Nanoscale Thermoelectric Energy Conversion Devices and Interdisciplinary Sustainability Education

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Purdue-Mexico Workshop on Sustainability; April, 29, 2013
Energy Sources
- Renewables, 6%
- Nuclear, 6%
- Biomass, 11%
- Gas, 20%
- Coal, 27%
- Oil, 32%

Conversion Devices
- Heat Engines 25%
- Burners 33%
- Electricity 42%

- More than 90% of primary energy is first converted to heat.
- Overall end-use exergy (12% of sources):
  - Motion 0.95 TW
  - Heat 0.73 TW
  - Cooling/Light/Sound 0.06 TW

Adapted from Cullen and Allwood, Energy, 2010
A. S. 15 August 2012
Seebeck coefficient

\[ S = \frac{\Delta V}{\Delta T} \]

Efficiency function of thermoelectric figure-of-merit (Z)

\[ Z = \frac{S^2 \sigma}{k} \]

\[ Z = \frac{(\text{Seebeck})^2(\text{electrical conductivity})}{(\text{thermal conductivity})} \]
Beating the Alloy Limit in Thermal Conductivity

Long and Short Wavelength Phonon Scattering

Thermal Conductivity Reduction

Thermoelectric figure-of-merit

The majority of ZT enhancement is from thermal conductivity reduction. 5% power factor enhancement at 800K.

Largest measured ZT~1.5-1.7 at 800-830K

Mg$_2$Si: Lattice thermal conductivity can be lowered by nanoparticles

- $ZT \sim 0.7$ for Mg$_2$Si/2.5vol%Si$_{1\%}$Bi at 775 K

Susan Kauzlarich, Tanghong Yi, Sabah Bux, et al.
J. Mat. Chemistry 2012
TE module & cold side heat exchanger for waste heat recovery

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

$T_{source} = 900K$, Input heat flux

$T_{ambient} = 330K$

TE Module

Microchannel Heat Sink

Pump Efficiency = 30%

ZT = 1
→ Material Cost: $2-3/W

Yazawa and Shakouri, Env. Science and Technology (July 2011)
Use of heat spreading inside TE module to reduce the material cost

\[ ZT = 1, \text{ Fill Factor} = 0.2 \rightarrow \text{Material Cost: } \$0.02-0.03/W \]

Yazawa & Shakouri; Journal of Material Research 2012
TE for topping cycle applications

$T_{hot} = 1900K$

Te System

Rankine cycle

Coal Power Plant

Prof. Chenn Zhou
Purdue Calumet

Coal Power Plant
TE / Steam Turbine combined cycle

Simplified Steam Turbine Model

Figure 1.1 Individuals’ emissions in high-income countries overwhelm those in developing countries

**CO₂e/ Person (tons)**

- **Australia**
- **Canada**
- **United States**
- **Brazil**
- **Russian Federation**
- **Germany**
- **Japan**
- **United Kingdom**
- **Ukraine**
- **Italy**
- **Indonesia**
- **South Africa**
- **France**
- **Iran, Islamic Rep. of**
- **Mexico**
- **Turkey**
- **Thailand**
- **Peru**
- **Myanmar**
- **Iraq; Colombia**
- **Congo, Dem. Rep.**
- **Algeria**
- **Nigeria**
- **Egypt, Arab Rep. of**
- **Philippines**
- **Uganda**
- **India**

**Population (billions)**

- **China**
- **Ghana**
- **Vietnam**
- **Pakistan**
- **Ethiopia**
- **Tanzania**
- **Bangladesh**
- **Sudan**
- **Chad; Kenya; Niger; Rwanda**

**Sources:** Emissions of greenhouse gases in 2005 from WRI 2008, augmented with land-use change emissions from Houghton 2009; population from World Bank 2009c.

**Note:** The width of each column depicts population and the height depicts per capita emissions, so the area represents total emissions. Per capita emissions of Qatar (65.6 tons of carbon dioxide equivalent per capita), UAE (38.8), and Bahrain (25.4)—greater than the height of the y-axis—are not shown. Among the larger countries, Brazil, Indonesia, the Democratic Republic of Congo, and Nigeria have low energy-related emissions but significant emissions from land-use change; therefore, the share from land-use change is indicated by the hatching.
Individual Emissions (2030)

Sharing global CO₂ emission reductions among one billion high emitters

Shoibal Chakravarty, Ananth Chikkatur, Heleen de Coninck, Stephen Pacala, Robert Socolow, and Massimo Tavoni

Chakravarty et al. PNAS, 106 (29), 2009
Sustainability Education through Engineering and Social Science Collaboration

Acknowledgement: NSF/TUES
Introduction to renewable energies

• Energy and thermodynamics
• Power plants
• Solar, wind, hydropower, geothermal
• Biomass, fuel cells
• Economics, environmental and societal impacts

Home energy audit (detailed online questionnaires)

Hands on labs

Student projects

No science/engineering prerequisite

http://seed.soe.ucsc.edu (EE80J)
Average energy usage of students in various majors

- Engineering
- Economics
- ENVS
- Undeclared
- Others

Minimum
Average
Maximum
Students Considered
Total Students
The Politically Incorrect Guide™ to
GLOBAL WARMING
and Environmentalism

You’ve heard plenty about “global warming.” But did you know:

- The Earth has often been hotter than it is now
- Only a tiny portion of greenhouse gases are man-made
- Most of Antarctica is getting colder
- The media only recently abandoned the “global cooling” scare
- “Global warming” hasn’t made hurricanes worse

Christopher C. Horner  Senior Fellow at the Competitive Enterprise Institute
Felix’s forecasts of US energy consumption in year 2000 (early 1970’s)
Wants to create a sustainable society but considers habits in isolation

Elizabeth Shove, Spring 2009
http://www.soe.ucsc.edu/classes/ee080j/Spring09/
But what if we see consumption as consequence of ordinary practice?

What is required in order to be a ‘normal’ member of society?
it is becoming normal to expect 22C (70F) inside, all year round, all over the world and whatever the weather outside

Cleanliness and showering
it is becoming normal to shower once or twice a day (in the UK, water used for showering is expected to increase five fold between 1991-2021)

Laundering
From once a week to once a day or more, but with lower temperatures than ever before

Comfort, cleanliness and convenience
By Elizabeth Shove, 2003
International Summer School in Renewable Energies *(since 2008)*

► US/ Denmark Program

  ► UC Santa Cruz; UC Davis
  ► Tech. University of Denmark; Aalborg

► Curriculum (1 month)

  ► Guest Lectures by Experts (technology, policy, business, social issues)
  ► Extensive Field trips (2 weeks); student projects

http://localrenew.soe.ucsc.edu/
Summary

• Energy challenge, CO₂/capita: role of thermoelectrics (waste heat/topping cycle)
• ErAs:InGaAs thermoelectrics (ZT~1.5-1.7 at 800K)
• Cost/efficiency trade off:
  – New TE module designs
• Improve STEM education through sustainability focus
• Teach about global issues, social awareness for science/engineering majors
• nanoHUB-U course on Nanostructured Thermoelectrics (Shakouri, Lundstorm, Datta; Fall 2013)

A. Shakouri, Annual Review of Materials Research, July 2011

K. Yazawa and A. Shakouri, Environmental Science and Technology, July 2011
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Research Professors: Zhixi Bian, Kaz Yazawa

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Alumni: Younes Ezzahri (Prof. Univ. Poitier), Daryoosh Vashaee (Prof. Oklahoma State), Zhixi Bian (Adj. Prof. UCSC), Mona Zebarjadi (Prof. Rutgers), Yan Zhang (Tessera), Rajeev Singh (PV Evolutions), James Christofferson (Microsanj), Kazuhiko Fukutani (Canon), Je-Hyoun Park (Samsung), Javad Shabani (postdoc, Harvard), Xi Wang (InterSil), Helene Michel (CEA), Gilles Pernot (Bordeaux), Ramin Sadeghian (H2scan), Shila Alavi (UCSC ASL), Tammy Humphrey, David Hauser
US Department of Energy; Energy Information Administration (2010)

1 Quad = $1.055 \times 10^{18}$ J
Fractional area coverage lowers stress.

\[ \tau_{\text{max}} \text{ vs. } l: \text{ for } l=1\text{mm to } l=L/2\text{mm} \& h=4\text{mm} \]

\[ \tau_{\text{max}}(\text{MPa}) \]

\[ l, \text{ half bonded region length (mm)} \]

- \( L=5\text{mm} \)
- \( L=10\text{mm} \)
- \( L=20\text{mm} \)

Ziabari, Suhir & Shakouri; Therminic Sept. 2012
Learn from history

- Environmental movement in 1960’s, 70’s
- Smoking story (Ronnie Lipschutz)

Now and Then

Robert Heinlein smoking in a UCSC classroom, circa late 1960s
Defining “comfort”
Fuel du Jour Phenomenon
Disruptive and wasteful

1978  Synfuels (oil shale, coal)
1988  Methanol
1993  Electricity (BEV)
2003  Hydrogen (fuel cells)
2006  Ethanol (Biofuels)
2008  Plug in hybrid