Transformative Research Opportunities in Energy Technology

Presented to
Symposium on Critical National Needs in New Technologies

**Board on Science, Technology, and Economic Policy
The National Academies**

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Outline

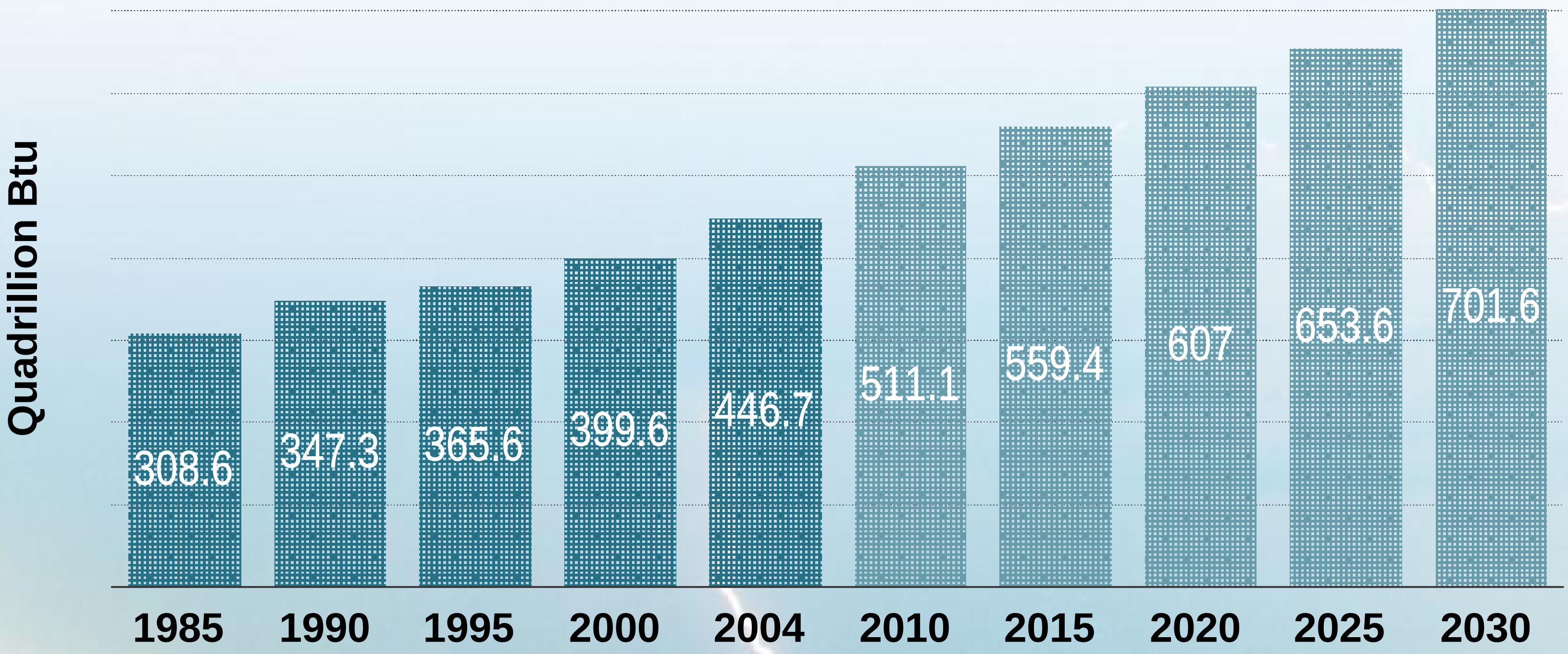
- The energy challenge
- Energy R&D at ORNL
- Grand challenges in energy technology
- Transformative research impacts

Energy is the defining challenge of our time

- **The major driver for**
  - **Climate change**
  - **National security**
  - **Economic competitiveness**
  - **Quality of life**
- **Incremental changes to existing technologies cannot meet this challenge**
  - **Transformational advances in energy technologies are needed**

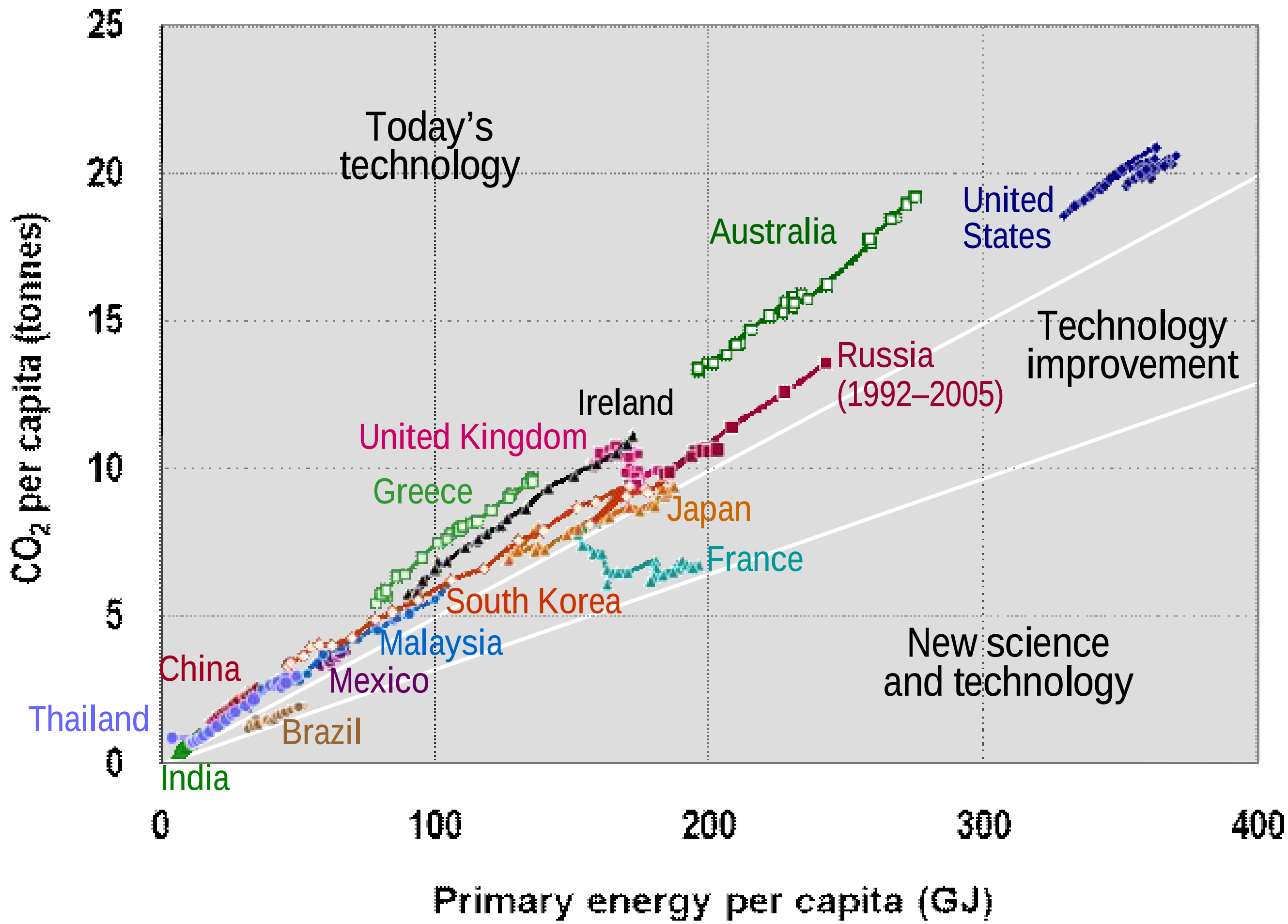
Global energy consumption will increase 50% by 2030

World energy consumption is projected to increase 50% by 2030



Source: International Energy Outlook 2007, DOE/EIA-0484(2007), Energy Information Administration, May 2007

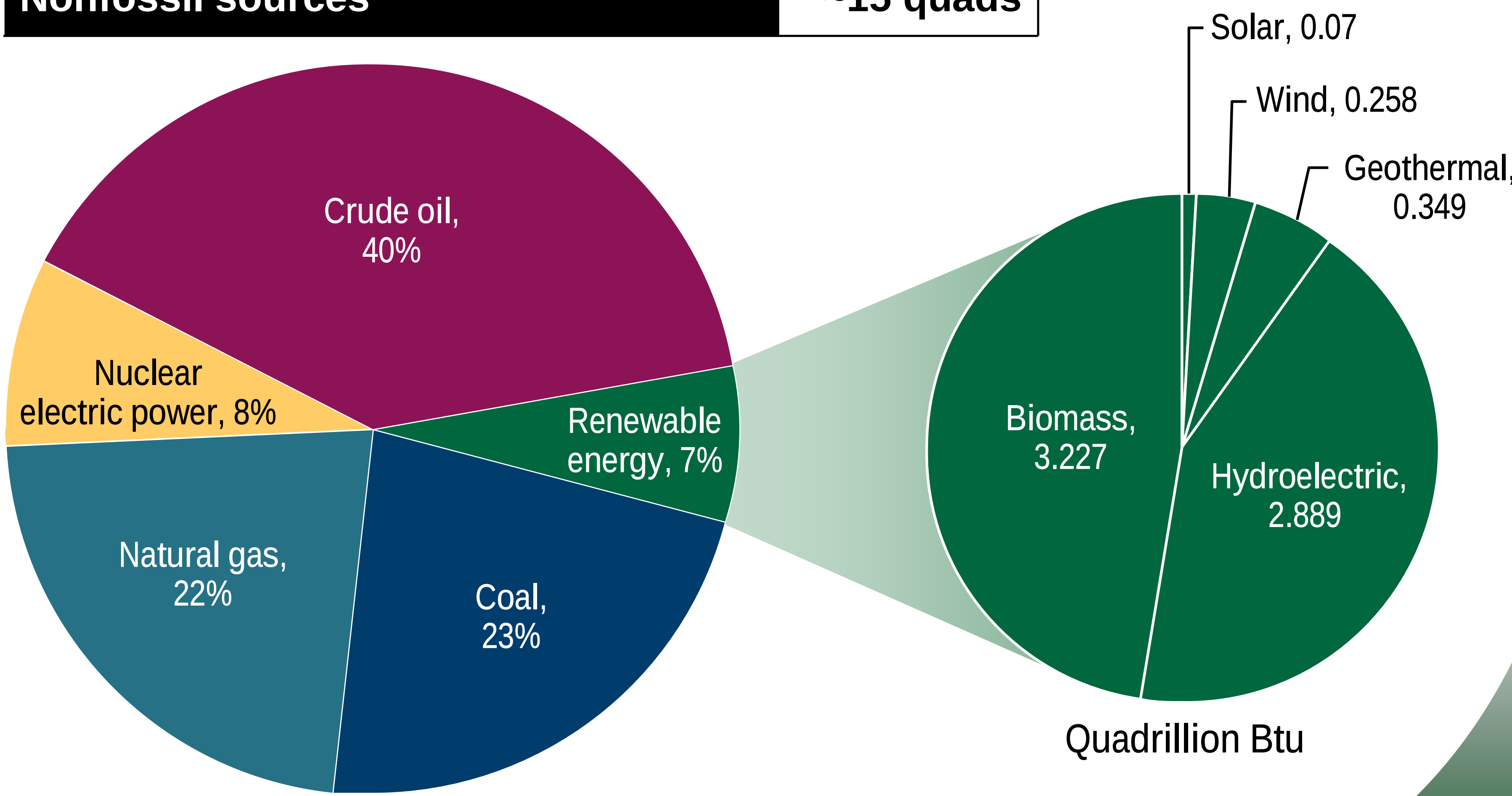
Emissions and energy (1980–2005)



Courtesy of DOE Energy Information Administration

Fossil fuels provide most of the nation's energy

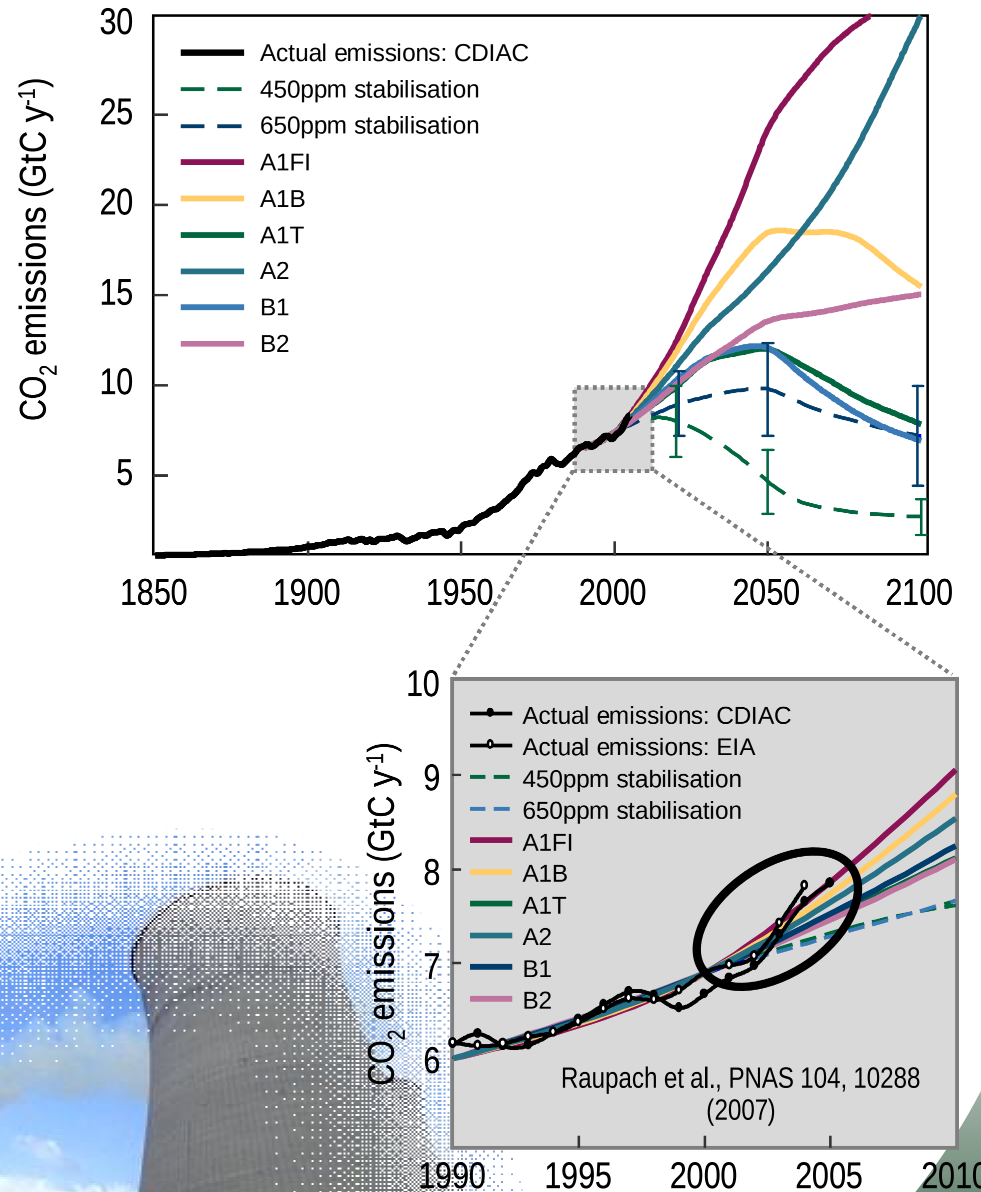
Total U.S. energy consumption, 2006	**~100 quads**
Nonfossil sources	**~15 quads**

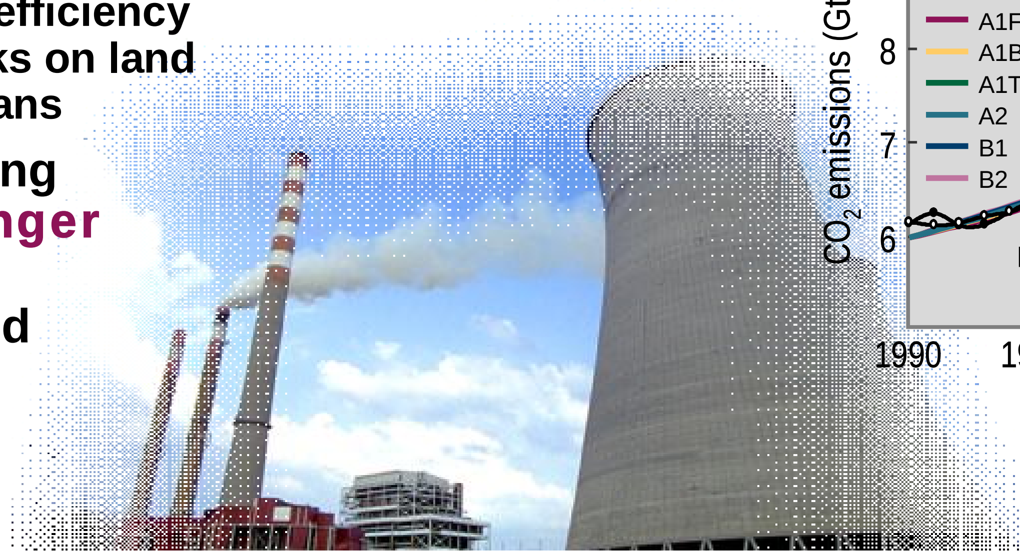


Source: Annual Energy Review 2006, Energy Information Administration

Human activity is affecting global climate

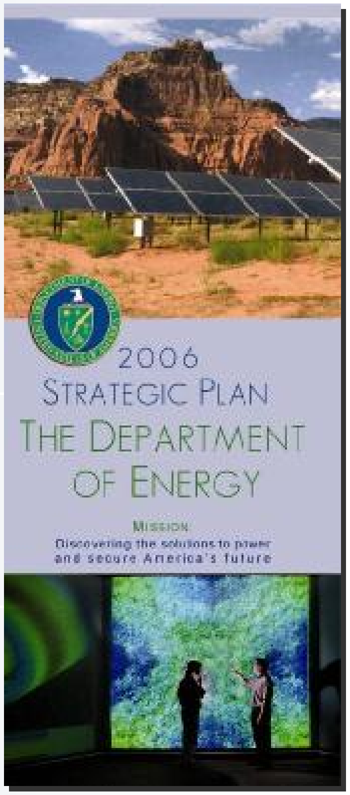
- **Growth rate of atmospheric CO_2 is increasing rapidly**
  - **1990s: 1.3% per year**
  - **2000–2006: 3.3% per year**
- **Three processes are contributing to this increase:**
  - **Growth in world economy**
  - **Increase in carbon intensity**
  - **Decline in efficiency of CO_2 sinks on land and in oceans**
- **Climate forcing is both stronger and sooner than expected**





Meeting the energy challenge: DOE perspective

Energy diversity	**Increase our energy options and reduce dependence on oil**
Environmental impacts of energy	**Improve environmental quality by reducing greenhouse gas emissions and environmental impacts to land, water, and air from energy production and use**
Energy infrastructure	**Create a more flexible, more reliable, and higher capacity U.S. energy infrastructure**
Energy productivity	**Cost-effectively improve the energy efficiency of the U.S. economy**



We need transformational discoveries and truly disruptive technologies

ORNL is DOE's largest science and energy laboratory

- $1.1B budget
- 4,200 employees
- 3,900 research guests annually
- $350 million invested in modernization

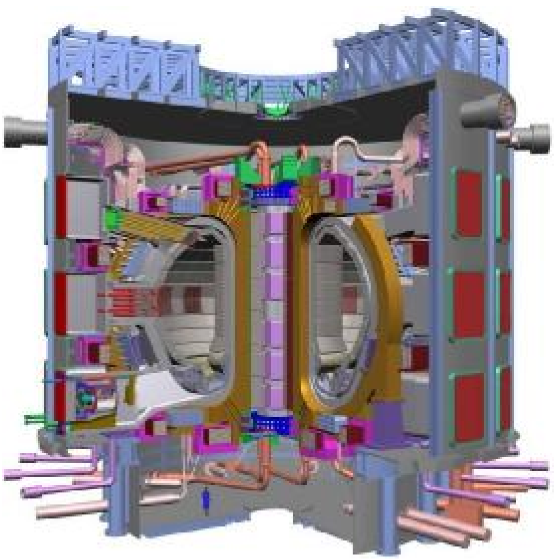
- World's most powerful complex for open scientific computing
- Nation's largest concentration of open source materials research

- Nation's most diverse energy portfolio
- Bringing the $1.4B Spallation Neutron Source into operation
- Managing the billion-dollar U.S. ITER project

Addressing the energy challenges of today . . . and tomorrow

Fusion and fission

- **Managing the billion-dollar U.S. contribution to ITER**
- **Advanced nuclear fuel cycle R&D**



Biofuels

- **$135M center for cellulosic ethanol research**

Energy efficiency

- **DOE's leading lab in transportation, industrial, and superconductor technologies**

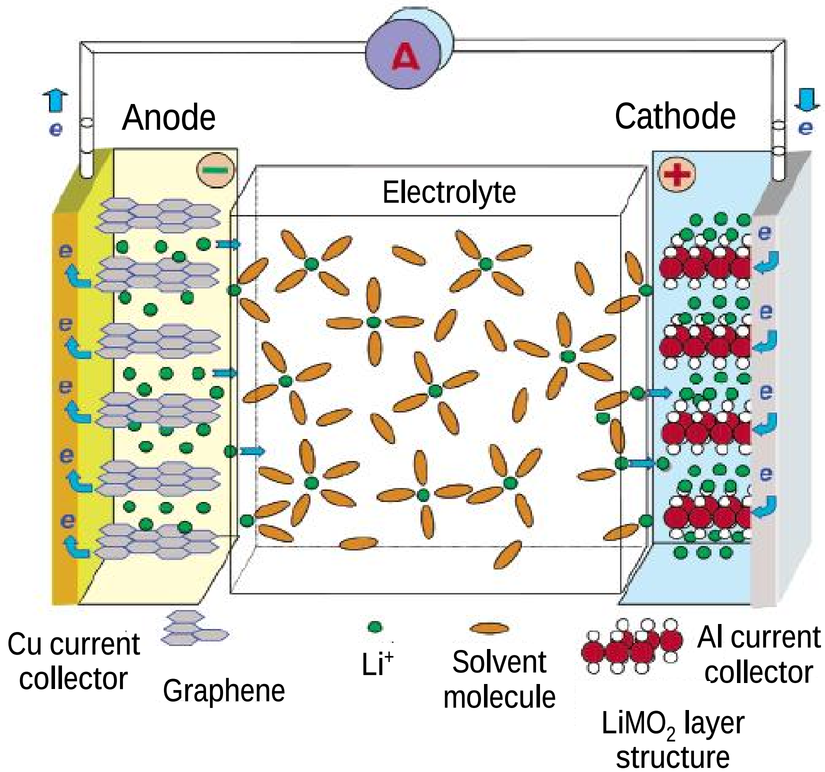
Grand challenges in energy technology

- **Electrical energy storage**
- **Carbon sequestration**
- **Next-generation nuclear**
- **High-efficiency, low-cost solar**
- **High-efficiency, low-cost solid-state lighting**
- **Cellulosic-based biofuels**
- **Fuel cells**
- **Materials for extreme conditions (enabling)**
- **Hydrogen (long term)**
- **Fusion (long term)**
- **Energy efficiency**

Meeting world energy needs will require efficient electrical energy storage

- **Today's electrical energy storage (EES) technologies fall far short of requirements for efficient use of electrical energy**
- **Revolutionary improvements are needed**
  - **To level the cyclic nature of intermittent renewable sources**
  - **To progress from today's hybrid electric vehicles to plug-in hybrids or all-electric vehicles**
  - **To enhance safety and reliability**
- **This will require transformational advances in materials, chemical processes, and battery and capacitor technology**

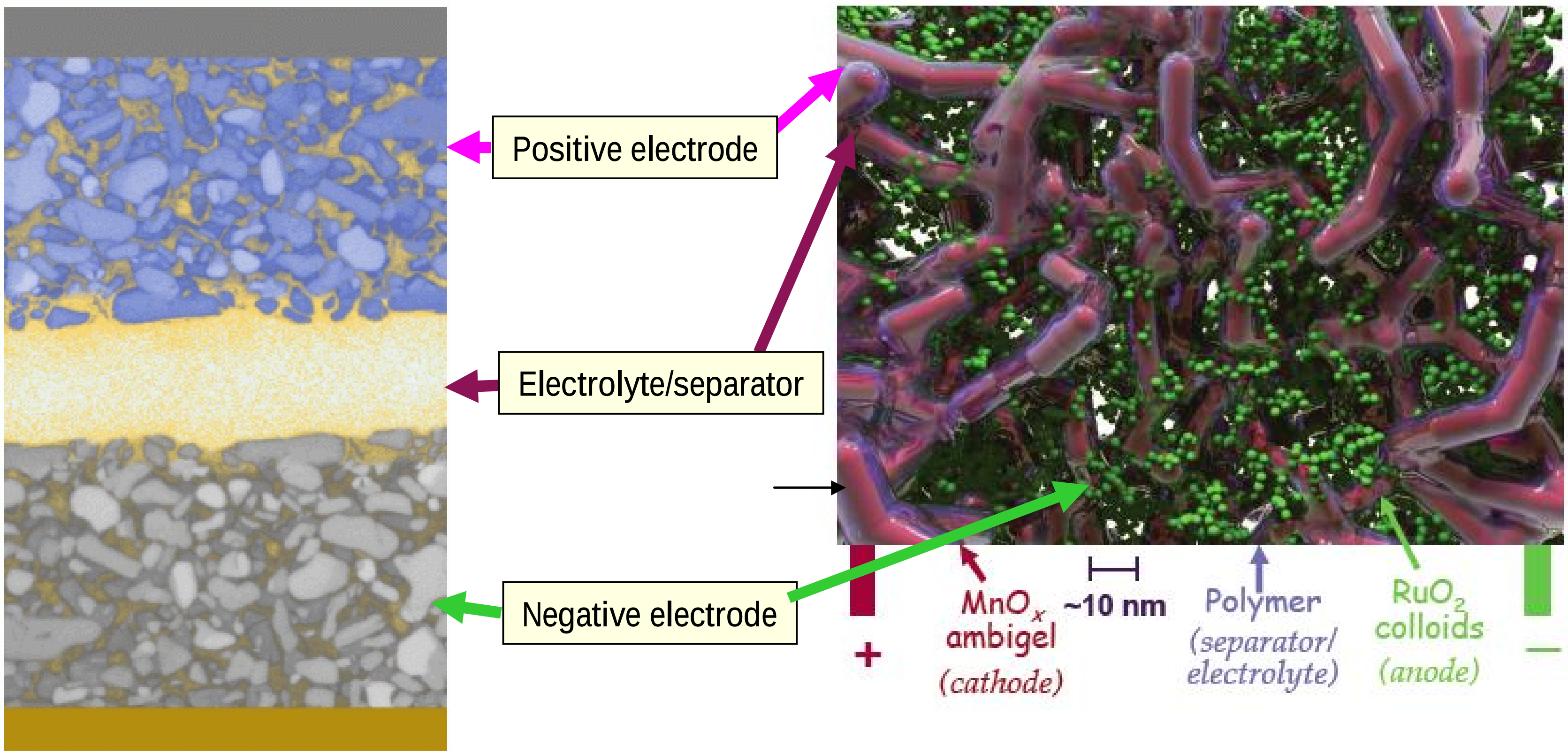
Chemical energy storage



- **Store more energy per unit volume**
- **Tolerate thousands of charge/discharge cycles**
- **Long lifetimes**
- **Safety**
- **Low cost**
- **Need a factor of >3 in energy density and 100 in recharge time**

- **Batteries are dynamic systems that change with every charge/discharge cycle**
- **The apparently simple interface between electrode and electrolyte is in fact a complex set of phases that change with time**

Chemical energy storage: Novel designs and strategies



Present-day electrochemical cell structure

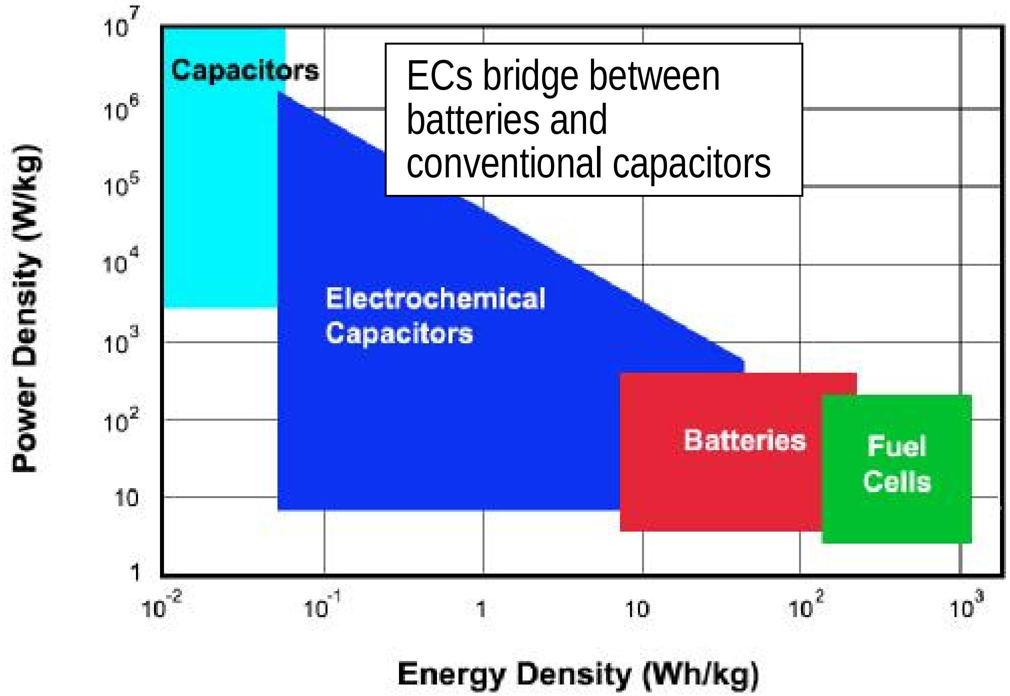
3-D battery: Self-assembled electrochemical cell structures containing multifunctional components

Courtesy of H. Feil, Philips Research Laboratories, Eindhoven

Capacitive storage

- **Store energy as charge, no chemical reactions, fast charge/discharge cycle, sub-second response time**
- **High power density, but need a factor of 100 in energy density**
- **Advances will require:**
  - **Understanding of charge storage mechanisms**
  - **Tailored multifunctional materials**
  - **New electrolytes**

Adapted from M.S. Halpe and J.C. Ellenbogen, MITRE Nanosystems Group, 2006



Solar energy has extraordinary potential

Solar

1.2 x 10^5 TW at Earth surface

>> 600 TW practical

Tide/ocean currents

2 TW gross

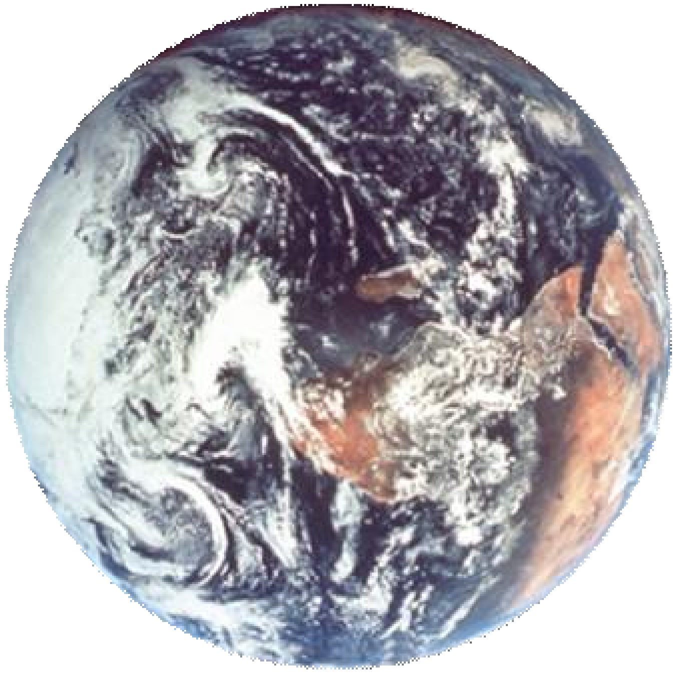
Wind

2–4 TW extractable

Geothermal

12 TW gross over land

Small fraction recoverable



Biomass

5–7 TW gross

All cultivatable
land not used for food

Hydroelectric

4.6 TW gross

1.6 TW technically feasible

0.9 TW economically feasible

0.6 TW installed capacity

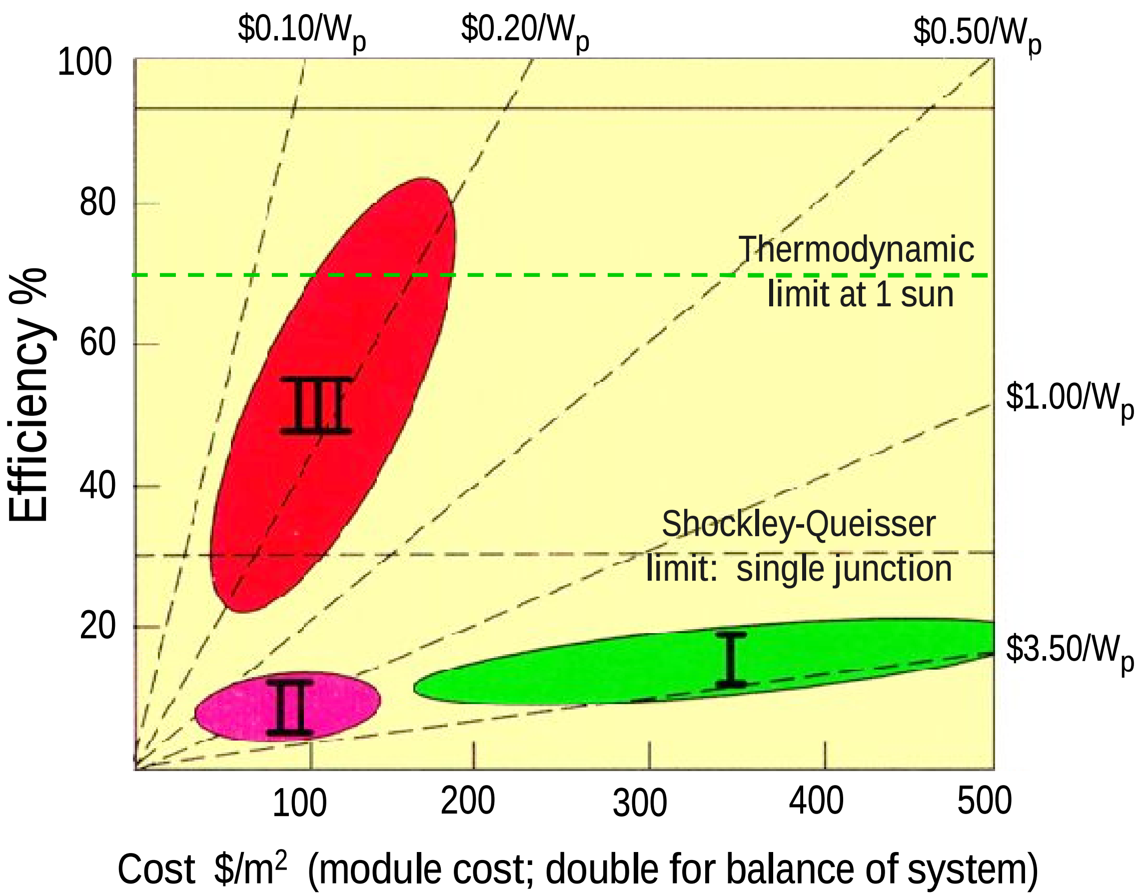
Energy gap

~ 14 TW by 2050

~ 33 TW by 2100

Courtesy of Nathan Lewis, Cal Tech

Cost of solar electric power



Competitive electric power	0.40/W$_p$ ($0.02/kWh)
Competitive primary power	0.20/W$_p$ ($0.01/kWh)
(assuming no cost for storage)	

I. **Bulk Si**
II. **Thin film, dye-sensitized, organic**
III. **Next generation**

Courtesy of Nathan Lewis, Cal Tech

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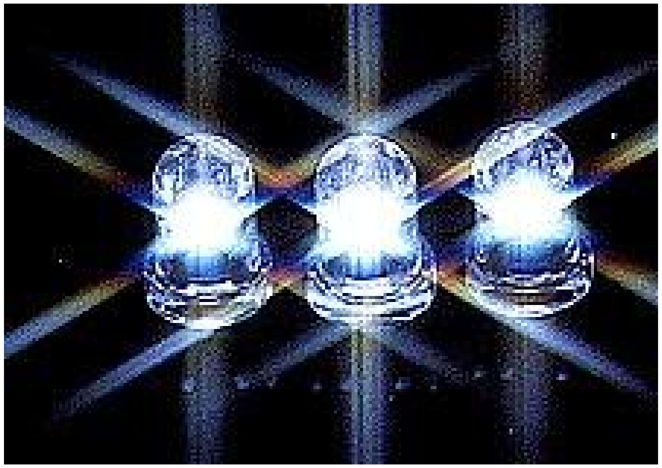
Technology needs for solar energy

- **Lower cost and higher efficiency**
- **Multi-junction, multiple exciton technologies**
- **Organic photovoltaics**
- **Artificial photosynthesis**
- **Catalysts for solar-powered fuel formation**

Solid state lighting

- **Lighting consumes 22% of U.S. electrical energy (8% of total U.S. energy) and produces 7% of CO_2**
- **Current technology is extremely inefficient:**
  - **Incandescent 5%**
  - **Fluorescent 20%**
- **Solid state lighting has potential efficiency of 50% and higher**
- **Technology needs:**
  - **Improved efficiency, lower cost**
  - **Improved approaches for white light**
  - **Synthesis of solid state lighting materials**
  - **Organic LEDs**
  - **Hybrid systems**



Transforming the new biology into bioenergy

- **Potential to replace 30% of U.S. transportation fuels without impacting food crops**
- **Technology advances in cellulosic-based biofuels are needed**
  - **Crops optimized for enzyme degradation**
  - **Enzymes that reduce thermochemical pretreatments and improve efficiency and thermal tolerance**
  - **Consolidated bioprocessing technologies**
  - **Production of diverse biofuels from diverse feedstocks**
  - **Overcoming plant cell wall recalcitrance**

Research to overcome biomass recalcitrance

Biomass formation and modification

Biomass deconstruction and conversion

Optimized crops

Improved enzymes and microbes

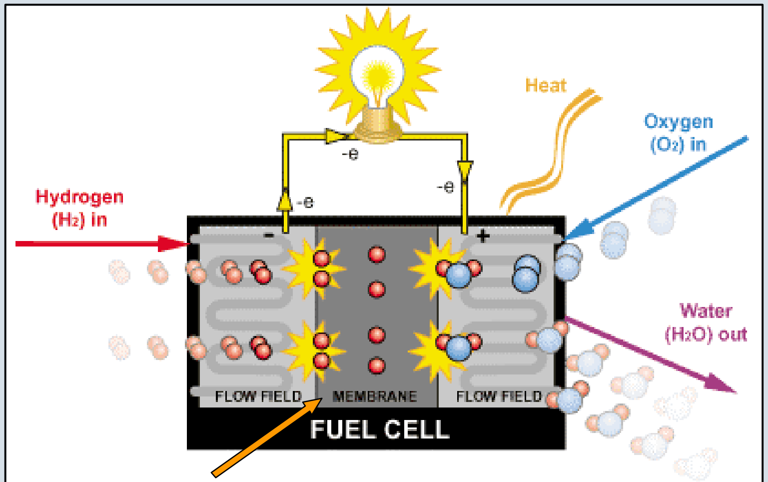
Consolidated processes

Fuel cells

Current status

- Engineering investments have been a success
- Limits to performance are materials, which have not changed much in 15 years

$2H_2 + O_2$ ® $2H_2O$ + electrical power + heat



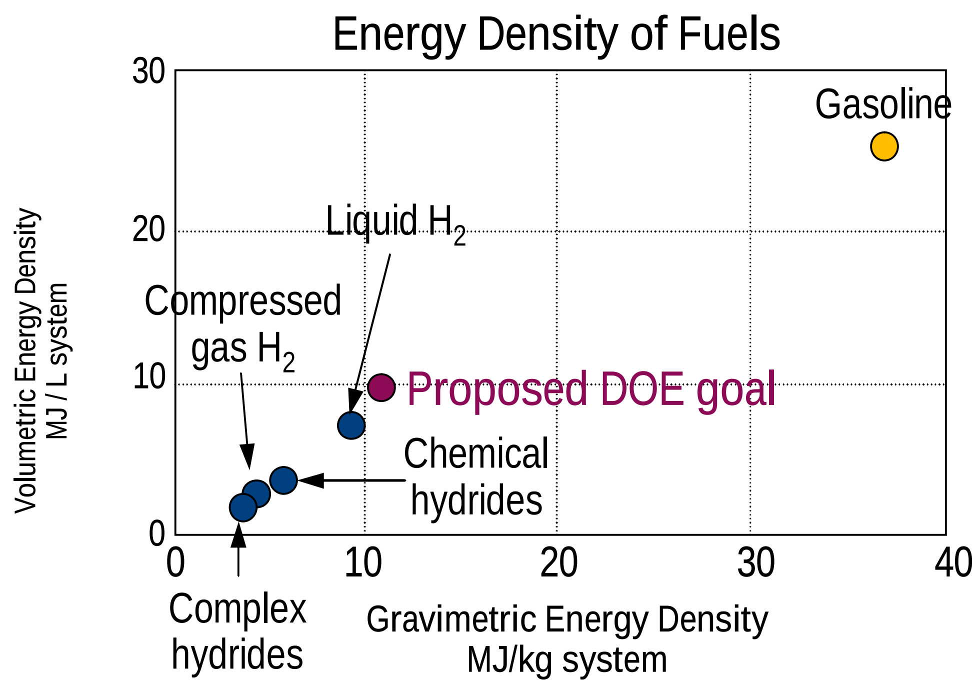
Membrane conducts protons from anode to cathode
proton exchange membrane (PEM)

Challenges

- Membranes
  - Operation in lower humidity, strength, and durability
  - Higher ionic conductivity
- Cathodes
  - Materials with lower overpotential and resistance to impurities
  - Low temperature operation needs cheaper (non- Pt) materials
  - Tolerance to impurities: CO, S, hydrocarbons
- Reformers
  - Need low temperature and inexpensive reformer catalysts

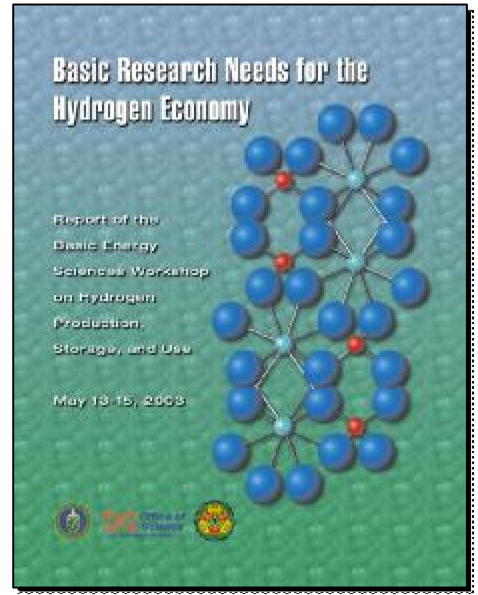
Hydrogen storage

Current technology	Target applications	System requirements
• Tanks for gaseous or liquid H_2 storage • Progress demonstrated in solid state storage materials	• Transportation: On-board vehicle storage • Non-transportation: applications for hydrogen production/delivery	• Compact, light-weight, affordable storage • No current storage system or material meets all targets



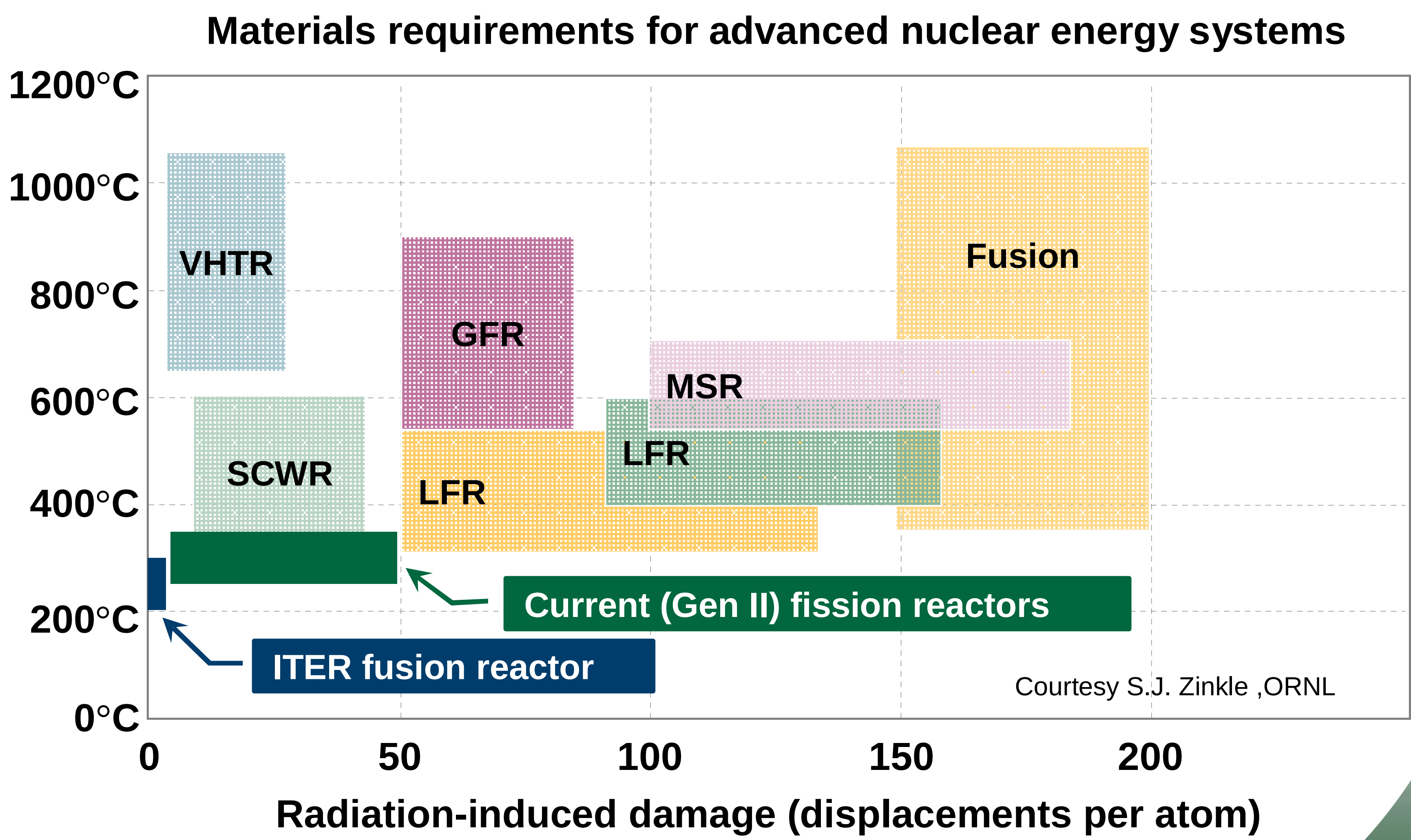
Technology needs for the hydrogen economy

- **Enormous gap between present state-of-the-art and requirements for a competitive hydrogen economy**
  - **Production: 9M tons ® 150M tons (vehicles)**
  - **Storage: 4.4 MJ/L (10K psi gas) ® 9.72 MJ/L**
  - **Fuel cells: \$3000/kW ® \$30/kW (gasoline engine)**
- **Significant R&D efforts are required**
  - **Simple improvements of today's technologies will not meet requirements**
  - **Technical barriers can be overcome only with high-risk/high-payoff research**
  - **Fundamental challenge: New storage materials (complex hydrides, nanoscale architectures)**



http://www.sc.doe.gov/bes/hydrogen.pdf

Materials under extreme conditions are a limiting factor for many energy technologies



Materials under extreme conditions: We must do better

- **Improving materials performance and reducing development times offer transformative opportunities**
- **Key research areas**
  - **Nanostructured materials**
  - **Lightweight materials**
  - **High-temperature applications**
  - **High-radiation environments**

40 years to achieve a 55°C improvement in upper operating temperature!

Advanced Materials & Processes (2006)

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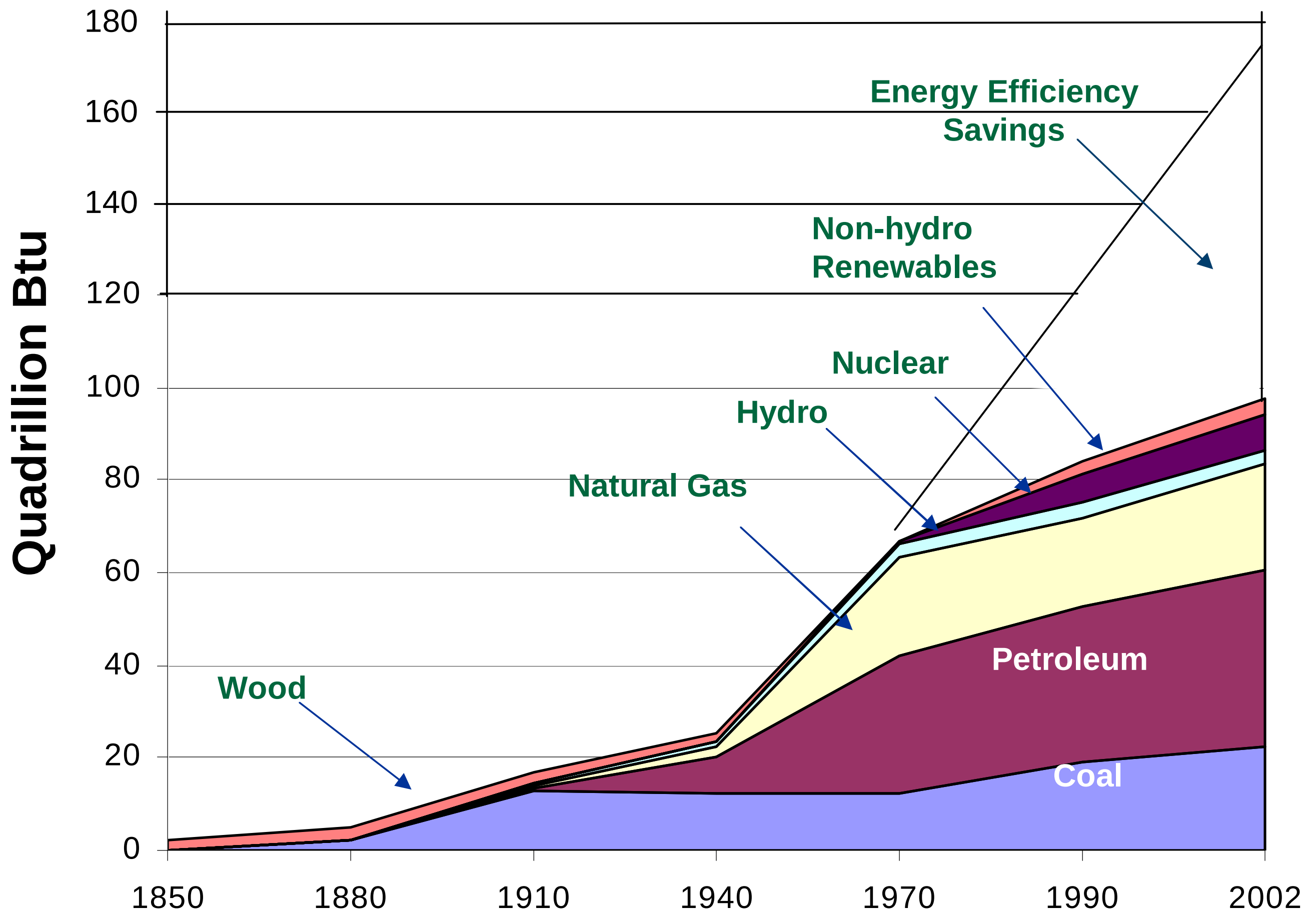
Energy efficiency savings have been essential to the stabilization of U.S. energy consumption



Key research areas

- Technology for zero energy buildings
- Combined cooling, heating, and power
- High-efficiency appliances
- High-efficiency industrial processes
- Smart grid technologies
- Low-emissions, high-efficiency engine technologies
- Materials for transportation: lightweight, high temperature, power electronics

Transformative research impacts

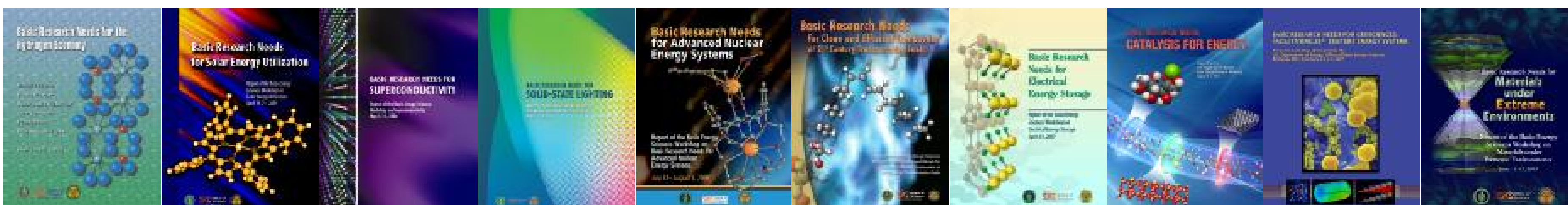
Carbon sequestration	Huge potential to expand the use of coal with acceptable CO_2 releases
Electrical energy storage	Enables electric vehicles and greater reliance on solar and wind power
Solar energy	Huge potential when combined with electrical energy storage
Nuclear	Huge potential with advanced fuel cycles
Fusion	Huge long-term potential
Biomass	Potential carbon-neutral renewable resource for up to 30% of transportation fuels
Solid state lighting	Reduce U.S. electrical energy consumption by up to 15%
Fuel cells	Clean stationary and transportation power
Hydrogen	Clean fuel for transportation and fuel cells
Materials	Enabling for many energy technologies
Energy efficiency	Highest potential near-term energy “source”

DOE's "Basic Research Needs …" workshops

Information resource for research and technology needs for energy-related applications

Basic Research Needs for a Secure Energy Future

- Basic Research Needs for the Hydrogen Economy
- Basic Research Needs for Solar Energy Utilization
- Basic Research Needs for Superconductivity
- Basic Research Needs for Solid State Lighting
- Basic Research Needs for Advanced Nuclear Energy Systems
- Basic Research Needs for the Clean and Efficient Combustion of 21st Century Systems Transportation Fuels
- Basic Research Needs for Geosciences: Facilitating 21st Century Energy Systems
- Basic Research Needs for Electrical Energy Storage
- Basic Research Needs for Catalysis for Energy Applications
- Basic Research Needs for Materials under Extreme Environments



www.science.doe.gov/bes/reports/list.html