Advanced Materials for Our Energy Future

ENERGY

Introduction

Since ancient times, advances in the development of materials and energy have defined and limited human social, technological and political aspirations. The modern era, with instant global communication and the rising expectations of developing nations, poses energy challenges greater than ever seen before. Access to energy is critical to the wealth, lifestyle and self-image of every country.

The global use of electricity captures the triumph and the challenge of energy. In the 130 years since Edison, Tesla and Westinghouse installed the first primitive electricity grids, electrical technology has undergone many revolutions. From its initial use exclusively for lighting, electricity now symbolizes modern life, powering lights, communication, entertainment, trains, refrigeration and industry. In the past century, 75% of the world has gained access to this most versatile energy carrier.

Such changes in our lives do not come from incremental improvements, but from groundbreaking research and development on materials that open new horizons. Tremendous opportunities currently exist for transitioning from carbon-based energy sources such as gasoline for engines to electric motors for transportation, as well as from coal-fired electric power generation to renewable, clean solar, nuclear and wind energy sources for electricity, and thereby dramatically increasing the capacity and reliability of urban grids in high density and recovering areas such as New York and New Orleans. These advances will require a new generation of advanced materials, including

- Battery materials for massive electrical energy storage
- High-efficiency and low cost solar cells
- Corrosion-resistant alloys for high-temperature power conversion
- Strong, lightweight composites for turbine blades
- Superconducting power distribution cables
- Advanced power handling electronics, and more

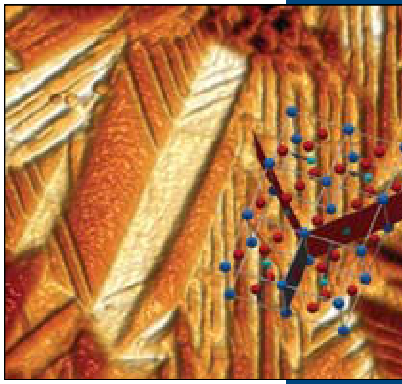
Modern transportation, by air, land and sea, is also an essential part of our lives. Revolutionary advancements in materials, including lightweight aerospace alloys, high-temperature engine materials and advanced composites, have been a critical part of improving the capability, safety and energy efficiency of our transportation vehicles. As we look to transportation options that further improve energy efficiency and safety and move us beyond the current fossil fuel paradigm, forefront materials research is needed for

- Improving combustion efficiencies
- Batteries for electric and hybrid vehicles
- Fuel cells
- Hydrogen storage
- New tire compounds and manufacturing processes
- Biofuel production, and more

Despite these technological triumphs, a large part of the world lives without adequate energy. 1.5 billion people have no access to electricity, and the electricity grid is woefully inadequate in many other areas of the world. The same dichotomy applies to all forms of energy—it is remarkably successful where it is developed, and desperately needed where it is not. Furthermore, the current reliance on fossil fuels puts substantial strain on the world's resources, with significant implications to the economic and national security of many nations, and leads to greenhouse gas emissions that threaten climate change.

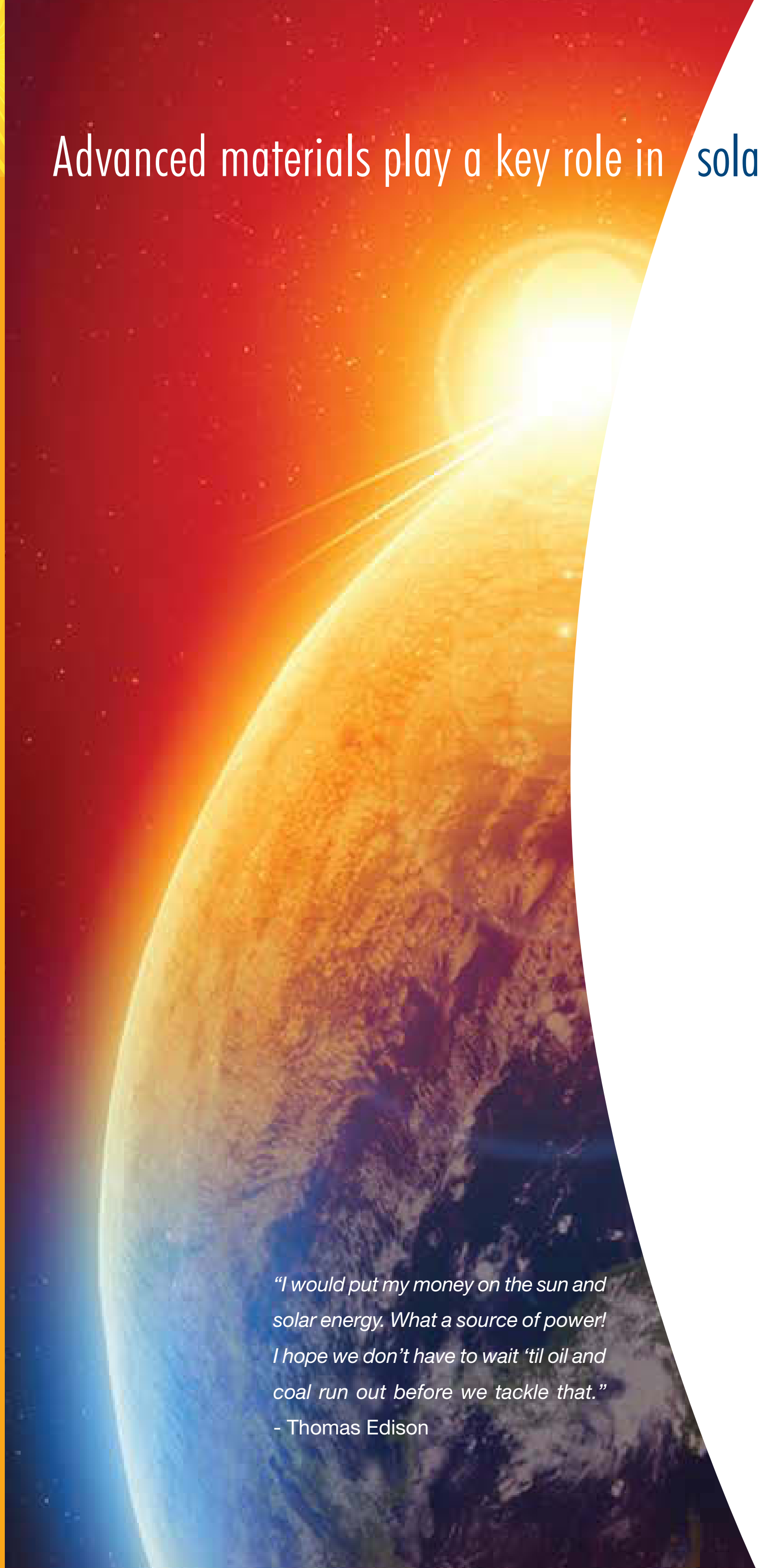
There is no "silver bullet" to solve the daunting energy requirements of the developed and developing world—twice the energy use in the next half-century—while simultaneously addressing environmental impacts. We must use and innovate across the full spectrum of the energy options available to us.

Advancing our science and technology, from fundamental breakthroughs in materials and chemistry to improving manufacturing processes, is critical to our energy future and to establishing new businesses that drive economic prosperity. This booklet provides examples that illustrate how materials research and development contribute to today's energy technologies and the challenges we need to meet to fuel tomorrow's energy needs.



Steel processing
Microelectronics fabrication
Ferroelectric material

Advanced materials play a key role in solar energy generation



"I would put my money on the sun and solar energy. What a source of power! I hope we don't have to wait 'til oil and coal run out before we tackle that."
- Thomas Edison

SOLAR ENERGY

More energy from sunlight strikes the Earth in one hour (13 terawatts) than all the energy consumed by humans in one year. Sunlight is an important carbon-neutral energy source and continues to grow at a rapid pace.

Materials scientists and engineers can provide materials-based solutions to efficiently capture the unlimited and free energy from sunlight to address the world's energy needs. Presently, around 0.02% of the total electrical power in the U.S. is obtained from solar energy, although a solar energy farm (10% efficiency) covering just 1.6% of the U.S. land area would meet current U.S. domestic energy needs. Materials science and engineering offers the potential to significantly increase the amount of electricity generated from solar energy. Advantages of producing electrical power from sunlight include

- Unlimited, free and renewable energy source
- Produces maximum energy during the day during periods of greatest demand
- Energy payback is less than 3 years
- Power output can be tailored to match requirements
- "Off Grid" installation possible for energy self-sufficient communities
- Low carbon footprint (less than 35 grams CO_2/kilowatt-hour)
- Materials used can be recycled

A variety of solar technologies can be used to effectively capture energy from the sun: Photovoltaics (PV), Concentrating Photovoltaics (CPV), Concentrating Solar Power (CSP) and Solar Thermal.

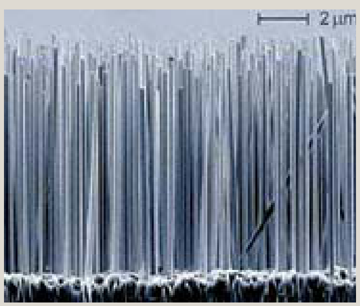
Silicon PV system – courtesy SunPower Corporation

Concentrating solar power tower – courtesy Sandia National Laboratories

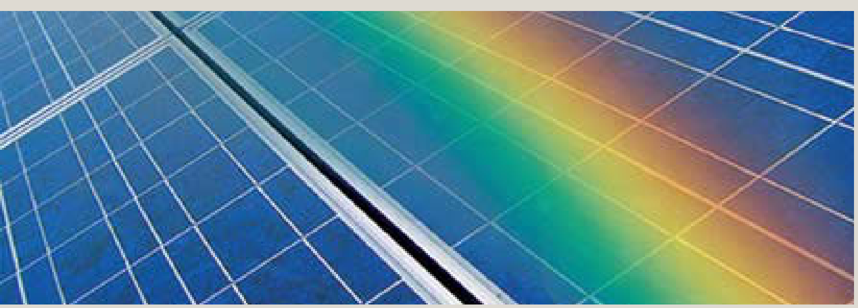
Research on advanced materials will improve solar energy efficiency

Flexible solar cell

Home solar power



Nanowire array



Silicon PV module

Photovoltaics (PV)

PV directly converts sunlight into electrical power. There has been significant growth in PV over the past decade, greater than 40% per year, and the cost of electricity from PV continues to decrease. The recent growth of PV has been driven by lower costs due to increased efficiency, primarily from advances in four main types of PV materials including: crystalline silicon; thin films such as cadmium telluride (CdTe), copper-indium-gallium-diselenide (CIGS) or amorphous silicon (a-Si); multifunction systems with solar concentrators; and organic flexible molecular, polymeric or nanoparticle-based cells.

Materials R&D challenges for PV technologies include the need to continue to increase solar cell efficiency by improving material properties and cell designs. This can be achieved by

- Identifying or developing alternate materials that are abundant, nontoxic, low-cost
- Developing novel nanoscale surfaces to reduce reflection and increase capture of the full spectrum of sunlight
- Extending the lifetime of photovoltaic systems by addressing materials aging issues
- Reducing manufacturing costs and creating efficient, high volume methods to recycle solar system materials at end-of-life
- Closing the gap between research and commercial cell efficiencies to reduce the cost of power from modules

Concentrating Solar Power (CSP)

CSP uses reflectors to concentrate sunlight to generate high temperatures to heat fluids that drive steam turbines to produce utility-scale electric power. Three main CSP types are parabolic trough, dish and power tower systems. Each makes use of reflective mirrors to focus sunlight on fluid such as oil, water, gas or molten salt. Materials research is needed to

- Improve optical materials for reflectors with greater durability and low cost
- Enhance absorber materials and coatings with higher solar absorbance and low thermal emittance
- Develop thermal energy storage materials with improved heat capacity
- Improve corrosion resistance of materials in contact with molten salts

The future

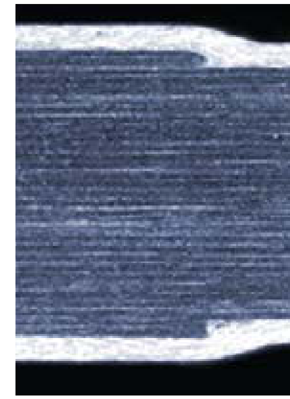
- Convergence of PV and nanotechnology to capture and convert solar energy more efficiently
- Inexpensive plastic solar cells or panels that are mounted on curved surfaces
- Unique forms of PV driven by the imagination of materials scientists: silicon nanowires, nanotubes, flexible plastic organic transparent cells, ultra-thin silicon wafers

Materials research makes renewable energy sources more practical for everyday use

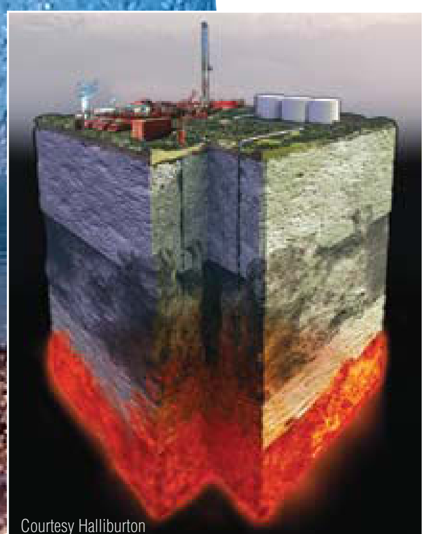
WIND POWER

Materials play a critical role in wind power. Today, wind turbines use blades made of polymer-matrix composite materials reinforced with fiberglass or graphite fibers. Compact electrical generators in the turbines contain powerful magnets made from rare earth materials. The rotation of the turbine blades is used to drive an electrical generator through a gearbox, which uses special alloys in order to accommodate a wide range of wind speeds.

Turbine sizes continue to increase. The growth of off-shore installations means long-time exposure to higher stresses and hostile environments that can challenge the durability of turbine materials. The turbine blades must have adequate stiffness to prevent failure due to deflection and buckling. They also need adequate long term fatigue life in harsh conditions, including variable winds, ice loading and lightning strikes. Current materials research continues to address these critical issues.



Layered composite blade material



Courtesy Halliburton

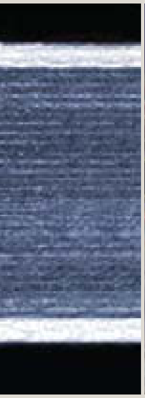
GEOTHERMAL POWER

Geothermal power is green energy generated by converting heat stored in the earth to electricity via heated water pumped in and out of deep wells, using a steam turbine or in a binary system using heat exchange fluids. Deep wells with depths of 3-10 kilometers are dug by hard rock tools and fitted with high alloy tubing. There are several conversion methods for geothermal power and there is massive potential for use of geothermal energy by countries the world over. Geothermal power can provide fully reliable power that is always available.

Current generation Enhanced Geothermal Systems (EGS) do not require naturally occurring hot water resources. Rather, high pressure cold water is pumped down an injection well into rock. Water travels through fractures in the rock, capturing the heat of the rock until it is forced out of a second borehole as very hot water, which is converted into electricity. New materials technologies are crucial for the success of EGS.

Geysers Geothermal Field, CA

Advanced materials enable renewable energy capture and generation



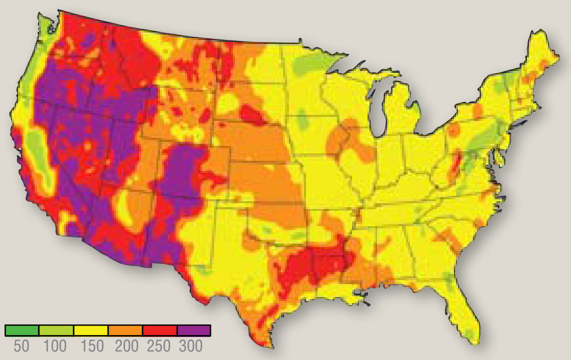
Wind turbine blade manufacture – courtesy TPI composites

Challenges

- “Smart” blade materials that automatically adjust pitch to accommodate wind speed variations for the most efficient operation will high strength materials that resist corrosion and fatigue
- Sensors included in turbine blades to continuously monitor fatigue damage and signal the need for repair
- Ground-mounted generators and gear trains are used with vertical axis wind turbines, where the main rotor shaft is vertical. Unique materials solutions for the gearing increase efficiency

Goal

Wind turbine installations need to grow by a factor of 10-20x and spread to appropriate sites in the U.S. to generate an average of 20% of our electricity needs by 2030.



Geothermal Recource in U.S. (^{o}C)

Synthetic diamond drill bit – courtesy Sandia National Laboratories

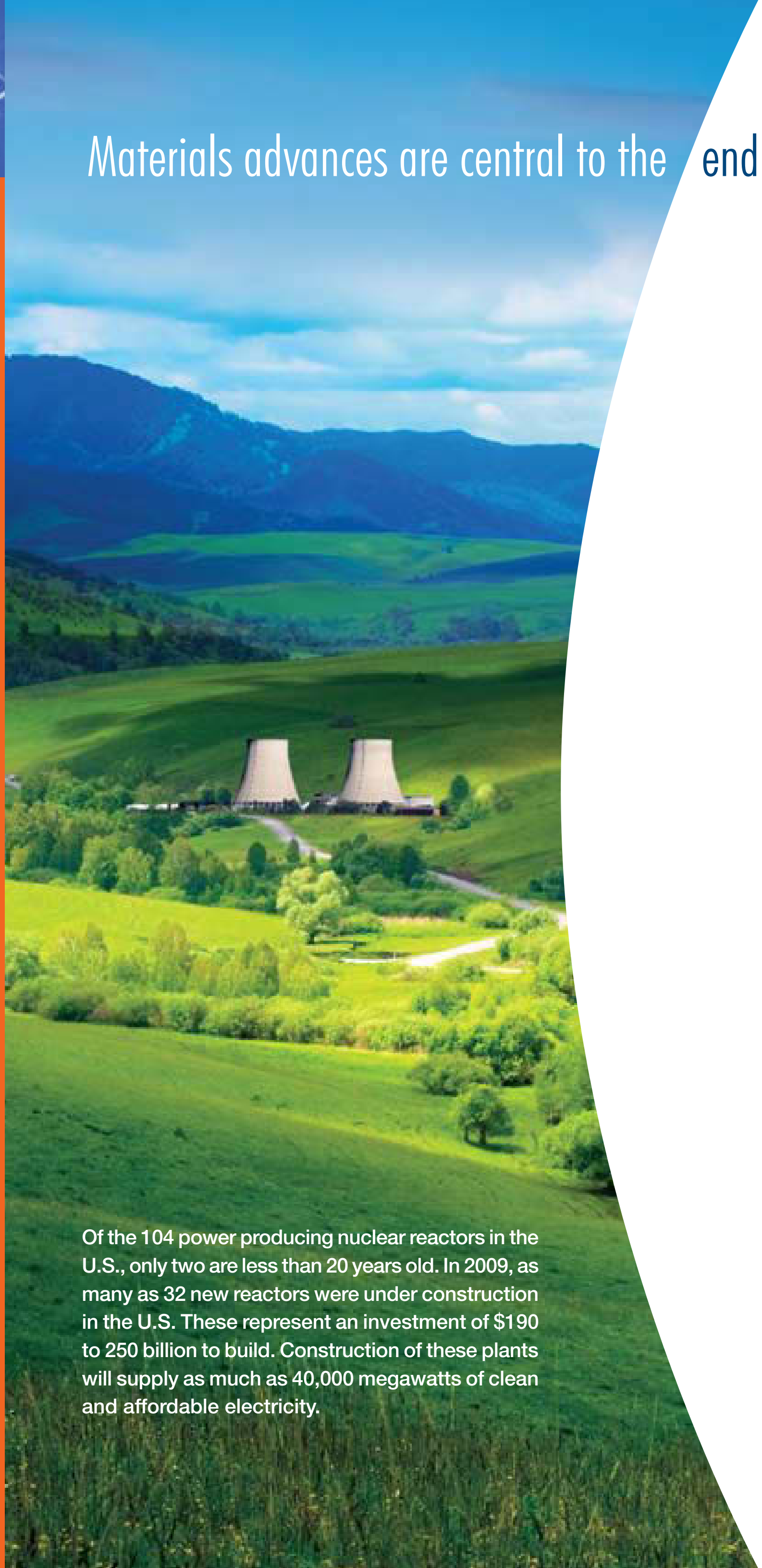
Status

Work has begun on the first application of an Enhanced Geothermal System (EGS) in the U.S. using a production well at a commercial geothermal site. This is the country’s first commercial project to tap into an EGS resource and produce substantial levels of electricity. This project will demonstrate the viability of geothermal power to generate clean, renewable electricity in several areas in the U.S.

Challenges

- New hard materials for drilling hard rock for deep geothermal wells
- New piping materials that resist the extreme hot corrosion conditions of fluids used to transfer heat in geothermal systems

Materials advances are central to the enduring success and continuing promise of nuclear energy



Of the 104 power producing nuclear reactors in the U.S., only two are less than 20 years old. In 2009, as many as 32 new reactors were under construction in the U.S. These represent an investment of $190 to 250 billion to build. Construction of these plants will supply as much as 40,000 megawatts of clean and affordable electricity.

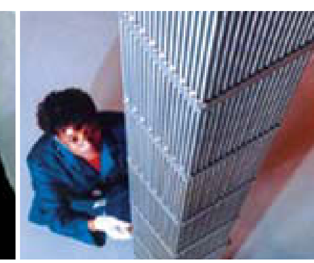
NUCLEAR ENERGY

Nuclear energy is one of the most mature emission-free electrical power generation technologies with low carbon footprint. In 2008, nuclear energy was responsible for over 70% of the power generated in the U.S. from pollution-free sources although it provided only 20% of the nation's electricity. Industry wide, U.S. nuclear power plants operate at over 90% of their rated capacity with a safety record superior to any major industrial technology. Currently, nuclear energy costs less than 2 cents/kilowatt-hour to generate, supports U.S. competitiveness and avoids reliance on foreign petroleum.

New generations of nuclear power plants hold a key to meeting the nation's energy independence and clean energy goals and will be a catalyst for job growth in the energy sector. These new plants will be expected to have passive safety systems, provide more efficient use of nuclear fuel resources and produce lower volumes of nuclear waste, and include operation at higher temperatures or radiation fields. Advanced materials offer the promise to meet the challenges of more demanding operating environments and solutions to effective nuclear waste disposal. Advanced materials developed by the application of computational modeling tools will provide more reliable performance at higher temperatures, in more corrosive environments, in higher radiation fields and for longer times. Such materials developments will spawn new classes of structural materials, advanced ceramics and coatings for fuels, and reactor components and their associated manufacturing technologies.

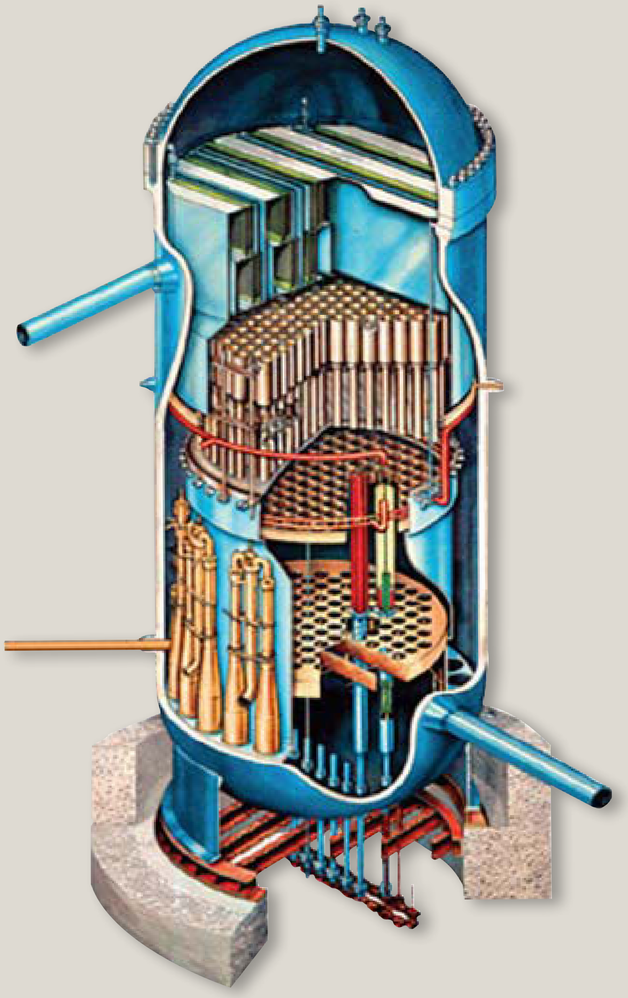
Nuclear power plant on Hutchinson Island, FL

Nuclear fuel pellet



Nuclear fuel assembly

New materials are needed to to sustain the environmental and economic benefits of nuclear power



Nuclear reactor cut-away – courtesy Duke Energy Corporation

Nuclear power plants make substantial contributions to state and local economies

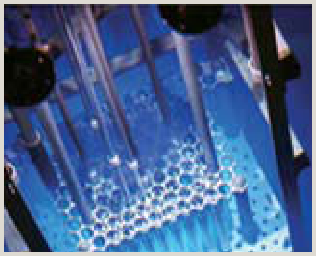
- Each nuclear power plant generates several thousand jobs during construction and over 400 high paying jobs during operation
- The typical nuclear power plant contributes approximately half a billion dollars in the local economy, generates nearly $430 million in sales of goods and services in the local community and nearly $40 million in total labor income (estimates based upon 22 U.S. nuclear power plants)
- The typical nuclear plant generates state and local tax revenue of nearly $20 million each year, benefiting schools, roads and other regional infrastructure; and federal tax payments of almost $75 million per year

Much of the success and reliability of nuclear power plants is the result of advances in materials

- Understanding of long term pressure vessel steel behavior
- Corrosion resistant nickel base alloys
- Dimensionally stable zirconium fuel cladding
- Uranium oxide fuel pellets

Materials R&D is needed to meet advanced reactor system and waste disposal requirements

- Develop new classes of structural materials capable of operating at temperatures 700°F higher than that of today's light water reactors
- Develop advanced computational materials performance modeling tools, key enablers to transition new materials into advanced reactor systems
- Develop proliferation resistant nuclear fuel through advances in ceramics and coatings technology
- Develop new materials to contain nuclear waste for geologic life times

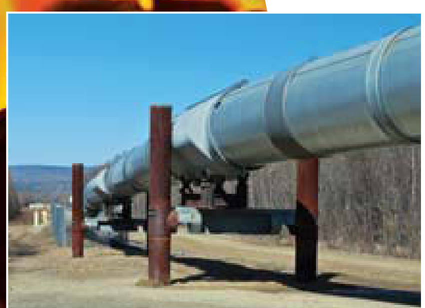


Nuclear fuel rods

Artist rendition of next generation nuclear plant

FOSSIL

Advanced materials increase the efficiency of energy production from fossil fuels



FOSSIL ENERGY

More than two thirds of the current and projected energy generation is from fossil fuels. Clearly this source of energy is of critical importance. Advanced materials have enabled several significant improvements in energy efficiency from systems converting fossil fuels into energy. Whether the fuel is converted to electricity in a combined cycle gas turbine or a boiler/steam turbine system, both systems produce higher efficiencies when operated at higher temperatures. Significant efforts over the past decades have resulted in advanced materials for use in both gas turbines and boiler/steam turbine equipment.

Coatings applied to hot components in gas turbines have allowed higher operating temperatures thereby resulting in efficiency improvements. The newest combined cycle gas turbine plants have net plant efficiencies of 60% or greater.

Advances in materials have also resulted in significant improvements in the overall efficiency of converting the energy in the fuel to electricity. Companies producing advanced materials and boiler manufacturers have worked together to develop new materials for use in supercritical boilers. These new materials and the new power cycles they enable have allowed efficiencies of coal fired power plants to be increased to 42%.

Through the development of advanced coatings and new methods of applying the coatings as well as new materials, significant reductions in fuel consumption with an associated reduction in green house gas and other criteria pollutant emissions have been realized.

Reducing the environmental impact of power generation from fossil fuels

Two significant challenges associated with fossil energy fired power plants are cost effectively reducing carbon dioxide (CO_2) and other criteria pollutants, and taking advantage of unconventional gas reserves.

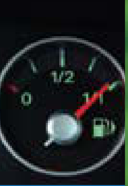
Opportunities to reduce CO_2 and other pollutants in a cost effective way

- Development of advanced materials and coating techniques to allow operation of steam cycles at higher temperatures and pressures to continue to increase the efficiency of the power plant
- Oxygen based processes show significant promise for yielding the lowest cost solution for carbon capture and sequestration. New methods to generate oxygen with lower power requirements are required to reduce the parasitic load on the power plant. Development of oxygen ion selective ceramic membranes has the potential to significantly reduce the cost of producing oxygen at large scales required for power production
- Development of high temperature metals with associated welding and forming procedures will enable construction of advanced ulta-supercritical plants. Efficiency gains of at least 8–10% are anticipated, resulting in substantially reduced releases of CO_2 and other fuel-related pollutants and greenhouse gases by nearly 30%

Opportunities to take advantage of unconventional gas reserves

- Development of improved propping agents that can survive extremely high stresses and are corrosion resistant
- Wear resistant coatings on drills to allow deeper wells
- Development of high strength, corrosion resistant alloys for use in well casings and deep well drill pipe

Electric arc furnace – courtesy CMC Steel Texas
Plasma spray coating process – courtesy Praxair Surface Technologies
Drill pipes
Welding process
Coated turbine blades – Siemens press picture



Advanced materials and chemistry are central to realizing gains from biofuels and hydrogen

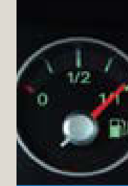
BIOFUELS

Biofuels from the structural portion of plants (cellulosic biomass) and algae offer the potential to replace up to 30% of U.S. transportation fuels, reducing the economic drain of $300 billion per year that leaves U.S. shores for the purchase of foreign oil and increasing the security of our energy supply. Breaking down cellulose, the chemically resistant building blocks of plants, requires aggressive chemical processes and catalysts, and materials with long lifetimes to contain and manipulate these corrosive chemistries. The cellular membranes of algae are rich in the raw materials for production of hydrocarbon chains of gasoline and diesel fuel, but need their own special chemical routes and catalytic materials for conversion. Many of these chemical processes and catalysts exist in nature, such as in the digestive systems of termites, where cellulose is converted to sugars that can be further fermented to alcohol. Advanced materials and analytical tools are needed to understand the subtleties of these natural fuel production processes, and then to design artificial analogs that directly and efficiently produce the desired end fuels.

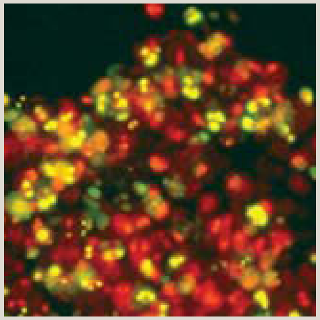
HYDROGEN

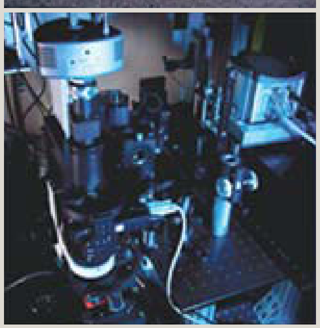
The cleanliness of hydrogen and the efficiency of fuel cells offer an appealing alternative to fossil fuels. Implementing hydrogen-powered fuel cells on a significant scale requires major advances in hydrogen production, storage and use. For transportation, the overarching technical challenge for hydrogen is how to store the amount of hydrogen required for a conventional driving range (>300 miles) within the vehicle constraints of weight, volume, efficiency, safety, and cost. Durability over the performance lifetime of these systems must also be verified and validated, and acceptable refueling times must be achieved. New materials for proton-conducting membranes that operate above the boiling point of water are seriously needed. Catalysts for the oxygen reduction reaction that produces water at the cathode present a special challenge—platinum, the best performing catalyst, is too expensive and limited in supply to meet widespread global transportation needs.

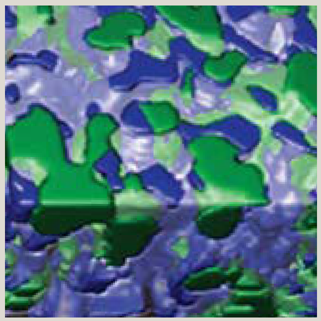
Beyond transportation, hydrogen from coal or biomass gasification offers high efficiency (up to 60%) electricity production for the grid. In these stationary applications high density storage is not an issue; instead the challenges are finding electrodes and oxygen ion-conducting membranes for solid oxide fuel cells that operate in the range 600-800°C. The challenges for hydrogen and fuel cells are overwhelmingly materials-centric, spanning storage in hydrogen compounds, conduction of protons or oxygen ions in membranes, and catalysts and electrodes for liberating or capturing electrons in chemical bonds.



Research and development efforts to meet the materials challenges in alternative fuels







Materials challenges are pervasive in implementing biofuel technologies and in developing new biofuel types

- Corrosion resistant materials for biofuel processing due to the corrosive nature of alcohols
- New catalysts for thermochemical conversion of lignocelluloses to fuels
- Materials for combustion processes
- Materials for capturing CO_2 for using as a nutrient to cultivate algae
- Improved materials and chemical processes for water filtration and desalination
- New analytical tools to characterize important biological processes like lipid formation as a function of gene modification

Plants and algae can directly produce hydrocarbon fuels like methane or octane. The metabolic systems of plants and algae have the complexity to produce these fuels, but have never experienced the selective pressure that would encourage their development. Nanoscale modification of genes and protein assemblies to enable plants and algae to directly produce hydrocarbon fuels is a new frontier of materials research.

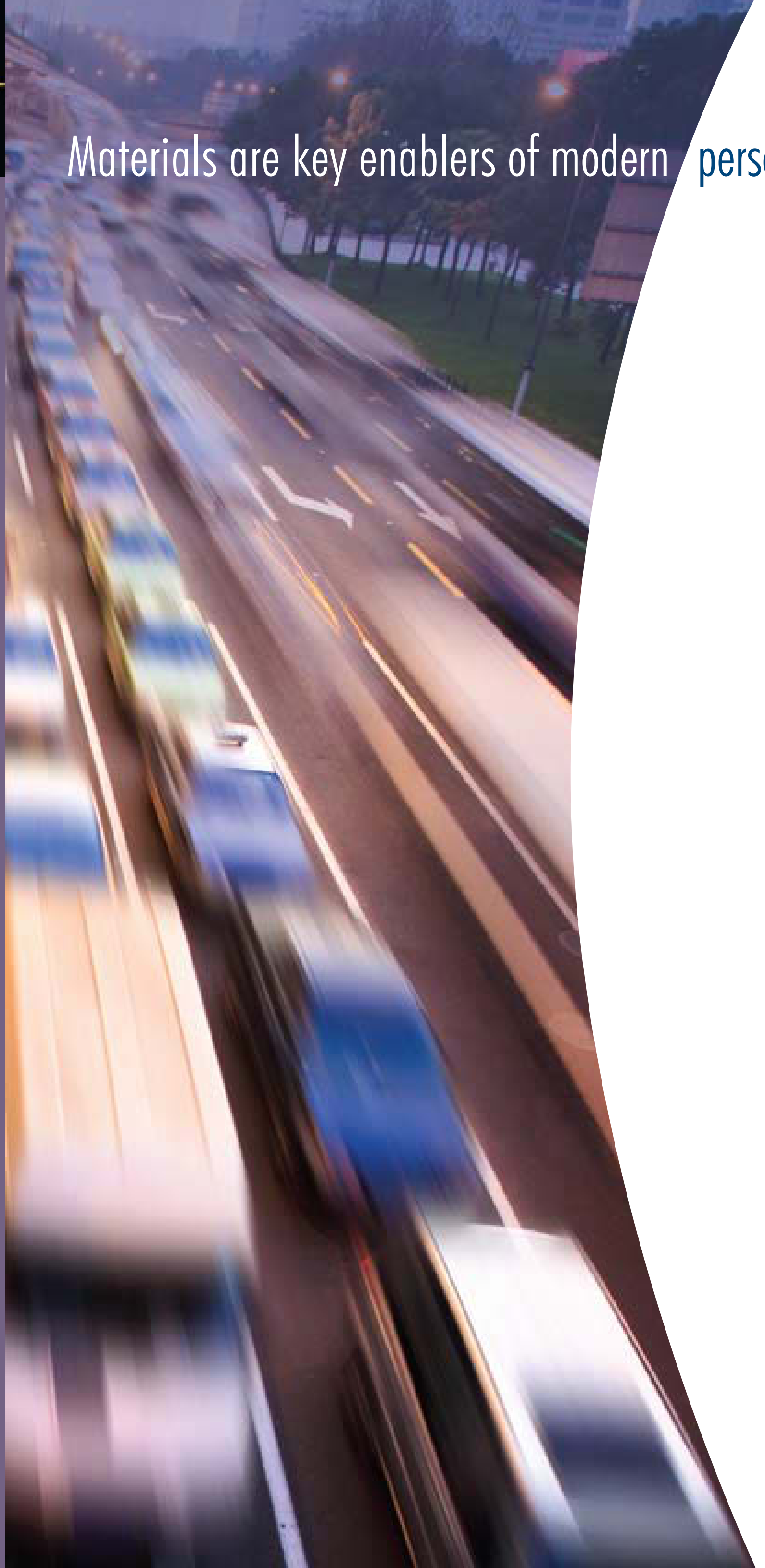
Further research is needed to improve the efficiency, refueling times, reliability and lifetime behavior of materials to enable commercialization of advanced hydrogen powered fuel-cell systems

New low-cost hydrogen compatible materials allow for commercialization of clean energy technologies for transportation, stationary power, portable power and infrastructure. As hydrogen is deployed in each of these technology areas, an increasing demand exists for safe, reliable and low cost hydrogen component materials. Further research is needed to develop

- Low-cost materials resistant to hydrogen-assisted cracking and embrittlement
- Reversible metal hydrides to improve the energy storage capacity of conventional hydrogen storage systems by a factor of two. Their energy storage capacity is up to ten times higher than that of lithium ion batteries

Microalgae for biodiesel
Biomass gasification plant
Advanced microscope for characterization of biological processes – courtesy Sandia National Laboratories
Solid oxide fuel cell microstructure – *Nature Materials (2006)*
Hydrogen storage system prototype – courtesy General Motors Company and Sandia National Laboratories
Fuel cell membrane

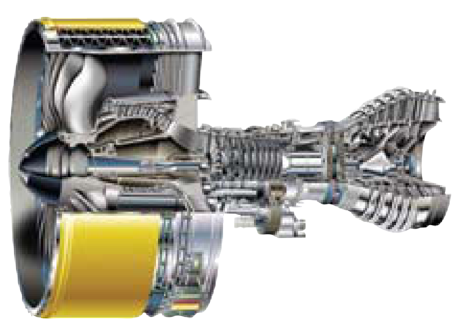
Materials are key enablers of modern personal transportation



ENERGY EFFICIENT TRANSPORTATION

Advances in materials science have been key enablers of our modern lifestyle, including personal transportation (e.g. automobiles), and mass transportation of people and products (by air, truck, rail, ship). For example, advanced rubber composites have dramatically extended the life of tires, and application of new steels has led to exhaust systems that commonly endure for the life of the vehicle. Similarly, the development of corrosion resistant coatings has now enabled long lifetimes of the body structure and improved cosmetic appearance. The challenges of the next generation will be somewhat different, but these challenges will be overcome through developments and application of new or improved materials.

The world's growing dependence on scarce oil resources in combination with concerns related to climate change and greenhouse gas emissions demand the development and deployment of vehicles with reduced petroleum consumption. At the same time, consumer requirements demand that the solutions be obtained at low cost, and preferably without any loss of performance, passenger safety or convenience. The future needs will be met through a combination of increased fuel efficiency, use of alternate fuels or energy sources, and "lightweighting" (or perhaps downsizing). Advanced materials research and development will play an important enabling role in all of these areas, and will contribute substantially to the technological needs of future vehicles.



Advanced jet engine – courtesy General Electric Company

First flight of Boeing 787

Advancing the development and deployment of vehicles with reduced petroleum consumption

Fuel cell powered vehicle – courtesy General Motors Company

Materials challenges and opportunities

Continued reductions in vehicle mass can be achieved through

- Advanced High Strength Sheet Steels (AHSS) developed to enable low-cost crash-resistant vehicle structures to be manufactured with reduced sheet thickness and vehicle weight
- Light metal developments and application of new aluminum, magnesium, titanium alloys, etc.
- Carbon fiber composites may also play an increasing role, especially where the weight savings can justify the much greater cost

Larger technology leaps will be associated with

- Electrification and alternate fuels such as hydrogen
- New materials developments to enhance energy storage (advanced batteries) and conversion
- Advanced magnetic materials and electric motors
- Membranes and catalysts for fuel cells
- Structural materials for high power-density drivetrains
- New material formulations and manufacturing processes to improve tire performance and fuel efficiency

Tire cut-away – courtesy Goodyear Tire & Rubber Company

Crash test – courtesy Insurance Institute for Highway Safety

Passenger train

Advanced materials significantly impact the energy efficiency of building systems

ENERGY EFFICIENT BUILDINGS

The building sector in developed countries accounts for 40% of primary energy consumption, 70% of electricity use and 40% of atmospheric emissions (more than those associated with transportation). In addition to human behavior, poor design and inadequate use of technology contribute to this excessive use of energy in buildings. Despite these numbers, tremendous progress has been made in energy efficiency during the last 10-20 years as a result of advances in materials leading to new green insulation materials, low emissivity windows and compact fluorescent lighting.

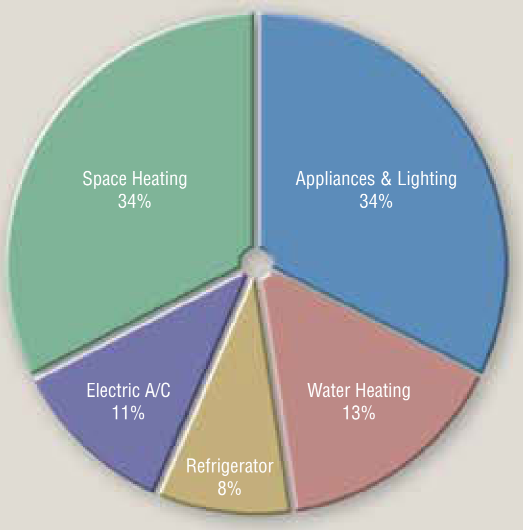
There are numerous places in a building where materials impact energy efficiency but they must work together to have maximum benefit. Integrated building systems, therefore, are essential to energy efficient and net-zero buildings. These building systems utilize new materials and integrated design approaches, but require a change in culture to bring designers, contractors, utilities and end-users together in the process. At present, net-zero buildings are technologically possible but are a major challenge. Achieving cost effective net-zero building systems requires lower cost multifunctional materials, more efficient solid state lighting materials, more corrosion resistant metals and improved manufacturing processes.

Low emissivity window

Solid state lighting

Compact fluorescent bulb

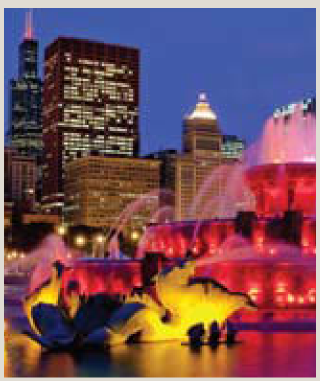
Materials research is fundamental to net-zero energy buildings



U.S. residential energy use

LED surgical lighting

Cool roofing



Decorative solid state lighting

Materials have increased the energy efficiency of today's buildings

- Low emissivity glass, significantly lowering the initial investment costs for heating and cooling
- Compact fluorescent lighting and light emitting diodes (LEDs), reducing lighting costs and heat loads
- Cool roofs, saving energy
- High efficiency fiberglass insulation

Areas of further research and development

Many opportunities exist for materials advances to reduce the energy use and atmospheric emissions attributed to the building sector. The energy and cost performance of walls, roofs, windows, mechanical systems, and on-site renewable electrical and thermal systems can all be improved through advances in materials.

- Phase change materials capable of storing or releasing large amounts of energy in the walls, floor and roof, thereby saving energy and smoothing the thermal profile
- Optical metamaterials and photonic crystals potentially enabling optical engineering using structured inorganic nanomaterials to positively influence the solar gain and provide long term durability
- Electrochromic, suspended particle and liquid crystal glasses responding to occupants and external conditions to actively control both light and solar gain

Potential impact

Low emissivity (low-e) windows are double or triple panes with a multi-layer coating consisting of six different materials in a stack of 18 invisible, microscopic thin films. If all existing buildings in the U.S. and those planned for the next five years used such low-e windows, the U.S. would save $40 billion in gas and electric costs each year and reduce annual CO_2 emissions by 123 million tons (equivalent to 20 million cars on the road).

Energy saving lamps and light emitting diodes (LEDs) use 80% less electricity and last 15-50 times longer than incandescent light bulbs. These are used today in vehicle headlights, displays and general lighting systems. Switching to energy saving lamps and LEDs has the potential to reduce annual CO_2 emissions by nearly 450 million tons worldwide.

Materials play an important role in storage and long distance transmission

ENERGY STORAGE AND TRANSMISSION

There are about 160,000 miles (257,500 kilometers) of transmission lines of 110 kilovolts and above located throughout the continental U.S. They transmit electricity, often over long distances, between power plants and substations. Energy resources (fossil fuels, nuclear, hydroelectric, renewable) provide regional concentrations of power that do not necessarily match regional consumption in either time or use or geographical distribution. Solutions include transmission of power over interstate distances and storage at both the source and the point of use, or increased use of distributed energy generation which alleviates transmission but still requires storage.

Energy storage has many benefits. It allows timing of delivery to match demand, mitigates and eliminates intermittency in power generation or bottlenecks in delivery, eliminates black-outs and brown-outs, and reduces coal and greenhouse gas production by replacing safety margins such as power over-generation required from utilities.

Electric power transmission, the bulk transfer of electrical energy from generating plants to substations, requires using high voltage and low resistance. Transmission lines, when interconnected, are referred to as power grids. North America has three major grids: The Western Interconnect, The Eastern Interconnect and the Electric Reliability Council of Texas (ERCOT) grid.

High temperature superconducting tape – courtesy American Superconductor®

Superconductor power distribution tape – courtesy Sandia National Laboratories and Zenergy Power

Advanced materials are needed to enable integration of renewable energy sources and controls

Electrical transmission – courtesy Argonne National Laboratory and Platts, a division of the McGraw-Hill Companies, Inc

Challenges limiting significant integration of renewable energy sources and controls include increasing demand, reducing dependence of fossil fuel and reducing CO_2 emissions. Development and use of advanced materials will provide opportunities to improve the electric grid in areas such as new grid concepts (smart-, green- and micro-grids); control systems for protection, measurement and communications; storage; scalability; security; and generation.

Energy storage solutions require short-term as well as long-term high capacity storage methods and materials

Short-term

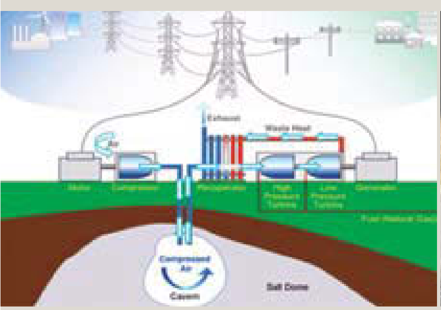
- Supercapacitors—carbon nanotube or other electrode materials with high internal surface area, high polar electrolytes
- Batteries—deep discharge and high cycle materials (lithium-based batteries, lead acid with new electrodes, flow batteries)

Long-term

- Compressed air energy storage—large scale caverns (salt, rock, others)
- Thermal energy storage (low freezing point liquids)

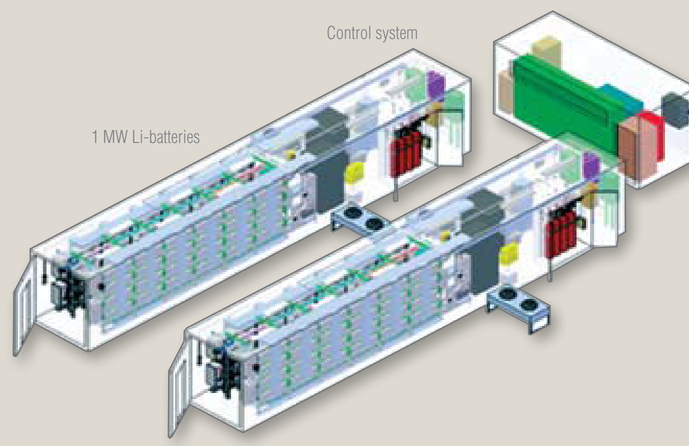
Improved transmission requires high voltage and low resistance

- Low conductivity materials and materials with high dielectric breakdown including copper and copper-aluminum alloy conductors; existing and new superconductors; glass, air, vacuum and new insulators



Compressed Air Energy Storage (CAES) system

Alabama 110 MW CAES Power Plant, Alabama Electric Cooperative's McIntosh



Lithium ion battery power conditioning system – courtesy The AES Corporation

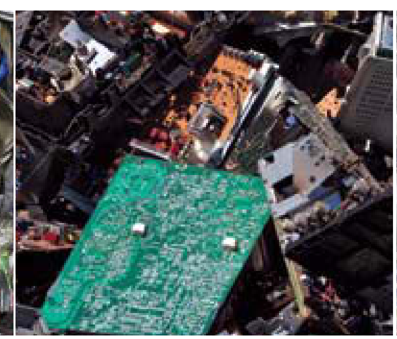
Meeting the needs of the present without compromising the ability of future generations to meet their own needs

SUSTAINABILITY

Sustainability is a process, a new approach to development and environmental stewardship in which scientific analysis is used to guide decision making to continually improve profitability, society and the environment. It is implemented through creation of short term goals and development of scientific tools for full life cycle impact analysis (measurements, standards, models and data).

Materials science has an immediate and direct connection to sustainability through

- Efficient use of energy-intensive materials that we use everyday. Recycling aluminum, steel, plastic and glass yield enormous energy savings
- Retention of strategic materials—scarce but critical materials for technology. The U.S. relies on many other countries for strategic materials whose supply could be restricted by military or political actions. Specifically, the U.S. depends entirely on its imports of chromium for stainless and tool steels, and high temperature furnaces; cobalt for gas turbines and jet engines; rare-earth elements, notably neodymium for levitated wind turbines; manganese for steelmaking; platinum for electronics; and lithium for batteries
- Mitigation of corrosion, pollution and other negative impacts of technology and economic growth



Materials research can build our legacy to future generations

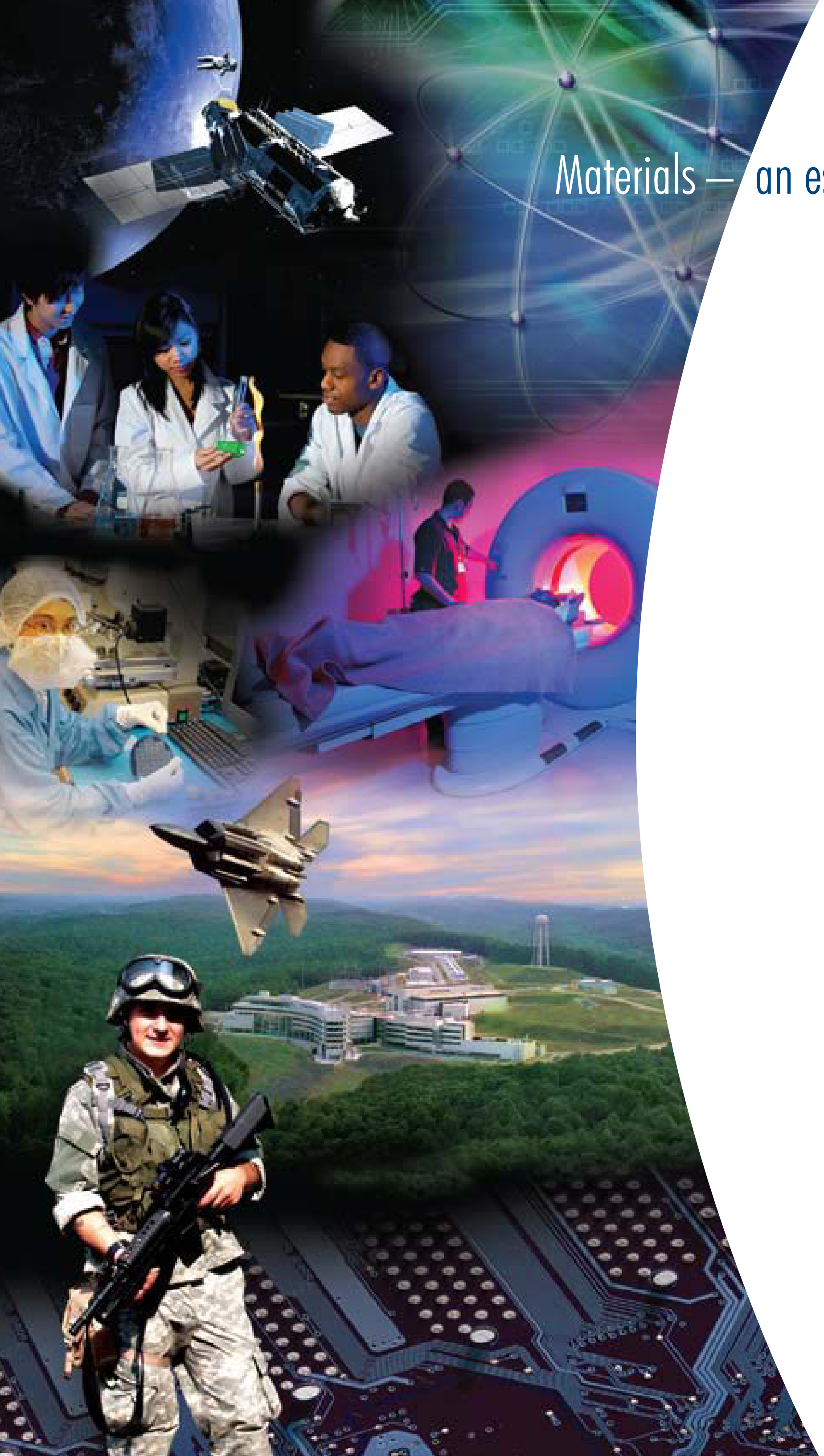
Sustainability is much more than environmental stewardship. Its concepts include: renewable energy, clean energy technology, renewable feedstocks, green manufacturing, materials management (substitution, recycling, reuse, repurpose, life cycle analysis), and water and air management.

The greatest challenge for materials scientists and engineers is to design, develop and commercialize recycle-friendly materials, products and systems. Opportunities to make significant contributions include

- Develop improved furnace materials for metal melting, gas management and refinement at higher, more efficient temperatures
- Develop materials extraction technologies to separate strategic materials in steels, vehicles, computers, solar systems, and other mass-produced products
- Develop alternative materials for electronic semiconductor thin films, metal connectors and contacts that are abundant, lower cost or nontoxic
- Develop greener manufacturing and energy production processes with materials that produce less air and water pollution, that purify water for drinking, and capture pollution before it reaches our atmosphere

Recycling:
Metal
Electronics
Paper
Rubber
Glass

Water purification



Materials — an essential foundation for our economy and national security

The connection is clear between materials research and the energy technologies that we rely on today and those we need for our future. Materials research and development is a global pursuit. It covers a broad set of science and engineering disciplines and engages researchers across academia, industry and government laboratories. Materials research seeks to understand fundamental physical and chemical properties, and then use that understanding to improve the technology base that we count on to meet our needs for energy, national security and defense, information technology and telecommunications, consumer products, health care, and more.

Advanced materials and the manufacturing techniques to make these materials can give our economy a competitive advantage for job growth. The demand for energy in the U.S. continues to rise. The U.S. Energy Information Administration projects the U.S. energy need will increase by twenty thousand megawatts each year for the next twenty-five years. The global demand for energy is increasing even more rapidly, especially in developing countries. The global competition will be fierce to develop advanced energy technologies to meet this demand and do so in a way that is sustainable and environmentally responsible. Being at the forefront of materials research will allow the U.S. to compete aggressively in important domestic and global energy markets, enabling us to prosper economically and address our national energy security.

Advances in materials science impact our lives every day—from strong, lightweight materials at the heart of commercial and military planes, to advanced integrated circuits that drive our computers and telecommunications, to the diverse array of high-performance plastics that we see everywhere. Beyond energy, materials research has led to the powerful diagnostic instruments used for healthcare (e.g. MRI), the improved armor saving the lives of our soldiers, and the satellites and spacecraft that let us communicate (e.g. GPS) and explore space.

Materials developments are often invisible to users of technology, but they are at the heart of so many important advances. The breakthroughs of the past took time and patient investment in the people and the infrastructure for scientific research. Creating the science and engineering needed for a prosperous and sustainable energy future will take the same long-term approach. This means investing in the leading-edge research and educating the next generations of scientists and engineers needed to secure our country's technological leadership.

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For more information on this booklet or materials research, contact any of the partner organizations. Copies of Advanced Materials for Our Energy Future are available from the Materials Research Society.

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