MATERIALS: FOUNDATION FOR THE CLEAN ENERGY AGE

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ABOUT THIS REPORT

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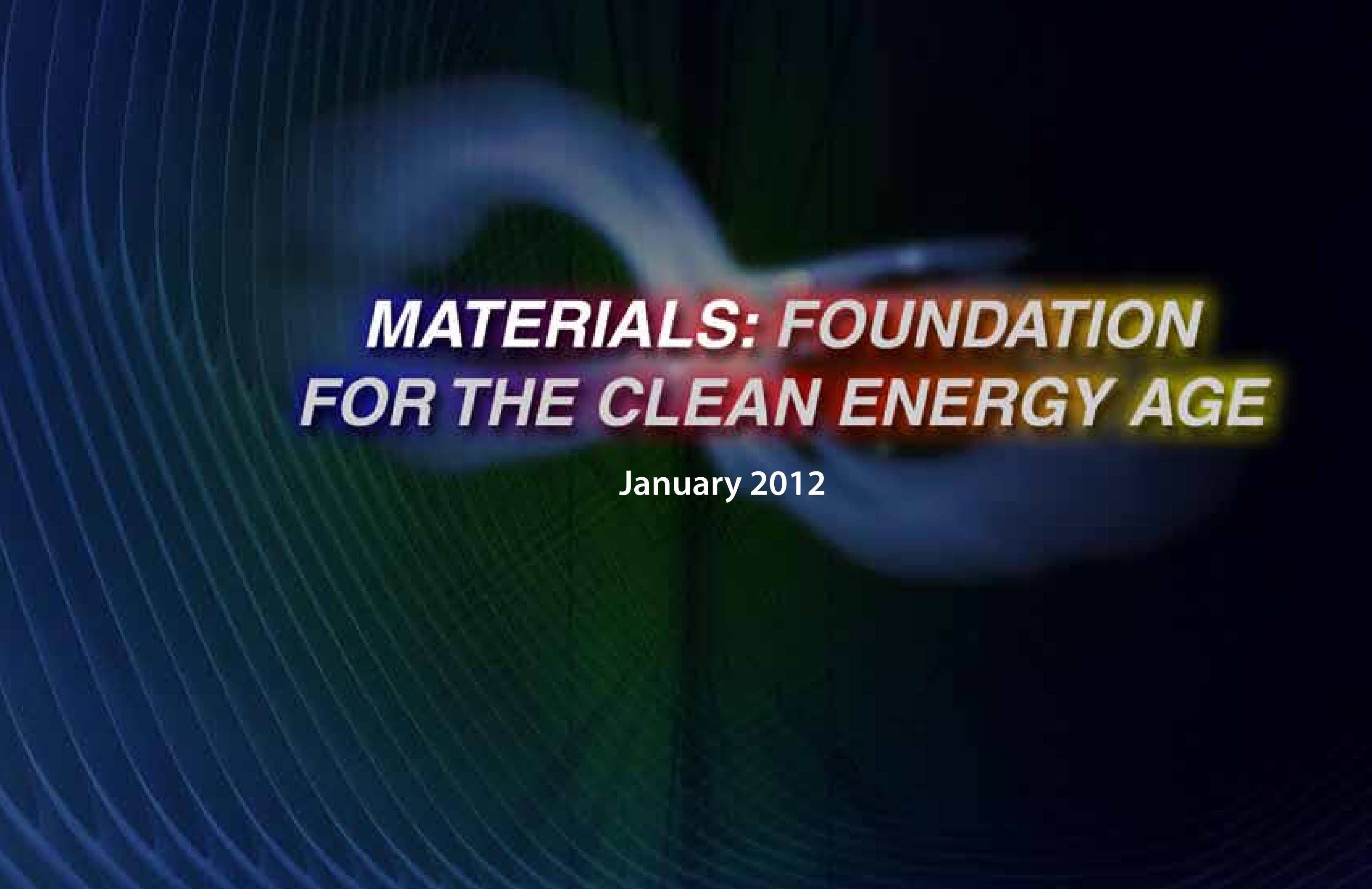

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Executive Summary

> *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.*
>
> *--Vision Statement of the Energy Materials Blue Ribbon Panel*

Materials make up every aspect of our world and have been critical throughout history in advancing both technological and cultural development, from the tools of the Bronze Age to the silicon driving the Information Age. The ability to effectively develop and deploy breakthrough materials technologies has always been inextricably tied to national prosperity and influence on the world stage. At no time has this been more evident than with the current imperative to secure a sustainable energy future for the United States and its international partners.

Energy availability and the impact of energy consumption on the environment will be the delineating factor of major economic and security issues for decades to come. The effectiveness and practicality of many critical energy solutions will depend on advancements in materials and their manufacturing processes.

The nations that assume leadership in producing materials for this next era of human progress—the Clean Energy Age—will have access to unprecedented opportunities for economic development by unleashing manufacturing innovations and efficiencies that are limited by current materials capabilities. The United States is well-positioned to take on that role by leveraging the strength of its strong industrial base, world-class universities, and national laboratories to revolutionize its energy sector for its own purposes, as well as help millions around the world fulfill their basic human needs.

Unlike other models for innovation, such as information technology, the Clean Energy Age will not come about based on a sequence of related breakthroughs within a defined family of technologies. The energy infrastructure is far too complex, encompassing everything from wells and mines, to transportation and manufacturing processes, to transmission lines and meters. These collections of technologies are pulled together in massive systems that require substantial investments of time and money to build, operate, and maintain. Within this context, it is highly unlikely that a "silver bullet" solution will materialize that can meet the world's escalating energy requirements, while also addressing the environmental impacts associated with energy use. Instead, what is emerging is a tapestry of contributing new technologies, many with the potential to make a measurable impact in the near future.

The key to making critical energy and carbon reduction solutions more effective, affordable, and widely implemented are materials and processing breakthroughs focused on removing barriers to progress and optimizing efficiencies. These innovations are not limited to making significant enhancements in energy products—more efficient solar cells and longer range car batteries, for instance. Also of great value is the power of materials technologies to vastly improve the productivity and profitability of manufacturing industries by enabling them to capture lost sources of energy, reduce wear on equipment and processing infrastructure, and turn out products more quickly and with less impact on the environment. The demand for the new materials responsible for this shift in manufacturing capabilities will, in turn, create businesses and industries focused on their production and distribution. Many materials technologies offering the best opportunities to change the energy and manufacturing landscape are on the cusp of realizing their fullest potential. The challenge now before them is making a swift transition from the laboratory to commercial application.

Industries, such as electronics, that have successfully established a bridge between application and basic science have grown exponentially, while concurrently driving astonishing social and economic change. Forging a link between potentially transformative energy materials under development and the applied processing and manufacturing technologies that make or use them will have an even more profound effect, since energy access impacts so many aspects of national security and well-being.

This report examines some of the most critical linkages—identified through the work of a national Energy Materials Blue Ribbon Panel[1]—and introduces strategies for expediting their development. Specific technologies offering significant impact are presented within the context of their contributions to key aspects of a strong, vibrant, and progressive manufacturing economy. This encompasses:

- ***Implementing more productive and profitable manufacturing processes*** by reducing losses in time, materials, and energy.
- ***Reinventing energy efficient transportation*** to not only reduce energy and environmental impact, but also jumpstart the development and growth of new supporting industries.
- ***Capturing more benefit from existing energy sources*** through conversion of waste heat to electricity and enhancing efficiency in energy processing and generation.
- ***Capitalizing on all available and emerging energy sources*** within the spectrum of energy generation and storage technologies.
- ***Accelerating innovation*** by employing cutting edge, computational tools and techniques to save time and money in bringing the next generation of energy materials and processing discoveries to market.

These technology overviews are drawn from a focused evaluation engaging nearly 150 leading experts in materials science and engineering (MSE)—the discipline dedicated to understanding, developing, manufacturing, and applying the materials that make most technologies functional.

Important progress is possible within the next two to 10 years, laying the groundwork for research and development focused on more sweeping transformation of the energy economy. Striking a balance between lower risk, near-term improvements, and longer-term initiatives is the most effective strategy for advancing to the Clean Energy Age in a systematic and productive way. This approach was conceptualized in the vision developed by the Energy Materials Blue Ribbon Panel as the framework for the identification of the technologies outlined in this report.

Energy and processing technologies through time have owed their very existence to the materials that make them up and make them work. Today's confluence of challenges—rapidly escalating global energy demand, an urgency to revitalize the nation's manufacturing sector, national security issues defined by access to energy sources—demand that MSE leverages this ubiquity to forge a pathway to a prosperous, sustainable energy future. While abundant technology, talent, and tenacity are available within the nation's MSE community to accomplish this goal, an array of other factors must also be addressed to ensure success:

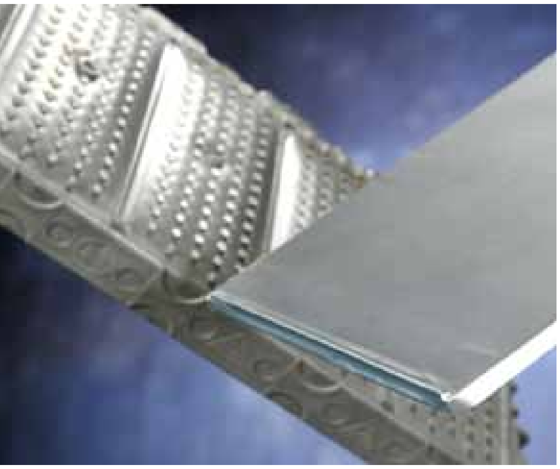
- ***Significant, sustained investment in materials science and engineering*** research, development, demonstration, and deployment. This will require consistent national policies that create the long-term confidence needed to marshal private-sector resources.
- ***Effective collaborative efforts*** engaging different parts of the federal government, as well as industry, academia, and other organizations.
- ***A national-level strategic plan and roadmap*** focused on integrating the diverse, interwoven technologies and subsystems of the energy sector. This approach would make it possible to pinpoint the most needed technologies and streamline development efforts. Aggressive, yet realistic, national targets would also inspire a more deliberate approach to addressing the most pressing energy challenges.
- ***Cultivating and educating the skilled workforce*** that will be needed to solve problems and sustain progress in the future. This can be achieved through more effective undergraduate and graduate curricula, new degrees focused on energy and carbon reduction, and improved synergies among disciplines. Engineers and scientists will also need to develop entrepreneurial abilities to ensure that innovations can become reality.
- ***New policies and practices*** that enable industry and universities to access the multi-billion dollar annual investments in the U.S. national laboratories. Development and commercialization processes that reduce intellectual property barriers and move at the speed of business also need to be implemented.

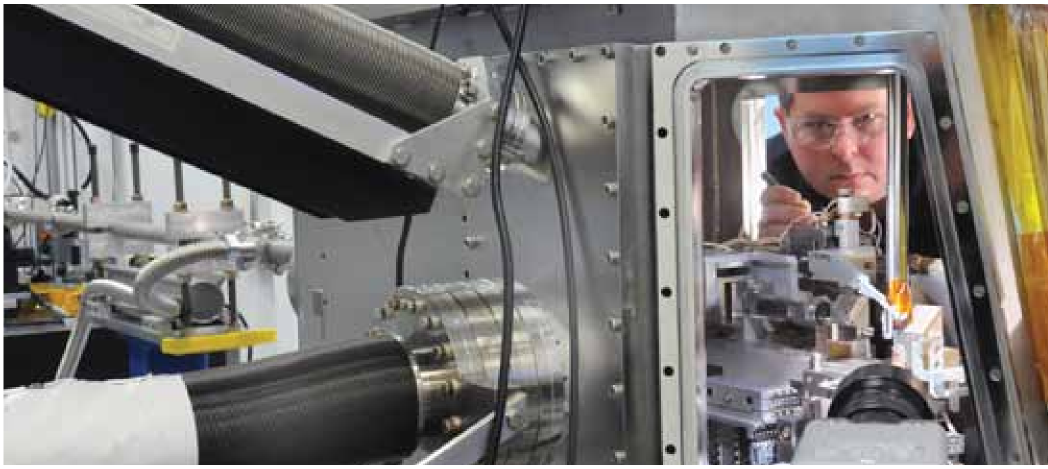
The United States has a window of opportunity to harness the power of its considerable intellectual, industrial, and economic resources to emerge as the market leader in materials and manufacturing processes that will comprise the infrastructure of the global clean energy economy. This cannot be achieved by a singular, isolated effort or by the random exploration of many. Instead, a broader perspective must be taken that integrates energy efficiency and carbon reduction in the same framework as cost, industrial productivity, and consumer needs.

Like the other ages of human development before it, the emerging Clean Energy Age will be about much more than the technology. It will come to describe a distinct manufacturing paradigm, a mode of commerce, a way of life—defined by the materials that form the foundation of its progress.

Notes:

1) The Minerals, Metals, & Materials Society (TMS). *Linking Transformational Materials and Processing for an Energy Efficient and Low-Carbon Economy: Creating the Vision and Accelerating Realization*. Warrendale, PA, 2010. http://energy.tms.org/docs/pdfs/VisionReport2010.pdf.


New generation lithium-ion battery
(Photo courtesy of Argonne National Laboratory)


Hard x-ray nanoprobe *(Photo courtesy of Argonne National Laboratory)*

(Satellite image courtesy of NASA)

Challenges and Opportunities

Disruption of the energy supply is not a new experience for the United States. And, with each incident—from the rationing implemented in the wake of the OPEC oil embargo in the 1970s, to the 2003 failure of the power grid that affected 45 million people in eight states, to the record-setting spike in oil prices in 2008—the nation and its citizens have generally responded with short-term conservation measures and heightened interest in longer term solutions.

Energy consumption in the last 60 years has escalated to support the technology, transportation, and living standards that Americans now enjoy, but at a rate slower than overall economic growth, as Figure 1 illustrates for the industrial, transportation, residential, and commercial end-use sectors of energy. Figure 2 presents how carbon dioxide emissions have followed a similar pattern, with the notable exception of the industrial sector. This marked decrease in industrial emissions can be attributed to concerted carbon reduction efforts, as well as shifts in the U.S. industrial mix.

Even though absolute energy consumption has steadily risen, energy intensity—the amount of energy consumed per constant dollar of the Gross Domestic Product (GDP)—has gradually decreased, from about 14,800 British thermal units (Btu)/dollar GDP in 1975 to about 7,400 Btu/dollar GDP in 2009.[2] This demonstrates the United States' ability to address energy and carbon emission concerns while maintaining economic growth. While some of this decline in energy intensity is related to a shift toward a more service-based U.S. economy, much of it has been driven by technological innovations that allow vehicles, buildings, and manufacturing plants to do more while using less energy.

The resources, expertise, and experience that underlie these important steps in energy efficiency and environmental impact can serve as a launching point to a complete transformation of the energy sector. This will encompass effectively utilizing new and

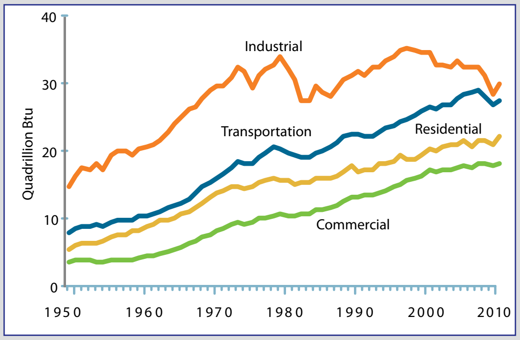


Figure 1: Total Energy Consumption by Sector[1] (1949–2010)[1]

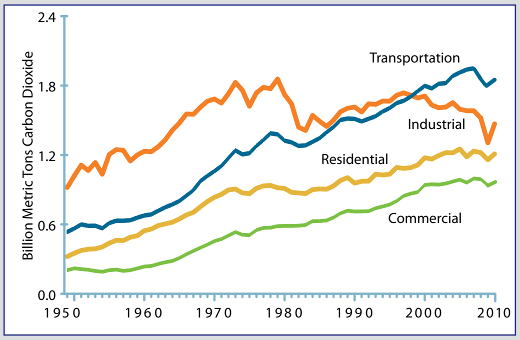


Figure 2: Total Energy-Related Carbon Dioxide Emissions by Sector[1] (1949–2010)

renewable sources of energy, optimizing the use of fossil fuels, and implementing affordable and effective manufacturing processes and product design strategies. At the core of any of these innovations are materials and materials processing developments that enable performance breakthroughs and significant cost reduction. Many companies, however, are often slow to incorporate new materials into energy systems at scale due to the significant investments and risks often associated with new technology.

Also at issue is time. Rapidly emerging economies, such as China, Brazil, and India, are now competing for finite energy supplies, while energy-intensive domestic industries, such as metals processing, struggle to maintain profitability in an era marked by uncertainty in energy pricing and availability. Fully resolving these issues is a generational challenge, with success in research, development, and deployment at scale measured in decades. It is vital that energy efficiency continue to be improved in the shorter term with materials technologies that can effect incremental, but meaningful, progress in addressing immediate supply issues and tensions.

The energy application areas offering the greatest opportunity for significant, near-term impact through materials innovation are outlined in Figure 3. This framework was developed by the Energy Materials Blue Ribbon Panel convened by TMS in 2010 as a means of prioritizing the materials and processing-driven breakthroughs that could make the highest impact across energy sources and use. Because the Panel's charge was to identify technologies in which materials innovation was the primary challenge, some energy opportunities, such as wind power and energy efficiency in buildings, were not included in the prioritization because they are less dependent on materials breakthroughs.

Subsequent studies[1,4] using this model to guide research and deliberation have identified a cadre of specific breakthrough opportunities that can yield significant results within the next two to 10 years. These technologies are summarized in the following pages, along with strategies to ensure that these potentially game-changing research innovations are transitioned effectively to realistic commercial implementation.

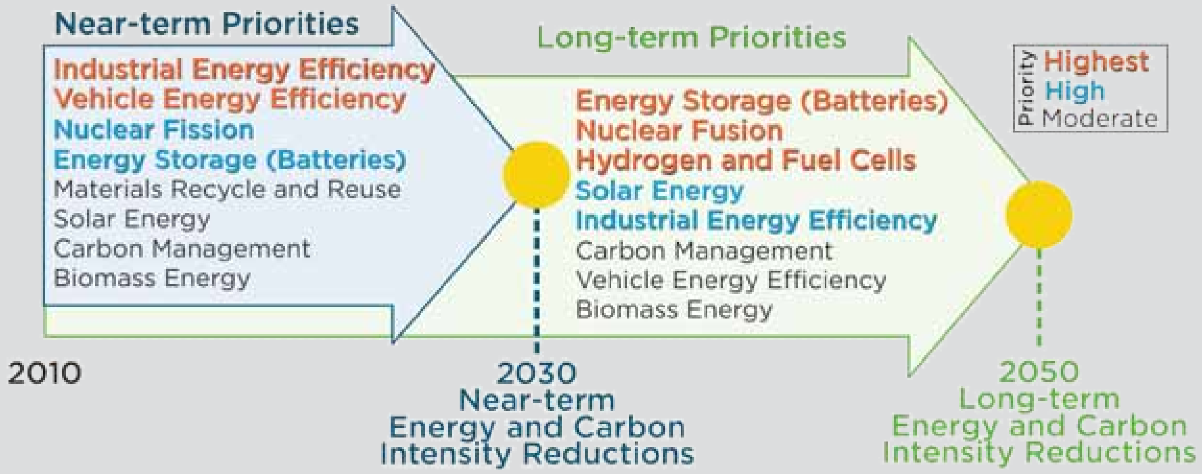


Figure 3: Energy Applications with Greatest Potential for Transformational Near-term and Long-term Impact through MSE Technologies[3]

Notes:

1) The Minerals, Metals, & Materials Society (TMS). *Linking Transformational Materials and Processing for an Energy Efficient and Low-Carbon Economy: Opportunity for Materials Science and Engineering*. Warrendale, PA 2011. http://energy.tms.org/docs/pdfs/Opportunity_Analysis_for_MSE.pdf.

2) U.S. Department of Energy, Energy Information Administration. "Table 1.7 Primary Energy Consumption per Real Dollar of Gross Domestic Product." Monthly Energy Review. November 2010. http://www.eia.doe.gov/emeu/mer/pdf/pages/sec1_16.pdf.

3) The Minerals, Metals, & Materials Society (TMS). *Linking Transformational Materials and Processing for an Energy Efficient and Low-Carbon Economy: Creating the Vision and Accelerating Realization*. Warrendale, PA, 2010. http://energy.tms.org/docs/pdfs/VisionReport2010.pdf.

4) The Minerals, Metals, & Materials Society (TMS). *Linking Transformational Materials and Processing for an Energy Efficient and Low-Carbon Economy: Innovation Impact Report*. Warrendale, PA, 2011.

Making Manufacturing More Energy Efficient, Productive, and Profitable

Manufacturing is a fundamentally energy-intensive enterprise. In an effort to reduce energy costs, many industries have implemented highly successful energy efficiency strategies. For instance, the energy consumption of aluminum production has decreased from about 16.1 kilowatt hours (kWh)/kilogram (kg) to 14.5 kWh/kg over the past 20 years. With additional improvements, this level is expected to drop to about 10 kWh/kg in the next 10 years[1] (See Figure 4: Energy Intensity of Aluminum Production). In another example, the North American steel industry since 1990 has reduced its energy intensities to make one ton of steel by 30 percent (See Figure 5: Energy Intensity of North American Steel Production). These improvements in steel production, however, are rapidly approaching a plateau and little progress on the energy efficiency and carbon reduction fronts can be expected without major processing advancements.[2]

Across all industries, these advancements can take a number of forms, most of them enabled by materials processing innovations that can be implemented in just a few years. Pathways include minimizing wasted material, combining and streamlining processing

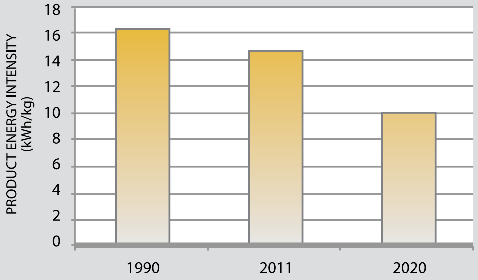


Figure 4: Energy Intensity of Aluminum Production

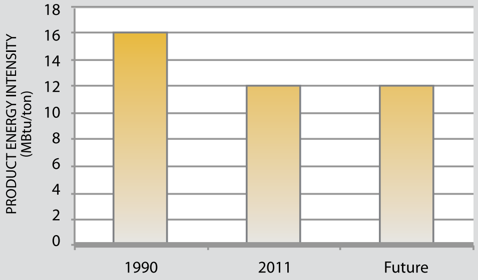


Figure 5: Energy Intensity of North American Steel Production

steps, recovering and recycling both materials and energy, and improving material tolerance to the extreme operating conditions of next-generation energy systems. Many opportunities represent small adjustments and extensions of successful technologies that can yield measurable results in the near-term, while laying the groundwork for the transformative approaches that will usher in the Clean Energy Age. Focused research and development investments in the technologies summarized in this chapter promise particularly significant returns in energy savings and carbon reduction.

CATALYSTS

Catalysts are substances that alter the rate of a chemical reaction, but are chemically unchanged at the end of the reaction, so they can be used again and again. They are important enabling technologies for many energy systems and an integral part of the production of more than 90% of all industrial chemicals,[3] including ammonia and methanol. Catalytic processes can yield products at a relatively constant rate over the life of a catalyst. However, as the catalyst ages, its reaction temperature increases, resulting in a decrease in selectivity—the measure of the percentage of reactants that are converted to useful products—and conversion efficiency. Advanced catalysts with higher initial selectivity and conversion efficiency can improve industrial processes and manufacturing by effectively boosting the yield of chemical production over the catalyst's life.

Impact Opportunity

The chemicals industry consumes more than 3,000 trillion British thermal units (TBtu) of onsite energy per year,[4] of which 104 TBtu of energy is estimated to be lost from catalyst non-selectivity in 42 high-volume production petrochemical processes.[5] Advanced high-volume catalysts with increased selectivity can reduce these losses by requiring less process heating fuel for catalysis, resulting in increased energy efficiency and a drop in carbon dioxide (CO_2) emissions and fuel costs. As an example, reducing catalyst selectivity losses by 25% would save 26 TBtu of energy, 42 million metric tons (MMT) of CO_2[5] and $331 million in fuel costs each year.[6]

GAS SEPARATING MEMBRANES

Conventional technologies to remove CO_2 and other impurities from air waste streams rely on expensive, energy-intensive processes that change the gas to a liquid state. Gas-separating membranes eliminate this step. A high-pressure gas mixture to be purified passes through the membrane, which has been designed to sift out the molecules of the substances that need to be captured or eliminated. This characteristic also makes gas-separating membranes potentially valuable tools in industrial processes requiring separation of hydrogen and oxygen from gas mixtures, as well as the production of pure hydrogen. Used to some extent in such areas as the production of ammonia and natural gas, the benefits of gas-separating membrane technology could be extended to other processes by optimizing selectivity involving similar-sized molecules, reducing maintenance, and designing membranes that can be more easily retrofitted into existing systems. Polymer membranes are currently in the widest use, but membranes comprised of ceramics, metals, and composites have demonstrated great promise to address a wider variety of filtration needs, operating temperatures, and service conditions.

Impact Opportunity

Gas-separating membranes offer significant potential to make carbon capture much more efficient and affordable. In terms of environmental impact, if advanced membrane-enabled carbon capture technology reduced CO_2 emissions from coal-fired power plants by 10%, it could decrease CO_2 emissions by more than 180 MMT.[7] In addition to their use for carbon capture, advanced membranes can also enable more efficient separation of oxygen and hydrogen, reducing energy use, CO_2 emissions, and fuel costs in new power plants and coal plant retrofits.

According to a study by the Lawrence Berkeley National Laboratory, using membrane technologies instead of existing separation processes requires 30% less energy. Within this context, wider deployment of gas-separating membrane technology could help significantly reduce the 2,600 TBtu consumed by the chemical and allied products industries each year for separation processes.[8]

Diffuse Reflectance Infrared Fourier Transform Spectroscopy is a technique that allows researchers to investigate the chemical reactions that occur on the surfaces of catalysts. *(Photo courtesy Oak Ridge National Laboratory/ Photo by Jason Richards.)*

COATINGS

Corrosion and wear affect the metallic surfaces of industrial equipment and lead to progressive deterioration that can reduce plant efficiency and cause equipment failures and/or plant shutdowns. Advanced protective coatings have been used with great success to protect surfaces from wear and corrosion in harsh environments. Wear-resistant coatings, for instance, are ideal for use with system components that operate in high-friction situations. These coatings can help extend component life, reduce the amount of material required for an application, and decrease the use of in-service materials, such as lubricants in machining operations. In other applications, coatings can protect components that need to operate at high temperatures, reducing the occurrence of thermally induced failure, as well as oxidation in metals that typically deteriorate at higher temperatures. Chemical, structural, and processing innovations in coatings are necessary, however, to reduce corrosion in biomass systems and improve oxidation resistance in many industrial processes.

Advancements in coating technology could also potentially save U.S. industries billions by reducing the damaging effects of corrosion and wear. The annual cost of corrosion in various industrial processes totals $3.7 billion of dollars in the petroleum refining industry, $1.7 billion in the chemicals industry, and $5.9 billion in pulp and paper production and processing.[10] A 10% reduction in corrosion costs in these three industries alone could save $1.1 billion each year.[11]

NET-SHAPE PROCESSING

Net-shape processing refers to any manufacturing method that can produce a component very close to its final shape, reducing material waste and often eliminating the need for costly secondary processing and finish machining. In addition to saving time and money, net-shape processing offers an avenue for tremendous energy savings, as well as reduction in associated CO_2 emissions, by eliminating or combining energy-intensive processing steps. For example, near net-shape strip casting is a net-shape processing technique that integrates casting and hot rolling into one step, reducing the need to reheat metal before rolling it.[12] Net-shape processing approaches have been found to be particularly effective in the manufacture of hard-to-form materials, such as high-performance, lightweight metals and composites, producing components with improved materials properties, and offering downstream savings opportunities for lightweight transportation manufacturing.

Impact Opportunity

As an example of how developing and deploying net-shape processing techniques could benefit metals manufacturing, a 2004 Lawrence Berkeley National Laboratory study determined that near net-shape strip casting in the iron and steel sector has the potential to save 400 TBtu of primary energy per year in 2025, assuming that the industry will consume 1,578 TBtu and that the fuel saved is natural gas.[12] This equates to a potential savings of 16.7 MMT of CO_2 per year and $2.041 billion in energy cost savings.[13]

High-density infrared transient liquid coating process *(Photo courtesy of Courtesy: Oak Ridge National Laboratory)*

ADDITIVE MANUFACTURING AND SURFACE TREATMENTS

Additive manufacturing comprises a group of processes that builds up parts by adding material, often in layers and frequently using laser technology. A particular benefit of this approach is the ability to modify only one particular area of a part, rather than having to modify the entire part. This has proved particularly useful in improving hard-to-form, high-value products, such as tooling, medical devices, hip and joint placements, and solar panels, while also helping to reduce energy-intensive finishing and heat treatment operations.

Another key application for additive manufacturing techniques is the repair and remanufacture of products through surface treatments such as thermal spraying and laser deposition. (See the Materials Success Story: Caterpillar Remanufacturing, page 11.) These technologies can enhance the damage tolerance of materials, protect components from harsh service environments, and repair surface fatigue, increasing the service life of parts. This, in turn, cuts downtime due to repair and replacement of parts, while also reducing the need for more expensive new parts.

Impact Opportunity

Remanufacturing parts through advanced additive manufacturing and surface treatment processes can reduce energy consumption to only 2%–25% of the energy required to manufacture new parts.[14] The associated reduction of CO_2 and landfill waste is also significant.

Additive manufacturing has a strong history of innovation and improvement that bodes well for its contributions to the advanced manufacturing economy. As an example, direct writing is a technique that is used in the production of thermal coatings, dielectric materials, and laser-printed electronics. When first used in 2004, direct writing technologies were slow, single-point delivery systems with poorly characterized materials. Since then, the rate of productivity of these technologies, measured in parts/hour, has improved 10% annually due to advances in manufacturing and deposition techniques and improved materials. This rate of improvement is expected to continue over the next 10 years.[15] (See Figure 6: Productivity of Direct Writing Techniques.)

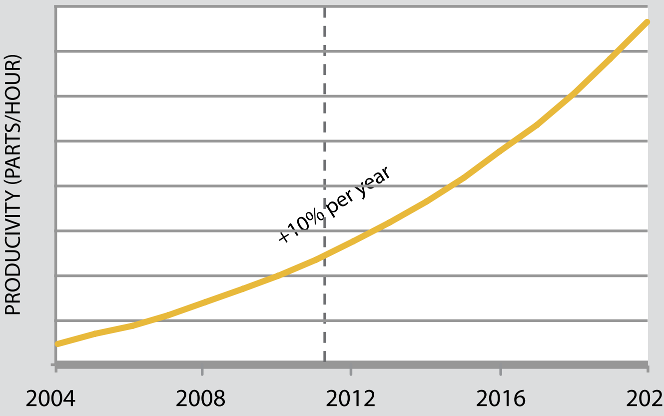


Figure 6: Productivity of Direct Writing Techniques

ENERGY EFFICIENT METALS PRODUCTION

Continued reductions in energy use and carbon emissions associated with the metals production industries require efficiency improvements across the spectrum of metals processing. These include streamlining processing steps and equipment needs, reducing reheating frequencies, and increasing production yields. Specific process improvements that could make a significant impact include the development of new materials for anodes and cathodes used in aluminum production; insulating materials for furnaces and reactors; recycling processes better capable of converting dirty, impure materials to high-grade product; and technologies that can produce titanium in a continuous process, rather than in batches. Material advances leading to energy and cost reductions in the primary production of lightweight metals can have even more far-reaching impact by making the use of these materials more affordable for the vehicle manufacturing sector.

Impact Opportunity

A 10% reduction in the estimated energy consumption of the U.S. steel manufacturing sector through more efficient production processes would result in a 148 TBtu energy reduction,[16] a 6.2 MMT reduction in CO_2 emissions,[16] and \$489 million in cost savings.[17] Similarly, a 10% reduction in the energy consumption of the aluminum manufacturing sector would result in a 60 TBtu in energy reduction,[18] a 3.6 MMT reduction in CO_2 emissions, and \$175 million cost savings.[19]

(Cover photo, JOM, vol. 62, no. 8 [2010])

Materials Success Story:

Caterpillar Remanufacturing

(Photo courtesy of Caterpillar Remanufacturing)

A division of Caterpillar, Inc., Caterpillar Remanufacturing (Cat Reman) formed in 1974 to provide product support to Caterpillar truck customers by offering remanufactured diesel engines at a percentage of the cost of new ones. Remanufacturing is the process of returning end-of-life products to the same condition as when they were originally manufactured, using advanced materials science and engineering technologies to reclaim and refurbish the core materials. What began as a small operation has grown to include more than 700 products, including hydraulics, drivetrain, and fuel systems.

Over nearly 40 years, Cat Reman has pioneered a process that can give 6,000 different heavy equipment components—from the smallest fuel system part to a complete power module—a new lease on life. In some instances, the products are returned to better-than-new performance, thanks to metal additive technologies that use lasers to deposit exacting layers of advanced wear coatings on the remanufactured part. This essentially creates a new surface designed to improve resistance to corrosion, abrasion, and heat, significantly increasing the performance life of the part—in some instances by almost 300 percent. This approach avoids costly repairs over time and reduces down time—and lost productivity—due to part replacement.

The additive manufacturing technologies utilized by Cat Reman include metal spray, which is used to rebuild engine cylinder bores and make carrier bore repairs in drivetrain systems. These components, in particular, are subjected to high pressure and temperature, resulting in metallic wear. Cat Reman also employs laser cladding technologies to apply metal onto substrates that are not ideal candidates for traditional welding due to the heat's effects on the surface material. Laser cladding has been used to recover large mining truck spindles, struts, and other load bearing products to better-than-new conditions.

"We see the future of these technologies growing exponentially, as costs are driven down and the volume and breadth of the applications increase within and across various industries," said Jihad Salahuddin, Remanufacturing and Components Division, Caterpillar, Inc.

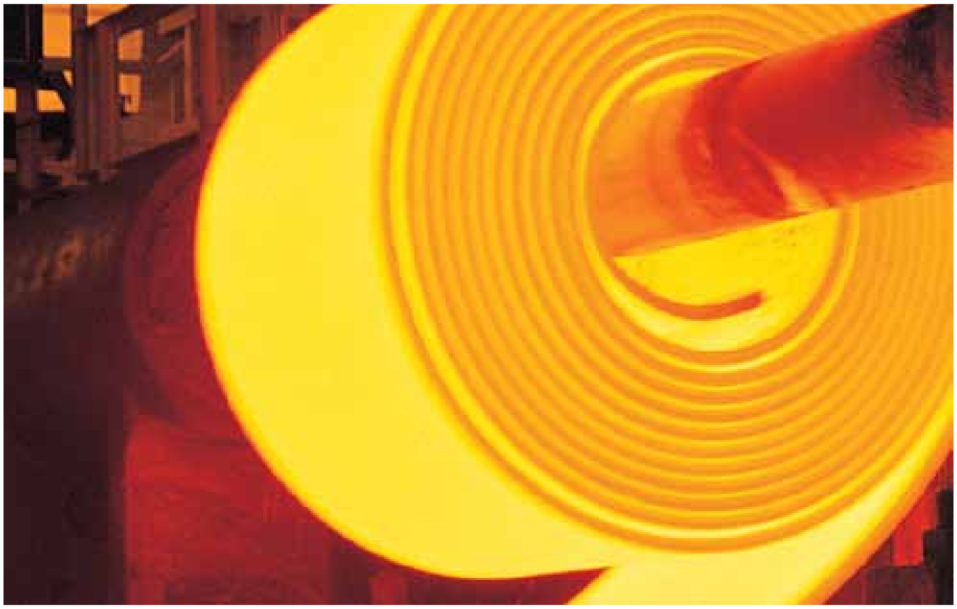
Cat Reman recycles 150 million pounds of end-of-life iron annually, due in large part to additive manufacturing techniques that minimize the need for raw materials to return components to service. Recycling also consumes only 2%–25% of the energy required for the manufacture of new parts.[14] As a specific example, Cat Reman remanufactures 100 engines a day, each requiring only 10% of the energy to manufacture a new engine.[14] By extension, this translates into a savings of an estimated 15 TBtu of energy[17] and 0.9 MMT of CO_2,[20] if one million engines were remanufactured instead of making new engines.

What's good for the environment has also proved good for business. Since its beginnings as a small internal operation, Cat Reman has grown to encompass 17 remanufacturing facilities, 2.5 million square feet of manufacturing space, and more than 3,500 employees. In 2002, Cat Reman began offering commercial remanufacturing services to Original Equipment Manufacturers (OEMs) in related industries. Business expanded into the auto, industrial, and electronics markets, as a growing number of customers benefit from the savings in energy, time, and materials inherent in remanufacturing to acquire warranted parts with same-as-when-new performance and reliability for a fraction-of-new price.

"Over the past 30 years, Caterpillar has been contributing to the additive manufacturing industry through remanufacturing with tremendous success," said Salahuddin. "This has not only been a key component of our sustainability strategy, but has also been identified as an important area of strategic growth and investment in order to add value to the enterprise and to our customers."

(Photo courtesy of Caterpillar Remanufacturing)

(Photo courtesy of Caterpillar Remanufacturing)



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1) International Aluminum Institute, "Energy Use: Primary Aluminum," 2011, accessed August 30, 2011, http://www.world-aluminium.org/Sustainability/Environmental+Issues/Energy+use.

2) Steel Recycling Institute, "The North American Steel Industry Reduces Energy Intensity," 2011, accessed August 30, 2011, http://www.recyclesteel.org/Sustainability/Energy%20Reduction.aspx.

3)John Armor, "A History of Industrial Catalysts," *Catalysis Today,* vol. 163, no.1 (2011): 3–9.

4) Prepared by Energetics Incorporated for the U.S. Department of Energy Industrial Technologies Program, "Manufacturing Energy and Carbon Footprint: Chemicals Sector," last updated August 1, 2011, accessed August 29, 2011, http://www1.eere.energy.gov/industry/pdfs/chemicals_footprint.pdf. This energy consumption does not include feedstock energy and off-site electricity generation, transmission, and distribution losses.

5) Maarten Neelis et al., "Approximation of Theoretical Energy-Saving Potentials for the Petrochemical Industry Using Energy Balances for 68 Key Processes," *Energy,* vol. 32, no. 7 (2007): 1,104–1,123. 104 TBtu is calculated by assuming a U.S. share of 19% of global non-selectivity losses, totaling 550 TBtu for 42 petrochemical processes cited. The 19% share assumption is based on a 2010 American Chemistry Council estimate of U.S. chemicals production as a share of global chemicals production.

6) U.S. Census Bureau, "2009 Annual Survey of Manufactures," December 3, 2010, accessed August 29, 2011, http://www.census.gov/manufacturing/asm/index.html. Calculation: $331 million = (26TBtu/3,195 TBtu) * $40.7 billion.

7) 1,828 $MMTCO_2$ are released from coal-fired power plants. Calculation: 180 MMT = 10% * 1,828 $MMTCO_2$.

8) Ernst Worrell, Lynn Price, and Christina Galitsky, *Emerging Energy-Efficient Technologies in Industry: Case Studies of Selected Technologies* (Berkeley, CA: Lawrence Berkeley National Laboratory, 2004), http://ies.lbl.gov/iespubs/54828.pdf.

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11) Calculation: $1.1 billion = ($3.7 billion + $1.7 billion + $5.9 billion) *10%.

12) Ernst Worrell, Lynn Price, and Christina Galitsky, *Emerging Energy-Efficient Technologies in Industry: Case Studies of Selected Technologies* (Berkeley, CA: Lawrence Berkeley National Laboratory, 2004), http://ies.lbl.gov/iespubs/54828.pdf.

13) Prepared by Energetics Incorporated for the U.S. Department of Energy, Industrial Technologies Program 2010, "Manufacturing Energy and Carbon Footprints: Iron and Steel," http://www1.eere.energy.gov/industry/pdfs/steel_footprint.pdf.

14) John Sutherland et al., "A Comparison of Manufacturing and Remanufacturing Energy Intensities with Application to Diesel Engine Production," *CIRP Annals—Manufacturing Technology,* vol. 57, no. 1 (2008): 5–8.

15) The Minerals, Metals, & Materials Society (TMS). *Linking Transformational Materials and Processing for an Energy Efficient and Low-Carbon Economy: Innovation Impact Report*. Warrendale, PA, 2011: 88.

16) Prepared by Energetics Incorporated for the U.S. Department of Energy, Industrial Technologies Program, "Manufacturing Energy and Carbon Footprints: Iron and Steel," http://www1.eere.energy.gov/industry/pdfs/steel_footprint.pdf.

17) U.S. Census Bureau, "Annual Survey of Manufactures: Statistics for Industry Groups and Industries," accessed August 30, 2011, http://www.census.gov/manufacturing/asm/index.html. Calculations: $4.89 billion * 10% = 489 million; 1.75 billion * 10% = 175 million.

18) Prepared by Energetics Incorporated for the U.S. Department of Energy, Industrial Technologies Program, "Manufacturing Energy and Carbon Footprints: Iron and Steel," http://www1.eere.energy.gov/industry/pdfs/steel_footprint.pdf.

19) U.S. Census Bureau, "Annual Survey of Manufactures: Statistics for Industry Groups and Industries," accessed August 30, 2011, http://www.census.gov/manufacturing/asm/index.html. Calculations: $4.89 billion * 10% = 489 million; 1.75 billion * 10% = 175 million.

20) John Sutherland et al., "A Comparison of Manufacturing and Remanufacturing Energy Intensities," 5–8; Prepared by Energetics Incorporated for the U.S. Department of Energy Industrial Technologies Program, "Energy and Carbon Footprint: Transportation Equipment," 2010, accessed August 29, 2011, www1.eere.energy.gov/industry/pdfs/transport_footprint.pdf. Calculations: Calculated by examining energy consumption and CO_2 emissions in the transportation equipment industry (NAICS 336).

Reinventing Energy Efficient Transportation

Achieving a markedly higher standard of fuel economy at an affordable cost and reduced environmental impact is a pivotal challenge for both the personal and mass transportation industries in the Clean Energy Age. Success will depend on the effective deployment of advanced materials innovations in nearly every system of the cars, trucks, airplanes, and other modes of transportation that have come to define modern commerce and quality of life. The technologies offering the greatest potential for reaching these efficiency and environmental goals are summarized in this chapter.

LOW COST MANUFACTURING OF LIGHTWEIGHT, HIGH-STRENGTH MATERIALS

A critical avenue to optimum fuel efficiency is more comprehensive integration of high-performance, lightweight materials into vehicle design and structure. Fortunately, this goal can build on a recent history of steady advancement and a vast store of research knowledge and manufacturing experience. For instance, performance of lightweight, high-strength materials—composites, aluminum, magnesium, titanium, hybrid materials, and polymer-based materials—has improved steadily over the past 20 years. This trend is expected to continue over the next 10 years.[1] (See Figure 7: Overall Performance of Lightweight, High-Strength Materials.) Certain high-strength steel alloys can also be used to reduce weight since they can support the performance of a component with thinner material. Hybrid materials, manufactured via a relatively new technology that uses innovative co-processing to combine dissimilar materials, are anticipated to yield a 25% decrease in weight and an increase in overall performance.[2]

While improvements must continue in enhancing tolerance of these materials to wear and corrosion in certain applications, cost remains the greatest limiting factor in their usefulness to the transportation sector. For instance, high-strength steels used in automotive applications require complex, costly heat treatments.[3] Composite materials offer characteristics that make them a preferred alternative to metals in certain structural components, reducing weight while improving strength and other performance considerations. However, the cost of producing high-performing composites makes them prohibitive for use in many applications. More efficient synthesis processes requiring fewer steps and reduced energy requirements must be developed to make these and other lightweight materials more affordable and feasible as structural options. A systems approach to vehicle weight reduction can optimize the use of lightweight, high-strength materials, enabling designers to develop vehicle strategies that increase fuel efficiency, reduce emissions, and decrease fuel costs while using smaller engines to achieve the same level of performance. (See the Materials Success Story: Ford Motor Company, page 16.)

Impact Opportunity

In 2008, the U.S. transportation sector was responsible for approximately 28% (28,103 TBtu) of total U.S. primary energy consumption.[4] Light duty vehicles alone produced 1,113 MMT of CO_2.[5] According to a study by the Massachusetts Institute of Technology (MIT), for every 10% reduction in vehicle weight, fuel economy could increase by 6% for cars and 8% for light-duty trucks.[6] By extension, if the weight of all vehicles in the U.S. car and light-duty truck fleet was reduced by 10%, the resulting energy savings would total 1,060 TBtu annually,[7] with a 72 MMT annual decrease in CO_2 emissions[7] and a $34 billion cut in fuel costs.[8]

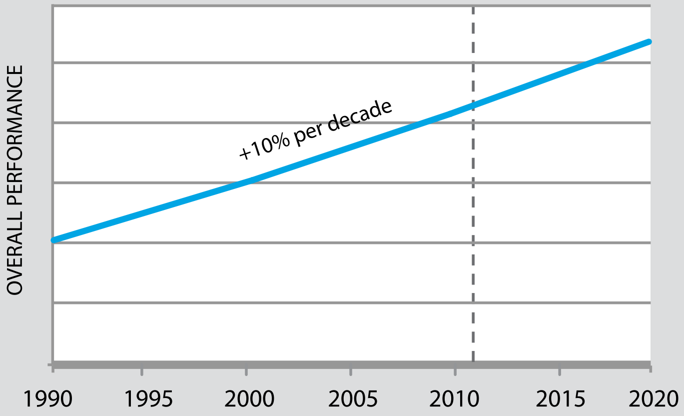
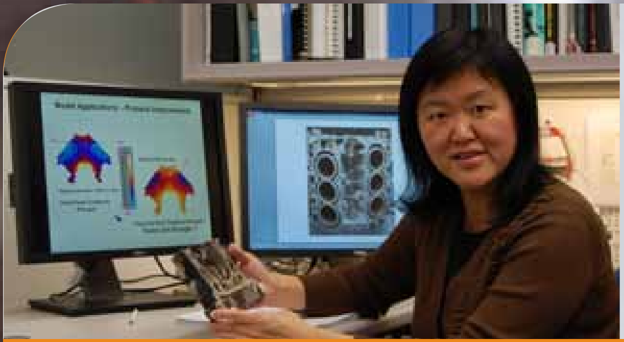


Figure 7: Overall Performance of Lightweight, High-Strength Materials

JOINING PROCESSES FOR MULTI-MATERIAL STRUCTURES

A challenge to integrating lightweight materials into complex vehicular structures is joining them effectively to dissimilar materials that also comprise the system. Advancements in joining processes—using lasers, electron beams, adhesives, heat treatments, or chemical reactions—are key to the mass production and increased use of multi-material structures in the transportation sector. This includes improving the robustness, life, and strength of joining processes that preserve core materials properties and eliminate defects. Advanced joining processes would enable more seamless construction of vehicle structures, while also permitting the use of lighter weight materials in more demanding operating environments, such as the higher temperatures near the engine.

(Image courtesy of The Boeing Company)



Materials Success Story:

Ford Motor Company

Mei Li, Ford Research and Advanced Engineering Laboratory, holds a section of the cylinder head designed using Ford's Virtual Aluminum Castings process.

Automotive manufacturers are pushing aluminum alloys and other advanced lightweight materials to the furthest boundaries of their capabilities. Strategies to decrease the weight of a vehicle component for the sake of fuel efficiency can potentially compromise its strength, while certain operating conditions stress the wear and corrosion tolerance of many lightweight materials. Success in deploying a new lightweight material is often measured in microns—a minute adjustment in the design or manufacturing process can make all the difference between bringing a quality, cost-effective product to market or having to shoulder the expense and competitive disadvantage of "going back to the drawing board."

Changing the shape of the drawing board to reduce time and costs, while also achieving an optimal outcome, is an approach that Ford Motor Company has used with great success through its Virtual Aluminum Castings (VAC) project. Initially developed for cast aluminum cylinder heads and engine blocks, VAC replaces the traditional product development process focused on building and testing a series of expensive physical prototypes. Analyses of these test results are often done without the benefit of knowing what the potential impact of the manufacturing processes has been on the component. Subsequent retooling of the design, then, is more of a "best guess", often resulting in failure of the component in later, more costly phases of new engine development.[15]

In comparison, by combining a vast knowledge base on cast aluminum research with readily available computer aided engineering (CAE) tools, VAC enables Ford engineers to design, cast, heat treat, and test specific aspects of vehicle parts in a virtual manufacturing environment, often quickly revealing microstructural issues that could otherwise set the process back by months. Also, rather than having the many areas of necessary expertise working separately on their particular aspects of the project, the VAC approach serves to bring these realms together to work simultaneously on problems, further cutting time and facilitating the exchange of information and ideas.[9]

High pressure die casting machine, Ford Research and Advanced Engineering Laboratory

A significant benefit of VAC has been its ability to take some of the guesswork out of identifying the optimum manufacturing process for a given component. By being able to model different processes, engineers can determine long before a prototype is cast how a material will perform within a particular design under certain conditions. Microscale differences in factors affecting component integrity can be addressed at the workstation until the process that potentially yields the best possible product in the most cost-effective manner is defined. The analytical power of VAC also provides valuable insights into how a design can be adjusted to ensure the lightest and most durable weight at the lowest cost.[16]

Ford's investment in "redrawing the drawing board" has provided a significant return to its bottom line, while also putting more durable, higher performing products in the hands of its customers. Reducing product and process development time by 15% to 25%, the VAC system has saved Ford more than $120 million in development costs for powertrain components. Ford's success has been widely noticed, earning it a place as a benchmark example of the power of integrated computational materials engineering (ICME)—an emerging discipline in materials science—in a study released by the National Academies in 2008.[10]

VAC is now fully integrated on a global scale into Ford Powertrain Operations and, according to Mei Li, technical expert and group leader of Light Metals Research and ICME, Ford Research and Advanced Engineering Laboratory, work is underway to introduce this approach to other aspects of Ford product development.

"The knowledge gained in metallurgy, physics, mechanics and the computational models developed for microstructural evolution and property predictions have been extended to other materials and processes," said Li. "This includes the development of computational tools for gear steels during the heat treatment process, and high-pressure die casting of aluminum alloys for additional powertrain and body applications." Li noted that her group is also developing tools based on the VAC approach for magnesium alloys and advanced heat-resistant alloys, as Ford continues to seek the competitive advantage in manufacturing lightweight, durable, and energy-efficient vehicles.

NEXT-GENERATION ENERGY STORAGE

Energy storage technologies, such as next-generation batteries and fuel cells, are integral to the successful commercialization and adoption of electric vehicles. Significant challenges remain to develop and deploy advanced materials technologies that can lower cost, improve safety, and increase energy output and storage capacity of vehicular energy storage. Progress has been made, however, leading to a steady gain in market share of electric vehicles, ranging from mild hybrids to all-electric powered. As an example, the costs of both the automotive pack and battery cell of lithium-ion storage systems are expected to drop over the next five years, with cell costs decreasing from $725/watt hours (Wh) to $555/Wh, and automotive pack costs declining from $925/Wh to $700/Wh.[11] Focused efforts that continue to improve the affordability, range, and efficiency of electric vehicles could be the game changer in the future of clean energy transportation.

Impact Opportunity

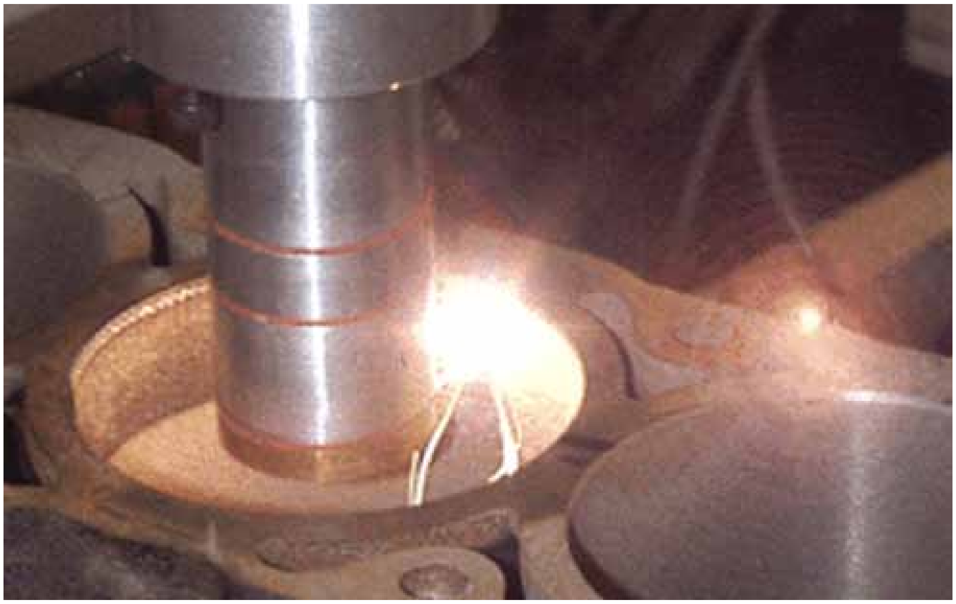
According to an MIT study, future battery-powered electric vehicles could significantly lower "well-to-wheel" energy intensities in light-duty vehicles. The study estimates that, in 2030, battery-powered vehicles could have well-to-wheel intensities of 2,715 Btu per mile and fuel cell vehicles could have well-to-wheel intensities of 2,075 Btu per mile. These numbers are 47% and 59% lower, respectively, than the well-to-wheel intensities of a 2006 Toyota *Camry* with a 2.5-liter engine.[12] From an emissions standpoint, the MIT study estimates that future battery-powered electric vehicles could have well-to-wheel emissions of 186 grams of CO_2 per mile in 2030,[13] a 54% reduction compared to the 2006 Toyota *Camry*, which emits 405 grams of CO_2 per mile.[14]

THERMOELECTRIC MATERIALS

Approximately 40% of a vehicle's energy input is lost as waste heat in the exhaust gas.[15] Thermoelectric materials can address this issue by converting the waste heat into useful electricity without releasing CO_2 emissions, and improve vehicle fuel economy by reducing vehicle electrical power requirements placed on the engine for such functions as lights, pumps, and electronic braking. Essential to large-scale market penetration of thermoelectric materials is improvement of their manufacturing processes, which are currently complex, labor-intensive, and expensive. Development of thermoelectric devices with low thermal conductivities and simultaneous high electric conductivities (measured as *ZT* [figures of merit] values) can improve the efficiency of waste heat harvesting even further. In fact, advances in thermoelectric technologies and processing techniques have the potential to nearly double the current *ZT* of commercial thermoelectric applications due to new methods of raw material purification and advances in nanomanufacturing techniques.[16]

Impact Opportunity

Advances in thermoelectric materials could help displace some portion of the 8,831 trillion TBtu consumed by cars and 7,572 TBtu consumed by light-duty trucks each year.[4] If thermoelectric materials development improves the total U.S. car and light-duty truck fleet fuel economy by 5% (identified by the U.S. Department of Energy Vehicle Technologies Program as a thermoelectric generator project objective), the resulting energy savings would total 781 TBtu, with a total CO_2 emissions reduction of 53 MMT and a $25 billion reduction in vehicle fuel costs.[4]



(Photo from "The Laser-Assisted Iron Oxide Coating of Cast Al Auto Engines" by Narendra B. Dahotre, S. Nayak, and Oludele O. Popoola, JOM, vol. 53, no. 9 (2001), pp. 44-46)

(Photo courtesy of Ford Motor Company)

Notes:

1) B. C. De Cooman, Kwang-geun Chin, and Jinkyung Kim, "High Mn TWIP Steels for Automotive Applications," in *New Trends and Developments in Automotive System Engineering*, ed. Marcello Chiaberge (n.p.: InTech, 2011), 101–128, http://www.intechopen.com/source/pdfs/13349/InTech-High_mn_twip_steels_for_automotive_applications.pdf.

2) J. Liu and M. Heinimann, "ALCOA Aerospace Technology Portfolio: Solutions to Meet the Challenges of Current and Future Applications" (presented at the AeroMat 2010 Conference and Exposition, Bellevue, WA, June 22, 2010); M. Heinimann et al., "ALCOA Advanced Hybrid Structures: Innovative Solutions for Future Aircraft Structures" (presented at the 2nd International IIR Conference: Composite & Lightweight Structures in Aircraft, Munich, Germany, May 6, 2008).

3) David Matlock and John Speer, "Third Generation of AHSS: Microstructure Design Concepts," in *Microstructure and Texture in Steels*, ed. A. Haldar, S. Suwas, and D. Bhattacharjee (Springer, 2009): 185–208; U.S. Department of Energy, EERE Vehicle Technologies Program, "Materials Technologies: Goals, Strategies, and Top Accomplishments," DOE/GO-102010-3111, August 2010, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/materials_tech_goals.pdf.

4) Oak Ridge National Laboratory, *Transportation Energy Data Book 29th Edition, Transportation Energy Use by Mode 2007–2008* (Washington, DC: U.S. Department of Energy, July 2010), Table 2.6, http://cta.ornl.gov/data/tedb29/Spreadsheets/Table2_06.xls.

5) Ibid, Table 11.7, http://cta.ornl.gov/data/tedb29/Spreadsheets/Table11_07.xls.

6) Lynette Cheah, John Heywood, and Randolph Kirchain, "The Energy Impact of U.S. Passenger Vehicle Fuel Economy Standards" (presentation, IEEE International Symposium on Sustainable Systems and Technology, Washington, DC, May 17–19, 2010), http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/IEEE-ISSST-cheah.pdf.

7) Lynette Cheah, John Heywood, and Randolph Kirchain, "The Energy Impact of U.S. Passenger Vehicle Fuel Economy Standards," (presentation, IEEE International Symposium on Sustainable Systems and Technology, Washington, DC, May 17–19).

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11) Lux Research Inc., "Projected Large-Format Li-Ion Costs," chart in Charles Murray, "Auto Industry Headed for EV Battery Glut," *Design News*, August 16, 2010, http://www.designnews.com/document.asp?doc_id=229273.

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13) Matthew A. Kromer and John B. Heywood, *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet*, 115, Table 50.

14) Calculation: Percentage change between 186 grams of greenhouse gas emissions per mile and 405 grams of greenhouse gas emissions per mile = 54%.

15) U.S. Department of Energy (DOE) Vehicular Thermoelectric Generator (TEG) Project Objectives (presentation by John W. Fairbanks, *Vehicular Thermoelectrics: A New Green Technology*, DOE Thermoelectric Applications Workshop, Coronado, CA, January 3–8, 2011).

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Making the Most of Energy Resources

Gas turbine engine *(Photo by Hemera)*

A tremendous amount of the nation's available energy represents untapped potential. The process of generating electricity, for instance, accounts for nearly 40%, or 39,579 TBtu,[1] of total U.S. energy consumption. Unrecovered waste heat for industrial processes, analyzed in a recent report from the U.S. Department of Energy, translates to 1,478 TBtu per year.[2] And, while renewable energy resources, such as wind and solar power, offer attractive options to fossil fuels for electricity generation, incorporating them more robustly into the electrical grid is severely curtailed because energy storage technologies that can help "smooth out" their inherent variability are still evolving.

The cornerstone of securing the nation's energy supply is ensuring that all existing energy resources are utilized as efficiently as possible. Strategic investment in the cadre of proven and promising materials and processing technologies discussed in this chapter is a key consideration in achieving that goal.

PHASE STABLE METALLIC MATERIALS

The route to greater energy efficiency in many energy systems must travel through brutal operating conditions, including extreme heat, intense radiation, punishing wear, and highly corrosive environments. Increasing the efficiency of industrial combustion and conversion systems, for example, requires higher temperatures and the use of aggressive chemicals that can degrade materials and cause them to fail. Advancements in other energy-related processes and technologies, such as nuclear fission and fusion, solar technologies, and fuel cells, similarly push materials to their limits.

Next-generation energy systems will only be possible when they are constructed from advanced metallic materials that can retain their strength and stability under the most challenging of conditions. Fortunately, the groundwork for this has already been laid through steady advancement in high-temperature materials, including improvements in certain chromium alloys that are expected to increase in thermal stability over the next five to 10 years. (See Figure 8: Temperature at Which Steels Are Thermally Stable.) Nickel-cobalt alloys—essential to the existence of high-temperature, high-pressure energy systems, such as steam turbines in coal-fired plants—have likewise made incremental, but continuous progress. (See Figure 9: Temperature at Which Nickel-Cobalt Alloys Are Thermally Stable.)

It is essential, however, that these materials be propelled to their next level of strength and performance, if the most promising, highest efficiency energy systems are ever to come online.

Impact Opportunity

Approximately 88% of the nation's electricity in 2010 was generated using steam turbine or gas turbine engines.[3] Incorporating advanced metallic materials capable of withstanding higher, but more efficient, operating temperatures into the design of these turbines could greatly improve the efficiency of U.S. electricity generation. For example, a 1% reduction in fuel consumed by U.S. power-generating gas and steam turbines would save $400 million in fuel costs[4] to major investor-owned electric utilities and 22 MMT of CO_2 emissions from coal and natural gas combustion.[5]

SURFACE TREATMENTS

Surface treatments on steam and gas turbine blades can offer great potential in enhancing the efficiency of electricity generation. Protective coatings applied by surface treatment processes significantly improve the tolerance of these components to wear, corrosion, and fatigue. This extends turbine life and decreases downtime due to repair or replacement.[6]

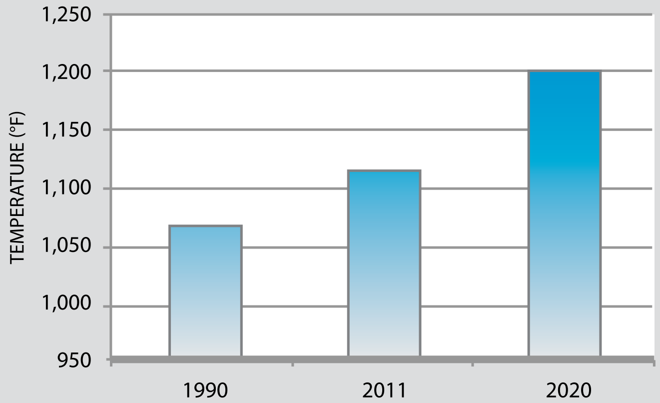


Figure 8: Temperature at Which Steels Are Thermally Stable

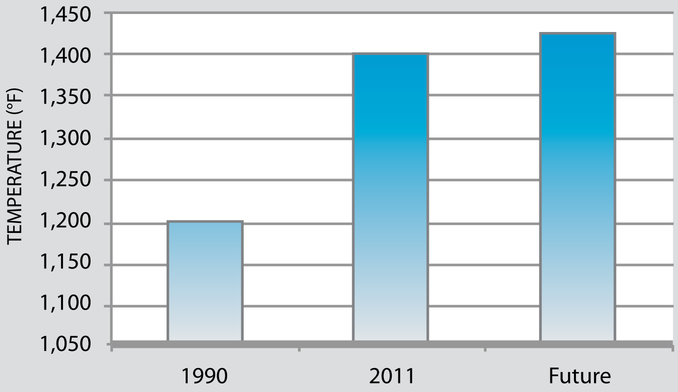


Figure 9: Temperature at Which Nickel-Cobalt Alloys Are Thermally Stable

The performance and durability of these surface treatments have improved five times since the 1950s, when thermal spraying—a coating process that involves spraying melted materials onto a surface—was first utilized. They are expected to improve by five times over the next 10 years.[7] A significant advancement in the battery of surface treatment technologies was the introduction of laser cladding in the early 2000s. This process involves depositing a layer of powder on a surface and then fusing the two materials metallurgically with a laser beam. Continued innovations in surface treatment processes and coatings—including the development of materials that are highly resistant to hot corrosion—will give turbine blades the strength and durability they need to operate effectively under the demanding conditions of high-efficiency electricity generation processes.

COMPOSITES FOR HEAT EXCHANGERS

Heat exchangers are specialized devices in large-scale industrial processes that help control a system's temperature by adding or removing thermal energy. Heat exchangers can also be used to recover heat generated as a byproduct of the manufacturing process, and then deploying it to a different, productive use. Composite materials integrated into heat exchangers could greatly enhance the waste heat recovery process in the manufacturing sector. This includes applications where heat is lost in streams of hot exhaust gases and liquids; through heat conduction, convection, and radiation from hot surfaces; and from heated product streams.[8]

Composites can achieve properties that are superior to those of any of the individual materials alone that comprise them, making them a preferred alternative to metals in certain applications. Decreasing the cost and weight of composites, while increasing their stiffness, strength, and resilience can boost their implementation as a means of more effectively tapping the potential energy that is lost as waste heat.

Impact Opportunity

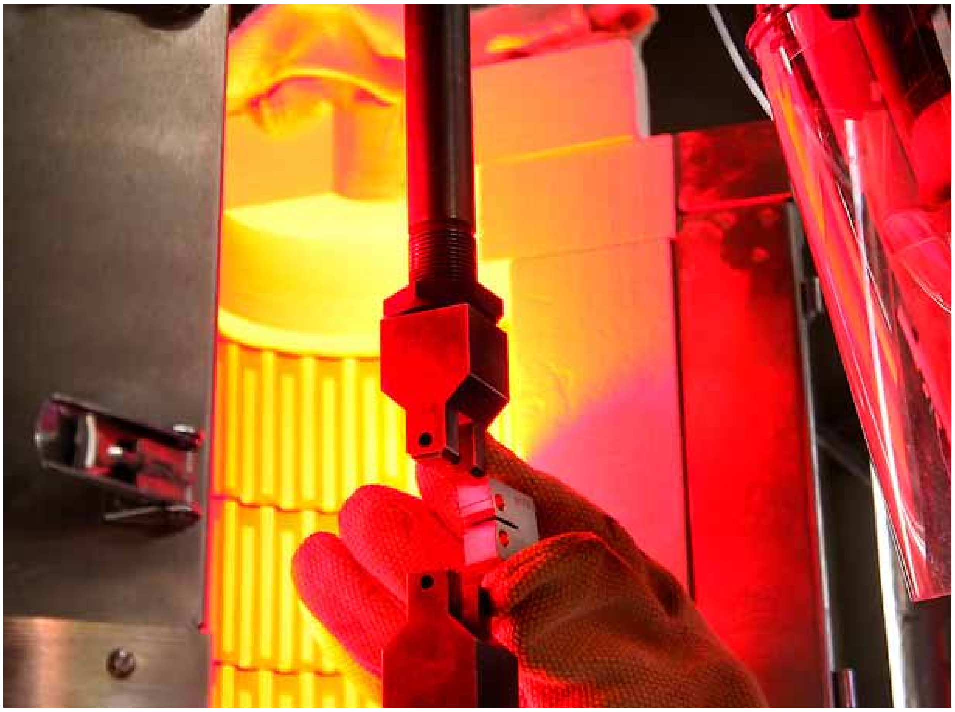
According to a 2008 report from the U.S. Department of Energy, unrecovered waste heat accounts for 1,478 TBtu of the 8,400 TBtu consumed by select manufacturing processes each year.[8] Improving waste heat recovery through such advancements as integrating structural composites into heat exchangers could have a total work potential—the maximum work that can be obtained by using the identified unrecovered waste heat to drive an engine—of 589 TBtu/year.[9] This could potentially reduce the emissions of the U.S. manufacturing sector by 34 MMT of CO_2 and save $56 billion each year.[10]

THERMOELECTRIC MATERIALS

Thermoelectric materials hold significant promise in converting waste heat into useful electricity. Development of low-cost, stable thermoelectric materials with low thermal conductivities and simultaneous high electric conductivities (measured as *ZT* [figures of merit] values) can offer an efficient alternative to processes such as mechanical generation and refrigeration, while also improving the harvesting of waste heat. To fully enable effective implementation of thermoelectric materials in industrial processes, sealants need to be developed that can protect thermoelectric elements from degrading when exposed to air, moisture, and extreme temperatures. Work is also underway to identify potential substitutes for common thermoelectric materials that are less susceptible to oxidation and better suited for high-temperature operating environments.

Impact Opportunity

Developing thermoelectric materials with a ZT of 2 or greater (the current ZT is about 1) may be able to provide thermal-to-electric efficiencies above 15%.[11] If thermoelectric materials operating at this level of efficiency are applied to 1,478 TBtu of unrecovered waste heat, this could replace 222 TBtu of grid-generated electricity that would normally be purchased,[12] resulting in a reduction of approximately 42 MMT of CO_2[13] and a cost savings of approximately $3.6 billion[14] for the U.S. manufacturing sector.



Cast stainless steel testing *(Photo courtesy of Oak Ridge National Laboratory)*

(Photo courtesy of A123)

Materials Success Story:

A123

In the fall of 2011, the AES Corporation, headquartered in Arlington, Virginia, opened the nation's largest "battery farm" for storing energy generated by its more than 60 wind turbines dotting the mountaintops near Elkins, West Virginia. The 32-megawatt project marks a step in resolving a fundamental challenge to incorporating renewable energy sources more robustly into the electrical grid—compensating for the variability of both supply and demand.

Stationary electrical energy storage (EES) for the power grid is still largely uncharted territory. The approach that AES has deployed entails more than a million rechargeable lithium-ion batteries utilizing the Nanophosphate® technology developed by A123 Systems, based in Massachusetts. The installation's goals are somewhat modest—storing a few minutes of energy at a time to feed to the grid when the wind dies down. Promising EES technologies that could store energy in the quantity and for the duration necessary to effectively address peak demands, provide sufficient back-up power, and stabilize frequencies on a large scale currently face significant economic and technical challenges for market entrance. A123 is intent on overcoming these issues based on its success in significantly advancing rechargeable lithium-ion technology for the transportation industry. With 90 MW of grid energy storage systems deployed in 2011, A123 is one of the largest manufacturers of lithium-ion batteries for the grid today.

Lithium-ion batteries are ubiquitous in a society that prizes the ability to exchange information rapidly—nearly every cell phone, laptop, and other imaginable portable communication and entertainment device are powered by them. Unlike the nickel-cadmium and nickel metal hydride batteries that preceded them for these uses, lithium-ion batteries store more energy per unit weight or volume, and operate at nearly 100 percent efficiency.[15] These characteristics make lithium-ion batteries attractive for consumer electronics, but the energy storage requirements for transportation are vastly different. When used early on for low-power consumer devices with an expected life of two or three years, lithium-ion batteries with a shorter lifespan or longer recharge times were acceptable. However, transportation applications require both high power and long life, making the early lithium-ion technology insufficient. When coupled with the additional safety considerations that come with large, high-power batteries, it was clear in the battery field that new chemistries were needed.

Building a better battery that offered all the benefits, while overcoming the limitations of lithium-ion technology to high-power application manufacturers was a particular quest for a group of researchers at the Massachusetts Institute of Technology (MIT) in the year 2000. Their solution was the development of an innovative lithium-ion cathode comprised of a chemically doped, nanoscale phosphate material that remained stable at high temperatures, while improving battery life by nearly ten times compared with conventional metal oxide cathodes. Using phosphates rather than heavy metals generally found in lithium-ion batteries also made the material a more environmentally sustainable alternative.

While laboratory results showed tremendous promise, the MIT team faced a significant hurdle in demonstrating that their invention could be commercialized. Two U.S. Department of Energy Small Business Innovation Research (SBIR) grants enabled them to establish their company—A123 Systems—in 2001, complete development, and demonstrate a cost-effective, pilot-scale process for manufacturing their lithium cathode material. With this proof, investors began coming forward and A123 took its first commercial steps in 2004 by entering the cordless power tool market. After swiftly becoming a dominant force in the U.S. high-end power tool battery arena, A123 turned its sights to the automotive sector, winning a contract with BAE Systems in 2006 to manufacture battery packs for hybrid electric transit buses, leading to its current position as the top manufacturer of lithium-ion batteries for commercial vehicles. It secured its presence in the passenger vehicle market in 2011 with the announcement that A123 batteries will power Chevrolet's 2013 *Spark EV*.

With this continued pushing of its technology to do bigger and better things, A123 has grown from a 10-person start up team to a publicly traded corporation employing 2,400 people within 10 years. In September 2010, it opened the largest lithium-ion automotive battery production facility in North America in Livonia, Michigan, with support from a DOE battery manufacturing grant. The 291,000-square-foot facility has been designed to enable the complete production process, including research and development, manufacturing of high-value components, and the final assembly of complete battery packs for vehicles.

(Photo courtesy of Invenergy LLC.)

(Photo courtesy of A123)

In addition to the SBIR grants, A123 has received funding from the United States Advanced Battery Consortium (USABC). Said Mike Wixom, A123 senior technical director, "The U.S. investments in the discovery stage of research and development were an essential factor in launching A123 Systems. However, follow up investments are critical to sustainable gains in production, job creation, and reduced petroleum consumption. Follow-on investments addressing advanced manufacturing and process development are also needed for continued progress against global competition and very aggressive cost targets."

The performance of its high-power batteries for hybrid electric vehicles, coupled with the long life from the Nanophosphate® chemistry, allowed A123 to consider an entirely new market for lithium-ion batteries: the electrical grid. Batteries for the grid offer the same advantage as batteries for vehicles by enabling fuel burning plants to operate at a higher efficiency. In handling the variable output required by the utility, a high-power grid battery can enable the plant to operate at a more uniform, efficient level. A123 and partner AES discovered that ancillary services like frequency regulation and spinning reserve could be offered cost effectively using this new generation of high-power lithium-ion batteries.

A123 is now leveraging the expertise and resources it has amassed over the decade to address the energy storage needs of an electrical grid that is currently ill-equipped to absorb a more significant percentage of abundant, but highly variable, renewable energy sources. In addition to its work on frequency regulation with AES and other clients, A123 has also embarked on a DOE-funded project with Southern California Edison Company to evaluate a utility-scale lithium-ion battery system at the Tehachapi Pass Wind Resource Area. The three-year project examines a wide range of applications to improve grid performance and facilitate the integration of wind generation into the electrical supply. Positive results could spur broader demand for lithium-ion grid products, bringing production to a scale that will make it more feasible and affordable.

From a broader perspective, development of efficient and cost-effective energy storage technologies for the electrical grid could revolutionize how the United States generates, uses, and deploys its power. A123 is intent on leading the charge as that revolution begins.

ENERGY STORAGE FOR THE ELECTRICAL GRID

Emphasis on cleaner energy and decreased reliance on fossil fuels and other nonrenewable sources has drawn greater attention to renewable sources for electricity generation. A fundamental challenge to significantly integrating renewable-generated power sources into the electric grid is their inherent variability. Stationary electrical energy storage (EES)—driven by materials advances in next-generation batteries for grid-scale application—can compensate for the inevitable fluctuations in supply of renewable energy sources, as well as hold energy stores in reserve to meet peak demands. This makes EES a critical enabling technology for effectively and economically incorporating renewable energy generation methods into the power mix. When the wind turbine stops turning or the solar panel has no sun to capture, EES provides the means to store energy for back-up power, load shifting, transmission and distribution deferral, and energy arbitrage needs. (See the Materials Success Story: A123, page 22.)

Impact Opportunity

Total U.S. energy consumption for electricity generation by the electric power sector was 39,579 TBtu in 2010,[16] with about two-thirds of this energy (27,028 TBtu) generated from fossil fuels, mostly coal (19,133 TBtu).[16] Effective, grid-scale EES technologies could address the issues of intermittent electricity generation from renewable sources and play an integral role in their increased adoption. This would help displace some portion of the 27,028 TBtu of fossil fuels that are consumed by the electric power sector, as well as the 2,271 MMT of CO_2 associated with this energy use.[16]

SOLAR MATERIALS

Harnessing the power of the sun as a source of electricity requires solar materials that can effectively absorb and convert photons into useful electrical energy. Current solar materials are only able to absorb a narrow range of energies from the broad solar spectrum, ranging from low-energy infrared to high-energy ultraviolet. Photons at the lower ranges are generally unabsorbed, while those at the higher ranges are absorbed, but mostly lost as heat. Increasing the absorption range and conversion efficiency of solar materials can reduce the cost of these materials and expand the contributions of renewable solar energy to U.S. electricity generation.

Progress has already been made in the area of photovoltaic (PV) solar cells—which convert solar radiation into electricity using semiconductors—with a number of promising breakthroughs on the near horizon. Thanks to processing and manufacturing changes, as well as the development of new and alternative materials, the efficiency of certain types of first- and second-generation PVs has increased by about 5% over the past 20 years. With further advancements, they are expected to increase efficiency by 3% in the next five to 10 years.[17] Currently, the efficiency rate—the ratio of electricity generated to sunlight captured—of commercial PVs stands at about 17% to 19%. While third- and fourth-generation PVs are still under laboratory development, their efficiency rate has already increased from 34% to 37% since 2005. In the next 10 years, advances in manufacturing methods and materials properties are expected to yield an additional 4% efficiency increase.[17]

Impact Opportunity

Solar energy as a 1% market share of U.S. electricity production (compared to current U.S. net electricity production from solar of 0.1%),[18] could displace 396 TBtu of conventional electricity generation,[19] decrease CO_2 emissions by 23 MMT,[20] and reduce fuel costs to investor-owned utilities by $402 million per year.[21]

COMPOSITES FOR WIND ENERGY

In wind energy, rotor power—and the potential energy captured—grows with the square of the diameter of the turbines blades. Lengthening the blades, however, also increases weight, making the turbine more costly to manufacture and operate.[22] The use of strong, lightweight composites to increase wind turbine blade lengths can help lower the cost of wind power production by significantly reducing this weight penalty. In addition, as wind turbine efficiency increases with size, layered composite materials offer significant opportunities for improving the performance in engineered structures, and can be used in both the blades and tower to address the increased stress.[23]

Impact Opportunity

Wind power represented a 2.3% share of U.S. electricity net generation (generating 94,647 million kWh of electricity) in 2010.[24] Low-cost composite materials that allow for the cost-effective design of wind turbines could help wind power gain an even larger share in the U.S. electricity generation sector, reducing fossil fuel consumption, emissions, and costs.

(Photo courtesy of A123)

Notes:

1) U.S. Energy Information Administration (EIA), *Monthly Energy Review, May 2011* (Washington, DC: EIA, 2011), Table 2.6, http://www.eia.gov/totalenergy/data/monthly/pdf/sec2_13.pdf.

2) BCS Incorporated for the U.S. Department of Energy (DOE) Industrial Technologies Program (ITP), *Waste Heat Recovery: Technology and Opportunities in U.S. Industry*, (Washington, DC: DOE ITP, 2008), 53, http://www1.eere.energy.gov/industry/intensiveprocesses/pdfs/waste_heat_recovery.pdf. The calculation of unrecovered waste heat uses a reference temperature of 77°F (25°C).

3) U.S. Energy Information Administration, Form EIA-860, "Annual Electric Generator Report," http://www.eia.gov/cneaf/electricity/page/capacity/existingunits2008.xls.

4) U.S. Energy Information Administration (EIA), *Electric Power Annual* (Washington, DC: EIA, April 2011), Table 8.1, http://www.eia.doe.gov/cneaf/electricity/epa/epat8p1.html.

5) U.S. Energy Information Administration (EIA), *Monthly Energy Review, May 2011* (Washington, DC: EIA, 2011), Table 12.1, http://www.eia.gov/totalenergy/data/monthly/pdf/sec12_9.pdf. Calculation: 22 MMT CO_2 = 1% * (1,828 MMT CO_2 + 399 MMT CO_2).

6) Sunniva Collins (Swagelok Company), Arthur Heuer (Case Western Reserve University), and Vinod Sikka (Oak Ridge National Laboratory), *Low Temperature Surface Carburization of Stainless Steels (Final Technical Report)*, December 2007, http://www.osti.gov/bridge/servlets/purl/920895-0kRFmv/.

7) A.S. Khanna et al., "Hard Coatings Based on Thermal Spray and Laser Cladding," *International Journal of Refractory Metals and Hard Materials* 27, no. 2 (2009): 485–491.

8) BCS Incorporated for the U.S. Department of Energy (DOE) Industrial Technologies Program (ITP), *Waste Heat Recovery: Technology and Opportunities in U.S. Industry* (Washington, DC: DOE ITP, 2008), 53, http://www1.eere.energy.gov/industry/intensiveprocesses/pdfs/waste_heat_recovery.pdf.

9) BCS Incorporated for the U.S. Department of Energy (DOE) Industrial Technologies Program (ITP), *Waste Heat Recovery: Technology and Opportunities in U.S. Industry* (Washington, DC: DOE ITP, 2008), 53, http://www1.eere.energy.gov/industry/intensiveprocesses/pdfs/waste_heat_recovery.pdf.

10) U.S. Department of Energy, Energy Information Administration, *2006 Manufacturing Energy Consumption Survey* (Washington, DC: U.S. Department of Energy, June 2009), Table 724, http://www.eia.gov/emeu/mecs/mecs2006/2006tables.html.

11) Pacific Northwest National Laboratory and BCS Incorporated for the U.S. Department of Energy (DOE) Industrial Technologies Program (ITP), *Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery* (Washington, DC: DOE, November 2006), http://www1.eere.energy.gov/industry/imf/pdfs/teg_final_report_13.pdf.

12) BCS Incorporated for the U.S. Department of Energy (DOE) Industrial Technologies Program (ITP), *Waste Heat Recovery: Technology and Opportunities in U.S. Industry*, (Washington, DC: DOE ITP, 2008), 53, http://www1.eere.energy.gov/industry/intensiveprocesses/pdfs/waste_heat_recovery.pdf. Calculation: 222 TBtu = 1,478 TBtu * 15%..

13) Prepared by Energetics Incorporated for the Industrial Technologies Program, "Energy and Carbon Footprint: All Manufacturing Sectors," 2010, accessed August 29, 2011, http://www1.eere.energy.gov/industry/pdfs/mfg_footprint.pdf. Calculation: 42 MMT CO_2 = (222 TBtu/2,850 TBtu) * 544 MMT CO_2; calculation assumes offsite electricity is displaced, as compared to onsite generated electricity.

14) U.S. Census Bureau, "2009 Annual Survey of Manufactures," December 3, 2010, accessed August 29, 2011, http://factfinder.census.gov/servlet/IBQTable?_bm=y&-ds_name=AM0931GS101. Calculation: $3.6 billion = (222 TBtu/2,850 TBtu) * $46 billion.

15) "Advanced Materials and Devices for Stationary Electrical Energy Storage Applications," U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability, December 2010, p. 21.

16) U.S. Energy Information Administration (EIA), *Monthly Energy Review, May 2011* (Washington, DC: EIA, 2011).

17) National Renewable Energy Laboratory, "Best Research-Cell Efficiencies," revised June 2011, accessed June 13, 2011, www.nrel.gov/pv/thin_film/docs/kaz_best_research_cells.ppt.

18) Solar Energy Industries Association and GTM Research, *U.S. Solar Market Insight™ 2010 Year in Review: Executive Summary* (Washington, DC: SEIA/GTM Research, April 2011), www.seia.org/galleries/pdf/SMIYIR-2010-ES.pdf.

19) Calculation: 396 TBtu = 1% * 39,579 TBtu.

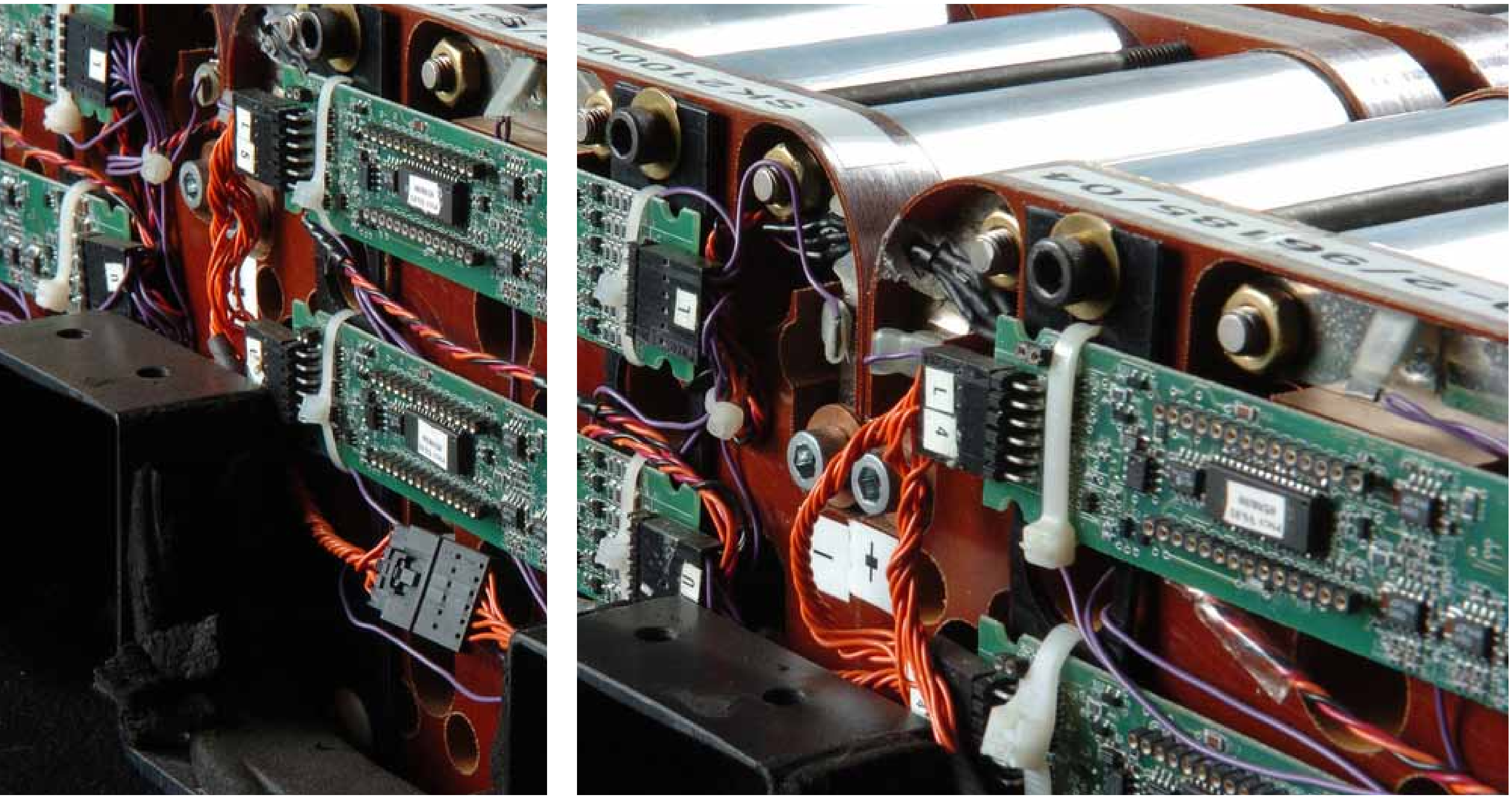
20) U.S. Energy Information Administration (EIA), *Monthly Energy Review, May 2011* (Washington, DC: EIA, 2011).

21) U.S. Energy Information Administration (EIA), *Electric Power Annual* (Washington, DC: EIA, April 2011).

22) U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), "20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply," DOE/GO-102008-2567 (Washington, DC: DOE, July 2008), http://www1.eere.energy.gov/windandhydro/pdfs/41869.pdf.

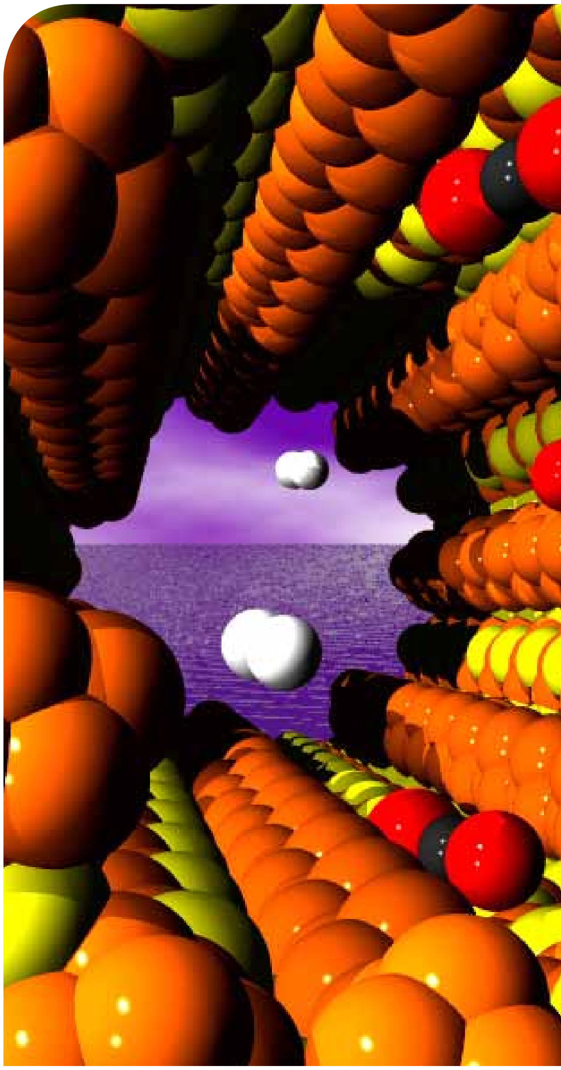
23) Ole Thybo Thomsen, "Sandwich Materials for Wind Turbine Blades— Present and Future," *Journal of Sandwich Structures and Materials,* 11, no. 1 (2009): 7–26.

24) U.S. Energy Information Administration (EIA), *Monthly Energy Review, May 2011* (Washington, DC: EIA, 2011), Table 7.2a, http://www.eia.gov/totalenergy/data/monthly/pdf/sec7_5.pdf.



Advanced lithium-ion battery *(Photo courtesy of Argonne National Laboratory)*

Accelerating Innovation

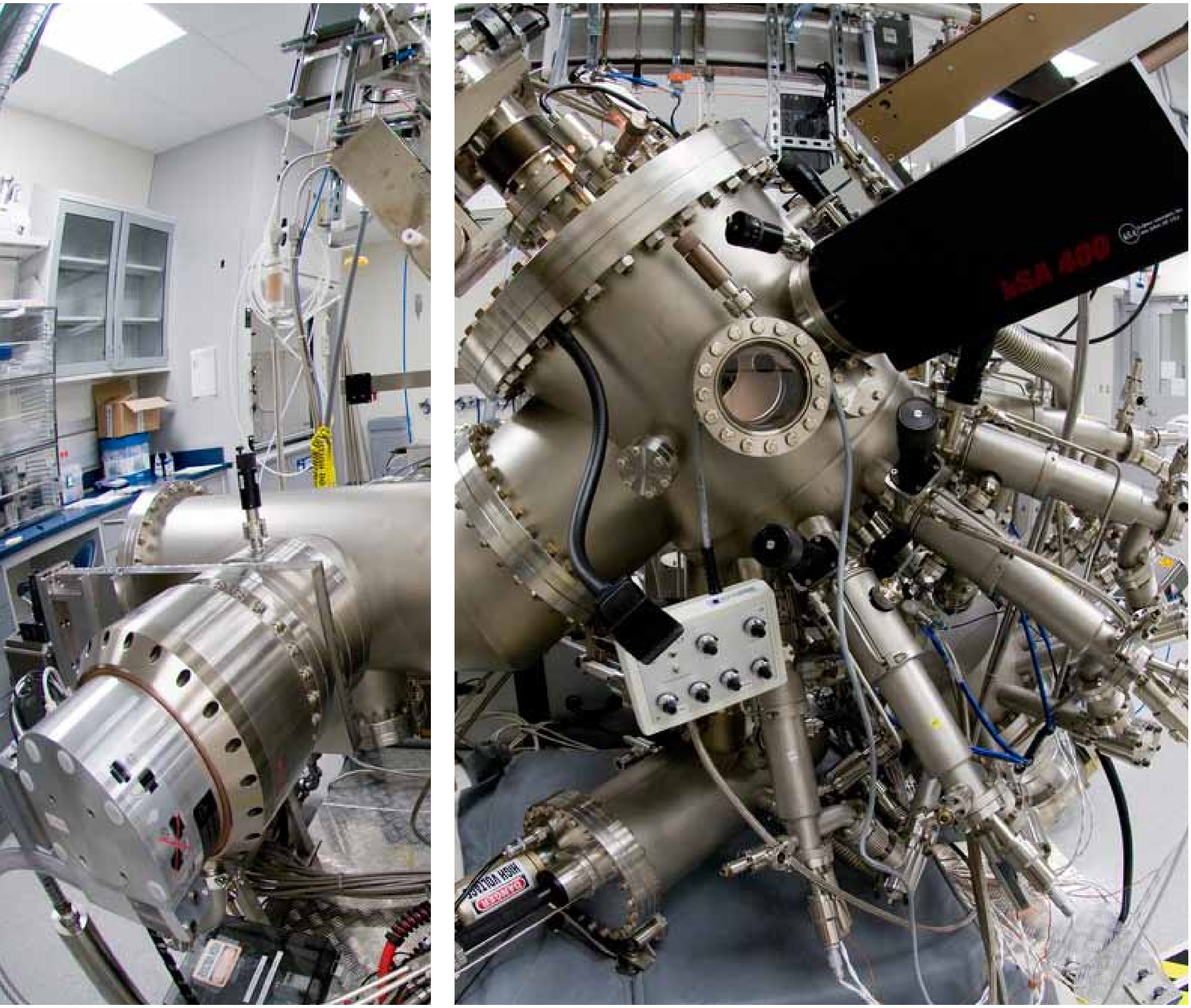


(Image courtesy of National Science Foundation//Credit: Gerasimos Armatas and Mercouri Kanatzidis)

The technologies presented in this publication and the needs they address are quite diverse, yet all share a common denominator: Their development and deployment can be accomplished quickly and cost-effectively through an exciting, emerging approach to propelling materials and manufacturing innovations.

Materials have continuously improved through the ages to address evolving societal needs. However, this development is extremely slow and expensive, compelling many applications to "make do" with existing materials technologies—the most optimal solution may still be years away on the drawing board.

Gordon Moore, co-founder of Intel, observed in 1965 that the number of transistors incorporated into a silicon chip would approximately double every 24 months. Now popularly known as Moore's Law—and adjusted to a timeframe of 18 months—this prediction has come to describe the business model driving the development of next-generation microprocessors. The urgency and complexity of the energy issues now facing the nation can



Complex oxide molecular beam epitaxy *(Photo courtesy of Argonne National Laboratory)*

be viewed in the same context, requiring a new paradigm for developing and deploying the materials necessary to enable next-generation energy technologies.

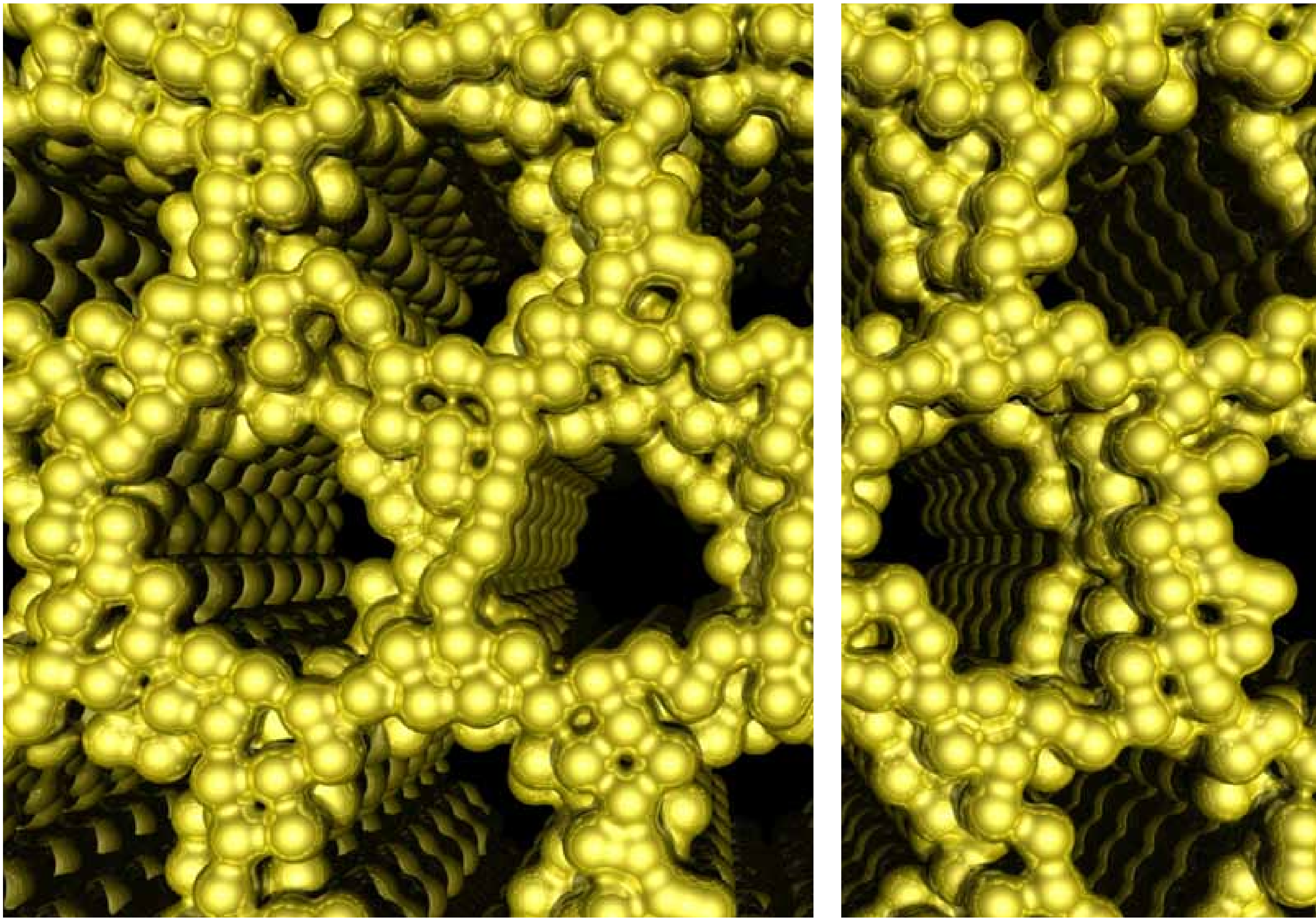
In recent years, an array of computational resources and approaches to using them have been introduced that offer the potential to cut the time now required for advanced materials development by half, while reducing associated costs significantly. (See the Materials Success Story: QuesTek Innovations, LLC, page 30.) Their power goes beyond a catalog of high-tech tools. They have formed the foundation for a new process of innovation, in which the needs of the end user and manufacturer are used to frame the design of the material and materials processing from the beginning, enabling technologies to advance more rapidly to their next level of performance and productivity.

The value of this emerging approach to fostering a more dynamic, innovative manufacturing economy is drawing attention, support, and investment from all sectors of the materials and manufacturing community. For instance, the Materials Genome Initiative, launched in 2011 as a critical, enabling element of the Advanced Manufacturing Partnership, seeks to create an infrastructure that will effectively integrate advanced computational and experimental tools, fueled by digital data, while also unifying design and manufacturing processes to support more rapid, effective deployment of materials solutions. Materials for clean energy systems are a primary focus of this multi-stakeholder effort.

While the work that formed the basis for this publication is a separate effort from the Materials Genome Initiative, a number of pathways leading to this type of "materials innovation infrastructure" has been identified in the course of this study. These include:

- ***Collaborative Databases:*** Increasing the depth and usability of open databases containing important data that characterize the structure and properties of materials can greatly improve the exchange of critical information needed for materials and process design, while enabling more complete, accurate simulation of relevant materials and processes.
- ***Predictive Modeling of Material Performance:*** Computer-assisted predictive modeling enables materials scientists to simulate the performance characteristics of materials in different operating environments. Prior to this, materials scientists could only observe potential issues after the materials failed. Improved predictive modeling can actually help prevent failure by facilitating the development of materials capable of resisting the various stresses of a given application. This, in turn, reduces the number of physical test models required and lowers the cost of manufacturing products.
- ***Process Modeling Codes:*** Critical to the effectiveness of predictive modeling are process modeling codes that can lead to the identification of previously unknown trends and correlations.
- ***Integrated Computational Materials Engineering (ICME):*** This emerging discipline in materials science and engineering pulls together the materials information captured through computational tools to design and build everything from individual components to entire systems, bringing them to market much more cost effectively and in a compressed timeframe.

Strengthening how materials and manufacturing innovation is achieved through an effective infrastructure of complementary development acceleration tools and concepts holds the key to decreasing the time and cost of translating the materials and processing discoveries outlined in this publication into real-world commercial applications. While the specific technologies presented in the previous chapters may form the foundation of the Clean Energy Age, this potentially transformative approach to their design and deployment is the gateway.



(Image courtesy of National Science Foundation/Credit: Scott Warren and Uli Wiesner, Cornell University)

Materials Success Story:

QuesTek Innovations LLC

Charles J. Kuehmann, QuesTek president and chief executive officer (left) with Greg Olson, QuestTek chief science officer and co-founder. (Photo courtesy of Andrew Campbell.)

The extraordinary punishment routinely endured by aircraft landing gears has always necessitated high strength materials to ensure both performance and safety. What has changed over the years are the increasingly stringent environmental impact, cost, and performance goals under which these planes fly.

For instance, because of their exposure to sea water and moisture in the atmosphere, landing gear steels must be both ultra-strong and highly resistant to corrosion to minimize costly repairs and downtime, as well as prevent potentially dangerous equipment failures. What's good for the aircraft, however, can be detrimental to the environment, since commonly used high-strength steels need to be plated with cadmium—a toxic element—in order to achieve acceptable corrosion resistance. Other materials, such as stainless steel, offer corrosion resistance without the need for a cadmium coating, but are lacking in strength. Coupled with these concerns is the ever mounting imperative to shave weight without compromising performance in order to reduce fuel consumption.

Development of optimum materials to meet these types of specific, evolving needs has generally unfolded over the course of decades—and usually only with incremental improvements. This has compelled aircraft designers to juggle compromises related to strength, corrosion resistance, and weight with materials created for a long past age of aviation.

Change is afoot, however, that could potentially transform how materials are designed, developed, and deployed. As an example, through a project supported by the U.S. Department of Defense's Strategic Environmental Research and Development Program (SERDP), which is planned and executed in partnership with the U.S. Department of Energy and Environmental Protection Agency, QuesTek Innovations, LLC, based in Evanston, Illinois, has presented a solution to the materials dilemma faced by landing gear designers with Ferrium® S53®, an ultra high-strength steel that offers superior corrosion resistance without harmful cadmium plating. The achievement earned QuesTek the SERDP Pollution Prevention Project of the Year Award in 2002 in recognition of S53®'s potential to reduce life cycle costs caused by environmental degradation, as well as toxic waste generated by the cadmium plating process. Even more impressive, as noted in SERDP Information Bulletin No. 15, "S53® was developed with only five prototypes over a two-year period, resulting in a development cost savings of approximately $50 million."

QuesTek Innovations has made it its business to reconfigure—and significantly accelerate—the materials development process by enabling the designer, from the beginning, to specify what is required of the material. Traditionally, materials development involves making samples of various chemistries that are tested and analyzed, with the process repeating for subsequent samples until a desired result is achieved. By utilizing advanced microstructure and property modeling, computational tools, and extensive databases of material parameters, QuesTek has reduced the need for this time-consuming and costly experimentation. Alloy composition and thermal processing precisely targeting design goals and constraints can be calculated and then modeled to identify and address potential issues before an expensive prototype is made for verification.

To date, QuesTek has invented and made four new commercially available ultra high-performance steels that are improvements over other steels that have been used for decades. They are currently in the process of designing and making commercially available more than 10 other alloys based on other elements such as aluminum, nickel, and molybdenum. Much of the funding for their research has come in the form of Small Business Innovation Research (SBIR) grants from the U.S. government.

QuesTek stresses, though, that its materials design approach goes beyond harnessing computational power. Like other companies pioneering these concepts, QuesTek presents its clients with a new way of thinking about the materials development process—one that integrates specific design and manufacturing requirements pushing for the next level of technologies, rather than focusing on modifying their needs to fit existing materials limitations.

"Integrated computational materials engineering (ICME) has great potential and the direct savings in alloy development time and cost will help drive adoption," said Charles J. Kuehmann, QuesTek's president and chief executive officer. "A much bigger impact will be when computational methods can be integrated all the way upstream into the component design community and downstream fully into the manufacturing and process industry. The new frontier is concurrent design of materials and devices. This will exploit

The ribbon cutting ceremony for the world's largest VIM furnace at Latrobe Specialty Metals. (Photo courtesy of Latrobe Specialty Metals Co.)

the inherent predictability of designed systems, acknowledging design output as not just a material, but a combined material and information system for rapid adaptability in manufacturing and service.

In 2007, S53® became the first commercially produced, computationally designed alloy, developed by QuesTek's leveraging its Accelerated Insertion of Materials (AIM) expertise, funded by the U.S. Defense Advanced Research Projects Agency and the U.S. Office of Naval Research. The first deployment of a flight critical part made from a computationally designed alloy occurred in 2010 when a T-38 took off with a Ferrium S53® landing gear. QuesTek continues to learn from and build on these accomplishments to refine its knowledge, expertise, and processes. Its newest landing gear steel, Ferrium® M54™, achieved an SAE Aerospace Material Specification in August 2011, within four years of having its initial design goals established, versus seven years for S53®. QuesTek designed M54™ to be a lower-cost alternative to an existing ultra-tough, ultra high-strength steel by reducing the amount of cobalt—the most expensive element in the alloy's composition—by about half of what is contained in the incumbent material, while computationally adjusting other factors to achieve equivalent or better material properties.

In addition to meeting the particular cost and performance needs of its clients, QuesTek's new steels have generated an economic ripple effect felt far from Illinois. A very visible testament to that is a 65,000-square-foot, 70-foot-tall specialty steel expansion built by Latrobe Specialty Metals Co. in the Appalachian foothills of western Pennsylvania. The facility houses the world's largest vacuum induction melting (VIM) furnace. Opened in September 2008, at a time when much of the U.S. economy was struggling, the expansion will serve as Latrobe's platform for securing its position as one of the world's leading specialty steel manufacturers, particularly for the high-performance alloys demanded by the aerospace and defense industries. Latrobe employs 600 people at its manufacturing headquarters, with nearly 200 more working throughout the United States in support positions.

A factor in Latrobe Specialty Metal's success has been its ability to offer new solutions that meet the rapidly evolving needs of its customers, thanks in part to QuesTek's accelerated development process. "During the last four years, we've introduced four new high-performance steels to customers worldwide, by licensing Ferrium® M54™ and S53®, as well as C61™ and C64™ from QuesTek," said Scott Balliett, Latrobe's director of Technology and Quality. "These new product offerings leverage our state-of-the-art vacuum melting facility and help us continue to expand our business."

Kuehmann believes that QuesTek's early successes represent just a glimpse of what the future can hold for the potentially transformative approach to materials design that defines his company. "At some point, all materials will be designed using computational models, and materials modeling will be inherent to component design and manufacturing," he said. "It may be 10 years from now, 20 years, or 50 years, but it will be done this way. QuesTek will continue to be a leader in this revolution, and when we look back on it, we want people to say that we helped make that happen. We'd also like to come up with some really great alloys in the process, ones that make people say, 'I didn't think you could make a material do that!'"

Forward to the Future

The materials and processing innovations outlined in this publication form the foundation of a new era of environmental sustainability and economic growth in the United States, fueled by significant cost, production, and energy efficiencies, as well as global leadership in the manufacture of the products and technologies responsible for these efficiencies.

Claiming this position in the coming Clean Energy Age will require a coherent, integrated approach engaging all facets of the manufacturing spectrum—from the laboratory researcher to the end user—focused on rapidly and cost effectively deploying materials-enabled energy solutions. Through its world-class intellectual, industrial, and economic resources, the United States already has the infrastructure in place to secure this future. The challenge lies now in marshalling these capabilities to yield their greatest possible collective potential. Of critical importance in this regard is rational, sustained federal support of broad-based research and development that advances these goals. Enhancing industry access to the knowledge, expertise, and cutting-edge resources available through academia, as well as the U.S. national laboratories, would also greatly facilitate the development and commercialization of potentially game-changing technologies and processes.

This document has been developed to provide insights into the United States' most promising opportunities for energy savings, environmental impact, and economic advantage in the next two to 10 years, made possible by investment in materials and processing innovations. Many of these are on the cusp of making a significant impact on some of the nation's most pressing energy needs. The next, necessary step relies on a focused, cohesive effort to move these technologies with alacrity from the laboratory to commercial implementation, ensuring the nation's progress, prosperity, and leadership in the new global energy economy.