Nanoscale Thermoelectric Energy Conversion Devices
and
Interdisciplinary Sustainability Education

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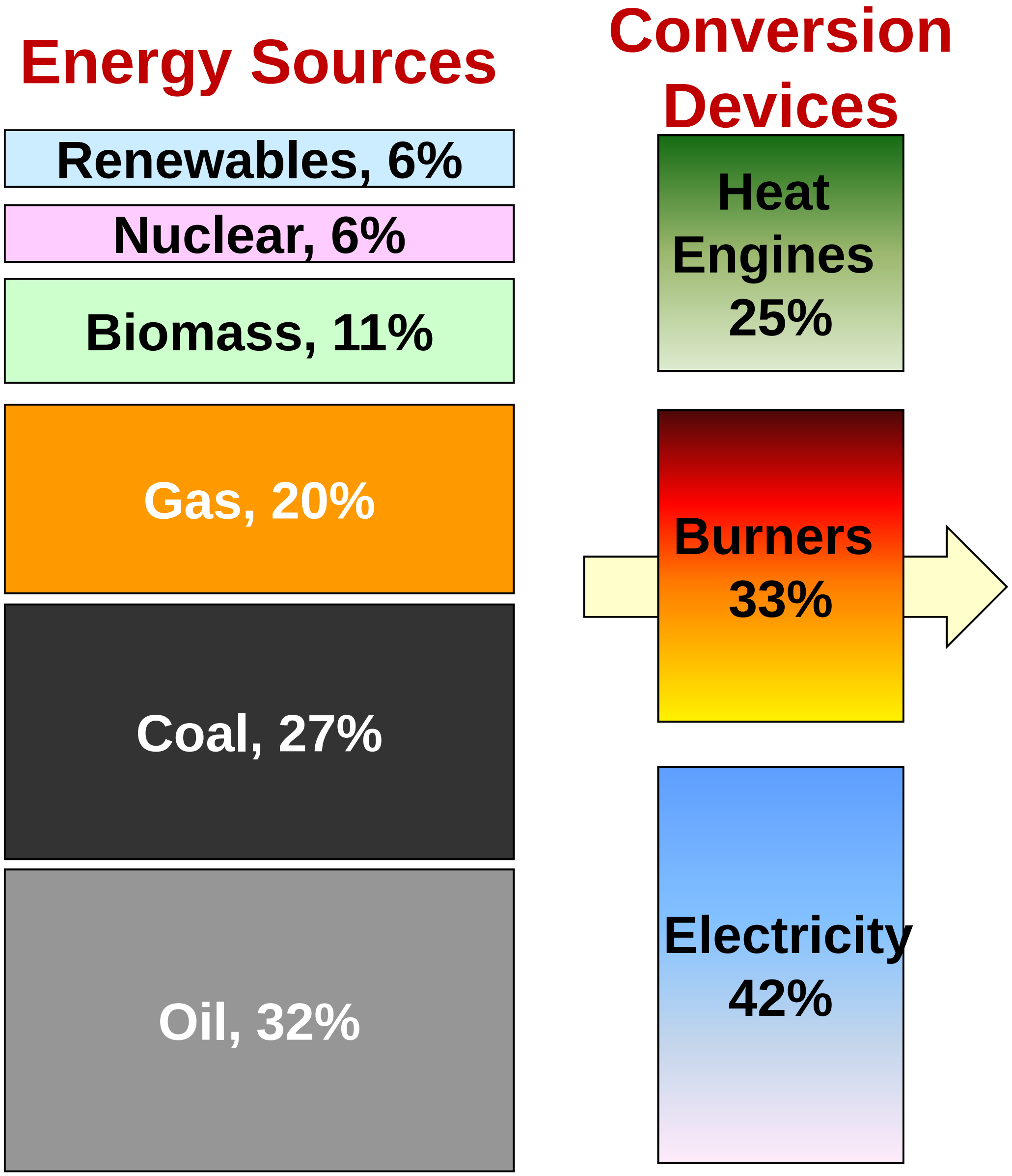
Purdue-Mexico Workshop on Sustainability; April, 29, 2013

Quest Quantum Engineered Systems & Technology

World Energy Use in 2005 (15TW)



- 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

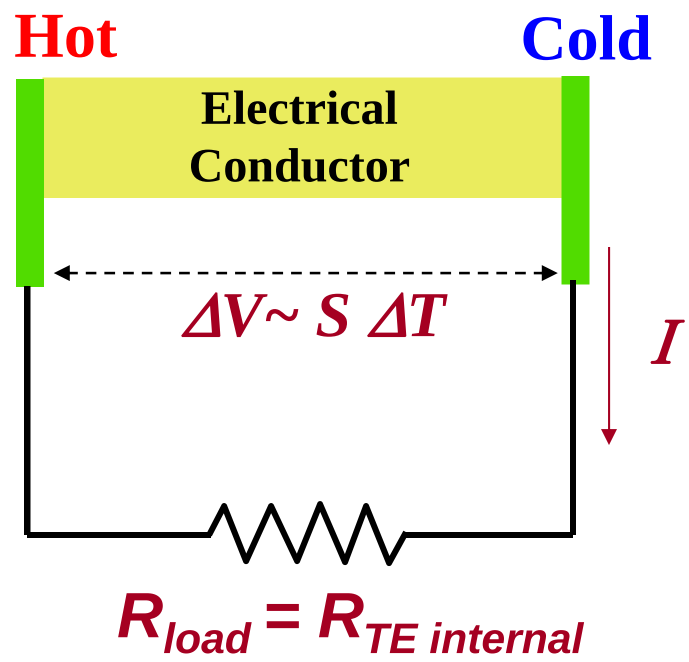
A. S. 15 August 2012

Adapted from Cullen and Allwood, *Energy*, 2010

Direct Conversion of Heat into Electricity

Seebeck coefficient
(1821)

$$S = \frac{\Delta V}{\Delta T}$$



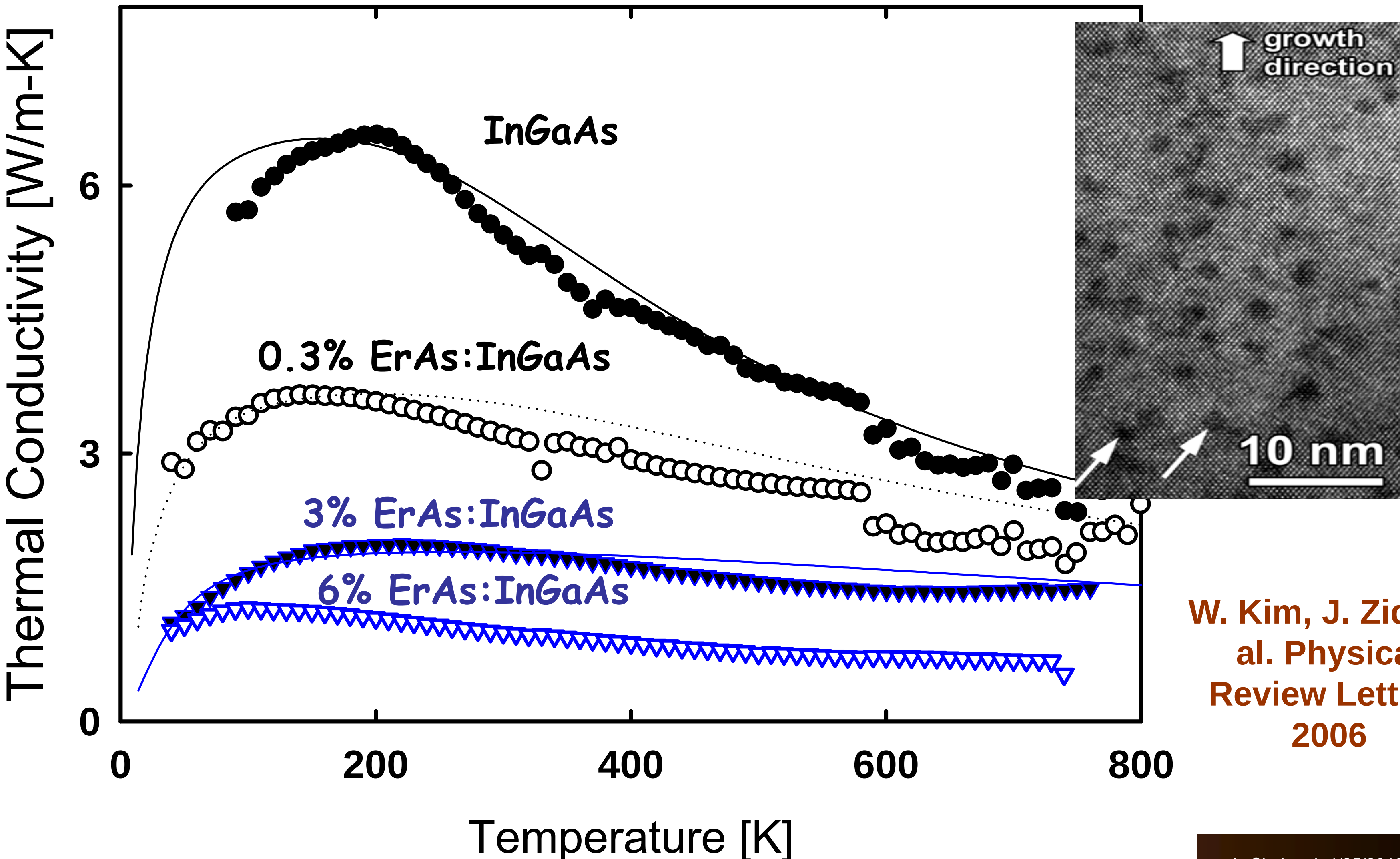
Efficiency function of
thermoelectric figure-of-merit (Z)

$$Z = \frac{S^2 \sigma}{k}$$

$$Z = \frac{(Seebeck)^2 (electrical \quad conductivity)}{(thermal \quad conductivity)}$$

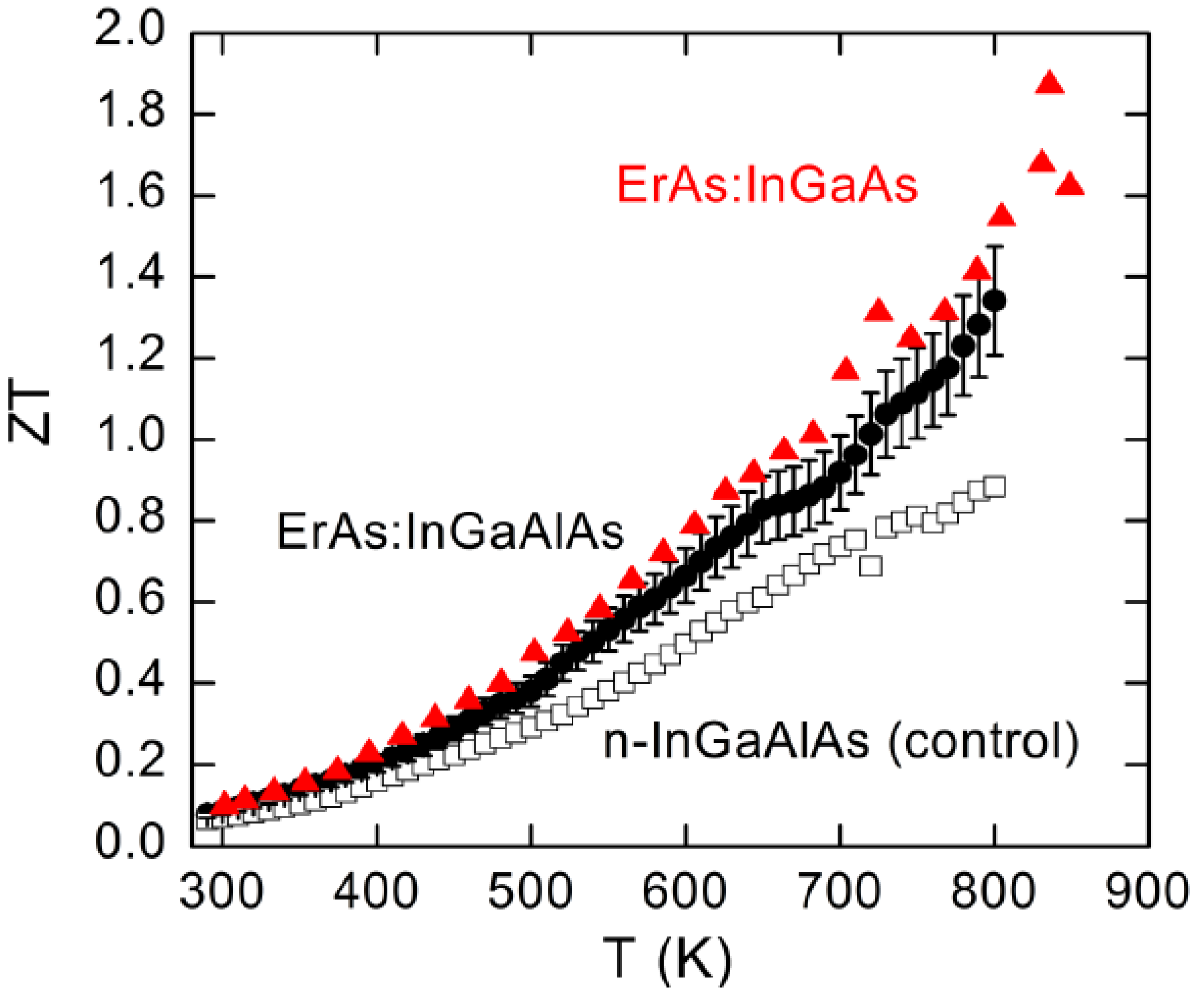
Beating the Alloy Limit in Thermal Conductivity

Long *and* Short Wavelength Phonon Scattering
➤ Thermal Conductivity Reduction



W. Kim, J. Zide et al. Physical Review Letters 2006

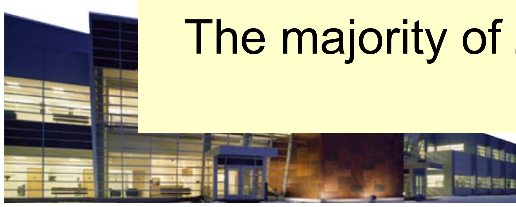
Thermoelectric figure-of-merit



Je-Hyeong Bahk

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

Zide et al. J. of Applied Physics (2010); Burke, Bahk, et al. to be published (2013)

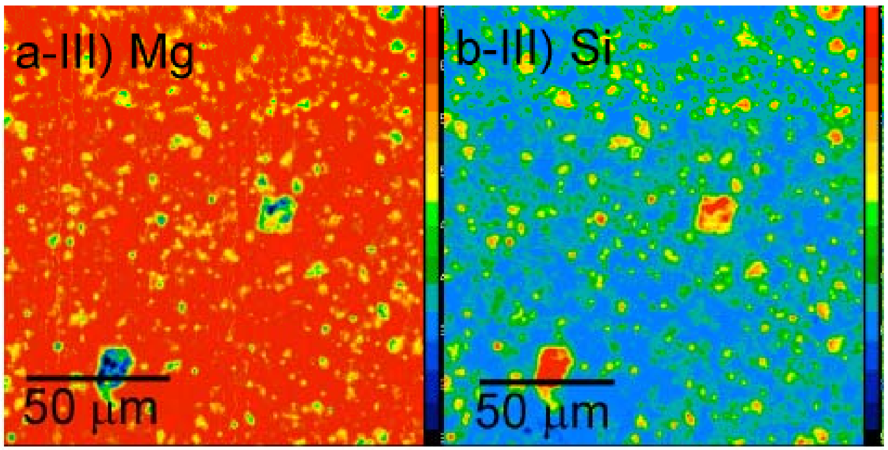


The majority of ZT enhancement is from thermal conductivity reduction.
5% power factor enhancement at 800K.

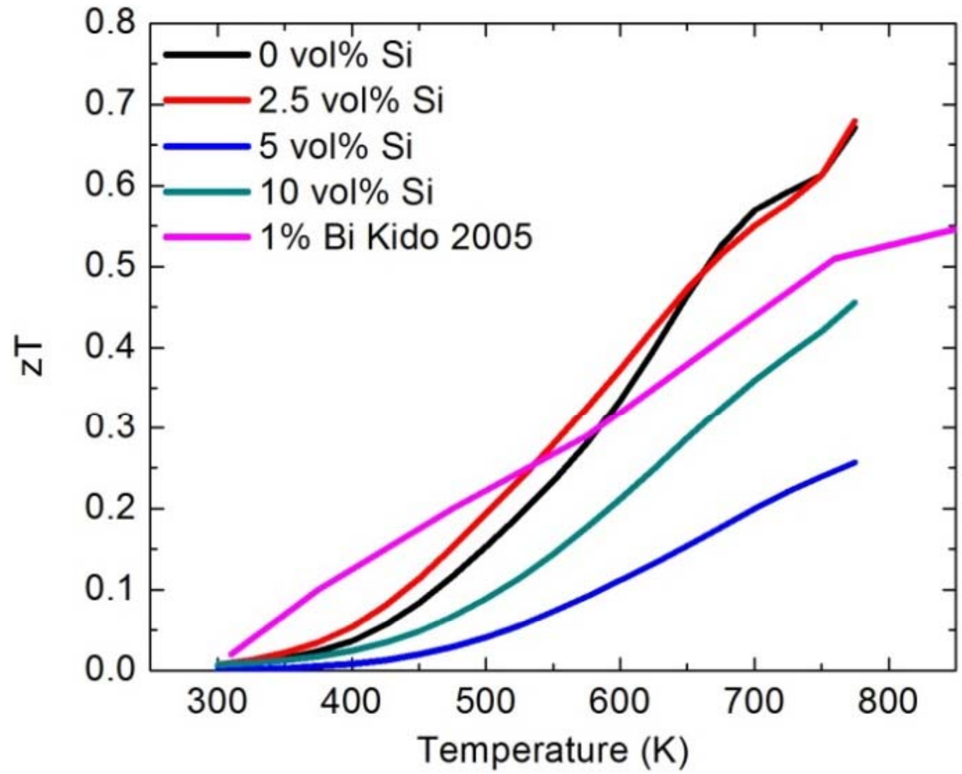
Mg_2Si: Lattice thermal conductivity can be lowered by nanoparticles

NSF/DOE

- ZT ~ 0.7 for $Mg_2Si/2.5vol\%Si_{1\%Bi}$ at 775 K



NSF/DOE



Susan Kauzlarich, Tanghong Yi, Sabah Bux, et al.
J. Mat. Chemistry 2012

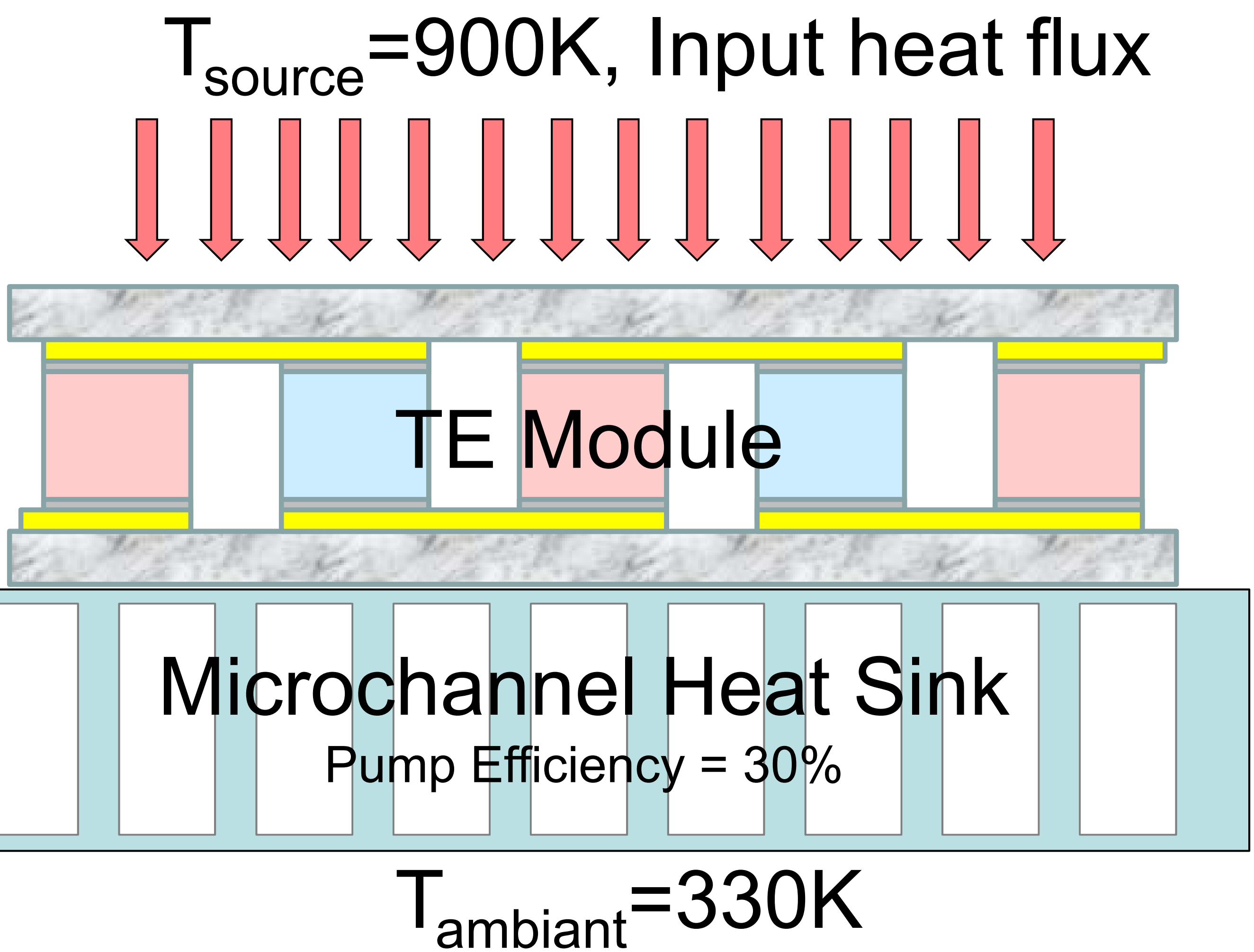
TE module & cold side heat exchanger for waste heat recovery

PURDUE UNIVERSITY Discovery Park

TE material:
$500/kg

Alumina substrate:
$ 5/kg

Copper heat sink:
$ 20/kg



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

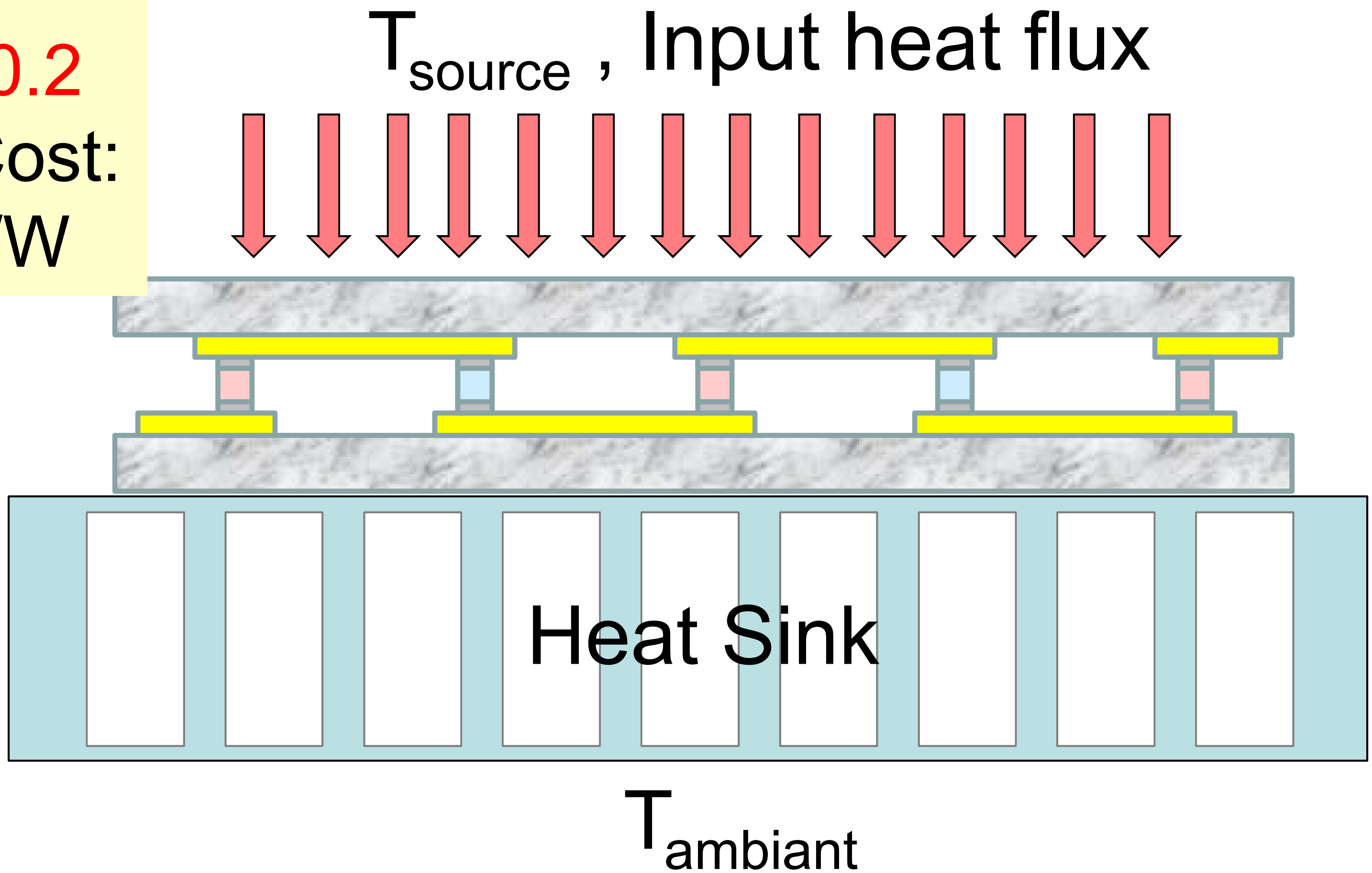
Purdue University Discovery Park

ZT=1,

Fill Factor=0.2

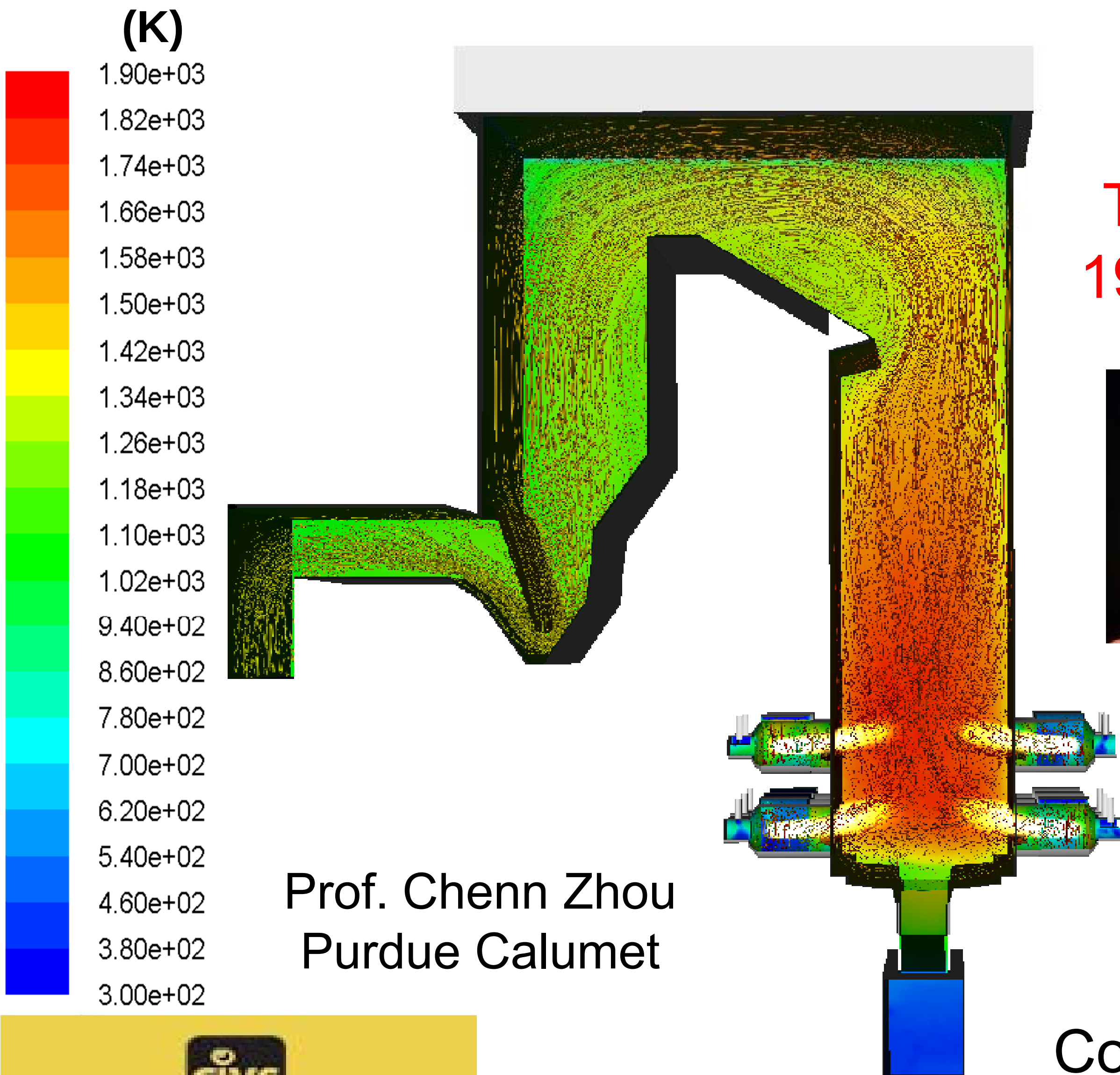
→ Material Cost:

$0.02-0.03/W

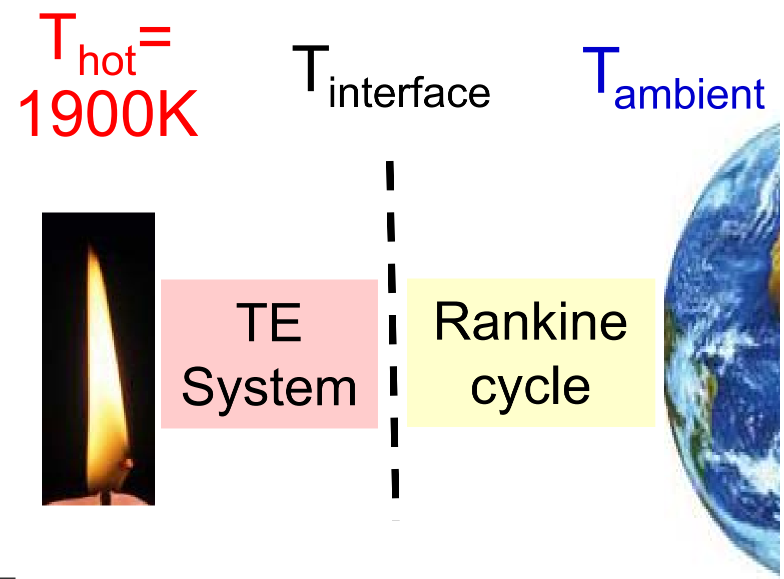


Yazawa & Shakouri; Journal of Material Research 2012

TE for topping cycle applications



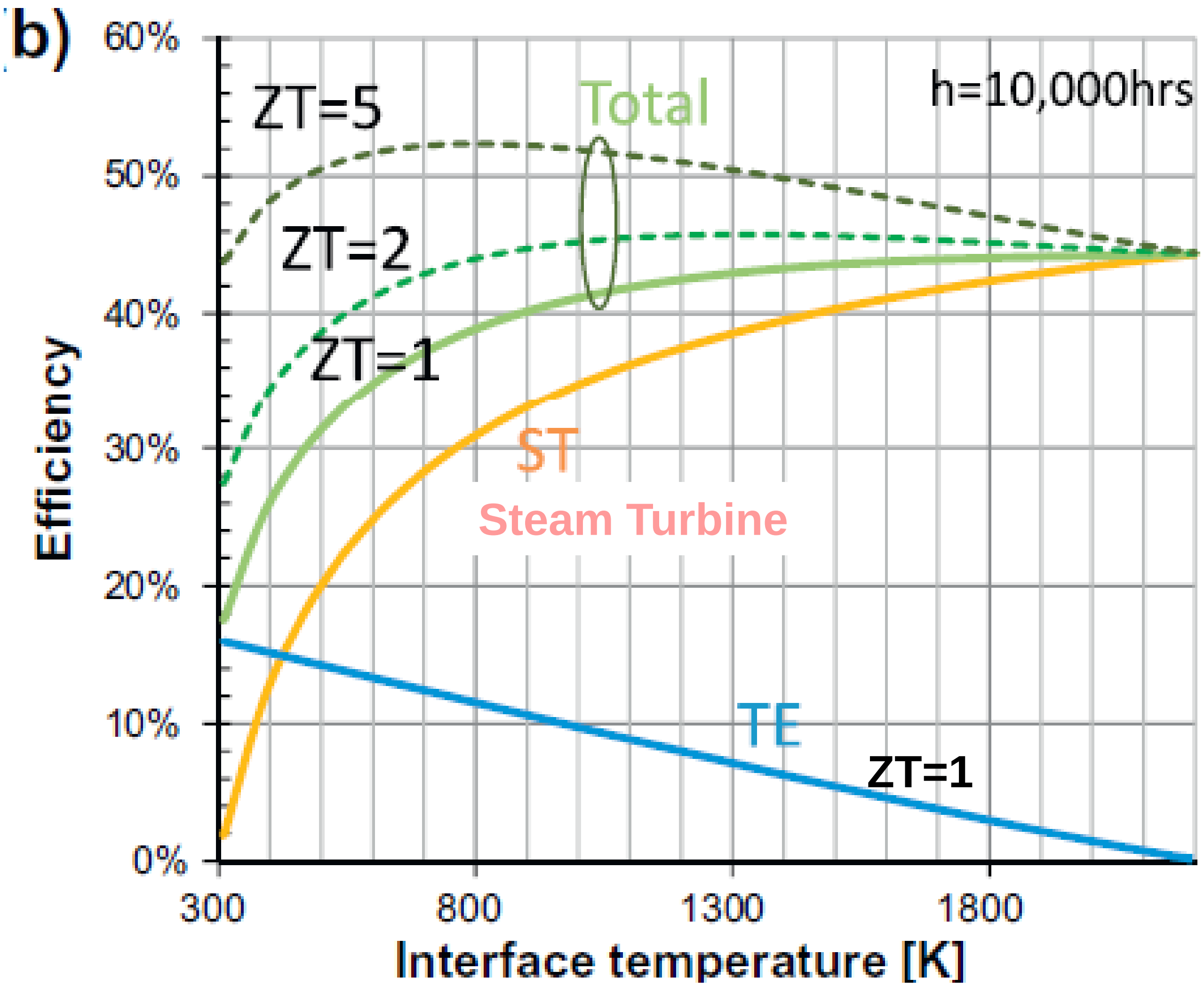
Prof. Chenn Zhou
Purdue Calumet

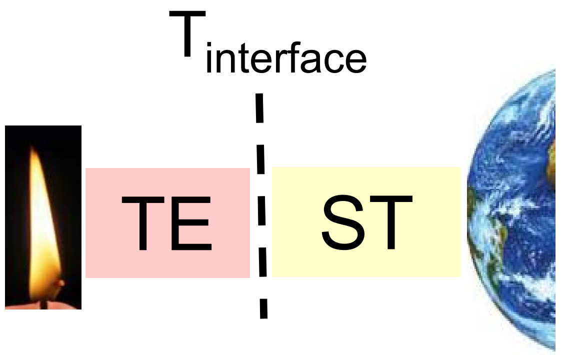


Coal Power Plant

CENTER FOR INNOVATION THROUGH VISUALIZATION & SIMULATION

TE / Steam Turbine combined cycle

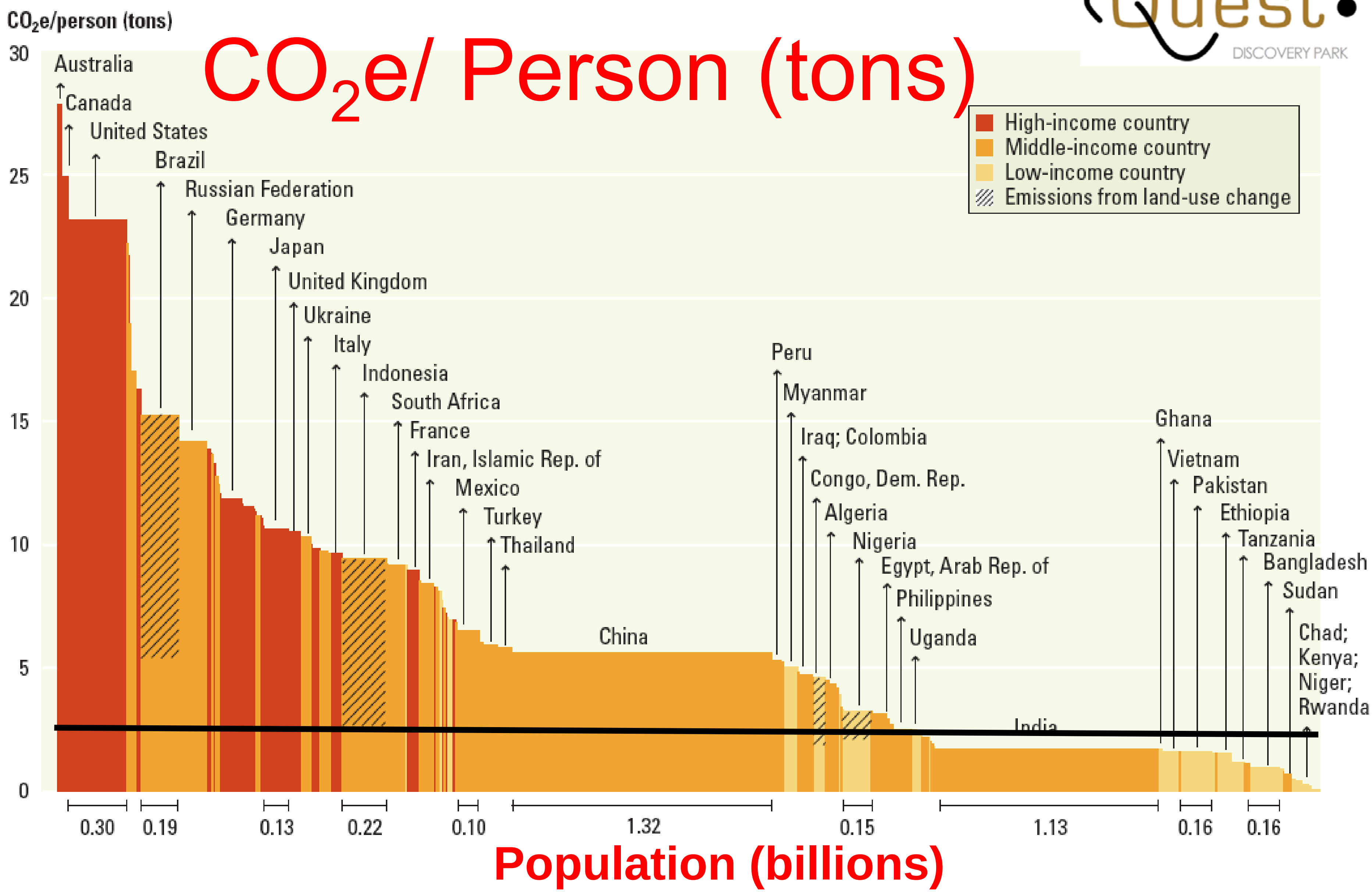




Simplified Steam Turbine Model

Yazawa & Shakouri, *Applied Energy*, 2013

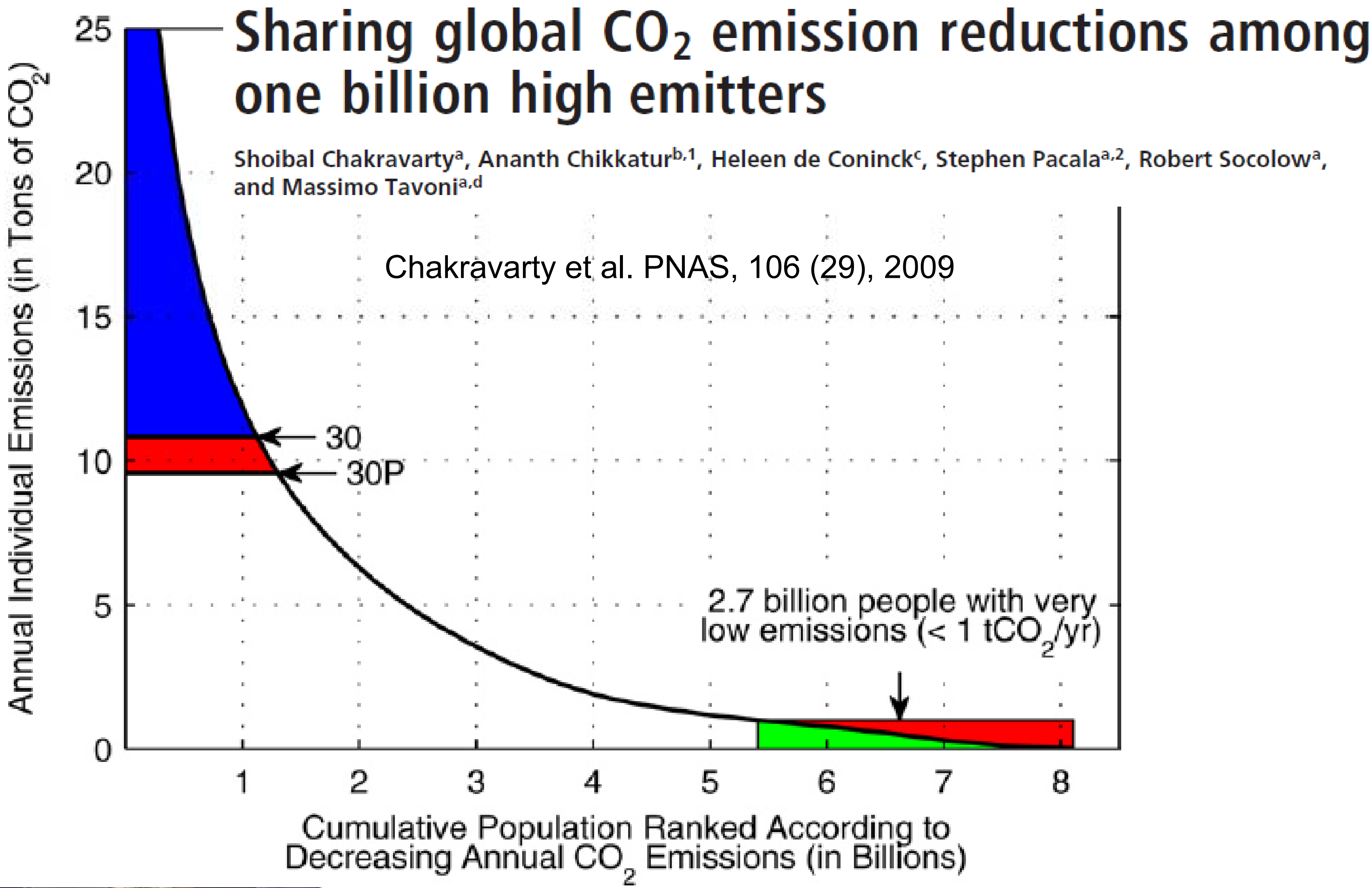
Figure 1.1 Individuals' emissions in high-income countries overwhelm those in developing countries



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 (55.5 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)



Chakravarty et al. PNAS, 106 (29), 2009

Sustainability Education through Engineering and Social Science Collaboration

Acknowledgement: **NSF/TUES**

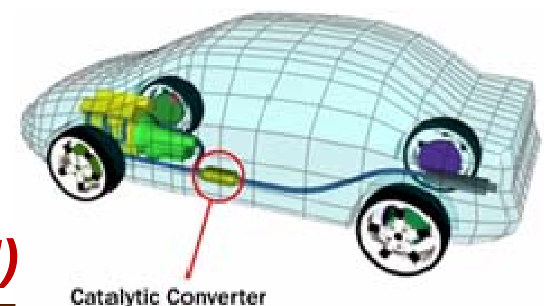
Introduction to renewable energies

- 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

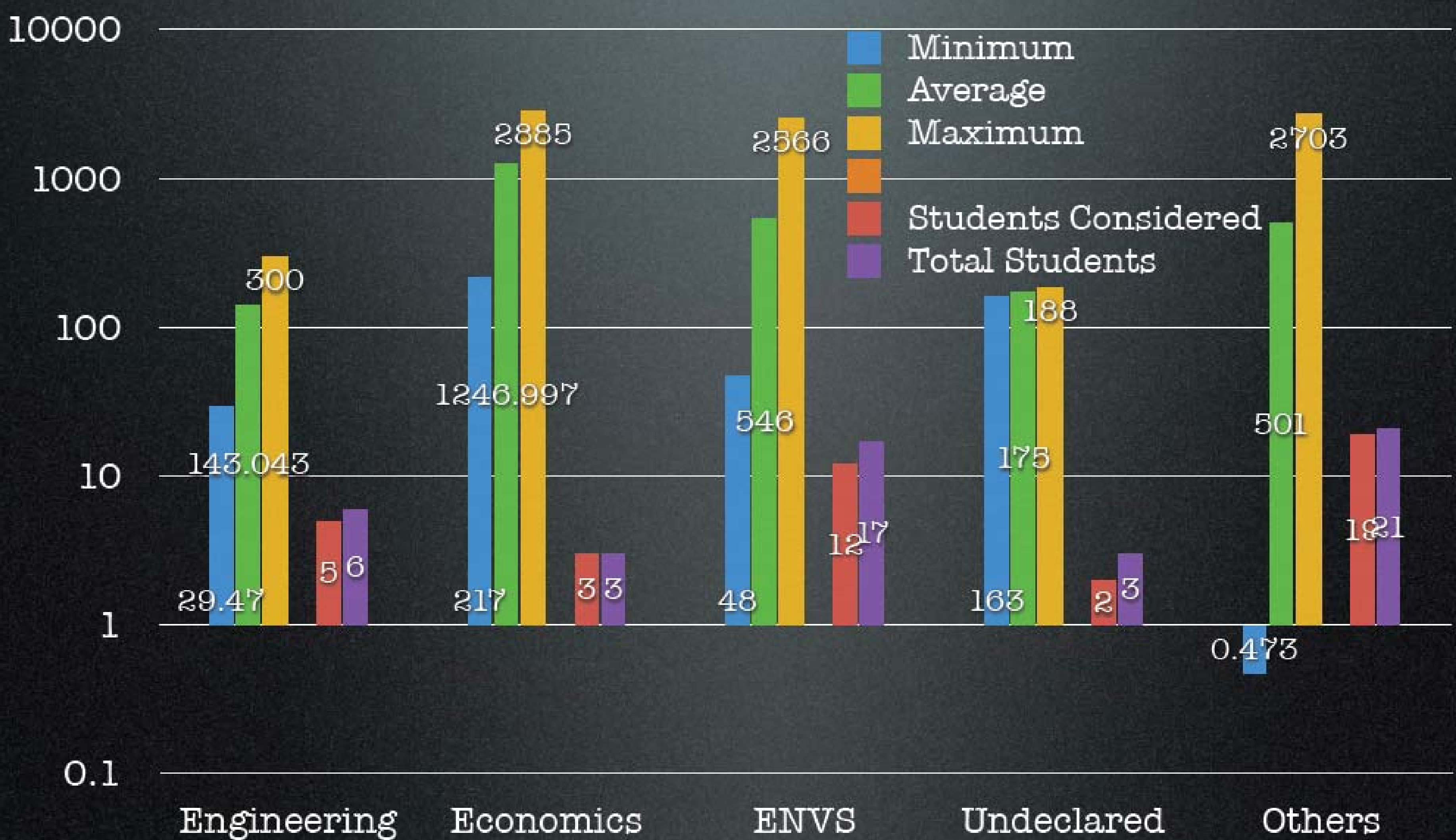
Student projects

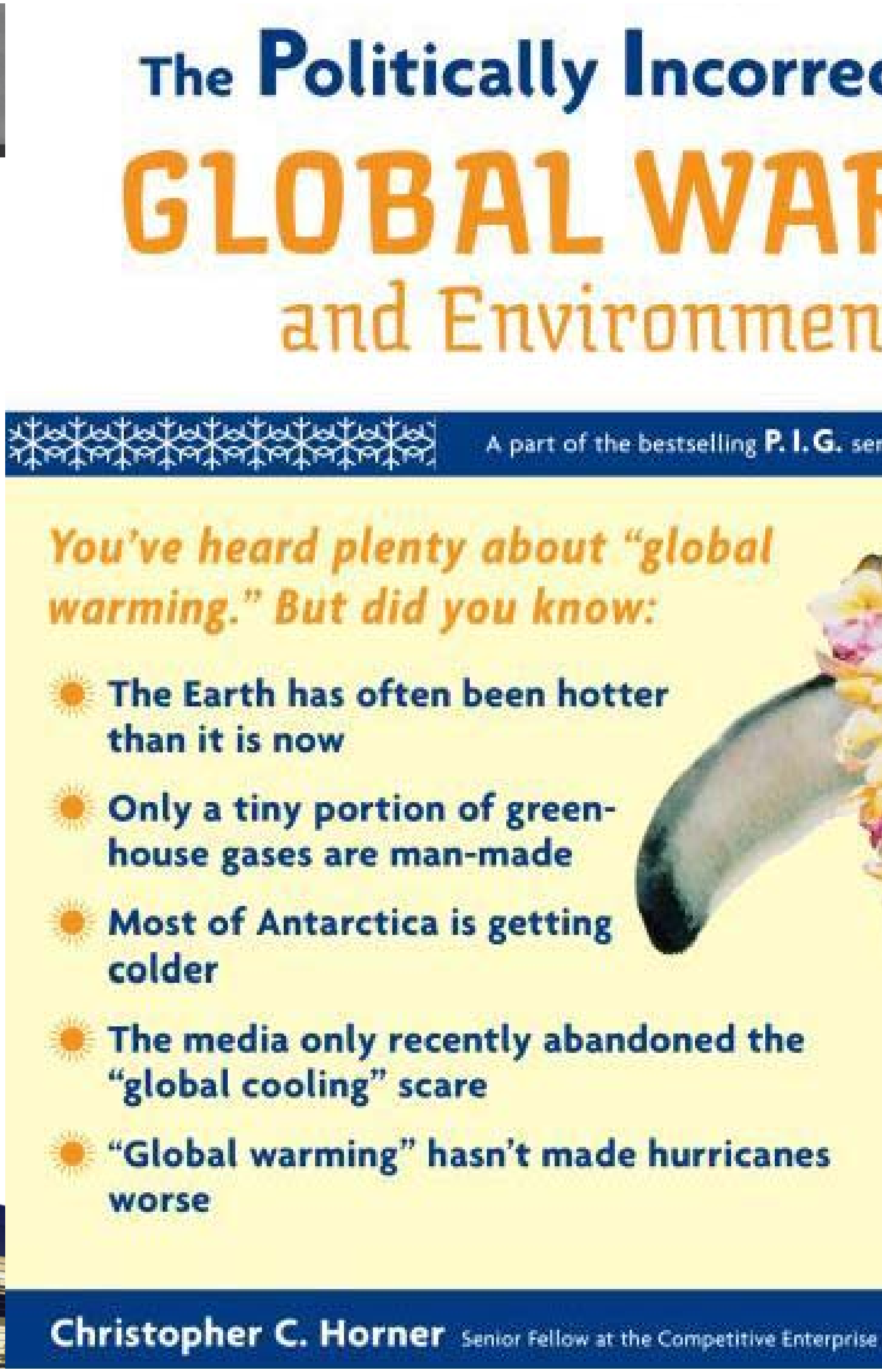


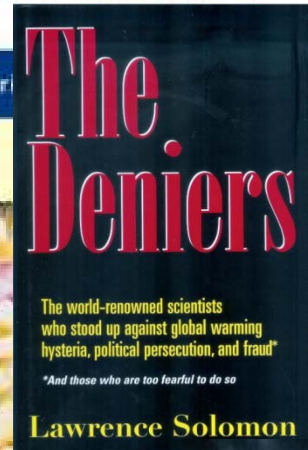
No science/engineering prerequisite

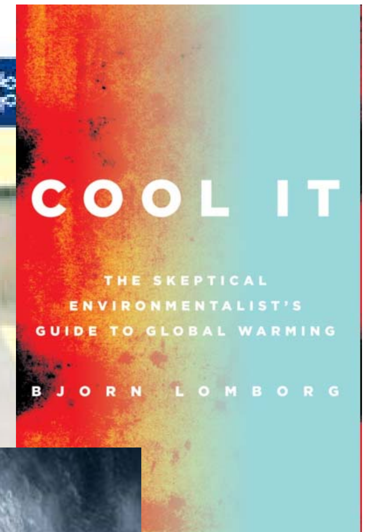
http://seed.soe.ucsc.edu (EE80J)

Average energy usage of students in various majors



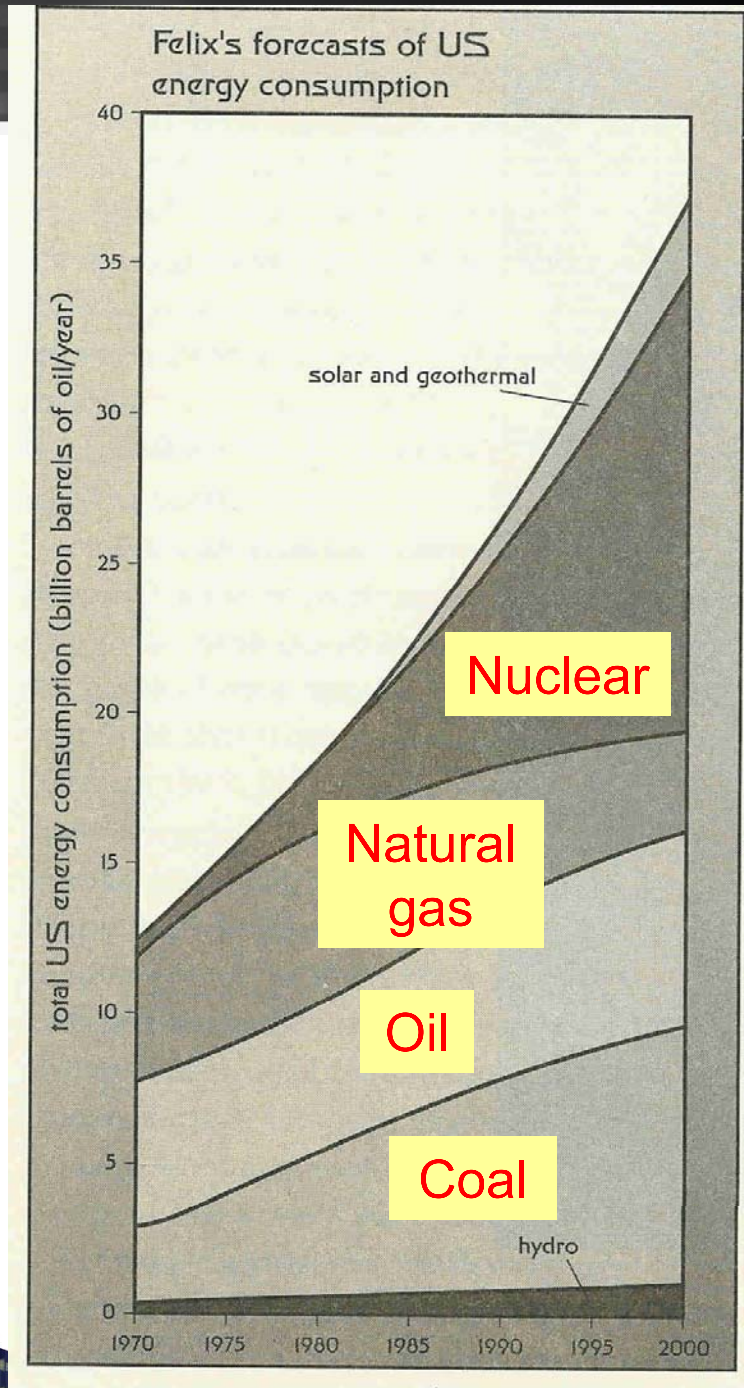

The Politically Incorrect Guide™ to
GLOBAL WARMING
and Environmentalism
A part of the bestselling P. I. G. seri
You've heard plenty about "global warming." But did you know:
The Earth has often been hotter than it is now
Only a tiny portion of green-house gases are man-made
Most of Antarctica is getting 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


The Deniers
The world-renowned scientists who stood up against global warming hysteria, political persecution, and fraud*
*And those who are too fearful to do so
Lawrence Solomon

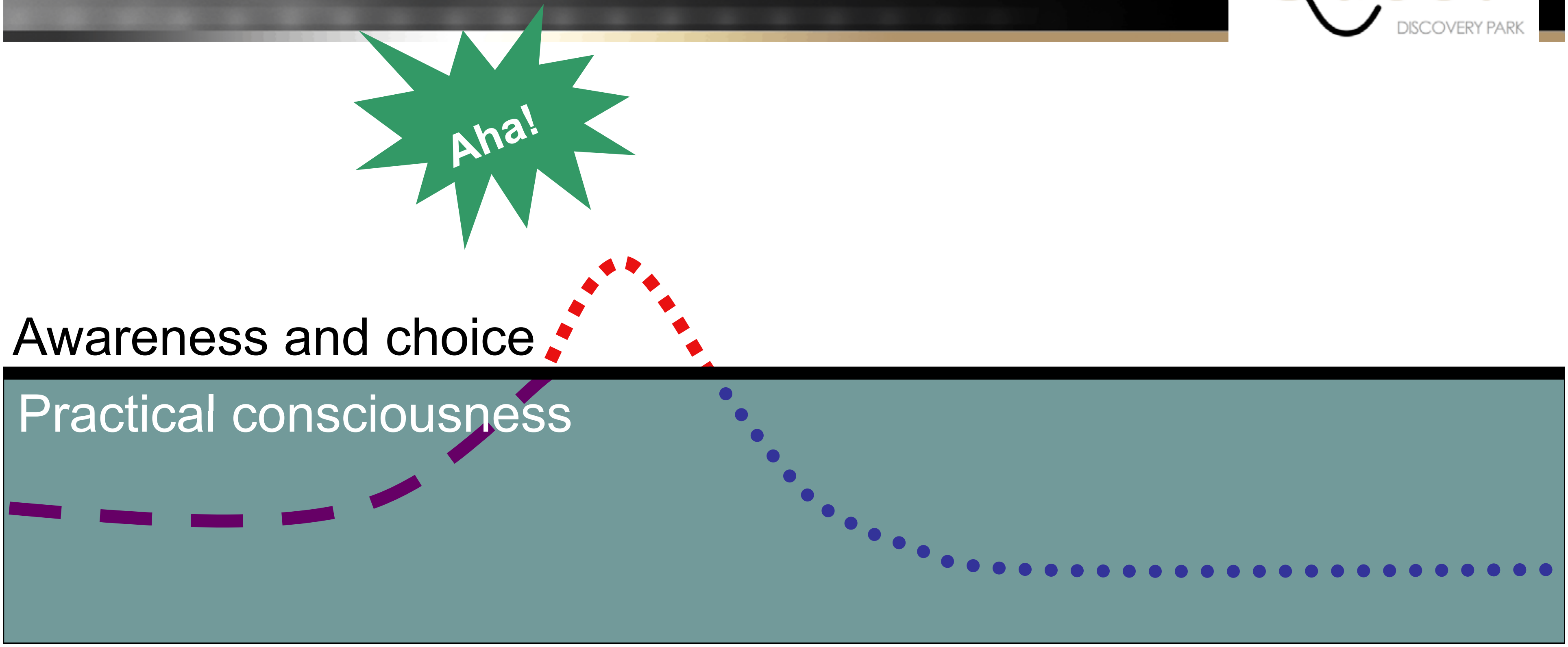

COOL IT
THE SKEPTICAL ENVIRONMENTALIST'S GUIDE TO GLOBAL WARMING
BJORN LOMBORG


an inconvenient truth
A GLOBAL WARNING

Felix's forecasts of US energy consumption in year 2000 (early 1970's)



Vaclav Smil, Energy at the Crossroads, 2005



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?

Comfort and indoor environments

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

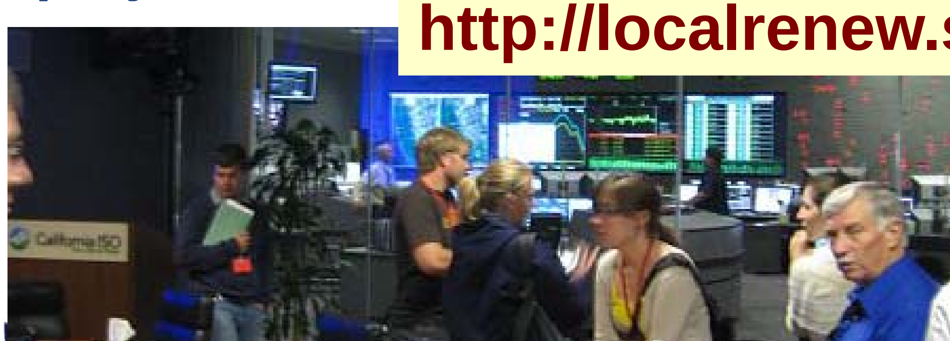
Comfort, cleanliness and convenience
By Elizabeth Shove, 2003

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, CO_2/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

Acknowledgement

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Collaborators: John Bowers, Art Gossard (UCSB), Tim Sands, Yue Wu (Purdue), Rajeev Ram (MIT), Venky Narayanamurti (Harvard), Arun Majumdar (Berkeley/ARPA-E), Josh Zide (Delaware), Lon Bell (BSST), Yogi Joshi, Andrei Federov (Georgia Tech), Kevin Pipe (Michigan), Stefan Dilhaire (Bordeaux), Natalio Mingo (CEA), Mike Isaacson, Sriram Shastry, Joel Kubby, Ronnie Lipschutz, Melanie Dupuis, Ben Crow, Steve Kang (UCSC), Bryan Jenkins, Susan Kauzlarich (Davis)

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-Hyoung 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

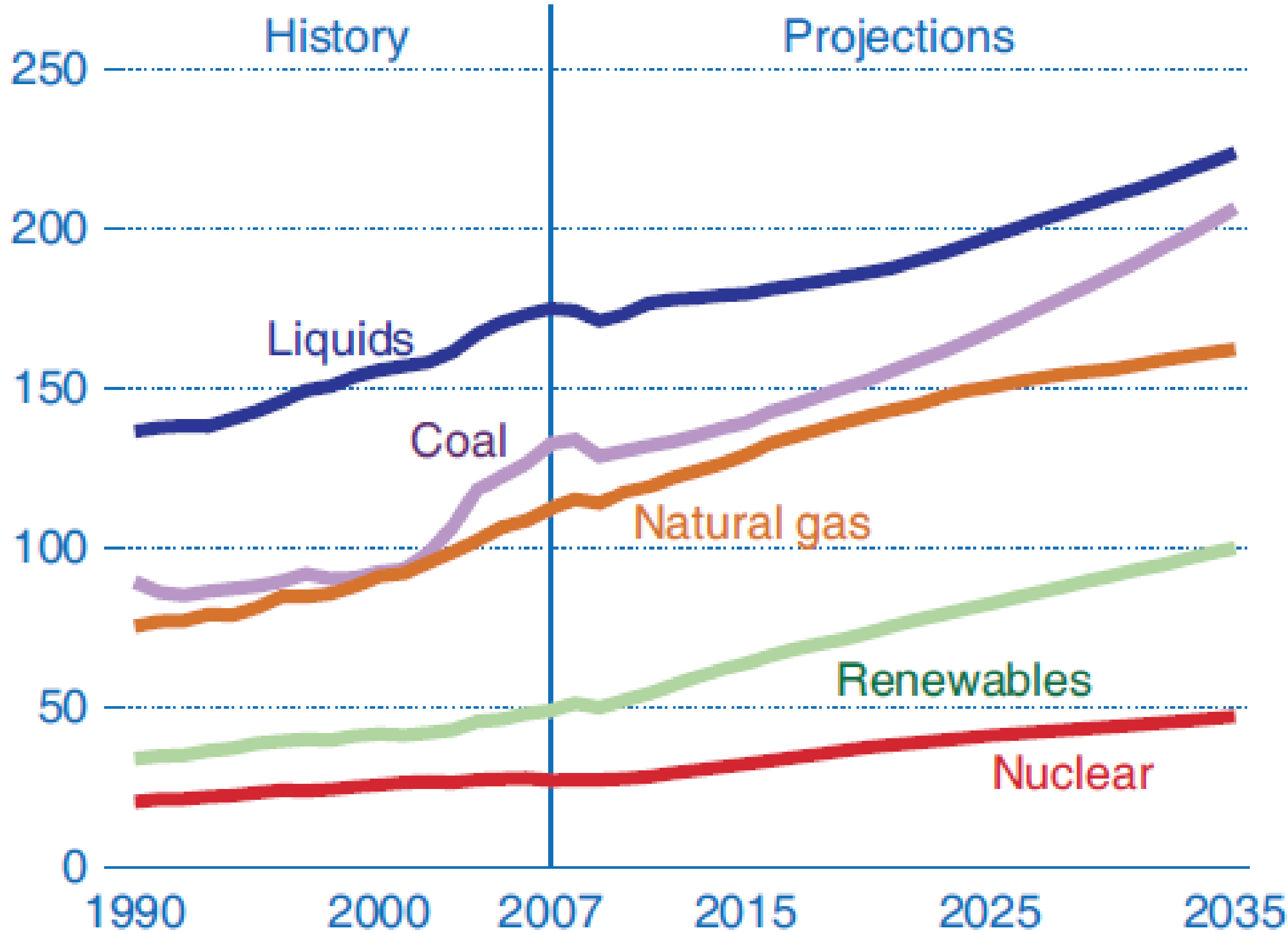
World Marketed Energy Use1990-2035

US Department of Energy; Energy Information Administration (2010)

1 Quad = 1.055 x 10^{18}J

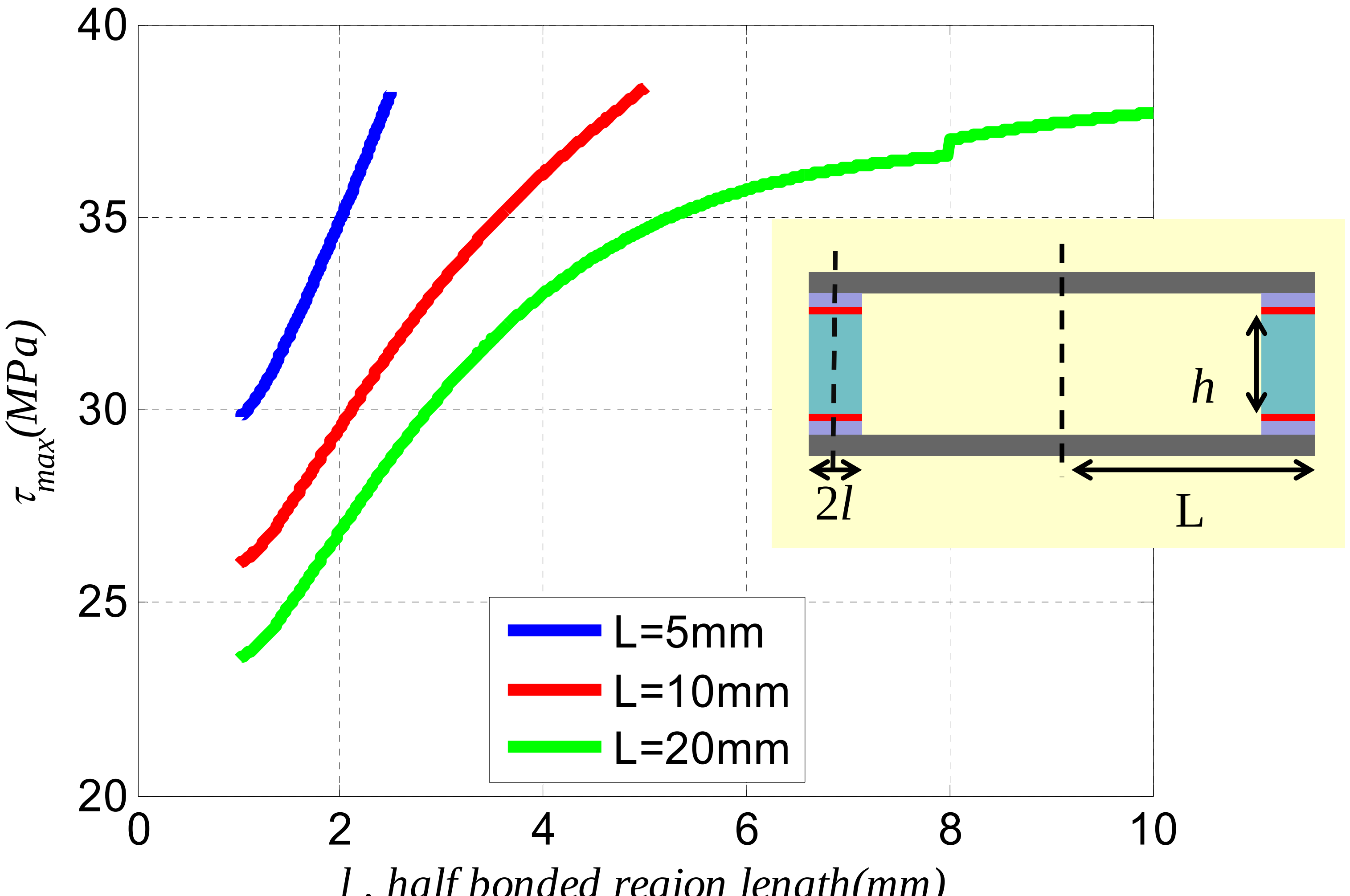
13TW

2050: 25-30TW



Fractional area coverage lowers stress

τ_{max} vs. l: for l=1mm to l=L/2mm & h=4mm



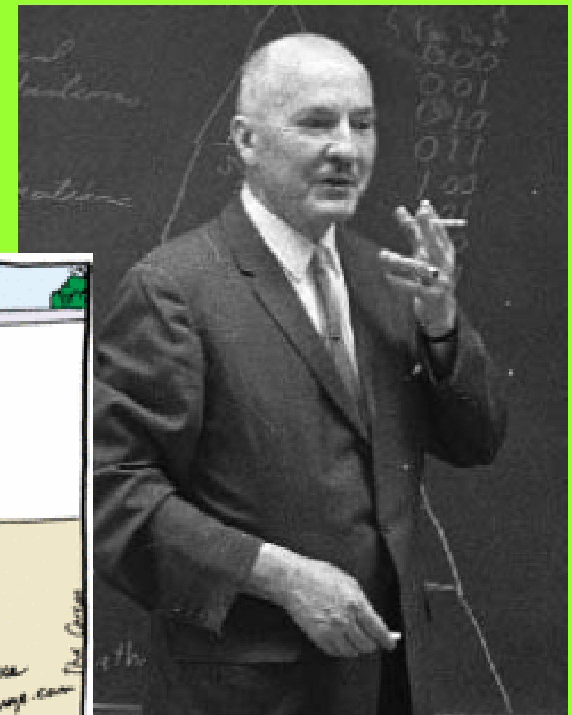
Suhir & Shakouri; Journal of Applied Mechanics, Nov. 2012

Ziabari, Suhir & Shakouri; Therminic Sept. 2012

Learn from history

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

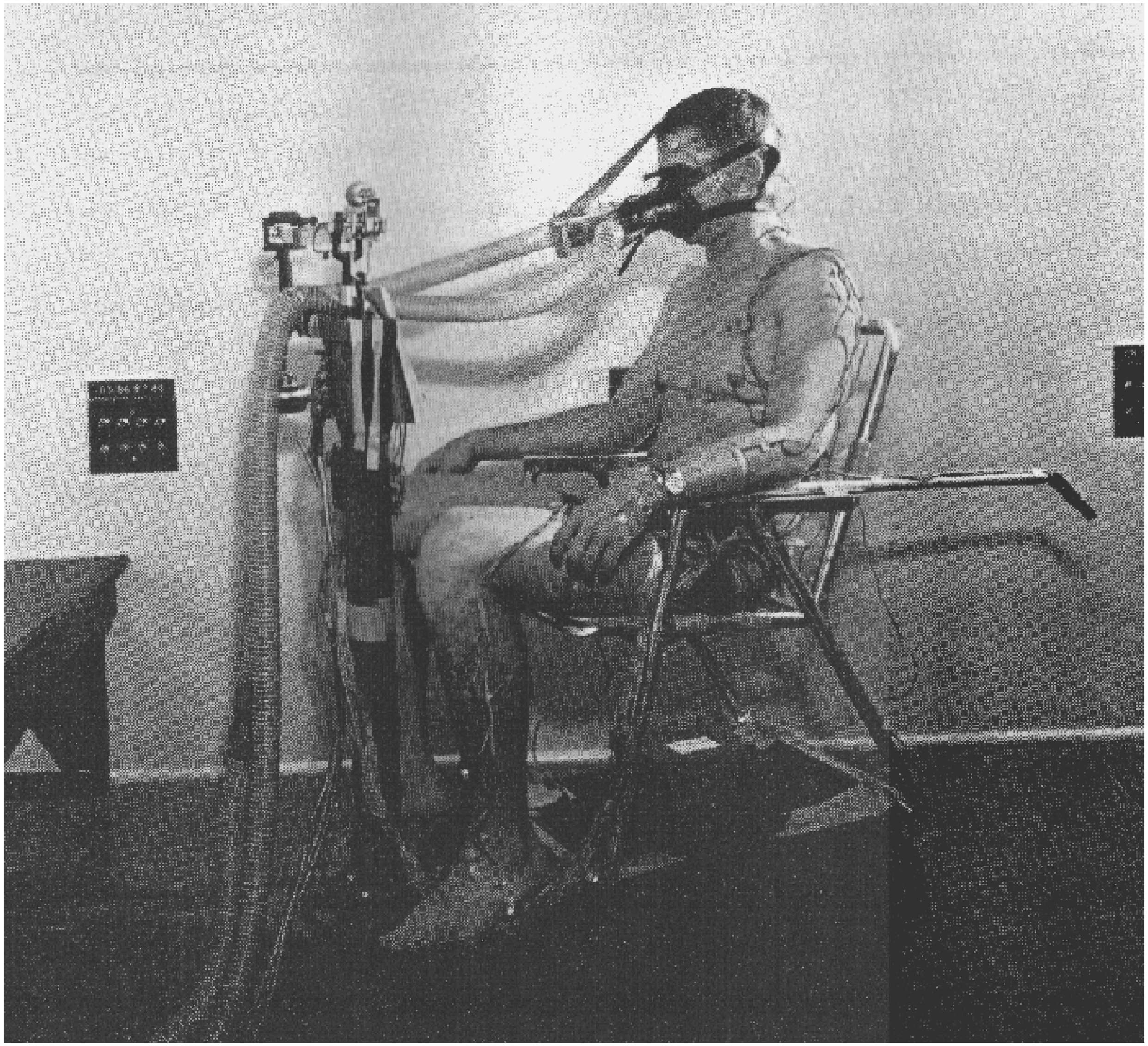
Now and Then



Robert Heinlein smoking in a UCSC classroom, circa late 1960s

Thermal comfort research

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