Daniel Nocera was a science-minded high-school junior in New Jersey at the beginning of the Arab oil embargo, in 1973. American fuel prices soared, the stock market crashed, Congress prohibited speed limits higher than fifty-five miles an hour, and President Nixon banned the sale of gasoline on Sundays. At the end of the decade, the Iranian revolution, followed closely by the outbreak of war between Iran and Iraq, precipitated a second oil crisis. By then, Nocera was a graduate student in chemistry at the California Institute of Technology. Within a short time, he had decided to devote his science career to energy.

Most of the energy we use comes from photosynthesis. Green plants store energy from the sun in chemical bonds, and we exploit that energy when we eat plants, or when we eat animals that have eaten plants, or when we burn either plants or substances ultimately derived from plants: firewood, peat, coal, oil, natural gas, ethanol. Photosynthesis has been understood in a general way for a long time and is familiar even to grade-school students—water and carbon dioxide in; oxygen and carbohydrates out—but the process is complex, and until fairly recently important parts of it remained mysterious. Nevertheless, Nocera decided in the early eighties that the chemistry of green plants was the likeliest place to seek an answer to civilization’s long-term energy difficulties. “For the past two hundred years, we’ve run this other experiment, with fossil fuels, and it’s not working out so well,” he told me last August, in his office, in the chemistry department at the Massachusetts Institute of Technology. (Next January, he will move to Harvard.) “I wanted to go back to what worked for two billion years before that.”

When the price of oil dropped in the mid-eighties, alternative-fuel research declined in popularity as an academic pursuit. “There weren’t even conferences for me to go to,” Nocera said, “because everybody had left the field.” But he persisted in his research, seeking a way to inexpensively replicate solar-energy conversion as performed by vegetation. His early work focused on certain reactions that underlie key parts of that process, and created a field now known as “proton-coupled electron transfer.” In 2000, he decided that he understood the fundamental science well enough to, in his words, “go for it,” and, at the 2011 national meeting of the American Chemical Society, he announced a tangible breakthrough: a cheap, playing-card-size coated-silicon sheet that, when placed in a glass of tap water and exposed to sunlight, split the water into hydrogen and oxygen. A video he made shows gas bubbles streaming from the sheet. He said the gas could easily be collected and either burned or used to power a fuel cell. He called the device an “artificial leaf.”

Two months later, I heard Nocera give an hour-long presentation to a large audience of environmentalists, scientists, engineers, economists, government officials, and others at the Aspen Environment Forum. The talk was moderated by an editor of the British scientific journal Nature, who described Nocera’s work as “the hydrogen economy reimagined,” and said that Nocera’s discoveries might constitute “an answer to the energy puzzle.” Nocera claimed that artificial leaves could enable people everywhere to live without being connected to any power grid. He predicted
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that, within a few decades, “you will be in control of your own energy,” and that the artificial leaf would enable his audience to turn a home into “a self-sufficient power station.” But he had a warning, too: “Don’t clap yet, because you don’t want to do it.”

Nocera’s forebears are Italian, by way of Brooklyn and Medford, Massachusetts, but his Mediterranean profile and graying beard give him a rabbincal look. “I grew up in a very Jewish part of New Jersey,” he told me. “To get back at my mother and father—who were Catholics, of course—I became the best Orthodox Jew in the world. I would go to temple on Saturday with my friends, and, because I was doing it out of a passion for irritating my mother, I was a much better Jew than they were.” At Michigan State, where he taught for thirteen years after earning a Ph.D. at Caltech, his secretary was a Black Muslim, and he sometimes accompanied her to her mosque. Such ecumenism, he said, made him tolerant of all religions while killing any religious feelings of his own. He does, however, think of himself as a spiritual person, and he said that his spirituality has manifested itself mainly in a quest to provide low-cost, carbon-neutral fuels to the world, whose energy consumption he expects to double in the next forty years.

Nocera’s father was a clothing buyer, first for Sears, then for J.C. Penney. Until Nocera reached eighth grade, his family moved so frequently that he made very few friends. “People ask me how I became a scientist, and this is literally how I did it,” he told me. “When I was in grade school, I didn’t invest in people. I would consciously not make friends, because I knew I would get attached to them and they would evaporate. The one thing I could bring with me when we moved was science.” He loved Heathkits—moderately priced build-it-yourself gadgets that were popular with nerdy tinkerers—and when he was in second or third grade he used a microscope to conduct minutely detailed subsurface investigations of small portions of his back yard.

A second scientific milestone—although he didn’t recognize it as such at the time—occurred when, as a teen-ager, he became an ardent fan of the Grateful Dead, and he sometimes left home for weeks to follow the group on tour. In Aspen last June, he had an animated discussion with two other conference participants about what one of them had identified as an overrepresentation of Deadheads in high-tech companies in Silicon Valley. The hypothesis was that a love for the Dead reflects an iconoclastic outlook that’s conducive to innovative thinking, and that Deadheads share what Nocera now thinks of as a Garcinian conception of open-source collaboration. “The Dead decentralized music,” he said. “They would let you tape their shows, and, back before there were computers and the Internet, there was this huge underground community that swapped recordings. I’d never really thought about it before Aspen, but what I want to do with energy is no different from what the Dead did with their music. I want to distribute it to everybody.”

The process that Nocera calls “artificial photosynthesis” could be described more precisely as solar-powered electrolysis of water, using energy from the sun to electrochemically split water into hydrogen and oxygen. In natural photosynthesis, photons from the sun, aided by chemicals in leaves, strip electrons from water, breaking it into oxygen molecules and hydrogen nuclei. The plant discards the oxygen—incidentally creating the part of the atmosphere that’s the most important to us—and combines the hydrogen with atmospheric carbon dioxide to produce cellulose (the material out of which the plant builds its structure) and starch (the plant’s fuel). “In terms of energy, those last parts are an afterthought,” Nocera said. “The plant does them because it needs to stand up and it can’t deal with a gas. But all I care about is the rearranged bonds.” Natural photosynthesis is starkly inefficient: many plants convert as little as one per cent of the energy in the sunlight that falls on them. But sunlight is plentiful, and the energy in the photons that strike the earth each hour is roughly equivalent to the total energy, from all sources, that humans use in a year. In 2009, Fred Krupp, who is the president of the Environmental Defense Fund, wrote that Nocera’s work “makes it conceivable that by mid-century we could satisfy our global energy needs by splitting—each second—
just a third of the water in M.I.T.'s swimming pool."

Electrolysis of water is sufficiently non-baffling to be performed routinely by schoolchildren: attaching electrodes to a battery and placing them in water causes oxygen to bubble from one and hydrogen to bubble from the other. To Internet energy cranks, this looks like a zero-carbon bonanza: free fuel! But hydrogen is really an energy carrier—a storage medium—rather than an energy source, since burning or otherwise converting it merely releases energy that was previously contained in the battery. Large quantities of hydrogen are used in industry, but the gas is too light to exist on earth naturally, and almost all the world's supply is manufactured by doing things like steam-reforming natural gas, gasifying coal, and partly oxidizing petroleum. The enthusiasm that many environmentalists express for the (still hypothetical) hydrogen economy depends, first of all, on finding affordable ways to produce hydrogen which don't add carbon to the atmosphere or consume more fossil fuel than they replace. Hence Nocera's focus on plants and the sun.

Nocera isn't the only scientist working on artificial photosynthesis. The field is at least four decades old, and interest in it has grown in recent years. Some of the earliest research was done in Japan, which imports ninety per cent of its oil and therefore has an incentive to find nonfossil alternatives, especially now that its zeal for nuclear reactors has weakened. In 2010, the U.S. Department of Energy and Caltech established the Joint Center for Artificial Photosynthesis, which has a five-year budget of a hundred and twenty-two million dollars. The center coordinates work by numerous researchers, who are exploring various approaches to solar-energy conversion. An important advance in artificial photosynthesis occurred in 1998, when John Turner—a scientist at the National Renewable Energy Laboratory, which is also funded by the Department of Energy—built a device that, like Nocera's, split water with no power source other than sunlight. Turner's device was extremely expensive and its components corroded rapidly, but before it stopped working it had converted approximately twelve per cent of the energy in the sunlight that fell on it, making it up to twelve times better at fuel production than a green plant.

Nocera's artificial leaf, in its current form, is less than half as efficient as Turner's, but it's far more durable and only a fraction as expensive. Earlier this year, Nocera founded a company, Sun Catalytix, to pursue artificial photosynthesis, energy storage, and renewable fuels. Sun Catalytix has received almost all its funding from three sources: a technology-venture-capital firm, the Department of Energy's ARPA-E program, and the Indian industrialist and billionaire Ratan Tata. The company has designed an inexpensive water-splitting device, which the Tata Group expects to test on some scale in India late this year or early next year. "Mr. Tata and I spoke for only fifteen minutes the first time we met," Nocera told me. "But he kind of shares my vision, which is sun plus water is energy for the world."

On campus maps, M.I.T.'s buildings have assertively unimaginative designations. Nocera's office is in Building 6, which is situated between Buildings 8 and Building 2 and across a shady quadrangle from Building 18. His office is on the third floor. In the hallway outside his office door on a recent morning were seven large liquid-nitrogen canisters, like empties left for the milkman. "We're always making stuff," he explained, "and when you make stuff you need liquid nitrogen. (It's used to keep things very cold.) He led me into a laboratory on the other side of the hall, and pointed out various pieces of equipment. "There's something in condensed-matter physics called quantum spin liquid," he said. "It's a very exotic state of matter, and we actually made it in this furnace. And that machine, over there, is a fifty-thousand-dollar microwave oven. One of the students in my group had the idea of cooking chemicals with microwaves, and that's what we do with it."

Nocera had just returned from an international conference on Lord Howe Island, a minimally populated six-mile-long volcanic outcropping in the Pacific Ocean several hundred miles northeast of Sydney. Because he travels so much, he spends less time than he would like working directly with the graduate students and postdoctoral fellows under his supervision. Nevertheless, he told me,
he can usually recognize most of them. “That’s Noémie,” he said, to demonstrate. “She’s from France. And that’s Elizabeth, from Texas. And that’s a random guy I don’t know.”

“I’m Oliver,” the guy said.

“Oliver! From Germany!” (Oliver Bruns, who is from Hamburg, wasn’t one of Nocera’s graduate students but was visiting from another group in the chemistry department.)

We moved to a large, glass-fronted cabinet. “This is a glove box,” Nocera said. “A lot of the compounds we work with would catch on fire or explode in air, so this box has no oxygen in it. If the catalysts I use for artificial photosynthesis had to live in a world of no oxygen, I’d be in trouble, but the weird thing is that discovering how to make those catalysts often involved working with compounds that catch on fire and explode.”

Every researcher who is interested in artificial water-splitting faces bigger challenges than a schoolroom demonstration of electrolysis might suggest. Most of those challenges arise because water is so chemically stable that its components resist molecular rearrangement—a good thing, since it prevents the spontaneous combustion of oceans, among other undesirable phenomena. For electrolysis to work, that molecular stubbornness has to be overcome—by turning up the voltage, by adding chemicals to the water, by using catalysts that promote the shuffling of bonds. But such measures also increase costs, and some of them reduce the longevity and reliability of the components. “In natural photosynthesis, the catalyst is the leaf,” Nocera said, and much of his research has involved looking for affordable materials that reliably perform similar functions.

In 2008, Matthew W. Kanan, a postdoctoral fellow who was working with Nocera—he’s now a chemistry professor at Stanford—was trying to find an improved catalyst for the oxygen-producing side of the water-splitting reaction. Nocera had successfully used compounds made of iridium and rhodium, but both metals are rare and expensive. “On the periodic table, elements that are next to each other usually have similar properties,” Nocera said, “and if you look up from iridium and rhodium, in the same column, you see cobalt, which is stuff you find in rocks.” Kanan prepared a cobalt compound and added it to the water in a test device, along with a phosphate buffer—to neutralize any acids formed in the reaction—and turned on the electric current. Before long, Kanan told me, a “golden-green layer” began to form on the surface of the electrode, and he assumed that his experiment had failed. He kept the power on, though, and after about an hour he saw a stream of bubbles. He and Nocera eventually determined that the bubbles were pure oxygen, and that the dissolved cobalt and phosphate had combined, on their own, to form a highly effective, low-cost catalyst, which now coated the electrode.

This was not just a chemical breakthrough but also a philosophical one. Researchers in the past, Nocera said, had focussed on finding catalysts that didn’t break down when they were submerged in water and exposed to sunlight, electric currents, chemical additives, and one another. (Platinum, iridium, and rhodium resist corrosion in almost any environment.) But Kanan’s discovery suggested that an effective way to increase long-term reliability might be to use materials that re-formed after decomposing. This is a trick that nature employs throughout the biosphere. “A leaf doesn’t have its own chemist—it has to assemble itself and heal itself,” Nocera said. “We realized that if we had catalysts that repaired themselves we could achieve sort of the same thing, and that’s what cobalt and phosphate have let us do.”

Kanan’s cobalt–phosphate catalyst, furthermore, deposits itself in a layer so thin that it’s virtually transparent to sunlight. Nocera’s earlier hydrogen-generating devices had been powered by external photovoltaic panels—the same solar panels you sometimes see on suburban roofs. These are made from materials—usually forms of silicon—that produce an electric current when they’re exposed to light. The transparency of the cobalt–phosphate catalyst enabled Nocera, in effect, to move the solar panel into the water, and to eliminate the wires. The artificial leaf, in its current version, is a piece of silicon coated on one side with Kanan’s cobalt–phosphate compound, and, on the other, with an inexpensive nickel-based catalyst (which is required for the hydrogen side of the reaction). Nocera said, “You drop it in a glass of water and hold it up to the sun, and it starts generating fuel.” When light penetrates the cobalt layer, a wireless electric current arises within the silicon, and the sandwich’s two faces become electrodes, causing hydrogen to bubble from one and oxygen to bubble from the other. Kanan’s catalyst, serendipitously, also allows the reaction to run in almost any water, including seawater and human wastewater—a huge advantage, since in much of the world pure water is scarcer than fossil fuel.

Whenever the artificial leaf is mentioned in a newspaper article or on the Web, Nocera finds out almost immediately, because his e-mail and voice-mail in-boxes fill up. Many of the messages come from young scientists who want to study with him. “The others are from people who say, ‘Nocera, I heard you invented this technology. Please come install it at my house tomorrow,’” he said. The inquiries from students gratify him, because they suggest that the scientific world is coming around to his point of view. His reaction to the other inquiries is more complicated. For one thing, Nocera’s artificial leaf hasn’t evolved to the point where he or anyone else could install it at someone’s house. For another thing, the people who contact him about buying the device are usually denizens of what Nocera calls “the legacy world”—the fortunate minority of the earth’s population which historically has enjoyed most of the considerable benefits of burning fossil fuels. These are not the people he views as the target users of his technology, at least in the near term. Since the early eighties, he has focussed on the non-legacy world—the billions of impoverished people who have little or no access to modern fuels or to any electricity grid. “If there’s one thing that’s unique to the technology development I’ve done, it’s been doing science with the super—poor in mind,” he told me. His emphasis is largely humanitarian; it
also arises from his belief, as a scientist, that the only way to meet the world’s projected energy needs without causing intolerable environmental harm will be to work, in effect, from the bottom up—an approach that’s very different from the ones that dominate energy research.

To contented inhabitants of the legacy world, mankind’s gathering energy and climate challenges often seem to be primarily automotive. Most carbon-neutral energy research has focused on providing renewable energy in the way that cars and other power-hungry devices need it: in very large quantities, stored compactly and delivered quickly. Fossil fuels meet those requirements, because they contain energy in a highly concentrated form. (“Every year, by burning fossil fuels, we release a million years of photosynthesis,” Nocera told me.) Non-nuclear zero-carbon alternatives almost always lack this characteristic, which is known as “energy density.” To use the sun to power an electric car, for example, you have to harvest light from an area that’s much larger than the car’s surface, and in order to travel long distances or at night you have to stockpile the energy in batteries, which are expensive and are incapable of storing more than about a hundredth as much energy as the same weight or volume of gasoline. The Tesla Roadster, an all-electric car, has a hand-assembled lithium-ion—battery pack, which weighs a thousand pounds, has a projected useful life of seven years, costs roughly forty thousand dollars to replace, and takes a long time to recharge—many hours if the energy source is the low-voltage trickle from a photovoltaic panel. “There’s always the promise that batteries are going to get better, but there’s a physical ceiling on how closely you can pack electrons,” Nocera said. “We could have chosen batteries instead of fuels a hundred years ago, but we didn’t, and there’s a reason. I like listening to people talk about batteries as their laser pointer is running out of juice.” The low energy density of batteries and sunlight helps to explain why the current proportion of total U.S. energy consumption that’s supplied by photovoltaic panels, rounded to the nearest whole percentage point, is zero.

Hydrogen is extremely high in energy density; a pound contains almost three times as much energy as a pound of gasoline. But as a fuel hydrogen has drawbacks, the most significant of which is that its physical density is extremely low. Storing an automotively useful quantity of hydrogen in a container the size of a car’s gas tank requires enormous compression and expensive composite materials. Furthermore, most hydrogen-powered demonstration cars have engines called fuel cells, which are costly and technologically complex, and which don’t function at some temperatures. And, of course, the environmental benefit of using hydrogen as a fuel is lost if the hydrogen is manufactured from fossil fuels.

The low-carbon-energy challenge looks different, however, if you ignore S.U.V.s and think of the billions of people who live in extreme poverty. For them, the main energy concern is not how to accelerate a four-thousand-pound vehicle from a stop to highway speed in a few seconds and cruise for hundreds of miles; it’s how to survive from one day to the next. For such people, Nocera told me, the main energy issue isn’t power or efficiency or energy density; it’s cost. “For the non-legacy world, energy has to be super-cheap,” he said. “If I could make alternative energy that was cheap enough for you to want to use it in your house—and I can’t—it still wouldn’t be cheap enough for the poor.” Providing energy for these people has been Nocera’s goal from the beginning. “In the next forty years, three hundred and fifty million Indians are going to become energy users,” he said. “We’ve got to get them energy, and it’s got to be CO₂-neutral, because if they use coal we’re screwed.”

Nocera’s vision for the world’s poorest people is of a gridless, decentralized energy system, in which every dwelling has an artificial leaf on its roof. When the sun shines, the leaf splits water—about a litre and a half per day—and after dark the residents burn the hydrogen in an inexpensive microturbine, which generates electricity till dawn at an average rate of about a hundred watts. By legacy-world standards, this is a truly minimal power level, but it’s sufficient, Nocera thinks, to transform the lives of people who currently
have none, or almost none. And it’s cheap. The components are not particularly efficient, but they are low-tech and commercially available today. And, because the fuel is produced in small quantities and used on site, the hydrogen can be stored in ordinary metal tanks, at modest pressure. Furthermore, the self-repairing cobalt-phosphate catalyst keeps the need for maintenance low—a critical factor, Nocera said, because “you can’t have a bunch of people running around the world fixing stuff.”

Nocera believes that the benefits of large-scale implementation would extend beyond direct, energy-related gains in users’ quality of life (illumination, cooking without burning wood, telephone-charging), and would include a global decline in the rate of population growth, which, historically, has slowed as affluence has risen. “The real issue driving our problems on the face of this planet is population,” he said. “One of the beautiful things about providing distributed energy to the poor is that it’s a positive feedback loop. If I give poor people energy, they become empowered, and every study that’s ever been done has shown that with financial gain and education population drops like a rock.”

It’s usually argued that complex technological gains trickle down to the poor—that the innovations required to reduce the sticker price of a Tesla Roadster from a hundred and ten thousand dollars to eighty thousand dollars will also eventually improve the lives of people at the bottom of the global income scale. But there’s reason to think otherwise: as energy technology has grown in both sophistication and efficiency, the worldwide gap between richest and poorest has widened, and the richest countries today often treat the poorest ones less as partners in progress than as cheap targets for resource extraction. Nocera believes that simple technology scales up more readily than complex technology scales down. “The poor are helping you,” he told his audience in Aspen, “because they’re going to teach you how to live for the future.”

Matthew Kanan, the Stanford chemistry professor who discovered Nocera’s cobalt–phosphate catalyst, told me, “Dan isn’t the only one who has made this point, but he’s right that the developing world’s energy trajectory is the one that’s the most important over the next several decades.” Focussing on people whose energy consumption is tightly constrained also reduces the likelihood of certain kinds of unintended consequences. A seldom discussed environmental danger posed by electric cars, for example, is that broad, rapid adoption would hugely increase, rather than reduce, demand for grid-supplied electricity generated by burning fossil fuels, since growth in renewable sources couldn’t conceivably keep up. (“I totally hate the electric car,” Nocera told me.)

Providing decentralized energy to the developing world carries a threat of unintended environmental consequences, too, of course. One possibility is that the artificial leaf could turn out to be the energy equivalent of a gateway drug. Historically, more energy has always meant more income, and more income has meant more consumption, and more consumption has meant more energy in every form—as well as increased demand for a rapidly expanding list of environmentally destructive possessions, including, eventually, the ultimate modern consumer good, the automobile. And although distributed energy production eliminates the need for a centralized electricity grid, it encourages the creation and enlargement of other environmentally problematic grids, including the ones used by phone calls, Web sites, food producers, airplanes, delivery trucks, and cars.

Among some scientists, Nocera has a reputation for hipping his discoveries. The playing-card-size device truly does split water, but it’s a prop, not a product, since producing enough hydrogen to meet even Nocera’s minimal goal of powering a single hundred-watt light bulb through the night would require an artificial leaf the size of a door. Photovoltaic panels have the same size constraint, which arises from the diffuseness of sunlight and from silicon’s ultimately limited ability to absorb it. “One thing the layperson messes up is that you can’t go faster than the sun gives out energy,” Nocera said. The advantage of the artificial leaf is not that it converts more solar energy than a conventional photovoltaic panel. The advantage is that it stores solar energy in a fuel, rather than in a battery, and is therefore potentially more versatile, as well as being less expensive to acquire, maintain, and exploit—as long as users’ energy requirements are minimal. Nocera’s claims have also often been amplified by reporters, and even by his own university’s public-relations office. He hasn’t always rushed to correct misimpressions, and at least some of his overselling has been intentional. Attracting funding for renewable-energy research requires showmanship, and the need for shrewd marketing has grown in recent years, as legacy-world interest in carbon-free energy has slackened. A further difficulty is that the science of renewable energy is genuinely daunting. Nocera’s challenge outside the laboratory has been to build enthusiasm for the artificial leaf even though, in anything like its current form, it is designed to meet a level of energy demand that by modern American standards is almost immeasurably low.

As Nocera concedes, artificial photosynthesis, if it turns out to be practical for anyone, is almost certainly decades from large-scale implementation—a discouraging fact that applies to virtually all renewables. Still, he believes that, if scientists and engineers were to apply the kind of effort to developing low-cost fuel cells for Third World homes that they now apply to developing high-performance batteries for American sports cars, they might accomplish something globally significant. They might also eventually find an economical way to replicate the far more challenging second stage of photosynthesis, in which hydrogen and atmospheric carbon dioxide combine to make a non-gaseous fuel—a breakthrough that would eliminate the problems associated with storing and transporting hydrogen. “If we all just focussed on this, in a coördinated way, I’m sure the science and engineering community could nail it,” he told me. For that reason, he doesn’t mind speculating publicly about outcomes that, realistically, he can’t deliver yet. “A lot of scientists get mad at me for speaking at things like this,” he said in Aspen, “because they think I’m going to give you hope.”

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