Powering the Future with a New Era of Science

Innovations hold the key to transforming U.S. energy supply, efficiency, and use. With rapid economic development occurring in much of the world, global energy demand is increasing dramatically, escalating the competition for dwindling resources and potentially exposing America's economy and energy security to greater volatility. At the same time, there is compelling evidence that carbon dioxide (CO_2) and other greenhouse gas emissions from human activities related to energy are affecting climate. In 2009, 87% of the 6.6 billion metric tons of U.S. carbon emissions were from energy use, accounting for 20% of global energy emissions. Scientific advances are essential for developing and deploying new technologies that can reduce carbon emissions and ultimately move the nation toward energy independence and a sustainable energy future.

98 QUADS
ANNUAL U.S. ENERGY CONSUMPTION

A quad represents a quadrillion British thermal units (Btu), equal to 172 million barrels of oil, 50 million tons of coal, or 1 trillion cubic feet of natural gas.

19 MILLION
BARRELS OF OIL CONSUMED DAILY

At $100 per barrel, this is roughly $2 billion of oil each day. 71% of U.S. oil consumption is for transportation. The U.S. imports 50% of the oil it uses, more than any other country.

83 PERCENTAGE OF ENERGY FROM FOSSIL FUELS

Most of our energy supply comes from nonrenewable, carbon-intensive fossil fuels: oil, natural gas, and coal. Coal is the largest domestically produced energy source, but its use releases more CO_2 per unit of energy compared to that for oil or natural gas.

104 NUCLEAR REACTORS

Located at 65 nuclear plants, 104 reactors provide almost 20% of the total net electricity generated in the U.S. Although the newest reactor entered commercial service in 1996, the U.S. generates more nuclear energy than any other country.

10 PERCENTAGE OF ELECTRICITY FROM RENEWABLES

Biomass and hydropower are the most heavily used renewable energy sources. For U.S. electricity generation, hydropower is the largest renewable source (6%), with wind, biomass, geothermal, and solar each providing about 1% or less.

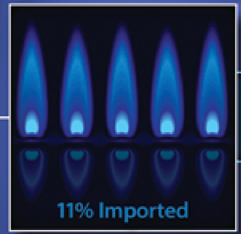
Tracking U.S. Energy Flow

Supply
75 Quads Domestic Production
23 Quads Net Imports

Conversion
58 Quads Direct Use of Primary Supplies
40 Quads Consumed to Generate Electricity

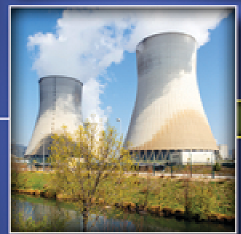
Consumption
42 Quads Used Energy
56 Quads Conversion Losses

Oil 36 Quads



Natural Gas 25 Quads

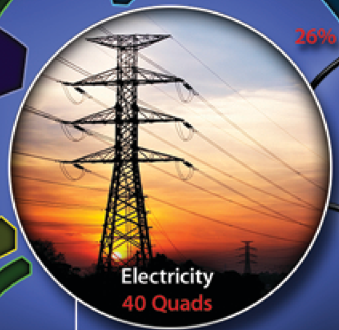
Coal 21 Quads



Nuclear 8 Quads

Renewables 8 Quads

Biomass and Biofuels	4.3 Quads
Hydropower	2.5 Quads
Wind	0.9 Quads
Geothermal	0.2 Quads
Solar	0.1 Quads

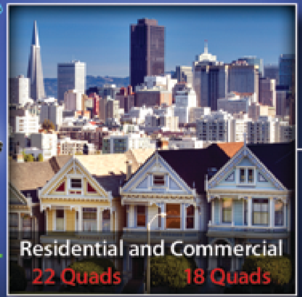


Electricity
40 Quads

26%
74%

Transportation
28 Quads

Industry
30 Quads



Residential and Commercial
22 Quads 18 Quads

3 TRILLION
MILES TRAVELED ANNUALLY

Some 235 million cars and light trucks cover most of the 3 trillion highway miles traveled in the U.S. each year. Light-duty vehicles use 60% of U.S. transportation energy. Heavy trucks (18%), aircraft (9%), and boats and ships (5%) account for most of the rest.

32 PERCENTAGE OF INDUSTRIAL ENERGY FOR REFINING

Petroleum refining is the largest industrial consumer of energy. Other energy-intensive industries include chemical (24%), paper (11%), and metal (8%) manufacturing.

113 MILLION
HOMES USE 22% OF U.S. ENERGY

Space and water heating account for more than half of residential energy use. The typical U.S. family spends $2,000 a year on home utility bills.

77 PERCENTAGE OF COMMERCIAL ENERGY FROM ELECTRICITY

There are roughly 5.3 million commercial buildings in the U.S., including shopping malls and other retail space, offices, schools, hospitals, warehouses, and hotels. Lighting is the largest consumer of electricity in commercial properties and a key target for energy savings.

160,000
MILES OF POWER LINES IN U.S. ELECTRIC GRID

This "grid" of high-voltage transmission lines consists of three large interconnected systems with more than 10,000 generating units and 3,200 electric distribution utilities. About two-thirds of the 40 quads used to generate, transmit, and distribute electricity is lost at power plants and in power lines, resulting in 13 quads of utilized electricity.

This diagram shows 2010 energy flow from primary sources (oil, natural gas, coal, nuclear, and renewables) through transformations (electricity generation) to end uses (transportation, industry, and residential and commercial sectors). Oil provided the largest share of the 98 quads of primary energy consumed, and most of it was used for transportation. Consumption of natural gas, the nation's second largest energy source, is split three ways—electricity generation, industrial processing, and residential and commercial uses (mostly for heating). Coal, our third largest source, is used almost exclusively for electricity. Nuclear energy and renewables each meet less than 10% of U.S. energy demand. Data are from the U.S. Energy Information Administration's Annual Energy Review (www.eia.gov/aer/) and Lawrence Livermore National Laboratory (flowcharts.llnl.gov).

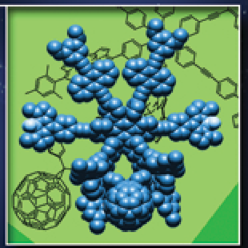
Examples of Science for Energy Innovation

American science is entering a new era of discovery with powerful tools for imaging, modeling, understanding, and manipulating matter on atomic and molecular scales. Empowered by capabilities unthinkable a few decades ago, researchers are unveiling scientific breakthroughs enabling a new generation of materials that can reduce our reliance on fossil fuels and catalyze the transition to clean energy technologies.

Supply

Bio-Inspired Processes for Producing Solar Fuels

Imagine if we could directly convert excess atmospheric CO_2 into energy-rich fuels by leveraging the principles of photosynthesis, the process by which plants and algae use the sun's energy to convert water and CO_2 into the chemical energy of life. Inspired by nature, scientists are designing systems for artificial photosynthetic fuel production. By applying the scientific principles that control photosynthesis, researchers are developing self-assembling components that can integrate the functions of light harvesting and catalysis for fuel production into an operational unit with overall greater efficiencies.

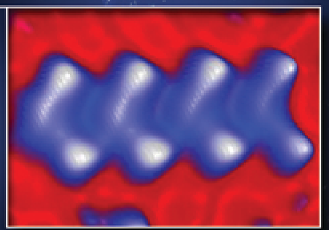


Artificial photosynthetic structure enhances light absorption.

Conversion

Nanofabrication of New Superconducting Materials

Superconductors can carry larger electrical currents without loss to resistance, which eliminates heat generation. Unlike metallic conductors that increase resistance and get hotter as wire diameter decreases, scientists have discovered superconducting organic chains less than 1 nanometer wide and just four molecular pairs in length. This research exploits diverse nanoscale techniques emerging in labs across the country and paves the way for fabricating new superconducting nanomaterials that can transmit electrical power far more efficiently than conventional cables and devices in the U.S. electric grid.

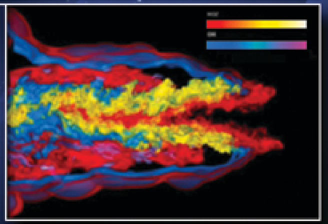


Smallest superconductor contains just four pairs of molecules.

Consumption

Simulations for Designing More Efficient Engines

Scientists combined computer modeling and laser-diagnostic tools to achieve a more complete understanding of the complex turbulent flows and chemical reactions in diesel combustion. This basic research led to new methods for simulating engine design that reduced the time and cost of developing a cleaner, more efficient diesel engine. Computational tools for engine design are now being adopted by industry.



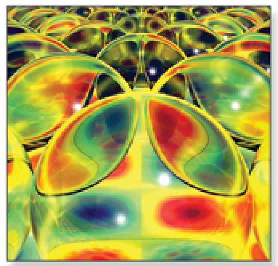
Computer simulation of combustion accelerates engine design.

Energy Science: Creating a Competitive Edge for the Nation

Overcoming America's energy challenges and gaining an edge in the energy innovation race require basic research to better understand the fundamental phenomena that limit the efficiency, performance, or lifetime of the materials and processes underlying energy technologies. Because no single energy source can meet all future demands, a diverse set of solutions is needed. The challenges are complex, requiring researchers in different disciplines to work together to advance scientific discovery at the leading edge of many energy applications.

The Basic Energy Sciences (BES) program of the U.S. Department of Energy's (DOE) Office of Science supports basic research to understand, predict, and ultimately control matter and energy at atomic and molecular levels. BES research—spanning physics, materials science, chemistry, geosciences, nanoscience, and physical biosciences—provides the scientific foundation for advancing a broad range of energy options. As illustrated by the examples below, this research is fundamental to numerous energy breakthroughs—including capabilities for tapping sunlight, maximizing the efficiency of electricity storage and transmission, or making fuels from carbon dioxide.

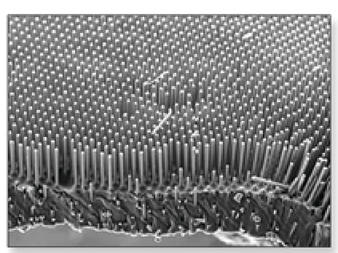
Solar Energy Science



Light-concentrating nanospheres that coat thin-film solar cells boost light-harvesting efficiency.

Among all energy options, sunlight is the most abundant, clean, and secure. Although enough sunlight strikes Earth each hour to fuel a year's worth of human energy needs, current solar energy technologies provide less than 0.1% of the world's electricity. Fully exploiting this enormous yet undeveloped potential is a grand challenge for energy science. Three key approaches to harvesting the sun's energy involve (1) converting sunlight to electricity in solar cells, (2) mimicking natural photosynthesis to store solar energy in the chemical bonds of fuels, and (3) capturing solar heat to drive electricity generation and chemical reactions. Basic research is needed to make the many solar-based routes for producing electricity, fuel, and heat competitive with the cost, reliability, and performance of fossil fuels. Scientists can improve solar technologies by designing new materials that absorb more of the wavelengths in solar radiation, characterizing the mechanisms that limit solar energy conversion efficiency, and adapting nature's strategies to develop low-cost catalysts and new paradigms for energy conversion.

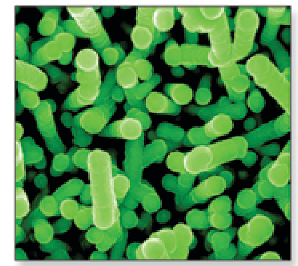
DOE Energy Innovation Hub for Solar Fuels



Like blades of grass on a nanoscale lawn, these light-absorbing nanofibers and other innovative components will make up the JCAP solar-fuels generator.

With a multidisciplinary team of nearly 200 top scientists and engineers, the Joint Center for Artificial Photosynthesis (JCAP), a DOE Energy Innovation Hub, is developing artificial systems that produce fuels from sunlight, water, and CO_2. Building on breakthroughs in nanotechnology, physics, chemistry, and materials science, JCAP researchers are using inexpensive, earth-abundant elements to nanoengineer new light absorbers, membranes, and molecular catalysts for producing fuels such as hydrogen, alcohols, or even gasoline. These new nanomaterials would work together like a multilayer, high-performance fabric that oozes solar fuel. JCAP's ultimate goal is to demonstrate a manufacturable device that produces fuel from the sun 10 times more efficiently than current crops.

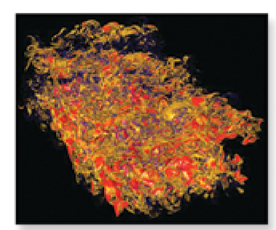
Electrical Energy Storage



Assembled using viruses, these nanowires are coated in silicon, which has a higher energy density than graphite, the material typically used in battery electrodes.

For grid applications, electricity must be reliably available 24 hours a day. Even second-to-second fluctuations can cause major disruptions that cost billions of dollars annually. New approaches for maximizing energy storage capacity are essential to expanding the use of electric vehicles; bringing solar, wind, and other intermittent renewables to the grid; and effectively managing electricity generation to meet peak demand. Today's energy storage devices—batteries and electrochemical capacitors—are limited by the performance of their constituent materials. Overcoming these limitations requires understanding the myriad interactions that transfer ions or electrons in these devices and the physical and chemical processes that degrade them. Recent advances in visualizing and building nanostructures are enabling the design of a new generation of devices that dramatically increase charge density and last longer by minimizing degradation from charge-discharge cycles.

Clean and Efficient Combustion

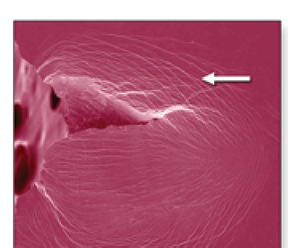


Using simulations, researchers can digitally experiment with new combustion technologies to gather data, such as this representation of dissipation rates in a jet flame.

As new transportation fuels derived from oil shale, coal, plant biomass, and other sources become available, development of these future fuels must be coordinated with evolving engine design. Combustion dynamics, turbulent flows, and chemistry are astonishingly complex, with hundreds of different fuel molecules and thousands of possible reactions underlying the release of energy stored in chemical bonds. Researchers are overcoming this complexity with powerful computational modeling. By enabling realistic simulations for testing different fuel formulations in existing and proposed engine designs, these models represent an experimentally validated, predictive capability for combustion. They will accelerate the integrated development of fuel and engine concepts needed to curb emissions and increase engine efficiency by 30% or more.

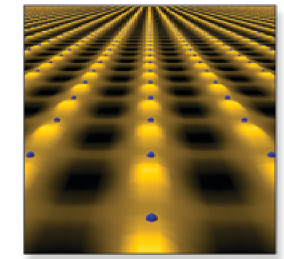
Materials in Extreme Environments

Future energy technologies will place increasing demands on materials that can withstand extremes in stress, temperature, pressure, chemical reactivity, radiation flux, and electric or magnetic fields. For example, increasing the efficiency of a coal-fired power plant will require new materials that tolerate higher operating temperatures and pressures, and next-generation nuclear reactors will need to withstand higher radiation flux in corrosive environments. These conditions can weaken chemical bonds and accelerate material aging, leading to reduced performance and eventually failure. With current research and computational capabilities, scientists can study the mechanisms of damage evolution from atomic to macroscopic scales. This research is revealing new strategies for developing self-healing materials or using extreme conditions to turn certain material properties on or off as needed. Beyond energy, these new materials would advance many other important application areas such as national security or industry that also require robust, reliable materials.



Fine white shear lines (see arrow) form to prevent crack extension in a new damage-tolerant metallic glass that is stronger and tougher than any other known material.

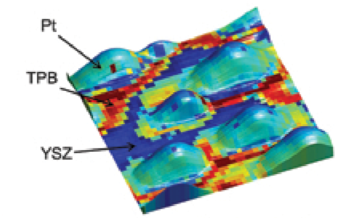
Superconducting Grid Solutions



Study of electron behavior in a network of copper oxide units (yellow) reveals a break in symmetry that may underlie the loss of superconductivity at higher temperatures.

As one of the greatest engineering achievements of the 20th century, the U.S. electric grid emerged by connecting isolated local grids largely based on technologies from the 1950s–70s. By 2030, U.S. electricity demand is expected to rise 50% or more with the growing use of electric vehicles—an increase the grid will struggle to meet. One potential new solution to this bottleneck is superconductivity—the loss-free transmission of electrical currents observed in certain materials at very low temperatures. Superconductivity is ultimately a phenomenon determined by electron behavior and molecular properties at scales ranging from a tenth of a nanometer to hundreds of nanometers. By applying today's nanoscale characterization and fabrication tools, scientists can attain the mechanistic understanding needed to design less expensive materials that work at higher temperatures and can carry larger currents over greater distances. Such advances will make the grid smarter and more reliable by automatically adjusting to large fluctuations in demand.

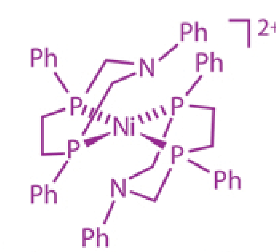
Catalysis for Energy Applications



New microscopy methods track electrochemical activity along the triple-phase boundaries (TPB) for platinum (Pt) nanoparticles on an yttria-stabilized zirconia (YSZ) surface of a fuel cell.

Chemical transformations are essential for generating fuels and other useful chemical products. As the ultimate enablers of these transformations, catalysts facilitate quicker, less energy-intensive conversion of molecules into desired products. Without them, most energy and materials needed for daily life would not exist. Whether extracting chemicals from complex fossil feedstocks or transforming plant biomass or CO_2 into fuels, the catalysts and reactions underlying these processes must be understood at the atomic level where the intricate breaking and forming of chemical bonds occur. This detailed understanding of catalyst structure and performance under technologically realistic conditions provides the foundation to design and control the synthesis of more efficient, less expensive catalysts with atom-by-atom precision.

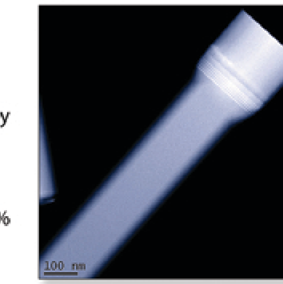
Hydrogen Production, Storage, and Conversion



A potential inexpensive alternative to platinum catalysts, this new synthetic nickle-based catalyst produces hydrogen 10 times faster than natural hydrogen-evolving enzymes.

Another option for attaining a secure energy future is expanding the use of hydrogen—the third most abundant element on Earth's surface. Exploiting hydrogen for diverse energy uses requires new science-based strategies for producing it from fossil fuels, biomass conversion, or the splitting of water; storing it chemically or physically; and converting stored hydrogen to electrical energy and heat at the point of use. A key research need is to understand the atomic and molecular processes that occur at the interface of hydrogen with materials, enabling the discovery and design of new membranes, catalysts, and fuel cells with higher performance and lower costs.

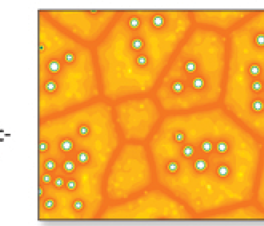
Solid-State Lighting



With a diameter 1,000 times smaller than a human hair, this flashlight-shaped nanowire is made of gallium nitride, a semiconductor used in the light-emitting diodes of SSL devices.

Traditional sources of artificial light, such as incandescent or fluorescent bulbs, are extremely inefficient because they generate light as a byproduct of indirect processes that produce heat or plasmas. Most energy consumed by incandescent bulbs is lost to heat; only about 5% is used to produce visible light. For fluorescent sources, only about 20% is converted to light. Solid-state lighting (SSL), an emerging technology based on direct electricity-to-light conversion using semiconductor materials, has the potential to generate visible white light at much higher efficiencies, possibly approaching 100%. Developing low-cost, efficient SSL technologies with high color-rendering quality will require detailed understanding of the mechanisms and material properties controlling electron conversion to light rather than heat. Applying the latest nanoscale techniques, researchers can experiment with radical new designs of SSL material at the atomic level and study conversion processes in nanostructures much smaller than the wavelength of light.

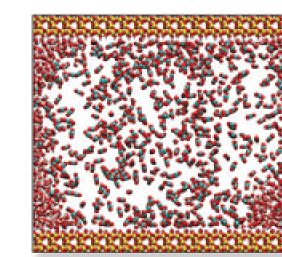
Advanced Nuclear Energy Systems



A computer model shows how nanometer-sized, atom-free regions called voids (white circles) form under irradiation and impact heat flow in nuclear fuels.

Recent advances in nanoscale research and predictive modeling of complex systems are transforming the science-based development of structural materials, fuels, separation processes, and waste forms for nuclear energy. In addition to extending the operational lifetime of existing reactors, these advances also support a new generation of nuclear energy systems based on materials that withstand extremes in temperature, radiation, mechanical stress, and corrosive conditions. With a more detailed understanding of the nanoscale phenomena controlling defects in system components, researchers are developing techniques for real-time monitoring of structural integrity in reactors and for recycling nuclear fuels in ways that minimize production of long-lived radioactive waste.

Geosciences for Sequestering Energy Byproducts



Simulation of water-CO_2 interactions between two parallel quartz layers at conditions found in the deep subsurface.

Even with a growing energy supply from clean alternatives, fossil fuels will continue to be major energy sources for years to come. Efforts to minimize the environmental impacts of fossil CO_2 emissions and radioactive waste from nuclear energy will increase demand to store these and other energy byproducts deep underground for centuries. Safely sequestering large quantities of these byproducts in rock formations thousands of meters deep requires research to understand and reliably predict and monitor their transport and fate as they alter or interact with fluids, minerals, and microbial life in the subsurface.

Side 1 image credits. Energy flow diagram images: iStockphoto. Earth's city lights: NASA Visible Earth. Photosynthetic structure: Center for Bio-Inspired Solar Fuel Production Energy Frontier Research Center (EFRC). Smallest superconductor: S. W. Hla and K. Clark, Ohio University. Combustion simulation: K. L. Ma and H. Yu, University of California Davis, and J. Chen, Sandia National Laboratories. **Side 2 image credits.** Solar energy science image: Light-Material Interactions in Energy Conversion EFRC. DOE Energy Innovation Hub image: Joint Center for Artificial Photosynthesis. Materials in extreme environments image: M. E. Launey, Lawrence Berkeley National Laboratory. Electrical energy storage image: Nanostructures for Electrical Energy Storage EFRC. Combustion image: K. L. Ma, H. Akiba, and H. Yu, University of California Davis, and E. Hawkes, Sandia National Laboratories. Superconductivity image: Brookhaven National Laboratory. Catalysis image: Oak Ridge National Laboratory. Hydrogen image: Center for Molecular Electrocatalysis EFRC. Solid-state lighting image: EFRC for Solid-State Lighting Science. Nuclear energy image: Center for Materials Science of Nuclear Fuels EFRC. Geosciences image: Center for Nanoscale Control of Geologic CO_2 EFRC.

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