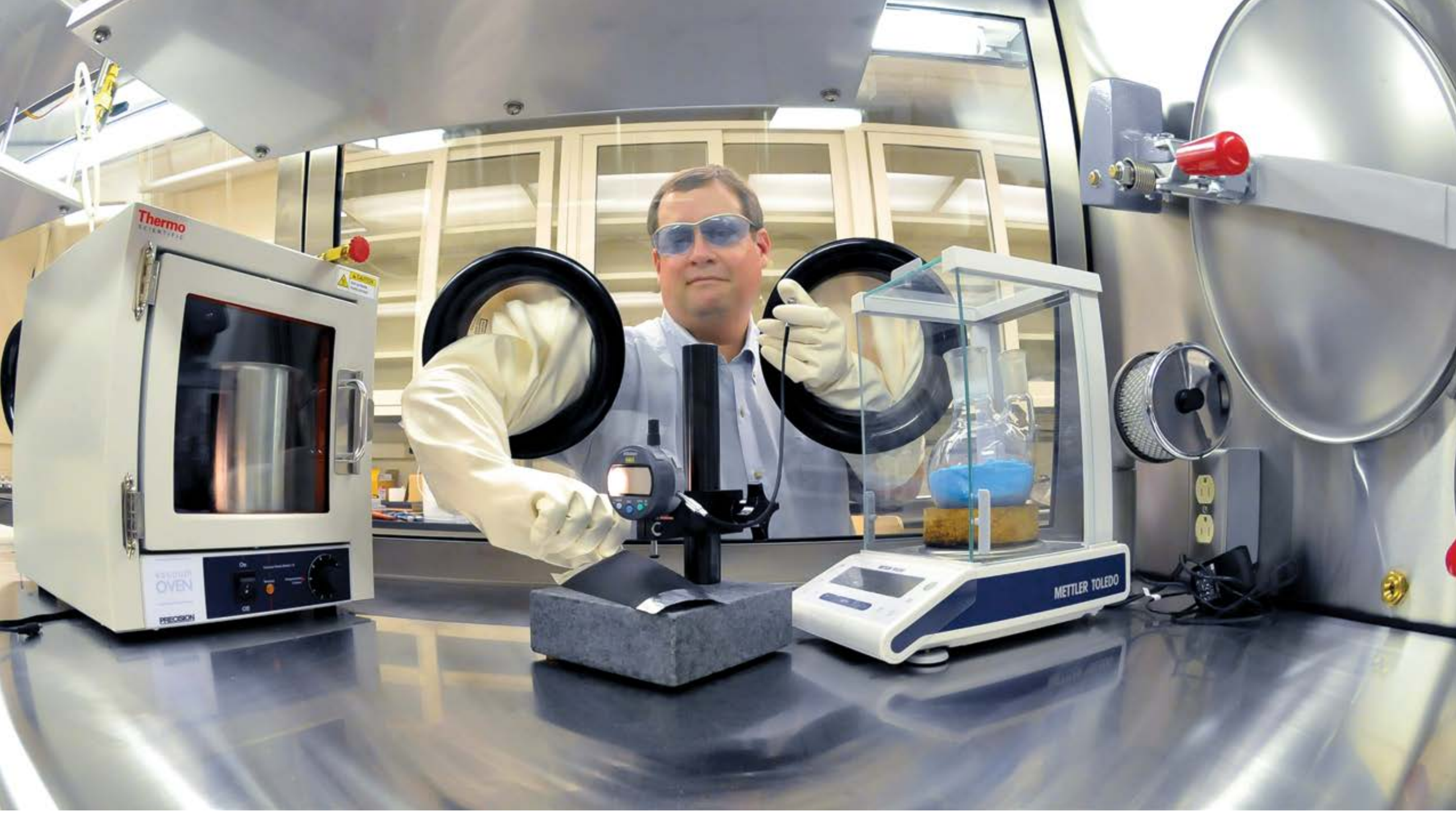


Innovating CLEAN ENERGY TECHNOLOGIES *with* MATERIALS SCIENCE

How does technology innovation happen? Over the past three decades, the Department of Energy has funded a very successful model leading to new commercial technologies for energy-saving "smart" windows and for advanced batteries and fuel cells to power pollution-free electric cars. The model starts with fundamental research into the properties of materials important for energy technologies, supported by the Office of Basic Energy Sciences (BES). The research, usually undertaken by individual investigators at universities or DOE national laboratories, often makes use of BES shared research facilities. Once the underlying science is fully understood, discoveries that show potential for useful technologies are passed on to the Office of Energy Efficiency and Renewable Energy (EERE). EERE in turn supports applied research to improve the technology and address potential manufacturing problems, often with commercial partners. Then the university or national laboratory where the research was done licenses the innovations to private sector entities who have the manufacturing facilities to launch commercial products. The innovation

Battery researcher at Argonne National Laboratory measuring the properties of an advanced cathode for lithium ion batteries. Batteries with improved cathodes are both safer and can store more electricity and have now been commercialized for use in electric cars. *(Argonne National Laboratory)* process from basic research to commercialization can often take two or three decades, but can result in economically significant technological advances, such as the three examples described here.

Improved Lithium Ion Batteries. In the mid-1990s, BES initiated and funded research to discover new materials that would improve the performance and safety of these batteries. Studies that used manganese instead of cobalt in the cathodes of the battery, paired with lithium as the carrier of electricity, showed promise. Further studies were undertaken to understand the structure and properties of these materials using BES shared research X-ray probes at Argonne National Laboratory. The result proved that using manganese in the cathodes could improve a battery's energy storage capacity and safety. Additional BES-funded research turned up new ways to synthesize these materials, creating a roadmap for development of the technology and leading to the issuance of multiple patents.

The investigators then approached EERE, which agreed to fund more applied work, including perfecting the battery design, testing the new cathodes in high-energy lithium ion batteries, and confirming their superior performance and reduced risk of overheating. The research also explored ways to enhance battery performance even further in the future. The new cell chemistry represented a radical leap forward in cathode design—more powerful, safer and longer-lasting—and, since manganese is less expensive than cobalt, such batteries are cheaper as well.

Argonne National Laboratory collaborated closely with materials companies, battery manufacturers and car makers to transfer the technology. The detailed knowledge of nanoscale structure, composition, and other properties provided by basic research enabled these companies to rapidly engineer production systems for the new cathodes and integrate them into full automotive battery systems. LGChem licensed the technology and created batteries for the Chevy Volt, a first-generation electric vehicle; GM has since licensed the technology as well for its just-launched Bolt; new manufacturing plants have been built in the U.S. to produce these batteries. Moreover, research at Argonne has led to more than 125 patented advances in battery-related technology that are available to industry.

Fuel Cells. Fuel cells, which directly convert fuels (such as hydrogen) to electricity without combustion, are not

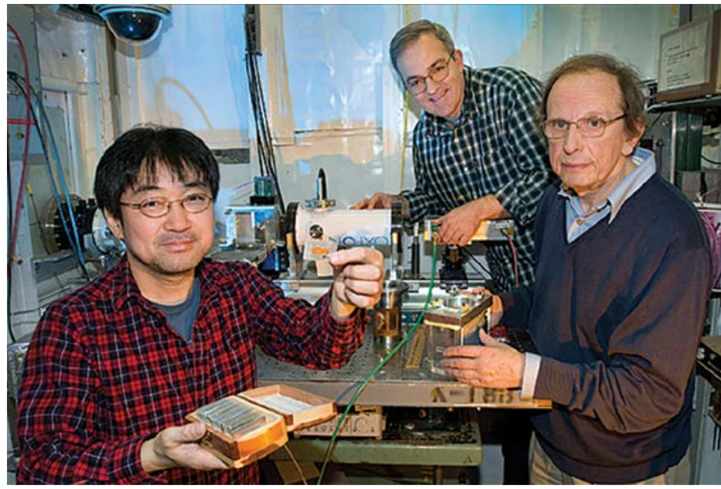
The hybrid-electric Chevy Volt shown here and the new all-electric Chevy Bolt use batteries that benefited from improved cathode research at Argonne National Laboratory.
(Argonne National Laboratory)

new. This direct chemical-to-electrical energy conversion is both more efficient (typically 45-50%) than burning fuel in a vehicle engine, and is cleaner, since the only exhaust is water vapor. Refilling a fuel tank with hydrogen takes minutes, not the hours required for recharging a battery. Engineers have long known that fuel cells could be a better way to power electric cars. But in the mid-1990s, fuel cells were too expensive and not very durable, and were adopted only for high-end applications such as space capsules.

The same problems faced plans to use electricity from solar cells to produce hydrogen and oxygen by splitting water—capturing renewable energy from sunlight in a chemical form (hydrogen) that can be easily stored and transported. In both fuel cells and hydrogen production, the problem was the cost of the electrocatalyst material that enables the reaction—typically nanoparticles made of expensive platinum.

BES funded a team of scientists at Brookhaven National Laboratory to tackle the problem at a fundamental level. Over several years, they developed new ways of making a catalyst using a monolayer of platinum just a single atom in thickness, deposited on another material. Brookhaven's shared research X-ray facilities helped reveal the properties of the material's surface—where the chemical activity takes place. When the scientists tested its catalytic properties, they found that the monolayers worked well and that their activity could be adjusted by choosing different underlying materials. Even more, to their surprise, scientists found that with palladium as the underlying material, the electrocatalyst worked better than pure platinum. They also discovered that adding small amounts of gold to the platinum catalyst greatly improved durability.

The investigators took their discovery to DOE's EERE office, which agreed to support applied research. That effort developed effective ways of making various nanoparticle cores and depositing the platinum monolayer on them. The scientists also worked with DOE's Los Alamos National Laboratory to test the electrocatalyst in real fuel cells. This research caught the automotive industry's attention, and vehicle manufacturers such as GM and Toyota helped to support the applied research. Ultimately it became clear that these new catalysts were both less expensive and more durable than the old solid platinum nanoparticle catalysts. Two catalyst companies have licensed the technology and are commercializing it. GM plans to introduce its first fuel-cell electric car in the early 2020's with the new catalysts a primary candidate for inclusion. Toyota, which recently started selling fuel cell electric cars in small quantities, is also evaluating the new catalysts to enable cost-effective high-volume production. US Plugpower, which powers the electric forklifts that are ubiquitous in warehouses like those of Amazon and Walmart, has already deployed 15,000 units that use fuel cells rather than batteries, avoiding the downtime for battery charging. Fuel cells, it appears, are about to go big-time.



Top: Chemists at Brookhaven National Laboratory at work on improved catalysts for fuel cells. The resulting technology is now fully commercial and will power advanced electric cars under development by General Motors. *(Brookhaven National Laboratory)*

Bottom: Forklift vehicles powered by fuel cells instead of batteries—such as these manufactured by Plugpower—do not need to be taken out of service for recharging and are rapidly being deployed at warehouses and distribution centers in the U.S. *(Plugpower)*

Smart Windows. By the late 1980s it became clear to scientists at DOE's National Renewable Energy Laboratory (NREL) in Colorado and DOE's Lawrence Berkeley National Laboratory (LBNL) in California that it was possible in principle to make electrochromic smart windows—windows whose optical properties (like transparency and tint) could be changed by applying an electrical voltage. Such windows could let in all the available light on cloudy days, but turn darker to reduce glare and air conditioning use when the sun is bright—saving energy and making office space more user-friendly. But while the potential for such windows was clear, and laboratory studies had demonstrated that very thin coatings of a nickel oxide material exhibited an electrochromic effect, the knowledge needed to understand the phenomenon in detail was lacking.

BES agreed to fund research on such electrochromic materials, both at NREL and LBNL. These materials typically involve five distinct layers, each very thin. A decade's work resulted in a much more detailed understanding of these materials, the process by which electrical charges move from one layer to another, and how that changes the optical properties. It also created working prototypes.

At that point, support for more applied research with the goal of a commercial technology was picked up by DOE's EERE and Advanced Research Projects Agency-Energy (ARPA-E) programs. It focused for another decade on finding better materials—it turned out adding tungsten oxide materials gave a more pleasing tint to the windows and produced the color change with a smaller electrical charge. The

These "smart" windows make use of specialized materials to change their tint and lower the amount of sunlight transmitted in response to environmental conditions, saving energy for cooling buildings and creating more comfortable working conditions. *(SageGlass, Inc)*

research also focused on production techniques to fabricate the thin metallic oxide layers. The applied work eventually attracted private sector investment as well.

Commercialization of the technology is now well underway, with the potential of saving half of peak cooling costs in office buildings, according to one estimate. Companies SageGlass and View both have products on the market, with installations in several hundred modern office buildings, art galleries, and restaurants. This initial generation of smart windows do save energy as well as providing a more comfortable working space, although experts believe that the energy savings do not quite cover the costs as yet. Heliotrope, a company spun out of LBNL, has a product in pre-production with a different production process that it expects will lower costs, enabling wider adoption. Boeing is even installing electrochromic windows in its new 787 Dreamliner. Smart windows, it appears, are well on the way to becoming a significant energy-saving technology.

These examples illustrate how an effective innovation process works, combining basic science, applied research, and partnerships with industry for commercialization—in these instances yielding three distinct and useful clean energy technologies.