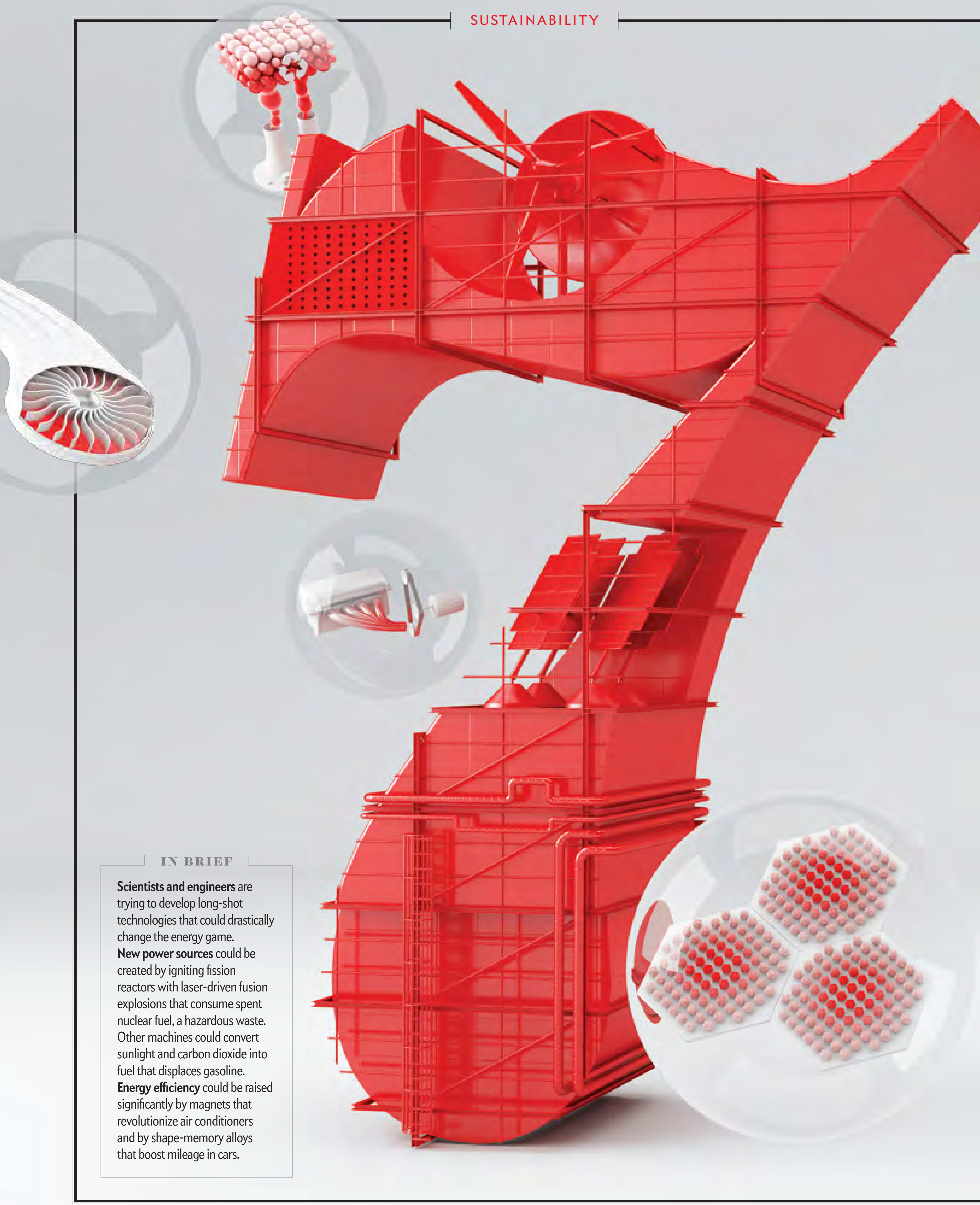
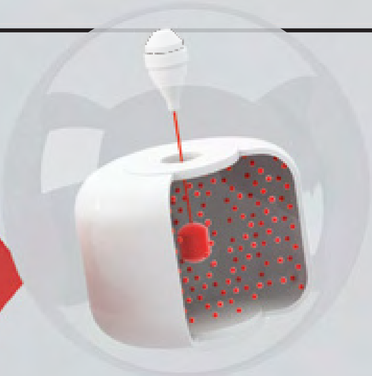


IN BRIEF

Scientists and engineers are trying to develop long-shot technologies that could drastically change the energy game.

New power sources could be created by igniting fission reactors with laser-driven fusion explosions that consume spent nuclear fuel, a hazardous waste. Other machines could convert sunlight and carbon dioxide into fuel that displaces gasoline.

Energy efficiency could be raised significantly by magnets that revolutionize air conditioners and by shape-memory alloys that boost mileage in cars.



RADICAL ENERGY SOLUTIONS

The failure rate may be 90 percent, but if any of these exotic technologies succeeds it could significantly improve energy security and efficiency

MANY PEOPLE ARE WORKING TO HARNESS RENEWABLE ENERGY SOURCES MORE effectively and to enhance energy efficiency. All good. Most of the efforts will probably result in welcomed but incremental improvements, however. Radical innovations are needed to drastically change the energy game.

For years scientists and engineers have touted some fantastic schemes: satellites that beam solar power to receivers on land; wind machines that hover in the atmosphere, generating electricity. Down on earth, however, researchers have recently received substantial government or private funding for a remarkable variety of long-shot technologies in a few key areas. The projects we profile here are leading examples of the payoffs that are possible—if, of course, the inventors manage to overcome daunting hurdles to bringing practical, mass-produced and affordable technologies to fruition.

—*The Editors*

LIKELY TO WORK?
On the following pages, our editors and advisers handicap these technologies in two ways:

LIKELIHOOD
of succeeding commercially

POTENTIAL IMPACT
on energy supply or use

Lowest ● ○ ○ ○ ○

Highest ● ● ● ● ●

Illustrations by Chris Labrooy

POWER PLANTS

Fusion-Triggered Fission

Lasers coax electricity out of spent nuclear fuel

LIKELIHOOD

POTENTIAL IMPACT

PHYSICISTS AND ENGINEERS HAVE LABORED for decades to harness nuclear fusion, the same process that blazes in H-bombs and the sun. The researchers can readily produce fusion reactions—slamming hydrogen nuclei together fiercely enough that they merge, releasing neutrons and energy. The hard part is doing it so efficiently that the reactions release more energy than used to start them, a condition called ignition, which could ultimately generate electricity.

Scientists at the National Ignition Facility in Livermore, Calif., have therefore come up with a new twist: using fusion to drive fission, the atom splitting that powers conventional nuclear reactors. Director Edward Moses claims the process could lead to prototype power plants in 20 years.

In the Livermore scheme, laser pulses produce fusion explosions at the center of a reaction chamber, emitting neutrons that split atoms in a thick blanket of uranium or other fuel lining the chamber's walls. Energy from these fissioning atoms would multiply the chamber's power output by a factor of four or more. The concept of fusion driving fission for peaceful purposes dates back to Andrei Sakharov, "father" of the Soviet H-bomb, who raised the idea in the 1950s.

If most of the power comes from fission, why not stick with conventional nuclear power plants and avoid the hassle of developing the fusion trigger? A fission reactor relies on a chain reaction in which neutrons from fissioning atoms trigger more atoms to split. Sustaining the chain reaction requires plutonium or enriched uranium fuel, both of which can be used in nuclear weapons.

In the hybrid fusion-fission plant, neutrons from the fusion explosions generate the fission, eliminating the need to sustain a chain reaction. This arrangement broadens the menu of possible fuels to include unenriched uranium, depleted uranium (a voluminous waste product of uranium enrichment) or even spent fuel from other nuclear reactors—waste that would otherwise have to be stored for thousands of years or undergo complicated and hazardous reprocessing for reuse in a fission plant.

Another benefit is the amount of burnup. A conventional reactor splits only a few percent of its fuel's fissionable atoms before the fuel must be changed out. Moses says fusion-fission plants could achieve 90 percent burn, thus requiring perhaps only a 20th as much fuel as a typical fission reactor. An "incineration" phase in the final decade of the plant's roughly 50-year life span would reduce the long-lived waste from 2,500 kilograms or so to about 100, albeit with declining power generation in those years.

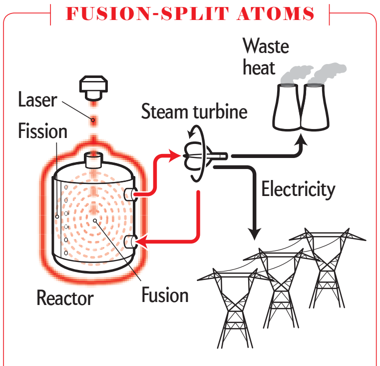
Researchers are also studying fusion-fission proposals based on magnetic fusion, a competitor to laser fusion that bottles the fusion reaction in powerful magnetic fields. In 2009 scientists at the University of Texas at Austin proposed a hybrid reactor with a compact magnetic-fusion trigger. Researchers in China are evaluating designs optimized for producing energy, for breeding conventional reactor fuel and for burning nuclear waste.

Fusion energy of any kind is a radical proposition. Even if Moses's facility demonstrated ignition this year, major technical obstacles would remain before a power plant could become reality. Tiny, exquisitely engineered fusion pellet targets would have to be mass-produced inexpensively. Ignition would have to occur 10 times a second, which requires an array of unproved technology (the National Ignition Facility manages at best a few target shots a day).

Hybrid approaches also require technologies not needed in pure fusion—in particular, the fission blanket, including fission fuels that can withstand a much greater barrage of heat and neutrons than they encounter in a conventional reactor. Proposals range from solid, multilayered "pebbles" to liquids composed of uranium, thorium or plutonium dissolved in molten salts.

The challenges are daunting, and Moses has mapped out an aggressive development path to achieve them. First, though, his facility must prove that laser fusion can actually achieve ignition. —*Graham P. Collins*

FUSION-SPLIT ATOMS



LIQUID FUELS

Solar Gasoline

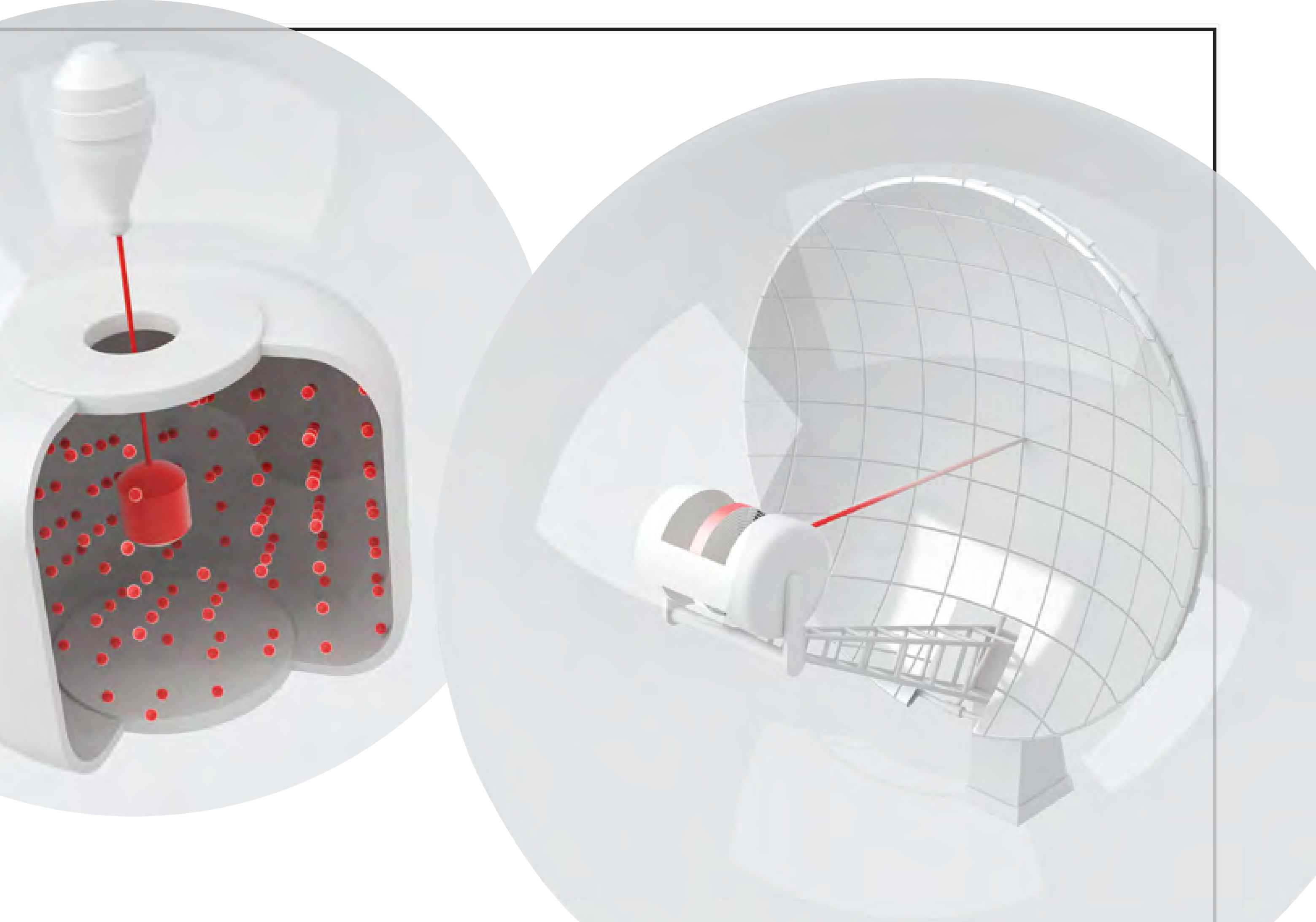
Concentrated sunlight and carbon dioxide propel vehicles

LIKELIHOOD

POTENTIAL IMPACT

THE SUN BATHES THE EARTH IN MORE ENERGY in an hour than civilization uses in a year. If scientists could convert even a fraction of that surplus into a liquid fuel, our addiction to fossil fuels for transportation, and the problems they cause, could end. "Chemical fuels would be the game changer if you could directly make them efficiently and cheaply from sunlight," notes Nathan Lewis, director of the Joint Center for Artificial Photosynthesis at the California Institute of Technology.

Graphics by Brown Bird Design

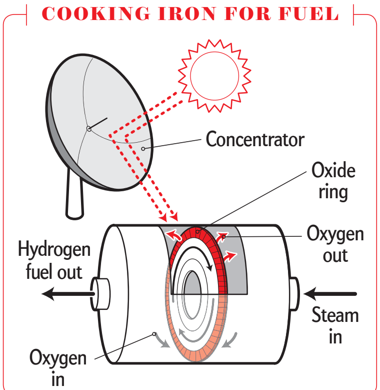


One intriguing effort at Sandia National Laboratories employs a six-meter-wide dish of mirrors in the New Mexico desert. It concentrates the sun's rays on a half-meter-long cylindrical machine shaped like a beer keg that is mounted in front of the dish. The mirrors focus sunlight through a window in the machine's wall on a dozen concentric rings that rotate once a minute. Teeth of iron oxide (rust) or cerium oxide rim the rings and rotate into the beam, heating to 1,500 degrees Celsius. That heat drives the oxygen out of the rust. As the teeth rotate back into the cooler, dark side of the reactor, they suck oxygen back out of steam or out of carbon dioxide that has been introduced into the chamber, leaving behind energy-rich hydrogen or carbon monoxide.

The resulting mixture of hydrogen and carbon monoxide is called synthesis gas, or syngas—the basic molecular building block for fossil fuels, chemicals, even plastics. The process could also absorb as much CO_2 as is emitted when the fuel is burned. Such a system of solar fuels "is like killing four birds with one stone," says Arun Majumdar, director of the Advanced Research Projects Agency–Energy: clean fuel supply, greater energy security, carbon dioxide reduction and less climate change.

Researchers elsewhere, including at the Swiss Federal Institute of Technology in Zurich and the University of Minnesota, are developing syngas-producing machinery. And some start-up companies are pursuing other paths. Sun Catalytix in Cambridge, Mass., dips a cheap catalyst into water and, using electricity from a solar panel, creates hydrogen and oxygen. Liquid Light in Monmouth Junction, N.J., bubbles CO_2 into an electrochemical cell that builds it into methanol. And Lewis himself is building artificial leaves from semiconducting nanowires that absorb sunlight to split water into hydrogen and oxygen.

COOKING IRON FOR FUEL



Of course, overcoming practical problems is the main hurdle. At Sandia, the teeth keep cracking, impeding the reaction. "You're cycling back and forth from 1,500 degrees to 900 degrees; that's a lot to ask of a material," notes chemist Gary Dirks, director of LightWorks at Arizona State University, who is not involved with the work. The next step is to make the rust structure more robust at the nanoscale or to find even better tooth materials. The high cost of the mirrors would also have to drop. Sandia's researchers suggest their syngas engine can make fuel for $10 per gallon ($2.65 a liter). "We haven't proved to ourselves that we can't do it," says chemical engineer and co-inventor James E. Miller, "but we're a long way from doing it." ***—David Biello***

LIKELIHOOD

POTENTIAL IMPACT

ELECTRICITY

Quantum Photovoltaics

Hot electrons double solar-cell efficiency

TODAY'S COMMERCIAL SOLAR CELLS CONVERT only 10 to 15 percent of the light they receive into current, resulting in expensive electricity. One reason is that a single layer of light-absorbing silicon has a theoretical efficiency limit of about 31 percent (the best laboratory cells reach 26 percent). New research into semiconductor crystals, or quantum dots, could boost the theoretical maximum above 60 percent, blazing a path for products that generate electricity at competitive prices.

In a conventional cell, incoming photons knock electrons loose from the silicon, allowing the electrons to flow freely into a conducting wire, establishing a current. Unfortunately, many of the sun's photons have too much energy; when they strike the silicon, it releases "hot electrons," which rapidly lose their energy as heat and return to their initial state before they are captured by the conducting wire. If hot electrons could be grabbed before they cooled, maximum efficiency could double.

One solution is to slow down how fast the electrons cool, creating more time for them to be captured. Last year chemist Xiaoyang Zhu of the University of Texas at Austin and his colleagues turned to quantum dots consisting of a few thousand atoms each. Zhu deposited lead-selenide dots onto a conducting layer of titanium dioxide, a common material. When he shone a light, the hot electrons took up to 1,000 times longer to lose their heat. Zhu "really showed that this concept is possible," says Prashant Kamat of the University of Notre Dame, who was not involved in the research.

Stalling the electrons is only part of the goal, however. Zhu is now looking for a way to help the conductor convert as many hot electrons as possible into current so the conductor itself does not also absorb them as heat.

Many obstacles remain to a working solar cell. "We need to establish all the physics," Zhu says—exactly how hot electrons cool, how they transfer into conductors. "Once we figure all that out, then we can say what the ultimate materials to use would be." The work, he predicts, "will take a while. But I'm confident we can do it. I want to see these solar cells on my roof." The commercial payoff could be huge. *—JR Minkel*

LIKELIHOOD

POTENTIAL IMPACT

WASTE RECOVERY

Heat Engines

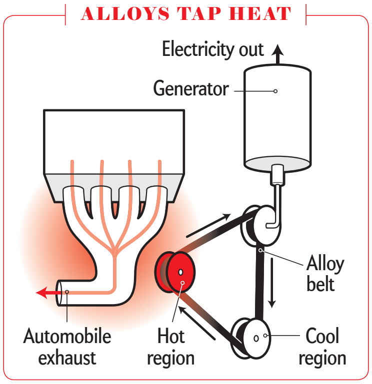
Shape-memory alloys produce extra power for cars, appliances and machinery

UP TO 60 PERCENT OF THE ENERGY generated in the U.S. is wasted—much of it lost as heat from millions of vehicles and power plants. Scientists at General Motors in Warren, Mich., are trying to capture this squandered energy using exotic materials called shape-memory alloys, which can convert heat into mechanical energy that in turn generates electricity. Team leader Alan Browne's first target is to recycle heat in a car's exhaust system to power air-conditioning or the radio so that the engine does not have to.

Browne plans to harvest heat with a belt made of thin, parallel strands of nickel-titanium alloy that "remember" a particular shape. All shape-memory alloys flip back and forth between two states: in this case, a stiff "home state" at higher temperature and a more pliable state at lower temperature. In GM's design, the belt is stretched over three pulleys that form corners of a triangle. One corner of the belt would lie close to the hot exhaust system, and another corner would be farther away, where it is cooler. By contracting at the high-temperature corner and expanding at the cooler corner, the belt pulls itself around the loop, spinning the pulleys. The pulleys can turn a shaft that drives a generator. The greater the temperature difference, the faster the loop turns and the more power it generates.

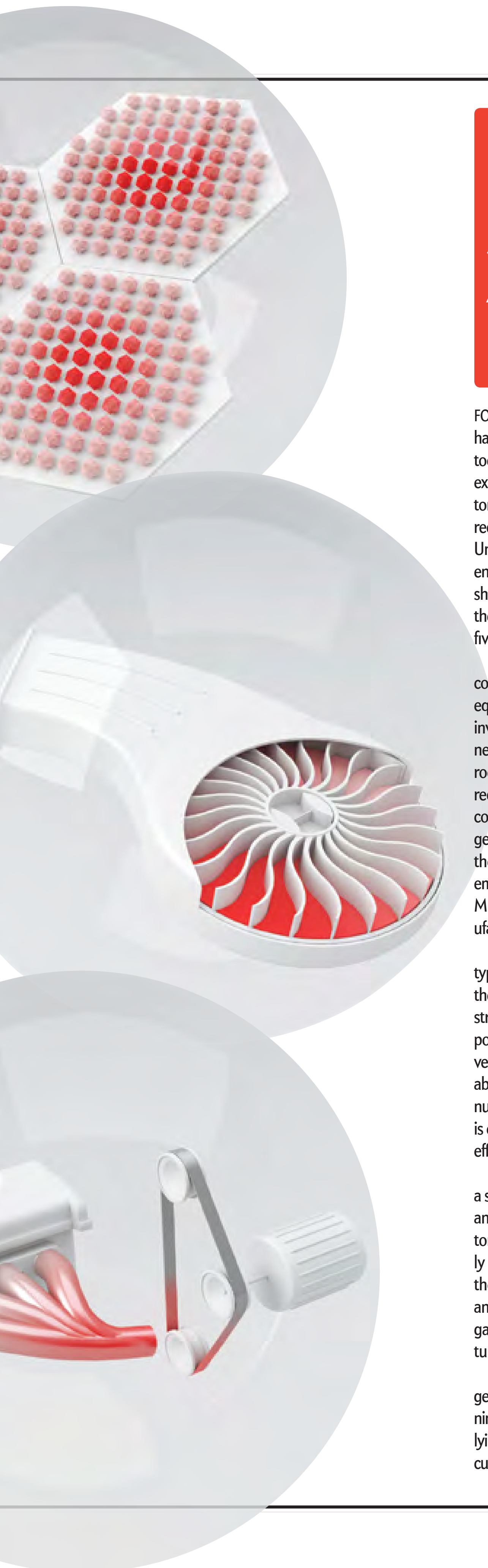
GM's prototype demonstrates proof of principle rather than actual hardware. A small, 10-gram strand yields a modest two watts, enough to power a night-light. Browne claims the technology could be scaled up to hit the marketplace within a decade, adding that no technical issues stand in the way of retrofitting shape-memory-alloy heat engines to household appliances or power-plant cooling towers. The alloys open up a world of applications that were previously considered impractical because they can function in temperature differences of as little as 10 degrees Celsius, explains Geoff McKnight, a collaborating materials scientist at HRL Laboratories.

ALLOYS TAP HEAT



The GM design is straightforward but is still a long shot. Shape-memory alloys suffer from fatigue, becoming brittle. Three months of continuous processing are needed to embed the home-state shape memory. The wires are difficult to join into a belt. Figuring out how to efficiently heat and cool the belt using air is also challenging. Browne is not saying exactly how his team is troubleshooting these issues, except to note that they are varying the gauge of the wire, the belt geometry, and the ways the belt is heated and cooled—every variable "science and man can think of."

GM isn't alone in the quest to recycle heat. Sanjiv Sinha of the University of Illinois is developing flexible, solid-state materials that convert heat into electricity. If heat engines can be built into existing and future hardware, the applications are endless: from thousands of cooling towers and factory boilers to millions of home radiators, refrigerators and chimneys, as well as tractors, trucks, trains and planes. Quintillions of joules could be generated worldwide, slashing fossil-fuel consumption. *—Bijal P. Trivedi*



VEHICLES

Shock-Wave Auto Engine

Gas-turbine cars go five times farther than piston-powered hybrids

LIKELIHOOD

POTENTIAL IMPACT

FOR MORE THAN A CENTURY PISTON ENGINES have powered nearly all cars and trucks. Even today's hybrid vehicles and the new range extenders such as Chevy's Volt use small piston engines to boost power and to efficiently recharge the batteries. But Michigan State University is developing a completely different design, known as a wave-disk engine or shock-wave engine, that eliminates pistons. If the project succeeds, future hybrids could go five times farther on a liter of gasoline.

The compact engine is only the size of a cooking pot and requires considerably less equipment than piston engines, says co-inventor Norbert Müller, a mechanical engineering professor at Michigan State. Pistons, rods and engine blocks are not needed. The reduced mass and higher fuel efficiency could propel "a plug-in hybrid car with regenerative braking as much as five times farther on the same amount of fuel, reducing emissions of carbon dioxide accordingly," Müller says. The system could also cut manufacturing costs by as much as 30 percent.

Müller and his team are testing a prototype wave-disk generator on a benchtop in their East Lansing lab. Their aim is to demonstrate a working, 25-kilowatt (33-horsepower) engine. He expects the energy conversion efficiency of his first machine to be about 30 percent, which trails the 45 percent number set by leading diesel engines. But he is optimistic that improvements could boost efficiency to as high as 65 percent.

In a conventional spark-ignition engine, a spark plug ignites a mixture of gasoline and air inside a chamber, which drives a piston that turns a crankshaft, which ultimately turns the car's wheels. In a diesel engine, the piston powerfully compresses the fuel and air, igniting it. The resulting combustion gases expand, driving the piston backward, turning the crankshaft.

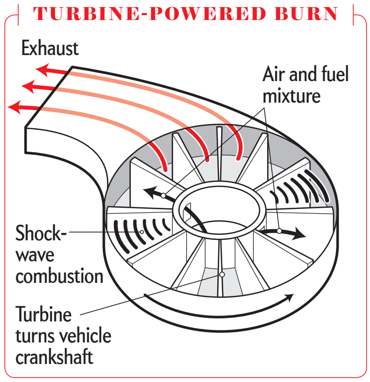
In the wave-disk design, the power-generating process takes place inside a spinning turbine. Imagine a desktop fan (a "rotor") lying horizontal on a tabletop, with many curved blades and a casing around the outer edge. Hot, pressurized air and fuel enter the gaps between the blades from the central spindle. When the high-pressure mixture ignites, burning gases expand in the confined space, forming a shock wave that compresses air in the remaining space. Subsequent reflections of the shock wave off the casing further compress and heat the air, which at the right moment is released through the casing. The force of the pressurized gases on the curved blades, plus that of the escaping gas jets, drives the rotor around, which spins a crankshaft.

Engineers began studying wave-rotor machines as early as 1906, according to the wave disk's other co-inventor, Janusz Piechna, an associate professor at the Warsaw University of Technology in Poland. They are already used in superchargers in some sports cars. The difficult part, however, is knowing how to manage the unsteady gas flows. Predicting the highly complex, nonlinear behavior of these intermittent flows requires detailed numerical calculations, which until recently were too time-consuming or imprecise to pursue, Müller says. High-fidelity simulation carried out at Michigan State and elsewhere is now guiding the precise shaping of the blade geometries and the split-second timing of the combustion to extract the best performance.

Whether computer models can lead to practical road machines remains unclear. "Wave-rotor technology can be rather difficult to implement," says Daniel E. Paxson, who designs flow models at the NASA Glenn Research Center in Cleveland. The Michigan State project "definitely pushes the envelope," he notes with a combination of pragmatic skepticism and admiration. "Whatever the ultimate results, I'm sure they'll learn a lot."

Müller seems to have little doubt that if his team builds the wave-disk generator just right it could find its way into greener hybrid vehicles, from motor scooters to family sedans and delivery trucks. "It's just a matter of time, effort and imagination—and money, of course." *—Steven Ashley*

TURBINE-POWERED BURN



APPLIANCES

Magnetic Air Conditioners

Unusual alloys keep rooms cool and food cold

LIKELIHOOD

POTENTIAL IMPACT

AIR CONDITIONERS, REFRIGERATORS AND freezers help cool our lives, but they burn through energy, consuming up to a third of the electricity used by U.S. homes. A radically different technology that relies on magnets could dramatically cut the load.

Most commercial coolers compress and decompress a refrigerant gas or liquid through a repeating cycle. As the refrigerant cycles, it draws heat out of the inside of a room or appliance. Compressors are energy hogs, however. And the most commonly used gases, when released, warm the atmosphere at least 1,000 times more than carbon dioxide does, molecule for molecule.

Researchers at Astronautics Corporation of America in Milwaukee are developing a cooler based on magnets that eliminate the compressors. All magnetic materials heat up to some extent when exposed to a magnetic field and cool down when the field is removed, a trick known as the magnetocaloric effect. Atoms store heat as vibrations; when a magnetic field aligns the electrons in a metal and keeps them from moving freely, the metal atoms vibrate more, heating up. Remove the field, and the temperature drops. This phenomenon was discovered in 1881, but it has been ignored for commercial purposes because, in theory, cryogenically cooled superconducting magnets would be needed to maximize the effect. In 1997, however, materials scientists at the U.S. Department of Energy's Ames Laboratory in Iowa, collaborating with Astronautics, hit on an alloy of gadolinium, silicon and germanium that showed a giant magnetocaloric effect at room temperature. The company has since found other such alloys.

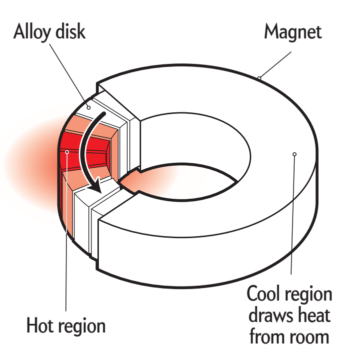
Astronautics is now designing an air conditioner aimed at cooling an apartment or house of about 1,000 square feet. A small, flat disk contains porous wedges made of one of the alloys. The disk is surrounded by a stationary, ring-shaped permanent magnet that lies in the same plane. The magnet has a gap in one side that concentrates the field there. As the disk spins, each magnetocaloric wedge passes the gap and heats up, then cools after it continues on. Fluid circulating inside the system is heated and cooled by the rotating wedges, and the cooled fluid draws heat from the room. The magnet is carefully designed to prevent the field from straying outside the machine, so it does not affect nearby electronics or people with pacemakers.

In conventional coolers, the compressor does most of the work. In magnetic coolers, the motor that spins the wheel does most of the work, and motors are typically far more efficient than compressors. Astronautics aims to have a prototype by 2013 that slashes electricity use by one third for the same amount of cooling provided. A big bonus: the unit uses only water to transfer heat, "and you can't get more environmentally friendly than that," says Steven Jacobs, manager of Astronautics's technology center.

The design could be adapted to refrigerators and freezers, although a lot of complexities must be mastered just to complete a successful prototype. Controlling how the water flows through the porous wedges is tricky; the disk spins 360 to 600 times per minute. Also, the magnet is made from an expensive neodymium-iron-boron alloy, so making it as small as possible while still providing a strong magnetic field will be a commercial necessity. "It's a high-risk technology, but it's got huge potential, and that level of performance is a reasonable target," says mechanical engineer Andrew Rowe of the University of Victoria in British Columbia.

Researchers are experimenting with other unusual cooling technologies. Sheetak, a firm in Austin, Tex., is developing a cooler that does away with refrigerants altogether, instead relying on so-called thermoelectric materials that get cold on one side and hot on the other when electrified. One way or another, consuming less fuel and reducing global warming emissions could leave the world a cooler place. —*Charles Q. Choi*

COOL AIR FROM MAGNET



EMISSIONS

Clean(er) Coal

Salt sucks carbon from smokestacks

LIKELIHOOD

POTENTIAL IMPACT

COAL IS THE CHEAPEST AND MOST PLENTIFUL energy resource in the U.S.—and as the most carbon-heavy source, a major driver of climate change. Engineers have devised various ways to strip carbon dioxide out of a coal plant's exhaust before it enters the atmosphere, but the processes sap up to 30 percent of the energy created by burning the coal in the first place. That burden can double the cost of electricity generated, which makes clean-burning coal a tough sell.

The idea is so appealing, however, that the Department of Energy's Advanced Research Projects Agency–Energy, along with other agencies, has been doling out seed money for research into technologies that might drive down that unacceptable percentage.

One especially enticing design, from the University of Notre Dame's Energy Center, uses a novel material called an ionic liquid—essentially a type of salt. Its first advantage is that it pulls in twice as much carbon dioxide as other, chemically similar carbon absorbers. Another plus is that in doing so, the salt undergoes a phase change from solid to liquid. The change releases heat, which is recycled to help drive the carbon out of the liquid so that it can be disposed of.

"Our modeling shows that we should be able to reduce the parasitic energy to 22 or 23 percent," says Joan F. Brennecke, a chemical engineer and director of the energy center. "Ultimately we'd like to get it down to 15 percent." Her team is building a laboratory-scale unit to demonstrate the technology.

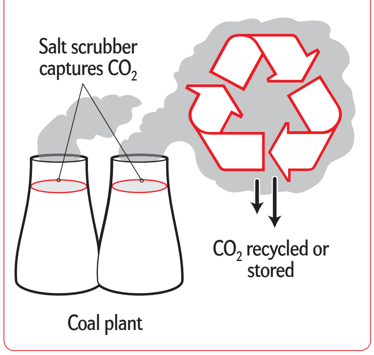
If the approach sounds theoretical at this point, it is. "This is a radical idea," Brennecke admits, "because these materials are totally new," discovered barely two years ago. Brennecke's group is just beginning to explore them, and unexpected problems could crop up at any stage. Even if the process works in the lab, it could prove impossible to scale up to the power plant level.

Furthermore, if the stripping process does work, the carbon then has to be stored somewhere. The leading idea espoused by scientists is to inject it underground, in porous rock formations—a process known as sequestration that has been field-tested but not proved on a large scale. A more experimental notion is to mix the CO_2 with silicates, reproducing the natural process that binds CO_2 into carbonate rock, rendering it inert.

Also to be confronted are the health and environmental issues that go along with coal mining and with disposing of the toxic ash left over after burning. The many problems make environmentalists see red when they hear the phrase "clean coal." Still, coal is so abundant and cheap that if a high-risk idea works out it could make a big difference in the fight against climate change.

—Michael Lemonick

STRIP OUT THE CARBON



MORE TO EXPLORE

Radical projects being funded by the U.S. Department of Energy's ARPA-E program: http://arpa-e.energy.gov
Fusion-triggered fission: https://lasers.llnl.gov/about/missions/energy_for_the_future/life
Quantum photovoltaics: www.utexas.edu/news/2010/06/17/quantum_dot_research
Solar fuels: http://pubs.acs.org/doi/abs/10.1021/bk-2010-1056.ch001
Shock-wave engines: www.nextbigfuture.com/2009/10/wave-disc-engines.html

SCIENTIFIC AMERICAN ONLINE
More exotic technologies are at ScientificAmerican.com/may2011/radical-energy