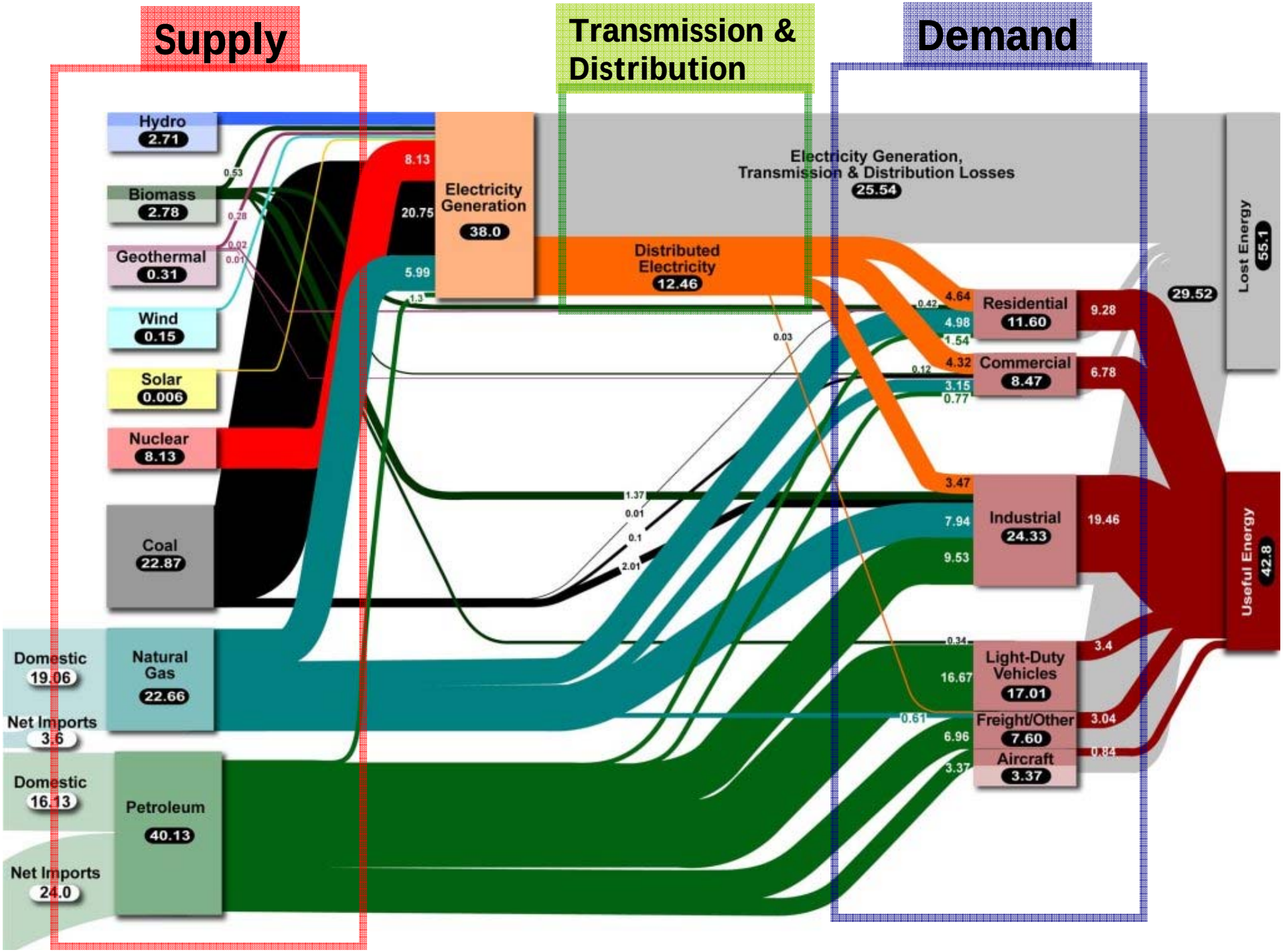
Game-Changing Innovations Needed for Clean Energy Future

Arun Majumdar

Director, Environmental Energy Technologies Division

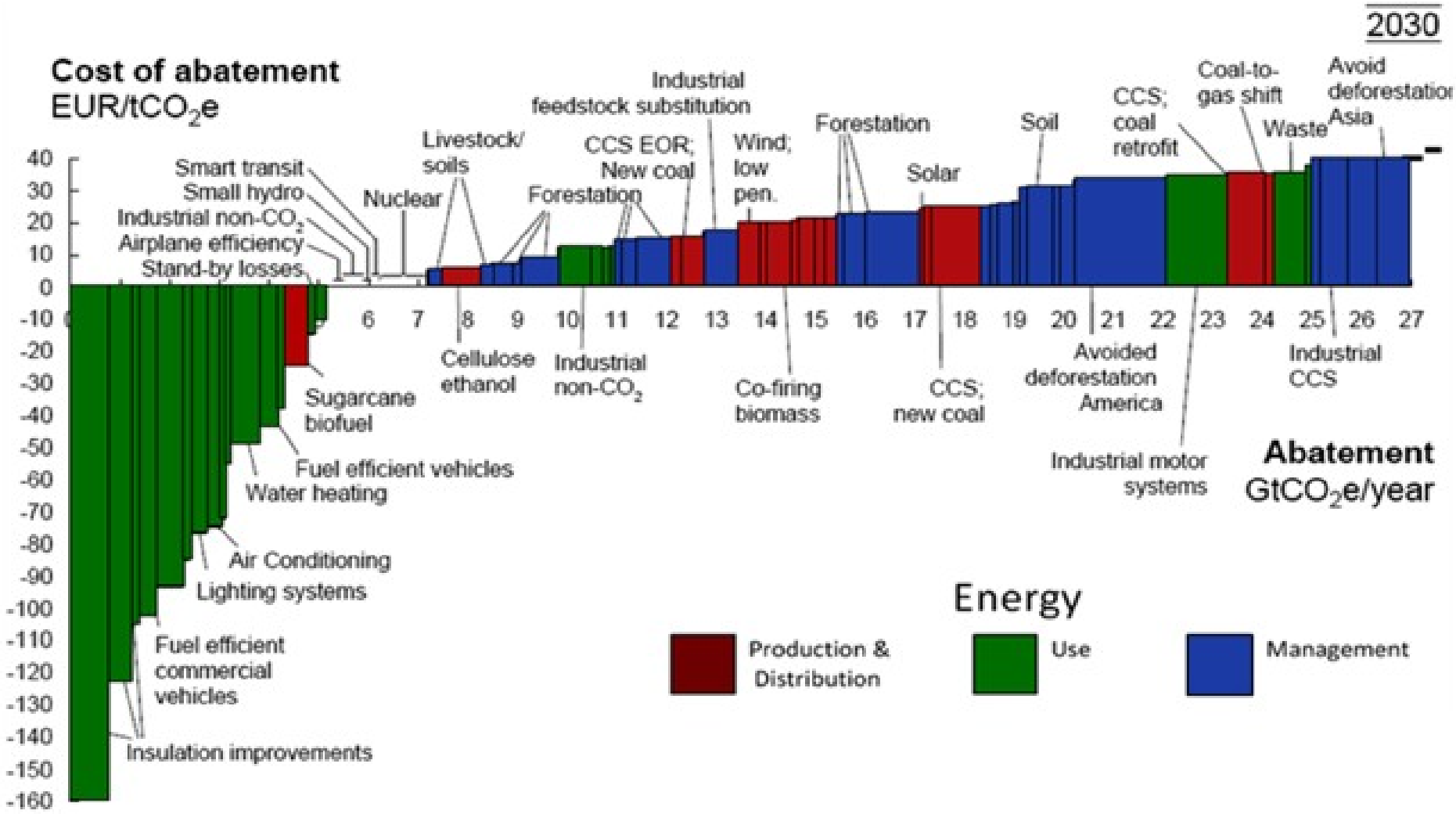
Faculty Scientist, Materials Sciences Division

Professor, Depts. Of Mechanical Engineering & Materials Science and Engineering, UC Berkeley


Supply
Transmission & Distribution
Demand
Hydro 2.71
Biomass 2.78
Geothermal 0.31
Wind 0.15
Solar 0.006
Nuclear 8.13
Coal 22.87
Domestic 19.06
Natural Gas 22.66
Net Imports 3.6
Domestic 16.13
Petroleum 40.13
Net Imports 24.0
Electricity Generation 38.0
Electricity Generation, Transmission & Distribution Losses 25.54
Distributed Electricity 12.46
Residential 11.60
Commercial 8.47
Industrial 24.33
Light-Duty Vehicles 17.01
Freight/Other 7.60
Aircraft 3.37
Lost Energy 55.1
Useful Energy 42.8
29.52
9.28
6.78
19.46
3.4
3.04
0.84
0.53
0.28
0.02
0.01
8.13
20.75
5.99
1.3
0.03
1.37
0.01
0.1
2.01
4.64
0.42
4.98
1.54
4.32
0.12
3.15
0.77
3.47
7.94
9.53
0.34
16.67
0.61
6.96
3.37

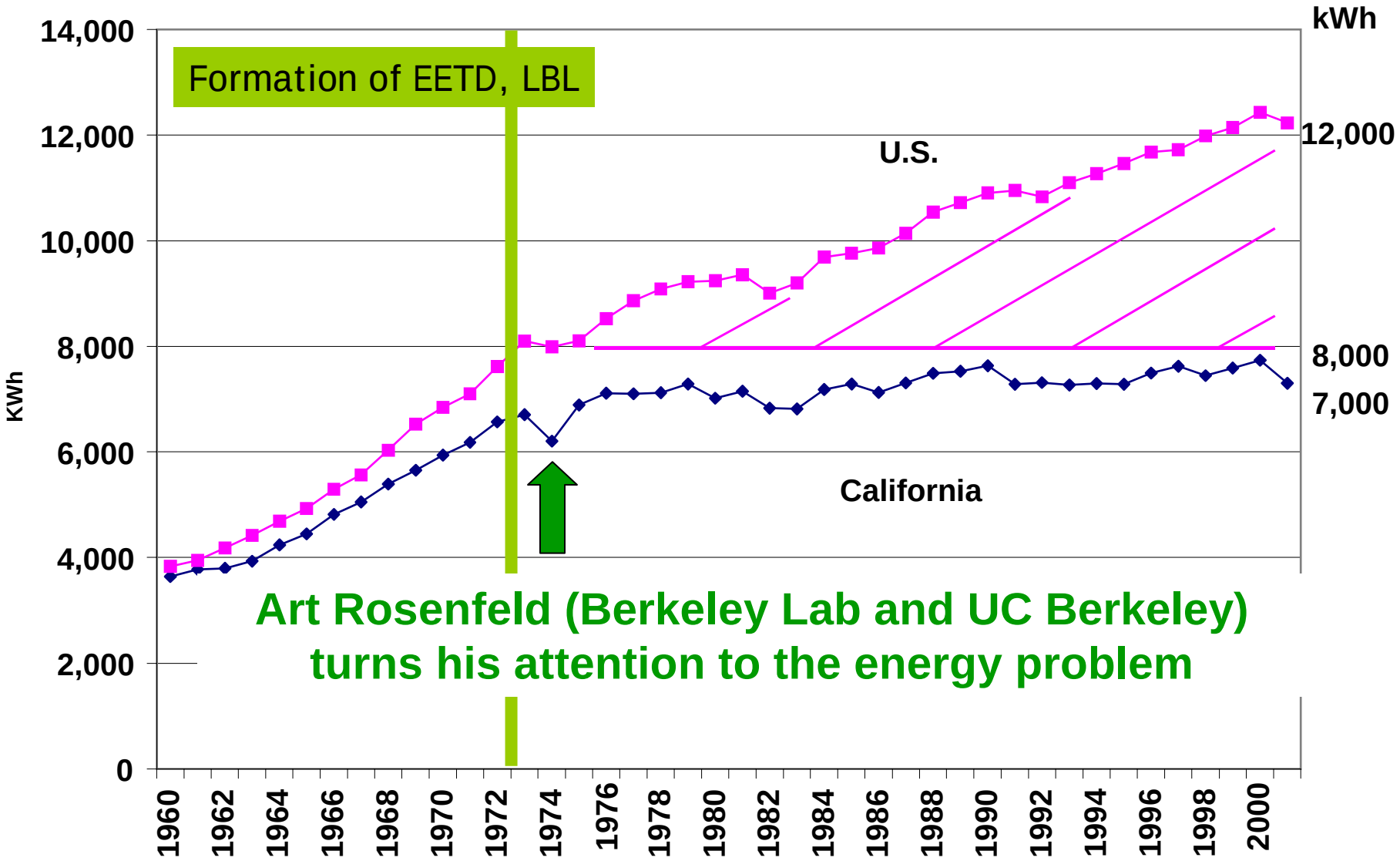
Our View: Energy Sectors

Production, Distribution, Use



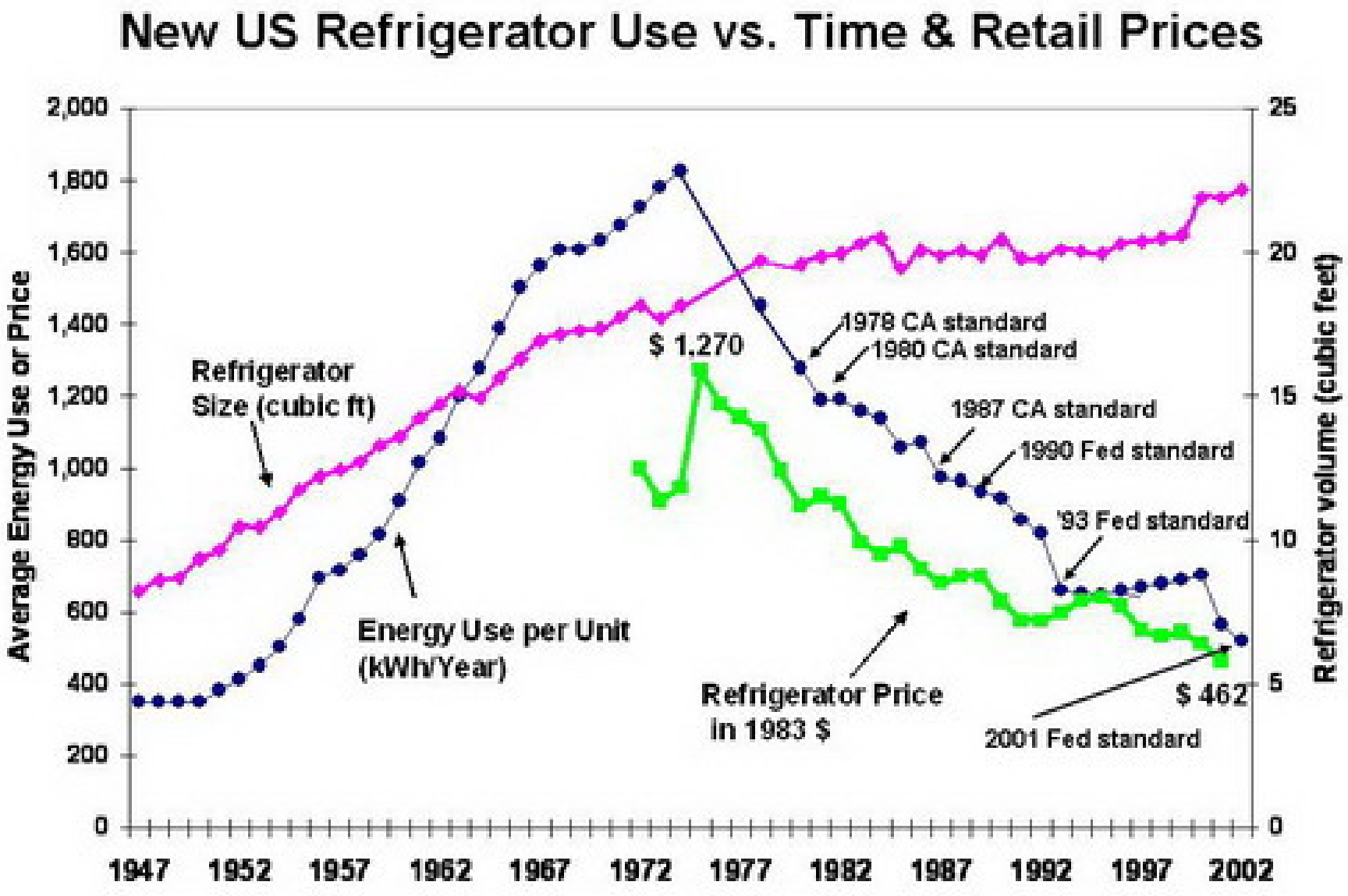
Courtesy: John Zysman, UCB

Per Capita Electricity in the U.S. and California (1960-2001)



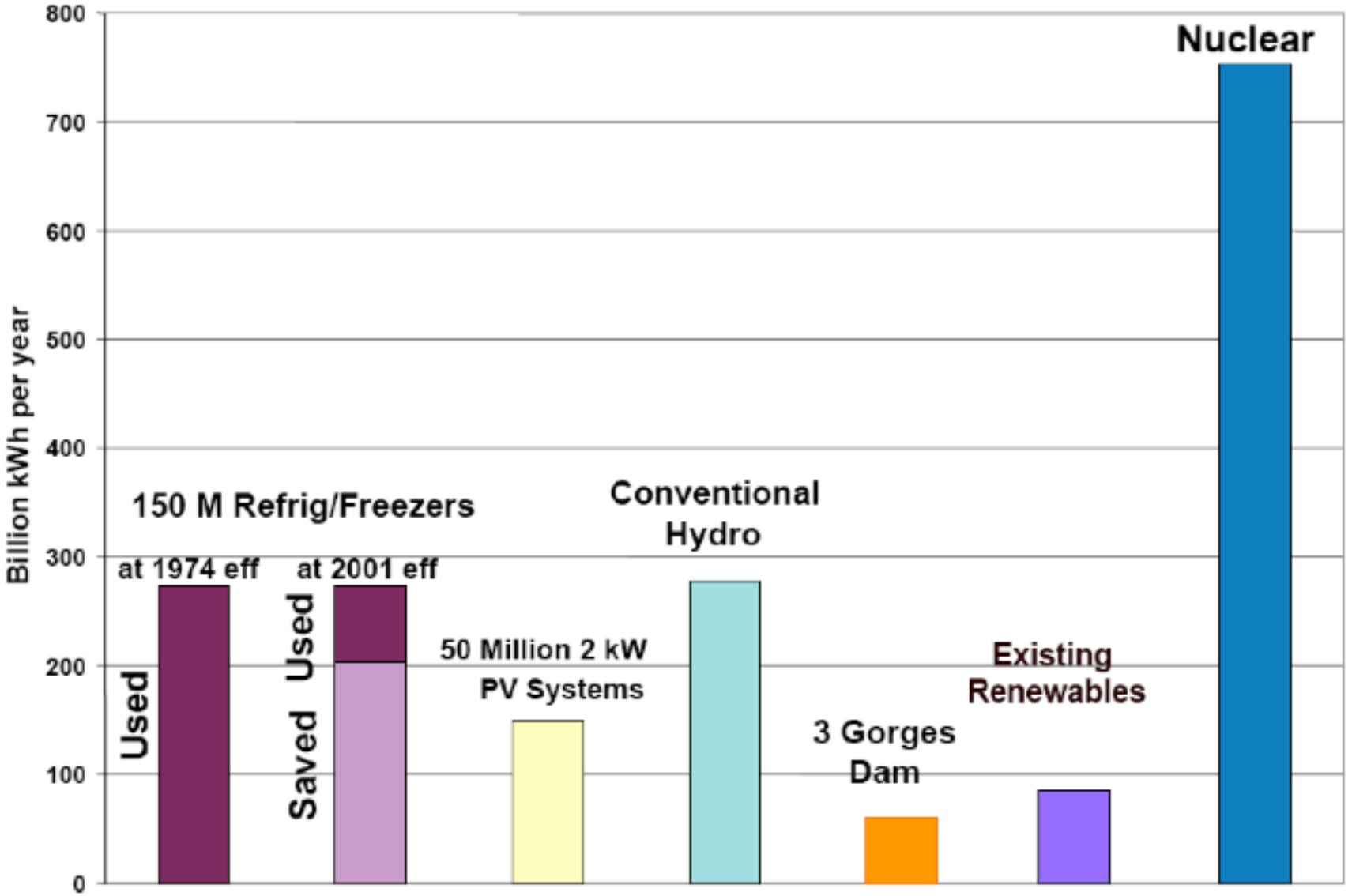
Art Rosenfeld (Berkeley Lab and UC Berkeley) turns his attention to the energy problem

U.S. Refrigerator Energy Use vs. Time



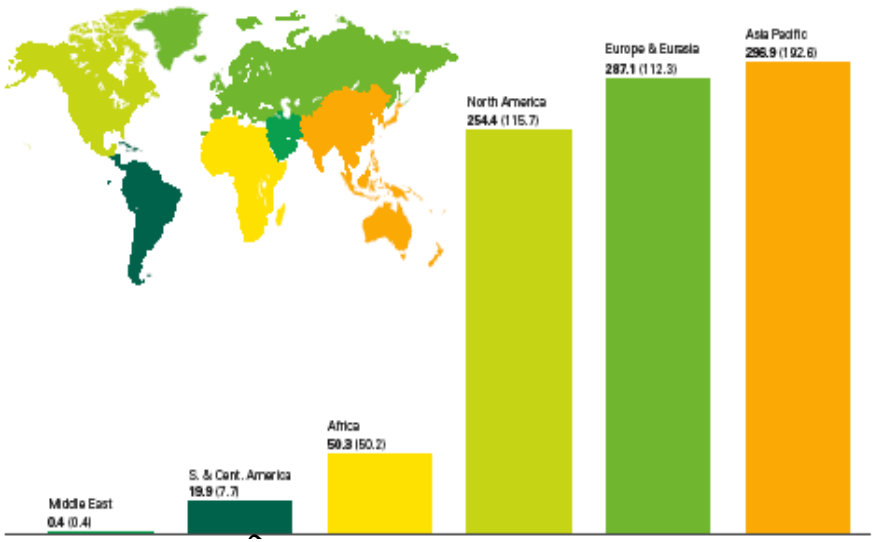
Source: David Goldstein

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

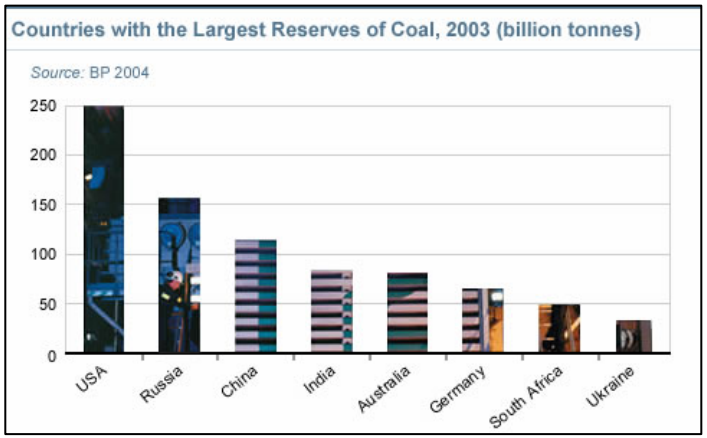


Global Fuel Reserves

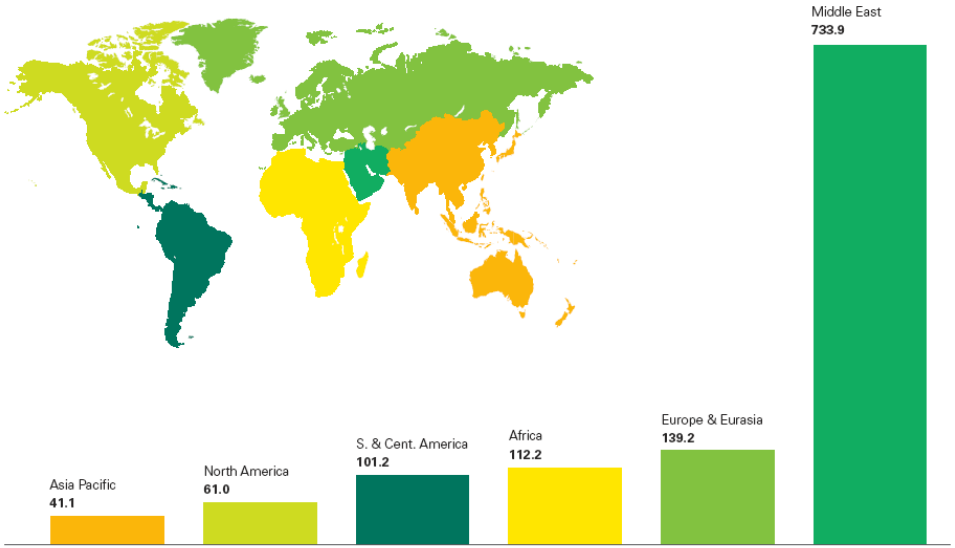
Coal Reserves



M. East
S. & C. America
Africa
N.America
Europe & Eurasia
Asia



Oil Reserves



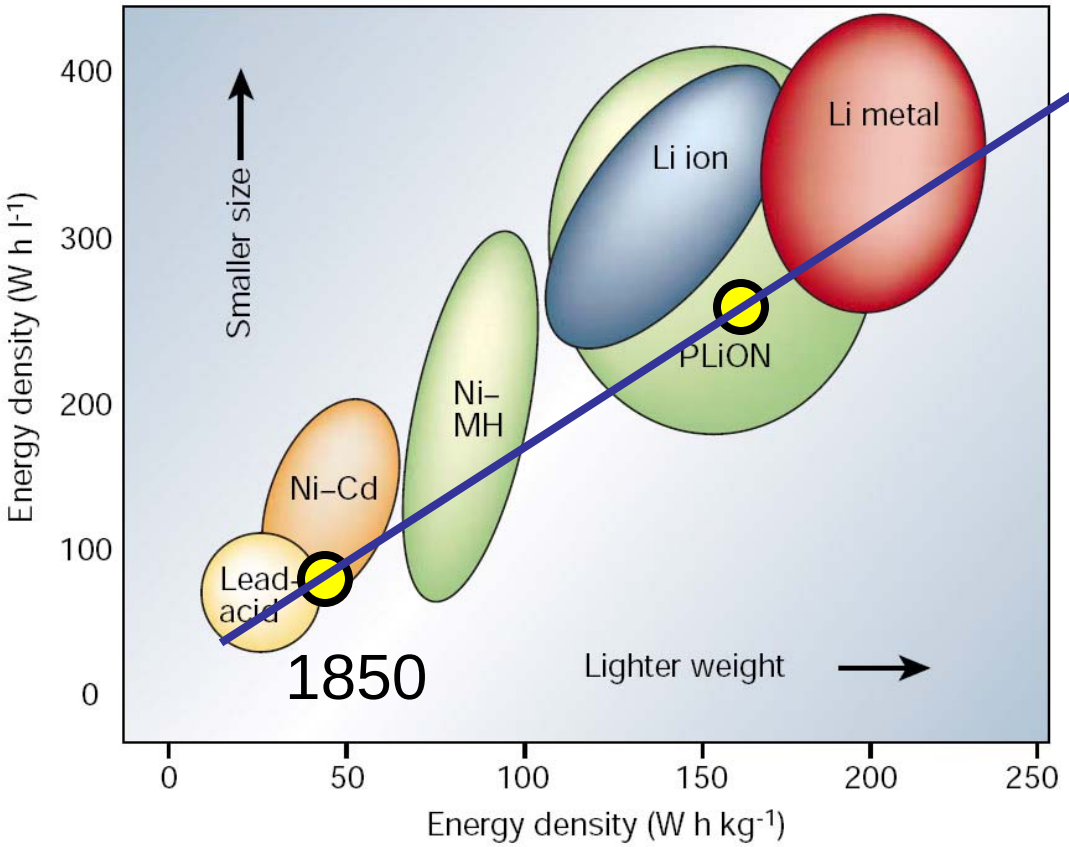
Asia
N.America
S. & C. America
Africa
Europe & Eurasia
M. East

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)

Energy storage capacity

Technology licensed to Seeo, Inc., a start-up.



Our objective:
300 Wh/kg (2009)

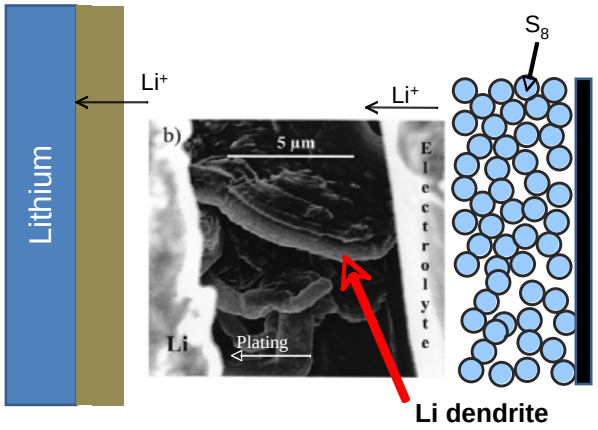
2007

Doubling energy storage capacity typically takes 60 years!

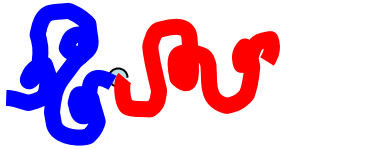
Tarascon, J.-M.; Armand, M.
Nature **2001**, *414*, 359

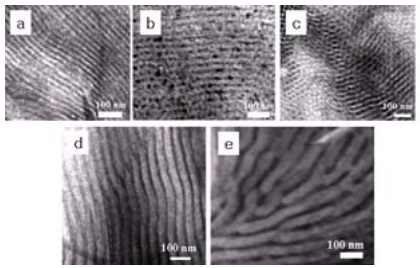
Courtesy: Nitash Balsara (LBL)

Batteries for Advanced Transportation Applications (BATT)

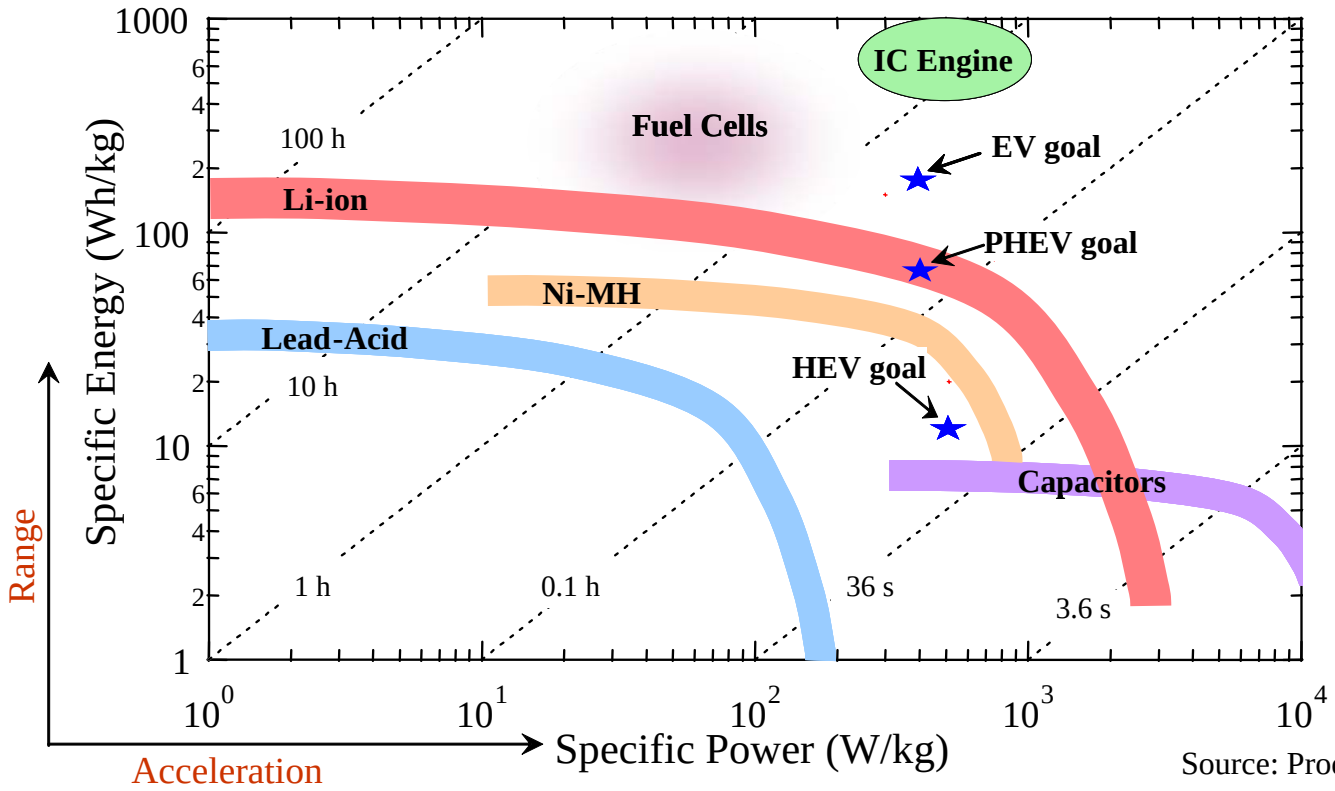


Block Co-Polymer
(PEO-Polystyrene)





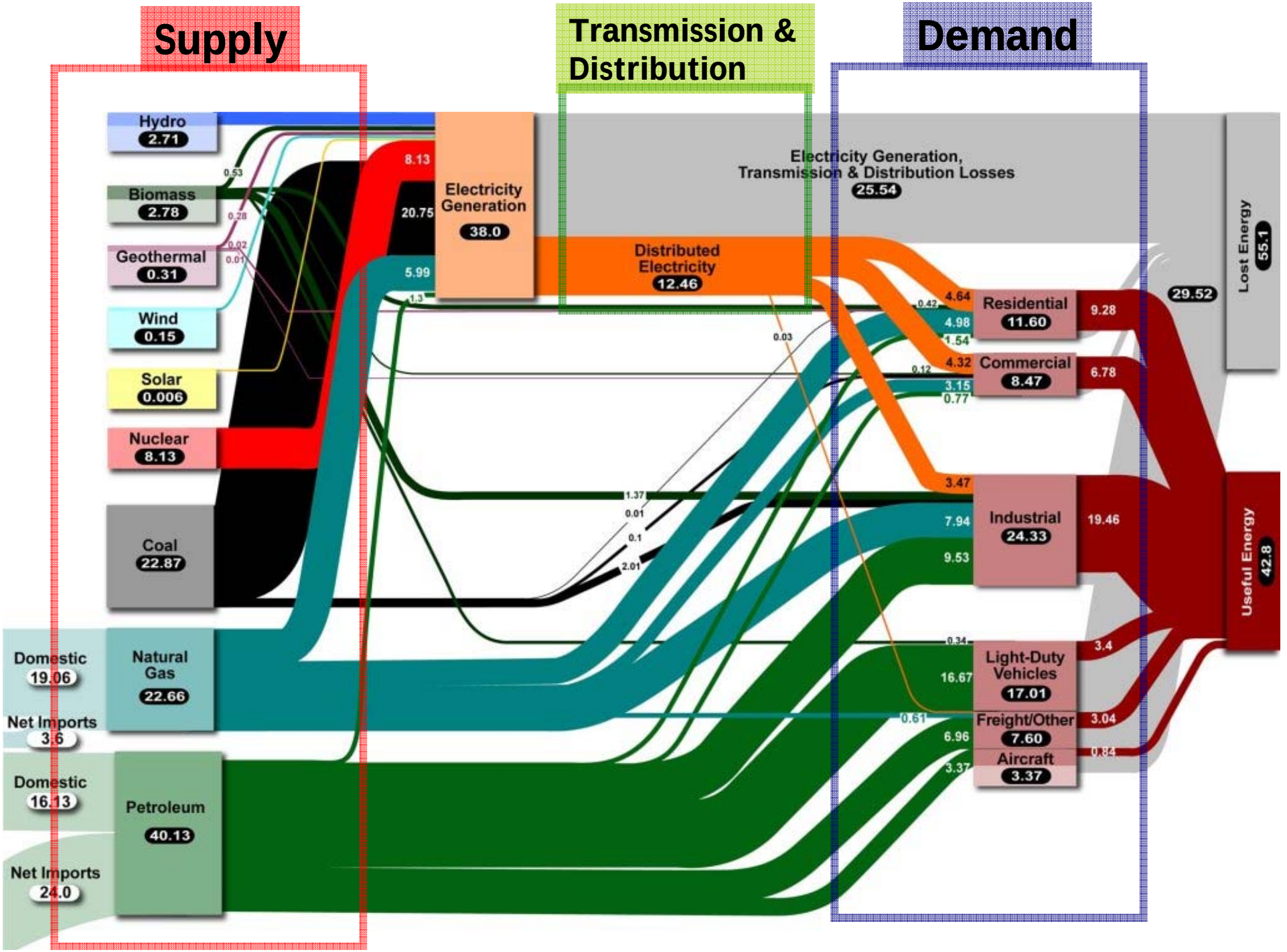
Balsara et al…



Source: Product data sheets

Game Changers in Transportation

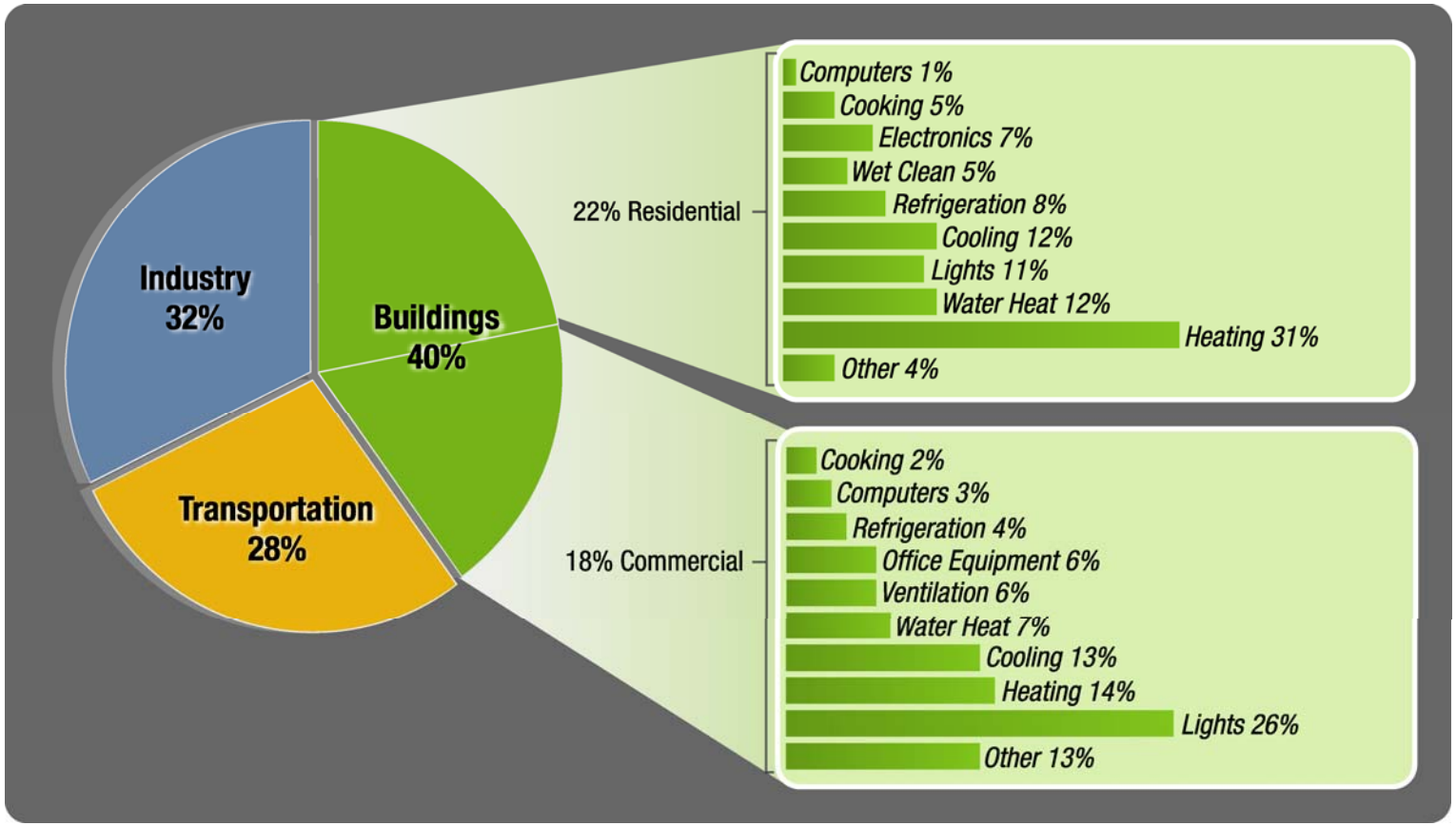
- **Electricity Storage Systems**
  - Energy Density - 300 Wh/kg
  - Power Density - 600 W/kg
  - Fast Charge/Discharge
  - Multiple deep discharge
  - Safe
  - Low cost
- **Composite Materials**
  - Light weight
  - Low cost
  - High strength
  - High toughness
- **System Integration**
  - Intra-Vehicle
  - Inter-Vehicle


Supply
Transmission & Distribution
Demand
Hydro 2.71
Biomass 2.78
Geothermal 0.31
Wind 0.15
Solar 0.006
Nuclear 8.13
Coal 22.87
Domestic 19.06
Natural Gas 22.66
Net Imports 3.6
Domestic 16.13
Petroleum 40.13
Net Imports 24.0
Electricity Generation 38.0
Electricity Generation, Transmission & Distribution Losses 25.54
Distributed Electricity 12.46
Residential 11.60
Commercial 8.47
Industrial 24.33
Light-Duty Vehicles 17.01
Freight/Other 7.60
Aircraft 3.37
Lost Energy 55.1
Useful Energy 42.8
29.52
9.28
6.78
19.46
3.4
3.04
0.84
0.53
0.28
0.02
0.01
8.13
20.75
5.99
1.3
0.03
4.64
0.42
4.98
1.54
4.32
0.12
3.15
0.77
3.47
1.37
0.01
0.1
2.01
7.94
9.53
0.34
16.67
0.61
6.96
3.37

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*

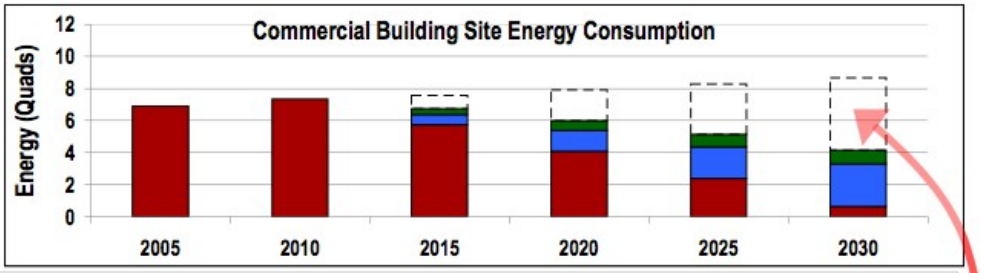
Goals

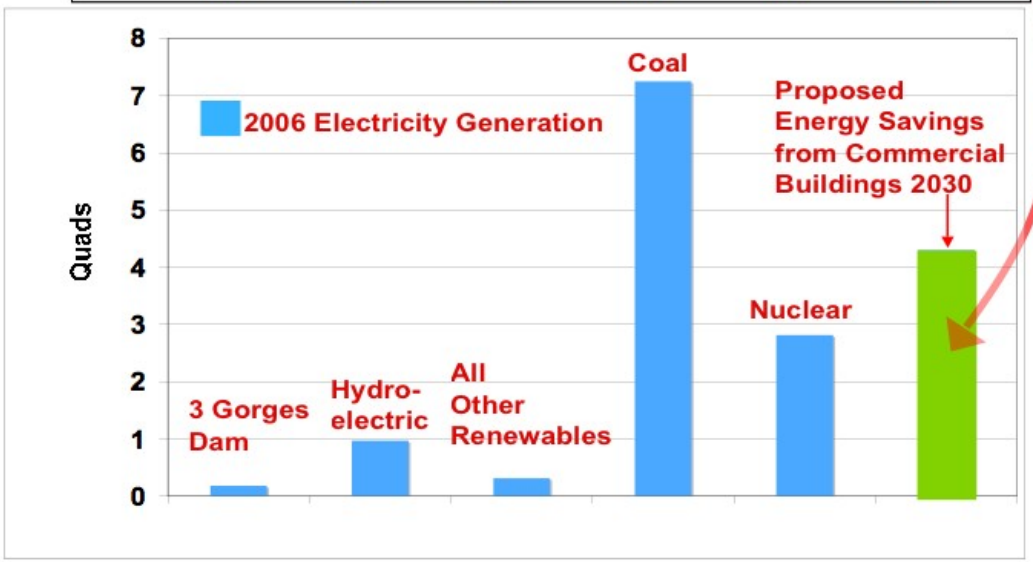
By 2030

– Reduce energy consumption

- 80% in new buildings (Zero Net Energy Buildings)
- >50% in existing buildings

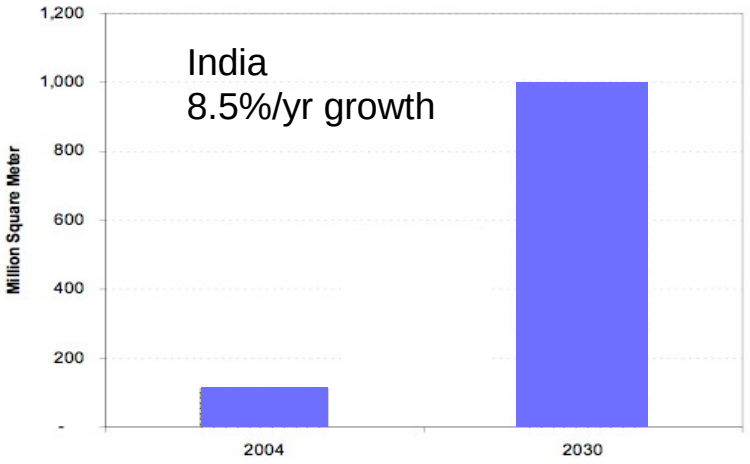
– Enhance health, comfort, safety/security





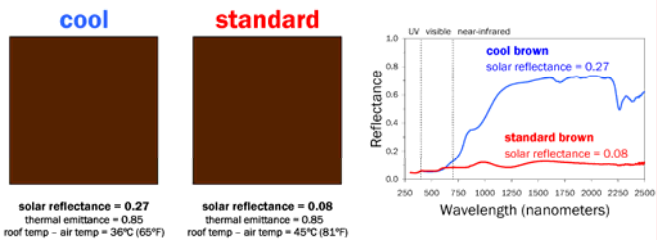
China

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.



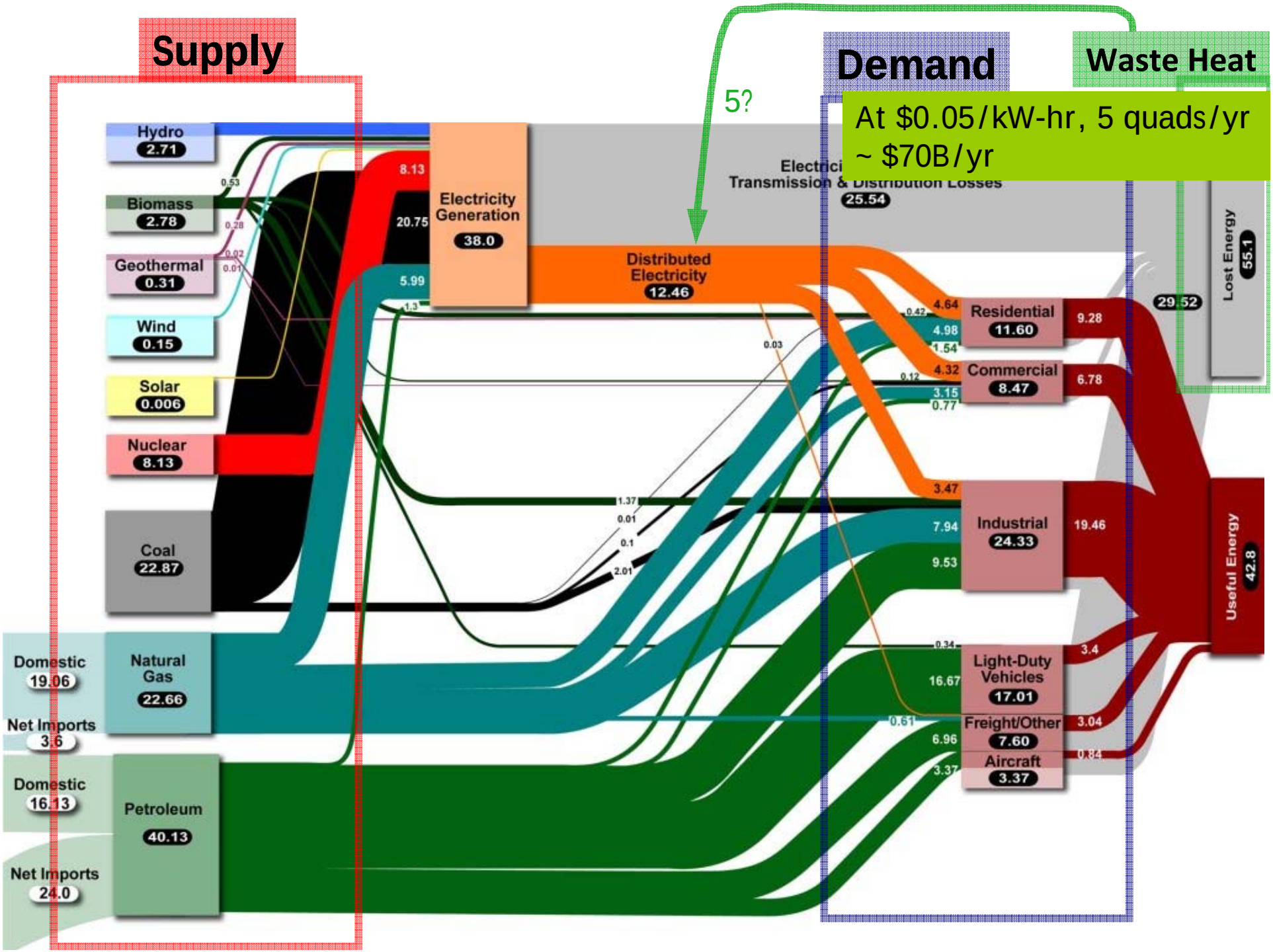
Game Changing Innovations in Buildings Industry

- **Science and Engineering**
  - Continuous Visualization, Monitoring, Reporting and Diagnostics (Self Tuning Buildings)
  - Building Design and Operating Platform
    - **Design:** Virtual Building (e.g. Boeing 787)
    - **Operation**: How can we get sub-systems to cooperate to minimize energy consumption
      - Communication, control, computation
  - **Components:** Solid-State Heating/Cooling; Thermal Storage in Building Walls; Electrical Storage; Coatings



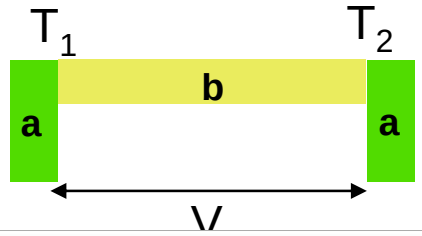
- **Innovations in Policy**
  - Building standards based on measured performance, NOT designed performance
  - Financial incentives and disincentives (carrots and sticks) for energy savings with respect to standards that can be shared by designer, builder and user (split incentive problem)

- **Demonstrations and Technology Test Beds**
  - Reconfigurable building
  - Energy consumption of federal, state and university buildings on Google maps

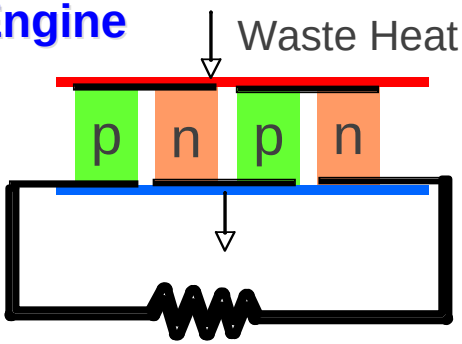

Supply
Demand
Waste Heat
5?
At $0.05/kW-hr, 5 quads/yr
~ $70B/yr
Hydro 2.71
Biomass 2.78
Geothermal 0.31
Wind 0.15
Solar 0.006
Nuclear 8.13
Coal 22.87
Domestic 19.06
Natural Gas 22.66
Net Imports 3.6
Domestic 16.13
Petroleum 40.13
Net Imports 24.0
Electricity Generation 38.0
Transmission & Distribution Losses 25.54
Distributed Electricity 12.46
Residential 11.60
Commercial 8.47
Industrial 24.33
Light-Duty Vehicles 17.01
Freight/Other 7.60
Aircraft 3.37
Lost Energy 55.1
Useful Energy 42.8
29.52
9.28
6.78
19.46
3.4
3.04
0.84
8.13
20.75
5.99
1.3
0.53
0.28
0.02
0.01
0.03
4.64
0.42
4.98
1.54
4.32
0.12
3.15
0.77
3.47
1.37
0.01
0.1
2.01
7.94
9.53
0.34
16.67
0.61
6.96
3.37

Thermoelectricity & Energy Conversion

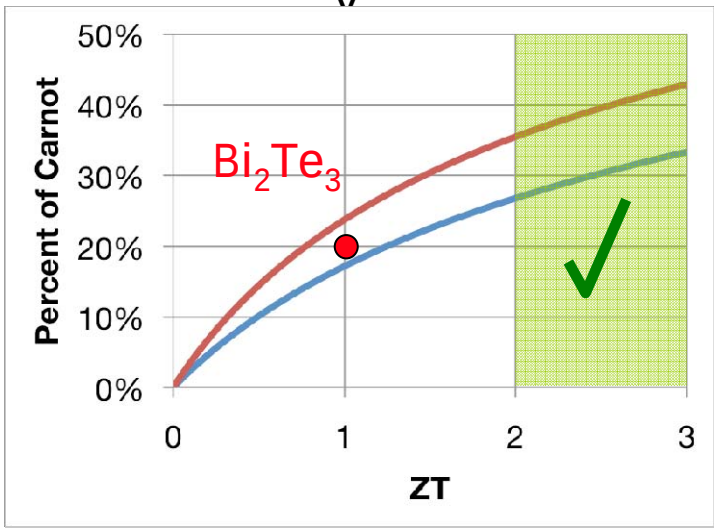
Seebeck Coefficient, S = V/ΔT



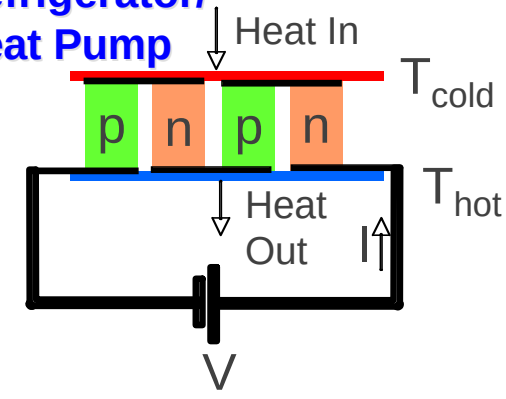
Engine

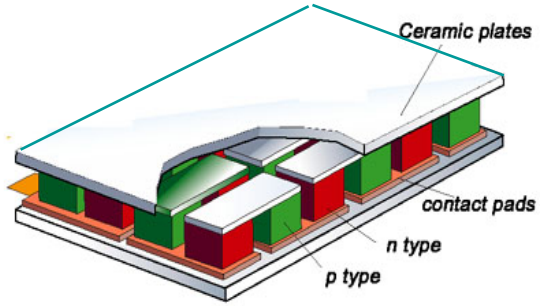


$$ZT = \frac{S^2 \sigma T}{k}$$



Refrigerator/ Heat Pump

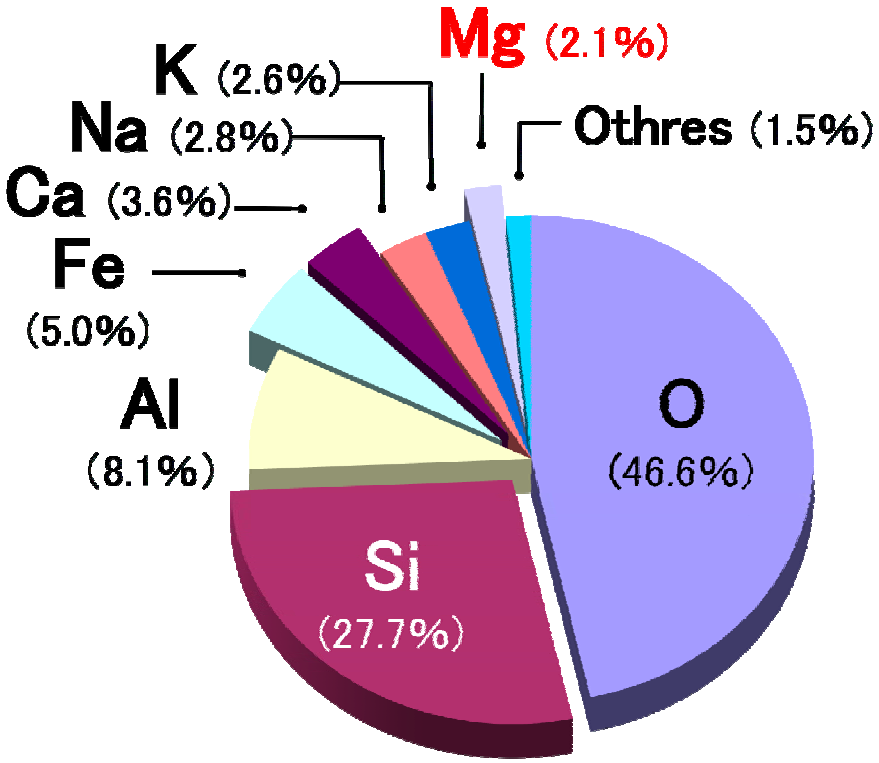




Bismuth Telluride

(low efficiency, expensive)

Abundance of Elements in Earth Crust



Bi_2Te_3
Current state-of-the-art
Bi ~ $5/lb, Te ~ $100/lb (First Solar demand explosion!)

Not enough tellurium in the earth's crust to recover a significant portion of waste heat worldwide or wide scale refrigeration

Limited efficiency above 100° C

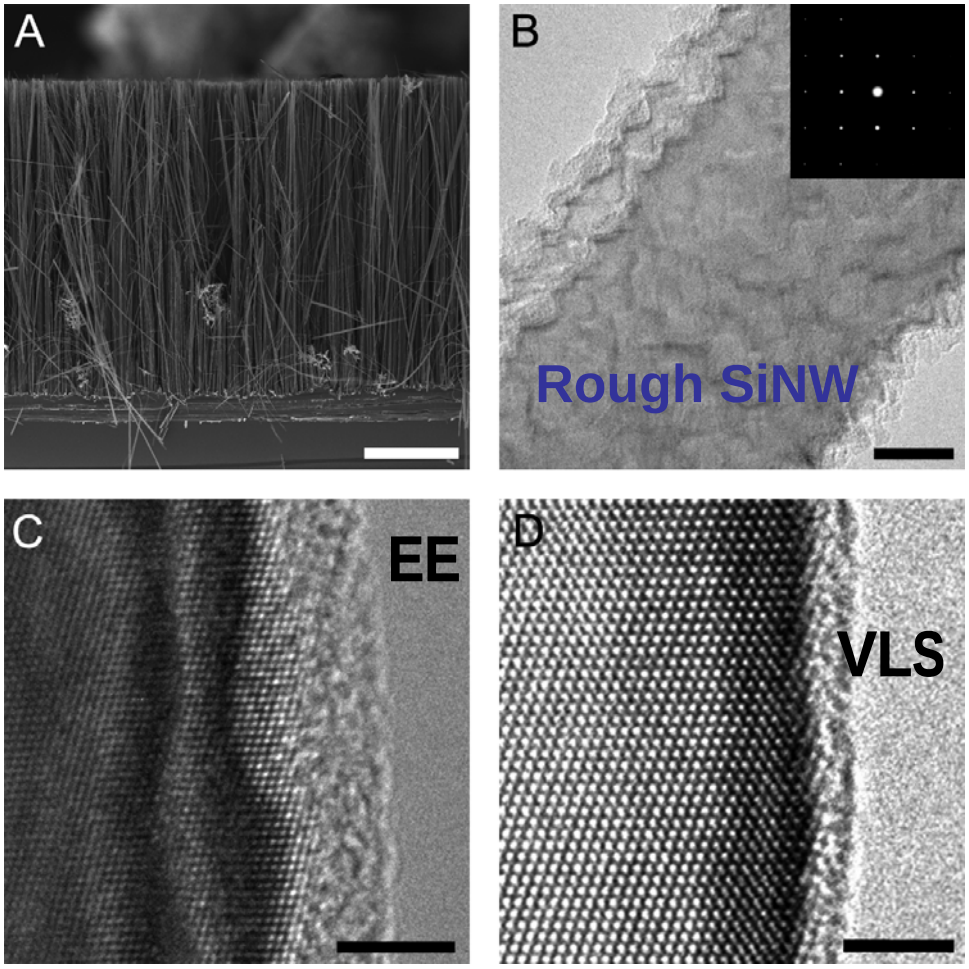
Electroless Etched Si Nanowires

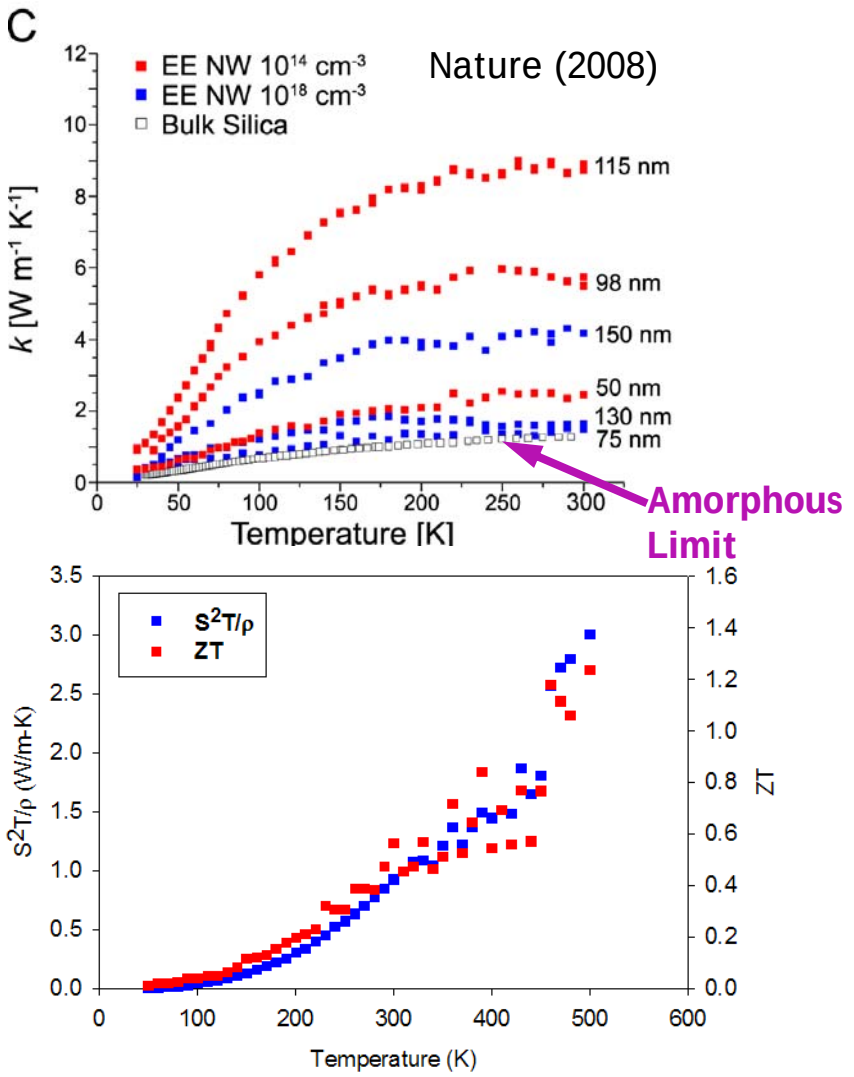
Wafer-Scale Wet Etching Process

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

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

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





Renkun Chen, Kedar Hipalgaonkar (Majumdar Lab)

Allon Hochbaum, Sean Andrews (Yang Lab)

Few Other Game Changers

- Understanding photosynthesis and replicating in artificial systems (Helios - SERC)
- Cellulosic hydrocarbon biofuels (Helios - EBI/JBEI)
- Solar energy storage (Helios)
- Carbon-free cement production
- Energy-efficient and cost-effective CO_2 capture from concentrated sources - Clean coal
- High-temperature materials for gas turbines