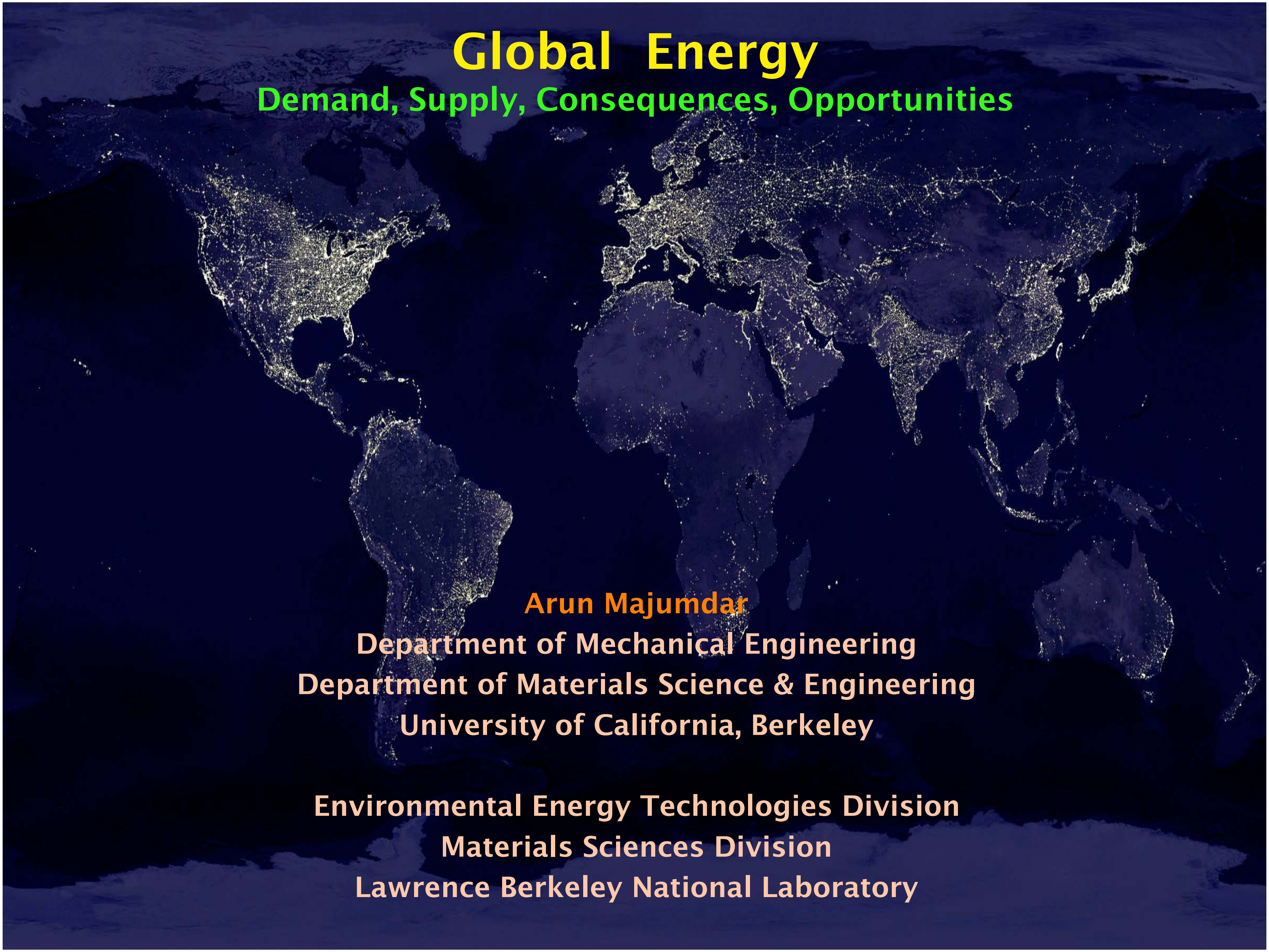


Global Energy

Demand, Supply, Consequences, Opportunities

Arun Majumdar
Department of Mechanical Engineering
Department of Materials Science & Engineering
University of California, Berkeley

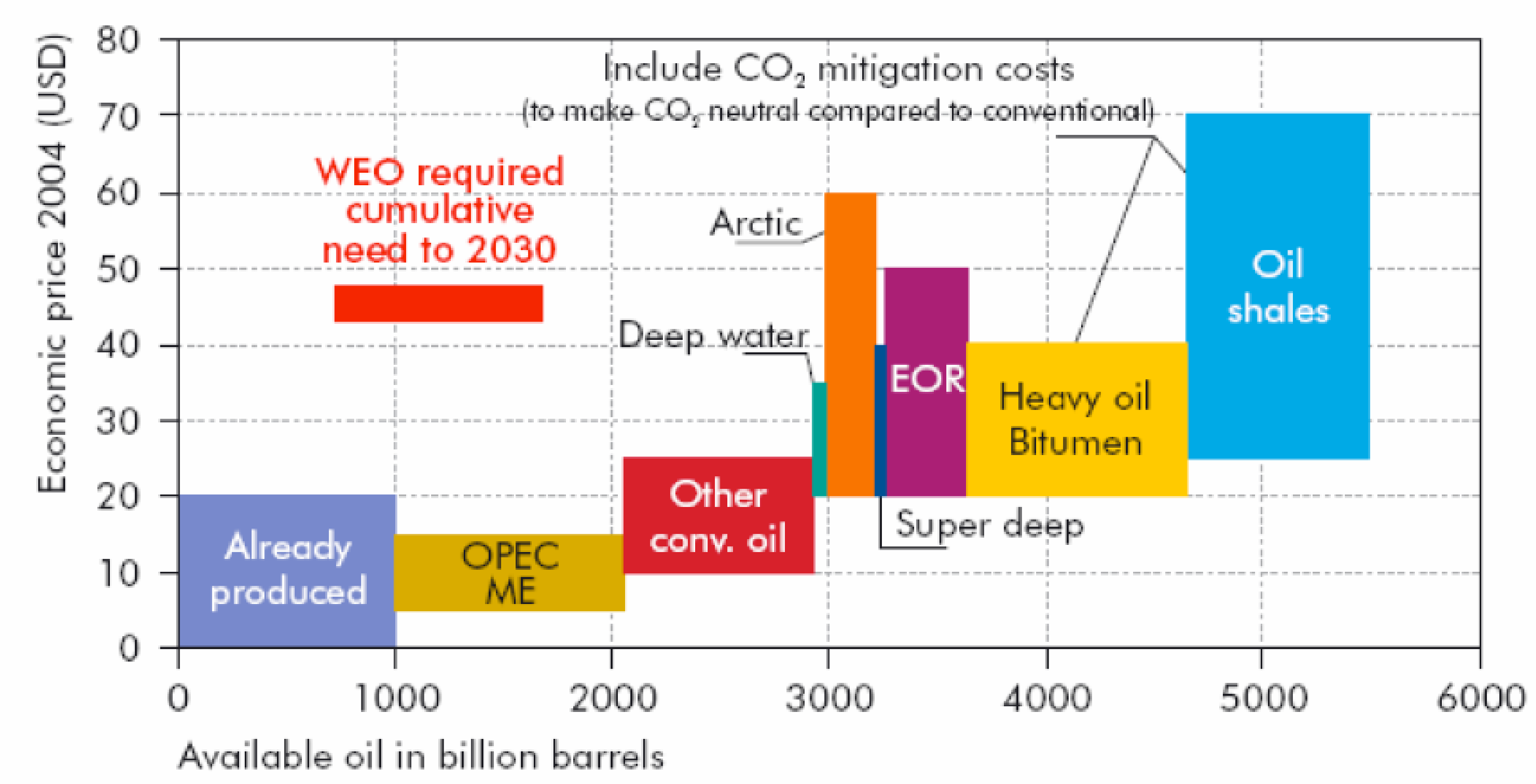
Environmental Energy Technologies Division
Materials Sciences Division
Lawrence Berkeley National Laboratory

Issues

- Availability of Fossil Fuel
- Energy Security
- Economics
- CO_2 emissions and Global Warming

Oil Supply Cost Curve

Availability of oil resources as a function of economic price



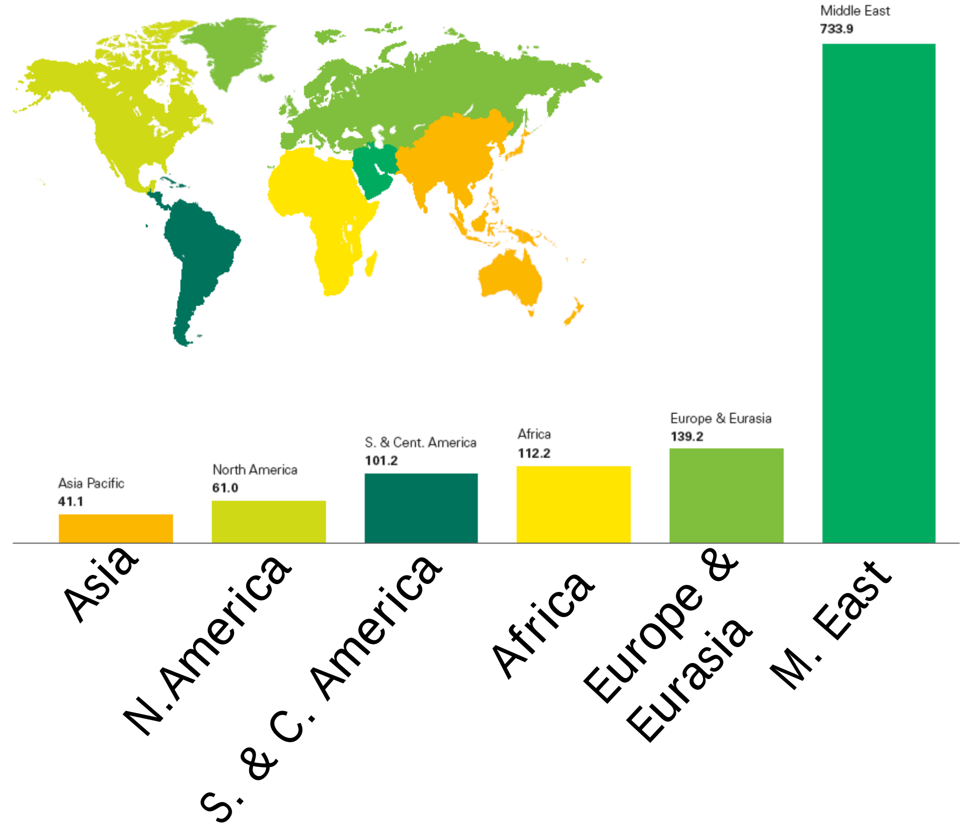
Source: IEA (2005)

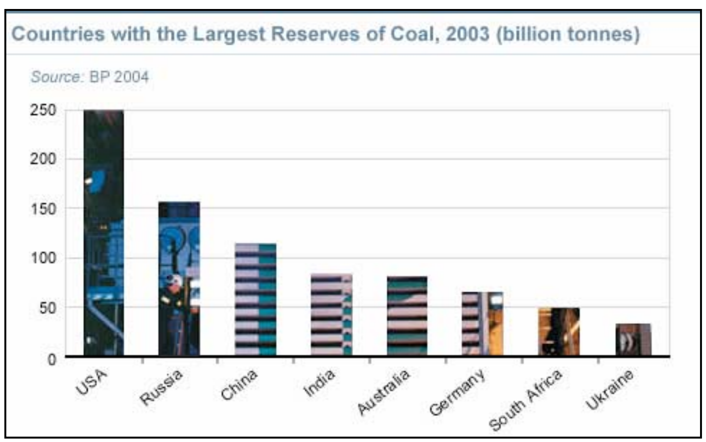
Ref: Steve Koonin (BP) Presentation

Global Fuel Reserves

Coal Reserves

Oil Reserves

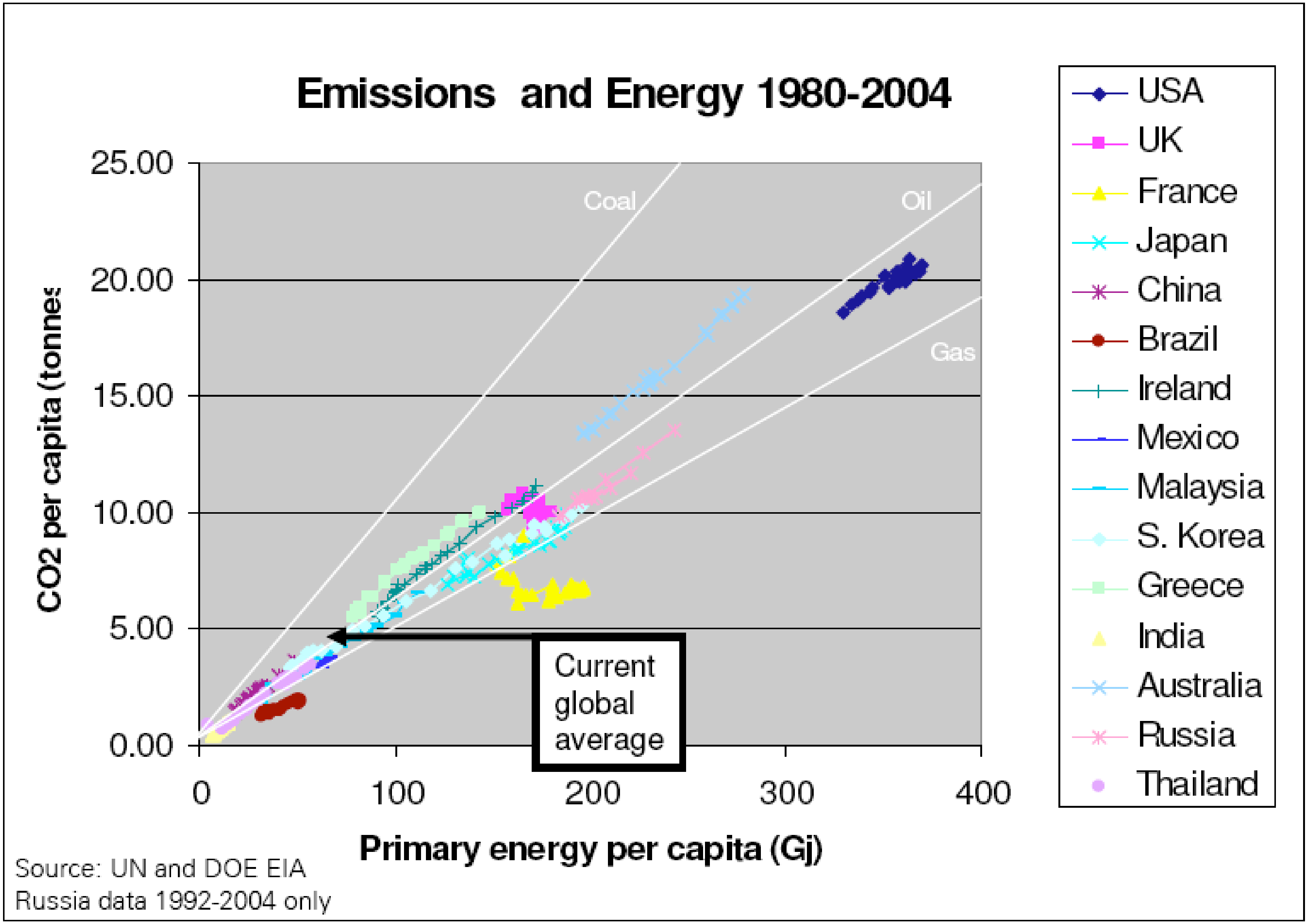




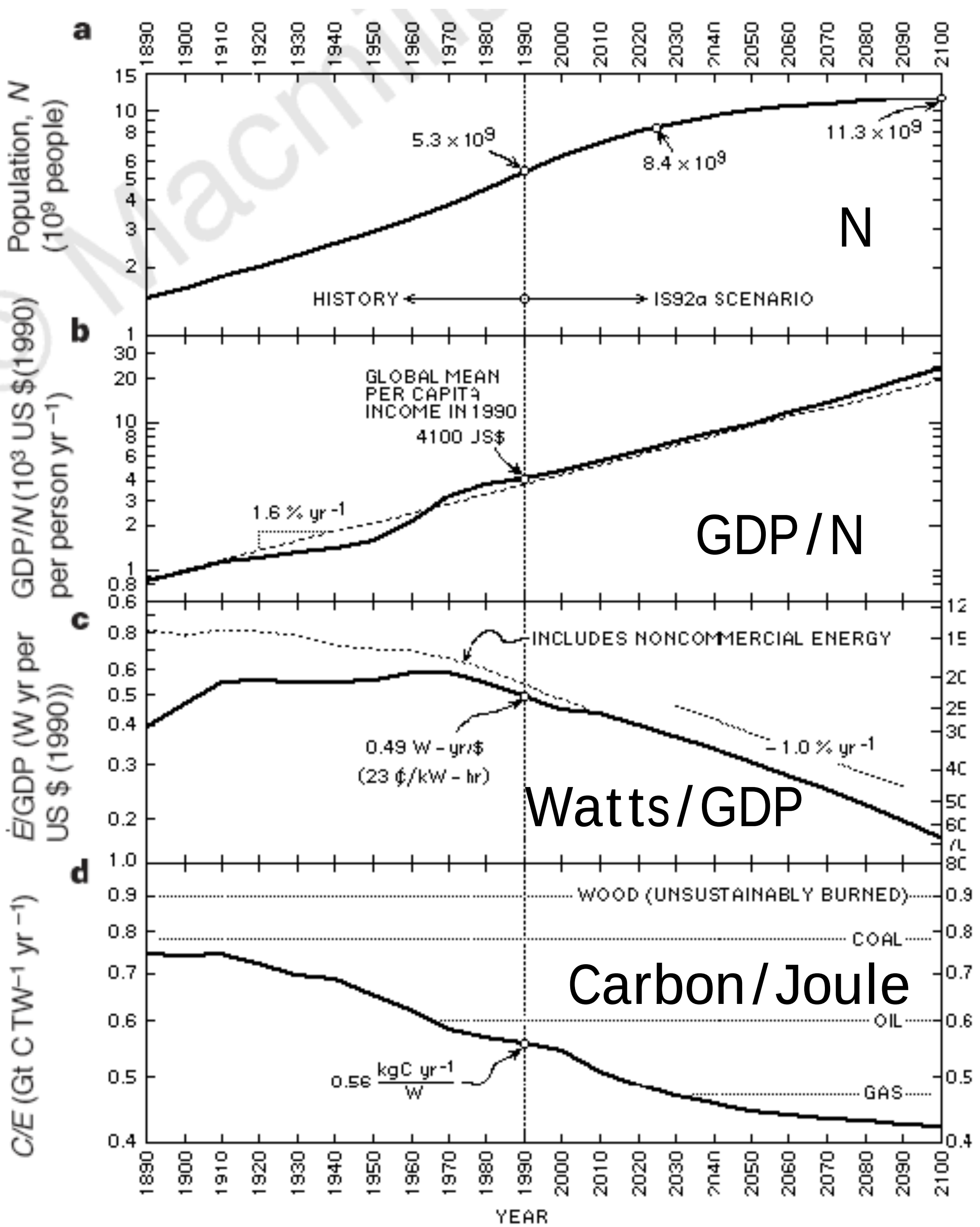
Source: John F. Bookout (President of Shell USA) ,"Two Centuries of Fossil Fuel Energy"
International Geological Congress, Washington DC; July 10,1985.
Episodes, vol 12, 257-262 (1989).

Source: BP Statistical Review of World Energy (2005)

Per Capita CO_2 and Energy



Population-Energy Equation

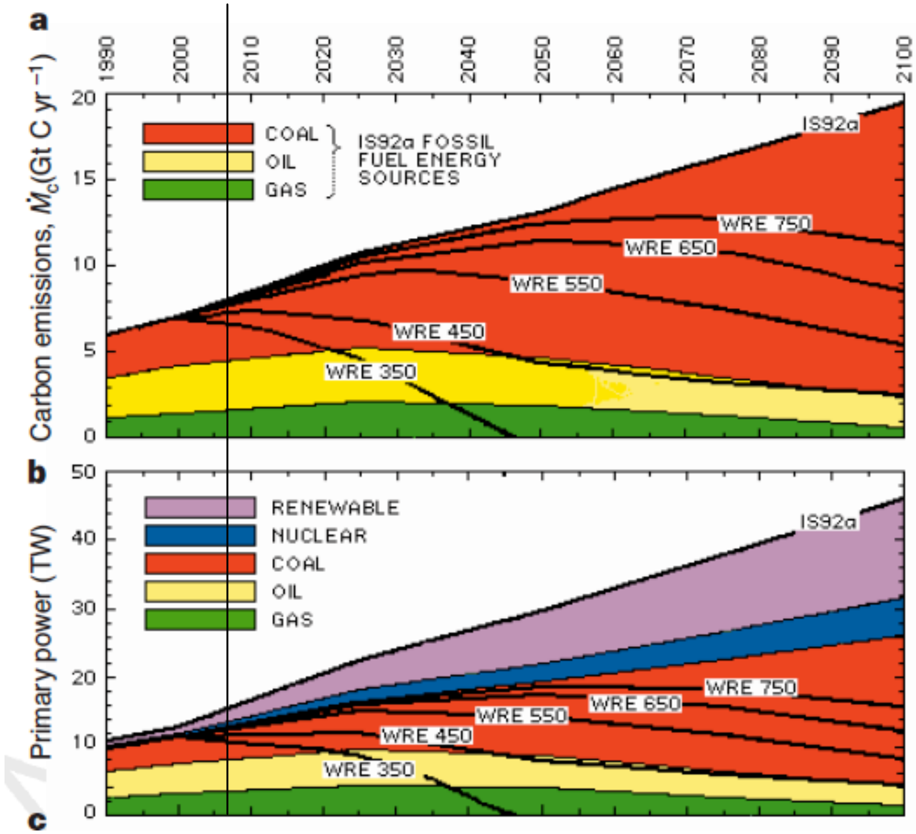


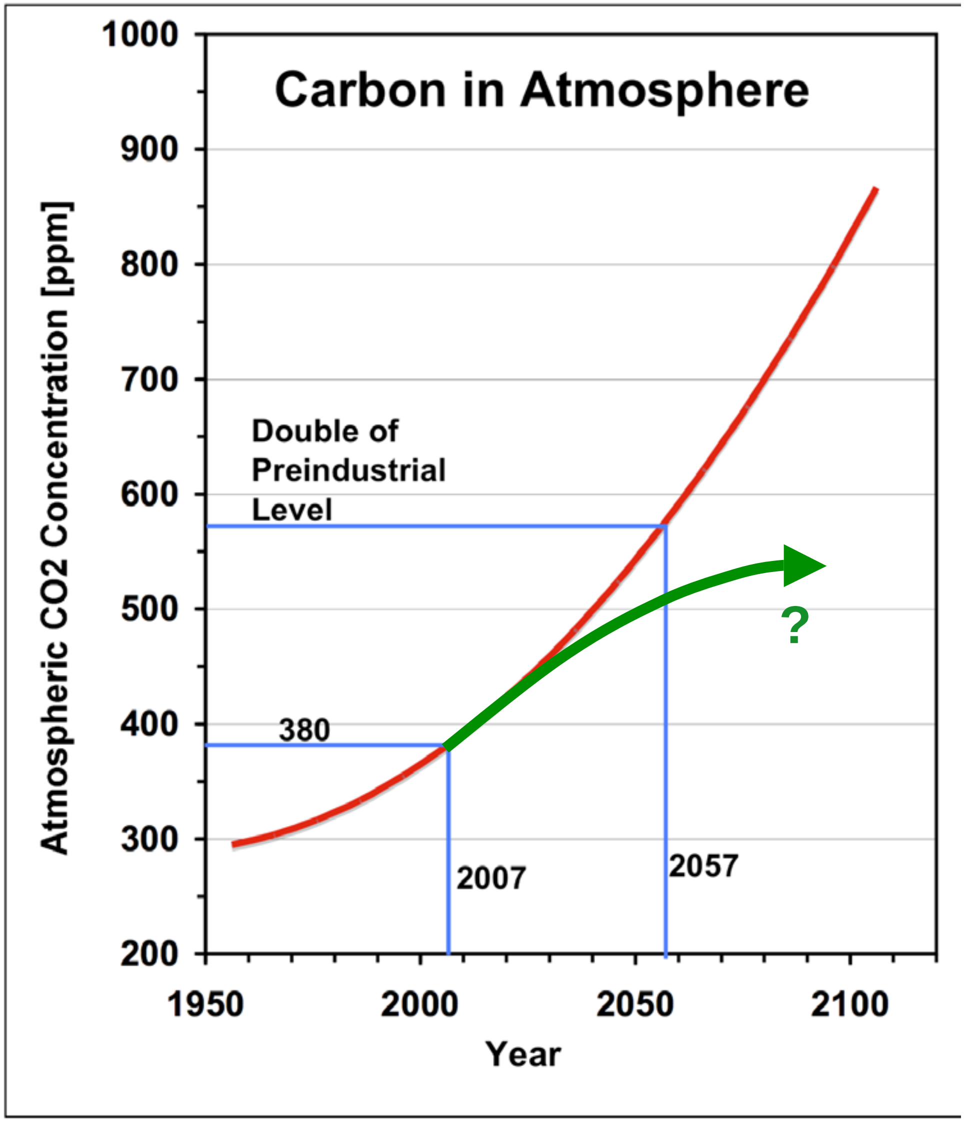
Power = N x (GDP/N) x (Watts/GDP)

C Emission Rate
= Power x (Carbon/J)

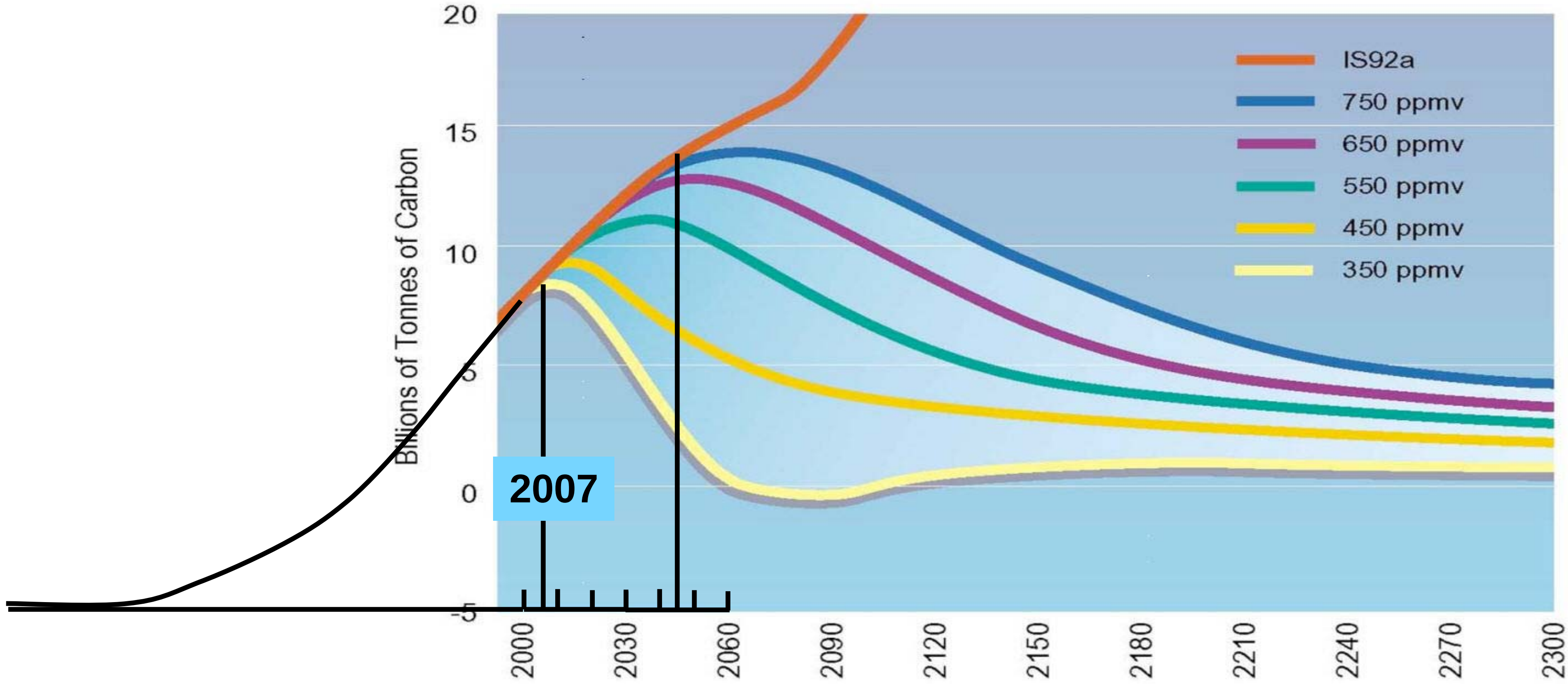
Hoffert et al., Nature (1998)

Global Energy & Carbon Balance





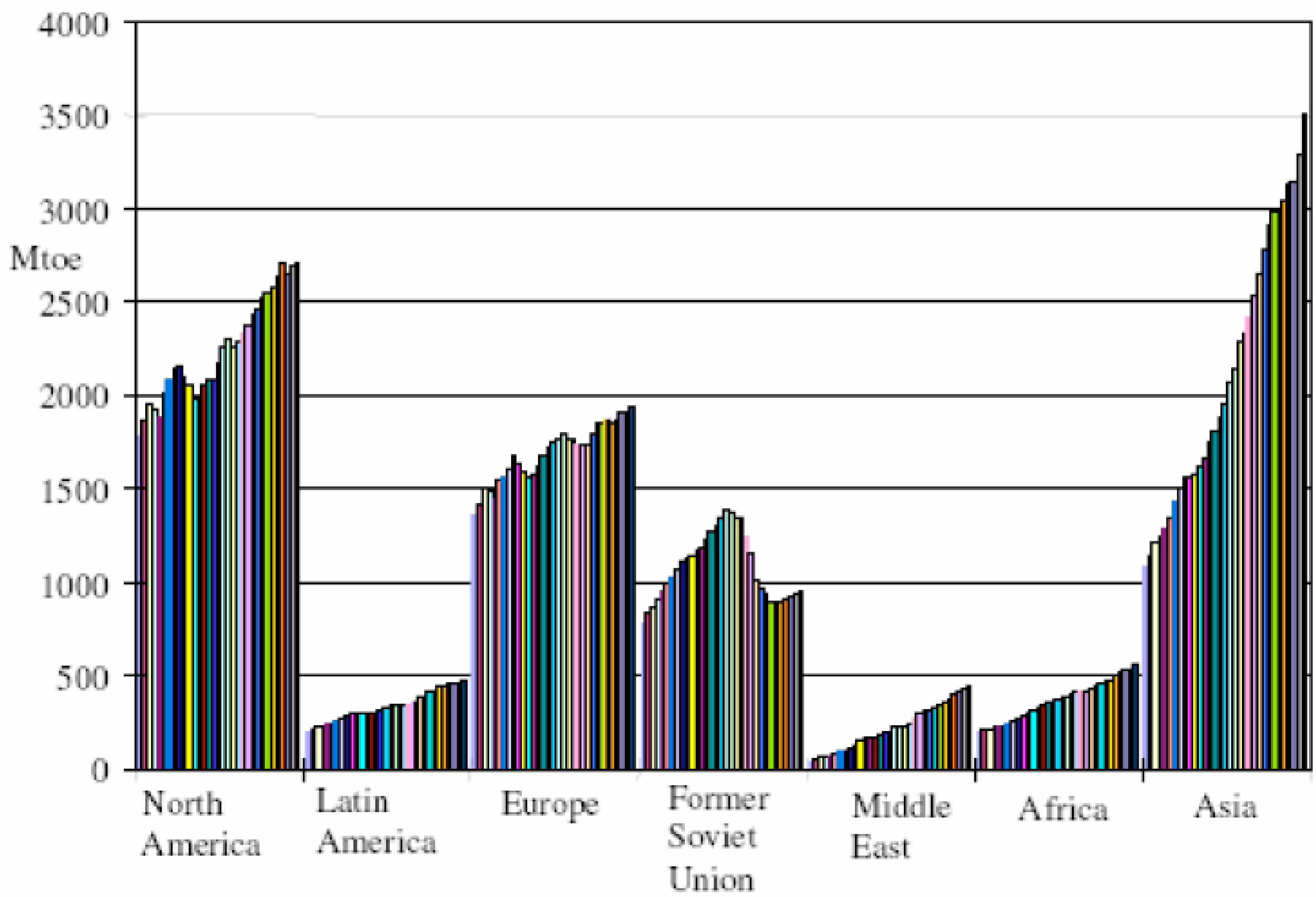
Emissions Trajectories for atmospheric CO_2 concentration ceilings



Source: Fourth Assessment of the Intergovernmental Panel on Climate Change; Summary for Policy Makers, February 2007.

Steve Chu, LBL

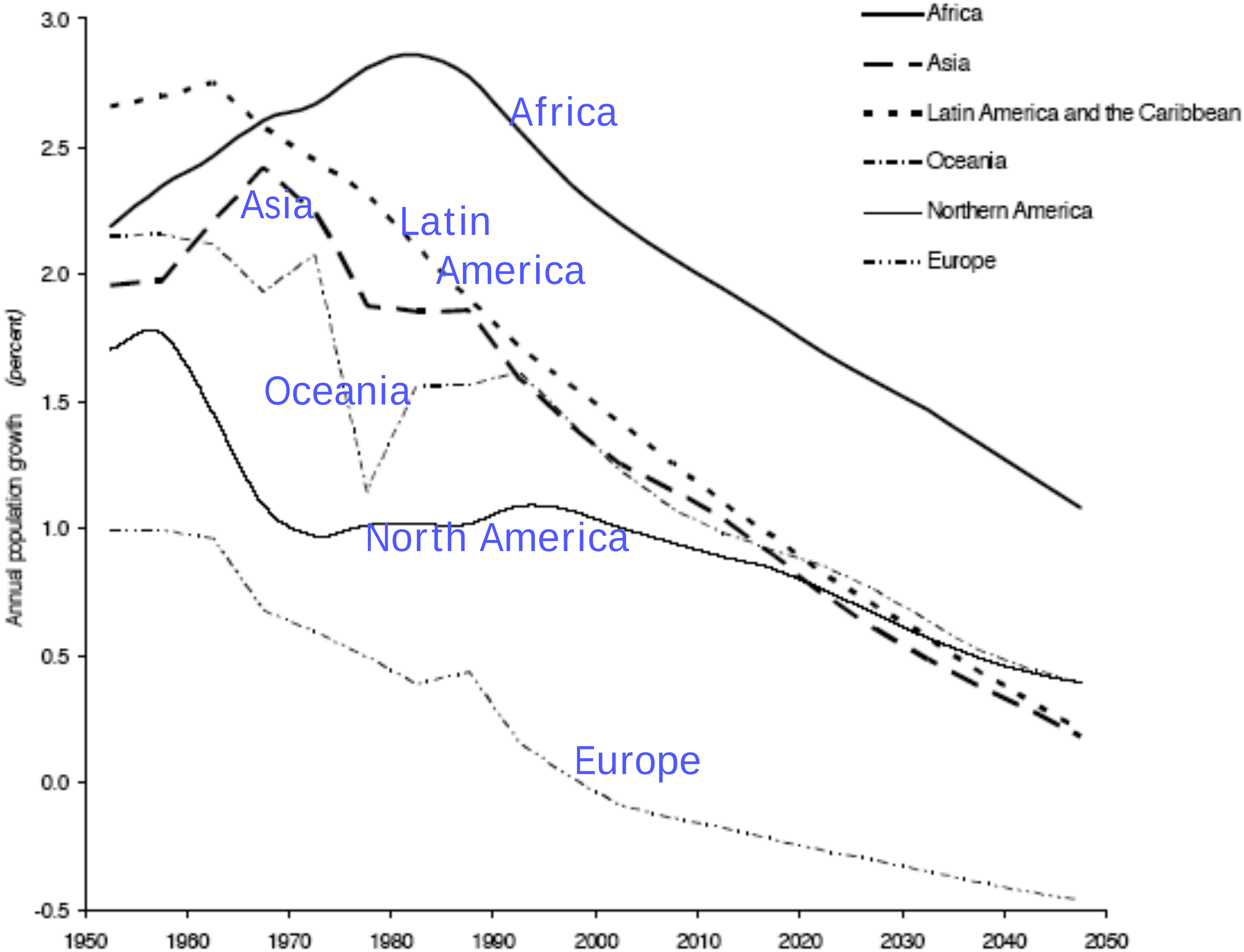
Annual Primary Energy Demand 1971-2003



Source IEA, 2004 (Excludes biomass)

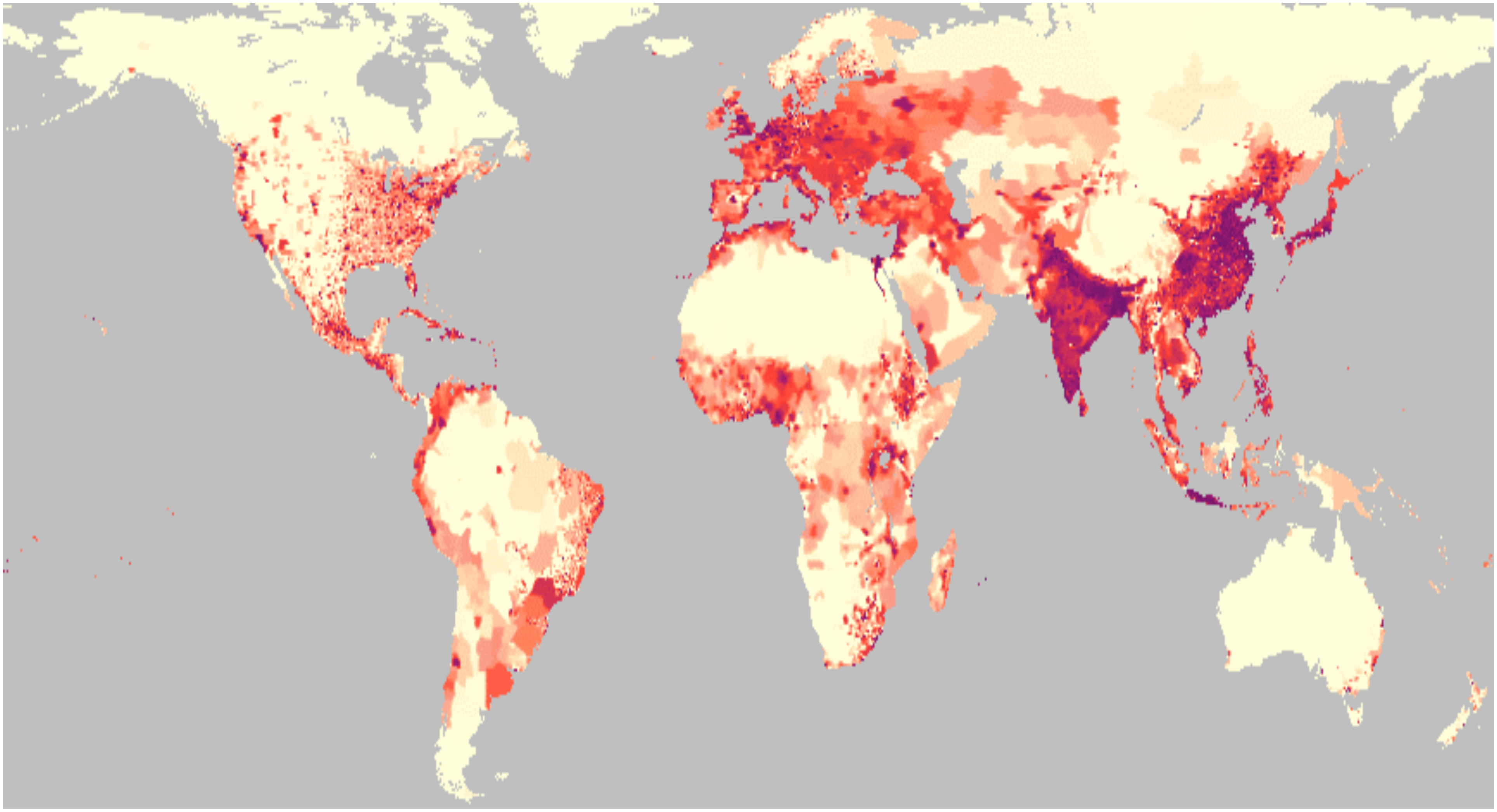
Ref: Steve Koonin (BP) Presentation

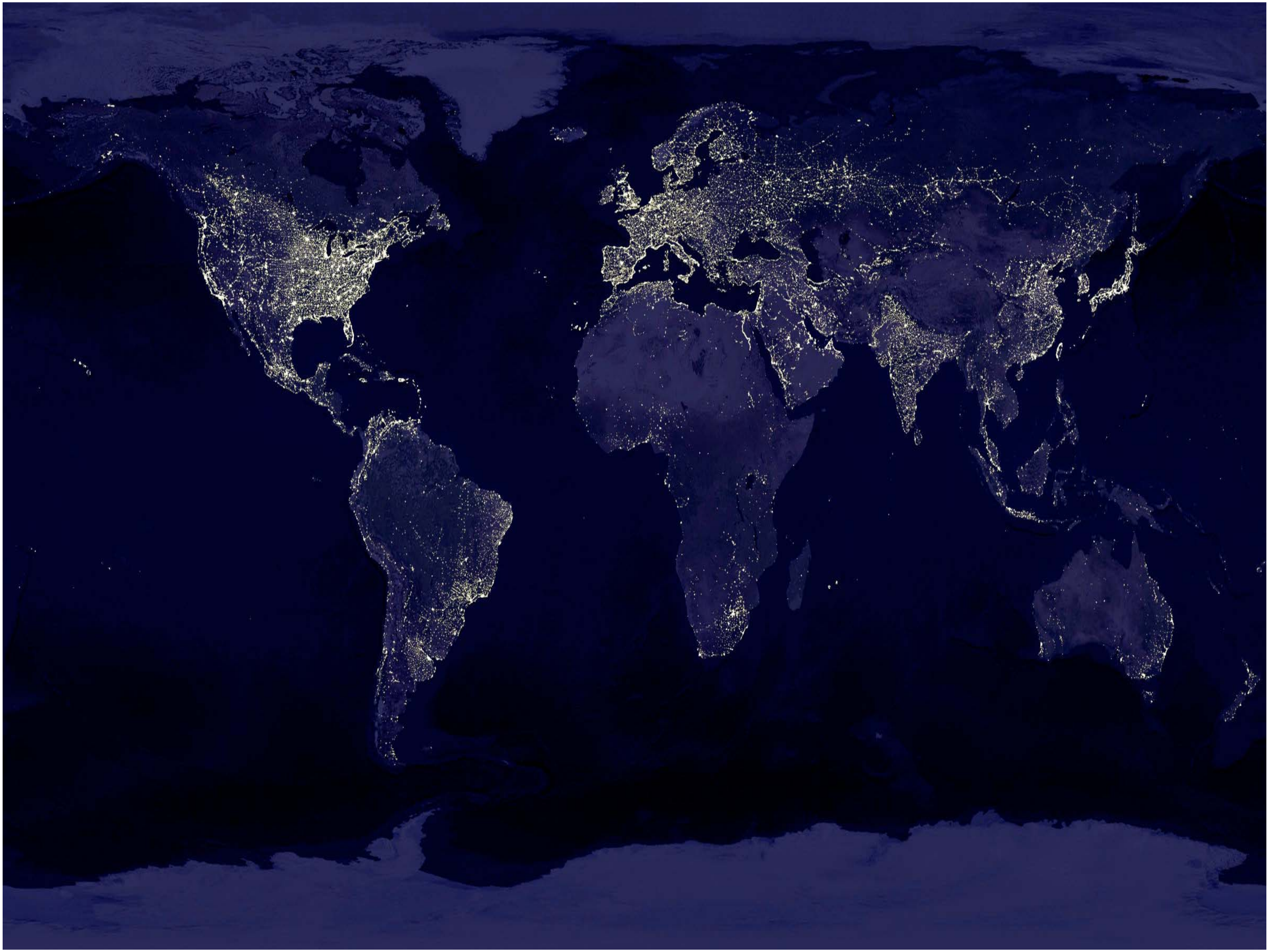
Annual Population Growth (Percent)

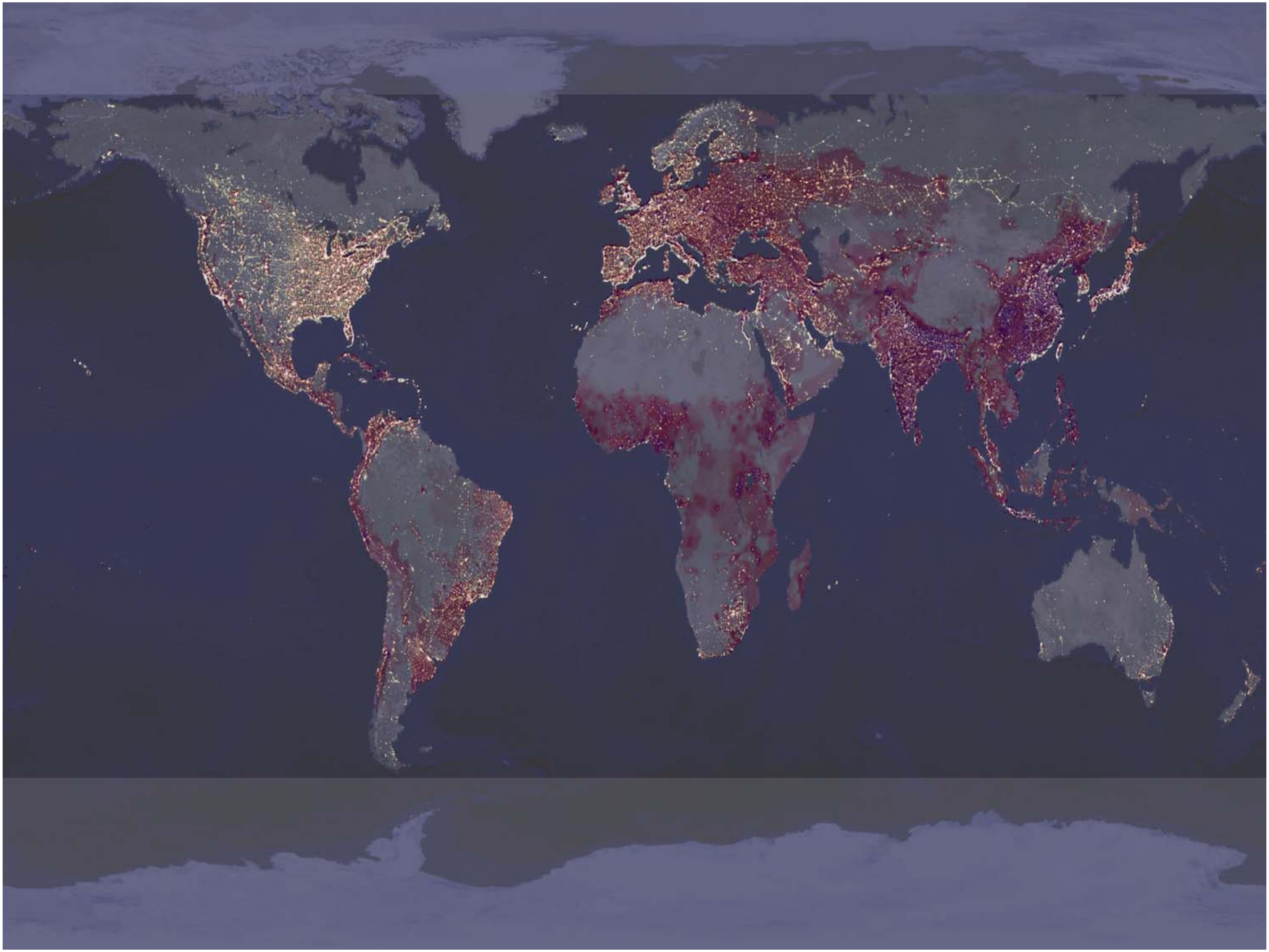


Demographics 2000-2050

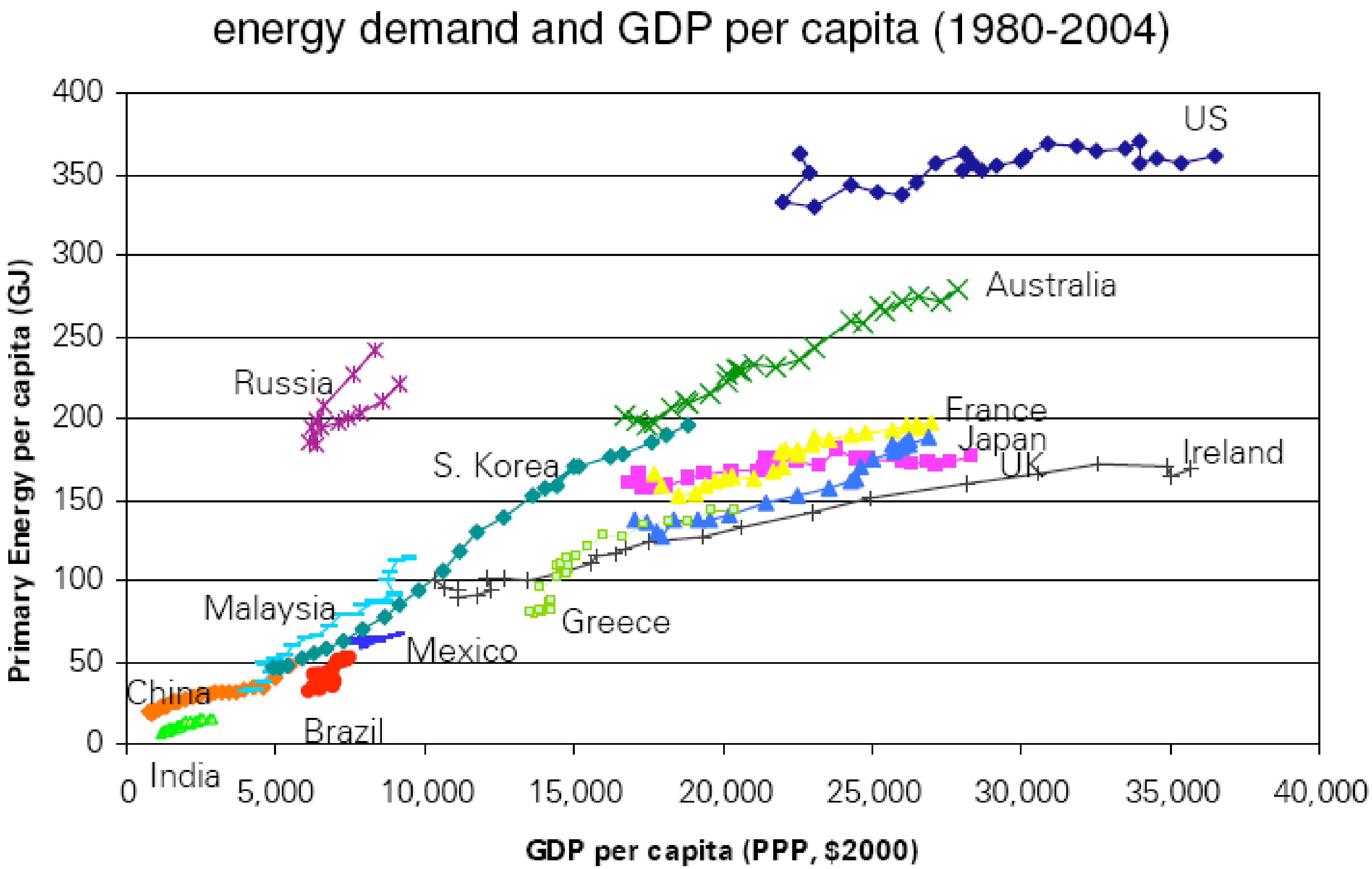
- 47% population growth from now till 2050
- Increase in the next 50 years will be more than twice the population of China
- Less developed countries will grow 58%. Developed countries will grow 2%.
- Less developed countries will account for 99% of increment in world population







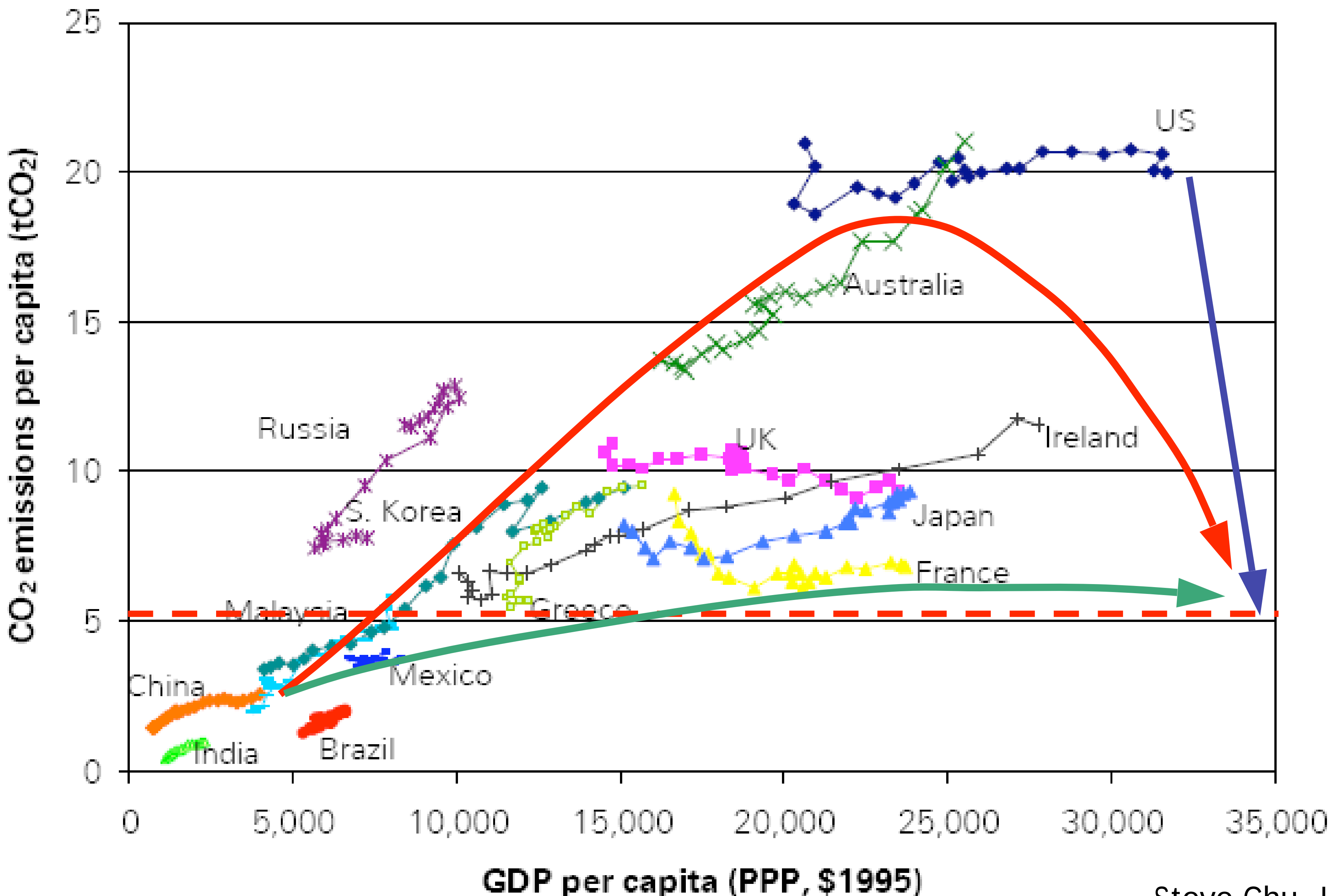
Economic Development & Energy Use



Source: UN and DOE EIA
Russia data 1992-2004 only

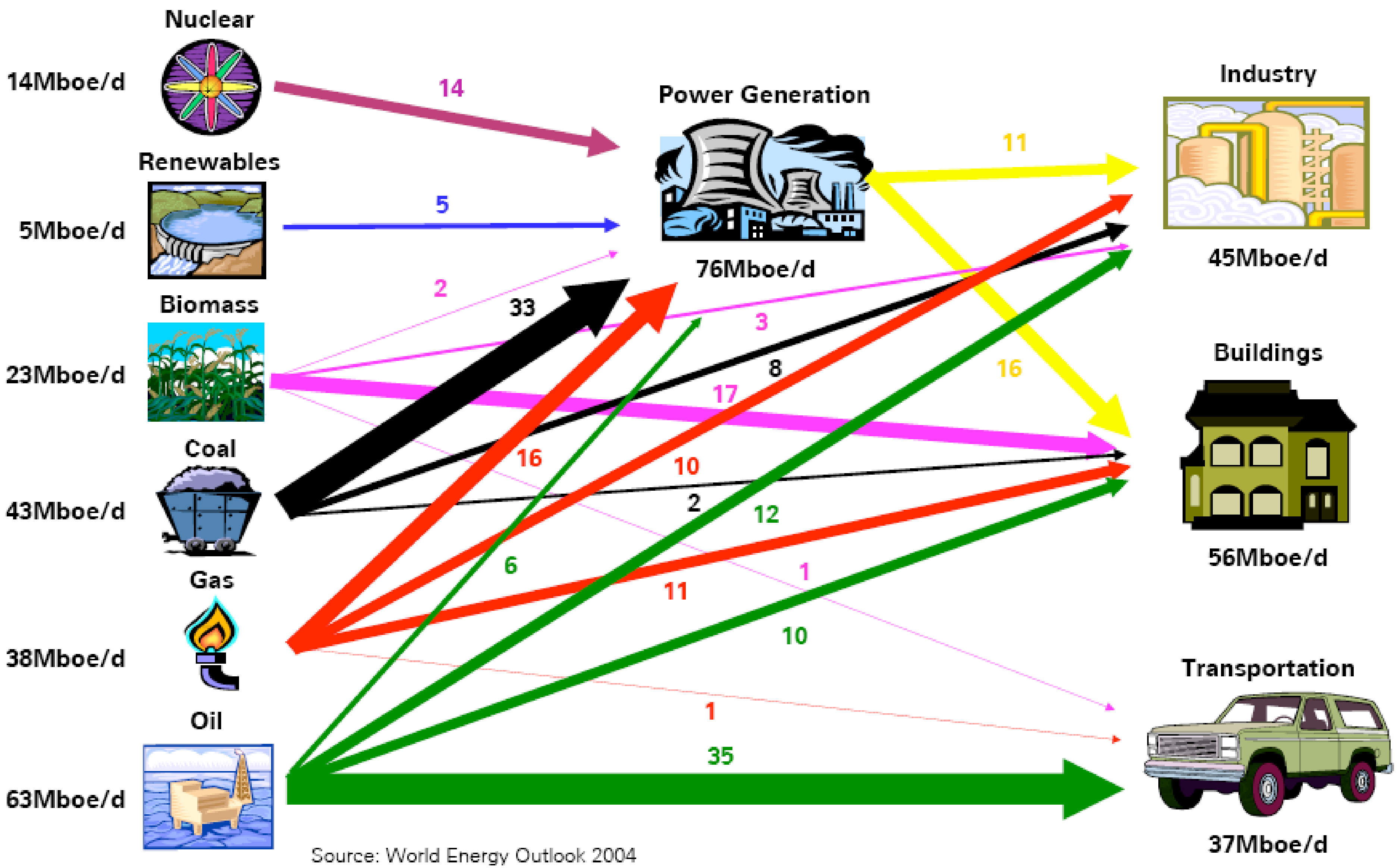
Steve Chu, LBL

CO_2 emissions of selected countries



Steve Chu, LBL

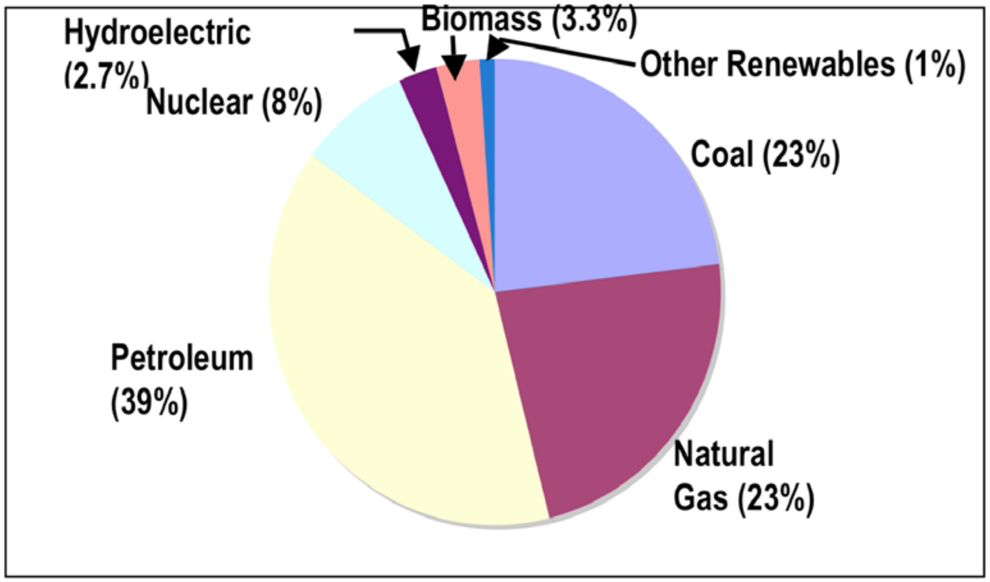
Global Energy Supply & Demand



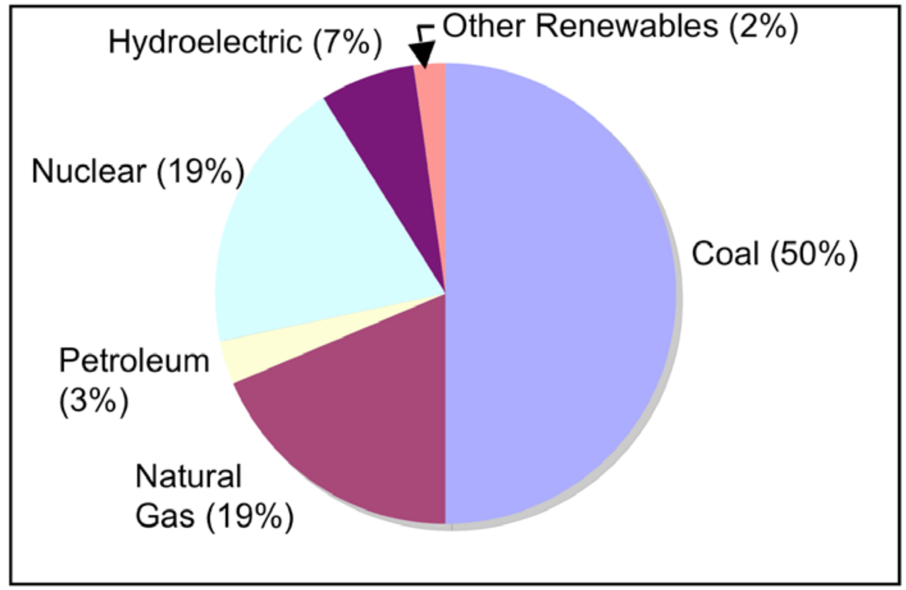
Ref: Steve Koonin (BP) Presentation

US Supply Side

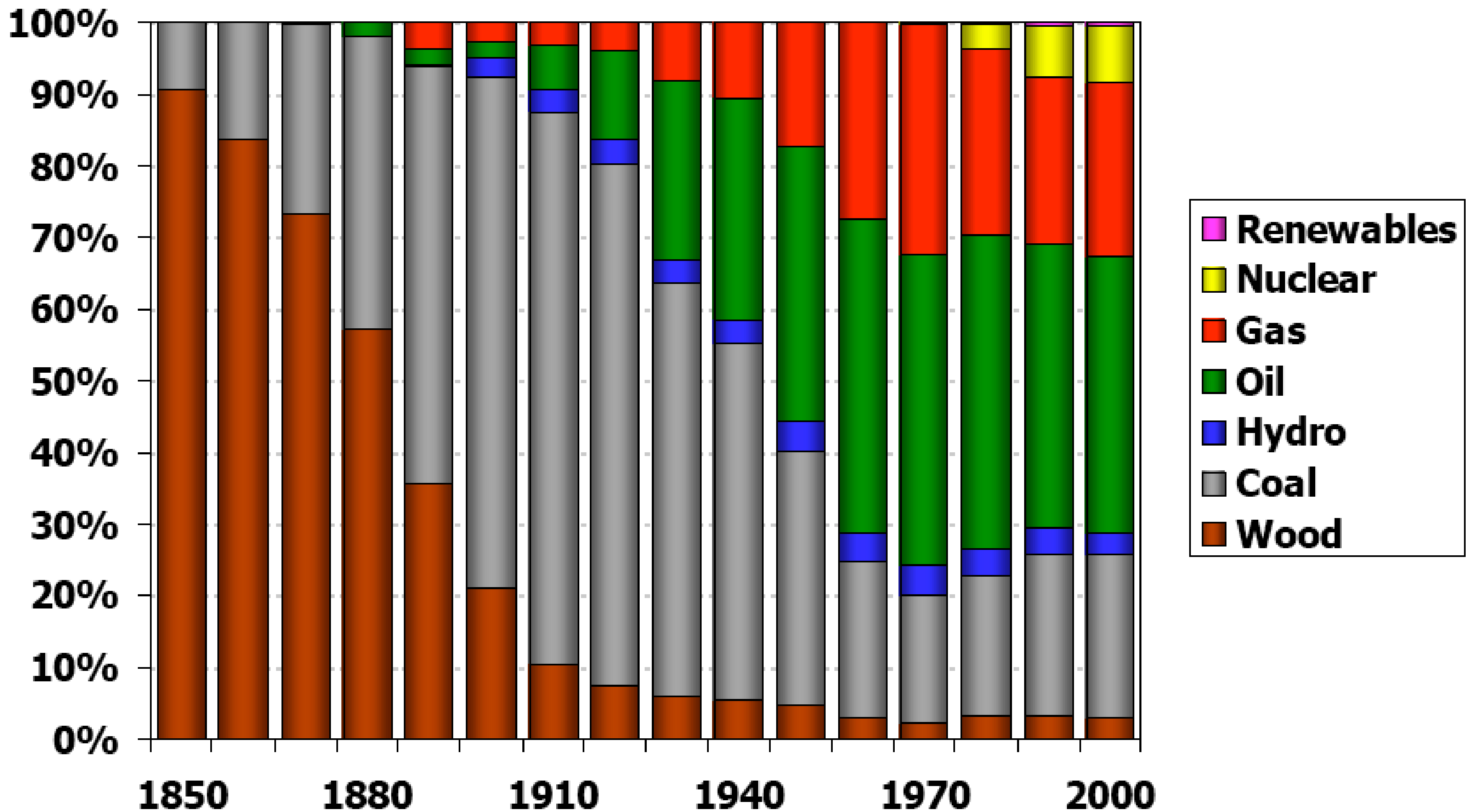
Primary Energy (2005)



Electricity Generation (2005)

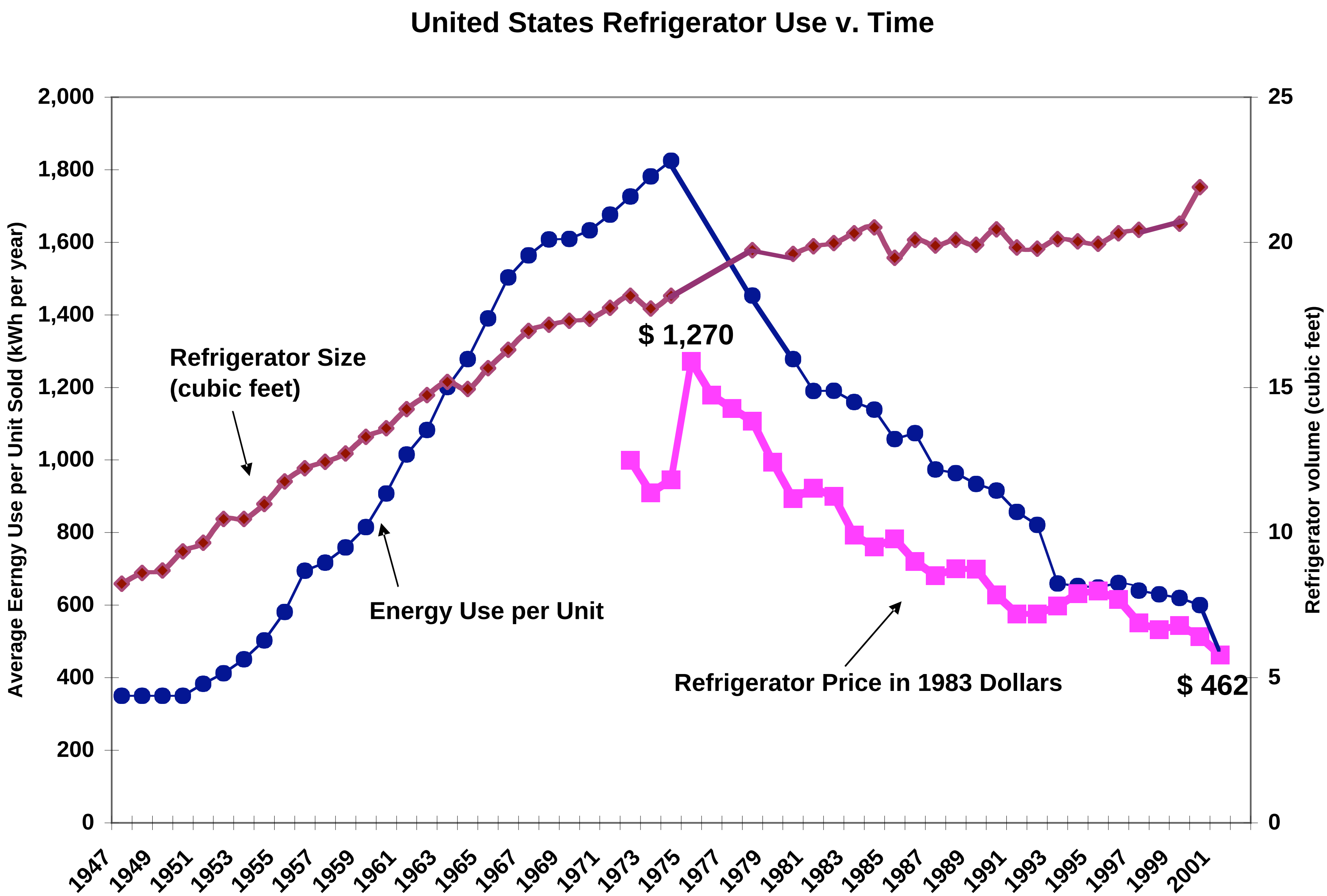


US Energy Supply Since 1850

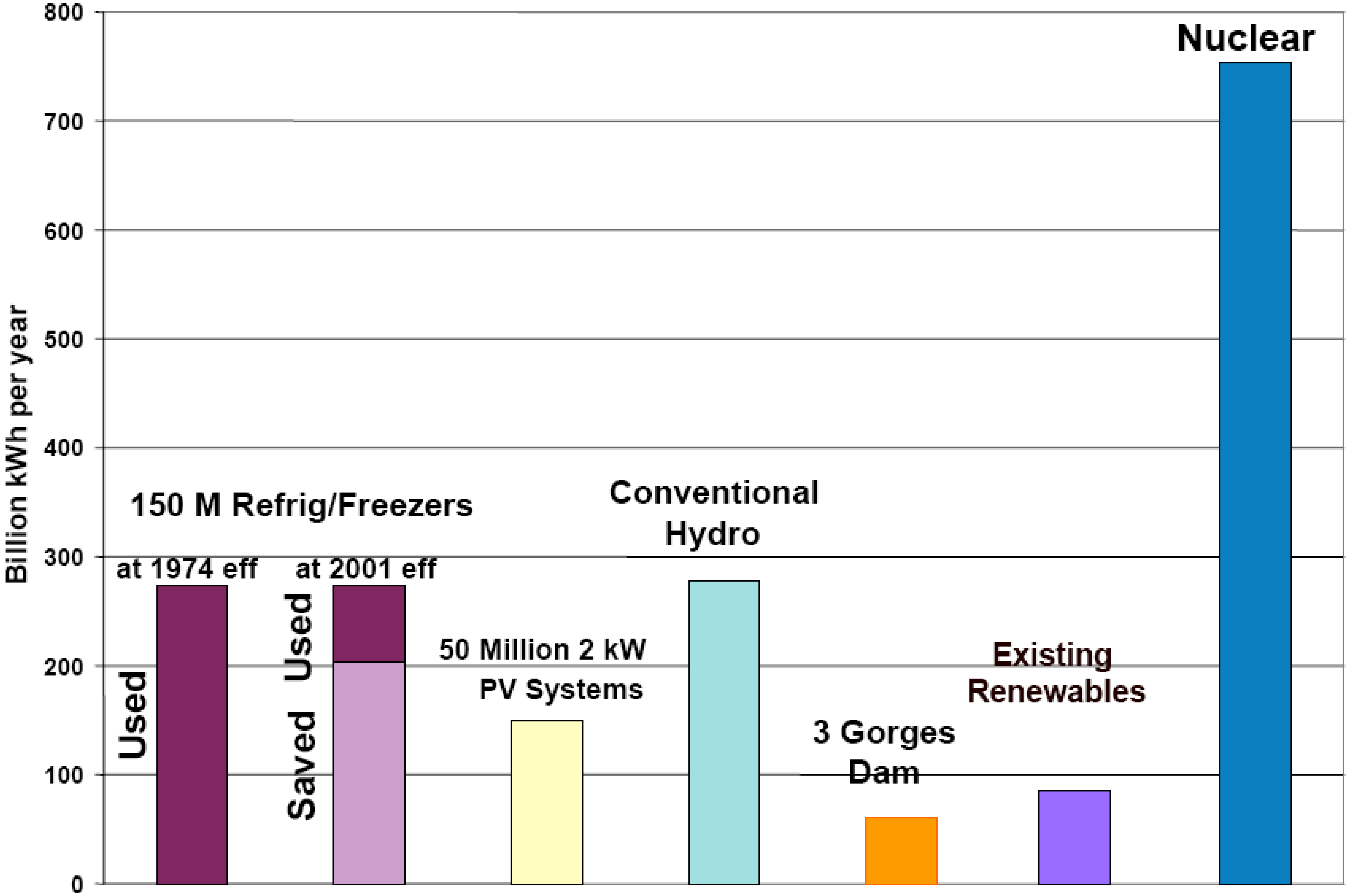


Source: EIA

U.S. Refrigerator Energy Use vs. Time



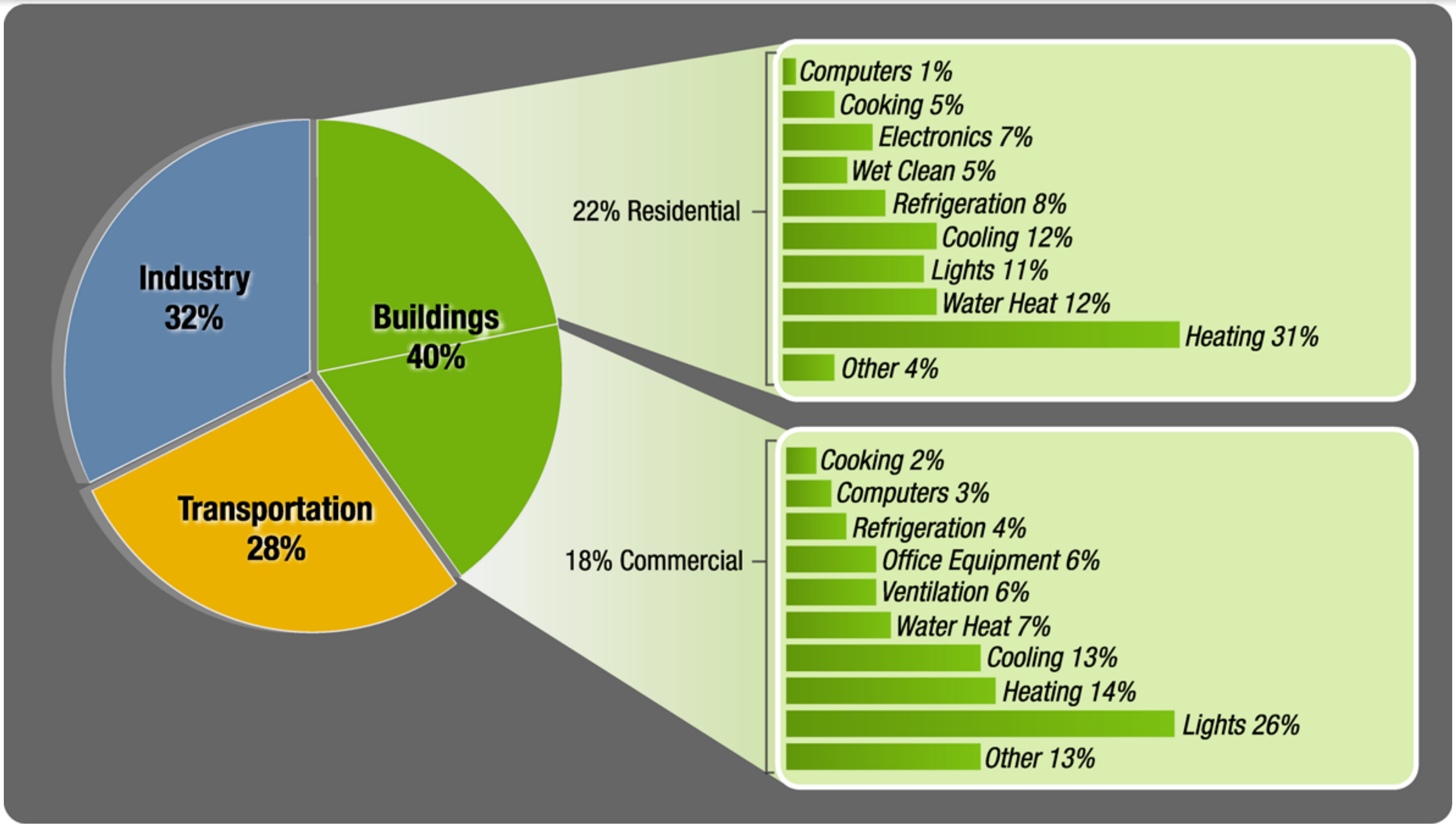
US Electricity Use of Refrigerators and Freezers compared to sources of electricity



Buildings Matter

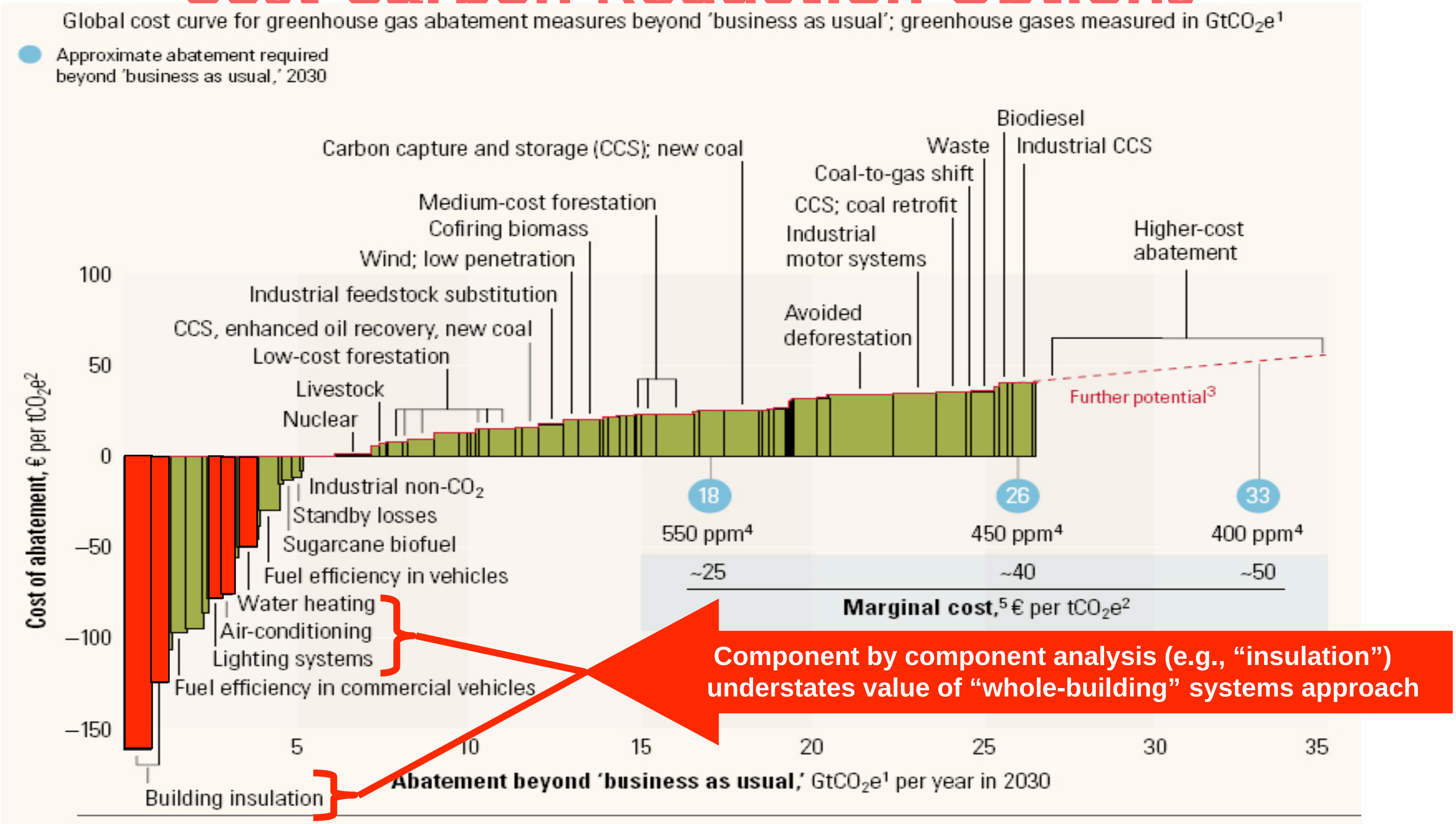
Buildings construction/renovation contributed **9.5% to US GDP** and employs approximately **8 million people**. Buildings' utility bills totaled **$370 Billion** in 2005.

Buildings use 72% of nation's electricity and 55% of its natural gas.



Source: *Buildings Energy Data Book 2007*

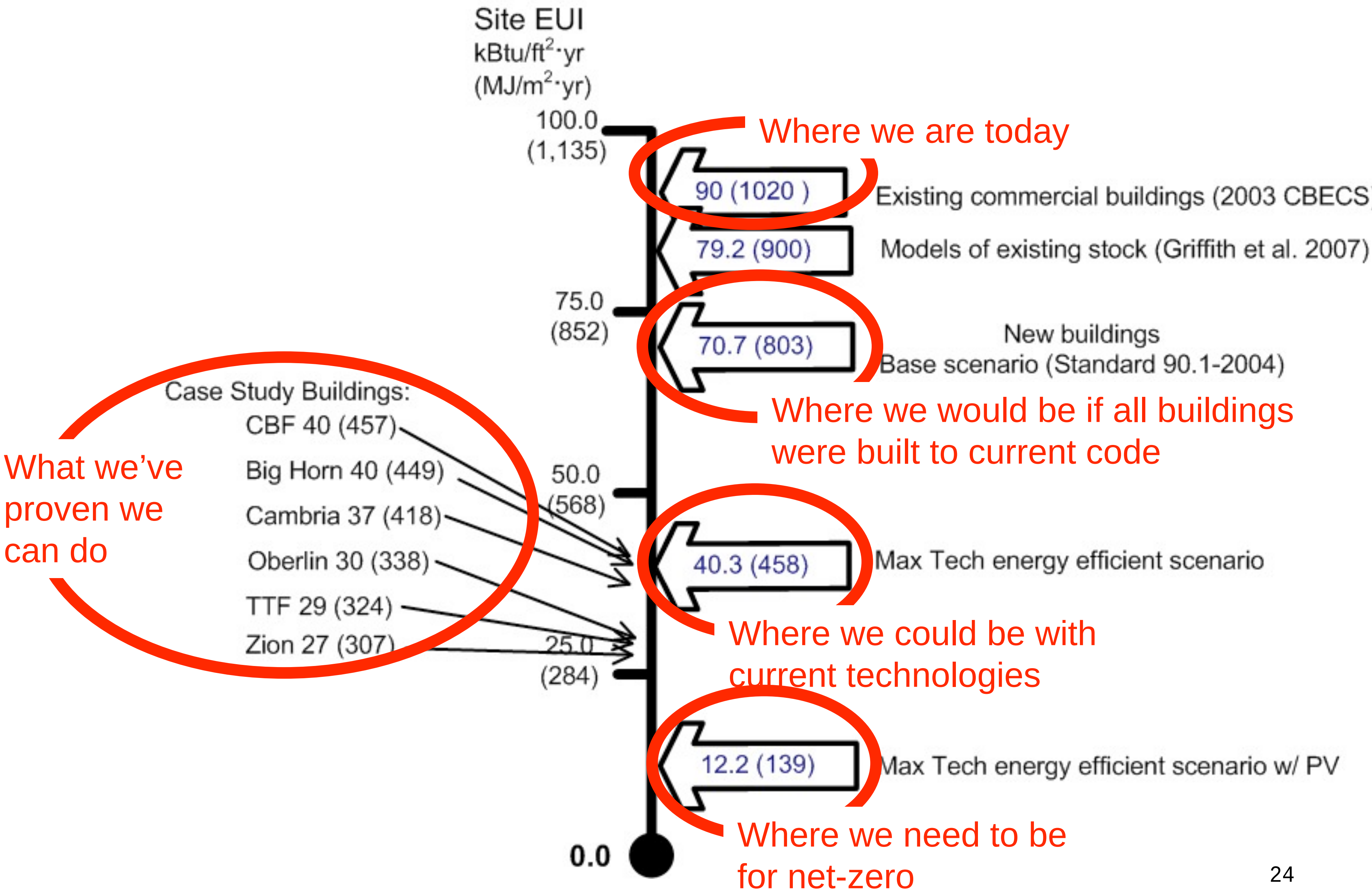
Energy Efficiency Offers Low or No-Cost Carbon Reduction Options

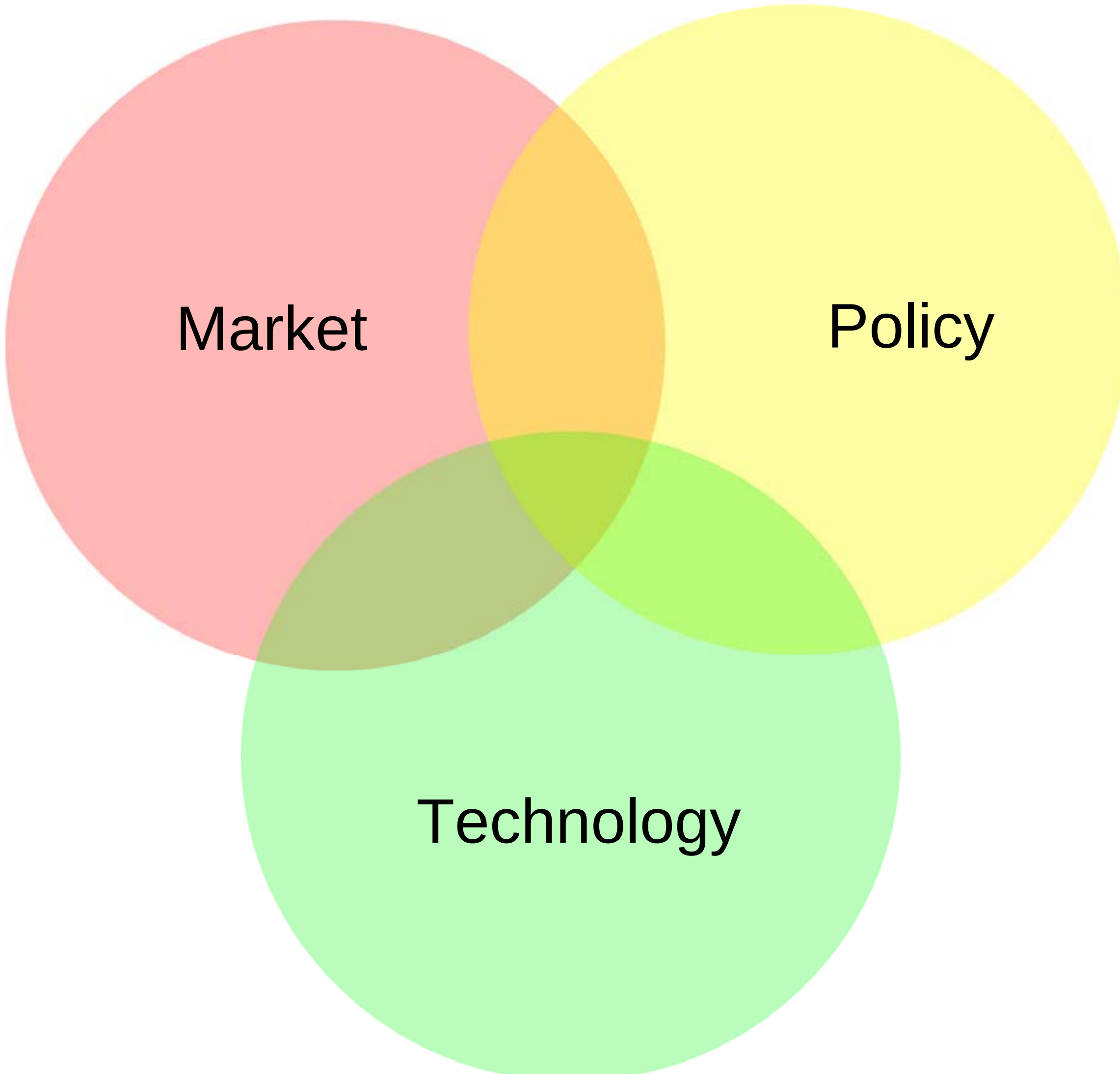


[1] $GtCO_2e$ = gigaton of carbon dioxide equivalent; "business as usual" based on emissions growth driven mainly by increasing demand for energy and transport around the world and by tropical deforestation.
[2] tCO_2e = ton of carbon dioxide equivalent.
[3] Measures costing more than €40 a ton were not the focus of this study.
[4] Atmospheric concentration of all greenhouse gases recalculated into CO_2 equivalents; ppm = parts per million.
[5] Marginal cost of avoiding emissions of 1 ton of CO_2 equivalents in each abatement demand scenario.

Source: McKinsey Global Institute, 2007

Energy Efficiency has Great Potential

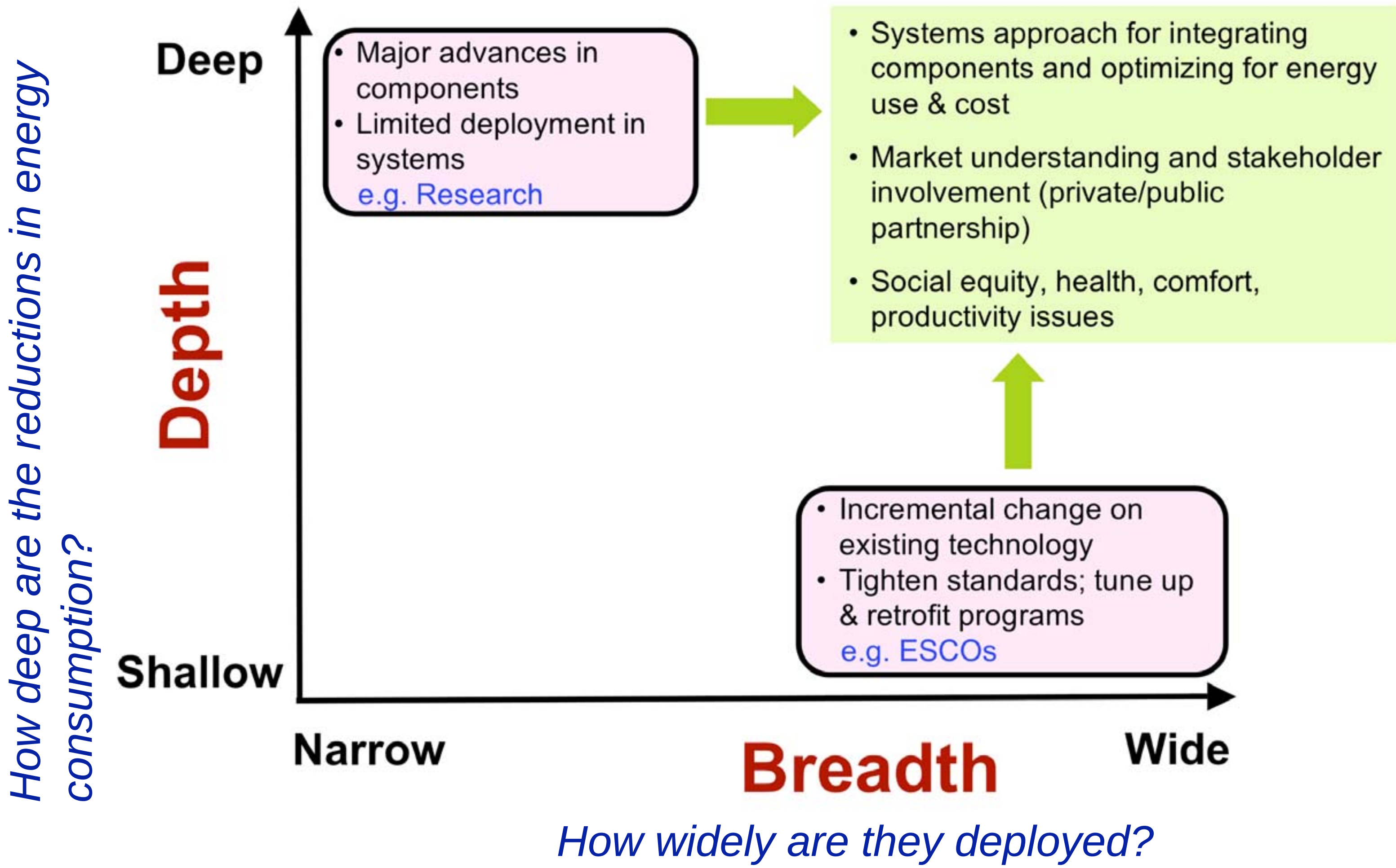



Market
Policy
Technology

High Performance Buildings Research & Implementation Center (HiPerBRIC)

National Labs-Industrial Consortium-University Partnership

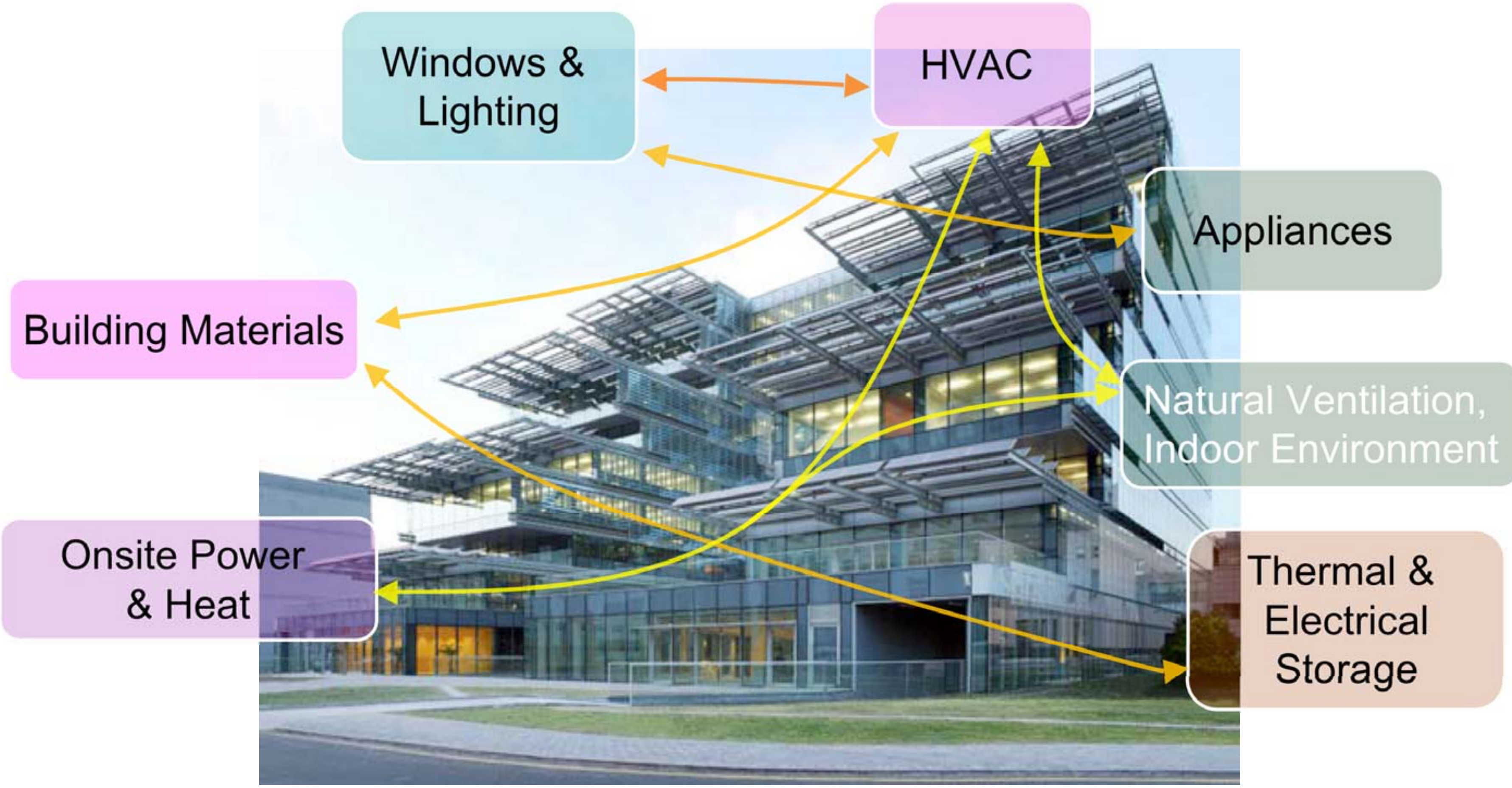
Gaps & Opportunities



- Incremental and component level research programs are unlikely to "solve" the problem, i.e. produce the changes in energy use needed.
- Problem too large to be attacked by a single entity

System of Systems

Integrated Whole Building Approach



Commercial Buildings Market Fragmentation

Technical Input on Energy

Architects & Engineers
- Aesthetic & Technical Design

Materials & Systems Supplier
- HVAC
- Lighting
- Building Materials

Construction Firms
- Construct the building

Developer
- Providing Specs
- Financing
- Operating

Market Demand on Energy Efficiency?

Property Management Firms
- Buy Portfolio of Companies

Tenants
- Lease space from Developer or Property Manager
- Professional firms, retailers, multinational corps…

Market Demand on Energy Efficiency?

Possible Solutions

- Make energy consumption visible to everyone
  - Find out where the leaks are - reduce liability risks
  - Sufficient granularity so that tenants and property manager can see the impact of their actions. Property managers can use tenant-level energy billing

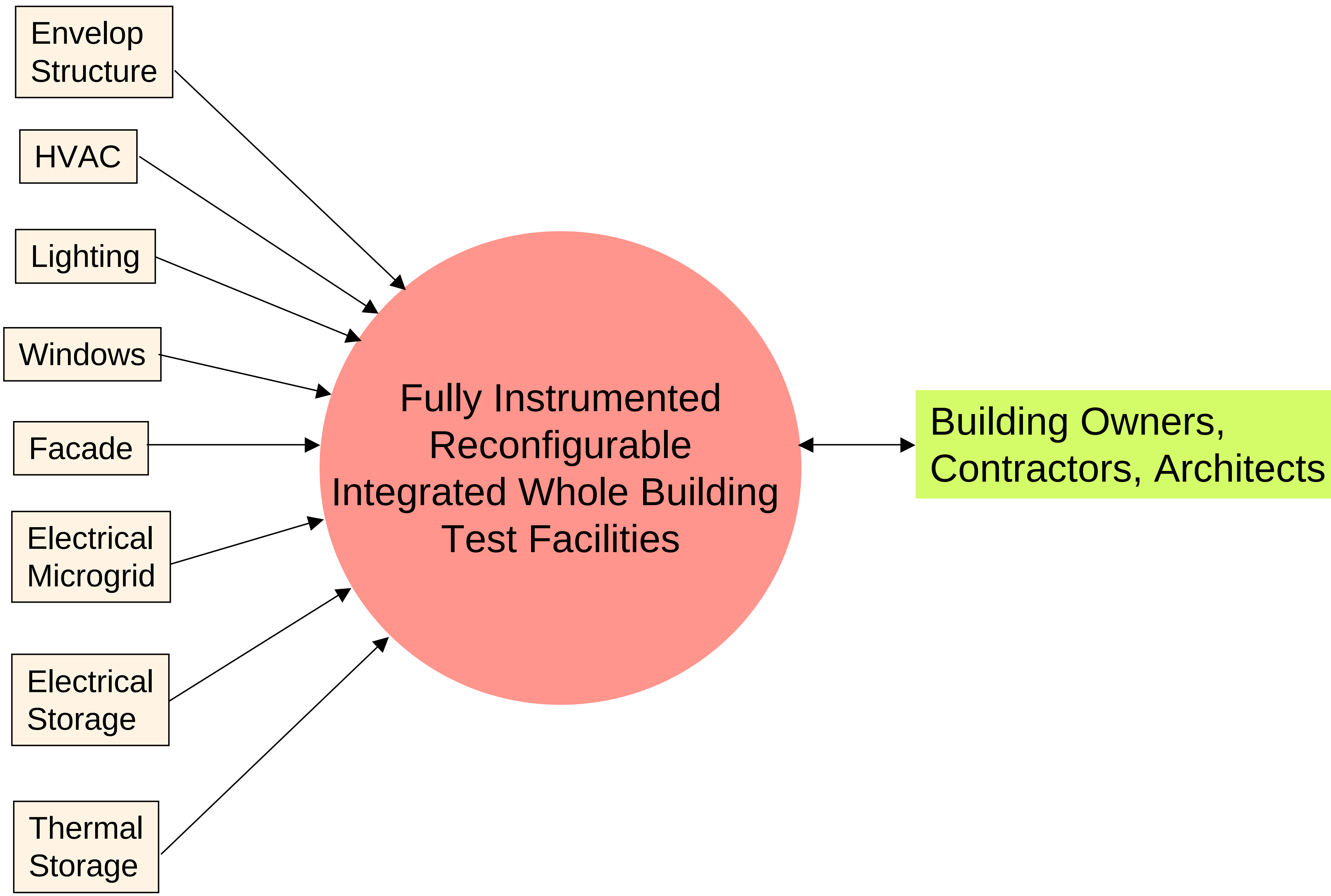
- Energy Performance Standards
  - Based on measured performance, not designed performance
    - Key to corrective action, reduced liability risk, …..
  - Account for climate and type of building
  - Move standards to lower energy consumption in future

- Price Signal
  - Performance below standard ➔ cost of carbon, etc…
  - Performance above standard ➔ financial incentives

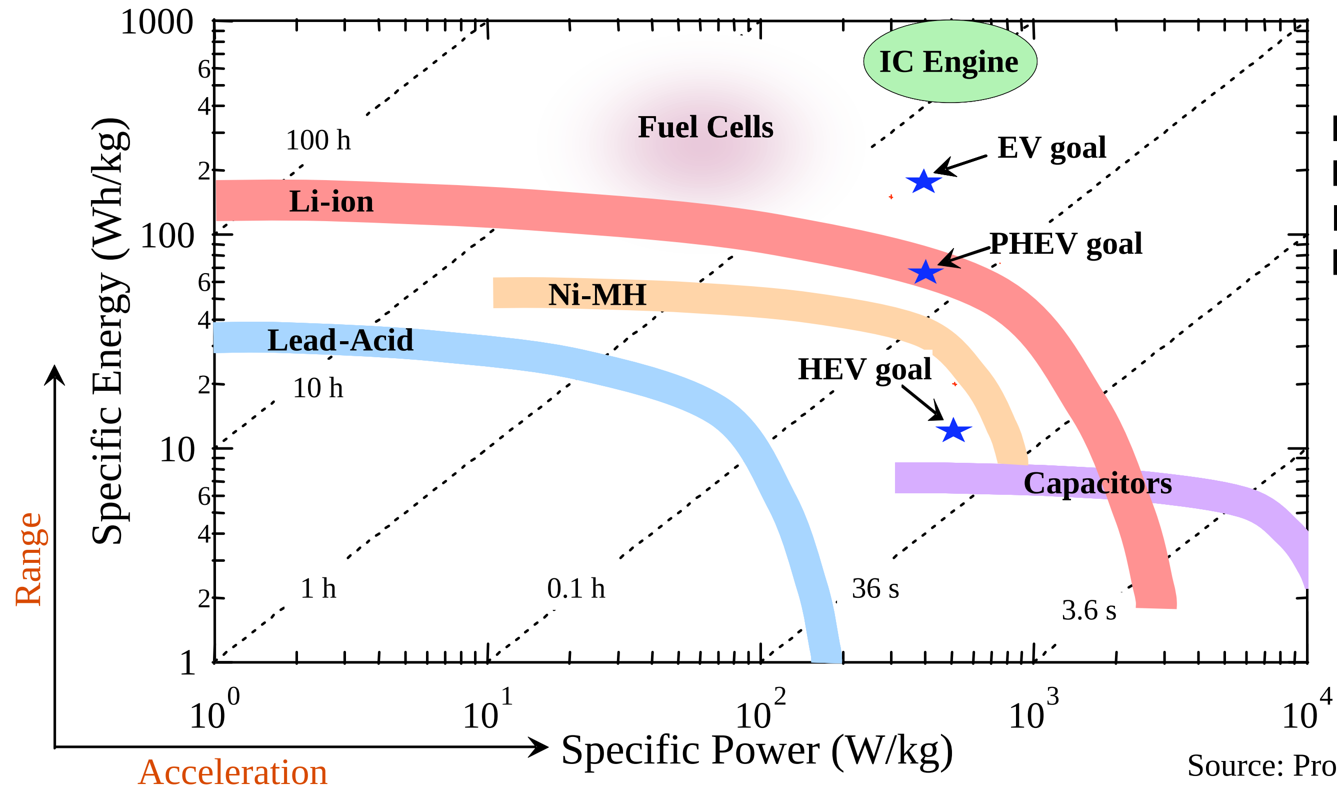
- Who wins and who loses
  - Shared benefits and costs between tenants and building owners
  - Allow owner to market space at higher rates for reduced operating costs
  - Mechanisms to ensure that efficiency investments are fully recouped at time of sale of used buildings

- Lifecycle accounting codes
  - Combine capital cost with operating costs

- Ratings, Public Campaign


Envelop Structure
HVAC
Lighting
Windows
Facade
Electrical Microgrid
Electrical Storage
Thermal Storage
Fully Instrumented Reconfigurable Integrated Whole Building Test Facilities
Building Owners, Contractors, Architects

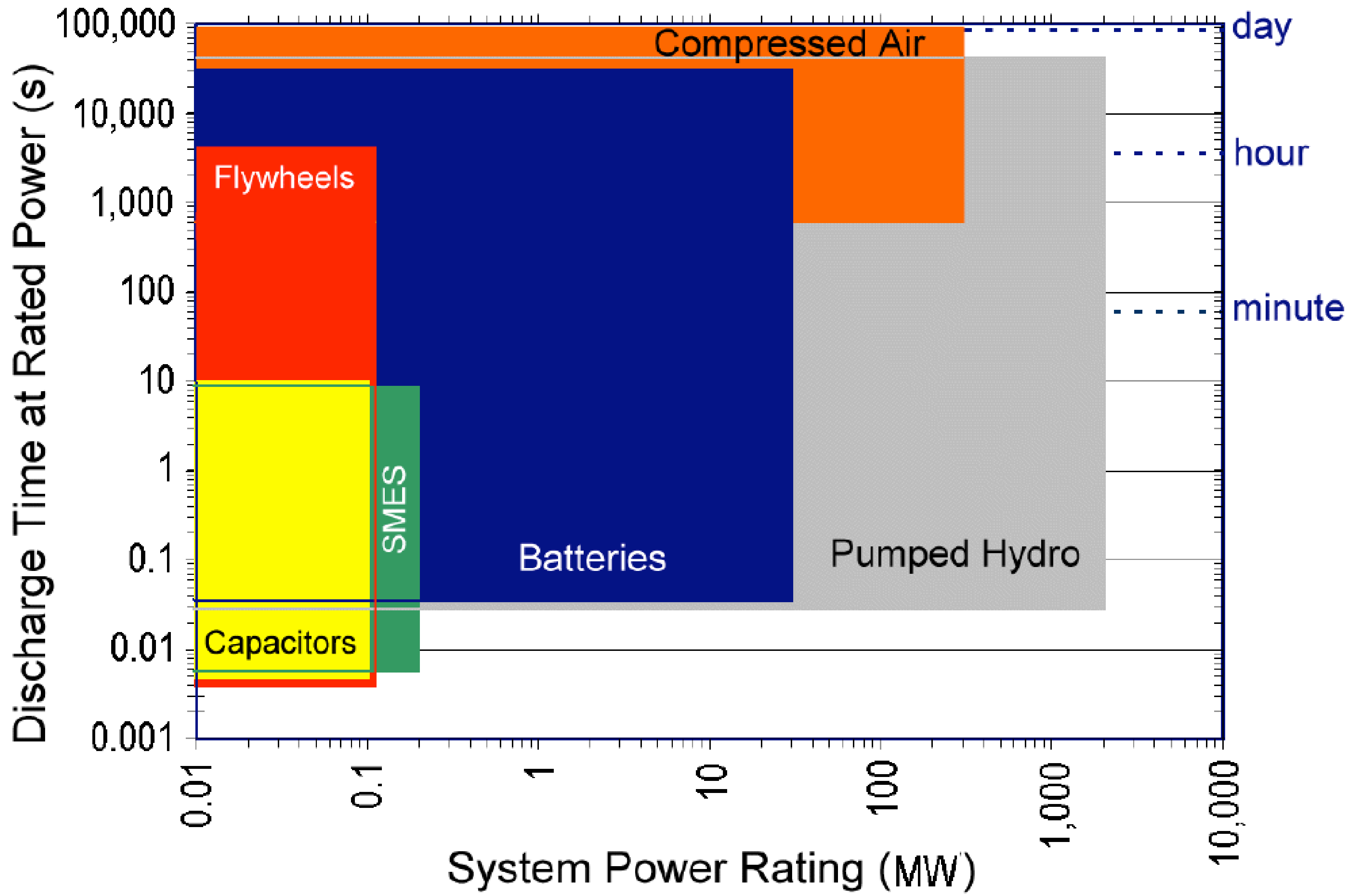
Batteries



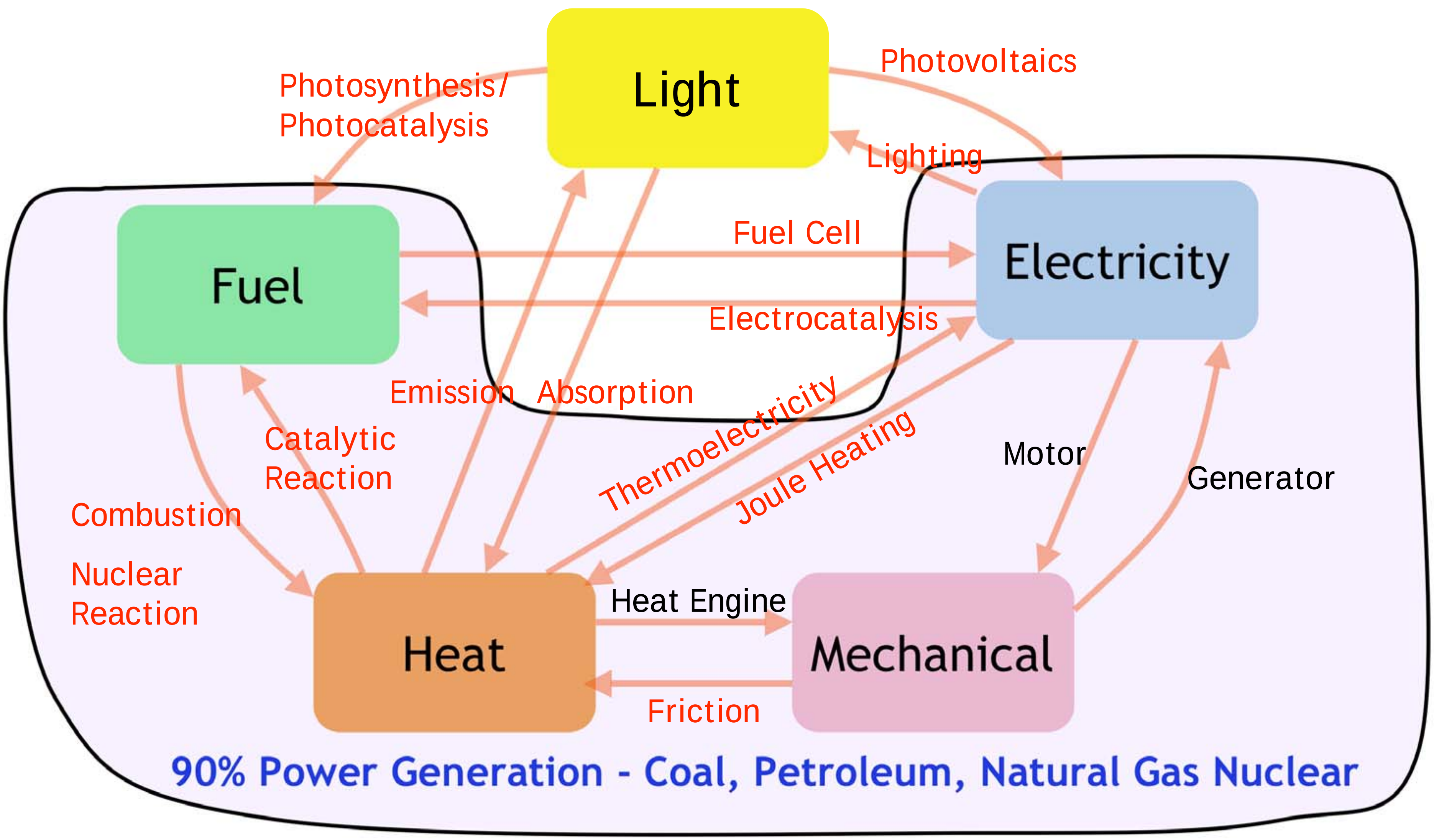
Source: Product data sheets

EV – Electric Vehicle
PHEV– Plug-in Hybrid-Electric Vehicle
HEV – Hybrid-Electric Vehicle

Discharge Time vs Power Capacity



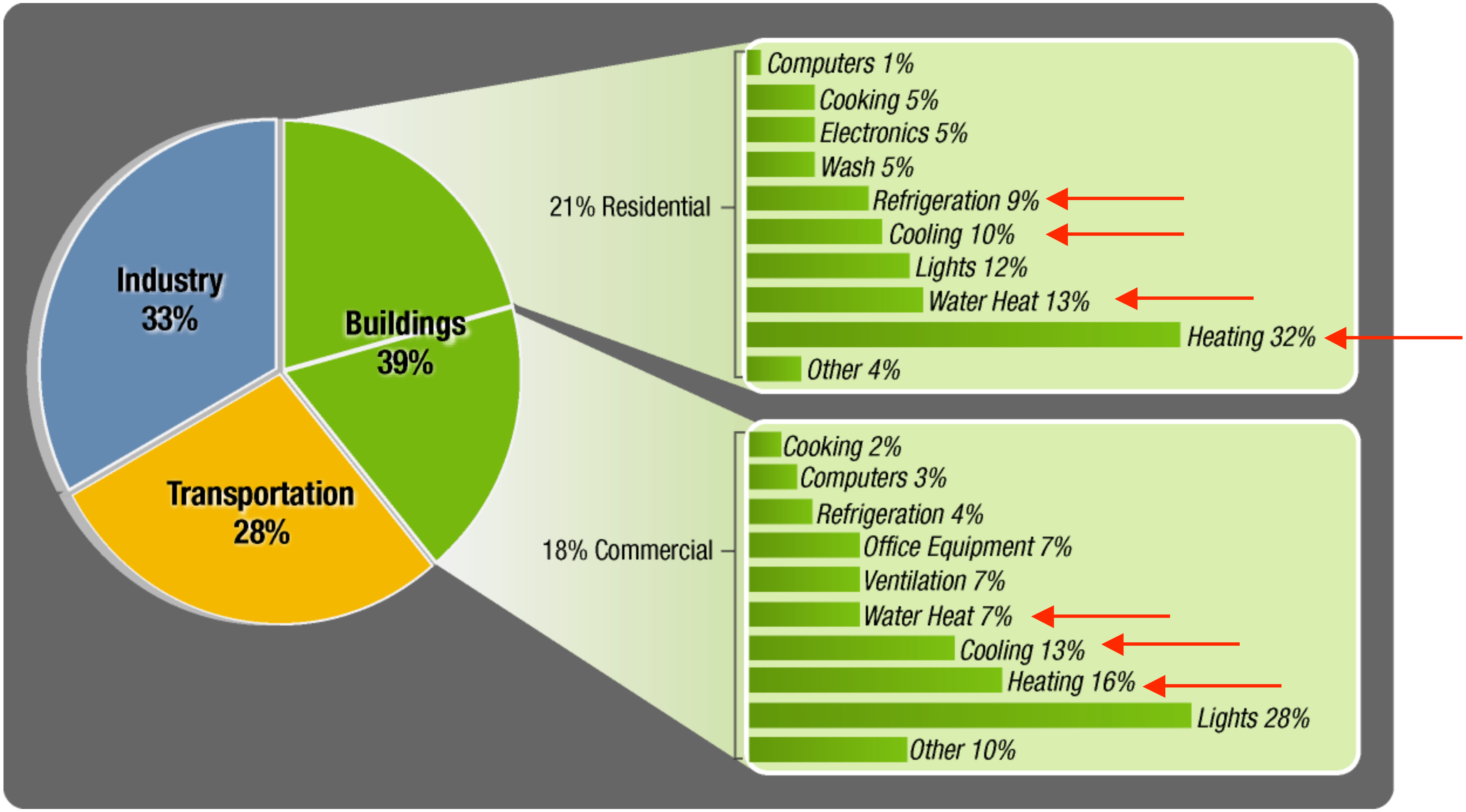
Energy Conversion



Building Energy Demand Challenge: End Use Energy Consumption

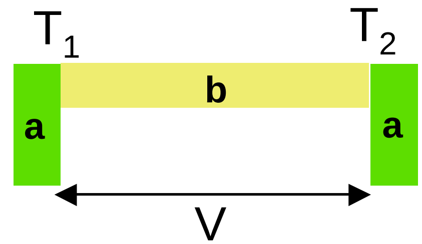
Buildings consume 39% of total U.S. energy

- ***71% of electricity and 54% of natural gas***

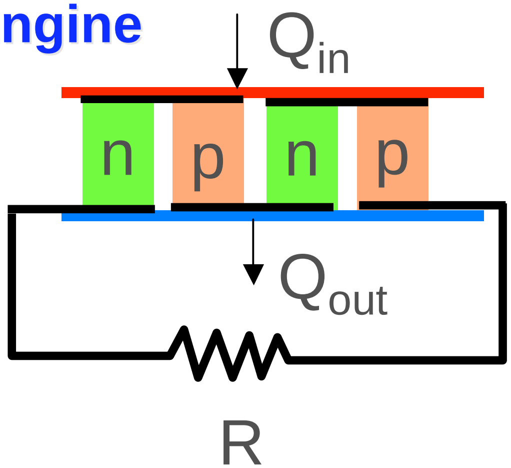


Thermoelectricity & Energy Conversion

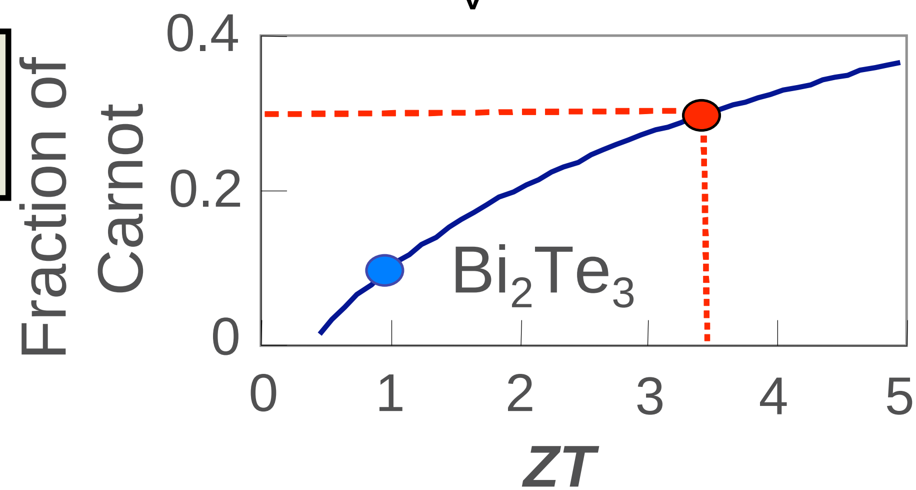
Seebeck Coefficient, S = V/ΔT



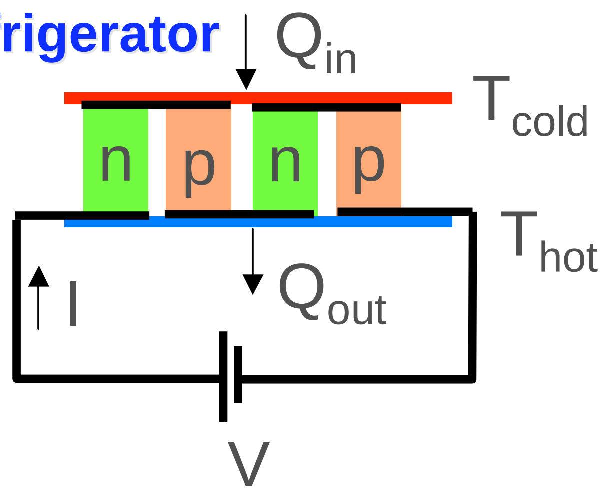
Engine



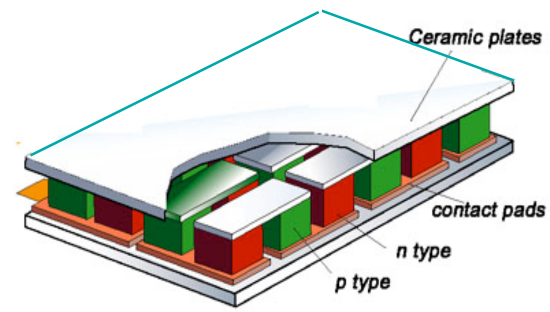
$$ZT = \frac{S^2\sigma T}{k}$$

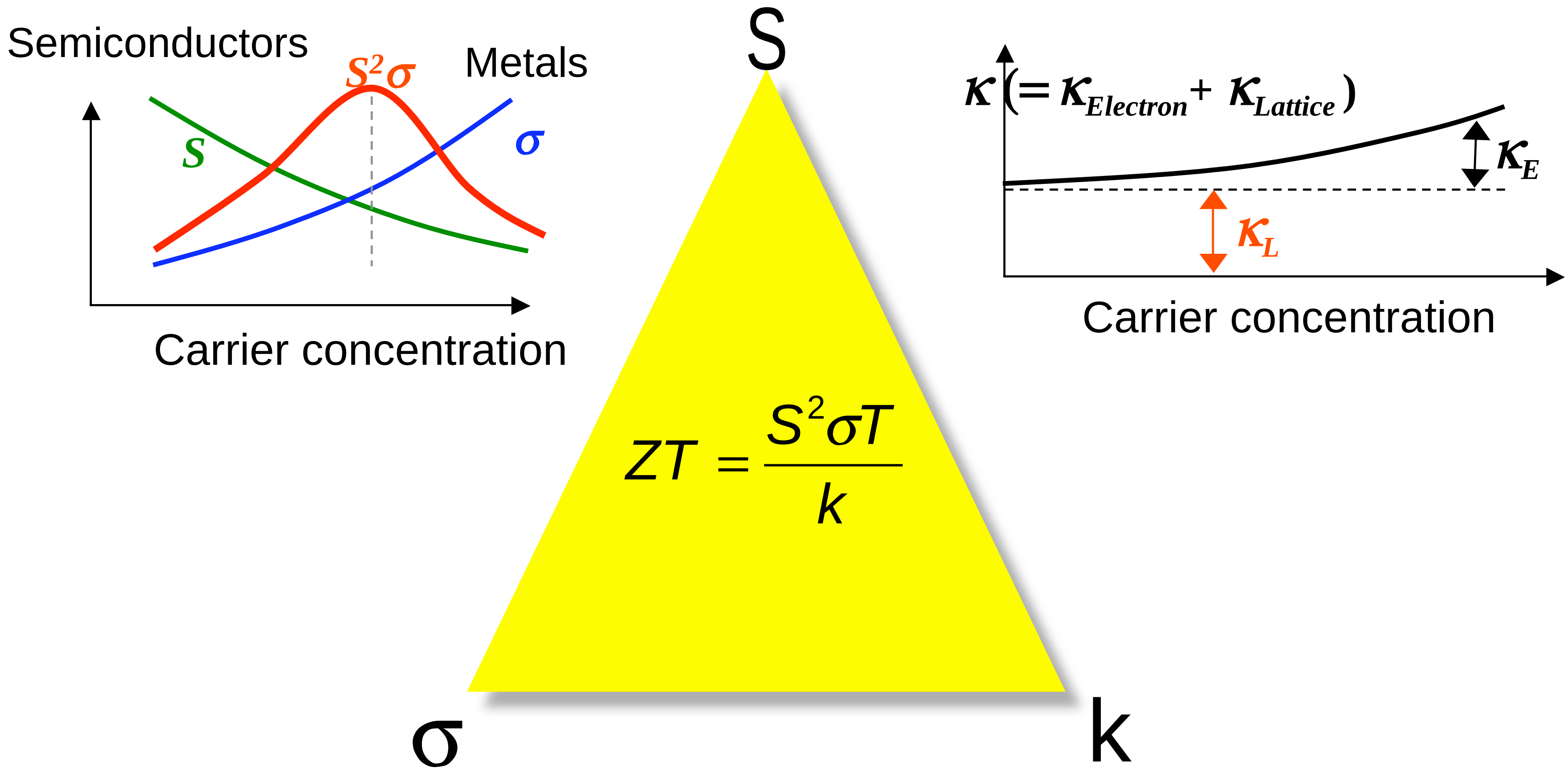


Refrigerator



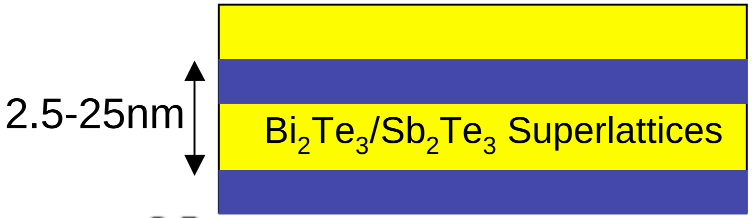
Bismuth Telluride
(low efficiency, expensive)



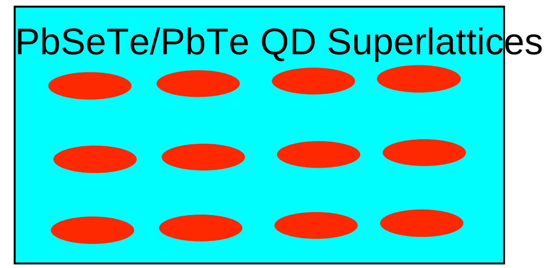

Semiconductors
S²σ
Metals
S
σ
Carrier concentration
S
ZT = S²σT / k
σ
k
κ (= κElectron + κLattice)
κE
κL
Carrier concentration

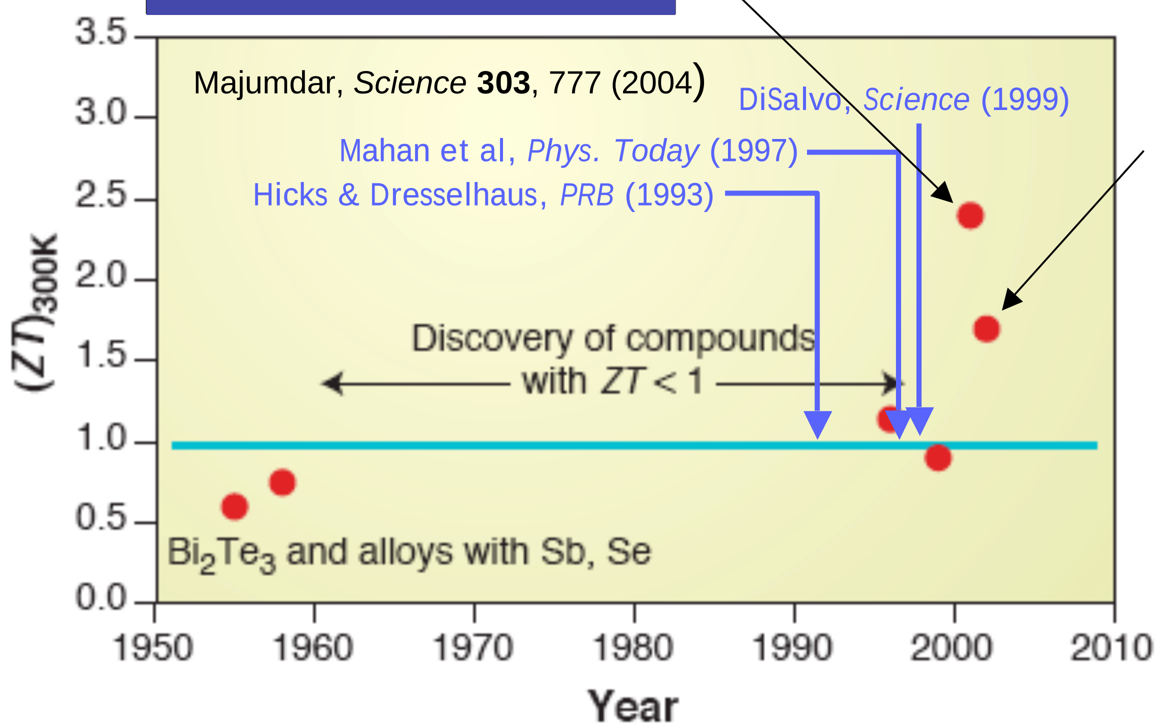
History

Venkatasubramanian et al. *Nature* **413**, 597 (2001)



Harman et al., *Science* **297**, 2229 (2002)

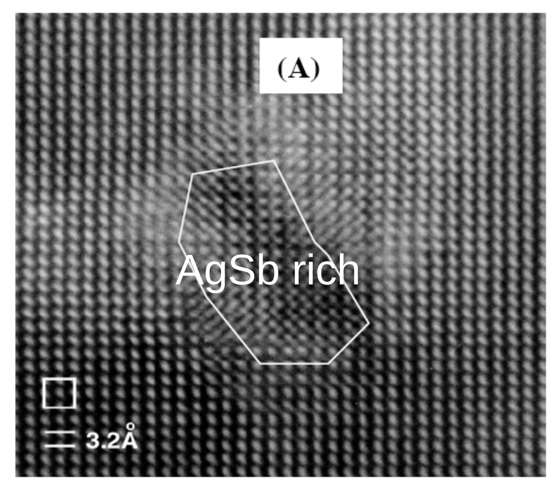




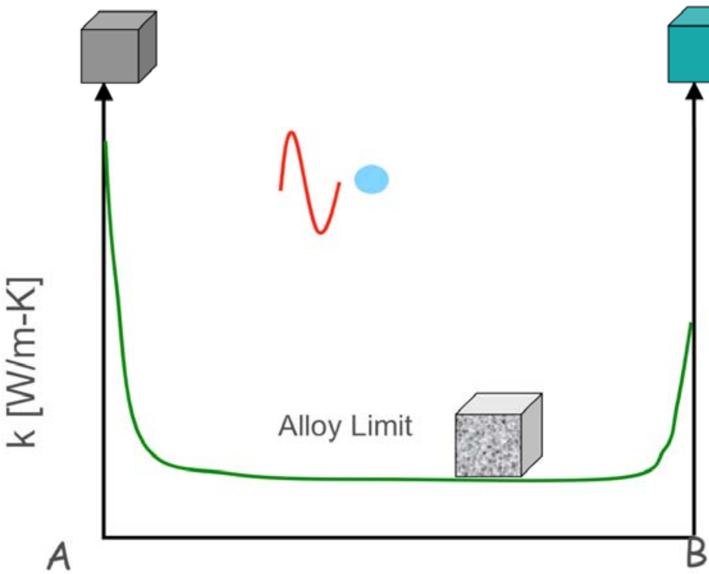
$$ZT = \frac{S^2 \sigma T}{k \downarrow}$$

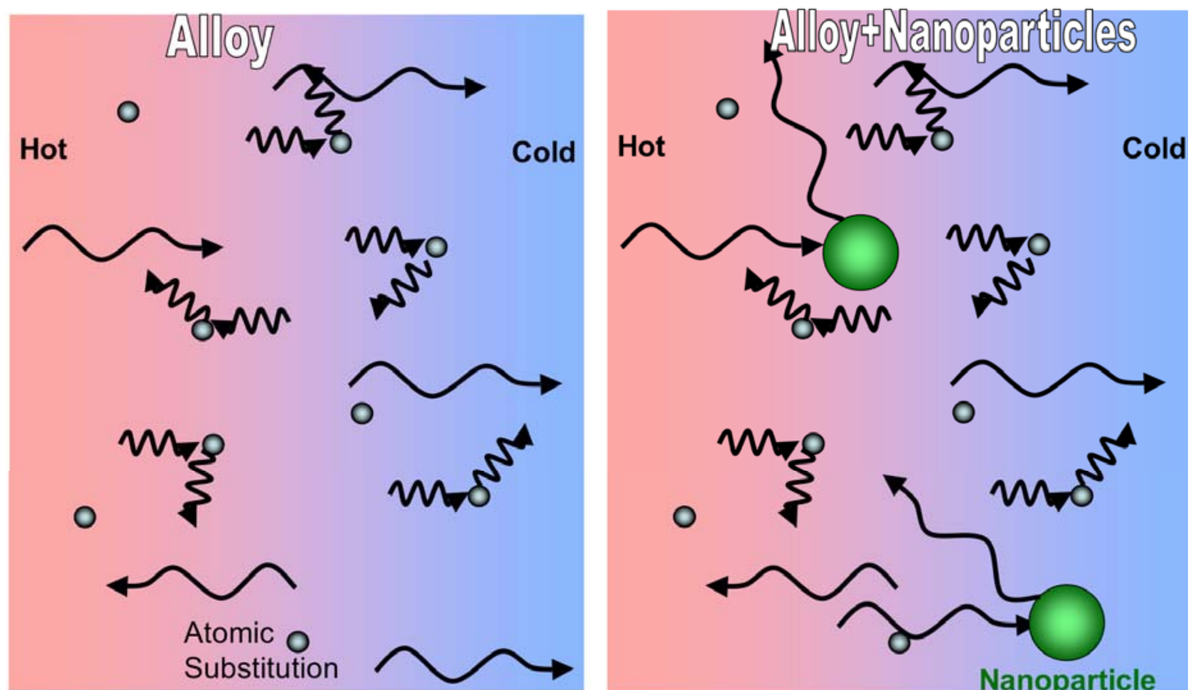
Hsu et al., *Science* **303**, 818 (2004)

$AgPb_{18}SbTe_{20}$
ZT = 2 @ 800K

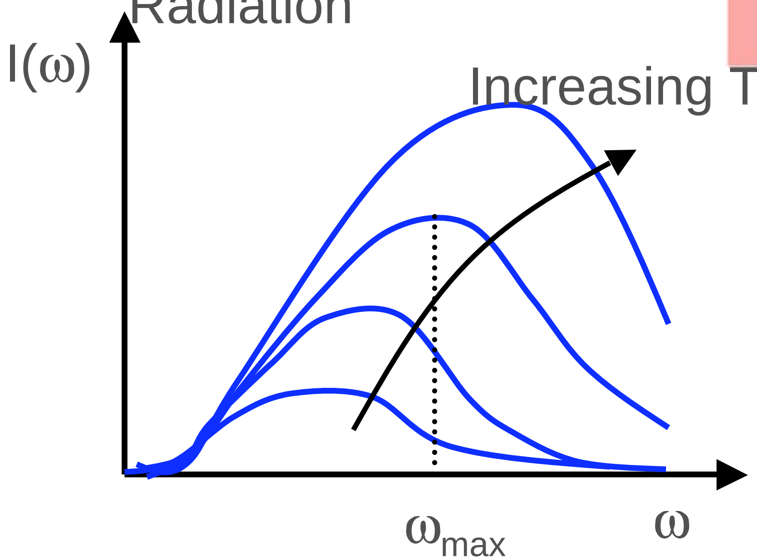


Beating the Alloy Limit



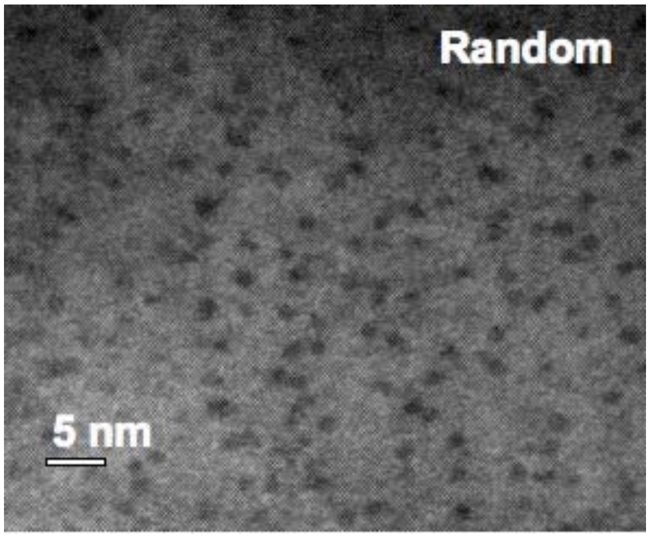


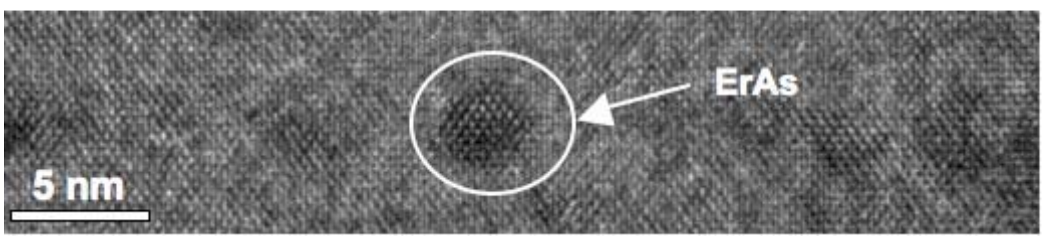
Blackbody Phonon Radiation

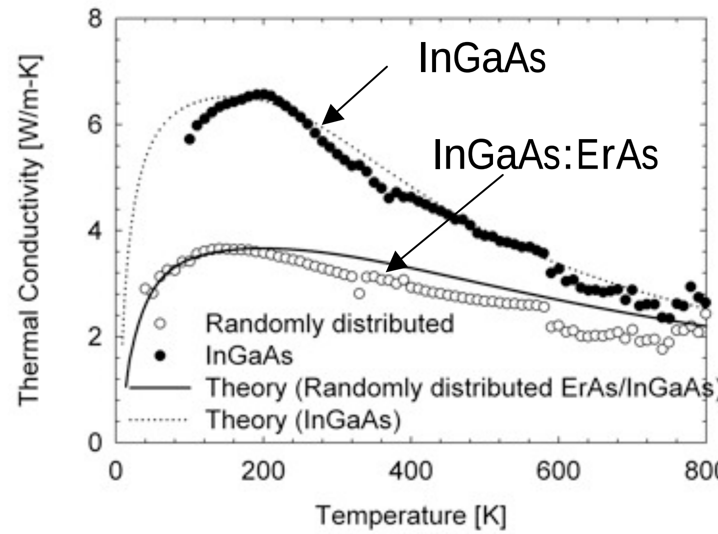


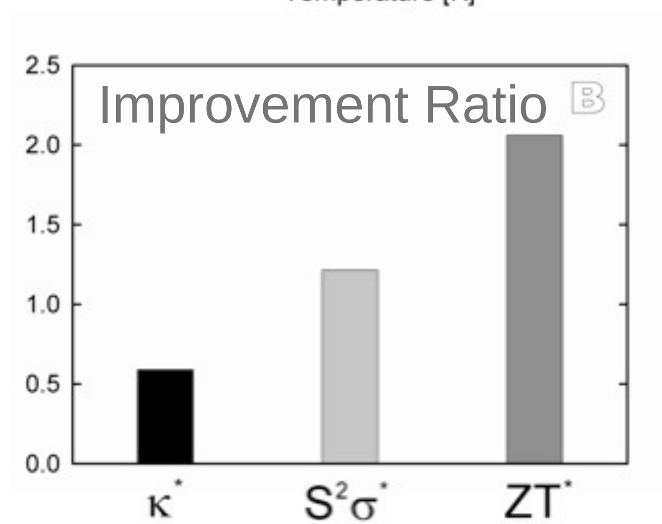
$$\boxed{C_{sc} \propto \frac{d^6}{\lambda^4}}$$

Thermal Conductivity of ErAs: InGaAs Nanocomposites









Kim, Zide, Gossard, Klenov, Stemmer, Shakouri, Majumdar, *Phys. Rev. Lett.* (2006)

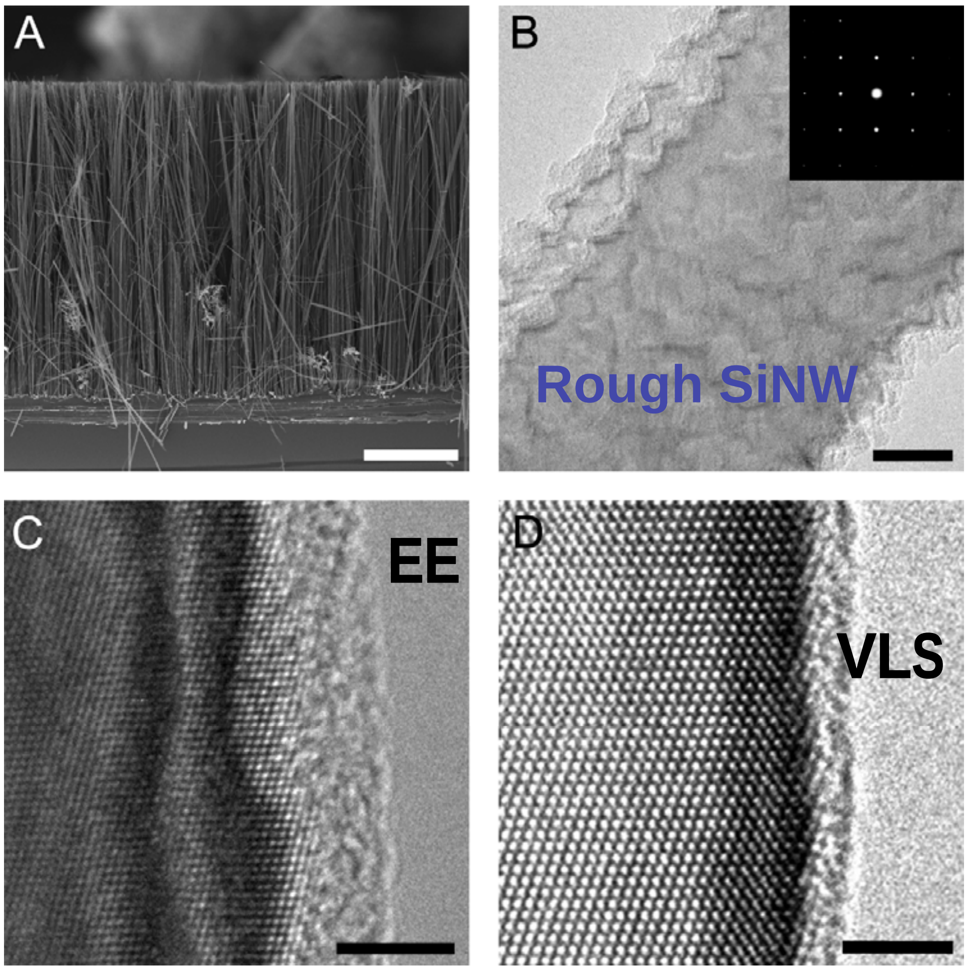
Electroless Etched Si Nanowires

Wafer-Scale Wet Etching Process

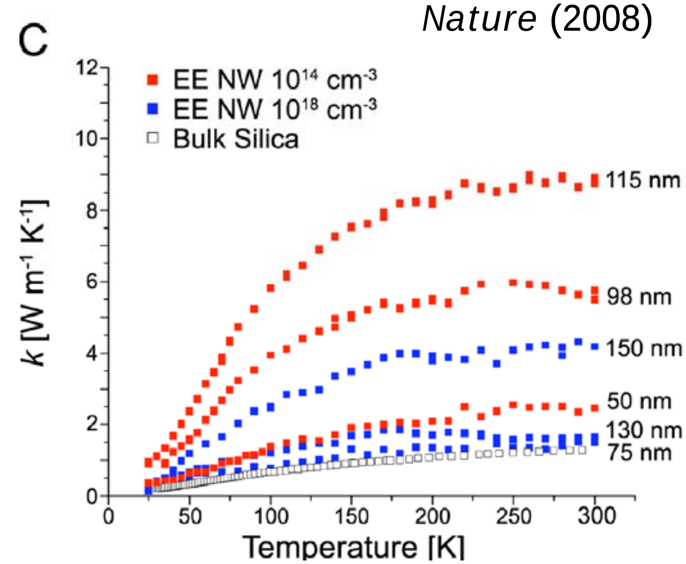
Reduction: $Ag^+ + e^-$ -----> Ag E^0_{red} = 0.7996 V

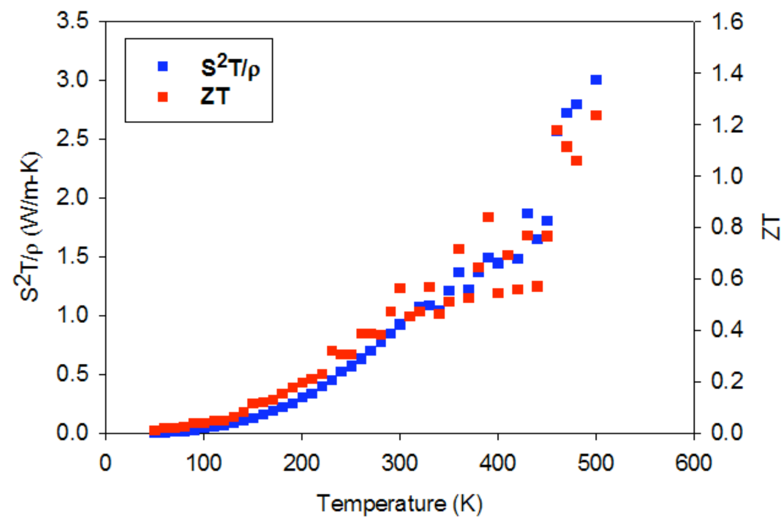
Oxidation: $Si + 6 F^-$ -----> $SiF_6^{2-} + 4 e^-$ E^0_{ox}= 1.24 V

Etching of Si at 50 ^{0}C in 5M HF, 0.02M $AgNO_3$ for 1h



Nature (2008)

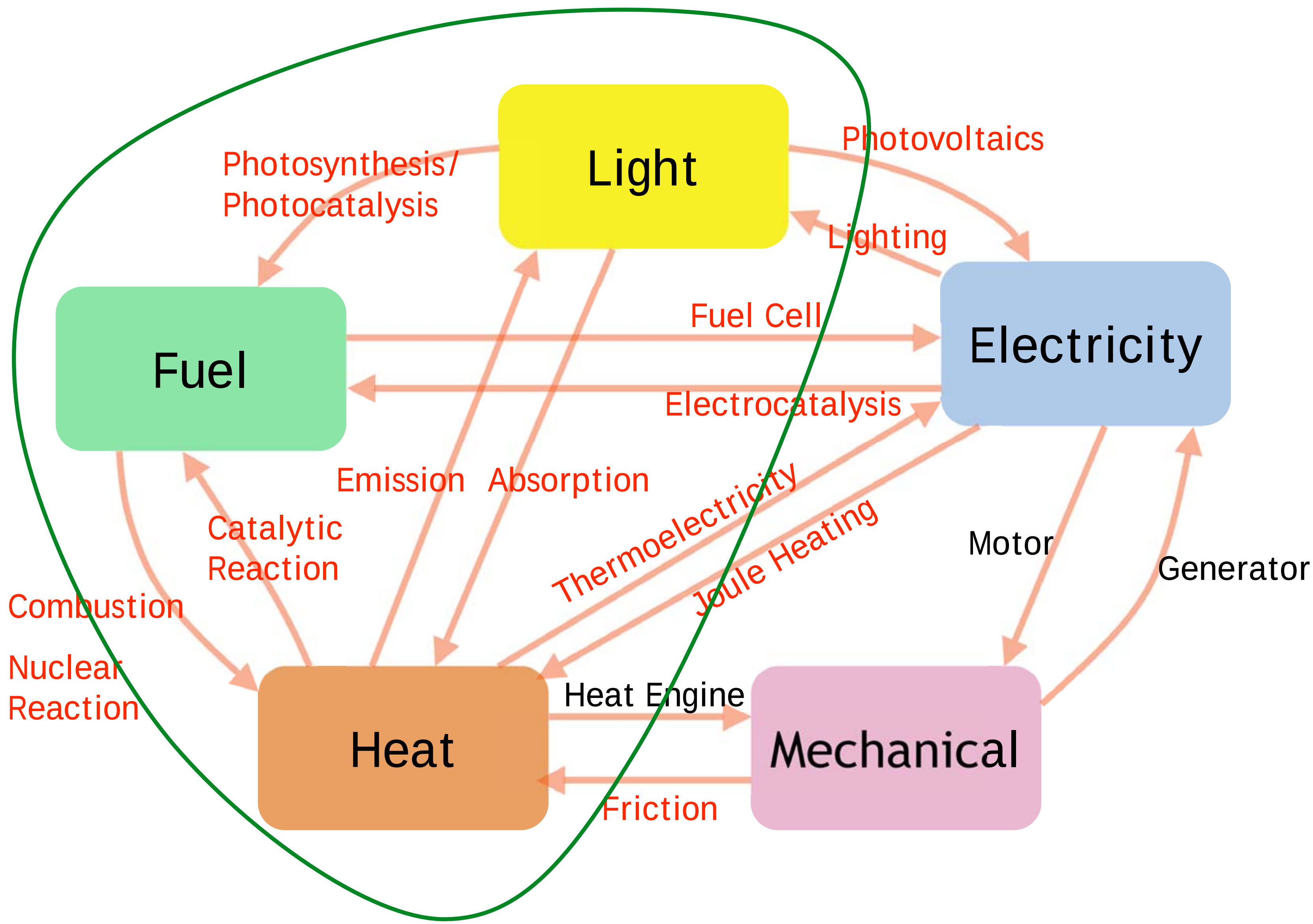




Renkun Chen, Kedar Hipalgaonkar (Majumdar Lab)

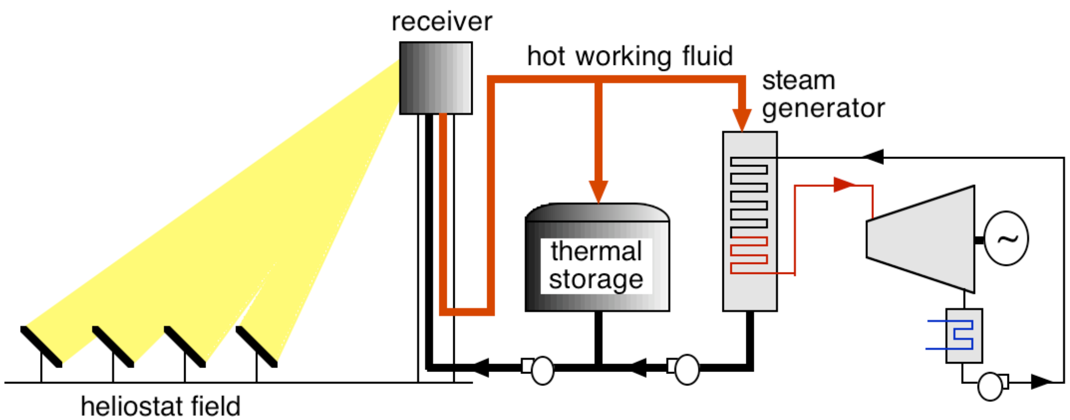
Allon Hochbaum, Sean Andrews (Yang Lab)

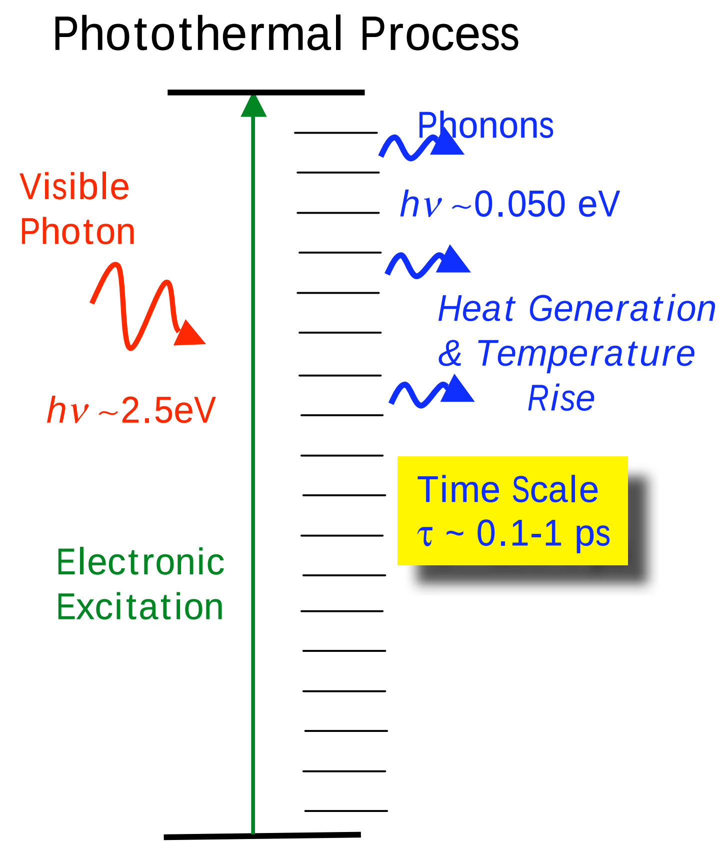
Energy Conversion



Solar Thermal

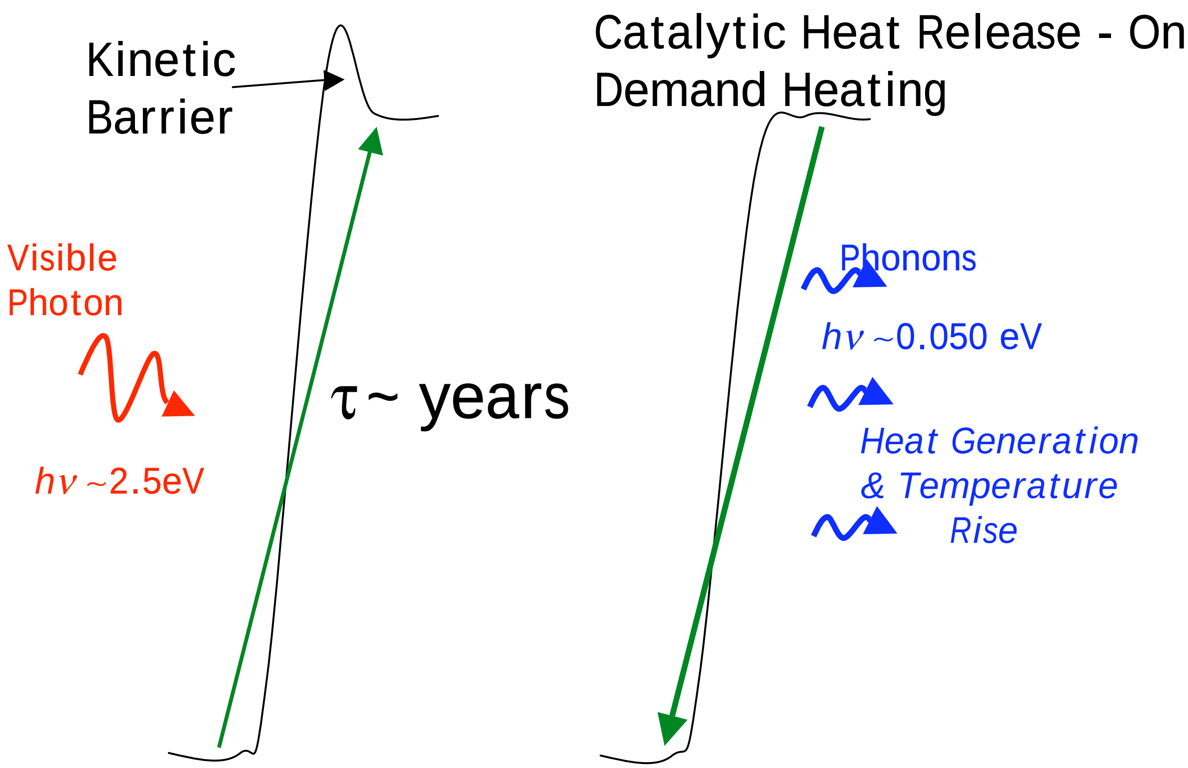
Traditional Approach





Concentration: Focusing mirrors over large area
Storage: Thermal
Conversion: Rankine cycle
Transmission: Electrical

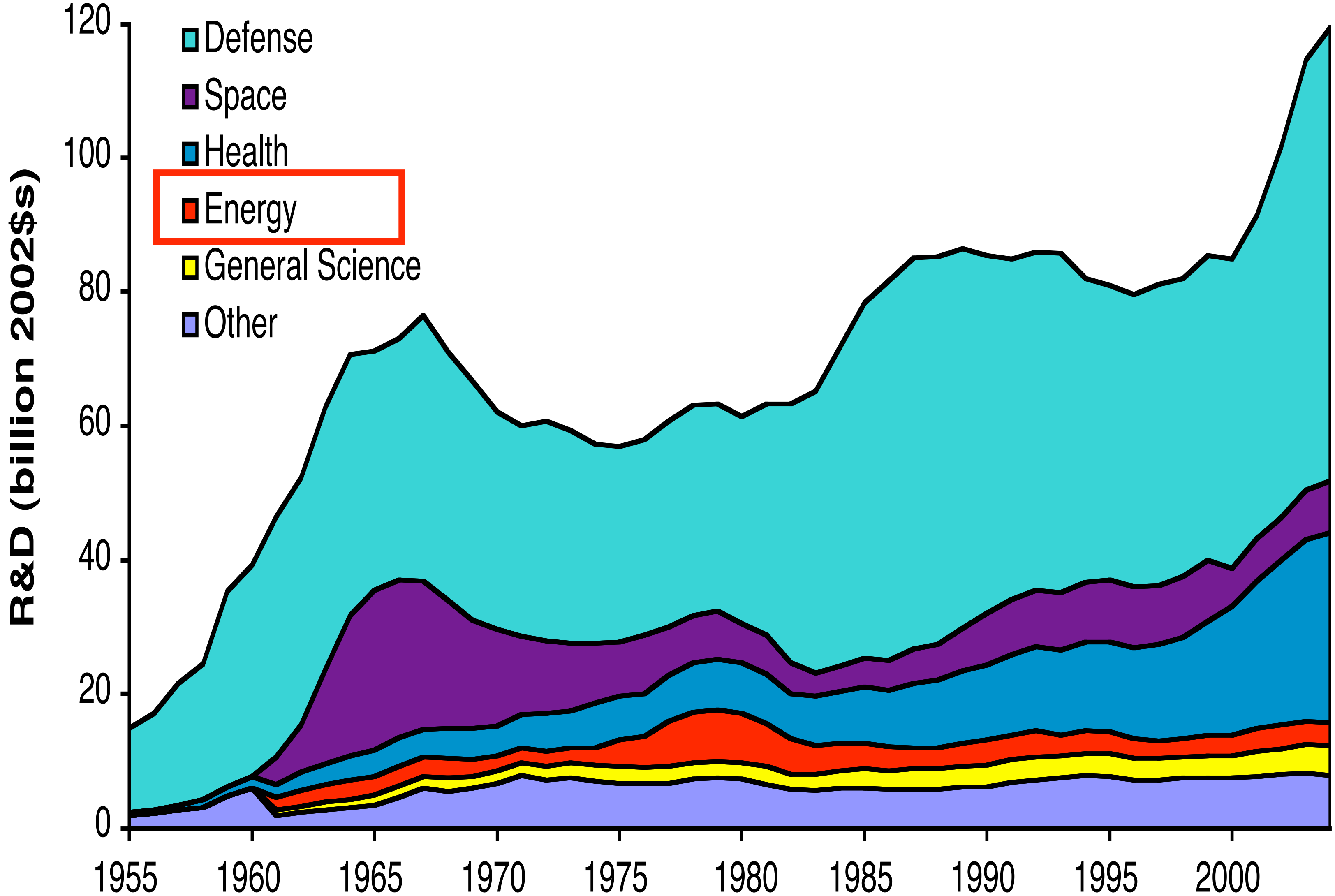
Solar Thermal Fuel



Separates

- Collection
- Storage
- heat generation

Federal R&D Investments, 1955 - 2004



Margolis & Kammen, *Science*, 1999