Nano-Bio-Info Pathways to Extreme Efficiency

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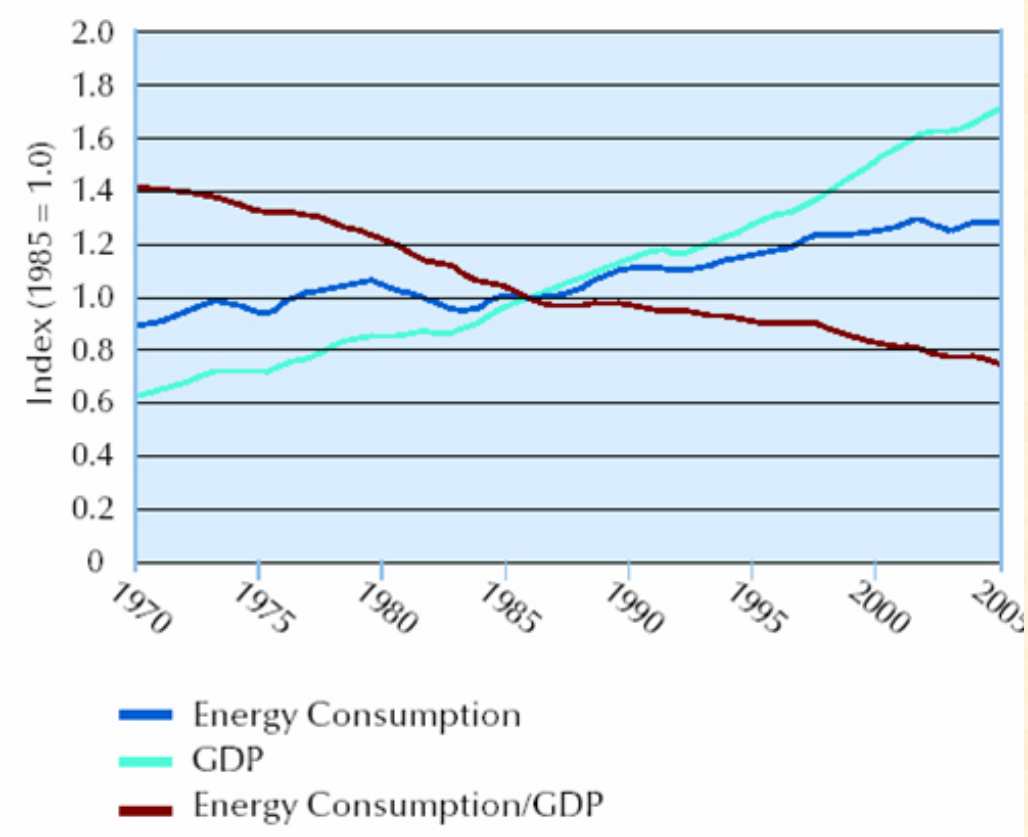
The Context

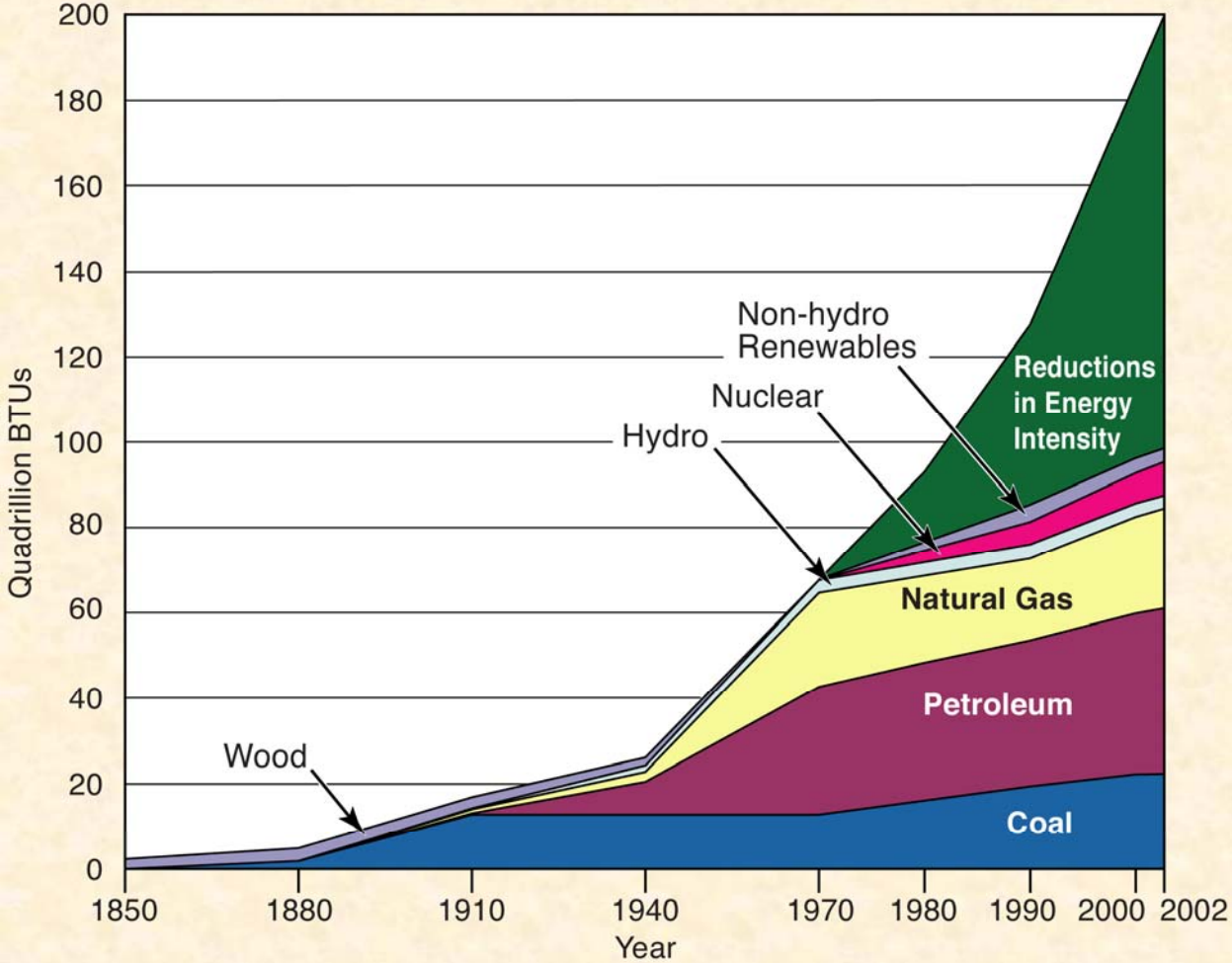
- **The United States and the World face enormous energy challenges**
- **Using energy more efficiently can help to address each of these**
  - **Allows energy resources to stretch further**
  - **Enhances energy security and reliability**
  - **Strengthens the economy**
  - **Protects global environment and public health**
- **The question is: How big a role can energy efficiency play?**

Energy intensity of the U.S. economy has declined significantly



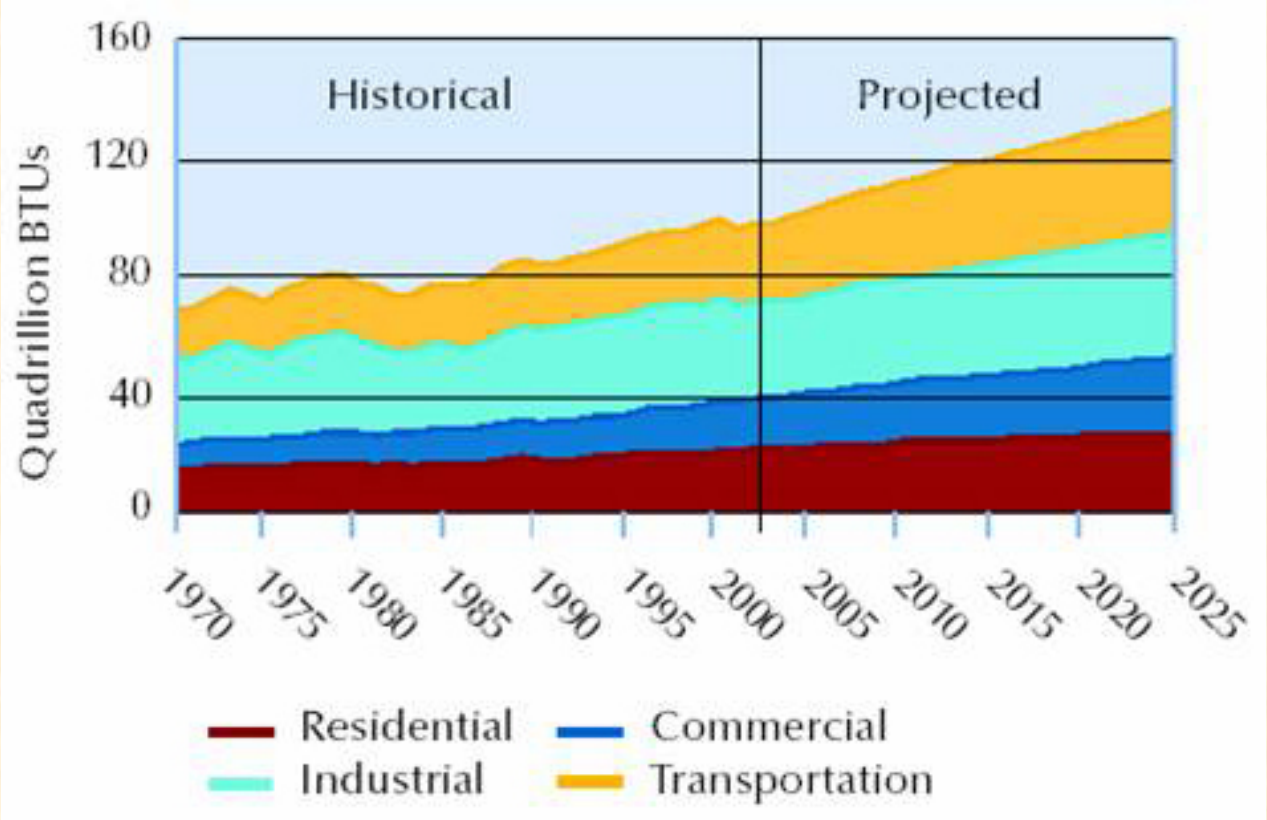
Source: Based on data from *EIA Annual Energy Review 2004*

Energy efficiency in the U.S. has played a significant role since 1970



Source: Based on data from *EIA Annual Energy Review 2003*, Table 1.3

Energy efficiency must help the U.S. meet its future needs



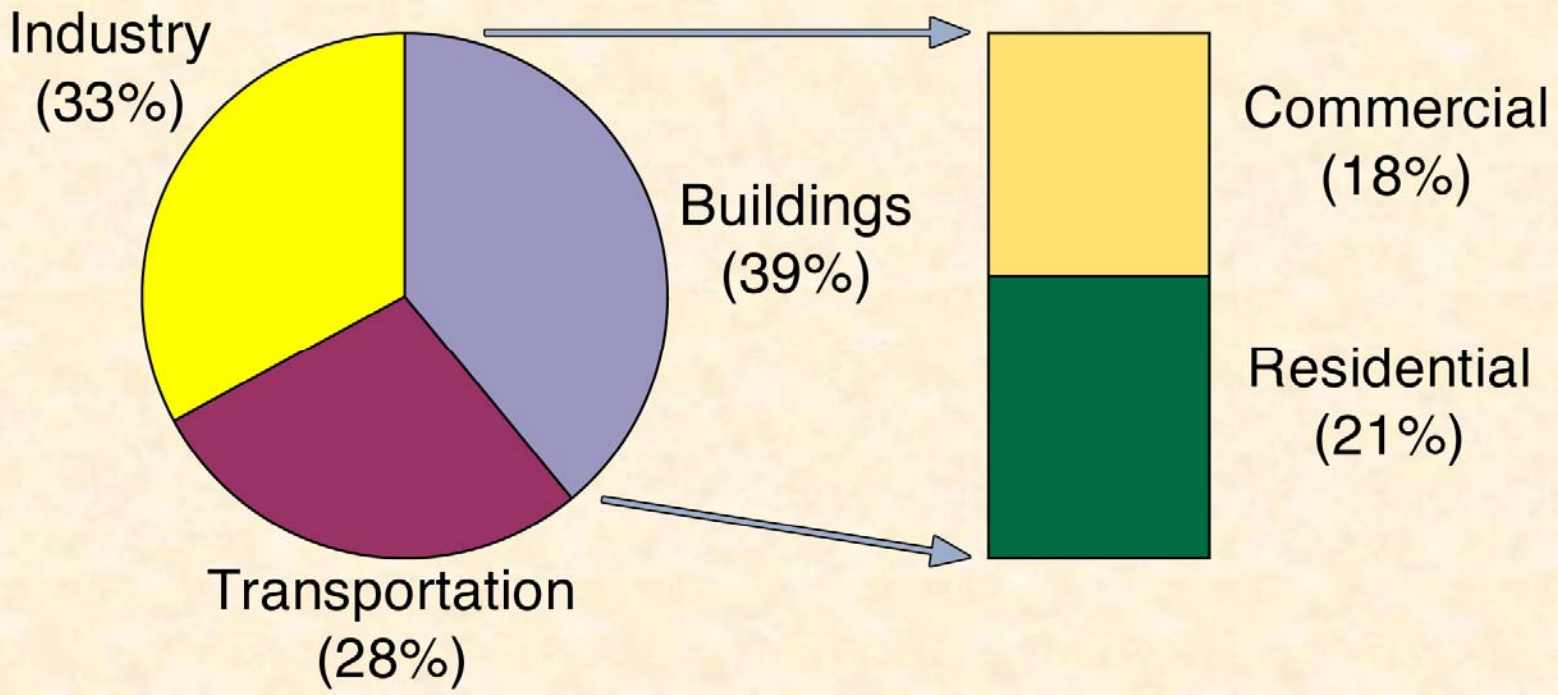
Assuming an annual growth rate of 1.5%:

~40% increase by 2025
~4.4X increase by 2100

With a 0.75% growth rate:

~16% increase by 2025
~2.1X increase by 2100

Energy efficiency improvements are needed in every sector



U.S. Energy Consumption by Sector: 2002

Source: EIA, *Annual Energy Outlook 2004,* Table A2

Is there any more low-hanging fruit?

- **Some energy modelers have concluded that efficiency gains are principally a short-term phenomenon.**
- **In the long run,**

  --renewables,

  --clean coal,

  --hydrogen,

  --gas hydrates, etc.

  are typically seen as the dominant pathway to meeting energy requirements while mitigating greenhouse gases and strengthening energy security.
- **In this context, several recent studies have examined the past role of energy efficiency and the potential for continued efficiency gains.**

U.S. energy models have historically underestimated energy efficiency

- **Five projections in early 1980s of U.S. energy forecasts, 1982-2000 were reviewed***
- **Energy demand median error for year 2000 was –5.2%**
- **Roughly the right energy quantities, but the wrong prices in the year 2000: Median error of +125% for industrial electricity, +197% for world oil price, and +324% for natural gas**
- **This suggests a serious underestimation of past technological change and energy efficiency improvements**

*Alan H. Sanstad, John A. "Skip" Laitner, and Jonathan G. Koomey, "Back To The Future: Long-Range U. S. Energy Price And Quantity Projections In Retrospect," forthcoming in *International Journal of Energy Technology Policy*.

Implementing current technology could reduce energy consumption significantly

- ***California's Secret Energy Surplus: The Potential for Energy Efficiency*** **by Michael Rufo and Fred Coito (2002) (www.Hewlett.org)**
  - **estimates that CA has an economic energy potential of:**

    13% of total base electricity usage in 2011

    15% of total base demand in 2011
- ***Natural Gas Price Effects of Energy Efficiency and Renewable Energy Practices and Policies*** **by Neal Elliott, et al., Am. Council for an Energy Efficient Economy (2003) (http://aceee.org)**
  - **by 2008 the U.S. could reduce:**

    electricity consumption by 3.2%

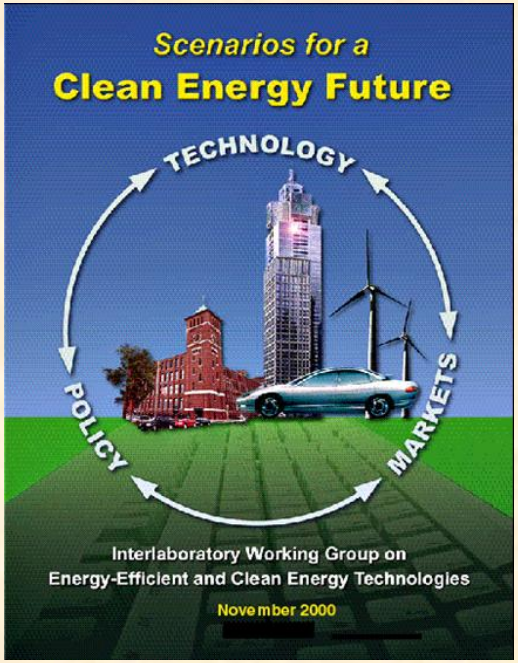
    natural gas consumption by 4.1%

Developing new technology could further reduce energy consumption

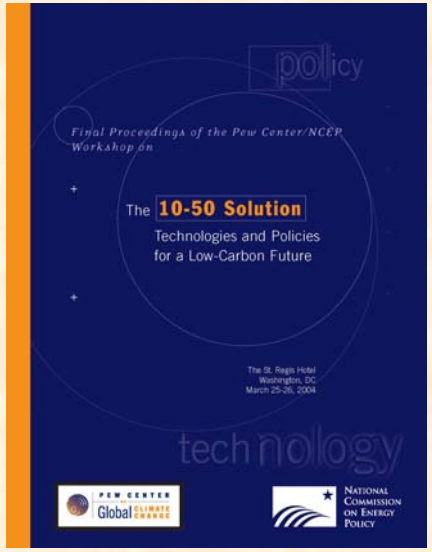
Technology Options for the Near and Long Term

(2003)

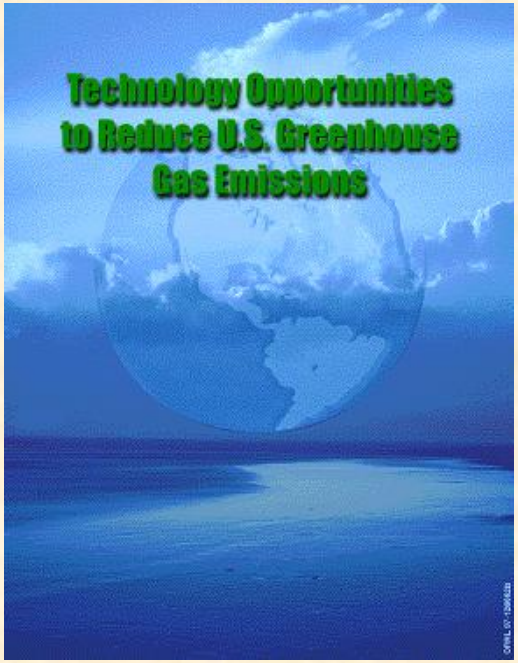
www.climatetechnology.gov



www.ornl.gov/eere/CEF/index.htm



www.pewclimate.org



www.ornl.gov/~webworks/cppr/y2003/rpt/110512.pdf

What is the potential for energy intensity reductions?

- **Lightfoot and Green* estimate a global maximum annual energy intensity decline attributable to energy efficiency of 0.8 - 0.9% through 2100**
  - Upper limits on attainable energy efficiency:
    - 72 mpg for cars and light trucks
    - 50% efficiency for combined heat & power
    - 230% residential energy efficiency increase
    - 120% chemical industry energy efficiency increase
- **Others suggest that energy intensity reductions of 2+% annually are possible, considering:**
  - Substitution to low-energy materials
  - Recycling of energy-intensive materials
  - Sophisticated and convenient mass transit
  - Higher vehicle occupancy
  - Sustainable land-use patterns with reduced distances traveled
  - Advanced energy-efficient technologies (nano-info-bio breakthroughs)

***Energy Intensity Decline Implications for Stabilization of Atmospheric CO2 Content,* ww.mcgill.ca/ccgcr/**

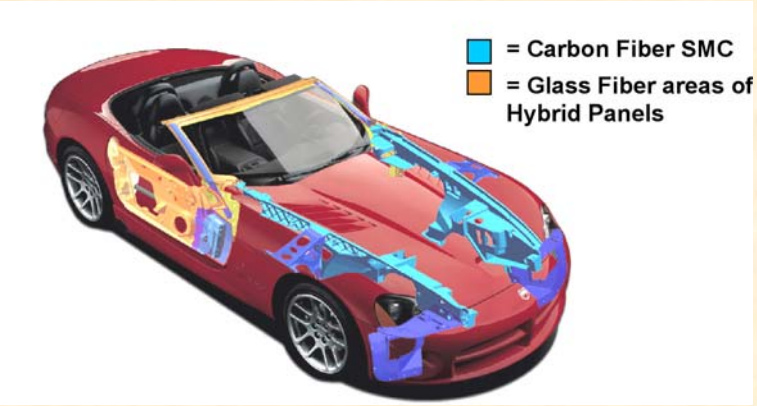
Nano-info-bio discoveries will lead to highly efficient technologies

- **Significant improvements are anticipated through:**
  - Super-strong lightweight materials
  - Energy-efficient distillation through supercomputing
  - Novel energy-efficient separations
  - Smart roofs
  - Super-durable materials for aggressive environments
  - Molecular-level control of catalytic materials
  - Self-optimizing sensor systems
  - Solid state lighting
  - Genomics for bioenergy: tailoring plants and microbes
  - Superconducting electric T&D

Nano/bio/info discoveries will have broad impact in daily life.

Super-strong lightweight materials

- **Nano structures and phases enable new properties at the macroscale:**
  - Enhanced mechanical strength
  - Improved high temperature tolerance
- **Lighter, stronger components for transportation:**
  - Magnesium alloys and carbon fiber polymer matrix composites offer the potential for mass reductions of >50% wrt steel
  - Nano structures can improve properties of Mg alloys
  - Incorporation of dispersed nano-sized particles has potential to dramatically increase mechanical properties of composites



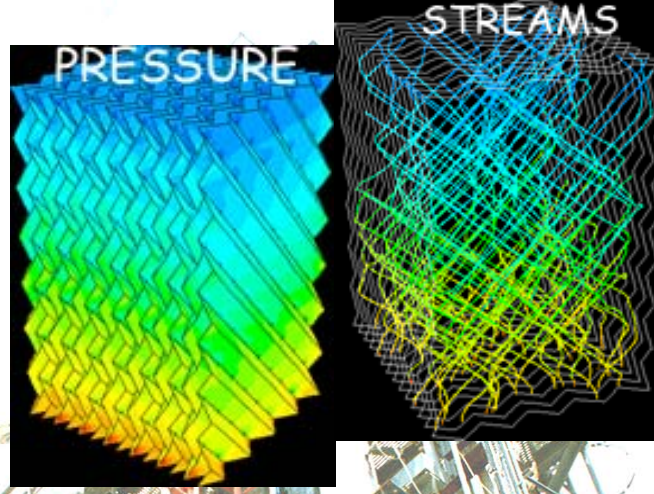
Lightweight composite materials:
Now in several production vehicles

- **Potential Opportunities and Annual Energy Savings:**
  - A 50% wt reduction in the light duty fleet would have saved 3.32 million barrels of oil per day in 2002.

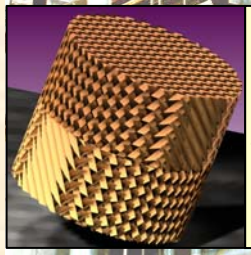
Sources: FreedomCAR Materials Roadmap (2004), Transportation Energy Databook (2004)

Energy-efficient distillation through supercomputing

- **Advanced modeling and simulation of complex industrial processes can lead to significantly improved design and operation**
- **Modeling of counterflows through structured packings can improve distillation hydrodynamics**
  - Empirically characterizing the hydrodynamics of a packing element requires a high-end supercomputing cluster capability
  - Terascale computers will be needed to perform an integrated hydrodynamic calculation for an entire distillation column
- **Potential Opportunities and Annual Energy Savings:**
  - Distillation accounts for ~3 quads of energy usage annually, about half in petroleum refineries
  - 10-20% reductions are possible with improved geometries of packing elements
  - Comparable savings possible through steam system engineering



Swirl motion in channels



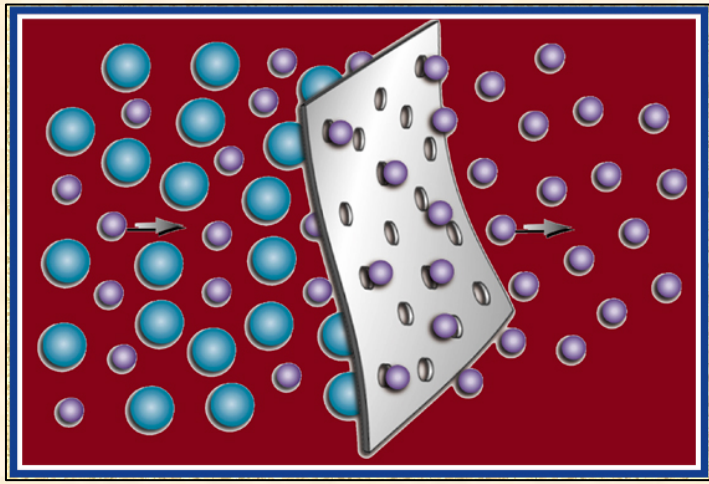
GraSPI is a computational tool developed by ORNL with US industry participation for designing packing elements used in distillation columns

Source: http://distillation.ornl.gov

Novel energy-efficient membrane separations

- **Nanoporous materials allow selective, molecular-scale separations at high throughput**
- **Further advancement requires:**
  - Improved understanding of transport mechanisms at the nanoscale
  - Advances in nanomanufacturing to fabricate media with engineered pore sizes and desired functionality
- **Potential Opportunities and Annual Energy Savings:**
  - ~8 quads are used in industry for separation processes.
  - Using less energy-intensive methods – membrane separation or adsorption – could result in substantial future energy savings:
    - Chemicals: ~0.32 quads
    - Wastewater: ~0.23 quads
    - Food and beverages: ~0.17 quads
    - Black liquor concentration: ~0.11 quads
    - Petroleum H_2 recovery from mixed gases: ~0.01 quads

Nanoporous alumina membrane



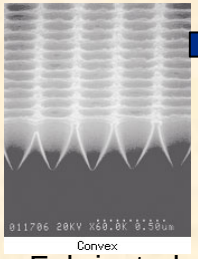
Molecular sieve membrane for separating gas molecules

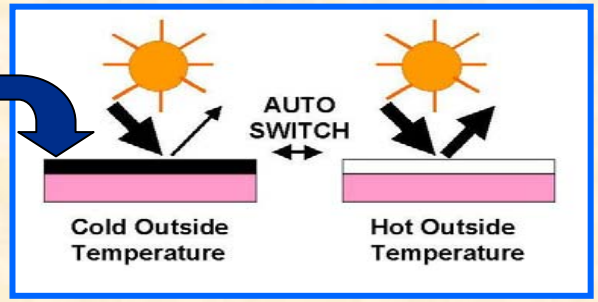
Sources: Materials for Separation Technologies (2004); Price et al. (2004)

Smart roofs

- **Nano technologies can change the reflectance of roof materials as a function of temperature**
- **The key: combine sub-wavelength optical structures and temperature-sensitive polymers to provide high reflectance to IR solar radiation in summer and low reflectance in winter**
- **The design mimics the structure of a moth's eye**
- **Potential Opportunities and Annual Energy Savings:**
  - Low-slope roofs with a reflectivity of 85% above 65ºF and 5% below 65ºF could save 1.2 quads

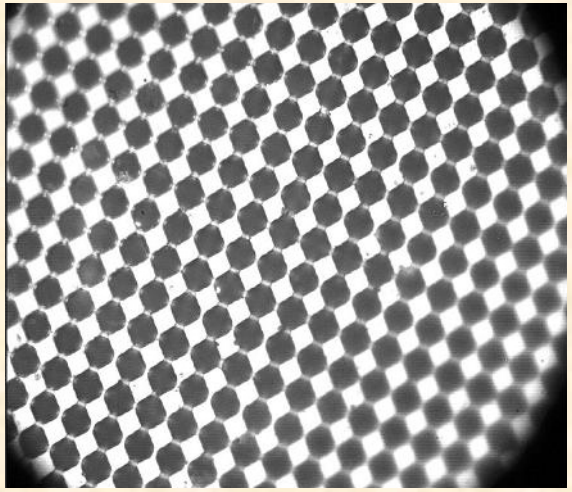
Moth Eye
Nano-Structure





Fabricated on
Si wafer

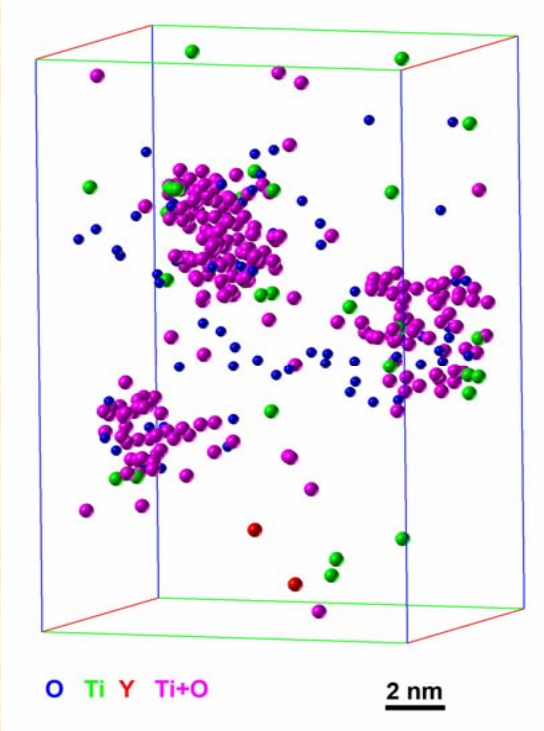
Periodic array of holes etched in a thin film of silicon on a barium fluoride substrate.



Source: Hadley et al., 2004.

Super-durable materials for aggressive environments

- **Nano structures and phases enable new properties at the macroscale:**
  - Enhanced mechanical strength
  - Improved high temperature tolerance
- **Result: higher temperature, stronger and more degradation resistant materials for industrial processes**
- **Potential Opportunities and Annual Energy Savings:**
  - Alloys for rolls, trays, fixtures in steel, heat treating industries: 5–20% energy savings
  - New high-temperature, crack-resistant alloys for boiler tubes: 5–10% energy savings
  - A 10% impact on industrial boilers, chemical reaction vessels, and furnaces can lead to energy savings of ~1 quad.

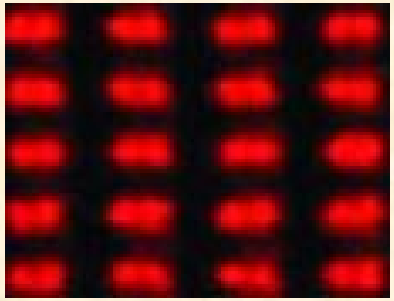


Nano structures of ~5 nm present in Iron based Cr, W, Ti alloy result in 150 C higher temperature capability (Source: Hoelzer, Miller, Maziasz, Fong)

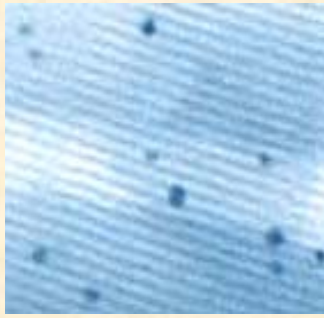
Molecular-level control of catalytic materials

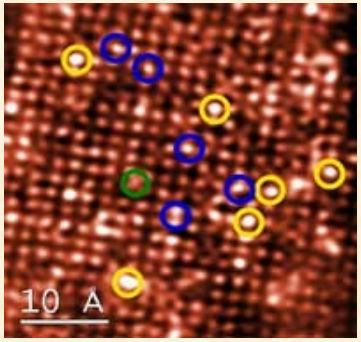
- **Catalysis – involving molecular-scale structures that drive chemical conversions – may be the most successful and broadly applied nanotechnology**
- **Continued scientific and technological developments needed:**
  - characterization tools
  - theory, modeling and simulation
  - synthesis techniques

  These will lead to unprecedented tailoring of catalysts and large increases in activity and selectivity
- **Potential Opportunities and Annual Energy Savings:**
  - Increased efficiency of existing catalytic processes (0.08 - 0.23 quads)
  - Less waste from byproduct formation
  - Reduced use of precious metal catalysts
  - Catalysts for highly selective conversion will enable entirely new processes



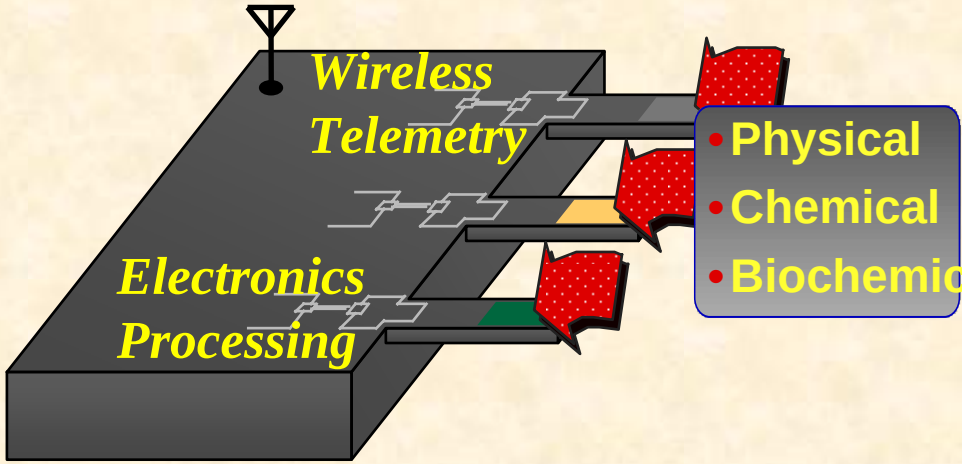
Emerging capabilities exist to image individual atoms and characterize catalytic centers



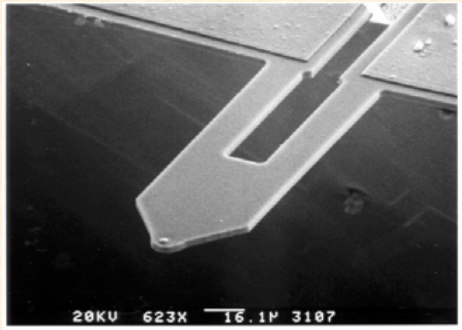


Self-optimizing sensor systems

- **Micro-sensors that flow through the process or become part of the product**
- **Optical sensor arrays selectively coated for phys/bio/chem sensing**
- **Intelligence distributed to the sensor with wireless telemetry**
- **Adaptive, flexible control and optimization**
- **Ultra-low power electronics**



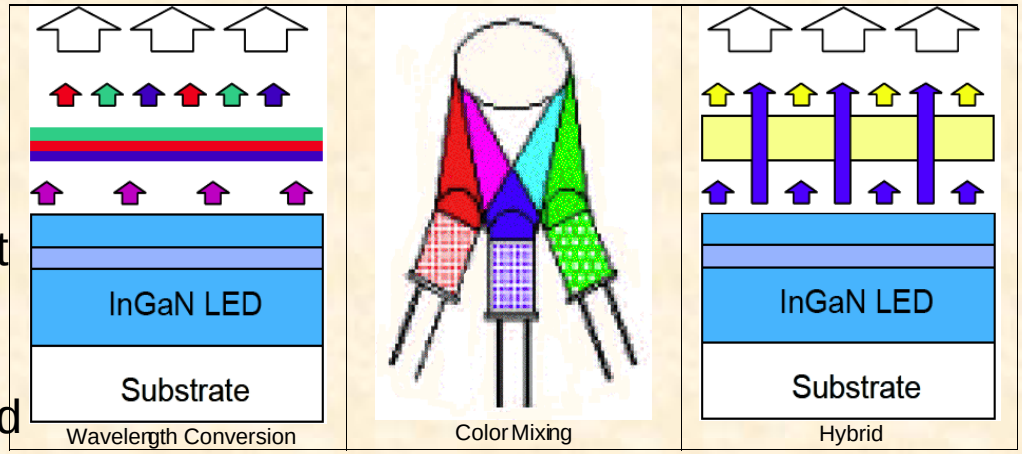
- **Potential Opportunities and Annual Energy Savings:**
  - Small motors: ~0.3 quads
  - Industrial buildings EMS: ~0.75 quads
  - Industrial energy systems:
    - Petroleum refining ~0.1 quad
    - Chemicals ~0.13 quad
    - Forest products ~0.15 quad
    - Food & beverage ~0.05 quad
  - Manufacturing: ~0.65 quad



Solid state lighting (SSL)

- **SSL uses the emissions of semi-conductor diodes to directly produce light**
- **A key difficulty that LED lighting faces is that it is inherently monochromatic. Several methods are being researched to produce white light**

- **Potential Opportunities and Annual Energy Savings:**
  - LEDs and OLEDs have the potential to replace incandescent and fluorescent lighting in a broad variety of end-uses
  - 3.5 quads/y in 2025 (one-third of reference energy use for lighting could be saved under an accelerated R&D scenario)

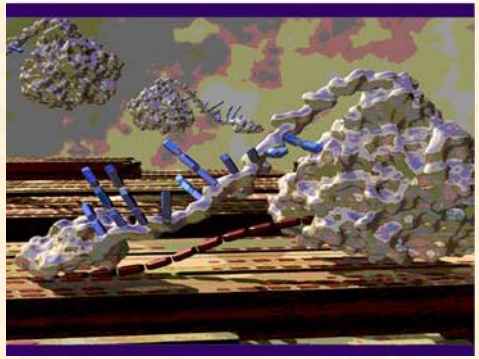


Three methods to produce white light

Source: Navigant, 2003a

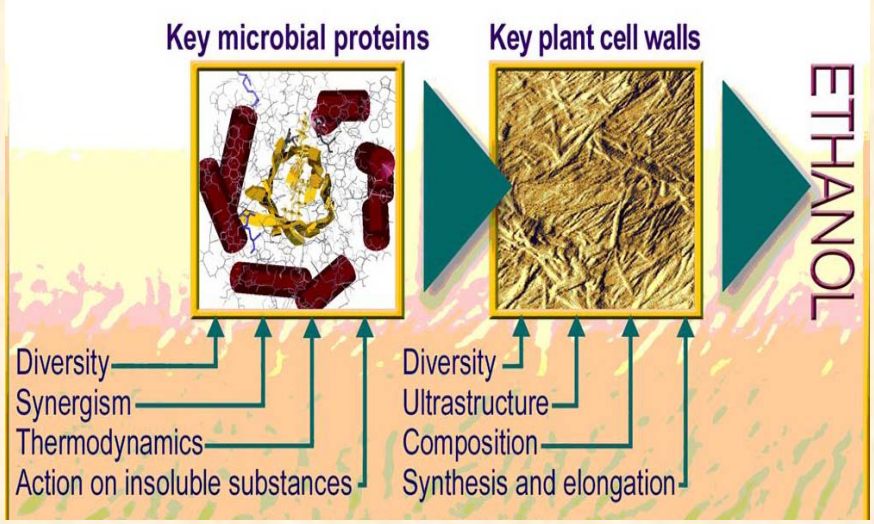
Genomics for Bioenergy: Tailoring plants and microbes

- **Plant architecture and composition can be tailored to maximize feedstock production**
- **"Protein machines" can dismantle plant cell walls to improve conversion to fuels and chemicals**
  - An important step in producing energy from plant biomass is breaking down the complex polymers (e.g., lignin and cellulose)



Cellobiohydrolase protein machines (gray) pulling up and degrading cellulose strands (red) from a plant cell wall.

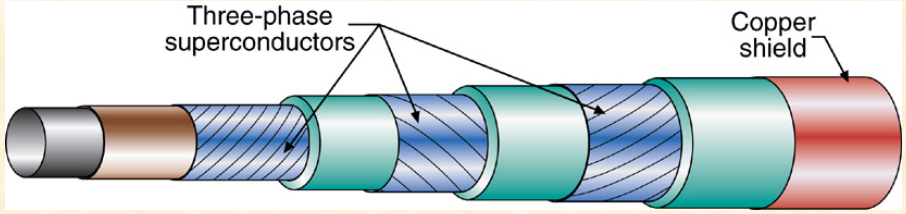
- **Potential Opportunities and Annual Energy Savings:**
  - Plants designed for high yield-low input
  - Plants designed for specific products
  - Biological routes to nanoparticles (e.g., ferrofluids and biologically doped magnetite)



Superconducting electric T&D

- **High-temperature superconductors can significantly increase the capacity of transmission cables**
  - 3-5 times the capacity
  - Improved siting opting
- **Potential Opportunities and Annual Energy Savings:**
  - Reduced transmission losses (typically 7-8%) by 20%, accounting for cryogenics
  - Increased efficiency of generators and motors
- **High-temperature superconductors can also enable:**
  - Fault-current limiting
  - Energy storage
  - Oil-free, more efficient transformers

3-Phase, Triax Cable Design



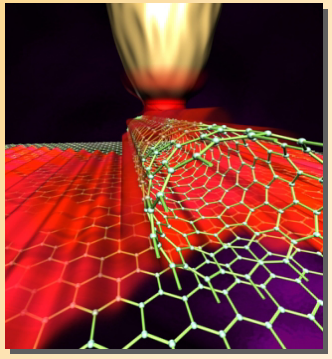
Superconducting cable system has operated for 5 years in Georgia (Southwire Company)

Nano-bio-info discoveries will enable energy efficiency to play a major role in the long run

New energy-efficient technologies

Science to meet energy needs

Nano



Manipulating atoms

Bio

DNA to living organisms

Info

PCs to petaflops

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