U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

LINKING TRANSFORMATIONAL MATERIALS and PROCESSING for an ENERGY EFFICIENT and LOW-CARBON ECONOMY: *Creating the Vision and Accelerating Realization*

Vision Report of the Energy Materials Blue Ribbon Panel

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The *Linking Transformational Materials and Processing for an Energy Efficient and Low-Carbon Economy: Creating the Vision and Accelerating Realization* project draws from an Energy Materials Blue Ribbon Panel of experts representing academia, industry, and government. Panel members include:

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CONTENTS

SUMMARY AND KEY RECOMMENDATIONS

Innovation in materials and material processing technologies is critical to achieving the longer-term objectives of an energy-efficient and low-carbon world. It is not enough to identify the chemical compounds or basic synthesis processes that enable advanced materials. These developments must be coupled with sustainable, energy-efficient, low-carbon-emitting, and economical processing in order to be translated into commercial products. While significant efforts have been made to identify breakthrough materials and their benefits, less attention has been given to the integration with materials manufacturing, including synthesis science, needed to propel promising materials candidates across the "valley of death" into cost-effective application at scale.

Linking Transformational Materials and Processing for an Energy Efficient and Low-Carbon Economy: Creating the Vision and Accelerating Realization seeks to better define the areas where materials science and engineering can make the most significant contributions. This initial report presents a vision for the future developed by the Energy Materials Blue Ribbon Panel.

The Panel's findings are that materials science and engineering (MSE) breakthroughs can be the key enabler for many energy efficiency and carbon reduction solutions. The Panel identified several areas where MSE can have the greatest potential impact:

- Battery technologies
- Industrial energy efficiency
- Vehicle energy efficiency
- Solar energy
- Nuclear fission and fusion
- Fuel cells and hydrogen technologies

The Panel also considered the materials and processing-driven elements that could make the highest impact across the areas of energy source and use. Four cross-cutting materials science and engineering themes emerged:

- **Functional surface technology**, including coatings, thin films, and catalysts
- **Higher-performance materials for extreme environments**, including thermal, radiation, chemical, and mechanical stresses
- **Multi-materials integration in energy systems** comprising design for manufacturability, joining, and multi-materials compatibility
- **Sustainable manufacturing of materials**, incorporating novel synthesis, net shape processing, closed loop recycling, resource recovery, and materials substitution

Reactor Vessel Head (Courtesy: U.S. Nuclear Regulatory Commission)

The Panel also identified a number of policy areas that can contribute to accelerating progress. These include:

- **Significant, sustained investment in materials science and engineering research, development, demonstration, and deployment.** Consistent national policies that create the long-term confidence needed to marshal private-sector resources are required as a key component.
- **Heightened collaborative efforts** from different parts of the federal government (U.S. Department of Energy, U.S. Department of Defense, and others), in conjunction with industry, academia, and other institutions (e.g., professional societies, venture capital, media, and international collaborators).
- Guidance from all institutions with vested interests in forming **a national energy roadmap** and full engagement with these entities to ensure that successful energy developments are aligned with this roadmap.
- **A concerted national effort to cultivate and educate the skilled workforce** that will be required for the future energy sector.
- **New policies and practices** to enable industry and universities to access the multibillion dollar annual investments in the United States national laboratories. Processes that move at the speed of business and that reduce intellectual property barriers are particular areas where improvements are necessary.

In summary, materials science and engineering breakthroughs will enable the United States to greatly reduce the energy and carbon intensity of its economy. Modest near-term improvements in today's massive energy infrastructure deliver incremental yet significant improvements. Meanwhile, transformational innovations in MSE hold promise to revolutionize the way the nation produces, transports, and consumes energy in the long term. By pursuing a balanced approach to material and manufacturing science research, development, and demonstration, the United States can deliver near-term improvements while also laying the foundation for radical advances in the longer term.

Hard X-Ray Nanoprobe (Courtesy: Argonne National Laboratory)

1. INTRODUCTION AND PROCESS

Innovation in materials and material processing technologies holds great promise to improve energy-related technologies in a myriad of ways. Materials and their manufacturing processes are critical to achieving the longer-term objectives of an energy-efficient and low-carbon world, both in terms of their integral impact on specific renewable and non-renewable energy technologies as well as the greenhouse gas impact of their manufacturing processes. New materials combined with innovative processing techniques can accelerate the transition of promising systems that deliver increased sustainability, energy efficiency, reduced carbon emissions, and ultimately, strategic advantage for the United States.

The Minerals, Metals, and Materials Society (TMS), with support from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program and funding through the Oak Ridge National Laboratory, is seeking to address these issues and opportunities through this two-part study, *Linking Transformational Materials and Processing for an Energy Efficient and Low-Carbon Economy: Creating the Vision and Accelerating Realization*.

The purpose of this study is to uncover opportunities for transformational impact by:

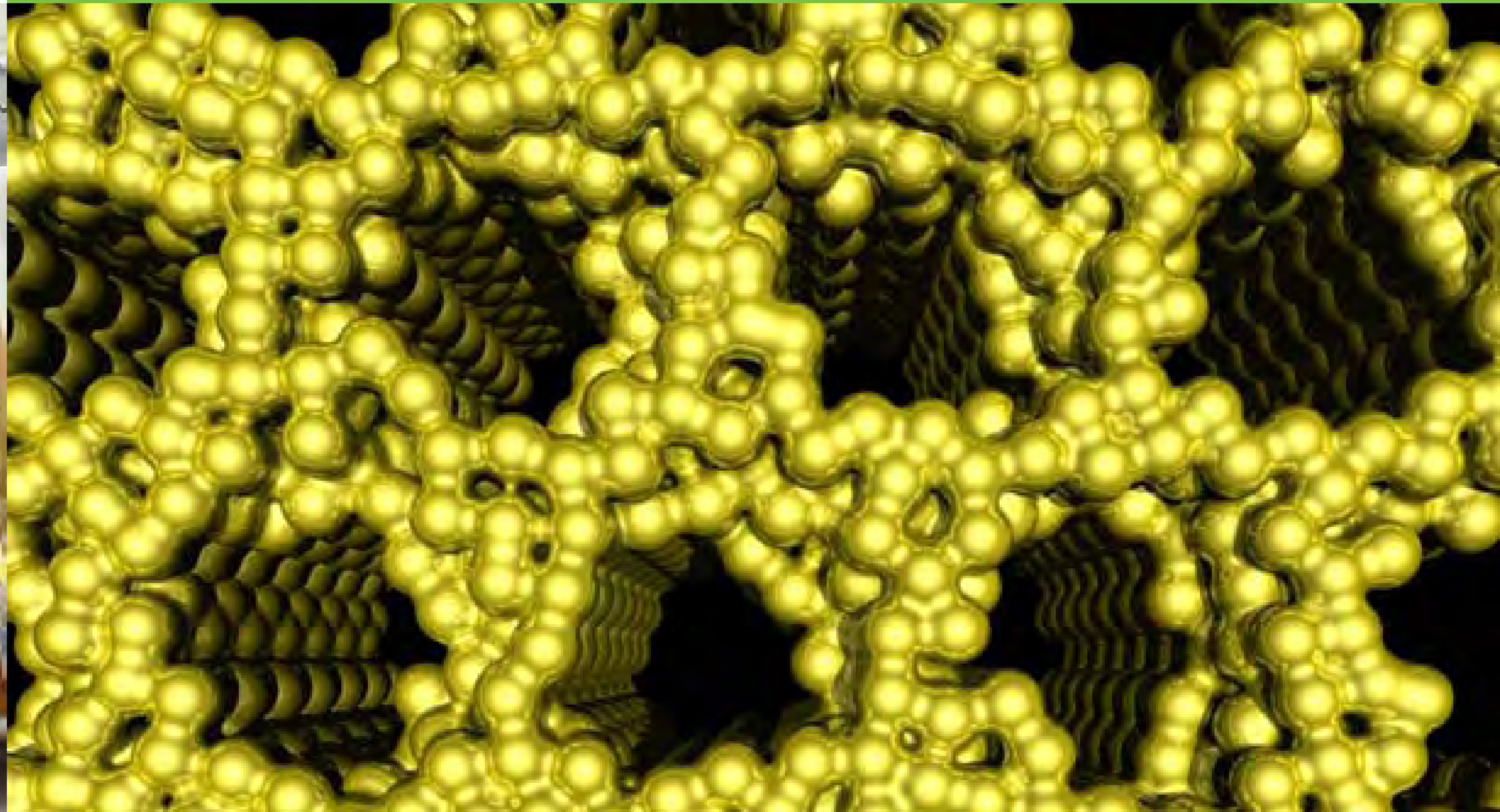
- Identifying areas where materials science and engineering (MSE) have the greatest leverage
- Taking a holistic materials and processing perspective and identifying common elements
- Seeking ways to compress the time from discovery to implementation
- Informing the focus for the nation's materials R&D portfolio

Phase I of the study entailed convening the Energy Materials Blue Ribbon Panel, consisting of 21 materials community thought leaders representing industry, academia, and government, to:

- Assess opportunities for transformational MSE contributions to energy sources, energy carriers and transmission, and energy use.
- Identify high-impact, cross-cutting materials and processing technologies.
- Evaluate the status of the U.S. science and technology infrastructure in these areas.

In Phase II of the study, four Technical Working Groups will be formed to develop technical roadmaps for each of the four cross-cutting materials science and engineering areas. A final report consolidating these roadmaps into a single blueprint that addresses interdependencies will be published by the end of 2010.

Nanostructured Platinum (Courtesy: National Science Foundation/Credit: Scott Warren and Uli Wiesner, Cornell University).



2. ABOUT THIS VISION

In a collaborative process designed to foster creative synergy across institutional boundaries, an Energy Materials Blue Ribbon Panel of industrial, academic, and government leaders (listed on the inside cover of this report) contributed key information and direction to inform this vision document. Panelists drew on their knowledge of MSE to explore the critical role that innovation in materials and material processing technologies will play in addressing U.S. energy and carbon challenges.

Materials science and engineering (MSE) is used in this report to represent the science and engineering of the full spectrum of materials, and includes both primary and secondary materials, manufacturing and synthesis processes, system integration, and performance.

This vision aims to accomplish the following:

- Broaden awareness of the potential that MSE holds for reducing and even transforming the U.S. economy's energy and carbon intensity.
- Serve those who are working to realize that potential.
- Inform the focus of the nation's materials R&D portfolio.

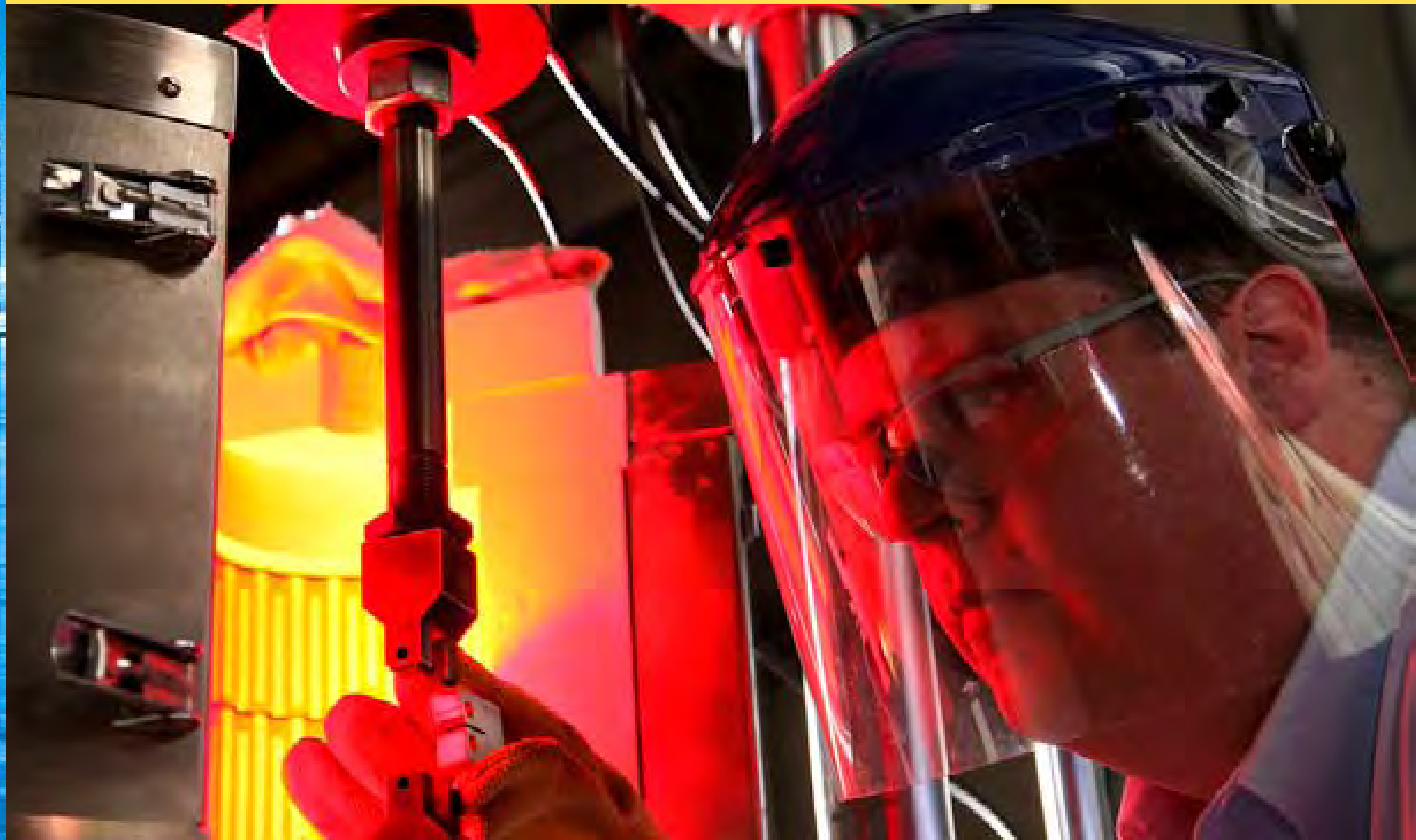
The vision document is specifically aimed at the following audiences:

- Government leaders seeking to target MSE support toward revolutionizing the U.S. economy's energy portfolio and environmental impact
- Members of the MSE field seeking to most effectively drive achievement of the nation's goals for improved energy efficiency and reduced emissions
- Members of the public who are concerned about efforts to address energy and its associated environmental impacts

Though roadmaps and reports that identify basic research needs currently exist for specific energy technologies or applications, this project has no direct precedent. Previous efforts have not attempted to address both energy and environmental goals while maintaining a dual focus on materials science and strategic needs. These previous efforts, though less directly related to the Panel's focus, still offer background and shape the context for debate.

Figure 1 serves as a schematic to map prior work and identifies the position of this Energy Materials Blue Ribbon Panel's work among other efforts. It

Cast Stainless Steel Testing (Courtesy: Oak Ridge National Laboratory)



sorts projects by the topic or topics they address and identifies the position of this Blue Ribbon Panel's project among other efforts. The topics include:

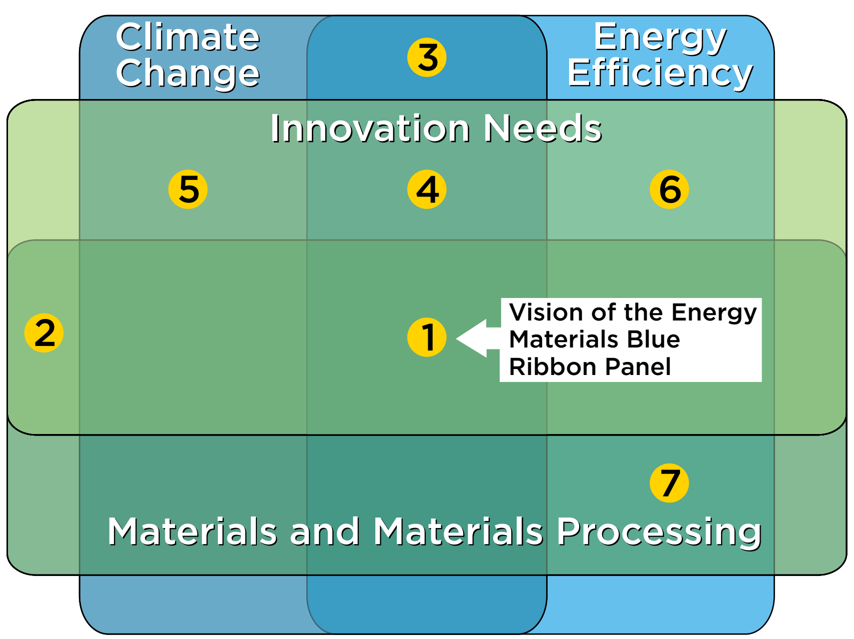
- **Climate Change** (left column) – Work oriented toward achieving the goal of reduced greenhouse gas emissions
- **Energy Efficiency** (right column) – Work oriented toward achieving the goal of providing efficient, secure energy
- **Innovation Needs** (top row) – Work that identifies strategic needs for innovation
- **Materials and Materials Processing** (bottom row) – Work addressing MSE topics, including materials processing

Several other studies have looked at the intersection of two or three of these areas of work. Many technology roadmaps (point 2) address materials and materials processing innovation needs that, if filled, would meet one particular industry's needs (e.g., chemicals, mining, additives manufacture, photovoltaics). Several groups have elaborated policy needs for climate change and energy security and have prepared policy roadmaps (point 3). Published documents such as the U.K. report *Towards a Low Carbon Future* discuss research and innovation needs to forestall climate change and strengthen the energy future (point 4). At least one strategic plan, the *U.S. Climate Change Technology Program Strategic Plan*, addresses research and innovation needs to enable the provision of low-carbon energy (point 5). Similarly, at least one other strategic plan, the *National Electric Delivery Technologies Roadmap*, names "critical technologies" to enable secure, efficient electrical energy (at point 6), and *nanoRoad: Nanomaterial Roadmap 2015* connects existing nanomaterials to potential energy-sector applications (point 7).

The breadth of this past work illustrates not just the timeliness of this study, but that it is also in line with government priorities and complemented by previous efforts. This study is unique in its combination of a broad perspective on energy and climate change coupled with a focus on the potential contributions of materials science and engineering through materials and processing innovations—the intersection of all four sets shown in Figure 1.

Additionally, this study focuses on the energy situation in the United States within a global context. While the Panel clearly recognizes the global nature of the energy industry, the projections for significant energy demand growth in countries such as China and India, and the global scale of the climate change challenge, this study primarily emphasizes how advances in MSE can improve the domestic energy situation.

Figure 1. Energy Materials Blue Ribbon Panel project scope addresses both climate change and energy efficiency by identifying innovation needs in materials and materials processing disciplines.



3. CHALLENGES AND OPPORTUNITIES

Providing energy sustainably is the defining challenge of our age. In the coming decades, energy availability and climate change will grow into major economic and security issues in nearly every corner of the world. The inherent tie between increased energy consumption and improved quality of life creates a pressing challenge as global economic growth brings millions of people out of poverty, particularly in developing economies. The United States is well positioned to transform its energy sector to help reduce the tension between increased economic activity and reliance on fossil fuels. By revolutionizing its energy sector, the United States can not only improve the sustainability and security of its economy, but can also establish global leadership for clean energy technologies and help fulfill the basic human needs of millions of people around the world.

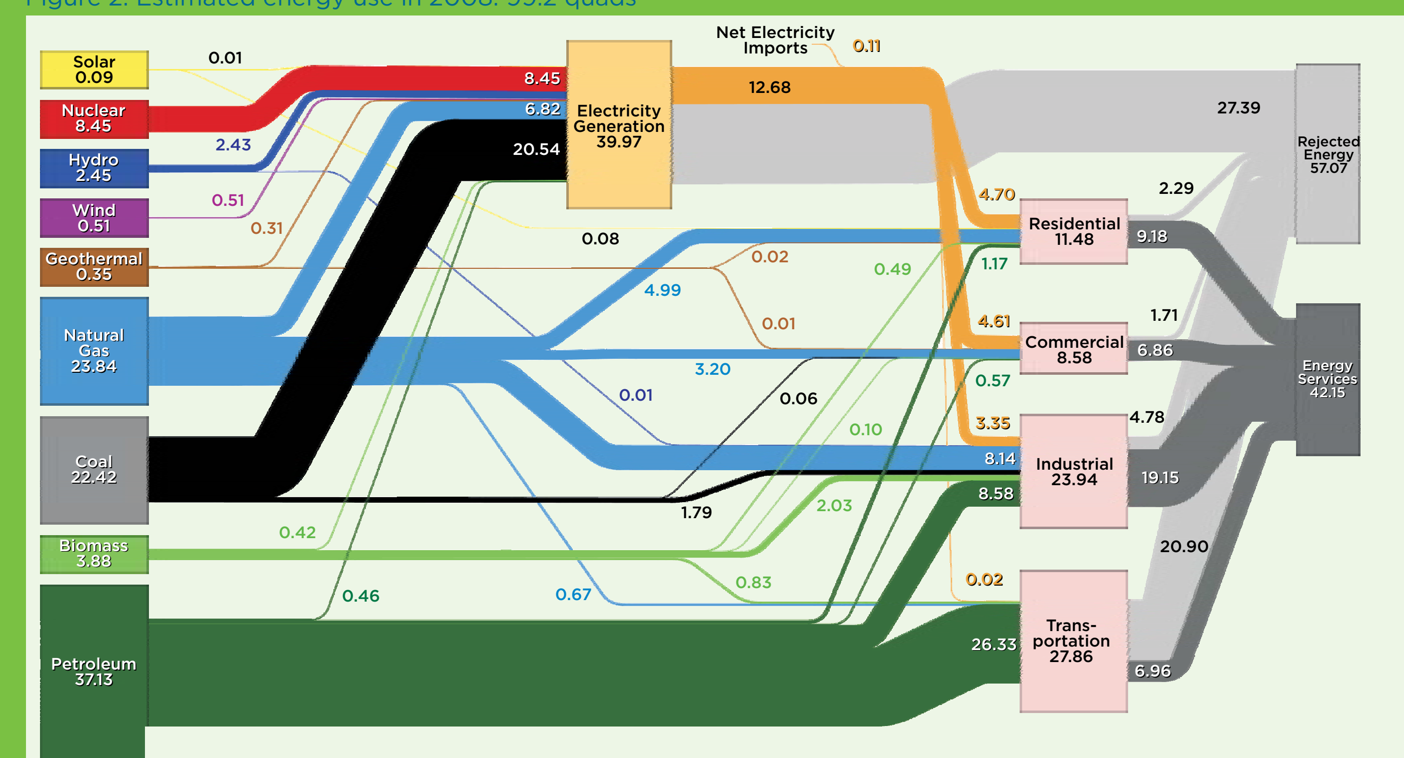
U.S. Energy Use and Carbon Emissions

The United States currently depends heavily on fossil fuels, especially for transportation, industrial use, and electricity generation. As illustrated by the following energy flow diagram in Figure 2, the U.S. energy supply is derived mainly from petroleum, natural gas, and coal, and it is consumed by the four largest demand sectors: transportation, industrial, residential, and commercial. Only seven percent of U.S. energy consumed in 2008 was drawn from renewable sources.[1]

The largest overall domestic sources of carbon emissions include electric power; transportation; and the direct use of fossil fuels in residential, commercial, and industrial applications as illustrated in Figure 3. Together, the industrial and transportation sectors are responsible for approximately half of all U.S. energy consumption and produce 63 percent of the country's carbon emissions.[2]

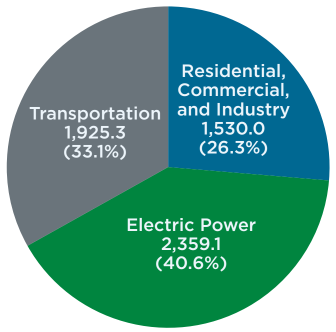
Approximately 86 percent of all energy consumed in the United States is derived from fossil fuels; approximately one third of these fossil fuels are imported petroleum and natural gas. Such widespread dependence on nonrenewable, high-carbon, imported energy sources presents a clear grand challenge to the United States and provides

Figure 2. Estimated energy use in 2008: 99.2 quads[3]



1. Source: Energy Information Administration
2. Source: Energy Information Administration
3. Source: Lawrence Livermore National Laboratory and the U.S. Department of Energy, 2009

Figure 3. Energy-related CO_2 emissions by end-use sector, 2008



2008 Total – 5,814.4
Million Metric Tons Carbon Dioxide Equivalent[4]

strong incentive to reform the state of the U.S. energy sector. The following sections present the multilayered, interrelated challenges that hinder efforts to transform today's energy consumption and carbon emission patterns.

Revolutionizing the U.S. Energy Infrastructure

The electronics and information technology industries have been models of rapid technological innovation during the past 20 years. Many people experience technological change at the pace of Moore's law, which has successfully predicted that computing power would double about every two years. This trend has set the pace for continual breakthroughs and demonstrates the potential impact of sustained innovation in a family of technologies. Each year, cell phones and audio devices shrink in size, deliver increased functionality, and become less expensive.

The energy sector is fundamentally different from the electronics industry. Energy infrastructure, including the energy sector's wells, mines, pipelines, gridlines, trucks, and meters, depends on collections of technologies that come together in massive systems that require substantial investments of time and money to build, operate, and maintain. Revolutionizing the U.S. energy infrastructure on the same scale as electronic breakthroughs would require decades, billions or trillions of dollars, and constancy of political will, often for little immediate return.

Policymakers, scientists, and the public would all mutually benefit if the effort required to address energy and carbon challenges was recognized as a long-term, continuous investment. The very nature of the energy sector demands multi-disciplinary solutions that cross many organizations and industries and often require displacement of long-lived, highly capital-intensive infrastructure. Therefore, significant, sustained R&D effort over decades will be required to realize continuous improvement of existing products and services and breakthrough applications of new technologies.

While the challenge of transforming the U.S. energy sector is great, cumulative past investments demonstrate that such challenges are surmountable. A national shared understanding of the realistic pace of change and the magnitude of the investments required is needed to support a shared constancy of purpose.

Integrating Systems of Energy Systems

For generations, engineers have effectively integrated diverse technology components to develop effective systems such as turbines and vehicles. To realize the scope and magnitude of change required to meet the energy and carbon challenges, the United States must now address the complex challenge of integrating systems of systems. One example is the electricification of vehicles powered by renewable energy sources. To fully realize the benefits of this concept, electric vehicles must be integrated with significant onboard energy storage capacity and a smart electric grid powered by increasing amounts of intermittent, distributed, renewable resources such as solar and wind.

Such complex, interdependent undertakings require not only breakthroughs in MSE and a host of other technologies, but also innovative government solutions. There is a great opportunity to develop a nationwide systems approach to energy policy. A national-level strategic plan and roadmap could dramatically advance the identification and commercialization of needed technologies and streamline development efforts. Aggressive, yet realistic, national targets would inspire a more deliberate approach to addressing the challenges of integrating the diverse, interwoven system of technologies and subsystems that compose the energy sector.

4. Source: Energy Information Administration

Competing in the Global Clean Energy Market

Many countries, including the United States, have deliberate national policies to support their industries' competitiveness and to direct the formation of emerging energy-related systems. The United States' position at the forefront of the global clean energy industry is not guaranteed. China, for example, is investing significantly in clean energy technology and is establishing a strong presence in the newly forming solar energy market. Clean technology and green innovation are receiving a global response to a global problem. While this trend presents an optimistic view of the world's energy future, it also poses a threat to the United States' future international competitiveness.

U.S. businesses have demonstrated great flexibility and innovation in responding to market demands and crises. It is time to turn that same promising resource of commercial know-how toward addressing energy and carbon challenges. Enormous opportunities exist for policymakers, scientists, engineers, and other stakeholders to address future energy and climate change risks. Given the United States' vast intellectual, technical, and economic resources, it is well positioned to develop the cost-effective solutions to energy and carbon challenges that the nation and the world require.

Developing Tomorrow's Energy Workforce

A skilled and educated workforce is the single most critical determinant of successful innovation. Enhancement of Science, Technology, Engineering, and Mathematics (STEM) education at the K-12 level and more effective curricula at the undergraduate and graduate levels are needed to capture the interest of today's youth and develop the future's clean energy technology workforce. Updated, relevant courses, laboratory experiences, and industry-sponsored energy research projects can all play an important role in refreshing the education of tomorrow's young people.

University enrollments in sciences and engineering remain relatively flat in recent years, with much of the growth occurring in disciplines, such as bioengineering, that are somewhat removed from the energy sector. Ironically, due to the emerging technologies in the areas of biological and life sciences and nanotechnology over the last two decades, many of the materials science and engineering departments have eliminated mineral beneficiation, extractive metallurgy, and chemical thermodynamics from their curricula; yet, these topics are the fundamentals that will be required to be able to chart a sustainable future regarding materials resources, recovery, and recycling. Bachelor's and master's curricula are also weak in critical areas of materials processing, welding, corrosion, joining, process engineering, and other classical areas of MSE. A trend in hybridization of degrees is creating workers with a good sense of "cutting edge" topics such as carbon nanotubes at the expense of deep knowledge of fundamental areas, such as electrochemistry, high-temperature materials, physical metallurgy, materials synthesis, and manufacturing.

At the graduate level, American students are only a fraction of total graduate enrollments in the STEM disciplines. Meanwhile, global economic development is creating unprecedented opportunities for non-U.S. students to return to high-paying, challenging careers in their home countries after completing their academic training in the United States. The United States has reaped great rewards from being a magnet for technical talent around the world, particularly because many of these bright young minds have chosen to remain in the United States well beyond their academic years. Despite the pressing need to prevent this loss of talent, U.S. policy restricts many foreign students who wish to join the domestic workforce after attaining advanced degrees in this country from doing so. Combined with the shortfall of indigenous technical talent provided by the U.S. primary and secondary system, the United States is facing a serious threat to its global supremacy as a center for innovation.

4. VISION FOR THE IMPACT OF MATERIALS SCIENCE AND ENGINEERING

The viability of every energy source—from the conventional to those under development—and opportunities for increased energy efficiency depend on the enabling power of materials technology. As the world takes deliberate steps to shift energy consumption and carbon emissions to more sustainable schemes, MSE will serve as a key enabler.

Vision of the Energy Materials Blue Ribbon Panel

Materials science and engineering (MSE) breakthroughs will enable the United States to greatly reduce the energy and carbon intensity of its economy. Near-term improvements in the materials employed in today's massive energy infrastructure will deliver significant payoffs that will serve a critical role in the ability of the United States to meet its national energy needs. Meanwhile, transformational innovations in MSE hold promise to revolutionize the way the nation produces, transports, and consumes energy in the long term. By pursuing a balanced approach to material and manufacturing science R&D, the United States can deliver near-term improvements while also laying the foundation for radical advances in the longer term.

Priority Application Areas

The need to meet national energy and carbon management goals creates opportunities for significant MSE contributions and advancements in applications that influence large segments of the energy sector. The Energy Materials Blue Ribbon Panel identified the areas in which MSE can most substantially contribute to energy savings and carbon management. The panel used two interconnected criteria to make its selections:

1. The components of the energy sector that will make the largest contributions to improving the U.S. economy's energy and carbon intensity
2. The areas where MSE advancements critically enable the realization of those large contributions

Typical approaches to considering opportunities for transformation in the energy sector have primarily focused on high-risk, high-payoff technologies that will provide new sources of clean energy in the long term. However, the Panel believes that the approach should be more balanced, because transformative effects can also occur with nearer-term, more incremental developments applied broadly. As a result, their approach also includes investments directed toward progressive, lower-risk, broad-payoff development efforts for energy generation, energy efficiency, and low-carbon technologies that will be employed in the near-term future across a large, existing infrastructure.

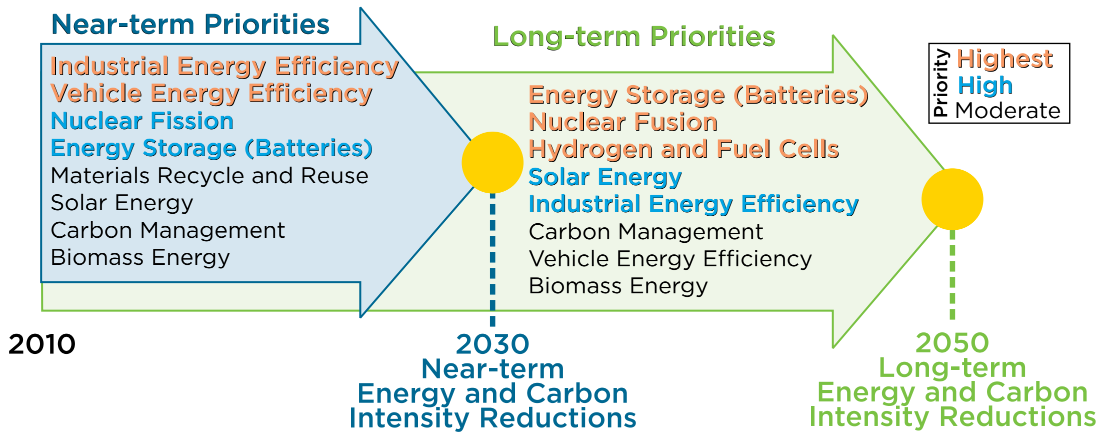
With this in mind, the Panel reviewed the major areas of energy sources, energy carriers, and energy use and sustainability, and rated them according to the criteria above with a view toward the short term (5–20 years) and long term (20–50 years). The results of that process are summarized and prioritized in Figure 4.

These prioritized energy application areas provide an overall perspective on how innovations in MSE can create significant near-term reductions in energy and carbon intensity while also laying the groundwork for further advances in the long term.

Industrial and Vehicle Energy Efficiency

Increased industrial and vehicle energy efficiency are the pathways with the greatest near-term impact. Given the scale of both of these applications, even small gains can be multiplied over many years

Figure 4. Energy application areas with greatest promise for transformational near-term and long-term impact through MSE technologies



within broad segments of the energy sector, and will provide a substantial reduction in energy and carbon intensity. The International Energy Agency anticipates that 36 percent of global CO_2 emissions reductions between now and 2050 will come from end-use efficiency measures—more than the CO_2 savings anticipated from solar, wind, biofuels, geothermal, and all other renewables combined.[5] Many of the critical innovations needed to realize these efficiency improvements are MSE issues, such as reducing vehicle weight to increase fuel efficiency and advanced materials that allow industrial processes to operate at higher temperatures. As transformational vehicle technologies and industrial processes become more developed, these two areas will also be important in the longer-term.

Nuclear Fission

Low-carbon electricity produced through increased commercialization of advanced nuclear fission is a high-priority opportunity for MSE to lead to breakthroughs in the near term. Today, 104 licensed nuclear power plants generate 20 percent of U.S. electricity, which accounts for 70 percent of all U.S. power generated from emissions-free sources.[6,7] Growth in nuclear power plant construction, which has lagged in the United States since the 1970s, can be accelerated by the development of next-generation systems and more effective solutions to waste reprocessing and storage, which are substantial MSE challenges. Advances are also needed in new materials to contain nuclear waste for its geologic lifetime, new proliferation-resistant nuclear fuels, new classes of structural materials, and computational materials science and engineering to further drive understanding of long-term radiation effects experienced by advanced reactor materials.

Battery Technologies

Enhanced flexibility and the use of renewable energy through improvements in battery technology for energy storage is not only a high priority in the near term, but also the highest priority for MSE innovation in the longer term. Energy storage is essential for integrating intermittent renewable energy sources such as wind and solar energy, for grid management and matching supply to demand, and for enabling both vehicle and stationary applications. While battery technologies are among the most promising energy storage options, they experience clear technical barriers to storage capacity, charge/discharge rates, reliability, and cost-competitiveness. Some of the most pressing needs lie in electrolytes, anode manufacturing, cathode materials, and membrane and solid state storage materials for fuel cells and hydrogen. MSE and especially processing and manufacturing have significant opportunities to advance the state-of-the-art in electrolytes, containment, anodes, cathodes, and separators, both for lithium batteries and for beyond lithium.

Solar Energy

The opportunity for MSE to have a significant impact on energy derived from solar sources will be moderate, but growing to a higher priority in the long term as advanced solar technologies enter the marketplace. This increased importance is based on the development primarily of alternatives to silicon and the increased energy conversion rate. More energy strikes the earth as sunlight in one hour than all the energy consumed on the planet in one year. To take better advantage of this resource via solar electricity, solar thermal energy, and solar fuels, MSE can serve the need to continue to increase solar photovoltaic efficiencies, decrease system costs, aid the concentration of solar power, and improve component recyclability.

5. *Energy Technology Perspectives 2008*, International Energy Agency, 2008. http://www.iea.org/techno/etp/fact_sheet_ETP2008.pdf (accessed May 17, 2010)
6. Source: Calculated from EIA data at http://www.eia.doe.gov/oiaf/1605/ggrpt/flowchart.html
7. Source: Figure 3 at http://www.eia.doe.gov/oiaf/1605/ggrpt/index.html

Biomass Energy

Energy derived from biomass is also a moderate near-term priority with similar potential in the future. Biomass energy holds the promise of converting organic residues and energy crops into heat, electricity, and transport fuels. Significant MSE challenges in this area include materials durability, corrosion resistance, and advanced catalysts to efficiently produce fuels.

Carbon Management

Carbon management is an area with moderate near- and long-term potential impact. Given the prevalence of fossil fuels as an energy source in today's world and in the projected future, carbon capture and sequestration (CCS) is expected to play an important role in carbon management. The International Energy Agency (IEA) has studied a number of global GHG reduction scenarios and concluded that CCS is "the most important single new technology for CO_2 savings"[8] in both power generation and industry. Materials durability will play an important role for CCS, as will effective catalysts to reduce the cost of separation steps that are currently energy-intensive and reduce plant efficiency.

Materials Recycle and Reuse

Resource conservation and waste minimization through advances in materials recycling and reuse is a near-term opportunity. Like energy efficiency, recycling and reuse can make an immediate impact on the energy sector and the U.S. economy. Enormous energy savings stand to be gained by advancing the recycling of energy-intensive materials such as aluminum, steel, plastic, and glass, and it is in the best interest of the United States to prolong the life of existing structures and retain strategic materials. While MSE contributes significantly to this area via extraction techniques, furnace materials, greener processes, and alternatives to rare or toxic resources, design paradigms that take into account lifecycle analysis, consumer behavior, and policies that provide mandates will also be key drivers.

Hydrogen and Fuel Cells

Hydrogen and fuel cells have been an area of substantial R&D focus to date and are a highest-priority area in the long-term. MSE innovations in catalysts and membrane materials, combined with increased infrastructure, could allow hydrogen fuel cells to make a major impact on the long-term state of the U.S. energy sector.

Energy from nuclear fusion is also a long-term priority. With daunting challenges not just in the MSE area, the potential energy benefits are large: abundant fuel supplies, no risk of nuclear meltdown accidents, no greenhouse gases emitted, and no production of waste with high actinide content and million-year-scale half lives. Lower-cost diodes, ceramics, radiation-damage-resistant materials, and materials to withstand extreme temperatures all stand to enable the advancement of fusion energy. The Panel viewed nuclear fusion as one of the highest priorities in the long term.

The Panel did not view certain energy sources, energy carriers, and energy use and sustainability topics as priorities. However, the lack of these elements in the prioritization does not imply the Panel's perception that these elements hold little or no promise for addressing the U.S. energy or carbon emissions challenges. Rather, the finding reflects the Energy Materials Blue Ribbon Panel's awareness that the primary challenge associated with those technologies is not MSE innovation. For example, if new wind turbines will require permanent rare earth magnet generators and China supplies the vast majority of the rare earths for the entire world, this is a pressing commercial, political, and regulatory challenge to resource availability, perhaps demanding a different solution than MSE innovation. Other examples of important energy sources, carriers, or end-use areas that are less dependent upon MSE breakthroughs to be successful include waste energy, hydropower, fossil, and geothermal energy sources; electricity transmission/distribution, supercapacitors, and mechanical energy storage; and energy efficiency in commercial and residential buildings.

8. International Energy Agency. *Technology Roadmap: Carbon capture and storage*. Paris: Organisation for Economic Co-operation and Development, International Energy Agency, 2009. http://www.iea.org/Papers/2009/CCS_Roadmap.pdf (accessed 7 June, 2010).
9. *Basic Research Needs for Solar Energy Utilization*, Department of Energy Office of Science 2005, http://www.sc.doe.gov/bes/reports/files/SEU_rpt.pdf (accessed May 24, 2010)

5. MSE TECHNOLOGIES NEEDED TO ACCELERATE REALIZATION

Materials science and engineering advances hold the power to accelerate technological innovation and enable the United States to realize the vision of the Energy Materials Blue Ribbon Panel. This section describes the specific MSE technology areas that hold the most promise for greatly reducing the energy- and carbon-intensity levels of the U.S. economy.

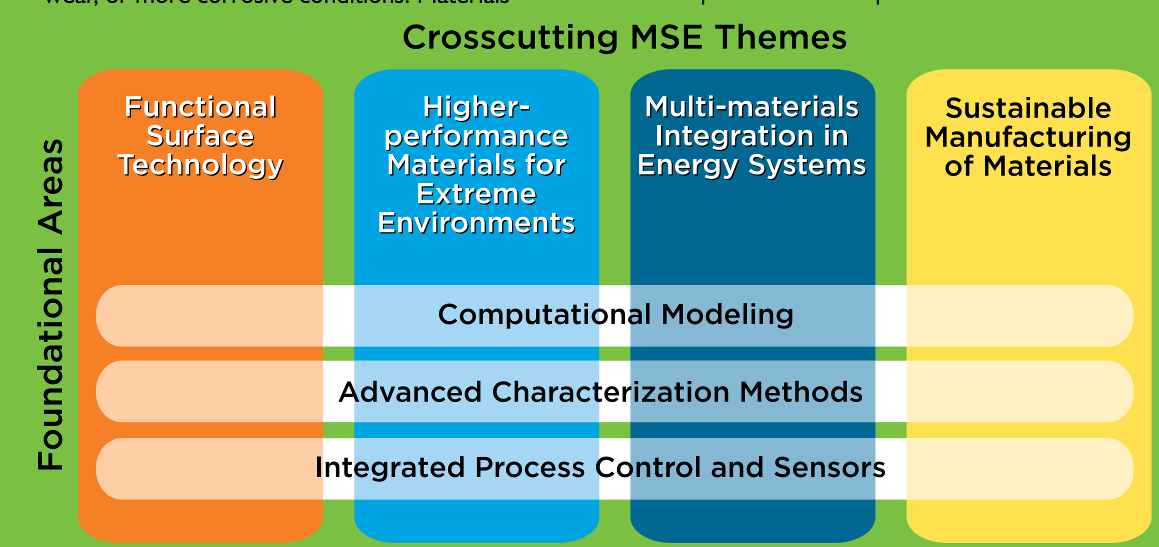
The diversity of the energy sectors and the number of materials that can be applied to a single application call for an approach that will maximize the impact of MSE innovations and spread the development risks across several areas. An R&D portfolio that balances near- and long-term improvements will deliver immediate benefits, support needed progress, and lay the groundwork for future game-changing technologies.

Four cross-cutting themes arise as the highest-priority targets for immediate and continuing support. They include:

1. **Functional Surface Technology** – Tomorrow's energy systems will require material surfaces that do more than simply extend equipment life by better withstanding service environments. These systems will also require surfaces that interact with process conditions to improve efficiency, speed reaction times, and produce and store energy in innovative ways.
2. **Higher-performance Materials for Extreme Environments** – For many energy systems, the path to realizing greater energy efficiency brings extreme conditions, such as higher temperatures, more intense radiation, greater wear, or more corrosive conditions. Materials are frequently the limiting factor in pushing energy systems to these extremes.
3. **Multi-materials Integration in Energy Systems** – Every energy system comprises different materials working together to deliver desired functionality. Integrating new materials, including those with intrinsic heterogeneity like composites and smart materials, creates design and manufacturing challenges, especially as systems become more complex and service environments become more demanding.
4. **Sustainable Manufacturing of Materials** – Manufacturing materials such as steel, aluminum, and cement is fundamentally energy-intensive. Reducing the energy and carbon footprint of materials manufacturing requires process innovations and novel synthesis methods that minimize energy and material losses, such as net-shape processes, reuse of processing waste, and recycling of end-of-life materials.

Underlying each of the cross-cutting themes are three foundational areas, which are groups of enabling tools that can facilitate and accelerate progress. The foundational areas include:

- **Computational Modeling** – Radical advances in computational power and data visualization tools have allowed computational systems to not only model experimentally proven phenomena, but also simulate theoretical interactions that can direct laboratory work in the hypothesis stage. Computational modeling holds promise to continue to transform MSE from an empirical, time-consuming, and costly endeavor into a more rapid discovery and development cycle based on the iterative interaction between computational and experimental tools.



- **Advanced Characterization Methods** – Experimental tools that allow scientists and engineers to characterize material structures and properties are fundamental to building MSE understanding and developing new materials with unique properties. As these tools improve, new materials can be developed faster and with greater control over properties, processing, and, ultimately, material performance in end-use applications.
- **Integrated Process Control and Sensors** – Achieving maximum efficiency from both materials manufacturing processes and energy systems demands careful process monitoring and control, often in extreme environments not conducive to using existing sensor technology. Materials-enabled innovations in integrated process control and sensors will provide improvements in energy and resource efficiency across the energy sector.

The cross-cutting MSE themes and foundational areas provide a compelling, comprehensive research agenda that, if pursued via a substantial effort, can deliver advances in materials and manufacturing approaches that impact the entire energy sector. Each of these areas of work is described in more detail in the pages that follow.

Functional Surface Technology

Existing and next-generation energy systems demand material surfaces that can effectively interact with service environments. Functional surface innovations can improve renewable energy technologies, storage and distribution, transportation and industry efficiency, and carbon management applications throughout the U.S. energy sector.

Complex Oxide Molecular Beam Epitaxy
(Courtesy: Argonne National Laboratory)

- **Catalysts** are important enabling technologies for many energy sources and systems. Effective catalysts can increase the efficiency of energy conversion and reduce the cost of purification and separation systems. More effective catalysts produced via cost-effective manufacturing techniques have great potential to support biomass energy generation, fuel cell and hydrogen technologies, carbon management, and energy efficiency for industry and internal combustion engine vehicles.
- **Nanomaterials and nano-level processing** can be used in the development of functional surfaces that reduce energy and carbon intensity. For example, nanoporous materials (membranes and sorbents) with greater surface area to volume ratios can enable more energy-efficient industrial separations, which today require more than six quadrillion Btu each year in the chemicals, petrochemicals, and forest products industries alone. There is also potential to engineer hierarchical micro- and nano-level surface topologies on inexpensive bulk materials to realize cost-effective efficiency improvements in both manufacturing processes and products.
- **Coatings** that provide environmental resistance, in combination with a substrate that provides the desired mechanical properties, form promising surface-modified materials systems. Such material systems can prevent parasitic energy loss in automobiles, avoid corrosion in biomass systems, and improve oxidation resistance in industrial processes.
- **Electrochemical material systems**, such as batteries, require functional surfaces to deliver electrical energy via chemical processes. Material and processing breakthroughs are needed to deliver advances required in electrolytes, containment, anodes, cathodes, and separators, both for lithium batteries and alternative battery material systems. Nanostructured materials, which are currently under fundamental-level investigation, have the potential to improve components like cathodes and electrolytes, which could help extend battery life while increasing efficiency and capacity.
- **Thin film technologies** hold promise for further reducing costs for solar energy, as do new materials for utilizing a wider spectrum of solar radiation. Next-generation photovoltaics will require materials and processing advances to help improve functionality and conversion efficiencies and, as a result, cost. Potential advances include a systems approach to reducing costs that uses low-cost materials, substrates, and interconnects, and organic, non-silicon solar cells that could increase efficiencies in the longer term.

Higher-performance Materials for Extreme Environments

Many energy systems are required to operate in harsh environments characterized by varying thermal, chemical, mechanical, and radiation stresses. Increasing the efficiency of thermal processes, the efficiency of industrial manufacturing and vehicles, and the use of nuclear fission and fusion power requires materials that can withstand conditions like higher temperatures, corrosive chemicals, and intense radiation environments. While surface aspects play a significant role in determining performance in extreme environments, improvements in bulk material properties are also needed to maximize the efficiency of many energy systems.

Handling a Complex Metal Hydride
(Courtesy: Sandia National Laboratories/
Photo by Randy Wong)

- **Metallic materials**, such as steels and non-ferrous alloys, are typically used to withstand extreme environments. As demands on material systems increase, advances in metallic materials promise to deliver higher efficiency in fossil fuel and nuclear power generation, solar thermal processes, industrial manufacturing, and vehicles. In addition, advances in metallic material processing can enable efficiency improvements, such as the ability to produce large forgings for use in the nuclear power industry. Further, nanostructured materials with internal dimensions in the 10–100 nm scale reportedly can attain strength levels that are 2.5–3 times higher than those of comparable micrometric materials, thereby providing a direct pathway to energy savings by increasing strength-to-density ratios.
- **Ceramics** offer exceptional hardness, strength, and corrosion resistance at significantly lighter weights than metals, making them attractive options for harsh environments such as high-temperature or high-wear applications. Nanostructured and nanoprocessed transparent ceramics are important enablers for several energy technologies, including nuclear fusion. However, concerns remain about ceramic materials' reliability, lifetimes, and cost; such concerns can be addressed through MSE innovations.
- **Engineered polymers** offer unique combinations of properties with distinct advantages for certain harsh environments. Engineered polymers deliver effective performance while reducing weight compared to metal components. For example, steel coated with epoxy materials or polyolefins can offer corrosion resistance while maintaining the bulk properties and relatively low cost of the base steel. MSE innovations that allow polymers to retain high performance at elevated temperatures would extend the benefits of these materials to more demanding energy applications, although issues regarding separation from end-of-life waste streams and recyclability must be addressed.
- **Electronic materials**, such as solid-state diodes and solar photovoltaic materials, hold great promise for improving energy and carbon intensity in the near and long terms. In the near term, high-volume, low-cost materials manufacturing of light-emitting diodes (LEDs) can aid further development of energy-efficient lighting. In the solar sector, moving from silicon to thinner, flexible substrates for photovoltaic modules holds promise to increase efficiencies and reduce cost. In the longer term, low-cost semiconductor diodes operating at 10-20 Hz can enable commercial deployment of laser-inertial fusion energy.

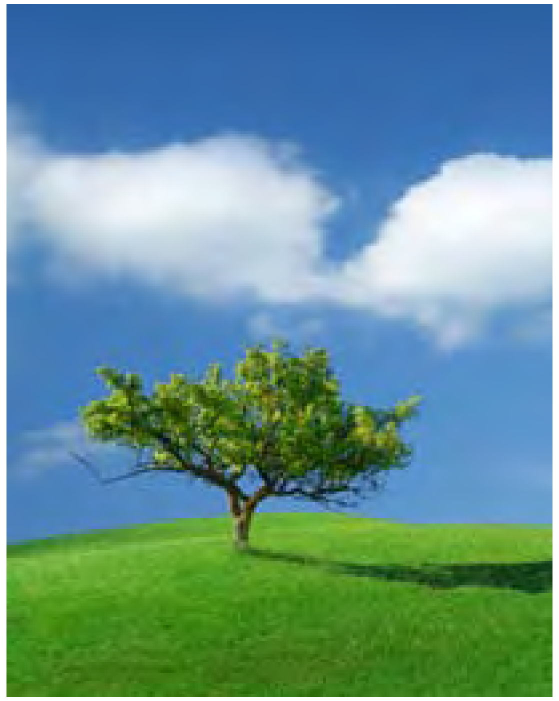
Multi-materials Integration in Energy Systems

Most energy technologies (such as batteries, fuel cells, and solar cells) involve systems of different classes of materials. In addition, vehicular and industrial systems depend on the integrated performance of multiple classes of materials and the interfaces between them. To optimize the efficiency of these systems, effective integration of heterogeneous components is needed to boost capabilities like performance, reliability, longevity, cost-effectiveness, and energy efficiency.

Advanced Li-Ion Battery
(Courtesy: Argonne National Laboratory)

- **Joining processes**, via lasers, plasma, electrical beam, or chemical reaction, offer significant potential to improve industry's ability to connect dissimilar materials. Advances in chemical and other joining processes hold promise to create reversible joints that perform well in service and permit recovery and recycling of dissimilar materials at the end of their useful service lives.
- **Composite materials**—including intrinsic composites as well as extrinsic systems, such as layered structures—offer potential performance improvements in many systems but also significant integration challenges. While composites are gaining increased use in the aerospace industry, lower-cost composites could find a broader set of applications in the energy sector. For example, less expensive, stiffer composites can provide advantages in the production, transportation, and efficiency of wind turbine blades.
- **Thermal management materials and processes** in batteries and fuel cells stand to improve the efficiency and reliability of these technologies. Hydrogen fuel cells are one area in which integration of new materials and processing methods, such as bipolar plates, carbon fiber, solid state storage, and thermal management technologies, offer great promise for advancing fuel cell performance.
- **Smart materials**, such as shape memory alloys and material systems with embedded sensors, also offer potential for improving system performance when effectively integrated into systems. Advanced smart materials, such as self-healing materials that can repair damage incurred during normal use, hold even greater promise for improving energy efficiency of energy systems. For example, advanced materials can reduce unexpected downtimes and associated shut-down and start-up cycles that decrease the energy efficiency of industrial processes.
- **Predicting the reliability of disparate material systems** comprised of multiple constituents with variable functionality and properties is another pressing need. Important phenomena affecting performance and durability occur in each constituent and, particularly, at the interfaces between disparate materials. Because of this complexity, present systems do not exploit the full potential offered by the materials. Physics-based protocols for quantitatively predicting these interactions as well as overall performance are needed to facilitate more aggressive design philosophies.

Sustainable Manufacturing of Materials



Minimizing the loss of both energy and materials is at the core of sustainable manufacturing. Many types of processing aspire to decrease resource consumption by producing near-net or net-shape outputs. Increasing process yields, recovering and recycling materials and energy, and improving thermal efficiency will all help to minimize material and energy waste streams.

- **Net shape processing methods**, characterized by limited or no losses and high yields, would substantially reduce the energy and carbon impact and resource consumption of manufacturing. Materials synthesis approaches to achieving a "pure net shape" product, such as casting, deposition, and atom-by-atom assembly, have the potential to revolutionize manufacturing as a way of creating products. Opportunities also lie with other innovative techniques, such as rapid manufacturing, desktop manufacturing, "reel-to-reel" processing, and intelligent processing.
- **Industrial heating and waste heat utilization** are areas where innovations in process design and materials can greatly increase manufacturing sustainability. The production of materials, such as steel, aluminum, glass, and cement, is incredibly energy-intensive—more than 1,500 trillion Btu per year of unrecovered waste heat losses can be identified in these materials manufacturing industries. However, the work potential of this waste heat is about 600 trillion Btu per year. Though tapping into such heat is technically challenging, even small efficiency gains will translate to significant energy and carbon savings. Advanced thermoelectric and other MSE breakthroughs are key to capturing and utilizing this untapped zero-carbon energy resource.
- **Cost-effective rejuvenation** of end-of-life products can greatly reduce the waste of materials and energy by prolonging the life of existing components and preventing their unnecessary replacement. MSE innovations that allow end-of-life components to be rehabilitated with minimal energy and material utilization and returned to service life—ideally in the same application for which the component was originally intended—would greatly reduce the life-cycle energy and carbon impact of these components.
- **Resource recovery and recycling**, especially of critical materials such as rare earth metals that are vital to wind energy and other energy technologies, is needed to address energy security and sustainability needs. While coatings and multi-materials integration promise to deliver energy and carbon gains, such material systems greatly complicate end-of-life management. For example, recycling approaches for solar panels or batteries are inadequate today. As these technologies gain greater market share in the coming years, the materials recycling challenge will loom ever larger unless MSE breakthroughs are realized.

Foundational Areas

Supporting each of the four cross-cutting MSE themes are the three foundational areas:

- Computational Modeling
- Advanced Characterization Methods
- Integrated Process Control and Sensors

The Panel repeatedly recognized the importance of various elements that make up these technology groups. While none of the areas represents the core materials or processing aspect that is critical to realizing transformational improvements in energy efficiency or carbon reduction, they are vital in achieving the needed acceleration of progress from research to realization.

Computational Modeling

Increasing hardware capabilities coupled with continued development in advanced algorithms have allowed predictive modeling to become a strong complement to experimentation in materials and process development as well as system performance across length and time scales. While computational materials science approaches continue to require benchmarking with experimental results, the Panel noted the increasingly important role that current and future computational modeling capabilities will play in guiding development and application.

Several key areas of computational modeling are important in this foundational area:

- **Computational Materials Design**–Modeling from the quantum to macroscopic scale and connecting these models across these length scales
- **Integrated Process Modeling**–Modeling of both primary and secondary manufacturing processes
- **Integrated Computational Materials Engineering**–An emerging area that couples the materials and process models across time and length scales
- **Systems-Level Modeling**–Multi-scale, multi-physics approaches to the systems-level simulation of complex energy systems, which are necessary to provide the basis for evaluating the impact of the introduction of new materials into these systems
- **Life-cycle Analysis**–A comprehensive examination of the environmental and economic effects of a product at every stage of its existence, from production to disposal and beyond

Models are fueled by databases, making updating, expanding, and, in some cases, developing databases that will support modeling an important foundational activity. A frequent challenge is the availability of public databases, due to the proprietary information included, especially in the processing area. Support of database development is often not considered exciting, but is an important area for government support.

Advanced Characterization Methods

The ability to image and measure materials and their structures has always been a critical aspect of materials development. The experimental understanding of how composition and processing influence material properties and, in turn, performance (the materials tetrahedron) is the basis upon which materials science and engineering rests. Advances in characterization methods and the

Ethanol Compatibility Test Chamber (Courtesy Oak Ridge National Laboratory/ Photo by Jason Richards)

information they reveal complement the progress in modeling described above to result in synergistic acceleration of progress.

The ability to characterize and manipulate materials, particularly at the nanoscale, offers promise of breakthrough discoveries and large-scale use of new materials. Advances in characterization methods such as light, electron, ion, and atomic force microscopy; X-ray, neutron, and other source-based methods; and electron- and ion-beam instruments for microchemistry, structure, and texture identification and surface structure analysis are providing increased understanding of materials at the atomic level. Nanomechanical evaluation methods provide data on the performance of materials at the nanoscale.

Increasing capabilities to characterize material in three dimensions are also of value. Extending beyond the 2-D limitations of past methods, these 3-D descriptions add immeasurably to the understanding of materials as well as the ability to more accurately model them.

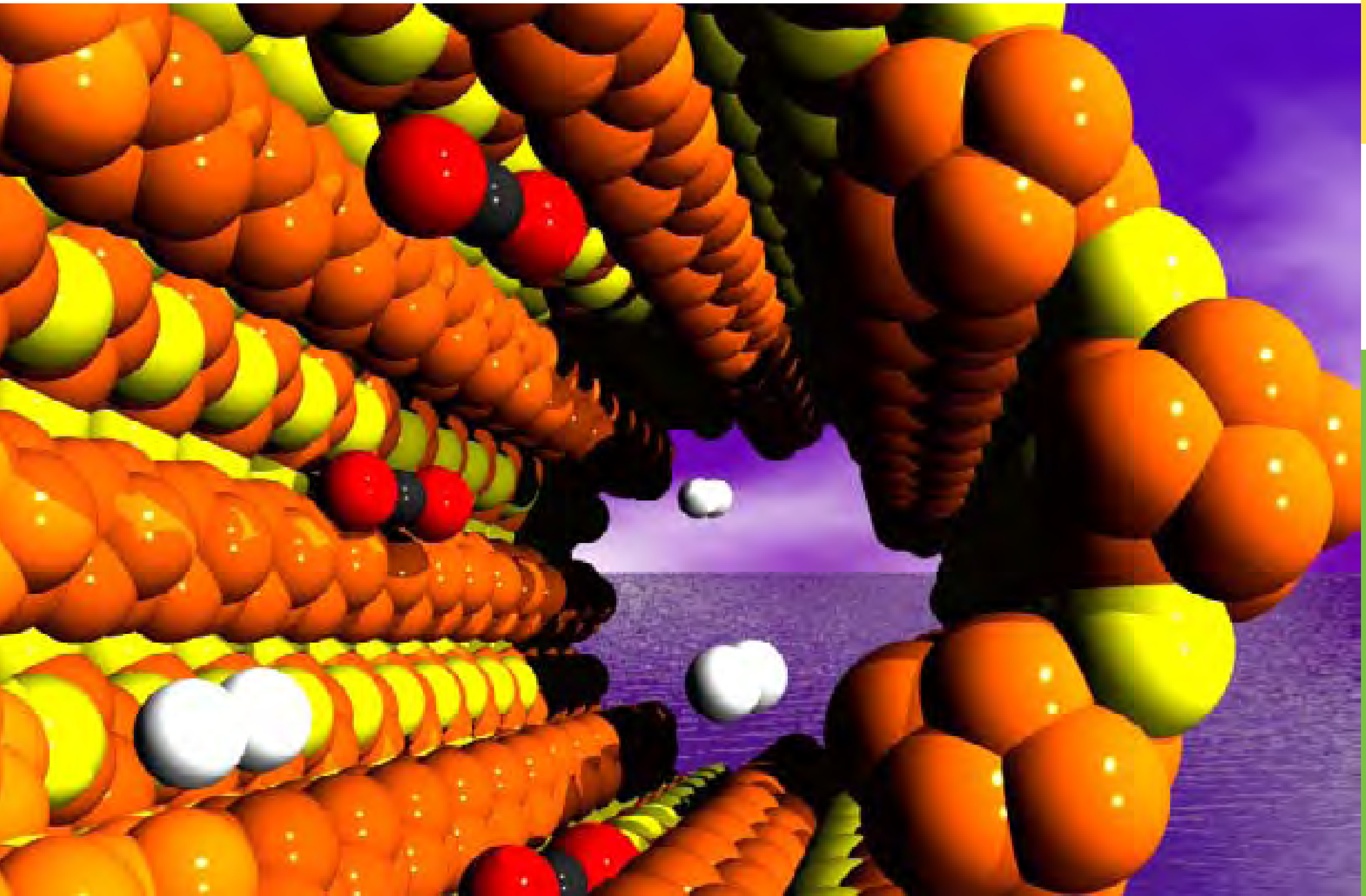
Integrated Process Control and Sensors

Monitoring and controlling not only materials-production processes, but also the processes occurring in the energy systems is an important foundational area. From a materials science and engineering perspective, the development and utilization of robust sensors are a key component.

Sensors that can tolerate harsh environments are especially important for materials production processes as well as a number of energy generation systems. Sensor materials development, design, and implementation, including in a wireless mode, apply across the energy source and use spectrum.

Smart materials are materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, electric fields, or magnetic fields. Coupling sensing and actuation functions into materials with structural or other functional purposes can facilitate materials and system performance.

Hydrogen Separation Method (Courtesy: National Science Foundation/Credit: Gerasimos Armatas and Mercouri Kanatzidis)



6. POLICY ENABLERS

Materials science is an essential component of energy infrastructure development and improvement efforts; new and improved energy technologies are inherently materials-limited. The United States must harness the power of materials science, engineering, and processing to compete internationally, create jobs, heighten sustainability, increase the efficiency of resource use, meet energy needs, and reduce climate change effects. The United States is well positioned to meet this materials advancement challenge and effectively support the MSE community in its pursuit of cross-cutting solutions. Combining industry, government, and academic resources can be a formidable force to develop materials and processing solutions to increasingly recognized materials and processing challenges.

But technology developments alone will not be sufficient to realize these ambitious goals. Also important is a policy framework and national commitment to provide the human and capital resources necessary.

The Energy Materials Blue Ribbon Panel also explored these areas and developed the following recommendations:

- **Significant, sustained investment in materials science and engineering research, development, demonstration, and deployment.** Consistent national policies that create the long-term confidence needed to marshal private-sector resources are required as a key component.
- **Heightened collaborative efforts** from different parts of the federal government (U.S. Department of Energy, U.S. Department of Defense, and others), in conjunction with industry, academia, and other institutions (e.g., professional societies, venture capital, media, and international collaborators).
- Guidance from all institutions with vested interests in forming **a national energy roadmap** and full engagement with these entities to ensure that successful energy developments are aligned with this roadmap.
- **A concerted national effort to work now to cultivate and educate the skilled workforce** that will be required for the future energy sector.
- **New policies and practices** to enable industry and universities to access the multibillion-dollar annual investments in the U.S. national laboratories. Processes that move at the speed of business and that reduce intellectual property barriers are particular areas where improvements are necessary.

7. NEXT STEPS

This vision sets broad recommendations and the framework for a coordinated effort to increase energy efficiency and reduce carbon emissions in the United States by leveraging MSE technologies. More detailed development of the scientific and engineering R&D priorities in each cross-cutting area is needed to create an actionable plan.

To better define the technology developments needed to achieve the desired impacts, TMS will convene a series of Technical Working Groups around each of the four cross-cutting MSE areas identified in this document. Composed of experts with backgrounds in academia, industry, and government, these Technical Working Groups will further define the key opportunities, focusing on the highest-leverage areas and developing timelines and priorities for funding. The result of this work, combined with the forward-looking view provided in this document, will provide visionary yet actionable recommendations that, if implemented, will bring the United States closer to a sustainable future.

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