Center for Information Technology Research in the Interest of Society

Energy Efficiency & Waste Heat Recovery

Http://quantum.soe.ucsc.edu

Sponsors: ONR/MURI TEC, Intel, Canon, National, Packard Foundation, DARPA/Heretic, NSF

Ali Shakouri, Professor

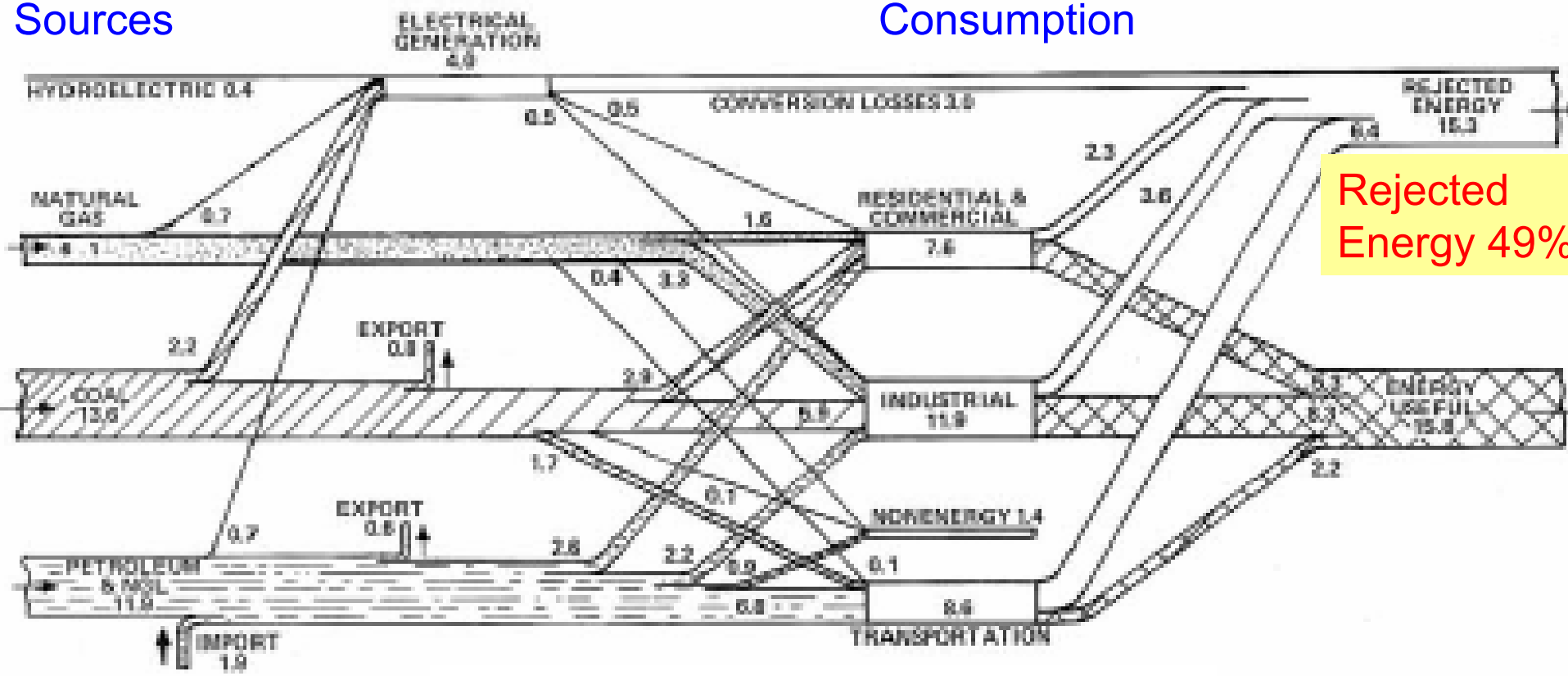
University of California Santa Cruz

CITRIS in Europe June 20, 2006

US Energy Flow 1950

Energy Sources

Energy Consumption

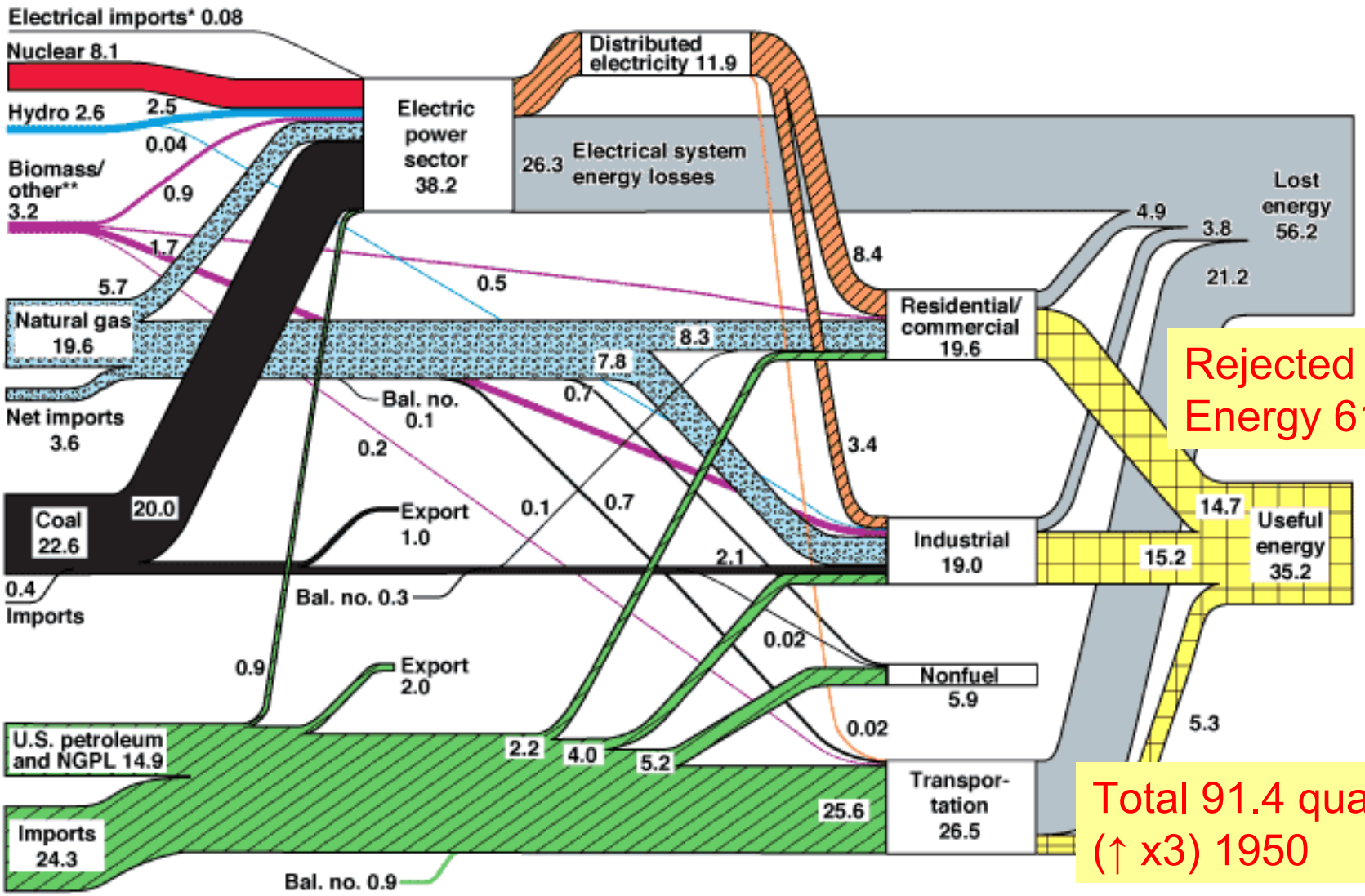


Rejected Energy 49%

Total 31.8 Quad

LLNL

U.S. Energy Flow Trends – 2002
Net Primary Resource Consumption ~97 Quads



Rejected Energy 61%

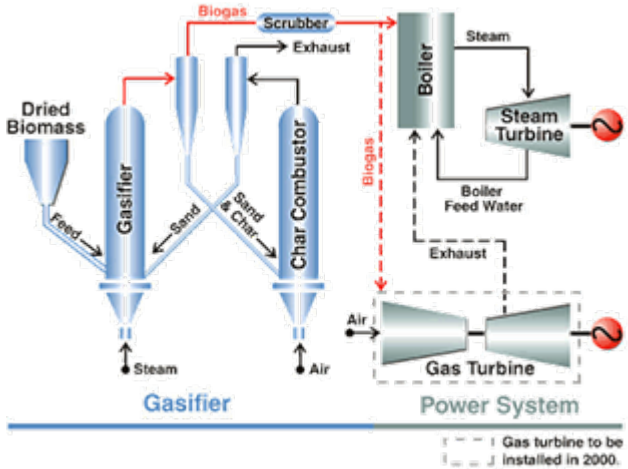
Total 91.4 quad (↑ x3) 1950

Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 2002.*
*Net fossil-fuel electrical imports.
**Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.

June 2004
Lawrence Livermore National Laboratory
http://eed.llnl.gov/flow

Are there Sustainable Solutions?

Solar



Biomass

Wind

Hydroelectric

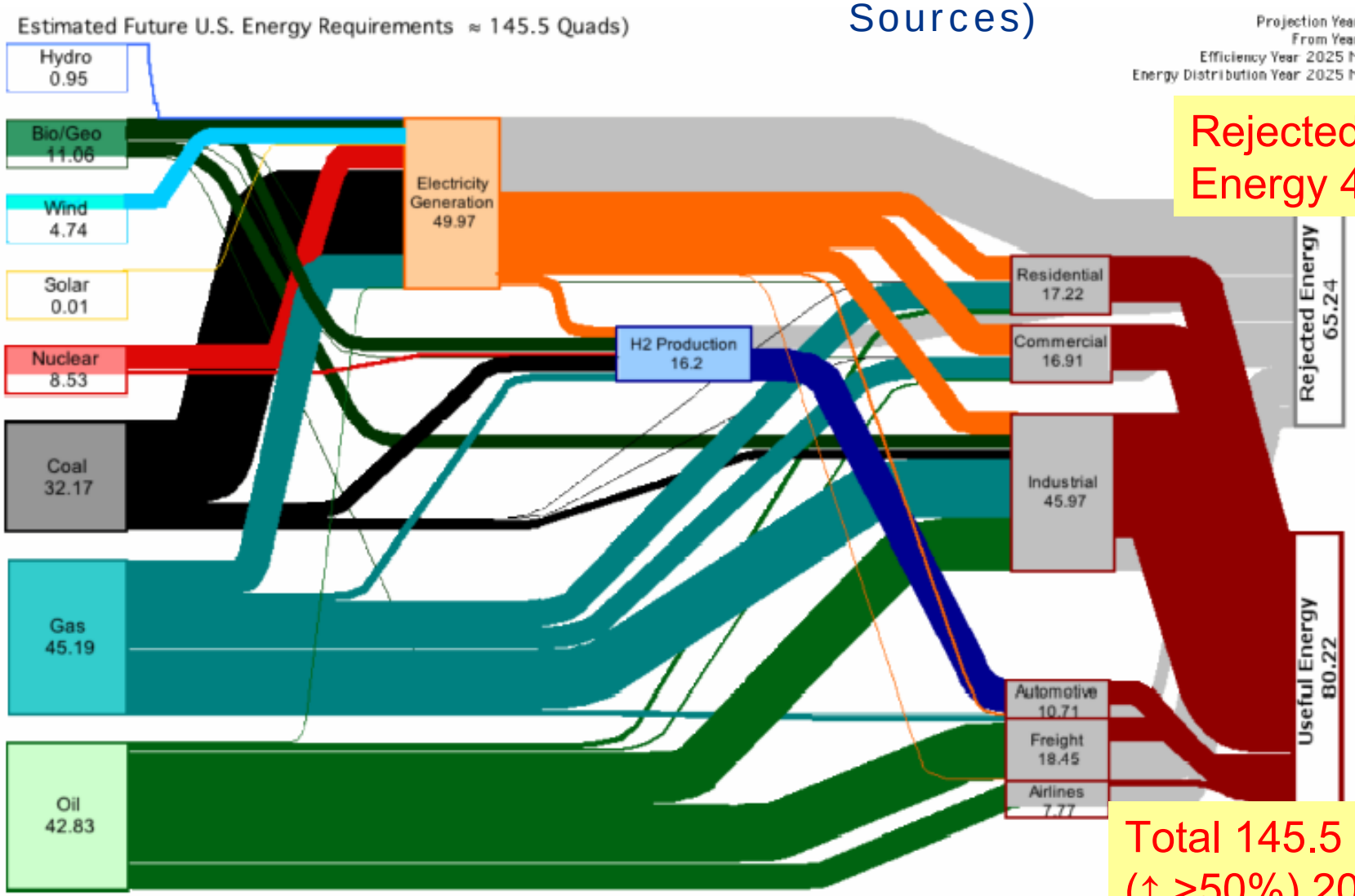
Geothermal

From the Oceans

http://zebu.uoregon.edu/2001/ph162/l14.html

US Energy Flow 2050

(Scenario Hydrogen Economy, H_2 from 50% renewable Sources)



Scenario 7. Scenario 6 except the light-duty fleet transitions entirely to 80 mpg equivalent hydrogen (H_2) fuel cell vehicles by 2050. H_2 produced using a mix of gas (20%), coal (25%), biomass (25%), wind electrolysis (25%), and nuclear thermochemical (5%).

Energy Efficiency is Important!

Airplane Speed- Past, Present, Future

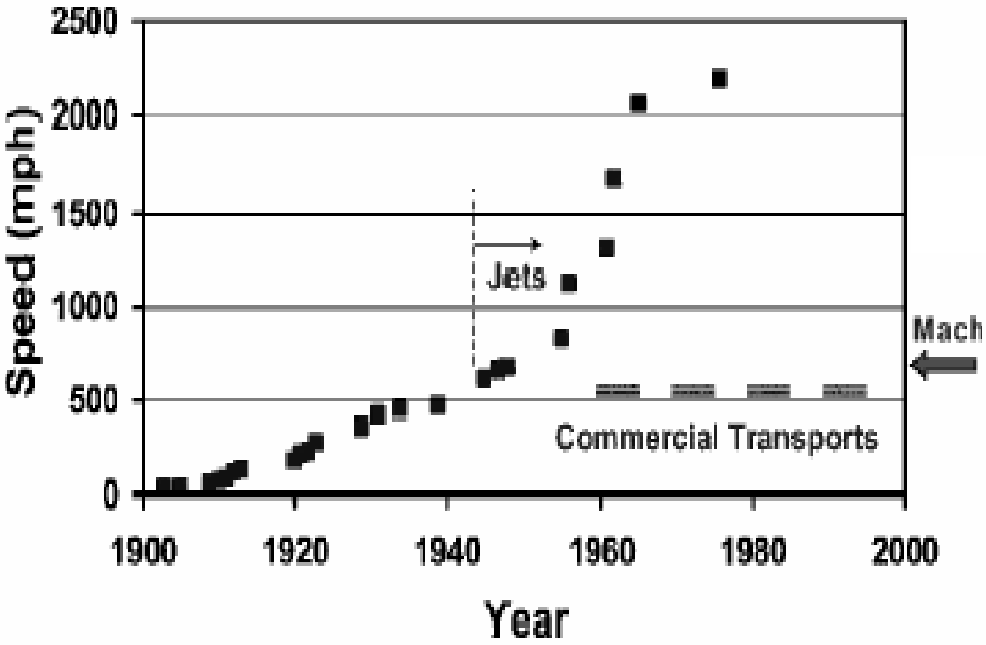


Fig. 6 Absolute airplane speed record (Refs. 10 and 11).

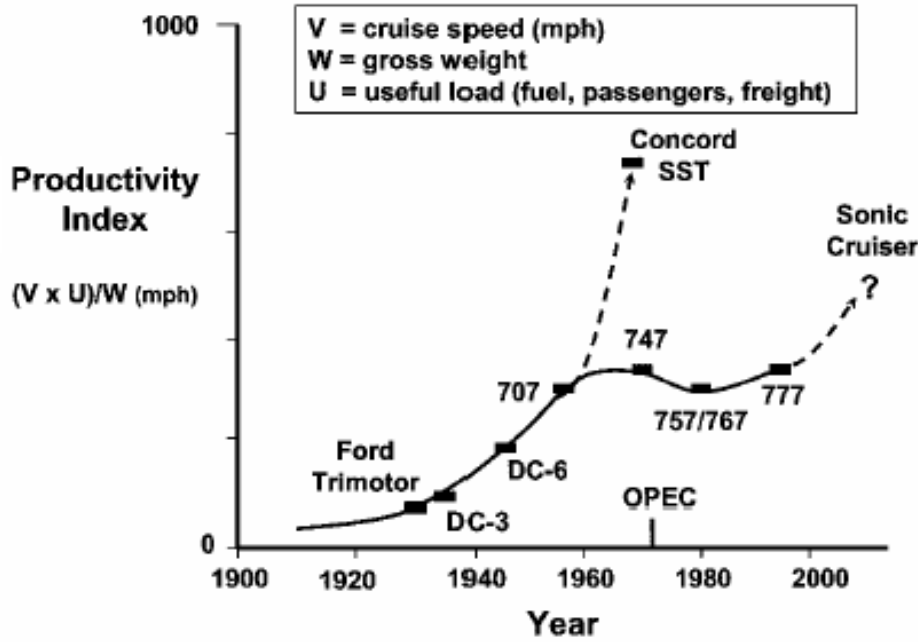


Fig. 7 Evolution in the productivity of commercial aircraft (Ref. 12).

McMasters & Cummings, Journal of Aircraft, Jan-Feb 2002

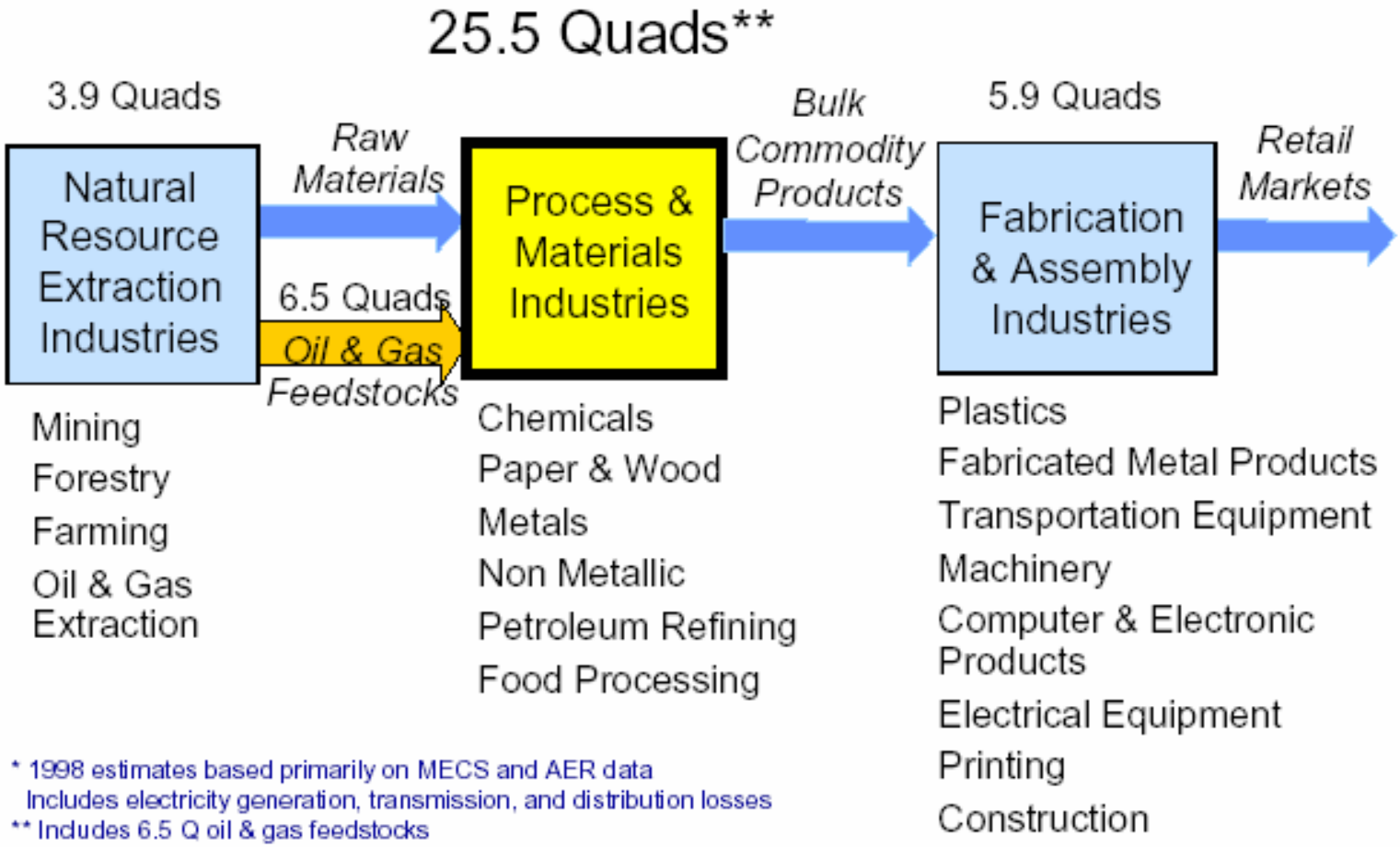
What areas are good for conservation?

- **Energy Usage Breakdown**
- **38% Buildings and Appliances**
- **36% Industry**
- **26% Transportation**

- **Buildings and appliances: better insulation; more efficient lighting, appliances**
- **Industry: there is a lot of room in overall system optimization for energy efficiency**
- **Transportation: There is some room to increase energy efficiency**

Important impact of sensors and sensor networks

Heavy Energy Use in Process Industries*



* 1998 estimates based primarily on MECS and AER data
Includes electricity generation, transmission, and distribution losses
** Includes 6.5 Q oil & gas feedstocks

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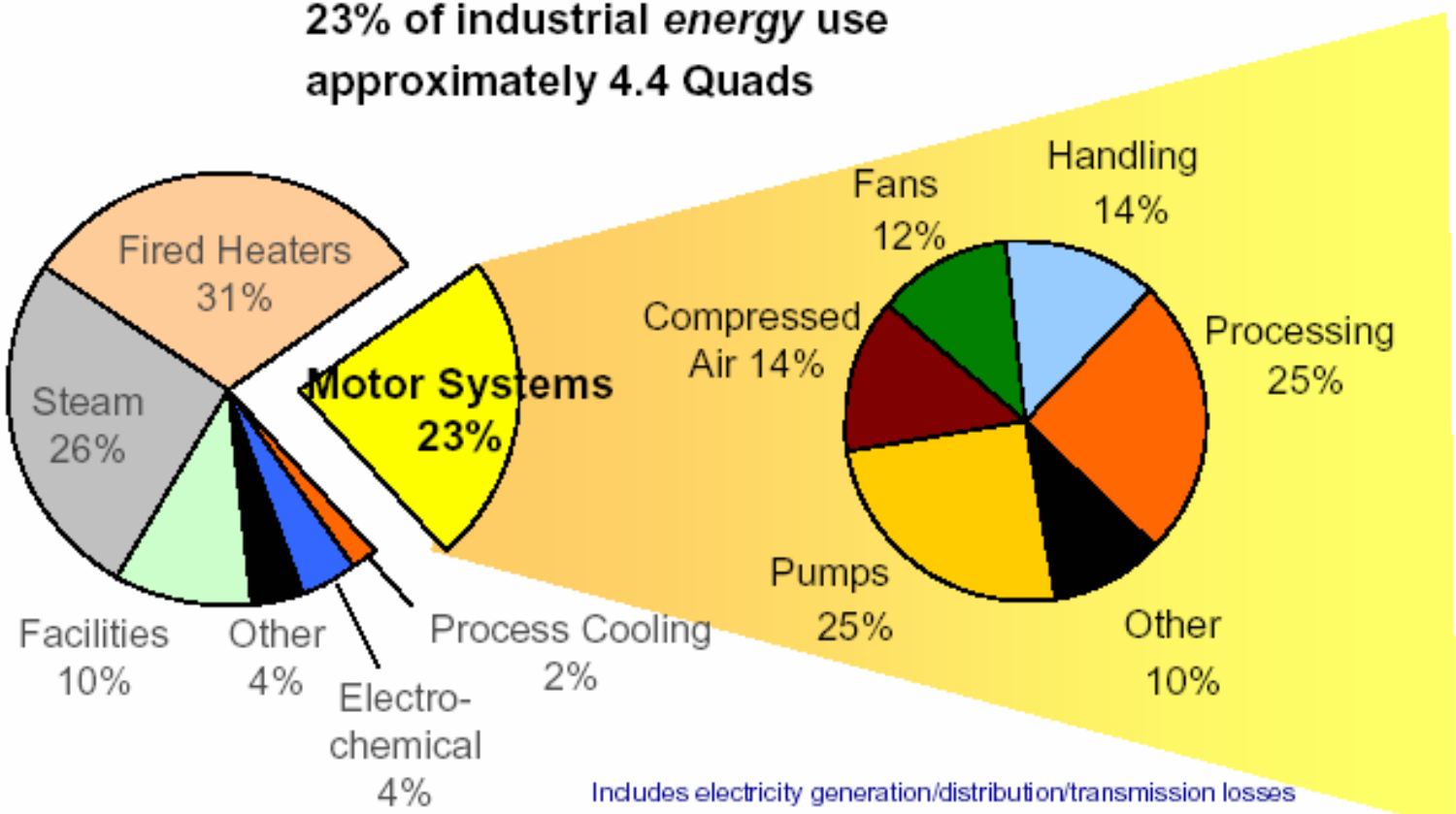
Manufacturing & Mining Energy Use

Motor Systems: 64% of U.S. industry's total *electricity* use
23% of industrial *energy* use
approximately 4.4 Quads



Includes electricity generation/distribution/transmission losses

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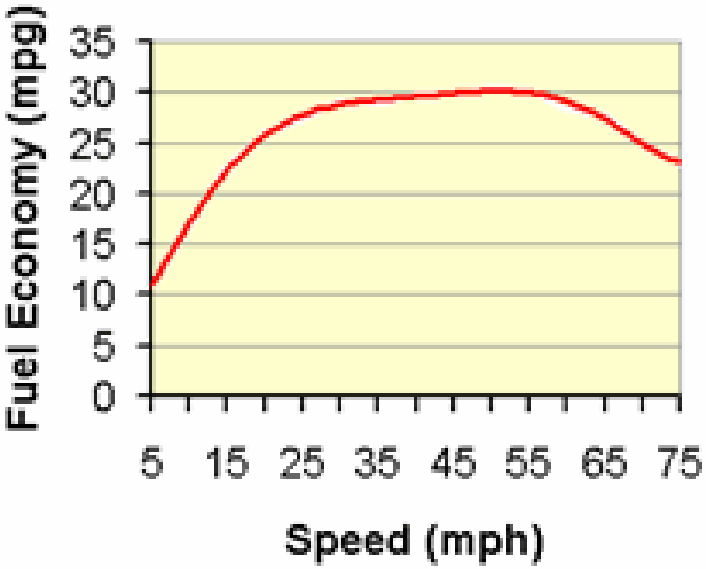
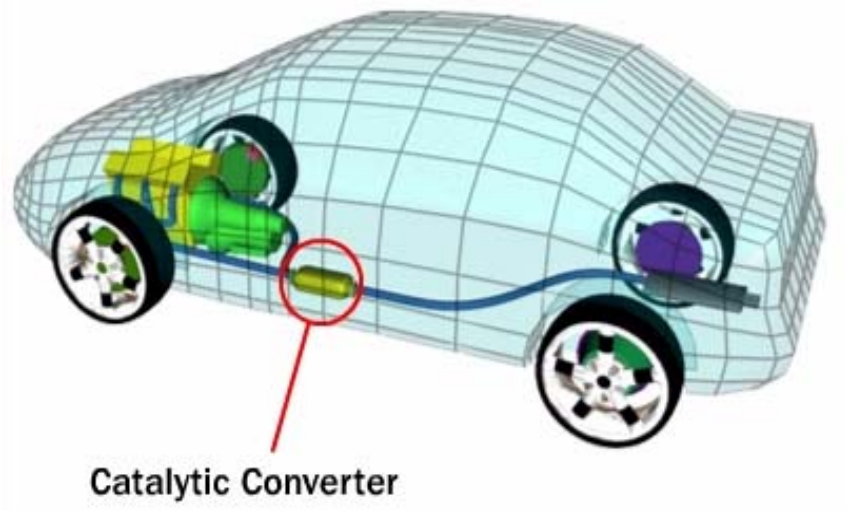
Energy Efficiency in Transportation

2/3 of the power in cars is dissipated (heat in the engine and in the catalytic converter)



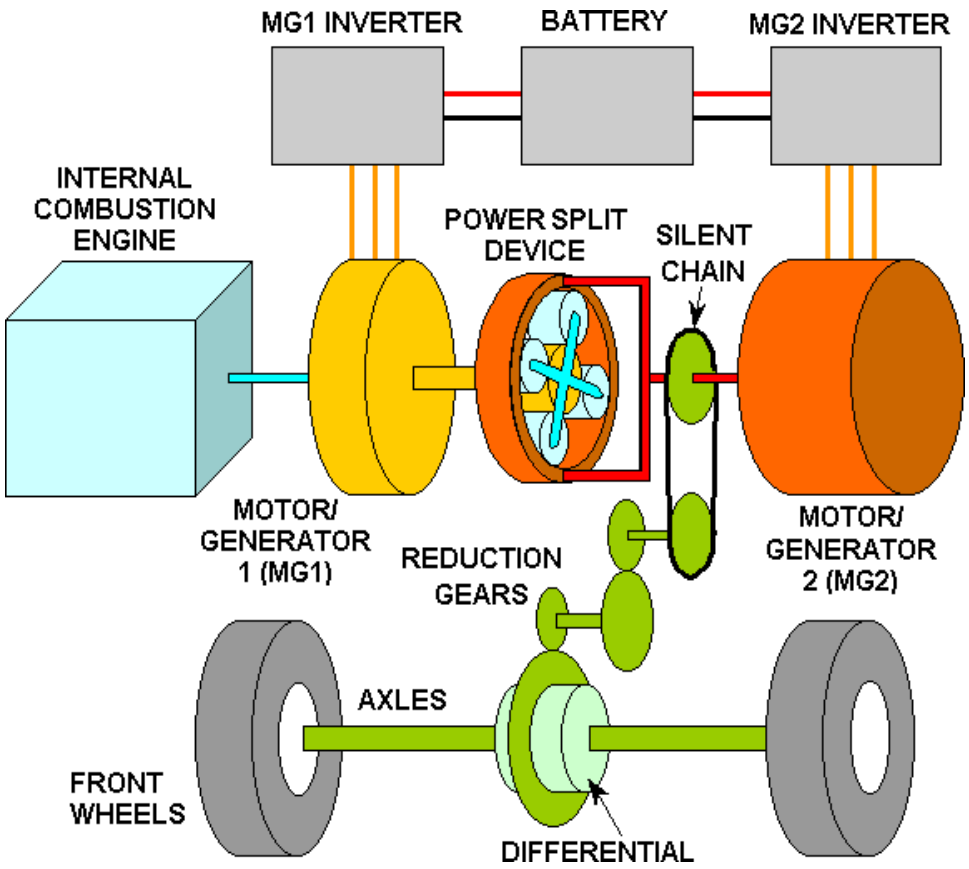


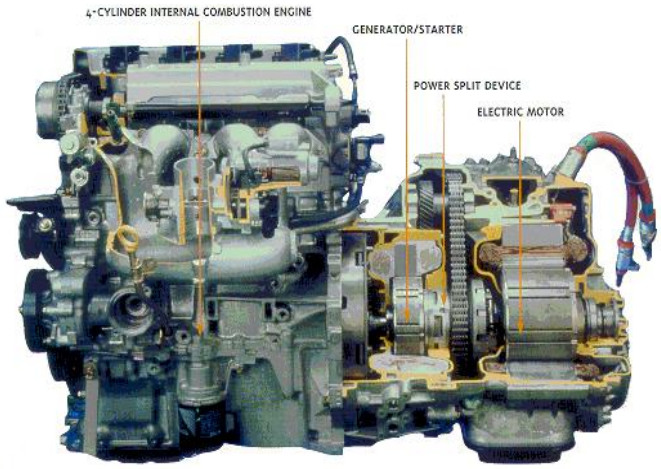
Terry J. Hendricks, International Conf. on Thermoelectrics; Long Beach, 2002

Improve Energy Efficiency in Cars (Tire Pressure Sensors)

- **One out of three light trucks** and **one out of four cars** has a tire that's significantly under-inflated according to a recent NHSTA survey in US.
- Gas mileage improves by 3.3 percent by keeping tires inflated to the proper pressure. **Under-inflated tires can lower gas mileage by 0.4 percent for every 1 psi drop in pressure of all four tires.**

Improve Energy Efficiency in Cars (Hybrid Engines)





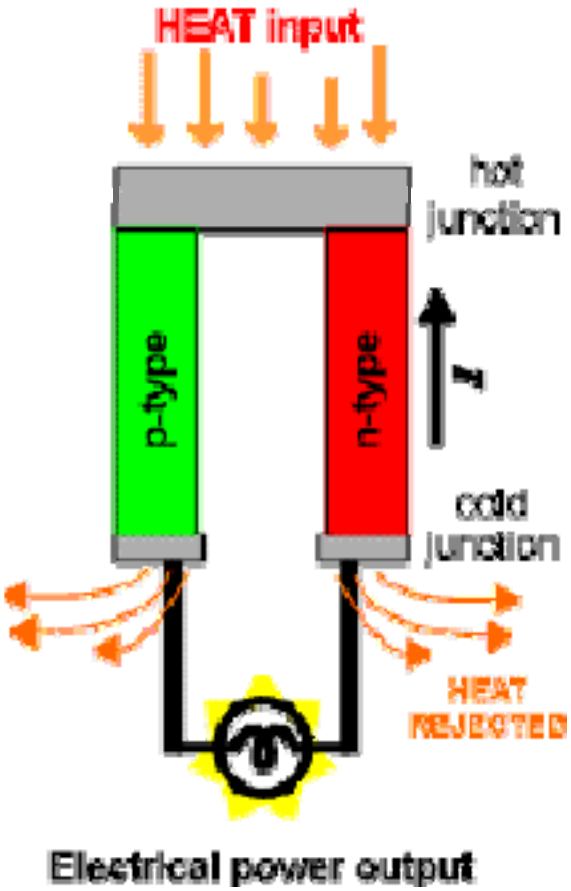
Prius Power Train

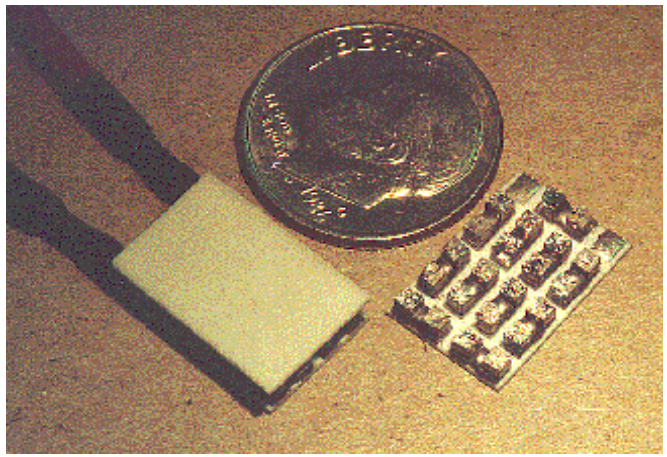
Major Energy Losses

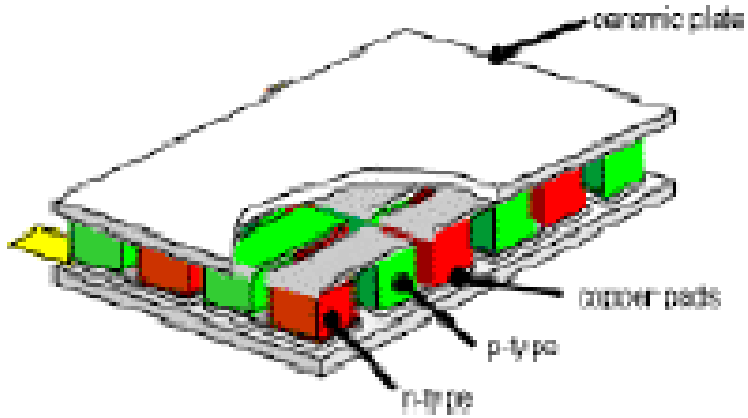
- **Transportation**
- **Electricity Generation**

- **How much the energy efficiency of engines and power plants could be improved?**
- **Can we do anything with the waste heat?**

Direct thermal to electric energy conversion

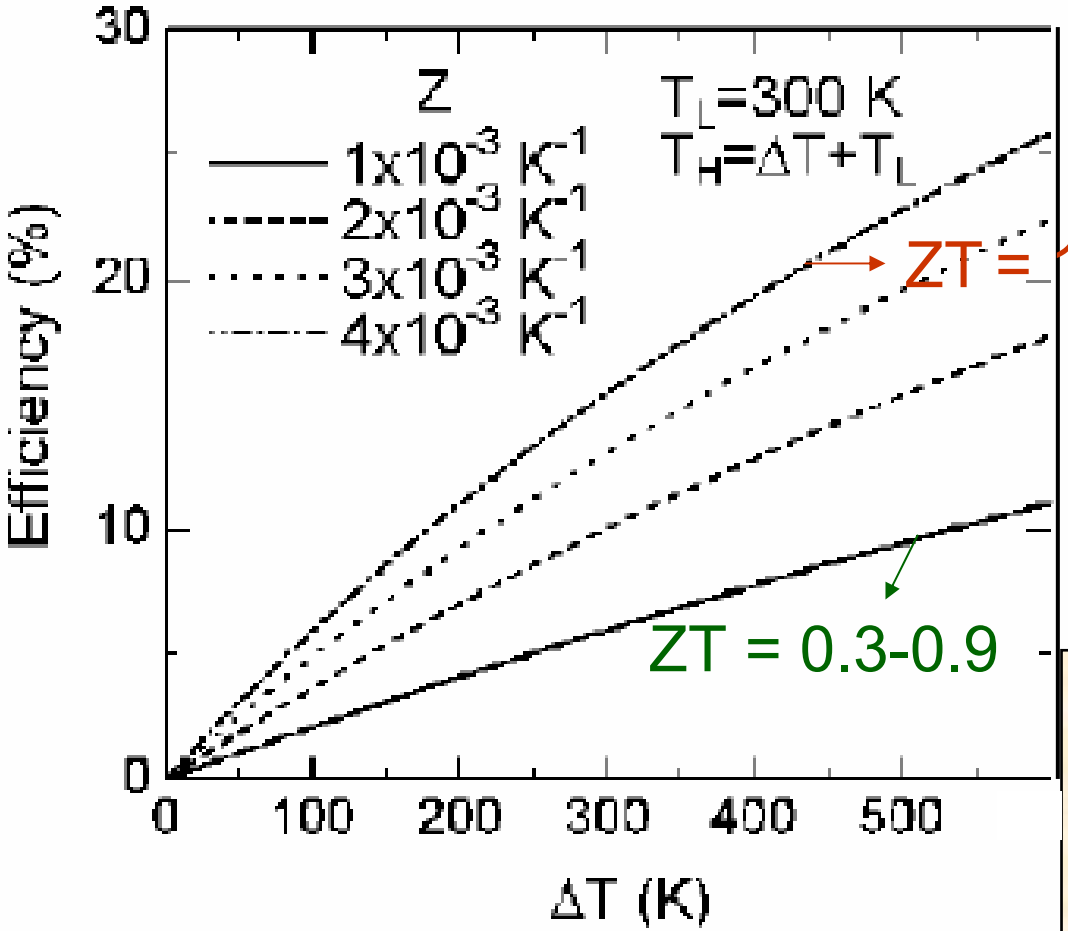


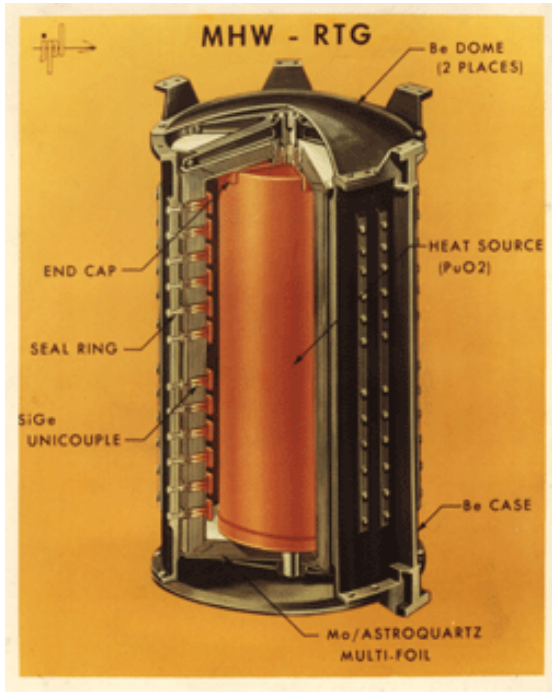




http://www.thermoelectrics.com/introduction.htm#seebeck

Efficiency of Thermoelectric Power Generation





$$Z \quad \frac{S^2}{\quad}$$

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

Highest ZT's

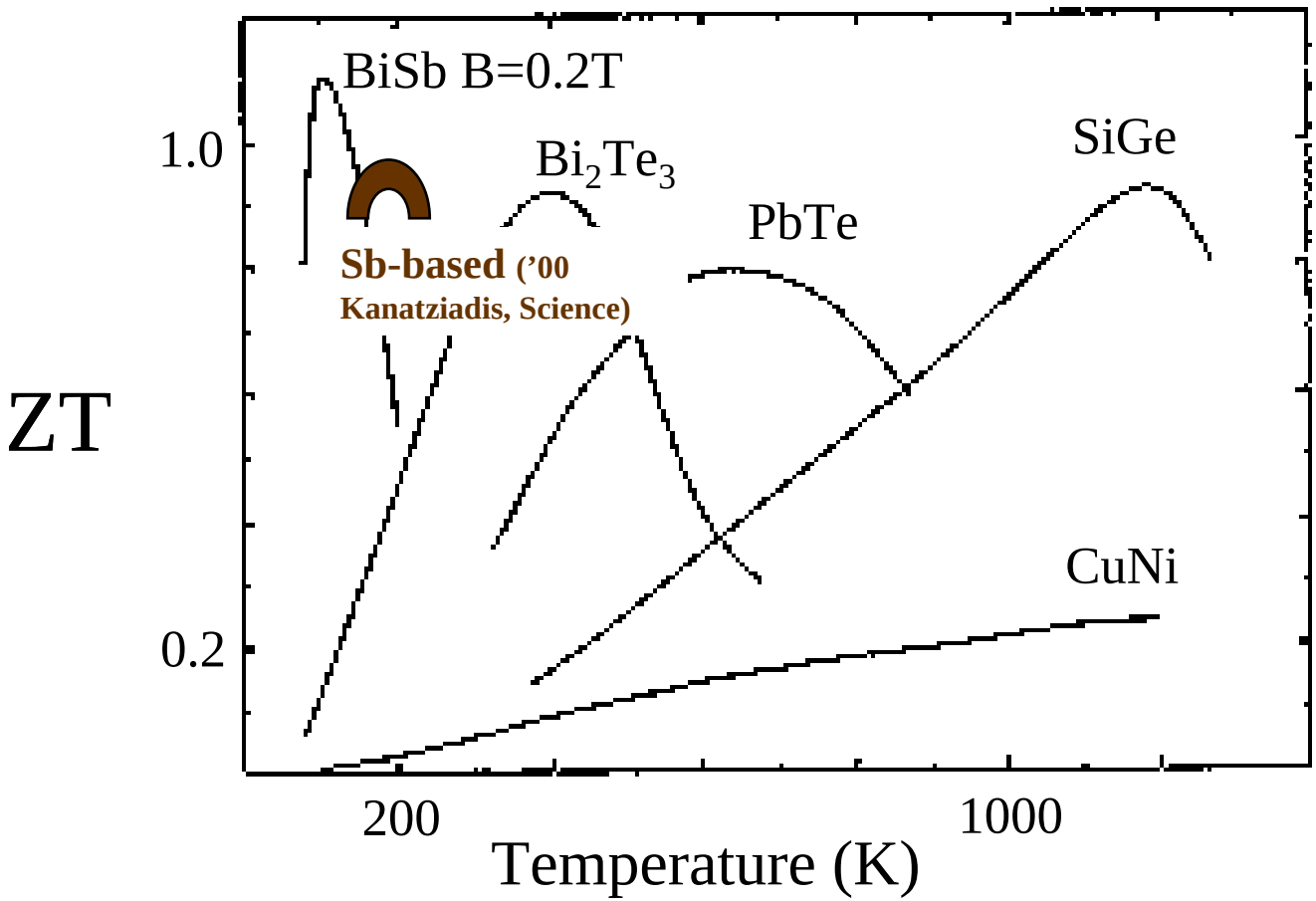
Recent Developments (superlattices and nanoparticles)

BiTe/SbTe Superlattice (Venkatasubramanian et al. RTI)
ZT (300K)~2.4, Nature, 2001

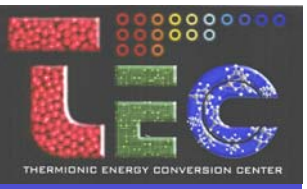
AgPbSbTe -based Kanatziadis et al.
ZT (800K)~2 (Science'04)

PbTe Q-Dots (Harman et al. MIT Lincoln Lab)
ZT (300K)~1.6-2.0, Science 2002

Skutterudites (ZT (500-700K)~1.5 ORNL, JPL '97)

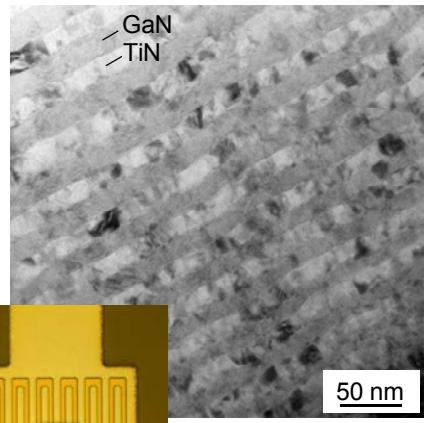


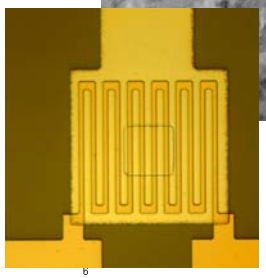
Semiconductors with Embedded Metallic Nanopaticles / Multilayers

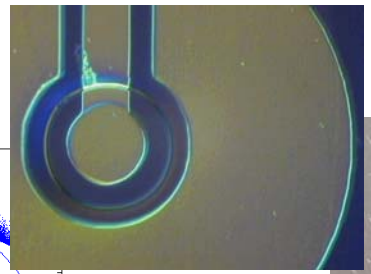


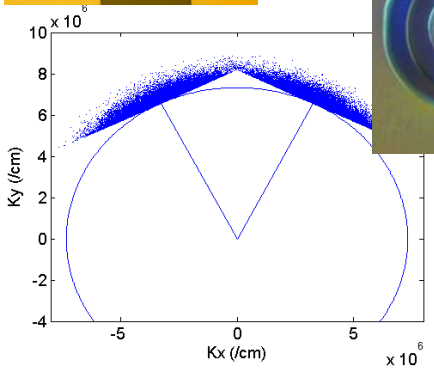
UCSC
Berkeley
Harvard
MIT
NCSU
Purdue
UCSB

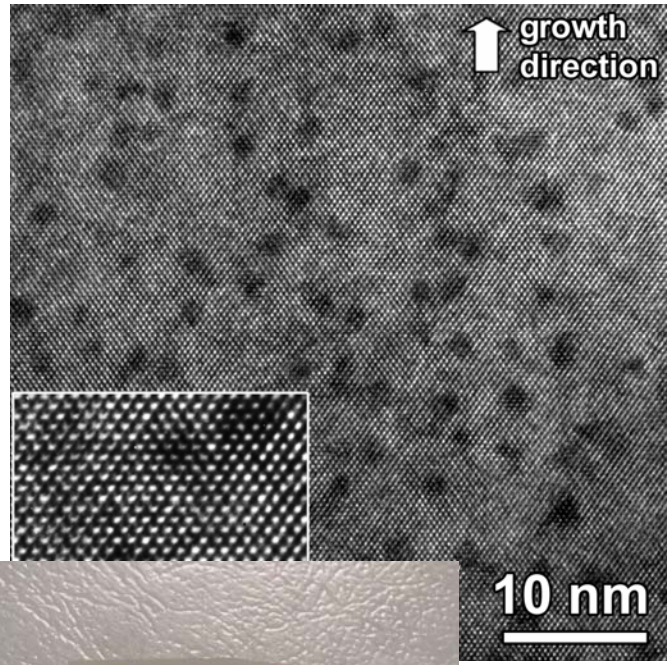
A. Shakouri (PI)

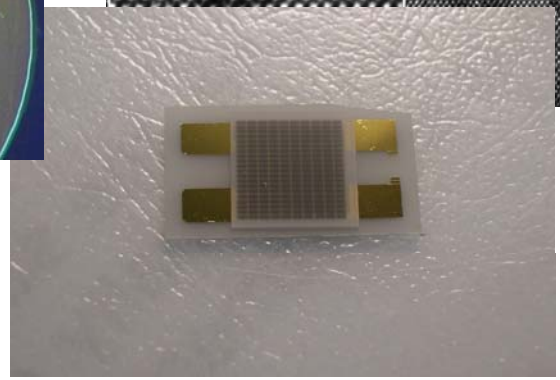












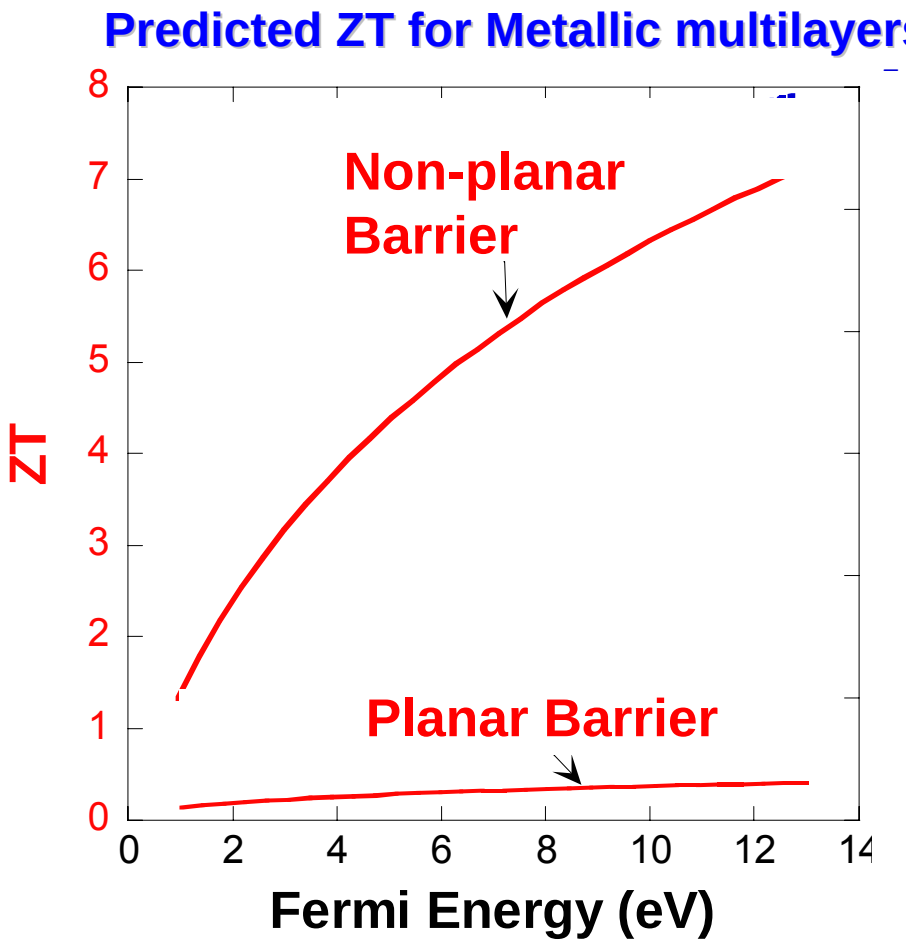
Thermionic Energy Conversion Center

TEC Center Goals

- T_{hot}=300-650C
- Conversion efficiency >20%
- Power >1W/cm^2

UCSC
Berkeley
Harvard
MIT
NCSU
Purdue
UCSB

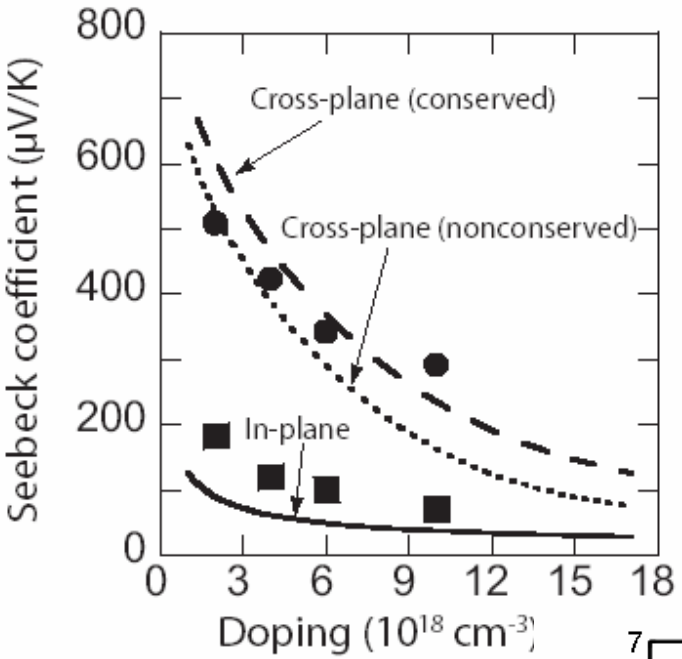
A. Shakouri (PI)



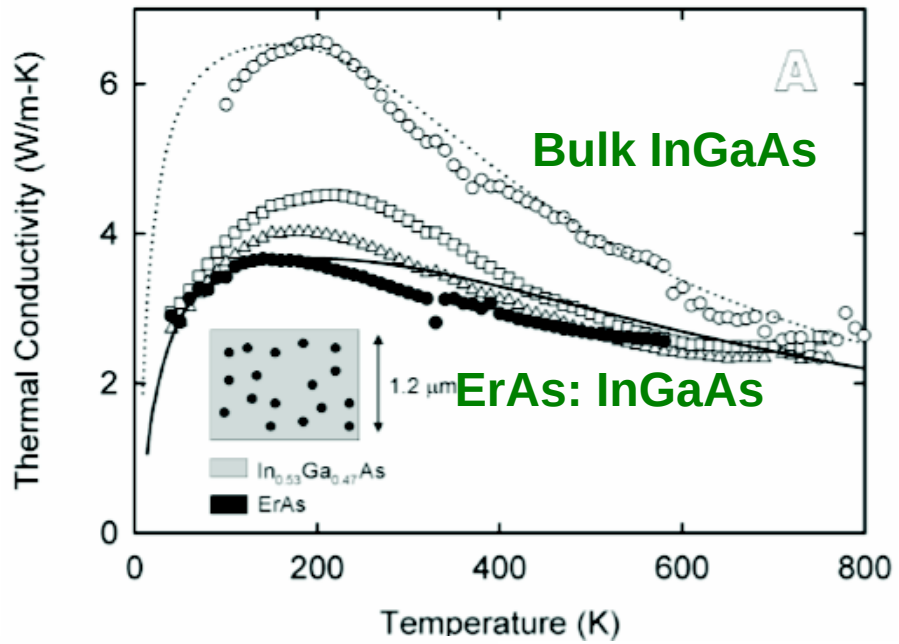
Assume
$\beta_{lattice}$=1W/mK

D. Vashaee., A. Shakouri,
Physical Review Letters
March 12, 2004

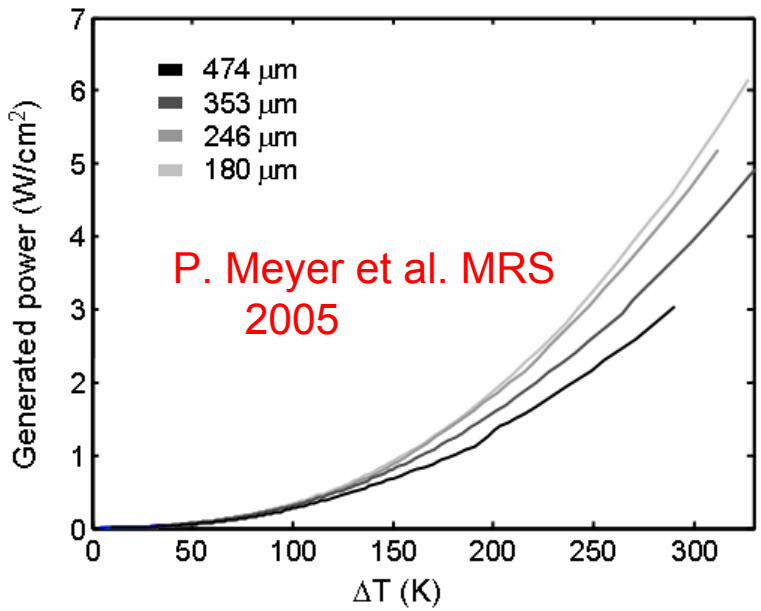
Some of the latest results



J. Zide et al. PRB 2006 (submitted)



W. Kim et al. PRL 2006



P. Meyer et al. MRS 2005

THERMIONIC ENERGY CONVERSION CENTER

Summary

- Sensors play an important role in intelligent systems used to increase energy efficiency in all major consumption areas (transportation, industrial and residential)
- A significant portion of the generated energy is waste as heat. Low cost waste heat recovery (e.g. high efficiency thermoelectrics) can have a big impact.