Science Fact

Energy for the Future: Solar-Derived Fuels, Artificial Leaves, and Electricity-Eating Microbes that Poop Out Gasoline

Richard A. Lovett

People old enough to remember the Arab Oil Embargo of 1973 will recall it as America's first nationwide energy crisis. Not that it had anything to do with environmental issues or depleted oil reserves; the triggering events were political, stemming from America's relationship with Israel during the 1973 Yom Kippur War, but it was an event that sent shockwaves through America's commuter culture. In a single year, gasoline prices jumped by more than 40% and even then, there were enormous gas lines in California. Nationally, highway speed limits were lowered to 55 miles per hour in an effort to conserve fuel, while elsewhere there was a sudden upsurge of interest in energy conservation and in alternative energy sources. All told, it was an unnerving wake-up call to Americans about just how dependent we had become on fossil fuels, especially from overseas.

Since then, oil prices (and oil politics) have yo-yoed like a kid on a bungee cord. As I write this, the fracking boom and a price war between Saudi Arabia and its rivals have produced American gas prices averaging $1.80 a gallon. Adjusted for inflation, that's 25 cents per gallon cheaper than before the start of the 1973 embargo—and less than half what we were paying only a few years ago. Even more amazingly, the stock market plummeted, partly because cheap energy prices were driving oil stocks down by more than enough to offset the benefits to energy-intensive industries that suddenly found themselves with unexpected windfalls. It would be hard to find another commodity that is both so important to the modern economy and whose price is so enormously volatile.

Simultaneously, we are wrestling with the long-term impacts of fossil fuels on global warming, sea level rise, ocean acidification, and such localized issues as an increase in the number of deadly heat waves. I realize that some of *Analog*'s more conservative readers won't accept anything I said in the above sentence, but arguing about that isn't the purpose of this article. The questions here are more specific: assuming we don't want to burn every last bit of fossil fuel on the planet, what might the energy sources of the future look like, and how might they protect us from the boom-and-bust cycles endemic to today's energy geopolitics?

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Solar-Electric Dream

George Parrott is a retired psychology professor from California State University, Sacramento. He's also living in the energy future. "Maybe not fifty years out," he says, "but at the edge of most things now possible."

His interest in reducing his ties to fossil fuels began in 2007, when, worried about increasing smog, he and his wife built a state-of-the-art, energy-efficient home. "Sacramento has the fifth-worst air quality in the U.S.," he says. "We believed that people who can afford it have an obligation to do as little damage to the environment as we can." In the next two years, the couple equipped their home with a 3.7-kilowatt solar-cell array, bought a pair of electric cars, added another 1.4 kilowatts to their rooftop array, and installed solar-heating panels to provide hot water for showers, laundry, and dishes. In the process, Parrott opted for an innovative solar-array layout of his own design, in which the panels serve as an awning to help shade the house from mid-summer heat.

The first array wiped out the couple's electric bill. The second freed them from the gas pump. The benefits were so large, Parrott calculated, that the solar panels would pay for themselves in about 6.5 years, thanks to tax credits and a California law that lets people sell home-generated power to the grid at market rate. That meant that on hot, summer days, when owners of less-well-designed homes were dialing up the air conditioning, Parrott could sell power to the grid at peak, midday rates. Later, he could buy energy back for such evening-time uses as doing laundry or charging the cars, for as little as one-fifth the price he'd sold it for earlier.

It's a model for a decentralized energy future in which people generate their own power, much as our ancestors once raised their own vegetables. "The world electricity market started with small decentralized power stations, near where the power was needed," says Wes Stein, solar research leader at Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO). "I think we're going to go full circle. Everyone's rooftop could become a generator, not just of electricity but of hot water—things we use in the home."

That said, it's going to be a while before everyone can live like Parrott; his home energy system is affordable only because of the fortuitous mix of California sun, tax breaks, and the buy/sell law that allows him to take advantage of the difference between peak and off-peak electrical rates. Nor can home energy generation take us completely off the grid. It also takes energy to build our cars, run the offices where we work, pave our streets, and build our energy-efficient homes. According to the U.S. Energy Information Administration, in fact, residential needs account for only 22% of total American energy use.

Also, history says we tend to find ever-new ways of using energy. "Our standard of living is defined by energy consumption," says Thomas Mason, Director of Oak Ridge National Laboratory, which carries out much of America's energy research. "Standard-of-living equals energy use, and vice versa." Projections are that by the 2070s, the world will have 9.4 billion people, all demanding developed-world standards of living. From one point of view, that is an incredibly pessimistic projection: a prescription for war, poverty and, if we continue relying on fossil fuels, global environmental collapse.

But it's also a challenge. "That's why we need better alternatives," says Mason.

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One alternative is Parrot's writ large: harness the power of the sun not just on myriads of rooftop collectors but in facilities that can supply the needs of entire cities or even nations. Stein notes, for example, that even without help from rooftop collectors, his own country could meet all of its electrical needs with a single, perfectly efficient, 30 x 30 mile solar array in the sunniest portions of its outback. "Land is not an issue," he says. "There's certainly enough to go around."

In the United States, which has thirteen times as many people as Australia, a comparable array would expand to about 100 x 120 miles, but it's still less than one tenth the area of New Mexico. Nor does it all have to be in one place; it could be broken up into smaller chunks scattered all across the Sunbelt (obviously the preferred approach from both an efficiency and security perspective, anyway). Sure, it would be ugly and might have environmental effects, but from a land-use perspective, it's definitely feasible. According to data from the Rocky Mountain Coal Mining Institute (an industry group), coal mining has already occurred on 5 million acres of U.S land (about 7,800 square miles), with another 450,000 square miles of coal seams yet to be touched. Compared to that, 12,000 square miles of solar collectors is small potatoes.

There are, however, two important caveats in this calculation. One is that according to the U.S. Energy Information Administration, electrical power is only about 40% of total energy needs. So if we want to use solar power for all of our energy needs, that 100 x 120 mile array becomes 250 x 120 miles. The other caveat is that solar technologies are far from perfectly efficient.

There are presently two basic solar technologies: photovoltaics (which generates electricity directly from light) and concentrating solar power (CSP), which uses mirrors to focus sunlight to produce heat.

Photovoltaics is a proven technology. But without tax breaks and the type of buy/sell law relied on by Parrott, photovoltaic cells aren't cheap. For years, they were used mostly in space or for limited uses such as providing power for instruments at remote weather stations.

But, just as the computer industry boasts Moore's Law, which says that computing power doubles every eighteen months, the photovoltaic technology has Swanson's Law, which holds that solar-panel prices drop 20% with each doubling of total production. At present, photovoltaic cells still represent a small fraction of total global energy production (the figures I've seen vary from less than 1% to as little as 0.1%), but the day is nearing when this might change rapidly. According to data gathered by Bloomberg New Energy Finance,[1] solar cell prices have fallen by a factor of more than 100 since 1997.

CSP is different, based on a concept that is simple—and ancient. All the way back in 213 B.C.E., Archimedes reputedly used it to set fire to invading warships by having the defenders of his city focus sunlight on them with hand-held mirrors. Modern attempts to replicate this feat have cast doubt on whether it was truly possible with the technology of his era, but the principle is the same one used by scouts the world over to start fires with magnifying glasses or construct solar ovens to bake bread.

With a large-enough array of mirrors, CSP technology can be ramped up into large-scale power plants capable of replacing their fossil-fuel counterparts. In fact, the only real difference between a CSP power plant and a coal-fired one is the source of heat. The holdup comes from the combination of construction costs and thermodynamics.

CSP's fuel, sunlight, is free. But the high-performance mirrors needed to concentrate it are expensive—pricey enough that to compete with fossil fuels, CSP plants have to be significantly more efficient.

That's where thermodynamics comes into play. A steam-driven turbine is a heat engine governed by a principle known as Carnot's theorem, which holds that the maximum possible efficiency of any heat engine is related to the difference between its operating temperature and the temperature of its ambient environment (its heat sink). In other words, hotter operating temperatures are better.

In theory, that's a simple fix: just focus the sunlight more intensely. But if you do this, things start burning up like Archimedes's invading warships—not literally, but chemically, as the heat takes a toll on turbine blades and pipes.

One solution is simply to wait for metallurgists to come up with alloys that can better withstand extreme conditions. A better solution is to find ways to design turbines that don't unnecessarily waste energy, allowing them to operate as close as possible to their theoretical maximums.

Traditional power plants employ steam turbines that use a two-cycle design to tap heat for electricity. In one cycle, they use heat to boil water, then use the pressure of the expanding steam to spin the turbine blades and generate electricity. In the second cycle, the steam is allowed to condense back into water, for reuse. And that's the problem, because the heat used to boil 212°F water into 212°F steam is lost—a fairly substantial inefficiency that has nothing to do with Carnot's theorem. An alternative technology, gas turbines, bypasses this by using gases that never have to be reliquefied—but gas turbines lose comparable amounts of energy by having to compress the gas at the start of each cycle, before heating it up.

A new approach that is drawing increasing attention is the use of supercritical carbon dioxide instead of water or gas. Supercritical fluids are substances normally thought of as gasses, held at combinations of high temperature and high pressure at which they have the characteristics of both a gas and a liquid. That means that when heated, they will expand like a gas, but is easy to recompress for the next cycle.[2] Using them could produce a 25 – 35% increase in efficiency.

Furthermore, supercritical carbon dioxide can be used at reasonable temperatures. "You need only 700°C to 800°C (approximately 1300°F to 1500°F)," says Stein. "That's pretty doable with the metals available today." The coal, nuclear, and CSP industries are all starting to look at supercritical fluids, he adds, but the greatest benefits might be to CSP because it has the most to gain.

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Don Quixote's Worst Nightmare

Solar isn't the only energy of the future. Another is wind.

Wind is the poster-child for alternative-energy success. On summer days in my part of the Pacific Northwest, a parade of big trucks heads eastward from Portland, Oregon, carrying giant pylons and turbine blades into the Columbia River Gorge, which funnels gale-force winds between the Pacific Ocean and the inland desert. In Oregon, wind power already accounts for nearly 10% of electrical needs. In Spain, it's 15%; in Denmark, 26%.

Even greater progress can come from moving wind farms offshore, says Jonathan Whale, a wind-energy researcher at Murdoch University in Western Australia. That's because bigger windmills are more efficient, so if you build them on offshore platforms, it's possible to use barges to bring in components far too large for trucks.

"When I started researching wind energy," Whale says, "a 600-kilowatt turbine was considered large. Now the standard model is a couple of megawatts. A single blade [can be] 82 meters." Don Quixote would have been stunned.

But wind has its disadvantages. The obvious one is that it's fickle: just when you most need it, it's likely to go flat calm—a problem that can make one region's power dependent on another's weather. "If the wind changes dramatically in the Baltic [where much of Europe's wind power is generated]," Mason says, "the Czech Republic sees their electric supply [become] unstable."

What's needed, not just for windmills but for solar-power facilities of all scales, are ways to store energy for later use.

Batteries are the most obvious option, for rooftop collectors or small-scale windmills. In a 2015 paper in *Science*,[3] in fact, a team led by researchers from Harvard University unveiled a new type of rechargeable battery that stored power in a watery solution of nontoxic, noncorrosive, low-cost chemicals. "This is chemistry I'd be happy to put in my basement," one of the scientists, Michael Aziz, told the news site phys.org. "The non-toxicity and cheap, abundant materials placed in water solution mean that it's safe—it can't catch on fire—and that's huge when you're storing large amounts of electrical energy anywhere near people."[4]

But at megawatt or gigawatt scales, batteries would be enormous and absurdly expensive. A better technology, says Stein, is "thermal storage," particularly appealing for heat-based power-generation methods like CSP.

Thermal storage works by retaining heat in well-insulated vaults of . . . well, anything hot. Ideally, the material would also be dense, so you wouldn't need vats the size of supertankers to hold it. "Molten salt is an example," says Stein. "Nearly all the CSP projects in Spain and the U.S. are integrating molten-salt storage. When clouds come over or it's nighttime, you use the heat to generate steam."

An even better way of storing energy is via "thermochemistry," in which the heat is used to drive chemical reactions "uphill"—i.e., in the direction in which energy is added, rather than released. It's like a battery except that that the process is chemical, not electrical. "You store the energy as chemical energy rather than straight-out heat," says Stein.

A big advantage of thermochemistry over thermal storage is that it's possible to retain the energy indefinitely. "You don't have to worry about heat leaking out," Stein says. But the ultimate dream involves *solar fuels*.

The simplest solar fuel is hydrogen, once the darling of the environmental community because it's easily produced (by electrolysis of water) and, when burned, produces nothing but water as a byproduct. There's just one problem: hydrogen is a beast to handle. It's explosive; its tiny molecules easily permeate out of storage containers; and it can turn pipeline metals brittle. To use it in a car, you either need to liquefy it or compress it, both of which take a lot of energy—not to mention a specially designed gas tank (among other things) to hold it.[5]

Better, says Ellen Stechel, a deputy director at the LightWorks solar-power program at Arizona State University, is to use solar power to make more useful chemicals, akin to conventional fossil fuels. Such fuels, she notes, "have really nice properties [such as] high energy density both by mass and volume. They're also extremely convenient. We can fuel very fast, whether it's a big truck, an airplane, or a car. You can't do that with hydrogen." Not to mention that we already have the infrastructure to handle them.

These fuels, she says, can be made from air, water, and sunlight. One method is to focus sunlight on a metal oxide, such as zinc oxide or tin oxide. It's a process akin to smelting, in which heat is used to drive off the oxygen and turn oxides into pure metals. But instead of saving the purified metal, Stechel's process cools it in an atmosphere of steam and carbon dioxide extracted from the air. This causes the metal to rapidly re-oxidize by "stealing" oxygen from wherever it can get it. If that's from water, what's left is hydrogen. If it's from carbon dioxide, the result carbon monoxide. The ultimate output is not only a recovery of the original metal oxide, ready for reuse, but a mix of carbon monoxide and hydrogen—"the building blocks," Stechel says, "to make any hydrocarbon you like."

It's not a far-out technology. "We believe it could be pushed to market in about a decade," she says.

But we don't actually have to wait for solar fuels to come online before we can start harnessing the power of the sun to help fill our gas tanks: just as we have hybrid gas/electric cars, we can make hybrid fossil/solar fuels.

The simplest way is by using solar energy to react natural gas with steam, producing a product called syngas. Syngas is a combination of hydrogen and carbon monoxide, a lot like the output of Stechel's metal-oxide cycle. (If you're into chemistry, the reaction is: $CH_4 + H_2O \longrightarrow 3H_2 + CO$.)

Solar-energy-produced syngas contains more energy than the natural gas that went into it—not a lot, but enough to catch attention. "The solar proportion is only 20 or 30%," says Stein. But that's a starting point. "Without knowing it, [consumers] will be using solar energy." And since many gas wells are in sunny areas, producers could install solar-powered syngas production facilities close to the wellhead, thereby adding value to their traditional output.

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Electricity-Eating Microbes

If we want to get even more radical, however, there's another technology that might even allow people like Parrott to create "electrofuels" via their own rooftop collectors.

Although they can be created by solar power, electrofuels aren't the same as solar fuels. They're a type of biofuel, although instead of being derived from traditional crops, they come from bacteria that "eat" electricity and "poop out" chemicals on which your car would happily run.

Pie in the sky? Not so. Between 2009 and 2014, a U.S. Department of Energy program called ARPA-E (for Advanced Research Projects Agency-Energy) doled out $48 million in grants for research that proved that, at least at the lab scale, such technologies are already feasible.

The research was a mix of investigative biology and gene engineering.

It began with exotic bacteria that live underground or in places like hot springs, where photosynthesis isn't possible. To survive, these organisms obtain energy from electrons derived from minerals in their native environments.

In the type of environments we enjoy, such organisms don't easily grow. But in the lab, their genes can be transferred into other bacteria that can then be supplied with electricity derived from solar cells, windmills, or any other desired source. When these organisms grow, they produce biomass—and while we normally think of energy-related biomass in terms of crops, like corn, switchgrass, sorghum, or sugar cane, biomass is biomass, whether it comes from a bacterium or a sequoia.

"It's the first fundamentally new way to think about biofuels in a long time," says Eric Toone, a biochemist at Duke University.

These bacteria might also be unusually efficient at harvesting energy for growth. "Plants are very inefficient," says Derek Lovley, a microbiologist at the University of Massachusetts, Amherst.

Most crops only capture 1 or 2% of the available solar energy. Electricity-eating bacteria may be able to capture 85–95% of the electrical power fed to them, Lovley says. Furthermore, there's no need to waste farmland growing them; they can grow anywhere there's a reliable source of electric power, whether it's a CSP station deep in the desert or a vat on a solar-electric roof.

So far, we're just talking about growing bacteria. In theory, you could harvest them, dry them out, and either burn them as fuel or ferment them into something better, like ethanol. But we can do better than that by making them put the energy they'd normally use for growth into chemicals that can be used as fuel without need for expensive, inefficient, processing facilities.

One of the fuels the gene-splicers have been able to get bacteria to create in the lab is butanol, a four-carbon alcohol, roughly equivalent to the butane often used in cigarette lighters.

It's not only a fuel, but a better one than ethanol, says Lovley, because it's a "drop-in gasoline substitute"—meaning it doesn't have to be blended with conventional gasoline to be usable in today's engines. It can also be stored and distributed in existing pipelines. "You can't do that with ethanol," he says, "because ethanol absorbs water."

Another option, says Pamela Silver, a synthetic biologist at Harvard Medical School, is octanol, an 8-carbon alcohol equivalent to the octane in filling-station octane ratings. "It's got a high energy capacity and it's not corrosive," she says.

Other research, by Robert Kelly, a chemical engineer at North Carolina State University, and Michael Adams of the University of Georgia, has found that it's possible to engineer a strain of *Pyrococcus* (a microorganism that lives in near-boiling-point hot springs) to make a compound called 3-hydroxyproprionic acid from carbon dioxide and hydrogen. 3-Hydroxyproprionic acid isn't a fuel, but it's an important intermediate for making plastics, meaning that tomorrow's shopping bags and milk jugs might be made from ingredients produced by bacteria in solar-power cells on your own rooftop. And 3-hydroxyproprionic acid might not be the only important feedstock chemical produced this way. If you combine rooftop chemosynthesis with 3D printers, the science-fictional dream of complete self-sufficiency in far-flung interstellar outposts or remote parts of the Solar System might be more feasible than previously thought.

There is one important caveat. So far, these processes have only been tested at very small scale, in the lab. Ramping them up to larger scale means that the bacteria are going to have to process substantial amounts of electricity—enough that there may be enough waste heat to give them the microbial equivalent of heatstroke. "If the organisms wind up 'melting,'" Silver says, "it won't be a good thing."

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The world of the future will need a mix of energy facilities: centralized and decentralized: residential, commercial, and industrial. Wind, solar, nuclear, electrofuel—and who knows what else that we haven't yet imagined. The more diversified it is, the less likely it is to be vulnerable to the political and economic fluctuations that, according to Wikipedia, have produced more than a dozen major energy crises, worldwide, since 1973.

Most of these changes, however, won't come about quickly. Your cell phone might be obsolete in two years, your laptop in five. But power plants are vastly more expensive and designed to operate for decades. "The energy industry is generally working with technologies that have twenty-, thirty-, or forty-year asset lives," says Stein.

For those hoping for a quick fix to global warming, that's bad news. But it also means that the system has enough inertia in it that even if we start making significant shifts in energy sources, our lives may not be all that radically affected. "If we do these technologies correctly," Stein says, "the consumer should not see any difference. They should still get their electricity. They should still get from A to B in their vehicle."

That's also an important lesson for those of us who read and write science fiction. We like to write about radical new ideas, whether they be scientific, technological, or cultural. When it comes to the energy future, this means we tend to write either dystopias or utopias. But the reality could (and hopefully will) be less dramatic: a gradual shift from things we take for granted today to things our descendants will take for granted that we can hardly imagine.

Maybe when we finally colonize the Moon, Mars, the moons of Saturn, and beyond, part of what we'll take with us are energy-producing bacteria scavenged from the insides of rocks or ocean-bottom hot springs. Maybe future colonists on Pluto-distant worlds will use these bacteria not only for power, but for constructing everything they need.

Or maybe they'll find an energy source nobody today has ever thought of. "It may very well end up being that this isn't going to work out," Silver says of her electrofuels research. "But it is a really cool idea."

And cool ideas, whether they work out or not, are what science fiction is all about.

Thermo-what? Novel Technologies that Might Replace Solar Panels

Solar panels and CSP generators aren't the only ways to harness sunlight for electricity. Here are three others:

• *Thermoelectrics*. Nearly 200 years ago, German physicist Thomas Johann Seebeck discovered that when different metals are joined in the right manner, with one metal hot while the other is cold, an electrical current will flow between them. It's a principle that has long been used to make temperature sensors called thermocouples, but it was never seriously considered as a source of power because it's relatively inefficient. Still, thermoelectric generators could power tomorrow's mobile phones, watches, laptop computers, and medical sensors (in some cases possibly even working from the owner's body heat). They might even increase automobile efficiency by converting waste heat into electricity. And who knows what could happen if thermoelectrics is merged with solar power. "It's a well-known effect but hasn't really been used in the solar world, yet," says Stein.

• *Thermionics*. Discovered by Thomas Edison in 1883, this is the "boiling away" of electrons from a hot cathode. It's the process that allows current to flow through vacuum tubes, making possible everything from pre-transistor radios to old-style tube televisions. Traditionally, thermionics uses electricity to heat the cathode—meaning that it's a net user of electricity, not a generator of it. But in principle, there's no reason the cathode couldn't be heated by focused solar power, converting it into a thermionic generator.

• *Artificial photosynthesis*. Sometimes referred to as the artificial leaf, this solar-panel-substitute uses sunlight to break water into hydrogen and oxygen. The oxygen is released to the environment, while the hydrogen is stored as fuel or used to power a fuel cell. The chemistry is complex, but more or less mimics natural photosynthesis, which also uses sunlight to split water into hydrogen and oxygen. "Whether you realize it or not, leaves are buzzing with electricity," says its leading proponent, Daniel Nocera, a chemist at Massachusetts Institute of Technology.

The process works well in tests. "We can put [an artificial leaf] in a bottle of water, hold it up to the sun, and see hydrogen and oxygen bubbles coming off," Nocera said at a 2011 meeting of the American Chemical Society. It also might be a way of making less expensive solar panels, because part of their cost is the wiring needed to collect the electricity. "This gets rid of all that," Nocera says.

Nukes of the Future

Nuclear power is also likely to play a big role in the future, even though we are currently suffering from what Alan Krupnick, an environmental and resource economist with Resources for the Future, a Washington, D.C., think tank, calls "a massive case of Fukushima shock" (a reference to Japan's Fukushima nuclear plant, which melted down in the aftermath of Japan's 2011 earthquake and tsunami).

Recent low prices for fossil fuels have also temporarily cooled interest in nuclear power. But when that interest rebounds, Oak Ridge director Mason believes the future will belong to small modular reactors and "generation III" nuclear power plants.

Small reactors are comparable to those long used on submarines and aircraft carriers: 50 to 300 megawatts, far less than the thousands of megawatts produced by large-scale reactors. They're also likely to be placed underground, and will be safer not only for that reason, Mason says, but because their smaller size means they won't need to keep large supplies of fuel on hand.

Generation III reactors could also be small, but what distinguishes them is that they're designed to be more failsafe than their predecessors. For example, cooling systems could be in gravity-fed reservoirs on their roofs. That would allow cooling water to flow into the reactor by gravity. When it heats up, it becomes steam, which rises back to the roof, condenses into water, and recycles for the next cooling cycle. It's a continuous, passive loop, dependent only on the fact that water flows downhill, while steam rises. "There is no need for operators or pumps," Mason says.

Another improvement would involve the use of "accident-tolerant fuels." Old-style fuels, Mason says, were encapsulated in a material known as zircaloy, which had the advantage of not absorbing neutrons (an impediment to reactor performance) but which, when overheated, could cause water to disassociate into hydrogen and oxygen (the source of the explosion that produced the Fukushima accident). Next-generation fuels will be encapsulated in materials that don't have this property. "It gives you a much greater safety margin," Mason says.

It's also possible to reduce the quantities of waste, while increasing the efficiency of fuel use. "In the current fuel cycle, it's only a couple percent of the potential energy that you've really used," Mason says. "You can do a whole lot better."

The best-known way of dealing with this is the breeder reactor in which uranium-238 (which composes 99% of natural uranium but isn't usable as reactor fuel) is converted to plutonium-239. Another is the thorium fuel cycle, which converts thorium-232 into uranium-233, an isotope that doesn't occur in nature but which makes good reactor fuel. "Because thorium is more abundant than uranium, there's been renewed interest in this," Mason says.

Combining these approaches, he says, it's possible to generate all of the world's electricity from nuclear sources. "[But] I'm not sure that would be valuable or desirable. I'm not sure you would want to put all your eggs in one basket."

Footnotes:

[1] *http://www.economist.com/blogs/graphicdetail/2012/12/daily-chart-19.*

[2] For those concerned about global warming, the carbon dioxide is continuously reused, not released into the atmosphere.

[3] Kaixiang Lin, Qing Chen, Michael R. Gerhardt, Liuchuan Tong, Sang Bok Kim, Louise Eisenach, Alvaro W. Valle, David Hardee1, Roy G. Gordon1, Michael J. Aziz, Michael P. Marshak1, "Alkaline quinone flow battery," *Science*, 25 Sep 2015: Vol. 349, Issue 6255, pp. 1529-1532, DOI: *10.1126/science.aab3033.*

[4] A rechargeable battery to power a home from rooftop solar panels, 25 September 2015, *http://phys.org/news/2015-09-rechargeable-battery-power-home-rooftop.html#jCp.*

[5] There are alternatives involving fuel cells, but these have their own problems.

About the Author:

Richard A. Lovett left academia in 1989 to become a full-time freelancer and short-story writer. His 3,000+ publications count 135 appearances in *Analog*, including 41 stories and a record ten AnLab wins. He also coaches distance runners, including six women who have either qualified for the U.S. Olympic Team marathon trials or are in serious contention to do. His short-story collection, *Phantom Sense & Other Stories* (all collaborations with fellow *Analog* writer Mark Niemann-Ross) was released in 2012 by Strange Wolf Press. Follow him on Facebook—Richard A. Lovett (writer) or find him on the web at *www.richardalovett.com.*