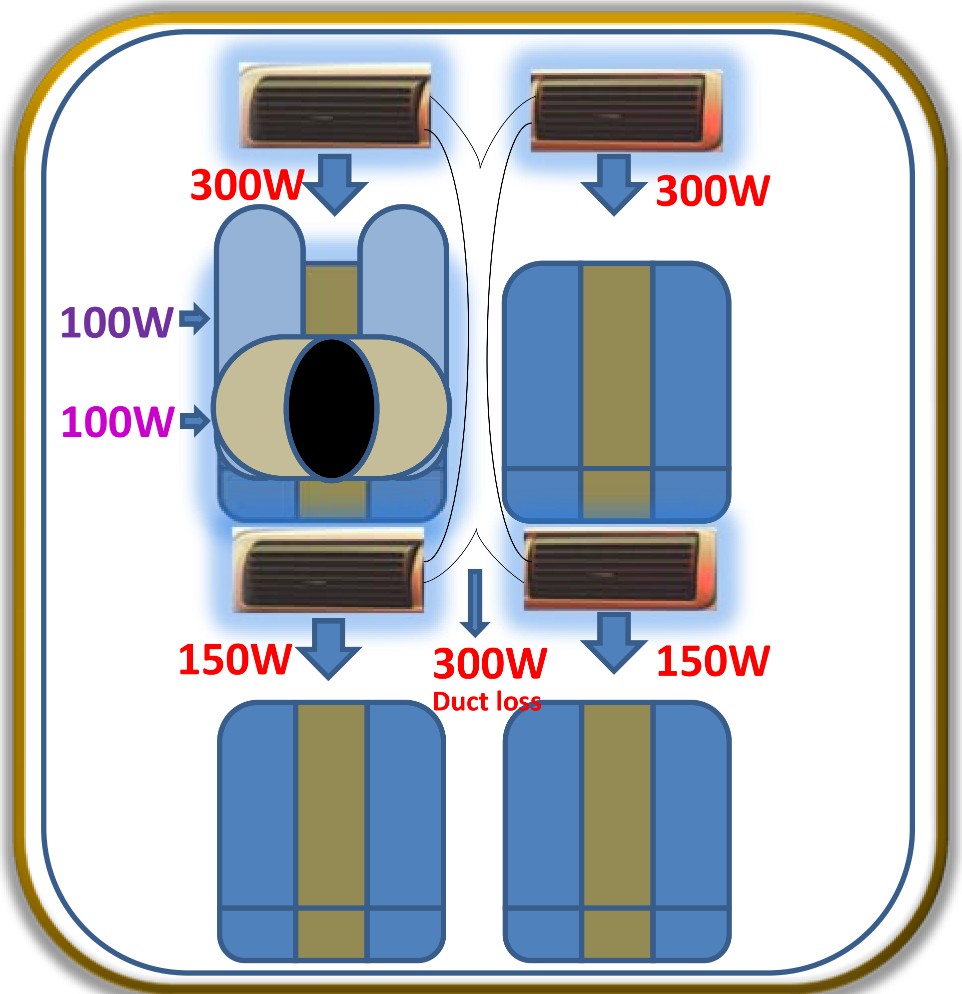
CCS heating to driver = 100W

CCS COP = 2.5 (assumed)

Zonal TED heating to driver = 100W

Zonal TED COP = 2.5 (assumed)

Total power used = 560W



Actions Needed

Short term actions needed for thermoelectrics to have a significant impact on global energy usage and emission reductions

- Promising new TE materials must be commercialized at a much faster pace.
- Other sources of gains (thermodynamic cycles, distributed and/or zonal heating, cooling waste heat recovery) have be explored fully and adopted where proven beneficial.
- Costs have to be driven down by readying architectures and design features that reduces TE material usage.

The U.S. government has to take on a leadership role . Otherwise, progress will be too slow to be impactful on a global scale

- The industrial sector is not well positioned to make the necessary up front investments to resolve key choke points in the time required.
- Transportation sector is experiencing extreme financial stress and is in massive transition.
- The home and industrial HVAC industry is hampered by the need to evaluate multiple immature technology options for the next generation product at a time of curtailed R&D investment.

Achieving Sustainability in Thermoelectric Advancements

Early government funding of integrated circuits and more recently, photovoltaics led to massive, sustained private sector, later stage commercialization investment

- Critical stage of broad acceptance had to occur to kick off commercialization investment.
- TEs are approaching that stage and can achieve the same result

At this time, only DOE is positioned to enable this process to take hold

If delayed, other more conventional technologies with less positive societal impact will be pursued and dominate the next generation of HVAC and waste heat recovery.

- Significant source of energy savings will not be realized
- Will use 2 phase refrigerants and have much less efficient heating
- Zonal temperature HVAC will be not practical or will be less efficient

Timing to meet societal goals (reduction in GHG emissions and reduced fossil fuel consumption) will lag

Potential Impact on DOE Mission Areas

Direct reduction in fossil fuel consumption and CO2 emissions in large market sectors

- Home heating and cooling
- Industrial heating, cooling power generation and waste heat recovery
- Transportation cooling, heating and waste heat recovery

Direct reduction in other greenhouse gas emissions from HVAC systems

Direct green, sustainable, long term job creation

- Waste heat recovery are all net new jobs
- HVAC a mix of about 65% net new jobs and 35% substitution job creation

TE Technology Insertion Roadmap

Improvement and Readiness

Present TE Capabilities

2-3 Years
Low material usage
High performance HVAC cycle

Enables PHEV, HEV, EV and small diesel zonal HVAC home heat pumps

3-5 Years
ZT 1.35 cooling/heating materials

Enables industrial and commercial heat pumps

5-7 Years
ZT 1.7 – 1.8 cooling/heating materials

Complete HVAC replacement all applications

Summary/Conclusions

- Long-term global forces favor adoption of TE technology for HVAC, heat pump and waste heat recovery applications. TE usage will have broad societal impact if the technology's shortcomings are overcome, and commercial viability is achieved on the necessary scale.
- Known approaches to TE efficiency improvements through higher ZT materials, alternative thermodynamic cycles and less TE material usage, can quickly deliver large scale emission reductions, less energy consumption and sustainable job creation.
- DOE is in a position to initiate critical programs that enable these transformational advancements, and thus strongly and favorably impact DOE mission areas.

Acknowledgements