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FOR THE TECHNOLOGY INSIDER | 06.18

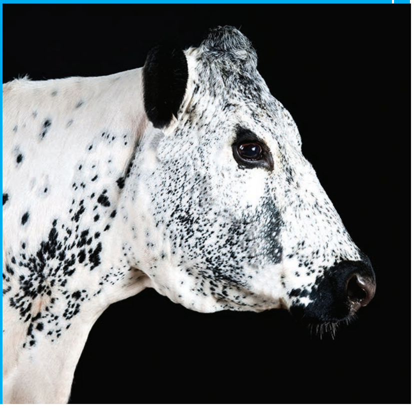
10 TECHNOLOGIES FOR A MORE LIVABLE PLANET

BLUEPRINTS FOR A MIRACLE

A SPECIAL REPORT

IEEE

Blueprints for a Miracle



The editors would like to acknowledge the following people for their advice, insights, and guidance in the preparation of this report: Andrew F. Burke, University of California, Davis; Robert Hebner, University of Texas at Austin; Jane Long, California Council on Science and Technology; Edward S. Rubin, Carnegie Mellon University; Vaclav Smil, University of Manitoba; Sonja Vermeulen, World Wildlife Fund. Their identification here should not be construed as an endorsement of the report; any errors are ours.

On the cover **Illustration for *IEEE Spectrum* by Francesco Muzi/Story TK**

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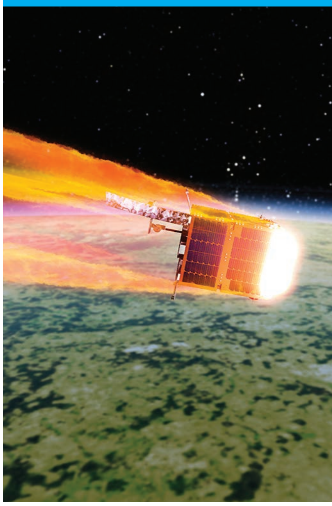

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Mighty Micro Magic
Algae is an excellent source of protein, and it absorbs CO_2 straight from the air, just like plants. A wee industry is starting to grow algae in mass quantities for people to eat. Watch this online video to hear Rebecca White, vice president of operations at one of the world's largest algae farms, describe technologies that keep algae humming along at 5 to 10 times its natural growth rate. https://spectrum.ieee.org/algaevideo0618

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SHUN KAWASAKI

THE FARM ON THE SECOND FLOOR

HARRY GOLDSTEIN'S ADVENTURE in vertical farming began at the deserted Shōwajima monorail station, on an island in Tokyo Bay. Goldstein, *IEEE Spectrum*'s online editorial director, had an hour before his appointment to tour the Espec Mic VegetaFarm plant factory.

It was a warm, sunny afternoon on the first day of March. But where was the farm? It wasn't vertical enough to be visible from the train platform. Fortunately, he'd downloaded a PDF map for just this eventuality.

Froggering across a service road jammed with semis and going left under an overpass, Goldstein emerged into a snarl of warehouses aswarm with forklifts loading beer kegs onto trucks and workers in hard hats tossing scrap metal into piles. It was a comforting sort of déjà vu for Goldstein, who encountered much the same scene in Minnesota and Wisconsin when he last covered indoor farms for *Spectrum* in 2013. (You can see images from Goldstein's trip to Japan in this issue and on our Instagram account, @ieeespectrum.)

The building itself was a bit of a disappointment. The term "vertical farm" is richly futuristic, conjuring visions of green towers gleaming in the sun. But the VegetaFarm turned out to be a shabby office building with Espec Mic's sign hanging on an ornamental gate out front. After a brief, mostly gestural exchange with a janitor, Goldstein was escorted into the grow room, an eerily quiet, moist, warm warren, like a library with plants instead of books. Having heard that some plant factories require workers to shower before entering the grow room, he was relieved that the only clothes he had to remove were his shoes and that he needed only a shower of puffed air to dust off the bunny suit he had to put on.

When the tour ended, Goldstein took the stairs down. On a landing, he snapped his last picture: a ladder leaning against a window, a mop propped next to it, a pair of men's trousers slung over a middle rung. He stealthily rounded the next corner and slipped through the empty lobby, avoiding the half-naked janitor the tableau suggested. ■

CONTRIBUTORS_

Richard Brewster

Brewster spent much of his career working on nuclear submarines and nuclear power plants. More recently, he's been the chief radio operator for one of Mercy Ships' hospital ships. In this issue [p. 13], he describes how he re-created the first flip-flop circuit, which turns 100 this month. It took decades for the flip-flop to become a building block of CPUs, Brewster notes. "It's like the Wright brothers invented flight, and then no one knew what to do with it."

Elie Dolgin

Dolgin, a Boston-based freelance science writer, reports in this issue on one company's efforts to make genetically engineered bacteria that can nourish cereal crops and replace energy-intensive chemical fertilizers [p. 62]. He found the company's R&D facility impressive. "Tons of robots, and nobody in sight anywhere," Dolgin recalls. He asked his guide if the process was so automated that it didn't require human intervention. The answer: "Yes. But also, it's lunch hour."

Matthew N. Eisler

Eisler is a Strathclyde Chancellor's Fellow and lecturer in history at the University of Strathclyde, in Glasgow. His 2012 book *Overpotential: Fuel Cells, Futurism, and the Making of a Power Panacea* (Rutgers) explored the long road to commercialize the fuel cell. The history of power-source R&D is replete with unintended consequences, Eisler says. The project he covers in this issue, about a carbon-capturing fuel cell, is one such story [p. 22].

Douglas Heingartner

Heingartner is an American journalist based in Amsterdam. While reporting for this issue on the fast-moving world of meat alternatives [p. 66], he says his own thinking on food sustainability went through a transformation. "I knew that our current methods of producing meat were pretty grim," Heingartner says. "But now I'm increasingly optimistic that we've advanced far enough, in terms of technology and willpower, to finally be able to do something about it."

David Wagman

Wagman is editorial director for IEEE GlobalSpec's Engineering360, a search engine and information resource for the engineering, industrial, and technical communities. A veteran electricity industry reporter, he explores a new path to carbon-free energy in "This Plant Runs on CO_2" [p. 26]. "The idea that steam in power generation could be challenged by carbon dioxide as a primary mover was a big reason to dig deeper into this technology," Wagman says.

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I Was a Russian Facebook Troll Named Martha

A dusty old Facebook account started sending me alerts. I ignored them—and my account went rogue

Back in the earliest days of Facebook, before you could attach a second name to your Facebook account and before businesses could set up pages, I created two Facebook accounts. I use my original name professionally and my married name for my personal life, so it made sense to have a professional account and a personal account. ¶ But before I really got going with Facebook, I started using Twitter for professional postings, so the Facebook account associated with my work email just gathered digital dust. For years and years. ¶ A couple of weeks ago, however, I started getting notices via email from Facebook pointing out that the account hadn't been updated in a while. I thought that was odd: Why would Facebook suddenly care about this old account? Is it really that desperate for traffic? And I also started getting notices whenever a friend on that account (which at that point was only me–that is, my other account) posted anything new. That was annoying, and given I'd never gotten these notices before, I was pretty sure "updates on your friends" was not something for which I had created an email alert. I tried to log on to my old work-related account to turn the notices off, but the password failed. I wrote that off to bad record keeping on my part, and I didn't have the time to fiddle with it, so I moved on to other things. ¶ Then last week, the notification emails started referring to me as "Martha." Huh? And they alerted me that I had changed my profile picture. And then came more emails, noting that I'd added two friends–one in the Ukraine, one in Tanzania–and suggesting a long list of possible friends, most of them tagged in Cyrillic. It looked like my dusty little Facebook account was turning into a Russian troll. (Ironically, my actual first name is of Russian origin–but I guess you can't have a Russian troll with a Russian name.)

I dug through all of Facebook's reporting mechanisms–there wasn't any option for "*I'm* a troll." I couldn't report my own profile for abuse, only someone else's profile or posts someone else had made. The online menus sent me through circle after circle.

Finally, I deactivated my account, citing "privacy concerns." But I wonder how many people out there have dusty accounts–particularly people who once upon a time set up a Facebook account (or perhaps their children set it up for them)–but *didn't* select activity alerts. Without those, I would have had no idea that I had become Martha, a Russian troll.

A Facebook spokesperson indicated that anyone facing this situation should go to Facebook.com/hacked to report it, but declined to respond to more detailed questions. I'm still in the dark regarding why–and how often–this happens, how the hackers carry it out, and, if the hacker had changed my alert email address, how I could have ever found out that one of my online personalities had been hijacked.

So if you get an alert on an old account, don't ignore it. It could be the start of something really wrong.

And finally, a word to Facebook: Your reporting mechanisms stink! Users shouldn't have to dig through countless menus to find reporting options, and then have to figure out what exact category of trouble might be close to the problem. The page Facebook.com/hacked offered nothing in the ballpark. Here's a suggestion: One menu option should be "I believe my identity is being used by a Russian troll." —TEKLA S. PERRY

A version of this article appears in our View From the Valley blog.

Update: After publication of "Not Your Father's Analog Computer" [February], the author learned that the concept of the function generator mentioned in it was described earlier in U.S. Patent No. 5,006,850, by Gordon J. Murphy. The author would like to thank Professor Murphy for bringing this patent to his attention.

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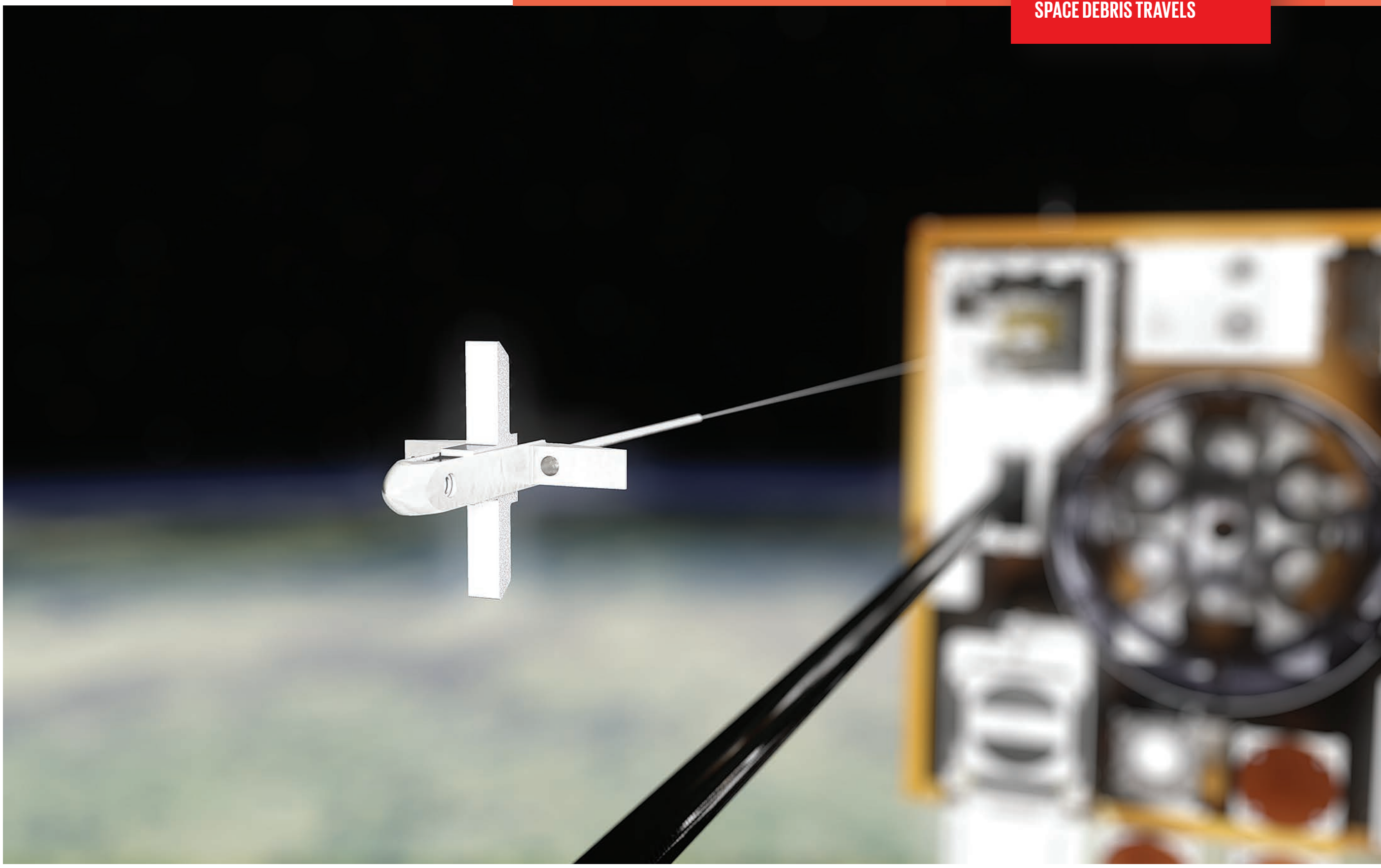
ILLUSTRATION BY James O'Brien

NEWS

28,000 KM/H: SPEED AT WHICH SPACE DEBRIS TRAVELS



BULL'S-EYE: A tethered harpoon with a pointed tip zooms toward its target in this conceptual rendering.

EQUINOX GRAPHICS/SURREY SPACE CENTRE/UNIVERSITY OF SURREY

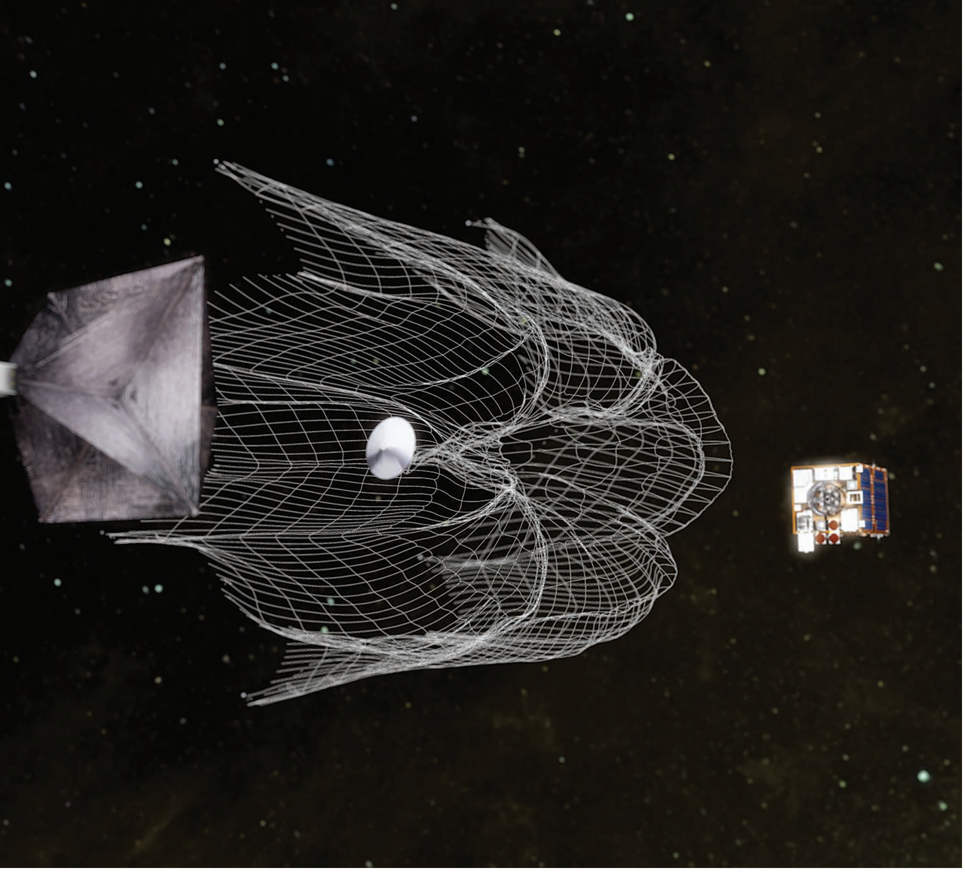
FISHING FOR SPACE JUNK

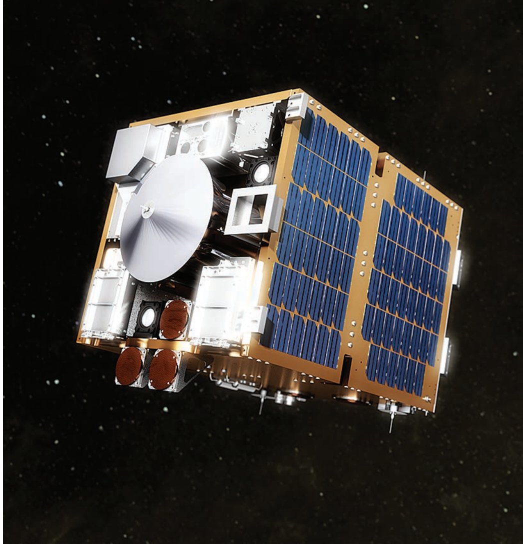
A European mission will test whether nets and harpoons can capture and remove space debris

A spacecraft may soon be able to snare space junk by firing harpoons and nets. A European mission was expected to begin tests in late May of space-age versions of those ancient tools to clean up Earth's cluttered orbital lanes.

Space junk has already destroyed at least one satellite, damaged others, and periodically forces the crew aboard the International Space Station to take evasive action. There are more than half a million pieces of space debris larger than a marble and tens of thousands of significantly larger specimens left over from spent rocket boosters and defunct satellites. To head off future catastrophe, experts from NASA and the European Space Agency have proposed removing 5 to 10 large pieces of debris each year.

For the new mission, plainly called RemoveDebris, collaborators launched a 1-cubic-meter spacecraft to the space station in April. The spacecraft was scheduled to deploy from the space station in May to complete four tests of technologies, including a net and harpoon, that could be used to clear space debris. »





SHOWTIME: Prior to the April launch, a technician applied the finishing touches to the RemoveDebris spacecraft [top right]. The 100-kilogram spacecraft [above] must now prove its ability to capture space junk. In one test, it will toss out a net to snare a CubeSat [left]. In another, the spacecraft will deploy a sail [right] to gracefully descend and burn up in Earth's atmosphere.

CLOCKWISE FROM TOP RIGHT: MAX ALEXANDER/SSTL; EQUINOX GRAPHICS/SURREY SPACE CENTRE/UNIVERSITY OF SURREY (3)

"The net and harpoon are simple concepts but uniquely implemented for this application," said Guglielmo Aglietti, principal investigator and director of the Surrey Space Centre at the University of Surrey, in England.

Other researchers have proposed using lasers or electrified cables to nudge space junk into orbits that lead it to burn up in Earth's atmosphere. A Japan Aerospace Exploration Agency attempt to test an electrodynamic tether failed in 2017 because the tether was unable to unroll and deploy. Several other missions have tested passive removal, which involves aged satellites using their own boosters or deploying drag sails to force self-immolation.

Given that limited history of testing, the US $18.7 million RemoveDebris mission could prove instructive as a low-budget demonstration. The European Commission and the Surrey Space Centre are leading an international consortium backing the mission.

If successful, the project could inspire a follow-up mission that will try to capture an actual piece of space junk, said William Schonberg, an aerospace engineer at Missouri University of Science and Technology who is not involved in the effort. "Hopefully, we will not have a disaster that costs human lives before we have the combined will to do something," he said.

Net Capture

For this test, the main spacecraft will release a CubeSat about the size of a bread loaf that will deploy and inflate a 1-meter balloon to make itself into a larger target. Once the CubeSat has drifted 6 meters away, the main spacecraft will launch a 5-meter-wide net at the target.

If all goes well, weighted masses on the net's edges will wrap it securely around the target. Motor-driven spools will tighten the neck of the net to prevent the CubeSat from escaping.

The entangled satellite will then be left to fall out of orbit and burn up in Earth's atmosphere. But future missions could also allow the spacecraft to reel in its netted prey.

Vision-Based Navigation

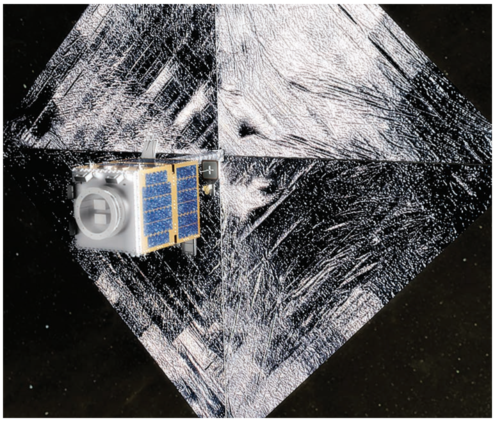
Any space-debris removal will require the ability to accurately track floating bits of stuff. The mission's second test involves a vision-based navigation system that uses a pair of cameras and a lidar sensor to follow potential targets.

The two cameras will ride aboard the mother ship and perform two sets of observations. First, the cameras will observe the net-capture experiment involving the first CubeSat. Then the cameras will turn their focus onto a second CubeSat, equipped with four extendable solar panels, that will deploy from the main spacecraft. Eventually, that CubeSat will drift out of orbit and burn up in Earth's atmosphere.

Harpoon Capture

In the harpoon test, the spacecraft will not attempt to spear a tumbling target moving along its own trajectory. Instead, it will extend a long arm to hold a stationary target, about the size of a ping-pong paddle.

Once the target is in place at a distance



of 1.5 meters, the spacecraft will fire a small harpoon that consists of a miniature projectile the size of a pen with a trailing tether. The tether will allow the spacecraft to reel in its target. It may sound simple, but it's a necessary step in demonstrating how well a harpoon could perform in real space conditions.

Drag Sail

The final test will prevent the spacecraft itself from becoming yet another piece of space debris. This test involves raising a drag sail on the end of a mast that will extend to 1 meter and ensure that the sail doesn't entangle the spacecraft. Once the sail's mast is ready, a motor will raise carbon fiber booms that open the sail's membrane, which measures about 10 square meters. The drag sail will act as a large brake, making the main spacecraft leave orbit faster and bringing the mission to an end.

—JEREMY HSU

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FAR RIGHT: PETER FAIRLEY

NEWS

ROOFTOP SOLAR TAKES HOLD IN IRAQ

Home and shop owners are installing solar arrays to smooth power outages

The souk, or marketplace, keeps buzzing in Sulaimani, a provincial capital in Iraq's semi-autonomous Kurdish region, even though the national power grid has just gone off-line. Merchants like Mohamad Romie emerge from shops to fire up their generators or switch over to commercial backup power suppliers.

This switch to local power is a more-than-daily ritual across Iraq, thanks to a stubborn electricity supply gap that hinders Iraq's development. Renewable power installations could shrink that gap—be they rooftop photovoltaics like those Mohamad and his brother Ali are installing through their company, Romie Electric, or utility-scale wind and solar plants. Rooftop power is already beginning to bridge gaps in Iraq's grid supply, while large utility projects must still gain domestic support and international investment.

Iraq has excellent solar resources, and six years ago it declared ambitions to build hundreds of megawatts of solar power plants (plus smaller wind farms). Then the Islamic State arrived, interrupting the country's renewable ambitions.

Suppliers such as Romie Electric are moving forward, however, by offering rooftop solar as an alternative to loud, dirty private generators or pricey district power. Solar suppliers generally package PV panels with lead-acid batteries to produce electricity for the 5 to 15 hours of each day without "government power."

Ali Romie estimates that their firm has installed US $200,000 worth of solar equipment over

POWER UP: This shop is one of a growing number of small businesses in Iraq that now focus on renewable energy installations.

the past two years and says both demand and competition are now growing. A typical system generates about 1 kilowatt. "People like this system because it has no noise and has no effect on the environment, especially small stores that don't need a high amount of energy to turn on their lights, TVs, and other devices," he explains.

Longer-lasting lithium batteries have eclipsed lead batteries in many energy storage markets, but ABB Group microgrids specialist Rob Roys says lead varieties may be a better fit for Iraq, with its daily power outages. "Lead-acid batteries do better when deep cycled" or substantially discharged and recharged, explains Roys.

Solar systems cost many times more than a generator up front but actually deliver cheaper energy because they consume zero fuel, according to Ramyar Ali, assistant manager for Aras Green Energy, a four-year-old renewable-equipment firm based in Sulaimani.

According to the International Energy Agency, power from generators burning government-subsidized fuel costs Baghdad residents 17 to 25 cents per kilowatt-hour. The Abu Dhabi-based International Renewable Energy Agency, meanwhile, recently estimated that rooftop PV in Germany was already generating power for 16 to 18 cents per kilowatt-hour two years ago.

Utility-scale solar and wind plants could someday also supplement the oil- and gas-fired generation that supplied 96 percent of Iraq's grid power in 2015. Large solar plants are particularly attractive, say experts in Iraq, since they are relatively quick to build and can supply peak usage in the summer, when air conditioners drive demand furthest beyond the national grid's limits.

But Samad Hussain, a top environmental official in the Kurdistan Regional Government in Erbil, says international firms that finance and build renewable power plants are apprehensive about security threats in Iraq. They also worry about getting paid, he says, because many Iraqi consumers do not pay their government power bills.

Othman Hama Rahim, a renewable-energy researcher at the Kurdistan Institution for Strategic Studies and Scientific Research, cites several domestic challenges to incorporating more renewables into Iraq's energy mix. One is dust storms, which may necessitate regular cleaning of solar panels. Another is that Iraq's energy leaders remain focused on exploiting its fossil fuel resources. As Hama Rahim puts it: "We have oil. This is another factor retarding renewable power generation here."

—PETER FAIRLEY

SOLAR SALE: A vendor selling home solar systems displays a photovoltaic panel at a market in Sulaimani, Iraq.

POST YOUR COMMENTS at https://spectrum.ieee.org/iraqsolar0618

TECH GIANTS RACE TO BUILD ORBITAL INTERNET

Public filings suggest Facebook is quietly developing a satellite-based Internet to rival efforts by SpaceX and OneWeb

Facebook may soon join SpaceX and OneWeb in the rush to deliver the Internet from orbit.

A recent filing with the U.S. Federal Communications Commission (FCC) revealed details of a multimillion-dollar experimental satellite from a stealthy company called PointView Tech. The satellite, named Athena, will boast a data speed 10 times as fast as that of SpaceX's Starlink Internet satellites, the first of which launched in February.

However, PointView appears to exist only on paper. In fact, the tiny company seems to be a new subsidiary of Facebook, formed last year to keep secret the social media giant's plans to storm space.

Many technology companies believe the future of the Internet is orbital. Around half the people on the planet lack a broadband Internet connection. SpaceX aims to put nearly 12,000 Starlinks into low Earth orbit (LEO), to deliver gigabit-speed Internet to most of Earth's surface. Rival OneWeb, funded by Japan's SoftBank, chipmaker Qualcomm, and Richard Branson's Virgin Group, plans similar global coverage using perhaps 2,500 LEO satellites.

In early 2019, PointView's Athena will also head out to LEO, on an Arianespace Vega rocket. Athena is about the same

PETER FAIRLEY

size and weight (150 kilograms) as SpaceX's and OneWeb's satellites, but Athena will use high-frequency millimeter-wave radio signals, which promise much faster data rates. The company estimates that its system, which will operate in the E band (from 60 to 90 gigahertz), will deliver data at download speeds of up to 10 gigabits per second, with uplink speeds topping 30 Gb/s. PointView now wants to find out if that system could provide fixed and mobile broadband service to underserved areas, according to its FCC application.

Space companies based in the United States must get permission from the FCC before launching any technology into orbit, and they often start building satellites and ground stations long before filing the paperwork. According to records in Delaware, PointView was incorporated there in April 2017. The company has filed no annual reports and has no named directors or shareholders. Instead, a paper trail leads to Facebook, in California.

To start, PointView Tech has the same corporate agent in Delaware as other Facebook subsidiaries, including FCL Tech, the company that managed its early connectivity tests. PointView's application to the FCC was also filed by the same Washington, D.C., law firm—and even the same lawyer—that wrote previous FCC applications for Facebook. (Neither the law firm nor Facebook responded to requests for comment).

PointView specifies in its application three ground stations in the Los Angeles area that will send data to Athena in orbit and receive it in turn. One is a so-called satellite teleport near Ventura that is shared by a number of satellite companies. The second is Mount Wilson Observatory, in the hills above L.A., another popular site for communications hardware.

But the third location, described in the application as housing a backup antenna, is an anonymous business park in the Northridge area of the city. Facebook was reported to have leased nearly 7,500 square meters of office space there in October last year, and the building is currently undergoing refurbishment.

In May, Facebook listed three job openings for its Northridge office, all related to communications and connectivity. An extraterrestrial product manager, for instance, is expected to have "in-depth technical knowledge of satellite [and]...millimeter-wave communication systems." One current Facebook staff member's LinkedIn profile says that he is working on "millimeter-wave communication product design & development" for satellites.

Facebook has long been interested in millimeter-wave systems. As early as 2015, FCL Tech filed an FCC application to "test potential new communication applications using the E band" from drones, in and around Los Angeles. In 2016, Facebook and its global connectivity spin-out Internet.org announced the first flights of its high-altitude solar-powered Aquila drones using E-band technology, and tests continued through 2017.

The company has also been thinking about satellites. In a 2016 letter to the FCC, the company wrote, "Facebook recognizes the important role that satellite plays in improving and expanding connectivity.... In remote, sparsely populated areas, where there are significant gaps in infrastructure and the economic barriers of installing that infrastructure are considerably higher, satellite services may provide the most efficient means to connect."

There are technical barriers to using E-band radio from orbit, however. High-frequency millimeter waves fade quickly and are easily absorbed by rain and particles in the air. Part of Athena's two-year mission will be to determine just how big of a problem that is. "PointView plans to publish many of its experimental findings," including measurements of atmospheric attenuation, says its application.

And because Athena is in low Earth orbit, it will fly above the three ground stations only a couple of times each day, and for less than 8 minutes at a time. If Facebook is serious about providing global connectivity, it will need to copy SpaceX and OneWeb and have thousands of satellites in orbit simultaneously.
—MARK HARRIS

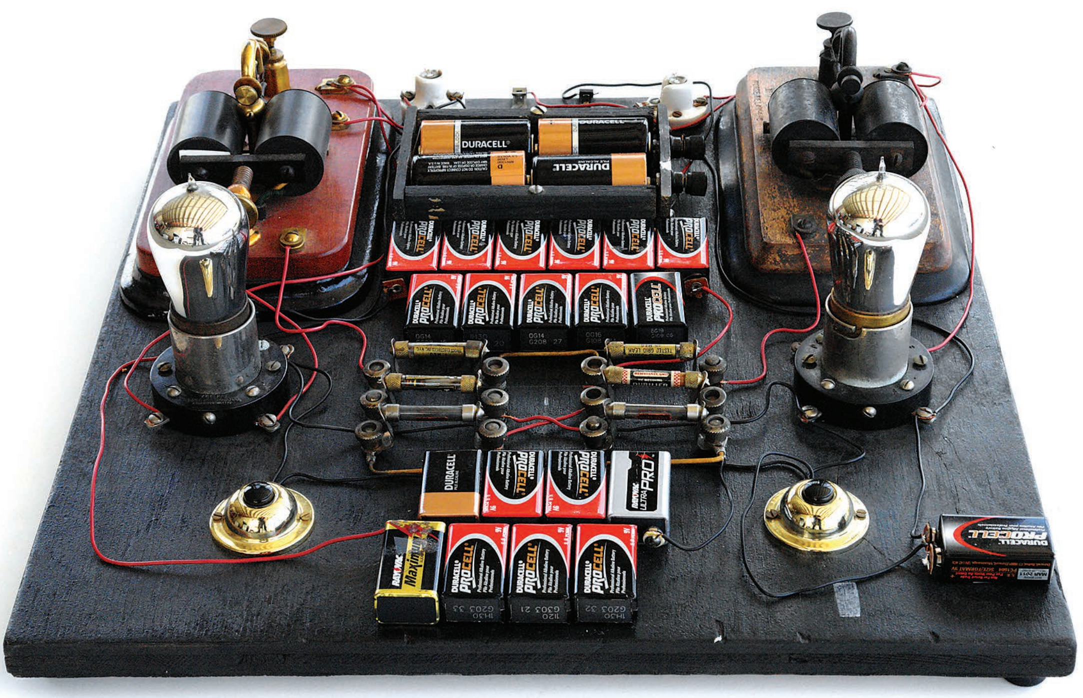
An extended version of this article appears in our Tech Talk blog.

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/secretinternet0618

ILLUSTRATION BY James Steinberg

RESOURCES

$450: THE COST OF A SINGLE INTEGRATED CIRCUIT FLIP-FLOP IN 1960



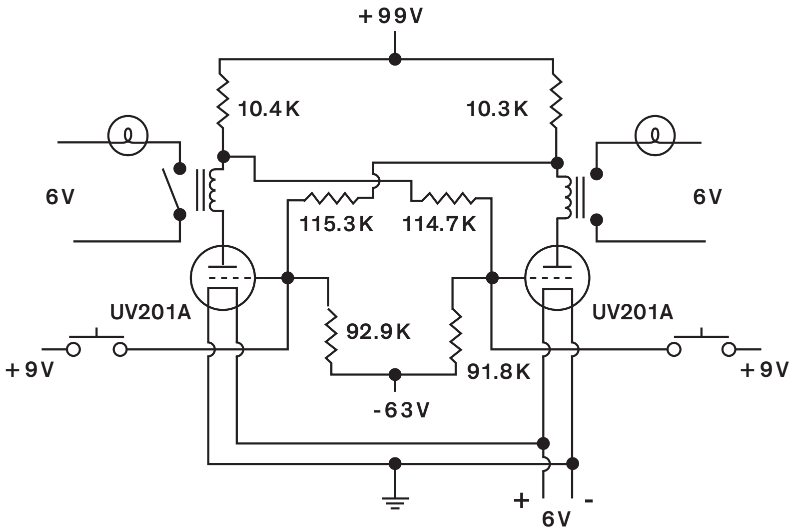
RICHARD BREWSTER

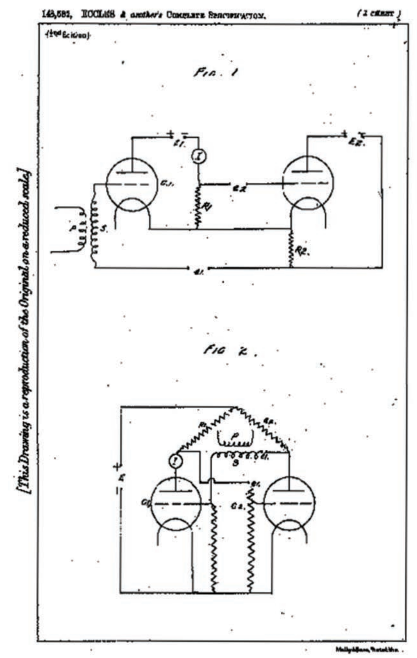
RE-CREATING THE FIRST FLIP-FLOP

A FUNDAMENTAL COMPONENT OF COMPUTERS TURNS 100

RESOURCES_HANDS ON

MANY ENGINEERS ARE FAMILIAR WITH THE NAMES OF LEE DE FOREST, WHO INVENTED THE amplifying vacuum tube, or John Bardeen, Walter Brattain, and William Shockley, who invented the transistor. Yet few know the names of William Eccles and F.W. Jordan, who applied for a patent for the flip-flop 100 years ago, in June 1918. The flip-flop is a crucial building block of digital circuits: It acts as an electronic toggle switch that can be set to stay on or off even after an initial electrical control signal has ceased. This allows circuits to remember and synchronize their states, and thus allows them to perform sequential logic. • The flip-flop was created in the predigital age as a trigger relay for radio designs. Its existence was popularized by an article in the December 1919 issue of *The Radio Review*, and two decades later, the flip-flop would find its way into the Colossus computer, used in England to break German wartime ciphers, and into the ENIAC in the United States. • Modern flip-flops are built in countless numbers out of transistors in integrated circuits, but, as the centenary of the flip-flop approached, I decided to replicate Eccles and Jordan's original circuit as closely as possible. • This circuit is built around two vacuum tubes, so I started there. Originally, Eccles and Jordan most likely used Audion tubes or British-made knock-offs. The Audion was invented by de Forest, and it was the first vacuum tube to demonstrate amplification, allowing a weak signal applied to a grid to control a much larger electrical current flowing from a filament to a plate. But these early tubes were handmade and unreliable, and it would be impractical to obtain a usable pair today. • Instead I turned to the UX201A, an improved variant of the UV201 tube that General Electric started ▸





CIRCUIT REVIVAL: Working from drawings in sources such as Eccles and Jordan's patent [left], I re-created the circuit and then adjusted resistances through trial and error [right].

LEFT: RICHARD BREWSTER AND ERIK VRIELINK; RIGHT: INTELLECTUAL PROPERTY OFFICE

producing in 1920. While still close in time to the original patent, the UV201 marked the beginning of vacuum-tube mass production, and a consequent leap in reliability and availability. I was able to purchase two 01A tubes for about US $35 apiece.

In a flip-flop, the tubes are cross-coupled in a careful balancing act, using pairs of resistors to control voltages. This balancing act means that turning off one tube, even momentarily, turns the second tube on and keeps the first tube off. This state of affairs continues until the second tube is turned off with a control signal, which pushes the first tube on and keeps the second tube off.

Achieving the right balance means getting the values of the resistors just right. In their laboratory, Eccles and Jordan would have used resistor decade boxes, bulky pieces of equipment that would have let them dial in resistances at different points in their circuit. For reasons of space, I decided to use fixed resistors of a similar vintage as the patent.

I was able to obtain a set of such resistors from the collection of antique radios that I've accumulated over the years. In the 1920s, radio manufacturing exploded, and the result is that I have quite a few early radios that are pretty nondescript and beyond repair, so I didn't feel too bad about cannibalizing them for parts. Resistors made before 1925 were generally placed into sockets, rather than soldered into a circuit board, so extracting them wasn't hard.

The hard part was that these resistors are very imprecise. They were handmade with a resistive carbon element held between clips in a glass enclosure. One way to get their resistance closer to the desired value is to open up the enclosure, remove the strip of carbon, make notches in it to increase its resistance, and put it back in. I adjusted several of the resistors this way, but it was too tricky to do with others, so for those I cheated a little and placed modern resistors inside the vintage glass casing.

I used modern battery supplies, in order to avoid the use of the numerous wet cells that the inventors probably used. One of the issues with tube-based circuits is that a range of voltages is required. Four D cells wired in series provides the 6 volts needed for the indicator lamps and the filament of the tubes. Connecting eleven 9-V batteries in series provided the 99 V required for the tubes' plate. A similarly constructed 63-V power supply is needed to negatively bias the tubes' grids. Old-fashioned brass doorbell buttons let me tap a 9-V battery connection to provide the control pulses. To show the flip-flop's state, I used sensitive antique telegraph relays that operate miniature incandescent lamps.

With a *lot* of trial and error and tweaking of my nearly century-old components, over the course of a year I was finally able to achieve stable operation of this venerable circuit!

If you are looking to replicate my efforts, and are willing to sacrifice some more historical accuracy for much greater ease in obtaining reliable parts, there are some good options. Some 6J5 tubes, first manufactured in the late 1930s, are a fine choice. These are reliable and a lot cheaper than the 01As, costing about $5 to $7 apiece.

The telegraph relays and the lamps can be eliminated and replaced with inexpensive NE-2 neon lamps. The latter would be wired between the plate of the 6J5 and the batteries, so as to illuminate when the tube is not conducting and extinguish when the tube conducts, thus dropping the plate voltage to a low value. Note that the 6J5 is a cathode-type tube, and so the cathode should be grounded and the filaments separately supplied by a 6-V battery, unlike in the original circuit.

The grid bias battery voltage selection will require some experimentation, as the 6J5 will likely require a lower value than the 63 V used with the 01As. And with regard to the resistances used, the values shown can be assumed to be approximate, but some effort should be made to have the three pairs rather closely matched. **—RICHARD BREWSTER**

↗ POST YOUR COMMENTS at https://spectrum.ieee.org/flipflop0618

THE POET AND THE MACHINE

SOME OF THE BEST POETS IN THE WORLD WERE CREATING POETRY ALGORITHMS IN THE 1960s

PROGRAMMER POET: Acclaimed author J.M. Coetzee developed software for composing verse on an early British supercomputer.

MICHELINE PELLETIER DECAUX/GETTY IMAGES

When we think of people who probe the historical uses of technology, English professors don't usually spring to mind. But Rebecca Roach, a postdoctoral researcher in modern literature at Kings College London, did just that when she came across a box of "incomprehensible material" last year while diving into the archives of the Nobel Prize–winning poet and novelist J.M. Coetzee at the Harry Ransom Center, at the University of Texas at Austin.

The box was full of computer printouts of seemingly random words. Then Roach remembered that Coetzee had published a lightly fictionalized autobiographical memoir titled *Youth* in 2002. In *Youth*, the protagonist, John, studies math at university to provide him work opportunities while he pursues his quest to become a world-class poet and novelist on the side.

As the real Coetzee had done, John emigrates to London from his native South Africa and takes day jobs programming, first for IBM and then the Atlas 2 supercomputer at the United Kingdom's Atomic Energy Research Establishment, in the 1960s. John appreciates the computer in a different way from his colleagues, Coetzee writes: "Although Atlas is not a machine built to handle textual materials, he uses the dead hours of the night to get it to print out thousands of lines in the style of Pablo Neruda, using as a lexicon a list of the most powerful words in *The Heights of Macchu Picchu*."

John then marvels at the unique word associations his programs generate, like "the nostalgia of teapots" and "furious horsemen." He plumbs the choicest selections for poems he writes and publishes in literary journals.

Roach realized that the printouts could be from Coetzee's real-life experiments in computer-assisted verse writing. Also in the box was what she suspected was Coetzee's original code. She photographed the printouts and brought them back to England to someone who had worked on the Atlas.

"He peered over these blurry photographs I'd taken," says Roach. The source code confirmed that the software was written for the Atlas. "They weren't written in any familiar, high-level computer language. They were written in Atlas Autocode, which was a specific language that was conceived for this particular computer," says Roach.

Lacking access to a working Atlas, Roach has not been able to run the programs herself. But she does have access to the published poems that Coetzee's programs generated. These appeared in South African publications, such as a 1963 issue of *The Lion and the Impala* and, drawing on Coetzee's 1960s digital experiments, a 1978 issue of *Staffrider*.

The *Staffrider* poem, "Hero and Bad Mother in Epic," features a fair amount of clunky repeated words like "sword drowses," "drowsy sword," "fiction drowses," "sword of fiction," and "punctual sword." But it also contains marvelous turns of phrase like "the geography of caution" and "the feminine kingdom."

Coetzee explained his aesthetic in *The Lion and the Impala.* He said his program generated every possible poetic combination of forms specified in the code, at which point the culling began: "[The author] wades through what has been printed (in this case 2,100 poems at a rate of 75 poems per minute), makes his selection, reduces it to standard form, and sends it to the editor."

Coetzee was not entirely alone in his avant-garde experiments. A small vanguard of other poets also had the access and the inclination to use computers. According to C.T. Funkhouser's *Prehistoric Digital Poetry*, other pioneering digital poets at the time include the Italian writer Nanni Balestrini, whose 1961 "Tape Mark" poems also used digital textual collage techniques.

These experiments strove to push the computer—then a distant hulking presence used almost exclusively for finance, scientific, or engineering calculations—toward the humanities, long before things like Google's Ngram viewer. The experiments have been long overlooked because "computer people aren't interested in the history; literary scholars don't understand it," says Roach.

But are computer-generated poems actually poetry? Looking at the work that Roach has resurfaced, the answer is "quite possibly"—with the right guidance. **—MARK ANDERSON**

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QUANTUM-COMPUTING STARTUPS EMERGE

DOES EVERY TECH COMPANY NEED A "QUANTUM PERSON"?

IBM is betting on quantum computing, but it can't win without the help of startups. And how long it will take for the bet to pay off is anybody's guess.

That was the message of the Q Summit, a one-day meeting of quantum-computing researchers, investors, and entrepreneurs hosted by IBM in Menlo Park, Calif., in April. Quantum computing would open the door to a new universe of problem solving, and it could disrupt some conventional digital technologies. The potential is big, but the risks are huge.

"We need startups in the quantum space," says Joe Raffa, director of IBM Ventures. "There's a huge amount of work to do," he says, to cross the "long revenue desert" between investment and commercially profitable results.

Initially, "the quantum computer will be way slower than the classic machine," says Vijay Pande, general partner at Andreessen Horowitz. But its rate of evolution is "hyperexponential, so suddenly, in some *n* years, it will jump over the classic machine. The real question is, when will this transition happen?"

Pande has some predictions. Within 10 years, for certain limited disciplines, he says, quantum computers will begin to dominate. New algorithms for new applications will emerge—algorithms that aren't currently being developed for classical computers because they would just run too slowly on conventional hardware.

But, says Pande, this all makes it very difficult to address quantum computing as a venture capitalist: "It's hard to talk about the market if I don't even know what the algorithms are."

Bill Coughran, a Sequoia Capital partner and former senior vice president of engineering at Google, says that as an investor he's "struggled with the question whether quantum computing is [in] 'development' or still 'research.' VC firms think [along] a 10-year time horizon, not 20 or 30 years. Are we on the cusp of a breakthrough?"

The question, he says, "is still open."

Startups working on these new algorithms have formed, however, with venture money behind them. Matt Johnson is the CEO of QC Ware, a startup building a commercial software package for quantum computing. Johnson says QC Ware is betting "that the people building the hardware will get it [to the point where] our software is useful."

Christopher Savoie, CEO of startup Zapata Computing, believes that chemistry will be the first field to benefit from quantum computing, and his company is developing algorithms for drug discovery and chemical design.

These two startups and six more are part of the IBM Q Network, an organization launched in late 2017 to accelerate the development of practical applications for quantum computing.

And despite Coughran's reservations, Sequoia has made an investment in a quantum startup, Quantum Circuits, just in case the answer to Coughran's question about being on the cusp of a breakthrough is yes. But he has still another concern.

"Most prominent teams today," Coughran says, "are built around people with strong academic track records, but those are not always the ideal teams with which to build real companies."

IBM's Anthony Annunziata, leader of the Q Network, admitted that to date, there are no commercial applications of quantum computing that beat conventional computing. "We are at the point of getting quantum ready," he says. "The era of the quantum advantage is still a few years out; it's hard to see how many."

It's not the right time "to go all in, to put tens of millions of dollars into this," Annunziata continues. "But it's exciting enough. Things are progressing well enough that [every tech organization] should have at least one person who is your quantum person, who can learn the basics and take it from there."

—**TEKLA S. PERRY**

A version of this article appears in our View From the Valley blog.

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ISTOCKPHOTO

THE INTERNET OF TRASH

IN 2016, MASAYOSHI SON, the CEO of SoftBank Group Corp., predicted that in the next 20 years there will be a trillion connected devices in the world and orbiting the planet. This spurred his investment in Arm Holdings, the chip-design company, which is profiting from increased demand for battery-sipping chips meant for low-compute jobs. Arm's microcontrollers are now inside rings, watches, and sensors on industrial equipment.

As we add computing and radios to more things, we're also adding to the problem of e-waste. The United Nations found that people generated 44.7 million metric tons of e-waste globally in 2016, and expects that to grow to 52.2 million metric tons by 2021.

There are two issues. We're adding semiconductors to products that previously had none, and we're also shortening the life of devices as we add more computing, turning products that might last 15 years into ones that must be replaced every five years.

In fact, many small connected devices such as trackers, jewelry, or wearables are designed to fail once the battery dies. At that point, the consumer tosses it out and buys another. The sports equipment company Wilson, for example, makes a Bluetooth-connected basketball. The challenge of putting a replaceable battery inside without messing up performance was too great, leading the engineers who built it to throw up their hands and say, when the battery fails, so does the connectivity.

Tile, which makes a Bluetooth tracking device with a battery expected to fail after a year, used to offer consumers a discount if they mailed an old tracker back, in a mailer that came with the original package. Tile would then dispose of the electronics for the customer.

I've owned many Tiles, but I've never sent one back. Instead, the trackers sit in a pile of dead devices that I periodically take to my local e-waste recycling center. Apparently, I'm not alone. This year, Tile changed its return policy and now encourages users to recycle the devices on their own.

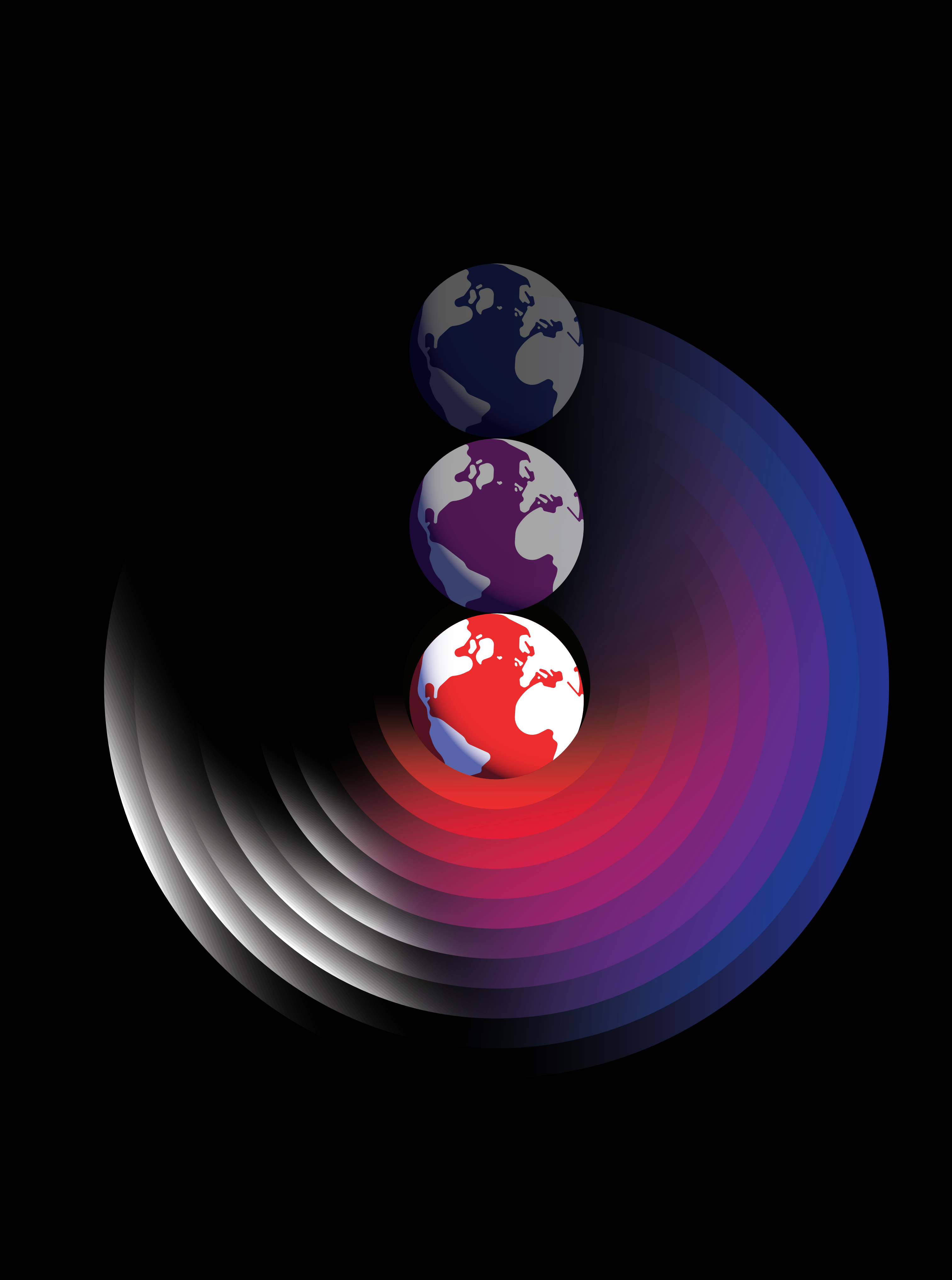
Spire makes an adhesive wearable that tracks activity levels and breathing, with a battery that dies after about 18 months. Cofounder and CEO Jonathan Palley hopes consumers will ship the device back to the company when that happens. Spire has designed each of the components inside the device's flat, 5.3-by-3.2-centimeter enclosure to be easily taken apart for recycling. Palley says it was a challenge to find glues that would allow the wearable to be machine-washed. Making something waterproof *and* easy to disassemble takes a lot of engineering.

Most companies developing IoT products aren't spending that kind of effort on the original design. However, some are creating recycling programs as the challenges associated with e-waste are better understood. For example, Dell uses 3,000 kilograms of gold in its computers and servers each year, and some of that is recycled from other Dell products.

Such programs make for good PR. But as we embed precious and toxic metals into more and more devices, the tech industry must start to design with recyclability and sustainability in mind. The process may start with the materials, but it should expand to make sure these goods have a long life. ■

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/iotwaste0618

ILLUSTRATION BY Jude Buffum



SPECIAL REPORT | PART 1: **WATTS** | PART 2: **VEHICLES** | PART 3: **FOOD**

Blueprints FOR A Miracle

DO YOU BELIEVE that climate change is a vast left-wing conspiracy that does little more than create jobs for scientists while crippling businesses with pointless regulation? Or, quite the contrary, are you convinced that climate change is the biggest crisis confronting the planet, uniquely capable of wreaking havoc on a scale not seen in recorded history?

Many of you are probably in one camp or the other. No doubt some of you will tell us how disappointed/angry/outraged you are that we (a) gave credence to this nonsense or (b) failed to convey the true urgency of the situation. We welcome your thoughts.

In crafting this issue, we steered clear of attempting to change hearts and minds. Your views on climate change aren't likely to be altered by a magazine article, or even two dozen magazine articles. Rather, this issue grew out of a few simple observations. One is that massive R&D programs are now under way all over the world to develop and deploy the technologies and infrastructures that will help reduce emissions of greenhouse gases. Governments, corporations, philanthropies, and universities are spending billions of dollars on these efforts. Is this money being spent wisely?

That question brings us to the next observation: The magnitude of the challenge is eye-poppingly huge. In 2009, representatives of industrialized nations met in Copenhagen and agreed on the advisability of preventing global average temperatures from rising more than 2 °C above their preindustrial levels. In 2014, the Intergovernmental Panel on Climate Change declared that doing so would require cutting greenhouse gas emissions 40 to 70 percent from 2010 levels by midcentury. These targets then guided the Paris Agreement, in 2015.

Even before Paris, Bill Gates had declared his belief that only a series of "energy miracles" could make meaningful progress in reducing greenhouse gases.

That got us thinking: What might those "miracles" be? If they were going to enable substantial cuts within a couple of decades, they would have to be in laboratories *now*.

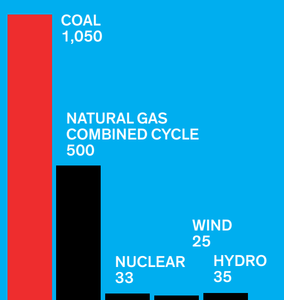
So we started looking around for these miracles. We focused on three of the largest greenhouse-gas-emitting categories: electricity, transportation, and food and agriculture. We considered dozens of promising projects and programs. Eventually we settled on the 10 projects described in this issue (and two others covered on our website).

We picked most of these projects because they seemed to hold unusual promise relative to the attention they were getting. And we threw in a couple for, well, the opposite reason. Our reporters went to see these activities firsthand, fanning out to sites in Japan; Iceland; Hungary; Germany; the Netherlands; Columbus, N.M.; Schenectady, N.Y.; LaPorte, Texas; Cambridge, Mass.; and Bellevue, Wash. They trooped up and down vertical farms. They flew in electric airplanes. They viewed entirely new microorganisms—genetically engineered with the help of robots—growing in shiny steel fermentation chambers. An algae-growing tank burbled quietly in our mid-Manhattan offices, sprouting the makings for a green-breakfast taste test.

After six months, we had soaked up some of the best thinking on the use of tech to cut carbon emissions. But what did it all suggest collectively? Could these projects, and others like them, make a real difference? We put these questions to our columnist Vaclav Smil, a renowned energy economist, who responded with an essay [p. 72]. Without stealing Smil's thunder, let's just say that they don't call them "miracles" for nothing. ■

ILLUSTRATION BY Francesco Muzzi/StoryTK

Watts



TOP EMITTER IN ELECTRICITY: COAL
Kilograms CO_2 equivalent/MWh

FEW ACHIEVEMENTS can rival the electrification of modern society. The world now consumes some 25,000 trillion watt-hours of electricity a year, four times as much as in 1973. It's hard to imagine life without the countless conveniences and essential services that all those watts provide. • Now, though, the environmental bill is coming due. Despite the recent dramatic rise in wind and solar power, we still get two-thirds of our electricity by burning fossil fuels, because they're cheap and abundant. Of course, they're also terribly dirty. In 2015 alone, power plants fueled by oil, natural gas, and especially coal burdened the atmosphere with more than 13 billion metric tons of CO_2 and other greenhouse gases. Experts agree that the chief way to avoid the worst of a rapidly changing climate is to deeply decarbonize the way we generate electricity. • Quietly, doggedly, engineers and scientists are now refining technologies to do just that. Among the projects are natural-gas-fired generators that capture carbon virtually for free, fuel cells coupled with coal plants that could cut CO_2 emissions by 90 percent, and new fission reactors that could rejuvenate the nuclear power sector. Ultimately, our pursuit of near-zero carbon emission will lead to power grids dominated by renewable sources and plentiful energy storage. Until that day arrives, technologies like the ones described here will help.

MOST IMPACT BY 2025: SOLAR PV + STORAGE
Today's top pick for low-carbon power

MOST IMPACT BY 2038: NEW FLAVORS OF FISSION
Retooled reactors to revive the nuclear sector

MOST OVER-HYPED TECH: SUPERCONDUCTING WIND TURBINES
Even offshore, they'll cost too much

SLEEPER TECH TO WATCH: SUPERCRITICAL CO_2 POWER
Fossil fuels with low-cost carbon capture

SOURCE: U.S. DEPARTMENT OF ENERGY/NATIONAL ENERGY TECHNOLOGY LABORATORY, 2013; PHOTO: DON FARRALL/GETTY IMAGES

ILLUSTRATIONS BY Francesco Muzzi/StoryTK

The Carbon-Eating Fuel Cell

At an Alabama power plant, FuelCell Energy and ExxonMobil aim to capture 90 percent of the CO_2 emissions BY **MATTHEW N. EISLER**

PHOTOGRAPH BY Bob O'Connor

AT THE 2.7-GIGAWATT James M. Barry Electric Generating Plant, in Bucks, Ala., an experiment is under way that could one day usher in a new era of nearly emissions-free fossil-fuel-powered electricity. This year, technicians and engineers will begin installing a pair of boxy white containers in the shadow of the main power plant. The containers house a novel type of fuel cell, designed not only to generate power but also to capture and concentrate up to 90 percent of the carbon dioxide coming from the main plant, which burns coal as well as natural gas. If implemented at scale, that level of carbon capture would give the Barry plant an emissions profile more like a geothermal plant's and without the intermittency of wind and solar power.

The technology comes from the Danbury, Conn., firm FuelCell Energy, which is partnering with oil-and-gas heavyweight ExxonMobil, as well as Southern Co., whose subsidiary owns and operates the Barry plant. The project is intended to demonstrate how newer, more efficient approaches to carbon capture could allow countries that rely heavily on fossil fuels for electricity—most of the world, in other words—to meet their targets for cut-

TALL ORDER: **Workers at FuelCell Energy's Torrington, Conn., factory assemble a stack for one of the company's molten carbonate fuel cells. With ExxonMobil, the company is reengineering its technology to capture carbon at a power plant in Alabama.**

ting greenhouse gas emissions. It's also a showcase for fuel cells, which have struggled to reach commercial readiness despite 180 years of R&D and countless false starts.

IN 1839, the British lawyer and amateur scientist William Robert Grove demonstrated that platinum foil could catalyze a reaction between hydrogen and oxygen that yielded electricity and a little water. Ever since, researchers, industrialists, and environmentalists have been captivated by the hydrogen fuel cell's potential as a clean, efficient source of power.

The technology, though, has proved extraordinarily difficult to perfect. Costly materials, durability problems, and the difficulty of securing a steady supply of hydrogen have derailed many a fuel cell project. Meanwhile, commercial applications have been slow to materialize. The U.S. auto industry's attempt in the early 2000s to position the fuel cell as the ultimate power source for electric vehicles fizzled when it became clear that the technology was far from ready. Nevertheless, many automakers continue to research fuel cells, giving hope to the promoters of a hydrogen economy; see, for example, "The Automotive Future Belongs to Fuel Cells," *IEEE Spectrum*, February 2017.

And in southern Alabama, fuel cell technology is squarely in the spotlight. Unlike the devices being developed for cars, which use pure hydrogen as a fuel, FuelCell Energy's molten carbonate fuel cells use the hydrogen bound up in natural gas or biogas. They're also much bigger, they're stationary, and they operate at a higher temperature, around 650 °C. The high temperature makes them less susceptible to poisons like carbon monoxide (created by processing carbonaceous fuels), which can damage the innards of lower-temperature fuel cells.

In a molten carbonate fuel cell, carbon is an integral part of the equation. At the cathode–also known as the air electrode–carbon dioxide and oxygen are fed to the cell, and they react to form charge-carrying carbonate ions suspended in a molten salt electrolyte. The ions migrate through the electrolyte to the anode–or fuel electrode–where they react with hydrogen (which is formed from a hydrocarbon fuel like natural gas or biogas) to produce water, CO_2, and electrons. The electrons then go into an external circuit to do useful work before returning to the cathode, while the carbon dioxide produced in the reaction gets recycled back to the cathode.

OLD TECH, NEW APP: Though carbonate fuel cells have been around since the 1950s, the idea of using them to cut CO_2 emissions is much more recent. "We were a bunch of guys drawing stuff on napkins," says Tony Leo [above], a FuelCell Energy vice president.

This power-source technology has another use. "As a molten carbonate fuel cell makes electricity, it pumps carbon dioxide electrochemically through the system," explains Tony Leo, FuelCell Energy's vice president of advanced applications and technology development. "It was something that we did not think too much about until we started to see that people were interested in capturing carbon dioxide." Against the backdrop of climate change, the company's engineers realized that the fuel cell's pumping action could be used to concentrate and collect carbon dioxide at the anode. To replenish the carbon dioxide needed to keep the fuel cell running, they could use pollution–industrial exhaust, that is.

At the Barry plant, the fuel cells will use the flue gas coming from the thermoelectric plant as their carbon source. The exhaust from a steel or cement plant could also work; worldwide, these sources each contribute about 5 percent of CO_2 emissions. The concentrated CO_2 can be stored deep underground or used as an industrial feedstock. Unlike the conventional amine-based method of carbon capture, which consumes electricity, the fuel cells will generate their own electricity to drive the process.

This latest incarnation of the molten carbonate fuel cell was years in the making, Leo says. Researchers who first investigated the technology in the 1950s were impressed by its apparent flexibility. The system's high operating temperature means that the catalyst can be made from cheap nickel rather than pricey platinum, and practically any hydrocarbon can be used as a fuel source, at least in principle. What's more, the heat it generates can also be captured and put to use. In the 1960s, the U.S. Army envisioned using molten carbonate fuel cells anywhere its troops were deployed, allowing soldiers to process whatever fuel was available. Natural-gas utilities wanted to integrate the technology into their pipeline grids, forming decentralized power systems that would compete with the electric utilities. But such efforts were stymied by the corrosive nature of molten carbonate, which led most sponsors to shelve the technology at a relatively early stage.

The energy crisis and environmental movement of the 1970s brought renewed interest in all kinds of clean power, including the carbonate fuel cell. It was in this ferment that FuelCell Energy, then known as Energy Research Corp., was founded. "What we thought made the most sense was a power generation system that could run on pipeline-volume natural gas, and high-temperature fuel cells like carbonate did that," Leo says.

One of the salient facts about advanced power sources is that new products typically take decades to enter the marketplace. As more than one observer has noted, there is no Moore's Law for batteries. Sustained government support is thus crucial. With help from the U.S. Department of Energy, FuelCell Energy was able to focus on the thankless task of improving the efficiency, cost, and durability of its molten carbonate fuel cells. After years of research and development, the company demonstrated a 2-megawatt plant in Santa Clara, Calif., which operated from 1996 to 1997. In 2003, FuelCell Energy shipped its first commercial unit. To date, it has installed

PHOTOGRAPH BY Bob O'Connor

several hundred megawatts of capacity in 50 locations around the world, most notably a 59-MW combined heat-and-power plant in South Korea. Today, the company is the leading provider of molten carbonate technology.

HAVING NURTURED FuelCell Energy in its fledgling years, the U.S. government also played a key role in getting the company into carbon capture. The Department of Energy had long supported research into so-called clean coal, and by the late 1990s it was pushing carbon capture and combined cycles as means to this end. In the early 2000s, with energy policy increasingly emphasizing sustainability, says Leo, FuelCell Energy started thinking about using its fuel cells as a carbon filter.

"We were a bunch of guys drawing stuff on napkins and just realized that, conceptually, it made sense," he recalls.

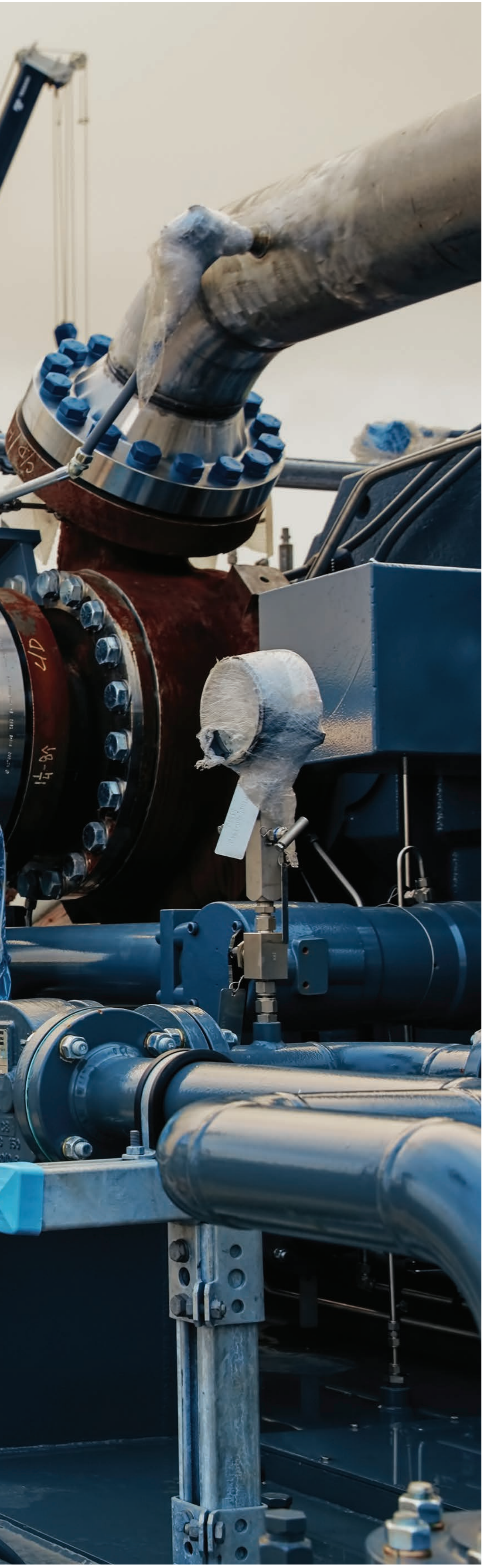
Assisted by the Environmental Protection Agency, FuelCell Energy studied how its fuel cells might operate on a simulated coal exhaust stream. Molten carbonate fuel cells don't tolerate some of the contaminants found in coal, such as sulfur, so the engineers figured out a way to extract those poisons from the exhaust stream. Along the way, they made a serendipitous discovery: The reaction process destroys 70 percent of the exhaust stream's nitrogen oxides, thus reducing conventional air pollutants.

But most battles on the fuel cell front are not so easily won. In September 2015, FuelCell Energy announced a US $23.7 million cost-shared project with the Department of Energy to demonstrate that its technology could capture 90 percent of the CO_2 from a small stream of coal exhaust and concentrate it to 95 percent purity. In the first phase of the project, a modified version of its commercially available 2.8-MW SureSource 3000 fuel cell system will capture 54 metric tons of carbon dioxide per day at the Barry plant. | CONTINUED ON PAGE 76

THE LONG VIEW: Founded in 1969, FuelCell Energy is now the world's leading provider of molten carbonate fuel cells. Its 14.9-megawatt installation in Bridgeport, Conn., supplies electricity to 3,700 homes.

PHOTOGRAPH BY Bob O'Connor

CO_2 CYCLER: Rodney Allam [above] invented a natural-gas-burning power plant that captures its own carbon dioxide at practically no cost.



BLUEPRINTS *for a* MIRACLE

This Power Plant Runs on CO_2

BY DAVID WAGMAN

Carbon capture costs next to nothing in NET Power's new plant, which uses supercritical carbon dioxide to drive a turbine

A FIRE BREAKS OUT in your office's server suite. You grab an extinguisher, aim its nozzle at the blaze, and hit it with a cloud of carbon dioxide. Out goes the fire. • Flames die when doused in CO_2. And yet under just the right conditions, CO_2 can also sustain combustion. That counterintuitive fact is at the heart of a new power plant being built in the Houston industrial suburb of LaPorte. The natural-gas-fired plant's novel design, from Durham, N.C.–based NET Power, uses a fuel mix that is 95 percent carbon dioxide at the point of combustion. What's more, it captures and sequesters carbon dioxide at virtually no additional cost. According to NET Power's calculations, once the company scales up and rolls out the technology commercially, its plants should cost no more to construct and operate than a traditional natural-gas plant, which simply vents its exhaust into the atmosphere. • The key to making CO_2 part of the solution instead of the problem is a strange state of matter known as a

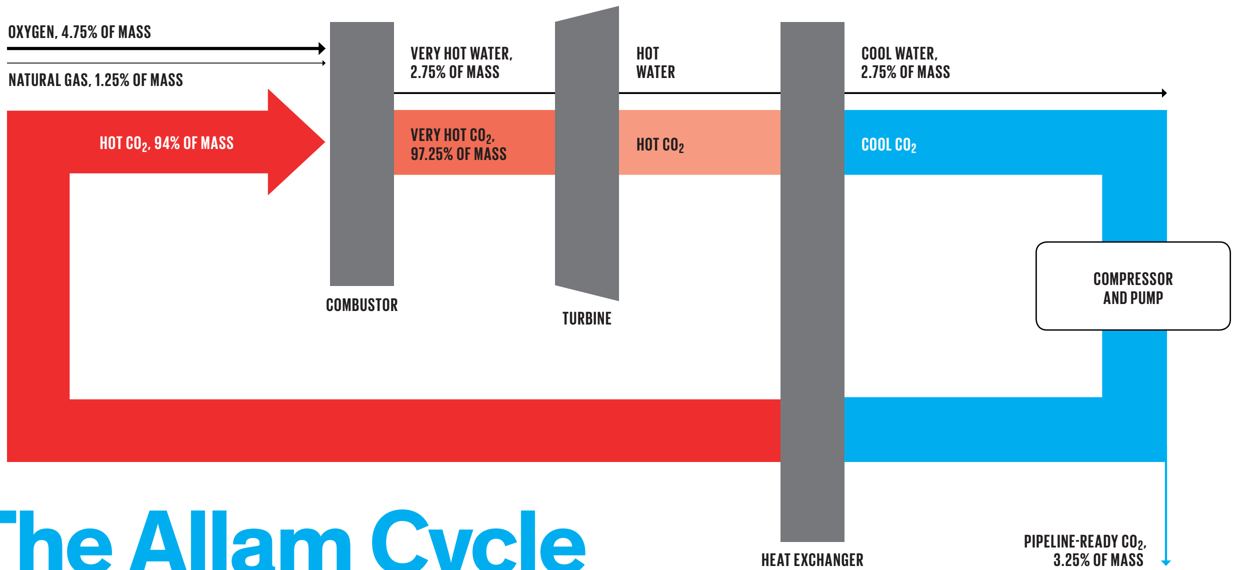
1 An air-separation unit strips oxygen from the air and sends it to the combustor.

2 Natural gas combines with oxygen and hot, supercritical carbon dioxide to burn in a combustor.

3 The resulting very hot CO_2 and water drive a turbine to generate electricity.

4 A heat exchanger extracts energy from the turbine's hot exhaust and delivers it to the stream of supercritical CO_2 further down the cycle. The cooled water drains away.

5 The cooled CO_2 is pumped and compressed up to high pressure.



The Allam Cycle

By using supercritical carbon dioxide as most of the mass, the Allam cycle can burn natural gas to generate electricity while delivering carbon dioxide at the proper temperature and pressure for sequestration.

7 Energy from earlier in the cycle heats the high-pressure supercritical CO_2 for a return trip to the combustor.

6 A fraction of the CO_2 is siphoned away to be sequestered or used to pump oil out of wells.

supercritical fluid. Above a certain temperature and pressure—31.1 °C, or a summer day in Phoenix, and 7.39 megapascals, or about 80 percent what you find on the surface of Venus—carbon dioxide turns supercritical. In that state, it can expand like a gas and yet still move with the density of a liquid; it can even dissolve things the way a liquid can. (In fact, it's used to decaffeinate coffee.)

Supercritical CO_2 can be pumped, compressed, and driven to spin a turbine with an efficiency that steam may never reach. Consequently, supercritical CO_2 has been proposed and developed for decades as a credible replacement for steam in all sorts of power generation, including nuclear power and concentrated solar towers.

But in LaPorte, Texas, they're doing something that could have way bigger consequences for climate change than adding a few—though much needed—percentage points to a solar tower's efficiency stats. After almost a decade of development, NET Power is putting the finishing touches on its US $140 million, 50-megawatt power plant there. The grid-connected plant is being tested this year, and its backers hope to scale up to commercial deployment by 2021.

"Their technology is actually excellent technology," says Nathan Weiland, a research engineer with the U.S. Department of Energy's National Energy Technology Laboratory, near Pittsburgh, who specializes in supercritical CO_2 power generation. "By all accounts it should work well." If Weiland's right, then burning fossil fuels without emitting carbon could become about as economical as burning fossil fuels in a conventional power plant *without* any carbon-control gear.

SUPERCRITICAL CARBON DIOXIDE'S latest use is largely attributable to British inventor Rodney Allam. After a 45-year career with industrial gas manufacturer Air Products and Chemicals, where he served as director of technology development at the European division, he retired for a single weekend in 2005 and began work as a consulting engineer.

In 2009, he met the principals of 8 Rivers Capital, NET Power's parent company, and signed on to work with its engineers on a seemingly impossible task. They were to create a technology that could burn fossil fuel without any carbon emissions and generate at an efficiency and capital cost on a

PREVIOUS PAGES: MICHAEL THAD CARTER/THE FORBES COLLECTION/CONTOUR BY GETTY IMAGES par with conventional power plants. In other words, Team Allam aimed to do carbon capture for free.

Following a false start with coal, NET Power's target became natural-gas-fueled "combined cycle" technology. A combined-cycle plant marries a gas turbine to a steam turbine. The first part burns natural gas, and the exhaust directly spins a turbine to generate electricity. The exhaust, still scorching hot, then enters a heat recovery system to generate steam, which spins a second turbine to produce more electricity.

Ordinarily, this combination delivers an efficiency of up to 52 percent (based on the total energy content of natural gas) and emits around 0.4 kilograms of CO_2 per kilowatt-hour. Compare that with a new coal-fired power plant, which emits roughly 8 kg of CO_2 per kilowatt-hour. If you simply tack on an existing carbon-capture system to a combined-cycle plant, the power needed to run the added equipment reduces the overall output by about 13 percent. Much of the energy penalty is because the plant's flue gas is mostly nitrogen from the air used for combustion, and it's an energy-intensive process to separate the relatively small amount of CO_2 from the huge mass of nitrogen.

The NET Power engineers decided they'd need a new type of power cycle, one that basically drops steam from the equation and doesn't use air. To end up with flue gas that's almost exclusively CO_2 and water, their cycle would have to inhale 95 percent pure oxygen. This concept, called oxyfuel combustion, is at the heart of several carbon-capture schemes. Most of these schemes have drawbacks, though.

First, to deliver the nearly pure oxygen requires attaching an air-separation system to the plant, which of course takes energy to run. Second, the gas might not have enough mass to turn the turbine efficiently. Air is about 75 percent nitrogen by mass, so nitrogen is the main thing driving a typical gas turbine. Without the nitrogen's mass, the exhaust simply doesn't have enough momentum. If you try replacing that mass with a lot more oxygen and fuel, the combustion would be so hot that you'd need to make your turbines out of exotic—and expensive—high-temperature alloys, or risk transforming them into melted heaps of slag.

Allam's counterintuitive approach stemmed from an idea he'd had long before he started working at NET Power: Burn the fuel and oxygen in supercritical CO_2 and the resulting exhaust has the necessary mass to spin the turbine. The heat of combustion expands the supercritical CO_2 exhaust through a turbine, from which it exits at around 3 MPa. The hot exhaust enters a heat exchanger, which transfers the gas's thermal energy to a supercritical CO_2 stream that's headed back to the combustor.

The turbine exhaust, meanwhile, exits the heat exchanger, having been cooled to air temperature. It falls out of its supercritical state and the water vapor produced in combustion condenses and drains away. The now highly pure CO_2 stream is then compressed, cooled, and pumped up to a supercritical 30 MPa for a return trip to the combustor.

The pumping step represents one key to the cycle's performance. Allam and his team realized that if they used compression alone to pressurize the CO_2 from 3 MPa all the way to about 30 MPa, the energy required would sap the cycle's overall efficiency. That's because compressing CO_2, which boosts pressure by decreasing gas volume, takes more energy than pumping it, which increases pressure by adding mass. So in the Allam cycle, the CO_2 is compressed to a superfluid at around 8 MPa, cooled, and then efficiently pumped to 30 MPa.

After compression and pumping, most of the CO_2 makes a pass through the other end of the heat exchanger to get warmed up before flowing to the combustor. But something less than 5 percent of the CO_2 is siphoned off to a high-pressure pipeline for sequestration underground or other uses.

So to sum up: The Allam cycle uses its own exhaust to drive a turbine and its own compressors and pumps to sequester carbon. In other words, carbon capture is integral to the process.

"I am absolutely confident what we have will work," says Allam. "It's pretty well standard equipment, and there is nothing innovative in the turbine."

IN LAPORTE, NET Power's low-profile plant sits next to an air-separation facility owned by the French firm Air Liquide. You reach it by a gravel road that splits a screen of trees and overgrowth. On a foggy January morning, the plant's most imposing feature is its bank of cooling towers, conventional fare for an industrial plant. A pair of construction cranes idle nearby.

Overshadowed in the maze of piping and structural steel is the turbine itself, which is exceptional mostly for its small size. The combination of high pressure and high temperature means the footprint of the turbine is not much larger than that of a family minivan. (A conventional turbine with about the same output is the size of a city bus, by comparison.) Project backers are counting on the smaller footprint to help improve the venture's overall economics.

NET Power's business plan calls for selling some of the industrial gases that are produced. In particular, nitrogen pulled from the air-separation unit could be sold to fertilizer plants, and other trace gases could go to chemical production and welding.

The plan | CONTINUED ON PAGE 77

BLUEPRINTS *for a* MIRACLE

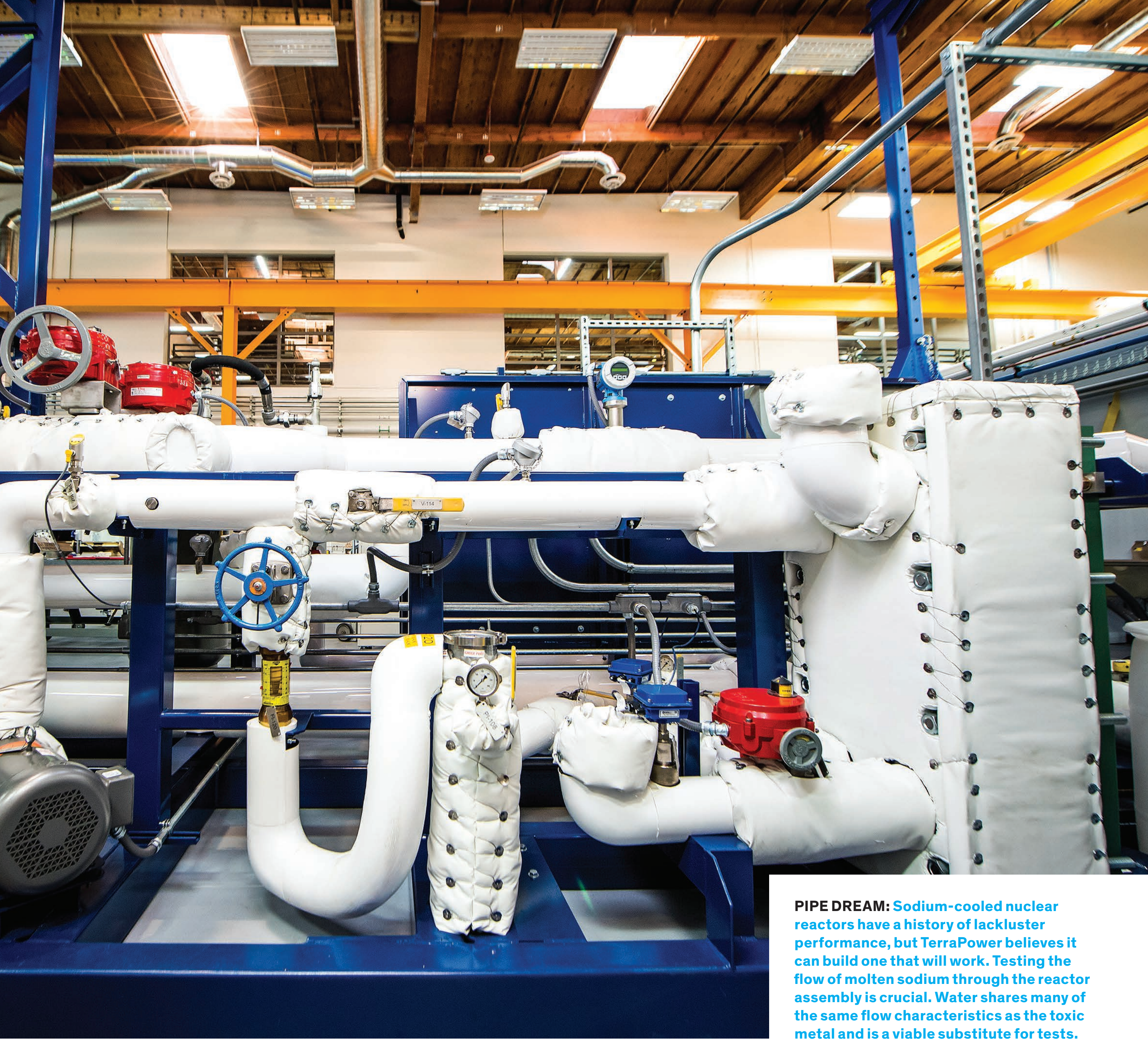
What Will the Electricity Miracle Be?

TerraPower's traveling-wave reactor is the kind of energy source we need for the 21st century BY MICHAEL KOZIOL

TERRAPOWER

TABLE TENNIS ISN'T meant to be played at Mach 2. At twice the speed of sound, the ping-pong ball punches a hole straight through the paddle. The engineers at TerraPower, a startup that has designed an advanced nuclear power reactor, use a pressurized-air cannon to demonstrate that very point to visitors. The stunt vividly illustrates a key concept in nuclear fission: Small objects traveling at high speed can have a big impact when they hit something seemingly immovable. • And perhaps there is a larger point being made here, too—one about a small and fast-moving startup having a big impact on the electric-power industry, which for many years also seemed immovable. • In a world defined by climate change, many experts hope that the electricity grid of the future will be powered entirely by solar, wind, and hydropower. Yet few expect that clean energy grid to manifest soon enough to bring about significant cuts in greenhouse gases within the next few decades. Solar- and wind-generated electricity are growing faster than any other category; nevertheless, together they accounted for less than 2 percent of the world's primary energy consumption in 2015, according to the Renewable Energy Policy Network for the 21st Century.

To build a bridge to that clean green grid of the future, many experts say

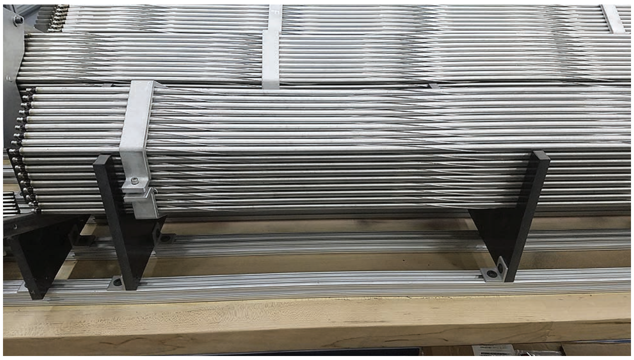


PIPE DREAM: Sodium-cooled nuclear reactors have a history of lackluster performance, but TerraPower believes it can build one that will work. Testing the flow of molten sodium through the reactor assembly is crucial. Water shares many of the same flow characteristics as the toxic metal and is a viable substitute for tests.

we must depend on fission power. Among carbon-free power sources, only nuclear fission reactors have a track record of providing high levels of power, consistently and reliably, independent of weather and regardless of location.

Yet commercial nuclear reactors have barely changed since the first plants were commissioned halfway through the 20th century. Now, a significant fraction of the world's 447 operable power reactors are showing their age and shortcomings, and after the Fukushima Daiichi disaster in Japan seven years ago, nuclear energy is in a precarious position. Between 2005 and 2015, the world share of nuclear in energy consumption fell from 5.73 to 4.44 percent. The abandonment of two giant reactor projects in South Carolina in the United States and the spiraling costs of completing the Hinkley Point C reactor in the United Kingdom, now projected to cost an eye-watering £20.3 billion (US $27.4 billion), have added to the malaise.

Elsewhere, there is some nuclear enthusiasm: China's 38 reactors have a total of 33 gigawatts of nuclear capacity, and the country has plans to add an additional 58 GW by 2024. At the moment, some 50 power reactors are under construction worldwide. These reactors, plus an additional 110 that



are planned, would contribute some 160 GW to the world's grids, and avoid the emission of some 500 million metric tons of carbon dioxide every year. To get that kind of cut in greenhouse gases in the transportation sector, you'd have to junk more than 100 million cars, or roughly all the passenger cars in France, Germany, and the United Kingdom.

Against this backdrop, several U.S. startups are pushing new reactor designs they say will address nuclear's major shortcomings. In Cambridge, Mass., a startup called Transatomic Power is developing a reactor that runs on a liquid uranium fluoride–lithium fluoride mixture. In Denver, Gen4 Energy is designing a smaller, modular reactor that could be deployed quickly in remote sites.

In this cluster of nuclear startups, TerraPower, based in Bellevue, Wash., stands out because it has deep pockets and a connection to nuclear-hungry China. Development of the reactor is being funded in part by Bill Gates, who serves as the company's chairman. And to prove that its design is viable, TerraPower is poised to break ground on a test reactor next year in cooperation with the China National Nuclear Corp.

To reduce its coal dependence, China is racing to add over 250 GW of capacity by 2020 from renewables and nuclear. TerraPower's president, Chris Levesque, sees an opening there for a nuclear reactor that is safer and more fuel efficient. He says the reactor's fuel can't easily be used for weapons, and the company claims that its reactor will generate very little waste. What's more, TerraPower says that even if the reactor were left unattended, it wouldn't suffer a calamitous mishap. For Levesque, it's the perfect reactor to address the world's woes. "We can't seriously mitigate carbon and bring 1 billion people out of energy poverty without nuclear," he says.

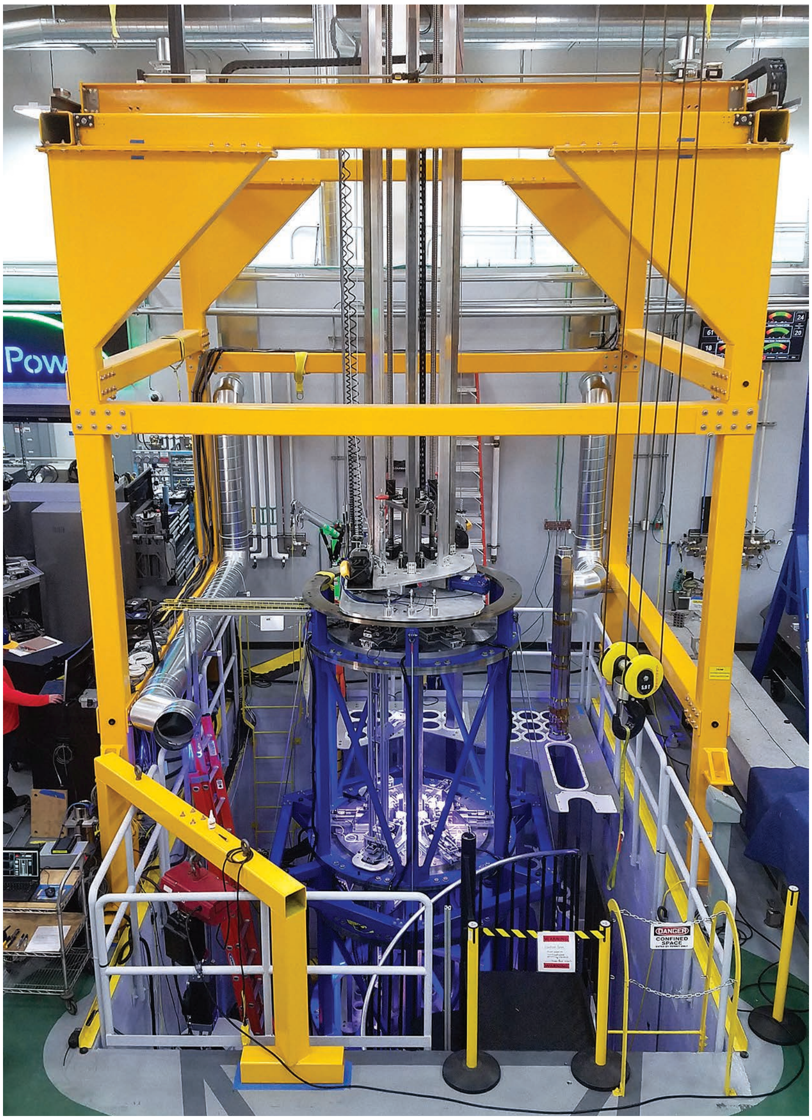
THE TERRAPOWER REACTOR is a new variation on a design that was conceived some 60 years ago by a now-forgotten Russian physicist, Saveli Feinberg. Following World War II, as the United States and the Soviet Union stockpiled nuclear weapons, some thinkers were wondering if atomic energy could be something other than a weapon of war. In 1958, during the Second International Conference on Peaceful Uses of Atomic Energy, held in Geneva, Feinberg suggested that it would be possible to construct a reactor that produced its own fuel.

Feinberg imagined what we now call a breed-and-burn reactor. Early proposals featured a slowly advancing wave of nuclear fission through a fuel source, like a cigar that takes decades to burn, creating and consuming its fuel as the reaction travels through the core. But Feinberg's design couldn't compete during the bustling heyday of atomic energy. Uranium was plentiful, other reactors were cheaper and easier to build, and the difficult task of radioactive-waste disposal was still decades away.

The breed-and-burn concept languished until Edward Teller, the driving force behind the hydrogen bomb, and astrophysicist Lowell Wood revived it in the 1990s. In 2006, Wood became an adviser to Intellectual Ventures, the intellectual property and investment firm that is TerraPower's parent company. At the time, Intellectual Ventures was exploring everything–fission, fusion, renewables–as potential solutions to cutting carbon. So Wood suggested the traveling-wave reactor (TWR), a subtype of the breed-and-burn reactor design. "I expected to find something wrong with it in a few months and then focus on renewables," says John Gilleland, the chief technical officer of TerraPower. "But I couldn't find anything wrong with it."

That's not to say the reactor that Wood and Teller designed was perfect. "The one they came up with in the '90s was very elegant, but not practical," says Gilleland. But it gave TerraPower engineers somewhere to start, and the

LEFT: MICHAEL KOZIOL; RIGHT: TERRAPOWER



FUEL FOR THOUGHT: **Mock fuel pins (not made of radioactive uranium!) sit ready for validation tests [far left]. An engineer readies a bundle of full-size mock fuel pins to test how they'll perform during their operational lifetime [center]. The full-scale reactor-core test assembly is more than three stories tall [this page].**

MICHAEL KOZIOL

hope that if they could get the reactor design to work, it might address all of fission's current shortcomings.

Others have been less optimistic. "There are multiple levels of problems with the traveling-wave reactor," says Arjun Makhijani, the president of the Institute for Energy and Environmental Research. "Maybe a magical new technology could come along for it, but hopefully we don't have to rely on magic." Makhijani says it's hard enough to sustain a steady nuclear reaction without the additional difficulty of creating fuel inside the core, and notes that the techniques TerraPower will use to cool the core have largely failed in the past.

The TerraPower team, led by Wood and Gilleland, first tackled these challenges using computer models. In 2009, they began building the Advanced Reactor Modeling Interface (ARMI), a digital toolbox for simulating deeply customizable reactors. With ARMI, the team could specify the size, shape, and material of every reactor component, and then run extensive tests. In the end, they came away with what they believe is a practical model of a breed-and-burn TWR first proposed by Feinberg six decades ago. As Levesque recalls, he joined TerraPower when the team approached him with remarkable news: "Hey, we think we can do the TWR now."

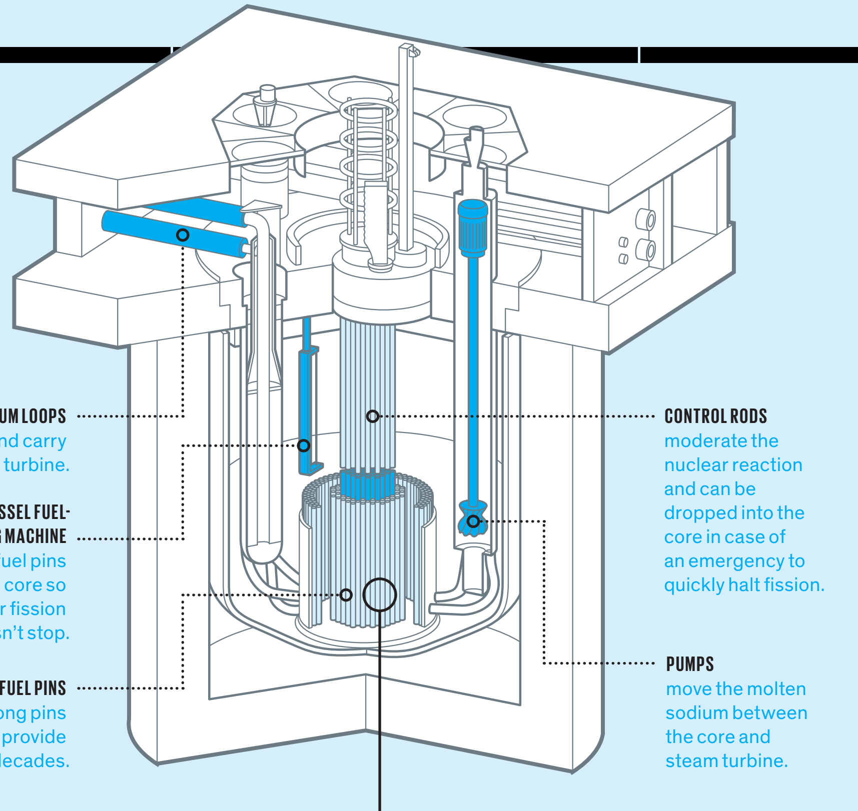
To understand why the TWR stymied physicists for decades, first consider that today's reactors rely on enriched uranium, which has a much higher ratio of the fissile isotope of uranium (U-235) to its more stable counterpart (U-238) than does a natural sample of uranium.

When a passing neutron strikes a U-235 atom, it's enough to split the atom into barium and krypton isotopes with three neutrons left over (like that high-speed ping-pong ball punching through a sturdy paddle). Criticality occurs when enough neutrons hit enough other fissile uranium atoms to create a self-sustaining nuclear reaction. In today's reactors, the only way to achieve criticality is to have a healthy abundance of U-235 atoms in the fuel.

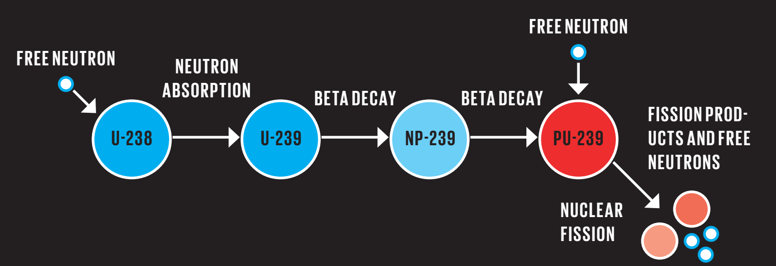
In contrast, the TWR will be able to use depleted uranium, which has far less U-235 and cannot reach criticality unassisted. TerraPower's solution is to arrange 169 solid uranium fuel pins into a hexagon. When the reaction begins, the U-238 atoms absorb spare neutrons to become U-239, which decays in a matter of minutes

Surfing the Sodium Wave

TerraPower's reactor is the latest in a long line of attempts at sodium-cooled reactors. The company is confident that extensive computer simulations and physical tests, combined with a new approach to the old idea of the traveling-wave reactor, has resulted in a design that will finally succeed. Here's how it works.



PACKING A PUNCH: The reactor's fuel, uranium-238, is quite stable. Bombarding it with neutrons eventually creates plutonium-239, a very unstable isotope that almost always breaks into a cascade of smaller atomic nuclei and free neutrons when struck again.



to neptunium-239, and then decays again to plutonium-239. When struck by a neutron, Pu-239 releases two or three more neutrons, enough to sustain a chain reaction.

It also releases plenty of energy; after all, Pu-239 is the primary isotope used in modern nuclear weapons. But Levesque says the creation of Pu-239 doesn't make the reactor a nuclear-proliferation danger—just the opposite. Pu-239 won't accumulate in the TWR; instead, stray neutrons will split the Pu-239 into a cascade of fission products almost immediately.

In other words, the reactor breeds the highly fissile plutonium fuel it needs right before it burns it, just as Feinberg imagined so many decades ago. Yet the "traveling wave" label refers to something slightly different from the slowly burning, cigar-style reactor. In the TWR, an overhead crane system will maintain a reaction within a ringed portion of the core by moving pins into and out of that zone from elsewhere in the core, like a very large, precise arcade claw machine.

To generate electricity, the TWR uses a more complicated system than today's reactors, which use the core's immense heat to boil water and drive a steam turbine to generate usable electricity. In the TWR, the heat will be absorbed by a looping stream of liquid sodium, which leaves the reactor core and then boils water to drive the steam turbine.

But therein lies a major problem, says Makhijani. Molten sodium can move more heat out of the core than water, and it's actually less corrosive to metal pipes than hot water is. But it's a highly toxic metal, and it's violently flammable when it encounters oxygen. "The problem around the sodium cooling, it's proved the Achilles' heel," he says.

Makhijani points to two sodium-cooled reactors as classic examples of the scheme's inherent difficulties. In France, Superphénix struggled to exceed 7 percent capacity during most of its 10 years of operation because

ILLUSTRATION BY James Provost

sodium regularly leaked into the fuel storage tanks. More alarmingly, Monju in Japan shut down less than a year after it achieved criticality when vibrations in the liquid sodium loop ruptured a pipe, causing an intense fire to erupt as soon as the sodium made contact with the oxygen in the air. “Some have worked okay,” says Makhijani. “Some have worked badly, and others have been economic disasters.”

Today, TerraPower’s lab is filled with bits of fuel pins and reactor components. Among other things, the team has been testing how molten sodium will flow through the reactor’s pipes, how it will corrode those pipes, even the inevitable expansion of all of the core’s components as they are subjected to decades of heat—all problems that have plagued sodium-cooled reactors in the past. TerraPower’s engineers will use what they learn from the results when building their test reactor—and they’ll find out if their design really works.

THE SAFETY OF the TerraPower reactor stems in part from inherent design factors. Of course, all power reactors are designed with safety systems. Each one has a coping time, which indicates how long a stricken reactor can go on without human intervention before catastrophe occurs. Ideas for so-called inherently safe reactors have been touted since the 1980s, but the goal for TerraPower is a reactor that relies on fundamental physics to provide unlimited coping time.

The TWR’s design features some of the same safety systems standard to nuclear reactors. In the case of an accident in any reactor, control rods crafted from neutron-absorbing materials like cadmium plummet into the core and halt a runaway chain reaction that could otherwise lead to a core meltdown. Such a shutdown is called a scram.

Scramming a reactor cuts its fission rate to almost zero in a very short time, though residual heat can still cause a disaster. At Chernobyl, some of the fuel rods fractured during the scram, allowing the reactor to continue to a meltdown. At Fukushima Daiichi, a broken coolant system failed to transfer heat away from the core quickly enough. That’s why the TerraPower team wanted to find a reactor that could naturally wind down, even if its safety systems failed.

TerraPower’s reactor stays cool because its pure uranium fuel pins move heat out of the core much more effectively than the fuel rods in today’s typical reactors. If even that isn’t enough to prevent a meltdown, the company has an ace up its sleeve. As Gilleland explains, the fuel pins will expand when they get too hot—just enough so that neutrons can slip past the fuel pins without hitting more Pu-239, thereby slowing the reaction and cooling the core automatically.

Because the TWR burns its fuel more efficiently, the TerraPower team also claims it will produce less waste. The company says a 1,200-MW reactor will generate only 5 metric megatons of waste per gigawatt-year, whereas a typical reactor today produces 21 metric megatons per gigawatt-year. If that number is right, the reactor could address the ongoing storage problem by drastically reducing the amount of generated waste, which remains highly radioactive for thousands of years.

SMIL SAYS...

Anything dependent on circulating hot liquid sodium for decades is neither easy to build nor to operate.

More than 60 years into the nuclear age, only Finland and Sweden have made serious progress in building deep, permanent repositories, and even those won’t be ready until the 2020s.

TerraPower plans to break ground on its test reactor next year in China. If all goes well, this reactor will be operational by the mid-2020s. But even if TerraPower’s reactor succeeds wildly, it will take 20 years or more for the company to deploy large numbers of TWRs. Thus for the next couple of decades, the world’s utilities will have no choice but to rely on fossil fuels and conventional nuclear reactors for reliable, round-the-clock electricity.

Fission will probably not be the final answer. After decades of always being 30 years away, nuclear fusion may finally come into its own. Societies will be able to depend on renewables more heavily as storage and other technologies make them more reliable. But for the coming decades, some analysts insist, nuclear fission’s reliability and zero emissions are the best choice to shoulder the burden of the world’s rapidly electrifying economies.

“I don’t think we should think about the solution for midcentury being the solution for all time,” says Jane Long, a former associate director at Lawrence Livermore National Laboratory, in California. “If I were in charge of everything, I would say, have a long-term plan to get [all of our electricity] from sunlight—there’s enough of it. For the near term, we shouldn’t be taking things with big impact off the table, like nuclear.”

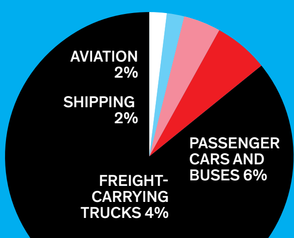
As the globe warms and the climate becomes increasingly unstable, the argument for nuclear will become more obvious, Long says. “It’s got to come to the point where people realize how much we need this.” ■

↗ **POST YOUR COMMENTS** online at https://spectrum.ieee.org/terrapower0618

ILLUSTRATION BY MCKIBILLO

BLUEPRINTS *for a* MIRACLE | PART 2

Vehicles



GLOBAL CO_2 EMISSIONS FROM TRANSPORTATION

OKAY, SO YOU eat local food, turn the thermostat down, sweat in the summer, and carpool. How very green of you. But your stuff comes from halfway around the world on smoke-belching ships, you drive 2 hours a day, and you fly somewhere every other month. So thanks for nothing! A single round-trip transcontinental flight spews the greenhouse gas equivalent of 2 or 3 metric tons of carbon dioxide per passenger. That's no way to run a planet. • To get the carbon out, we'll have to relearn how to walk, as it were. We'll need to electrify our cars, boats, and airliners, starting with hybrid designs that cut carbon emissions–and then, when better batteries finally come, with pure-electric designs that cut emissions even further. • Already engineers can see their way clear to greater savings in greenhouse gas emissions than the world has managed since we began to feel the threat of global warming. But we still have to fit the new forms of transportation into a system based on alternative energy. It does little good to electrify a car or boat if it must draw its power from generators fired by coal or oil. Nor does it make sense to save energy by using lightweight materials if the materials themselves require vast amounts of energy to make. Engineering proceeds within the constraints assigned to it: These problems will yield if governments get the incentives right. Carbon taxes are one solution; research subsidies are another. We'll need ingenuity, too. Fortunately, that shouldn't be hard to manage.

MOST IMPACT BY 2025: **HYBRID-ELECTRIC PROPULSION**

It now leads the electrification of road traffic

MOST IMPACT BY 2038: **PURE-ELECTRIC PROPULSION**

Fabulous new batteries will come...someday

MOST OVER-HYPED TECH: **THE HYPERLOOP**

Shooting small pods through a vacuum tube is fraught with unknown technical difficulties

SLEEPER TECH TO WATCH: **FUEL CELLS**

They lack power but pack a lot of energy

SOURCES: U.S. ENVIRONMENTAL PROTECTION AGENCY; INTERNATIONAL ENERGY AGENCY; PHOTO: INA FASSBENDER/AFP/GETTY IMAGES

ILLUSTRATIONS BY Francesco Muzzi/StoryTK

BLUEPRINTS *for a* MIRACLE

Turning Pollution Into Fuel

Methanol-fueled cars could drive us toward an emissionless future BY JEAN KUMAGAI

CARBON RECYCLING INTERNATIONAL

JUST OFF A TWO-LANE highway that winds through the black volcanic rock fields of southwest Iceland sits a nondescript industrial plant. Its multistoried network of pipes and tubes reveal little about what goes on there. Each year hundreds of thousands of tourists pass right by, on their way to visit the strange and beautiful Blue Lagoon, an outdoor spa whose steaming milky blue water flows directly from the nearby Svartsengi geothermal power station. If tourists notice the plant at all, it's maybe to wonder why it's here. • As it happens, this plant also depends on the Svartsengi facility, not for its silica-infused water but for its carbon dioxide. And what's going on inside the plant has the potential to dramatically decarbonize the transportation sector. The plant belongs to Carbon Recycling International (CRI), whose engineers have developed a novel method of using renewable energy to produce methanol fuel from waste streams of CO_2 and electrolyzed water. Methanol generated this way, CRI is betting, could have a real impact on climate change.

Over the past decade, CRI engineers have been refining and vetting their process at the plant, which is named for the late Nobel Prize–winning chemist George A. Olah. A pipeline carries about 5,500 metric tons of CO_2 per year from Svartsengi, which also supplies the elec-

ROAD TO METHANOL: Iceland's Carbon Recycling International has pioneered a way to produce methanol fuel using renewable energy and waste CO_2. A nearby geothermal power station supplies CO_2 and electricity to the methanol plant and mineral-rich water to the famous Blue Lagoon spa [above].

tricity to split water into hydrogen and oxygen. The hydrogen and CO_2 are then combined to form water-laden methanol, which is distilled into pure methanol. Opened in 2012, the plant now produces 4,000 metric tons, or 5 million liters, a year. Some of the fuel, which CRI has dubbed Vulcanol, is used to operate a test fleet of methanol-burning sedans built by the Chinese car giant Geely Auto Group. The carmaker's founder, billionaire Li Shufu, has been pushing methanol transportation in his country. Geely has a factory in Shanxi province that can produce up to 100,000 methanol cars a year and is constructing another factory in Guizhou province.

Of course, in an ideal low-carbon world, the roads would be filled not with methanol cars but with electric vehicles charged by renewable energy. We're still well short of that goal, however. Today, EVs make up a tiny fraction of cars in every country where they're sold. Even under the most optimistic assumptions, it may be midcentury before a majority of cars on the road are all-electric.

In the meantime, methanol is among the most promising alternatives for significantly shrinking our cars' carbon footprint. If you power a methanol plant with a renewable energy source and capture the CO_2 coming from the exhaust of, say, a steel plant, you can halve the total carbon being released into the atmosphere. So even though burning methanol in a car's internal combustion engine does release CO_2, along with some water vapor, you're first capturing CO_2 from the steel plant. That is, you're basically recycling the carbon and extracting some useful work before it gets released. In contrast to carbon capture and storage, which aims to permanently sequester CO_2 deep underground, this type of cycle is known as "carbon capture and utilization."

"Many people are convinced that EVs will solve our climate problem," says G.K. Surya Prakash, a professor of chemistry at the University of Southern California and a longtime collaborator of Olah's. "But the technology isn't there yet, the batteries aren't there yet. And many third-world countries don't have enough electricity even for basic needs, so what's all this talk about EVs?" Methanol, by contrast, is doable right now, he says. The simple alcohol can be burned in an internal combustion engine, and it can be stored, transported, and distributed using the same basic infrastructure that's now used for gasoline and diesel.

"That's the beauty of methanol," says Prakash. "You don't have to build an entirely new infrastructure from scratch."

IF THE IDEA OF METHANOL CARS sounds vaguely familiar, that may be because it's not new. Back in the 1980s, such vehicles were heavily promoted by the government of California, as a way to address the state's air pollution as well as its dependence on foreign oil. Ford Motor Co. spearheaded the development of a flex-fuel car, which could burn gasoline as well as alternative fuels like methanol. California's fleet of methanol vehicles eventually reached 15,000. But falling oil prices and the U.S. corn lobby's push for ethanol ultimately killed the methanol car.

This time around is different, says Paul Wuebben. He was one of the leaders of California's methanol experiment and now serves as CRI's senior director of fuel applications. (Wuebben's colleagues call him "Mr. Methanol," a nickname that makes him both slightly embarrassed and rather proud.) "Methanol is coming back strongly," he says.

The European Union, India, and Israel are all investing in methanol transportation, Wuebben notes. And in China, methanol accounts for 8 percent of transportation fuel, and the market research firm IHS Markit is projecting demand to grow by 7 percent per year. The availability of methanol-gasoline blends there ranges from 5 percent methanol (M5) to 100 percent (M100). While most of China's methanol is produced from coal or using coal power, Geely's Li recently called for the creation of a "liquid sunshine economy," in which the fuel's production would be solar powered. And in April, the Chinese car startup AIWays, working with the German car engineer Roland Gumpert and the Danish fuel cell company SerEnergy, unveiled a methanol fuel cell sports car at the Beijing Motor Show.

And Iceland's CRI is riding the methanol wave. At the company's headquarters in Kópavogur, just out-

CARBON RECYCLING INTERNATIONAL

EXPANSION PLANS: Carbon Recycling International's methanol plant, in Iceland, produces 5 million liters of fuel a year. The company plans to build plants 10 times as large in China by leveraging its partnership with the carmaker Geely, which has been investing in methanol cars.

side Reykjavík, Benedikt Stefánsson, the business development director, says it's been quite a ride. CRI was founded by two Icelanders and two Americans in 2006, the same year that Olah, Prakash, and Alain Goeppert published *Beyond Oil and Gas: The Methanol Economy* (Wiley), laying out a grand vision for weaning the world from its habit of consuming some 97 million barrels of oil a day. The following year, CRI opened a small pilot plant. But the global financial crisis of 2008–2009 hit Iceland particularly hard, and investment funding dried up. CRI cobbled together enough money from local investors and family members to complete the Olah plant in 2012. Subsequent investments from Canadian methanol producer Methenex and Geely allowed the company to expand the plant and start developing projects outside Iceland.

Stefánsson says the right way to view a methanol-fueled car is as a replacement for a traditional gasoline- or diesel-powered car, for the vast majority of consumers who aren't ready to make the leap to a fully electric car. In Iceland, he notes, government incentives favoring EVs have led to a recent uptick in battery electric vehicles and plug-in hybrids. Nevertheless, he says, Iceland's cold climate exacerbates the vehicles' already limited electric range. So owners of hybrids still find themselves pulling up to the pump regularly.

SMIL SAYS...

Current and planned projects have an annual capacity equal to just 0.3 percent of annual emissions from stationary sources.

Of course, even if methanol fuel is similar to gasoline in many respects, it's not *exactly* the same. For starters, methanol's energy content is about half that of gasoline, so an M100 car has to be filled up twice as often. "Methanol is a unique product, so you have to handle it in parallel with gasoline," says Daniel Sperling, director of the Institute of Transportation Studies at the University of California, Davis. He's highly skeptical that methanol cars will ever expand beyond their current niche.

"The auto industry is investing tens of billions of dollars in electric drive technology," Sperling says. "They don't need or want another product."

For different reasons, Edward S. Rubin, a professor of engineering and public policy at Carnegie Mellon University, in Pittsburgh, also doubts methanol's prospects. In a recent paper, he and several collaborators examined the extent to which converting CO_2 to fuels—as CRI is doing—could mitigate climate change. Their conclusion: "While CCU [carbon capture and utilization] does have the potential to mitigate some CO_2 emissions (provided that a continuous supply of carbon-free electricity is available), an alternative system employing CCS [carbon capture and storage] together with the same carbon-free electricity is a far more effective mitigation option."

"If your chief goal is to solve the climate problem, methanol isn't the best way to do it," Rubin says. Climate models suggest that to stave off the worst effects of a changing climate, the electricity grid and other industrial sectors need to be deeply decarbonized by midcentury, he says. CCU may be more attractive than CCS because you may be able to make money doing it, he notes, but it also prolongs the time it will take to bring down greenhouse gas emissions to the levels needed to avoid dangerous impacts. "The timescale of climate-change mitigation means we really can't afford to wait."

Stefánsson agrees with this sense of urgency but argues that any scheme to mitigate climate change should include liquid fuels from CO_2. "In any scenario, we need rapidly increasing investment in carbon capture," he says. "But CCS has zero impact on the use of fossil fuels in transport. It is also a perpetual cost, which is why adoption has been so slow." And there's still no good near-term technology for electrifying long-distance and heavy-goods transport or shipping or aviation, he adds.

"Right now, the world is still flush with fossil fuel resources," says USC's Prakash. Absent a strong system of rewards and penalties that discourages the use of those resources, people will use them. Methanol offers a bridge from our highly carbonated present to a low-carbon future, in which electricity comes from renewables or nuclear and cars are electric. In the meantime, Prakash says, methanol can help. Rather than wastefully flaring natural gas in the Bakken Formation, for instance, why not place a methanol plant there and produce fuel? Rather than curtailing wind and solar when the power grid can't absorb their output, why not use the excess for methanol?

"Methanol gives us a way to store not just kilowatt- or megawatt-hours of power but gigawatt-hours," Prakash says. "It could be a game changer." ■

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ILLUSTRATION BY MCKIBILLO

BLUEPRINTS *for a* MIRACLE

The Prius of the Sky

Electric propulsion will develop in the air as it did on the ground, by initially using batteries to assist a fuel-burning generator

BY **PHILIP E. ROSS**

SIEMENS

I AM SITTING IN THE COCKPIT of one of the most extraordinary airplanes in the world. It's a two-seat trainer called the 330LE, made by Extra Aircraft but fitted with an electric motor by Siemens, a huge company not known for aviation. I pull my feet clear of the control pedals just before the pilot turns the thing on. • The propeller immediately spins into transparency. And yet it's so quiet that we could easily converse without headsets. That's the first sign that this plane is powered by electricity. • We start rolling down the little runway, in a grassy field outside of Budapest. It's 10 o'clock on a sunny morning, and there are farms off in the distance. Suddenly we lurch into the sky and begin climbing steeply, shrinking the farmhouses into cuteness. A cow down below doesn't even look up. That quick-off-the-mark acceleration, a kind of aeronautical equivalent to the "Ludicrous" mode of the Tesla Model S, is another sign of electric operation. You get all the performance the motor can give, and you get it instantly.

Then we swoop, swerve, and soar, leaving my belly behind. Not bad for a merely semi-aerobatic plane, as Gergely György Balázs, head of Siemens's Budapest research outfit, described it to me, somewhat apologetically, just before I climbed in. (Lucky

BLUE SKY CONCEPT: This is the fully aerobatic version of the Extra 330LE, a light plane modified by Siemens to run purely on electricity. On an early test in late 2016, it set a record for electric flight by climbing to 3,000 meters in 4 minutes and 22 seconds.

me—the pilot of the *fully* aerobatic model was away on business.)

After 15 exhilarating minutes, the battery is down by half, to less than 10 kilowatt-hours, and it's already time to land. That's the final sign of electric propulsion. For although today's lithium-ion batteries—racks of which are stowed just ahead of the cockpit—store far more energy than they could just a few years ago, they can't come close to a tank of gasoline. So, for years to come, all-electric planes will be limited to short hops, mostly between neighborhoods rather than between cities.

Aviation is the source of between 2 and 3 percent of global greenhouse gas emissions. But the sector's effective overall emissions are believed to be greater because a great deal of the emissions are in the stratosphere. Aviation's share of overall emissions is expected to climb sharply over the next couple of decades as air travel increases and emissions from other sources—notably electricity generation and passenger cars—decline.

In 2016, 23 countries agreed to limit the carbon emissions of their commercial aircraft beginning in 2020, according to standards set by the International Civil Aviation Organization (ICAO), an agency of the United Nations. So researchers all over the world are working hard to find ways to do it.

But how can electric planes help, if they are limited to ridiculously short hops? Because they are seen as a critical step in a grand technological evolution in aviation that will recapitulate the migration, just beginning now, of the automotive industry from combustion engines to electric motors. In perhaps 15 years, hybrid passenger aircraft that combine electric and combustion power trains will begin serving in short- and medium-haul routes. Hybrids burn fuel, but they do so frugally.

"We can make a huge impact at the scale of a small battery-powered trainer because there the physics isn't working against us," says George Bye, CEO of Bye Aerospace, who is partnering with Siemens to supply his company's planned electric trainer with motors. "But for the higher speeds and masses that you need for airliners, you have to go to a hybrid configuration. The industry is working hard on that."

Hybrids are needed, for now, because although aviation fuel gives 12,500 watt-hours per kilogram, lithium-ion batteries give only 160 Wh/kg, including the weight of packaging and everything else you need to make the battery safe.

To get hybrids up in the air will require lots of technological advances. These advances will come, of course, from R&D programs aimed at building hybrid planes. But they'll also come out of efforts—such as Siemens's—to introduce electric trainer aircraft and, perhaps most of all, to build an envisioned industry of intra-urban air taxis whisking people around in what amount to overgrown drones. Siemens itself is working with Airbus Helicopters on one such all-electric project, called CityAirbus. Airbus also has another, parallel effort, called Vahana, under way at its subsidiary in Silicon Valley. And there are many other startups, including China's Ehang, which provided the first public demonstration of a passenger flight early this year, when an engineer took to the skies in the company's octocopter.

IN AVIATION, most hybrid designs depend on the series architecture, in which the fuel-burning engine—either an internal-combustion design or a turbine—drives a generator that powers electric motors, which spin the props and also charge the batteries. In this scheme, the batteries provide the burst of power needed to take off, a stratagem that lets technicians tune the fuel-burning engine to run at its ideal rate. Those massive jet engines you see hanging from the wings of your plane are fully engaged only during takeoff; at other times, they're basically just idling and weighing down the aircraft.

There are other advantages. By distributing power by wire, the hybrid design lets you put the propellers exactly where you want them, without having to organize everything around the placement of enormous engines. Some hybrid designs envision putting the propeller at the back of the plane, or even on top of the vertical stabilizer.

Two major consortia are working on hybrids. In Europe, Airbus has teamed up with Siemens and Rolls-Royce in an alliance that is separate from the CityAirbus endeavor. In the United States, Boeing and JetBlue are part of a rival project managed by the startup

BATTERIES GO HERE: **This more lightly powered version of the Extra 330LE carried the pilot [right] and the author through semiaerobatic maneuvers in a field outside Budapest.**

SIEMENS

Zunum Aero, based in Kirkland, Wash. Both consortia are talking about getting hybrids into the air by the early 2020s.

The Airbus group plans to begin with a modified version of an existing plane, the 100-seat British Aerospace 146, in which one of the four wing-mounted nacelles holds not an engine but a 2-megawatt electric motor. It will draw power from a generator spun by a small gas turbine housed in the fuselage (and thus offering little air resistance). If the electrical system fails, the three conventionally powered propellers could fly the plane safely. Airbus reportedly is preparing a hybrid for possible demonstration at next year's International Paris Air Show.

The U.S. consortium has released almost nothing about its plans. In August 2017, GE Aviation produced a white paper outlining the substantial work it said it was doing on hybrid-electric motor-generators. In one ground-based experiment, GE Aviation used a motor rated at 1 MW to turn a 3.3-meter (11-foot) propeller. In another experiment, it used the compressors of a GE F110 jet engine to power a generator rated at 1 MW; meanwhile, the engine continued to produce thrust.

Though detailed information from both consortia is scarce, interviews make it clear that they are focusing on improvements in four technological categories: battery capacity, motor and generator weight, power electronics efficiency, and airframe materials and design. In the European consortium, for example, Siemens specializes in the motor, the generator, and the electronics. In addition, the company has modified some small airplanes to create all-electric designs, in the belief that it can optimize the parts together only with the plane they'll be installed in.

"We are gaining experience with the complete system of electric propulsion, with everything that's between the pilot and the propeller," says Frank Anton, head of Siemens's eAircraft department. "The only way you can learn this is by flying the technologies."

Electric motors can be relatively small and light, opening up many options. You can mount a bunch of small props on the wings and swivel them to help with a short takeoff. NASA is even investigating a design that would place a bank of little propellers all along the wing, directing the flow of air over the control surfaces as needed, to improve the lift-to-drag ratio. The result: shorter, thinner wings.

"Separate the generation from the propulsion," Anton says, "and all of a sudden you can have all sorts of applications that use vectorized thrust."

The key challenge of cutting the weight of an electric power train depends on two things. First, the energy density of the batteries must rise, which will be an incremental process, at least until today's lithium-ion batteries give way to some entirely new technology, like metal-air batteries. And second, the power density of the motor and the engine-generator system that runs it must also go up. That's Siemens's specialty.

SMIL SAYS…

An all-electric intercontinental jetliner would need batteries whose energy density is three orders of magnitude higher than today's best designs.

In the nose of the fully aerobatic Siemens plane sits the company's SP260D aviation motor, which at 50 kg (110 pounds) and 260 kilowatts of power reaches a whopping 5:2 kilowatt-to-kilogram ratio. (The semi-aerobatic plane has about the same ratio, but it's only a little more than half the size.) The Extra first flew in public in 2016, at the Dinslaken field, in Germany; in 2017 it set a record for electric flight by topping 340 kilometers per hour (211 miles per hour). And Siemens engineers are working hard now to raise the motor's power density still further.

At the Budapest research center, Balázs walks me over to a lab bench, where he hands me part of a motor that's been cut in half. It's a slice of a stator—the stable part around which the rotor revolves—and embedded in its sawed-off face are the rectangular cross sections of copper windings, which fit together like so many bricks on a wall. That rectilinearity is key to achieving high power levels—it prevents any air gaps that might interfere with the conduction of heat from the wires to the liquid-cooled housing. You have to wick away that heat or the wires' insulation will break down, and then short out.

"We need a much more homogeneous heat exchange than we could get from round wire, and we also hope the electrical isolation will be better—which matters in an aviation motor," Balázs declares. Siemens had the wire specially made at Furukawa Electric Co., a Japanese supplier.

The engineers here are the ones doing such workaday research, shaving weight off by the gram. That handcrafty approach makes these hand-built gems more costly than any Rolex. When I heft something to gauge its weight, Balázs flinches visibly. Carefully, I put it back.

In a few years, he tells me, thousands of these motors will be made every year for those air taxis, which Siemens and all its air-taxi rivals predict will swarm over cities like locusts. That's when unit costs for the motors will drop, and probably to levels well below today's comparable

| CONTINUED ON PAGE 78

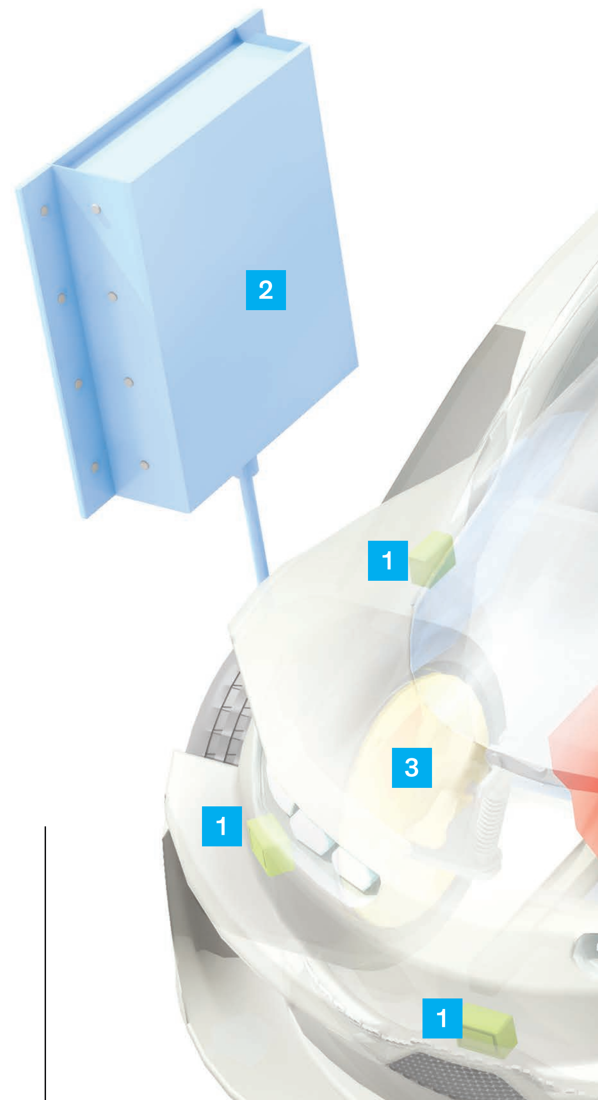
ILLUSTRATION BY MCKIBILLO

BLUEPRINTS *for a* MIRACLE

What Will the Transportation Miracle Be?

The EV of 2028: quiet, safe, and efficient

BY PHILIP E. ROSS

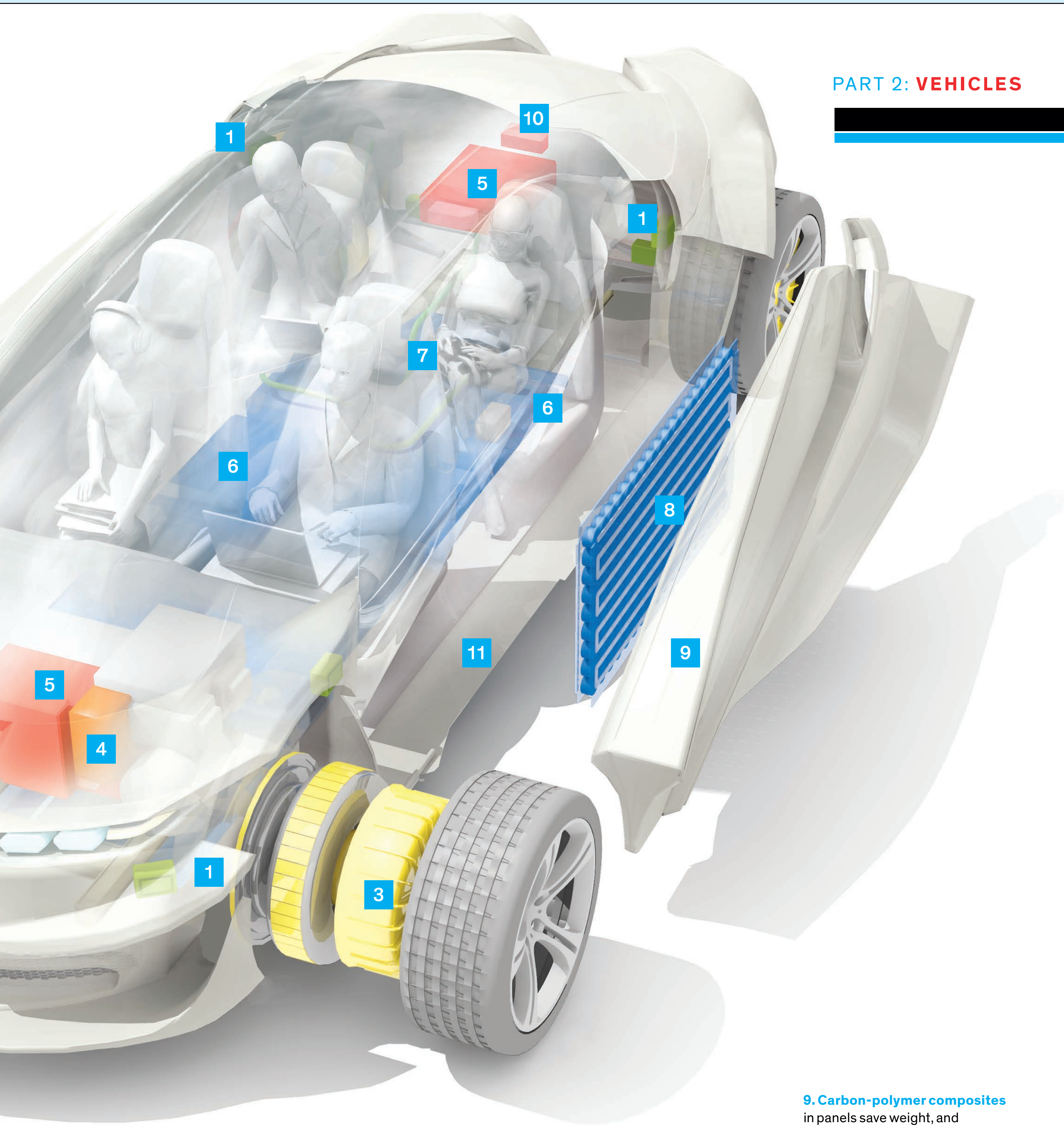


IN 10 YEARS, electric vehicles will become more energy efficient, and more important, they will begin to supplant fuel-burning cars, which will save even more energy. • Thomas Bradley, Zachary Asher, and David Trinko of Colorado State University ran some simulations for *IEEE Spectrum*. They found that if the 2028 EV's batteries offer equal performance for half the weight of those in the 2018 Tesla 3, and if lightweight materials shave off another 500 kilograms, the car would get 12 percent more energy efficiency in the city and 18.5 percent more on the highway. But if the Ford F-150 pickup (today's best-selling U.S. vehicle) were merely to become a plug-in hybrid while shedding 10 percent of its weight, then its fuel efficiency would triple, going from 20 miles per gallon equivalent to 90 mpge in the city and from 26 to 79 mpge on the highway.

SMIL SAYS...

Electric vehicles are now less than 0.3% of the global car stock: No realistic growth rate can get them even to 30% by 2030.

ILLUSTRATION BY Bryan Christie Design



1. Lidar will give autonomous cars second sight—beyond what cameras and radar provide.

2. Inductive charging system will let the car juice up without plugs.

3. In-hub motor saves on weight and thus on fuel while offering torque steering.

4. Gallium nitride inverter offers better energy efficiency than today's silicon version.

5. Power electronics based on compound semiconductors will save energy and weight.

6. Lithium-ion batteries are expected to roughly double their energy-storing capacity over the coming decade.

7. High-voltage cabling offers the burly connections an all-electric car requires.

8. Ultracapacitors give quick bursts of power and easy brake regeneration.

9. Carbon-polymer composites in panels save weight, and that savings allows for further reductions in weight throughout the entire supporting frame.

10. Processors will turn tomorrow's car into a rolling supercomputer.

11. Superlight metals in the chassis further ease the load on the propulsion system.

Food

MOST IMPACT BY 2025: PLANT-BASED "MEAT"

Comin' right up: a great fake steak

MOST IMPACT BY 2038: "IN VITRO" MEATS

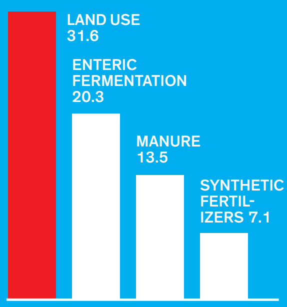
Cellular agriculture will cleave the meat from the bone

MOST OVER-HYPED TECH: VERTICAL FARMS

Growing veggies near cities won't substantially cut greenhouse gas emissions

SLEEPER TECH TO WATCH: NITROGEN FIXING

Cereal crops that make their own fertilizer



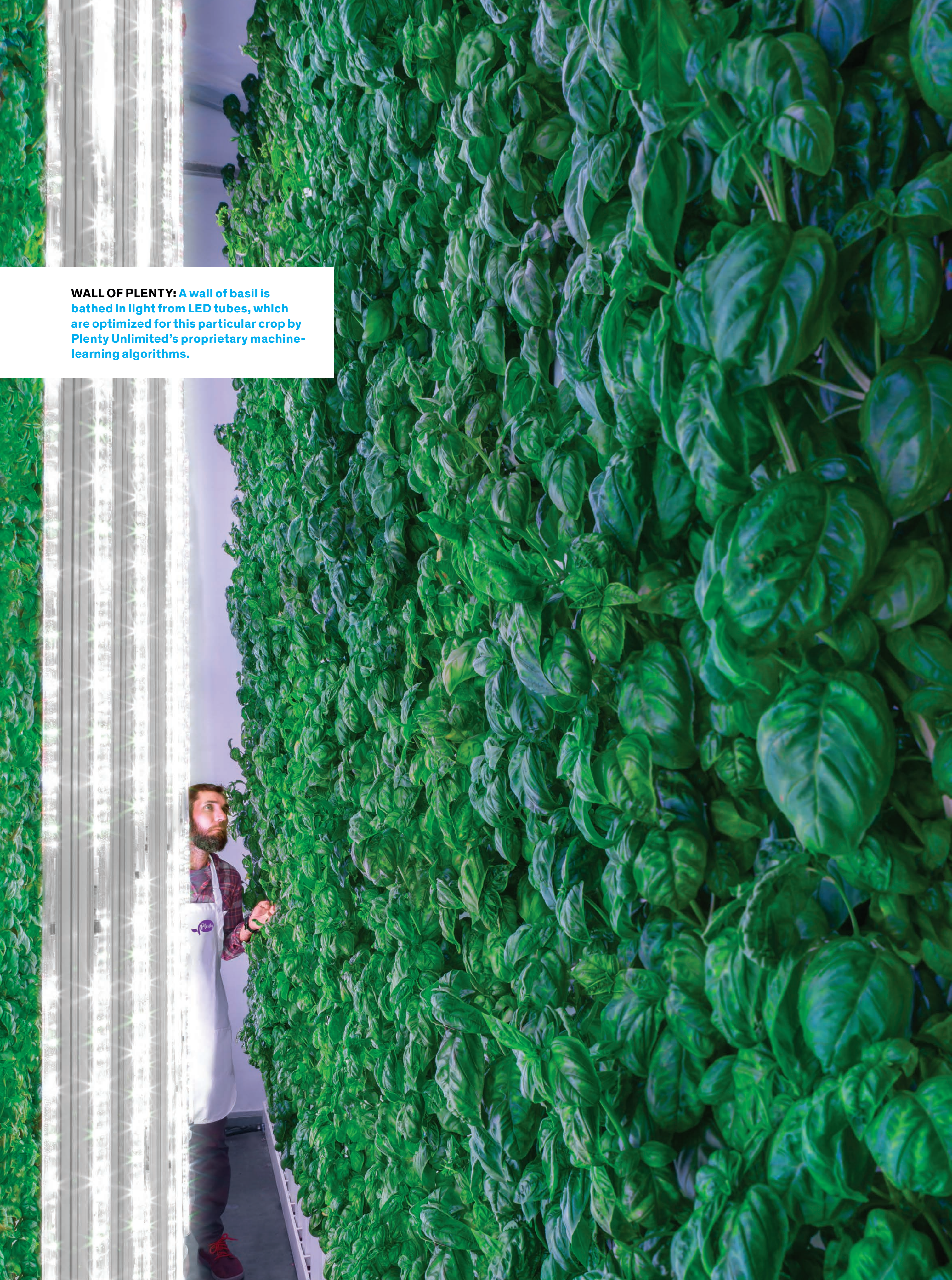
TOP EMITTER IN AGRICULTURE

Hundreds of millions of metric tons, CO_2 equivalent

TO APPRECIATE the life-changing nature of modern technology, you need go no further than your supermarket and behold the dazzling bounty on offer. You'll probably find half a dozen varieties of apples, 12 kinds of eggs, and 50 kinds of deli meats and cheeses. A kilogram of ground beef costs less than dry-cleaning a sweater. • And it's all made possible by factory farming, a practice whose toll on the planet has been heavy. According to the Food and Agriculture Organization of the United Nations, farming, deforestation, and other land-related activity account for 21 percent of greenhouse gases. By the U.N.'s reckoning, agriculture is second only to energy in emissions. Globally, the agriculture-and-land-use sector is the source of at least 10 billion metric tons of CO_2-equivalent greenhouse gases every year. • That includes livestock—1.4 billion cattle and 1.9 billion sheep belching methane—and synthetic fertilizers, the use of which adds some 710 million metric tons of CO_2-equivalent greenhouse gases per year. Technological solutions are on the way, including an improving array of alternatives to meat and crops genetically engineered to use bacteria to scavenge, from the air, the nitrogen they need to thrive.

SOURCE: THE FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS; PHOTO: RICHARD BAILEY/GETTY IMAGES

ILLUSTRATIONS BY Francesco Muzzi/StoryTK



WALL OF PLENTY: A wall of basil is bathed in light from LED tubes, which are optimized for this particular crop by Plenty Unlimited's proprietary machine-learning algorithms.

The Green Promise of Vertical Farms

Indoor farms run by AI and lit by LEDs can be more efficient than field agriculture, but can they significantly reduce greenhouse gas emissions? BY HARRY GOLDSTEIN

I EMERGE FROM THE TOKYO Monorail station on Shōwajima, a small island in Tokyo Bay that's nestled between downtown Tokyo and Haneda Airport. Disoriented and dodging cargo trucks exiting a busy overpass, I duck under a bridge and consult the map on my phone, which leads me deeper into a warren of warehouses. I eventually find Espec Mic Corp.'s VegetaFarm, in a dilapidated 1960s office building tucked between a printing plant and a beer distributor. Stepping inside the glass-walled lobby on the second floor, I see racks upon racks of leafy green lettuce and kale growing in hydroponic solutions of water and a precisely calibrated mix of nutrients. Energy-efficient LEDs emit a pinkish light within a spectral range of 400 to 700 nanometers, the sweet spot for photosynthesis.

I'm here to find out how plant factories, called vertical or indoor farms in Western countries, can help reduce the greenhouse gas emissions associated with conventional field agriculture. According to the World Bank, 48.6 million square kilometers of land were farmed worldwide in 2015. Collectively, agriculture, forestry, and other land uses contributed 21 percent of global greenhouse gas emissions, per a 2017 report from the Food and Agriculture Organization of the United Nations, mostly through releases of carbon dioxide, methane, and nitrous oxide.

Vertical farms avoid much of these emissions, despite the fact that they rely on artificial light and have to be carefully climate-controlled. Indeed, according to vertical farms evangelist Dickson Despommier, who's widely credited with taking the fledging industry mainstream, these kinds of farms could significantly reduce the amount of land devoted to farming and thereby make a serious dent in our climate change problem.

"What if every city can grow 10 percent of its food indoors?" he asks, and then answers himself: That shift could free up 881,000 km^2 worth of farmland, which could then revert to hardwood forest. That's enough, Despommier claims, "to take 25 years' worth of carbon out of the atmosphere." He adds that Japan, which began experimenting with plant factories in the 1980s, is now the world's leader, and most of those farms lie near or within cities. As he noted in his 2010 book *The Vertical Farm: Feeding the World in the 21st Century* (Thomas Dunne Books), the vertical farm solution to anthropogenic climate change is both "straightforward" and "simple."

But how realistic is it?

PLENTY UNLIMITED

DETERMINING WHAT contributes to agriculture's share of overall greenhouse gas emissions is fairly straightforward. Paul West, codirector and lead scientist of the Global Landscapes Initiative at the University of Minnesota's Institute on the Environment, says that half of agriculture's share of greenhouse gas emissions comes in the form of carbon dioxide from clearing forests for cattle and soy in South America and for oil palms in Southeast Asia. Another huge chunk comes from livestock and rice paddies, which release staggering quantities of methane. Nitrous oxide from fertilizer accounts for a good portion of the rest.

I ask West whether vertical farms could help. He notes that the vast majority of calories produced on cropland come from grains like wheat, rice, corn, and soy, none of which are particularly good candidates for indoor farming.

And it's true—I don't see any rice, wheat, corn, or soy growing at the VegetaFarm in Tokyo. Instead, the 160-square-meter space is filled with a fecund profusion of leafy greens. The farm produces 1,000 heads of lettuce per day, according to Shun Kawasaki, production manager and plant scientist.

To enter the farm, Kawasaki and I don clean-room bunny suits, face masks, and rubber boots, step on a sticky mat, walk through an air shower, and exit into the plant room. Each of the six racks holds five tiers of water-filled canals on which float rafts of plants. Two bunny-suited workers tend this indoor garden, occasionally pushing a new tray of seedlings onto one end of a shelf and another ready-to-be-harvested tray off the other.

Through his mask, Kawasaki tells me that besides controlling temperature, the HVAC ducts and fans snaking under the shelving also pump in carbon dioxide to keep levels at about 1,000 parts per million, about two and a half times the typical outdoor level. Trays of lettuce and kale soak up light from LED tubes, which stay on for 16 to 17 hours per day and use up to 70 percent of the 600 to 700 kilowatt-hours consumed per day.

If you have US $1 million, you can buy a medium-size VegetaFarm like this one from Espec Mic, including the racks, control systems, HVAC, and lighting. Besides the lettuce and kale, the Tokyo farm grows bok choy, mint, mizuna, and shiso, and is experimenting with basil and radishes. Lettuce grown in the field takes about 60 days from seed to harvest. In the VegetaFarm, it takes 40 days. Other plant factories claim faster rates, in the 30-day range. So instead of one to three harvests per year on a conventional farm in the middle latitudes, a plant factory can produce one harvest every month or so. And unlike field-

WORKING THE (INDOOR) FARM: **A bunny-suited farmer wrangles trays of frill lettuce toward harvest in Espec Mic's VegetaFarm.**

HARRY GOLDSTEIN

LEDs ARE KEY TO GROWTH: The Japan Plant Factory Association runs a prototype plant factory on the Chiba University campus. Here it researches different crops as well as lighting systems from the likes of Advanced Agri, Future Green, Kyocera, Philips, Showa Denko, and Toshiba.

HARRY GOLDSTEIN (2)

grown lettuce, which is harvested all at once, the indoor harvest is continual and the yields extremely high, with no loss from pests or inclement weather.

After the tour, Kawasaki gives me a sample of Espec Mic's Mineraleaf green lettuce, freshly harvested and packaged on-site that day. One of the major benefits of plant factories is that you can tune the plant's chemical composition to engineer its nutrient content and flavor profile. The company grows its Mineraleaf lettuces in seawater pumped up from 800 meters, which makes for a tender, delicious leaf–maybe the tastiest lettuce I've ever had–that's also dense in calcium, potassium, and magnesium. A 100-gram package sells for about 200 yen (about $2). On the package, where you might expect to see an image of a lush field or the Jolly Green Giant, there are photos of plants basking in pink light.

Proponents of urban indoor agriculture tout a number of benefits–such as increasing city dwellers' access to fresh produce and revitalizing run-down warehouse districts. But the most audacious claims center on indoor farms' environmental benefits over those of conventional field agriculture, including the elimination of pesticides and much more efficient use of water. According to Toyoki Kozai, professor emeritus at Chiba University and president of the Japan Plant Factory Association, plant factories use water 30 to 50 times as efficiently as a traditional greenhouse does. Many plant factories don't even wash their produce. Instead, as at VegetaFarm, harvested plants go straight into packaging, and they're clean enough to eat.

Kozai says that a vertical farm is most economically viable when its output is consumed fresh within a few kilometers of the farm itself. That cuts down on fuel for transportation and processing as well as the loss of produce en route to the consumer.

Reduction of the fuel used to transport food–known as food miles–is an obvious benefit of urban vertical farms. And yet, the carbon savings are relatively minor, says West. "Eighty percent or more of the emissions for agriculture happens on the farm–not in the processing, not in the transportation," he says. Real reductions in greenhouse gases will come from "how we are managing our soils, how we are managing the crops on the land, the types of mechanization that's used, the types of fertilizer." West says he's all for "urban gardening and vertical systems, but I don't see it being at the scale that's needed to meet food demand or have environmental impact on a massive scale."

Certainly, Japan's vertical farming industry is still tiny, despite being around for several decades. Eri Hayashi, director of international relations and consulting at the Japan Plant Factory Association, says there are 182 plant factories in Japan. One of the largest is Spread Co.'s Kameoka plant near Kyoto. Its two 900-m^2 towers have a total cultivation area of 25,200 m^2 and produce 21,000 heads of lettuce per day. In September, Spread will open the Techno Farm in Tokyo, which the company says will exploit advanced automation to more than double productivity, to 648 heads per square meter.

According to a 2014 market study by the Yano Research Institute, total revenue for the Japanese vertical farm industry was 3.4 billion yen ($31.2 million) in 2013. But Japan's domestic market for vegetables that year was 2,253 billion yen, according to the Statistics Bureau of the Japan Ministry of Internal Affairs and Communications, which means that vertical farms accounted for a scant 0.15 percent of the country's vegetable market.

Still, interest in vertical farms has never been higher. Outside of Japan, the most active markets are China, Taiwan, and the United States, Hayashi says. As the concept has spread, new hybrids have sprung up. These include indoor aquaponics farms, where fish poop fertilizes the plants, and the "aeroponics"-based AeroFarms in Newark, N.J., which employs proprietary spray nozzles to mist plant roots with water and nutrients. A recent white paper by investment firm Newbean Capital counted 56 commercial warehouse, aquaponics, and rooftop greenhouse farms in the United States in 2017, up from 15 in 2015, and notes that at least three 6,500-m^2 farms are under construction.

PLENTY UNLIMITED

ONE OF THE BIGGEST farms slated to open this year is Plenty Unlimited's 9,300-m^2 facility located just south of Seattle. Unlike most indoor farms, which grow trays of plants on multilevel racks, Plenty will grow its plants "on the vertical plane," says Nate Storey, Plenty's cofounder and chief science officer. "Imagine rows of towers with product growing on either side of them," he explains. "That orientation allows us to put about three times more product into a given space than we could if we stacked it."

Plenty has attracted $200 million in investment from SoftBank chief Masayoshi Son's Vision Fund as well as from funds that invest for Amazon's Jeff Bezos (who also owns Whole Foods), Bloomberg.com reported. With Bezos involved, Plenty could be positioned to do what no other indoor farming company has been able to do so far: grow produce indoors on a global scale.

Plenty's betting big on a suite of technologies that Storey believes can usher in a new era of farming, one powered by renewable energy and lit by LEDs, with sensor networks collecting tens of thousands of data points that feed into machine-learning algorithms to

OVER THE RAINBOW CHARD: **A worker tends to double-sided walls of rainbow chard at one of Plenty Unlimited's facilities. Tubes of LEDs tuned for these specific plants light the leaves from multiple angles, something conventional vertical farms are now starting to experiment with by lighting the leaves from beneath as well as above.**

optimize growing conditions for particular plants at specific stages of their life cycle.

"We came to realize that the future of these farms really rests in the hands of artificial intelligence," Storey tells me. "We're trying to improve both the amount that we can produce for a given cost or unit of energy as well as the quality of that product."

Plenty will start with greens and herbs, but in the next 12 to 18 months the company intends to branch out into fruits that until now have been grown indoors only experimentally. "I think that the industry as a whole will be surprised at the speed with which we begin to introduce crops that have historically only been viable in the field," Storey says.

He is also concerned with extending the shelf life of produce, along with saving food miles. "Half of what people are buying they're just chucking in the trash, right? That is a huge carbon cost," says Storey. "By delivering something that's superfresh, that has two weeks more of shelf life in your fridge than something you bought that was transported a very long way, we basically chop the carbon cost in half.... If we can get consumers to eat everything that they buy, we've done a lot better."

But can superfresh lettuce save a forest? Despommier's thesis relies on converting farmland back to hardwood forest. To free up 881,000 km² of land, you'd need an area equivalent to Spread's 25,200-m² Kameoka plant multiplied by 35 million. Despommier's vision for skyscraper-scale vertical farms coupled with much shorter growing seasons could certainly cut that number from millions to tens of thousands, but even an optimist can't imagine such a building boom within this century. And in the unlikely event such a boom were to ensue, you'd be getting only a small percentage of the vegetables and fruits grown on traditional farms and none of the wheat, corn, soy, or rice, at least not in the foreseeable future. Nor will vertical farms raise livestock or grow oil palms, which are mainly what people are clearing hardwood forests to make room for.

As West puts it, "We have heard that people can't live on bread alone. Well, if they can't do that, they're not going to live on kale either as their main source of calories."

SMIL SAYS...

Vertical farms are fine for growing leafy veggies, but not for displacing hundreds of millions of hectares of grains and legumes that feed the world.

IF NOT KALE, then what? Neil Mattson, an associate professor of plant science at Cornell University, in New York, has been looking into which crops make the most sense to grow indoors. He's the principal investigator on a $2.4 million grant from the National Science Foundation, and he and his team are analyzing how plant factories stack up against field agriculture "in terms of energy, carbon, and water footprints, profitability, workforce development, and scalability." It is probably the best-funded, most comprehensive study on indoor farms to date, one that will help quantify how much they can mitigate climate change.

Mattson notes, for example, that it makes no sense to grow wheat indoors. His Cornell colleague Lou Albright looked at the lighting costs of vertical farms for a 2015 presentation, and he calculated that if you grew wheat indoors, just the electricity cost per loaf of bread made from that wheat would be $11.

"Lou Albright would say indoor production like that doesn't really make sense until you get completely renewable energy," Mattson says.

For its part, Plenty is committed to integrating renewable energy sources into its power mix. The Seattle facility will source hydroelectric power. But to make a dent in, say, methane emissions by moving rice cultivation indoors, the amount of renewable energy you'd need would be truly massive: Of the 48.6 million km² of land being farmed, 1.61 million km² are devoted to rice cultivation.

Plenty's Storey isn't daunted. "We can grow things like rice and wheat and sorghum. We can grow commodities," he says. "It doesn't work for us right now, but I wouldn't rule out a future in which it starts to make sense."

It may well be that before that future arrives, we'll be growing more of our food in plant factories. Will it be the 10 percent that Despommier hopes for? Even if plant factories and vertical farms wind up being only a small part of the overall solution to reducing greenhouse gas emissions in the near term, they might be our insurance policy. As climate change starts to erode the viability of croplands, we may be forced to grow indoors, where the climate is still under our control. ■

↗ **POST YOUR COMMENTS** online at https://spectrum.ieee.org/verticalfarms0618

ILLUSTRATION BY MCKIBILLO

POND TO PLATE: Technician Jose Alvarado fills shipping totes with freshly harvested *Nannochloropsis*, the only type of algae grown on this New Mexico farm.

Algae 2.0

New tech could turn algae into the climate's slimy savior

BY **AMY NORDRUM**

"**THOSE ARE THE KINDS** of bubbles we want to see," says Rebecca White, pointing to tiny pockets of gas that are barely visible on the surface of an artificial pond in New Mexico. Their small size means the carbon dioxide she and her colleagues have injected into the water has mostly dissolved, instead of just escaping into the air. • We're less than a kilometer from the U.S.-Mexican border, surrounded by desert grasslands. It's one of the last places I'd expect to find a thriving population of marine algae. Yet here in this massive pool swirls more than a million liters of *Nannochloropsis*, a salt-loving alga that flourishes on the brackish water pumped from below. • Until 1973, long before the algae moved in, farmers grew cotton on this land. Then the well water they were using became so salty that they let the fields go fallow and never planted again. Algae's ability to prosper in places that would kill most other crops, combined with their astounding nutritional profile, has wooed experts worried about the future of the global food supply.

White, who oversees operations at this 97-acre algae farm and a sister site in Imperial, Texas, for Houston-based Qualitas Health, is familiar with the promise and pitfalls of large-scale algae production. A veteran of algae's biofuels craze, she worked here in 2012 when a different company spent US $104 million building the farm to produce "green crude." After three years, crude oil prices tanked, undercutting biofuels, and the facility closed.

The new hope for algae is that they could rebalance the global carbon equation as a food, not a fuel. Despite appearances, algae are an excellent source of protein. If meat-eaters started to eat more algae, the industry's theory goes, that shift could slash carbon emissions by reducing demand for beef and pork.

Algae could also replace fertilizer-intensive crops such as corn and soy as fillers in processed foods, including fish, pig, and cow feed. With enough algae in human and animal diets, society could avoid planting new fields even as the population increases, and perhaps even allow existing farmland to return to forests, which absorb more greenhouse gases per square kilometer.

There's one more big reason to let algae seep into the food supply: Though algae are not technically plants, they need CO_2 to grow. And to grow large amounts very quickly, farmers must inject CO_2 directly into the crop. That means every algae farm doubles as a carbon sponge.

PHOTOGRAPHS BY Amy Nordrum

DESERT-GROWN: While a soybean farmer harvests only once a year, each pond of algae shown here at the Qualitas farm in New Mexico will produce 33 harvests in 2018.

QUALITAS HEALTH

New technologies aim to capture emissions from power plants and pipe them into algae ponds, in a twist on carbon sequestration. One variation of this dream even calls for placing an algae farm next to every coal-fired power plant to ingest the CO_2 produced there.

Today, though, algae production is still a boutique industry focused mostly on nutraceuticals and food dyes. Qualitas's New Mexico farm churns out *Nannochloropsis*, or "nano," as White calls it, for omega-3 supplements. With just 48 ponds in production, adding up to about 50 acres, this site nevertheless qualifies as one of the world's largest microalgae farms.

The algae industry will have to scale up in a big way to deliver the carbon offsets and the protein the world needs. Eventually, producers will also have to persuade food manufacturers that algae deserves to be used in their products—and convince consumers that it belongs on their plates.

But if everything goes according to plan, these microorganisms could reshape the food supply as dramatically as corn and soy have over the past 50 years. And this time, the planet may be better off for it.

ALGAE REPRESENT one of Earth's oldest life-forms. Algae also constitute some of the world's simplest organisms. Many species are unicellular and lack advanced structures such as stems, leaves, and petals.

For such tiny organisms, algae already wield an outsize influence on the planet. Consider *Prochlorococcus*, the smallest and most abundant type of phytoplankton in the ocean, which forms the basis of the marine food chain. "It's amazing that it does so much with so little," says Zackary Johnson, a marine biologist at Duke University, in North Carolina.

Now, scientists want to use algae's superpowers to build a more sustainable food system for land dwellers. Agriculture, forestry, and other land uses (a category defined by the Food and Agriculture Organization of the United Nations) emit 21 percent of greenhouse gases globally. There is rising tension between the need to clear more land to produce food for more people and the desire to keep global emissions in check.

In theory, algae could ease that tension while also providing high-quality sustenance. Protein composes up to 70 percent of the dry weight of *Spirulina* and some species of algae. (Like *Prochlorococcus*, *Spirulina* is technically not a type of algae—it's a genus of cyanobacteria, but "we allow them into the club," says Stephen Mayfield, director of the California Center for Algae Biotechnology at the University of California, San Diego.)

Thanks in part to algae's high protein content, 1 hectare of algae ponds can generate 27 times as much protein as a hectare of soybeans. And protein from algae is more nutritious than protein from soy, because it contains vitamins and minerals in addition to all the essential amino acids.

Meanwhile, the global demand for protein will more than double by 2050. Setting aside for a moment the question of whether people who wish to eat steak would be willing to take a swig of algae instead, producing the latter could satisfy demand without requiring large tracts of land to be cleared for pastures or crops.

But growing algae has never been an easy affair. Despite algae's reputation as a fast-proliferating weed, it still takes a lot of electricity and ingenuity to reliably produce large amounts of it. Farms use electricity that's primarily still generated from fossil fuels to pump water and constantly stir the bubbling mixture. Algae also need some fertilization with nitrogen and phosphorus, the production and application of which generates emissions.

Given all of this, one life-cycle assessment concluded that a protein powder made from algae would be no better than animal protein from a sustainability perspective, and slightly worse than other vegetable-based proteins, such as soy. Another analysis found that while growing algae for food would avoid some future emissions from deforestation, long-term reductions in emissions would be possible only by producing algae-based food and fuels at the same facility.

So for algae to have any measurable impact on emissions, producers must find ways to grow more of it with less. And to sell it at a price palatable to consumers and food companies, they must also lower their own costs. That means finding a cheap supply of CO_2. The gas, which to many industries is nothing more than a problematic byproduct, is currently Qualitas's most expensive nutrient.

DAVE HAZLEBECK believes in the power of technology to help the fledgling algae industry reach its full planet-saving potential. His company, Global Algae Innovations, operates a 33-acre algae farm in Kauai, Hawaii, that doubles as a site to demonstrate dozens of technologies that can grow algae faster with fewer emissions and at a lower cost.

The company's boldest experiment to date is to divert the flue gases of a nearby coal-fired power plant into their ponds, as the algae's primary source of CO_2. It's a three-step process: After CO_2 is captured with an absorber (akin to a scrubber) that dissolves the gas into recycled water, that carbonated water is stored in covered pools. When the company is ready to grow algae, it pumps the carbonated water into an open pond and inoculates it with one of several algae strains.

Using this method, Hazlebeck says the farm could theoretically capture 90 percent of the CO_2 from the plant, which would support up to 1,000 acres of algae. He figures that if the United States stuck an algae farm next to every power plant located in an algae-friendly climate, those farms could sequester 800 million metric tons of CO_2, offsetting 198 coal-fired power plants. With that CO_2 the farms could produce 400 million metric tons of algae, which is roughly equivalent to how much protein meal the entire world currently makes in a year.

Those figures make a strong case for putting algae everywhere, but White, of Qualitas, isn't convinced. As soon as I ask her about Hazlebeck's proposal, she grabs a paper napkin and starts doing her own calculations. To qualify for tax credits for carbon sequestration under a newly proposed bill, a U.S. facility must capture at least 100,000 metric tons of CO_2 in a year (a small amount, considering that many

FRESH IDEAS: Rebecca White of Qualitas stands in front of an energy-efficient harvester at the farm. Most of the water is removed from the algae at this stage, and then recycled back into the ponds.

PHOTOGRAPH BY Amy Nordrum

Raising Algae

On farms such as Qualitas's, algae grow in large ponds and are harvested all year. This multistep process incorporates techniques from both the biofuels industry and traditional agriculture.

1


2


3


4


5


6


1. For several weeks, algae live in open ponds called raceways. Paddle wheels mix in CO_2 and nutrients and prevent the algae from settling. 2. When the algae are ready to harvest, employees crank open a valve connected to a system of underground pipes. Gravity pulls the algae down a slope in the land to a large holding pond. 3. The algae travel through a series of physical filters, including a large metal grate and two small screens that catch and remove debris. 4. The filtered algae move to a large holding tank. The metal arms on this repurposed tank can skim debris from the top layer. 5. Next, the algae pass through a harvester that removes up to 90 percent of the water between cells. Tiny straws capture the algae as the water is forced out. 6. The filtered, dewatered algae are cooled in a dairy tank and poured into totes, which are loaded into refrigerated trucks and sent to a processing facility.

PHOTOGRAPHS BY Amy Nordrum

coal-fired power plants emit millions of tons of CO_2).

To find out how much algae it would take to absorb that much CO_2, White figures that an algae farm produces about 14.5 metric tons of algae per acre per year—considered the industry standard. To produce 1 kilogram of algae, White's team uses 2.7 kg of CO_2. That means a farm with at least 2,300 acres of algae would have to be built next to each power plant. For comparison, the average U.S. farm today is 440 acres.

White is skeptical that farmers could come up with enough land and water to pull this scheme off—even with algae's advantage of growing on land and in water that's not suitable for other crops. "It's not feasible—it's aspirational," she says.

A better solution, she believes, would be to capture CO_2 directly from the air, using affordable commercial technology that doesn't yet exist but which several companies are working on. Power plants could pay to operate direct air-capture systems and give the gas to algae farms as a carbon offset. This would "significantly lower the cost of algae production" by eliminating the need to buy tanks of CO_2, White says, and it would create a kind of symbiosis between the two industries.

SMIL SAYS...

Algae reshaping the food supply as dramatically as corn and soy? Those crops are now planted on 300 million hectares. A large algal farm is 20 hectares. Do your division!

THE ALGAE INDUSTRY has had a lot of false starts. German scientists and employees of Britain's Imperial Chemical Industries independently began studying algae's potential as a food source during World War II. Around the same time, Stanford University researchers produced 45 kg of a popular edible type called *Chlorella* while piloting a concept for an algae production facility.

Needless to say, the idea didn't catch on. It may have been the taste—one report described *Chlorella* as having "a vegetable-like flavor, resembling that of raw lima beans or raw pumpkin." Testers on a flavor panel were less generous—they reported "unpleasantly strong notes," a "lingering, mildly unpleasant aftertaste," and a "gag factor."

Another reason for algae's stagnancy is that raising microalgae is a relatively new affair. That means many of the technologies that other farmers count on to plant and harvest crops are still being developed for algae. The paddle wheels that stir the Qualitas ponds were custom-built by metalworkers a few towns away.

At Global Algae Innovations, Hazlebeck is trying to change that. The company has invented a drier that he says uses one-tenth of the energy of a typical drier, and ponds that circulate algae with one-third the energy that other farms use for that purpose while producing two to three times as much algae.

Those advances could help the industry reduce its energy use and boost productivity to the point where growing algae proves both profitable and sustainable. The company is now selling the first of its inventions to other algae farms—a harvester that uses one-thirtieth the energy required to remove water from algae compared with traditional processes.

Back at the Qualitas farm in New Mexico, Aaron Smith, a technician who operates the harvester, was wiping off the window of his work station when we stopped by. He'd just pressure washed the entire system the day before, but it was already splattered with bright green goo.

The harvester's guts are made of long, slim straws with tiny holes only 0.04 micrometers in diameter. The straws fill up with wet algae, and the machine uses pressure to force most of the water through the holes, while the algae remain behind. The design borrows heavily from a system originally developed by General Electric for wastewater treatment plants—one industry where algae have successfully been put to work.

White calls this technology "a massive breakthrough for the industry." Growers will need more breakthroughs like this one to expand production—she was one of only three people who raised their hands last year at the algae industry's largest conference, when a presenter asked who there had grown more than an acre of algae.

So how long until algae overhauls our food system? Stephen Mayfield, the UC San Diego algae expert who cofounded the biofuels company that originally built the New Mexico farm, estimates the industry is 10 years from solving the remaining challenges and "hitting that tipping point to where we're going to replace bulk protein."

In the eyes of White, who grew up on a cotton farm, the algae industry is finally pointed in the right direction. And, having raised more microalgae in her career than perhaps anyone else in the industry, she has high hopes for where it could lead: "We want to be a part of every meal, every snack, every day." ■

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ILLUSTRATION BY MCKIBILLO

Breaking Big Ag's Fertilizer Addiction

To replace chemical fertilizers, "organism engineers" are designing strange new microbes. BY **ELIE DOLGIN**

BIG AG IS ADDICTED to nitrogen fertilizers. It's a massive problem for the global climate, yet it may yield to a microscopic solution: microbes rewired to "fix" nitrogen from the air and turn it into a natural type of fertilizer that corn, wheat, and other cereal crops can use. • Until the Green Revolution changed agriculture in the mid-20th century, farmers fed cereal crops either by spreading nitrogen-rich manure on their fields or by planting a legume crop (such as beans or peas) whose root systems contain microbes that naturally nab atmospheric nitrogen, and then plowing that crop under to fertilize the cereal crop they actually wanted to grow. But these inefficient methods couldn't begin to support the 7 billion people alive today. The Green Revolution ushered in a new era of chemical fertilizers, enabling farmers to feed the booming global population—but also creating a dangerous addiction.

And so, every year, the world's farmers lavish on their crops some 120 million metric tons of nitrogen fertilizer made via the century-old Haber-Bosch process. This industrial operation requires high pressure and temperature, so fertilizer factories burn a lot of fossil fuel, releasing carbon dioxide right away; later, the unused fertilizer in the soil returns to the air as nitrous oxide (N_2O), a gas that has 300 times as much heat-trapping power as carbon dioxide. The combined emissions from fertilizer production and use are equivalent in their effect to as much as 1.3 billion metric tons of CO_2 a year.

Biologists have long sought a better, cheaper, and more environmentally friendly way to fix nitrogen. They've tried to make cereal crops form symbiotic relationships with nitrogen-fixing bacteria, as legumes do. They've tried to convince bacteria such as *Azospirillum* and *Klebsiella* to set up shop in the roots of wheat and rice plants. Yet, despite more than half a century of effort, no one has yet managed to endow any of the world's major grains with a viable nitrogen-fixing bacterial partner.

Enter Joyn Bio, a Boston-based spinoff launched last September from two companies: Bayer CropScience, which boasts a vast library of agricultural microbes, and Ginkgo Bioworks, a pioneering biotech firm that creates custom-made bacteria for industrial applications.

Ginkgo's Boston research hub is home to an assembly line of robots that are programmed to manufacture, read,

GINKGO BIOWORKS

MUTANT MICROBES: Joyn Bio is trying to reprogram bacteria to give them a very particular superpower: the ability to capture nitrogen from the air and give that essential nutrient to the roots of cereal plants such as corn, wheat, and rice.

or edit strands of DNA. Joyn's idea is to synthesize variations on some of the genes that are believed to play a role in nitrogen fixation, including those involved in the cooperation between legumes and the bacteria specific to their root systems. Snippets of this synthetic DNA are then slotted by machines into microbes growing in rows of tiny fermentation chambers, before another set of automated tools characterizes the genetically altered microbes' performance every which way. Synthesize, build, test, repeat.

Joyn is hoping this engineering approach to the fertilizer-replacement challenge—combined with computational power to integrate terabytes of data into predictive metabolic models—will make the company succeed where others have failed. "Our goal is to use all the tools of synthetic biology to take naturally occurring microbes that have evolved in plants, and see what we can do in the lab to create organisms that replace significant amounts of fertilizer for crop plants," says Johan Kers, head of nitrogen-fixation research at the company. "If we can do that, we'll have a big party."

THEY MAY HAVE a lot of guests to invite. Joyn is structured like a scrappy startup, with fewer than 20 full-time employees split between research sites in Boston and West Sacramento, Calif. But as a joint venture between Bayer—which will become the world's largest supplier of seeds and crop chemicals after its US $62.5 billion buyout of Monsanto—and Ginkgo, one of only a handful of private biotech companies valued at more than $1 billion, the spinoff has ample resources.

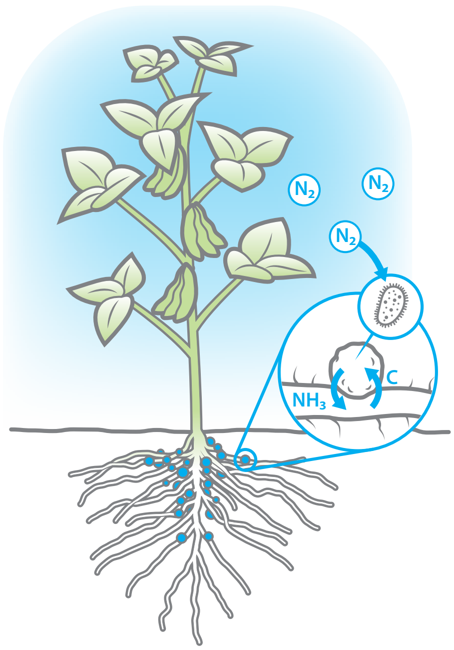
The lab space and microbial production capacity comes from Ginkgo, the bacterial strains and greenhouses from Bayer. The parent companies, together with a hedge fund, also put in $100 million to bankroll Joyn's R&D operations over the next five years. "These things all came in on day one, so we're really hitting the ground running," says Joyn CEO Mike Miille.

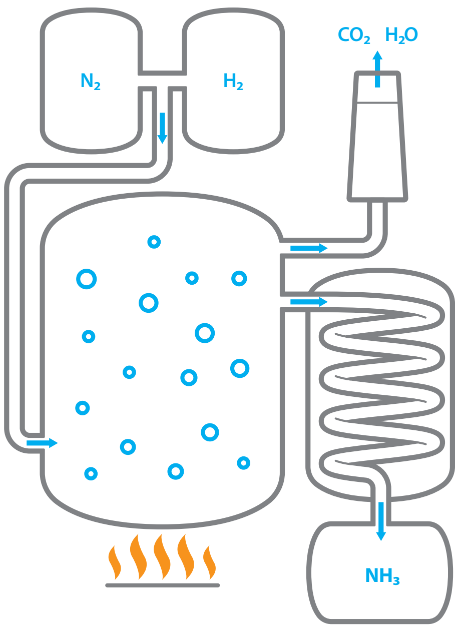
Joyn has already sequenced the genomes of around 20 different bacterial species, all of which naturally take gaseous nitrogen from the air and use enzymes to convert it into ammo-

How to Feed a Plant

NATURE'S WAY: In the root nodules of a bean plant, nitrogen-fixing bacteria use enzymes to convert atmospheric nitrogen into ammonia. The bacteria give that essential nutrient to the plant in exchange for carbon-based sugars.

INDUSTRY'S WAY: In a fertilizer factory, the Haber-Bosch process combines atmospheric nitrogen with hydrogen from natural gas to produce ammonia. The reaction chamber requires temperatures of 400 °C (752 °F) or higher and pressures upwards of 20 megapascals (200 atmospheres). The factory uses a huge amount of electricity to maintain these conditions, and also emits CO_2 as a by-product of the reaction.





nia, which plants use to make DNA, proteins, and other essential building blocks of life. Some of these critters use the same well-characterized enzymes found in the nitrogen-fixing bacteria that live in the root nodules of legume plants, differing only in that they don't naturally share their biochemical bounty with crops. Others may use weird new enzymes that have yet to be discovered because no one has ever embarked on this kind of screen. "We're sampling the solution space for this engineering problem," Kers says.

Once Kers and his team close in on a few enzyme-encoding genes of interest, the next steps will largely be outsourced to Ginkgo's foundries, so named to evoke metallurgic factories that manufacture metal parts to exacting specifications. At Ginkgo HQ, these foundries form a glass-encased core that expanded late last year and now spans the length of two football fields. There, software and robotics automate much of the drudge work of organism design.

That kind of process engineering and rapid prototyping is unparalleled in the biotech industry, says Paul Miller, chief scientific officer of Synlogic, a Boston-area company that's partnering with Ginkgo to develop microbial therapeutics for diseases. "Ginkgo is really a world leader when it comes to a massively parallel engineering capability and the ability to iterate around organism-design ideas on a large scale," Miller says.

For Joyn, the tight relationship with Ginkgo means it can build hundreds of engineered microbes with slight variations in one or more genes. Foundry scientists, called organism engineers, can test the performance of each microbe through chemical analyses on a mass spectrometer. Kers and his colleagues can study the data, input it into their model, and order a new batch of engineered bugs. Those that look promising are shipped off to West Sacramento for further evaluation alongside corn plants raised in greenhouses and, eventually, in the fields.

BOOSTERS OF SYNTHETIC biology think the design-build-test framework that has proven itself in Silicon Valley will also work in microbial engineering. "These are some of the smartest and most talented people in the business," says Andrew Hessel, a biotechnologist who until recently worked as a researcher at Autodesk Life Sciences, which builds software for biological design. "People have been trying to hack this forever, and now they actually have the tools to do it for real."

But nitrogen fixation is not merely an engineering challenge; it's also an ecological one. "And boy, has it proven tricky," warns Allen Good, a plant scientist at the University of Alberta, in Canada. "It's one thing to take a piece of DNA and put it in bacteria and get it to fix nitrogen," he says. "But to build

ILLUSTRATION BY James Provost

a symbiotic relationship is so much more complex than that."

In the root system of a bean plant, bacteria supply the plant with ammonia and receive sugar in return. Both sides profit—that's the essence of symbiosis. But if you engineer a strain of bacteria to give ammonia away, you force it to incur a cost that nonengineered bacteria don't shoulder. Naturally occurring microbes may therefore outcompete the engineered ones, eliminating them quickly. You could get around the problem by engineering symbiosis—by getting the plant to reciprocate—but that isn't easy to do. Cereals and nitrogen fixers don't play nice together. And, like a teacher trying to cajole a classroom full of selfish toddlers to share their toys, scientists have struggled to promote cooperation in the soil. "You really need to have a signal exchange between partners—between the plant and the microbe," says Philip Poole, a plant microbiologist at the University of Oxford.

In addition to the scientific challenge of engineering microbes and plants, there's also a societal one: Consumers are still distrustful of genetically modified organisms (GMOs) in foods, and the designation brings additional regulatory scrutiny. There are, however, ways of using the tools of synthetic biology that tiptoe up to the GMO line without crossing it—for example, by mutating bugs at random and then selecting for the best ones. That's the strategy of Pivot Bio, one of the few other companies developing nitrogen-fixing bugs. Pivot, based in Berkeley, Calif., starts with microbes that can naturally capture airborne nitrogen but fail to do so in agricultural settings. The company characterizes these critters with all the fanciest genomic tools available, building computational models to better understand gene circuitry, then tries to breed progeny that don't have the feedback mechanisms that normally shut off nitrogen fixation in fertilizer-rich soils.

"My team has the best synthetic biologists in the world, and they can do the craziest transgenic things out there," says Pivot's CEO and founder, Karsten Temme. "But we've put on handcuffs and said we're not going to build transgenic microbes because that's not culturally acceptable, and it means you have to go through a regulatory process to get approvals."

NOT SO JOYN. According to Brynne Stanton, head of metabolic engineering at the company, Joyn will use all the synthetic biology tools at its disposal. Only later, if Joyn succeeds in engineering a robust nitrogen-exchanging symbiosis with corn, will the company see if it's possible to get to the same end products in a way that doesn't get them slapped with a GMO label. "We are really starting with a blank slate," says Stanton, as she sips from a can of coconut water that bears the words "non-GMO" on its label.

Many leading experts, even some who work with Pivot, applaud this approach. "To be able to reach a product that's not GMO—at this point, I don't see how that would be possible," says Jean-Michel Ané, who studies plant-microbe interactions at the University of Wisconsin-Madison and serves on Pivot's scientific advisory board. In his academic research, Ané is coleading a $5.1 million project called Synthetic Symbioses, which is taking the genetic engineering strategy one step further: modifying DNA of both corn and a nitrogen-fixing microbe so they're fully reliant on each other. Others, like Luis Rubio, a biochemist at the Technical University of Madrid, are trying to cut the microbe out of the equation entirely and simply engineer the ability to fix atmospheric nitrogen into the plants themselves, which would then be self-fertilizing.

Whatever works, the initial commercial products from Joyn or its rivals will likely displace only small amounts of chemical fertilizer, maybe 10 to 20 percent, executives say. That modest reduction might help limit local impacts, such as air and water pollution, but "it wouldn't make much of a dent in global N_2O emissions unless combined with other nitrogen best-management practices," says David Kanter, an environmental scientist at New York University who studies nitrogen pollution.

These companies have to start somewhere, though—and in Pivot's case, that means deploying its nitrogen-producing microbes alongside traditional fertilizers in large-scale field testing taking place this growing season on farms across the U.S. corn belt. "Eventually," says Pivot's Temme, "we want to replace all the fertilizer."

Mille, of Joyn, has equally lofty ambitions. "Nobody is sitting here saying this is easy. There are a whole bunch of things that are unpredictable," he says. But, he adds, "this is really going to push the technical boundaries forward." As his company's organism engineers work through their design-build-test cycle, they just might find an unpredictable little microbe with big potential. ■

SMIL SAYS...

Unfortunately, symbiosis does not come free; legumes pay a considerable price for sharing their photosynthetic products with bacteria.

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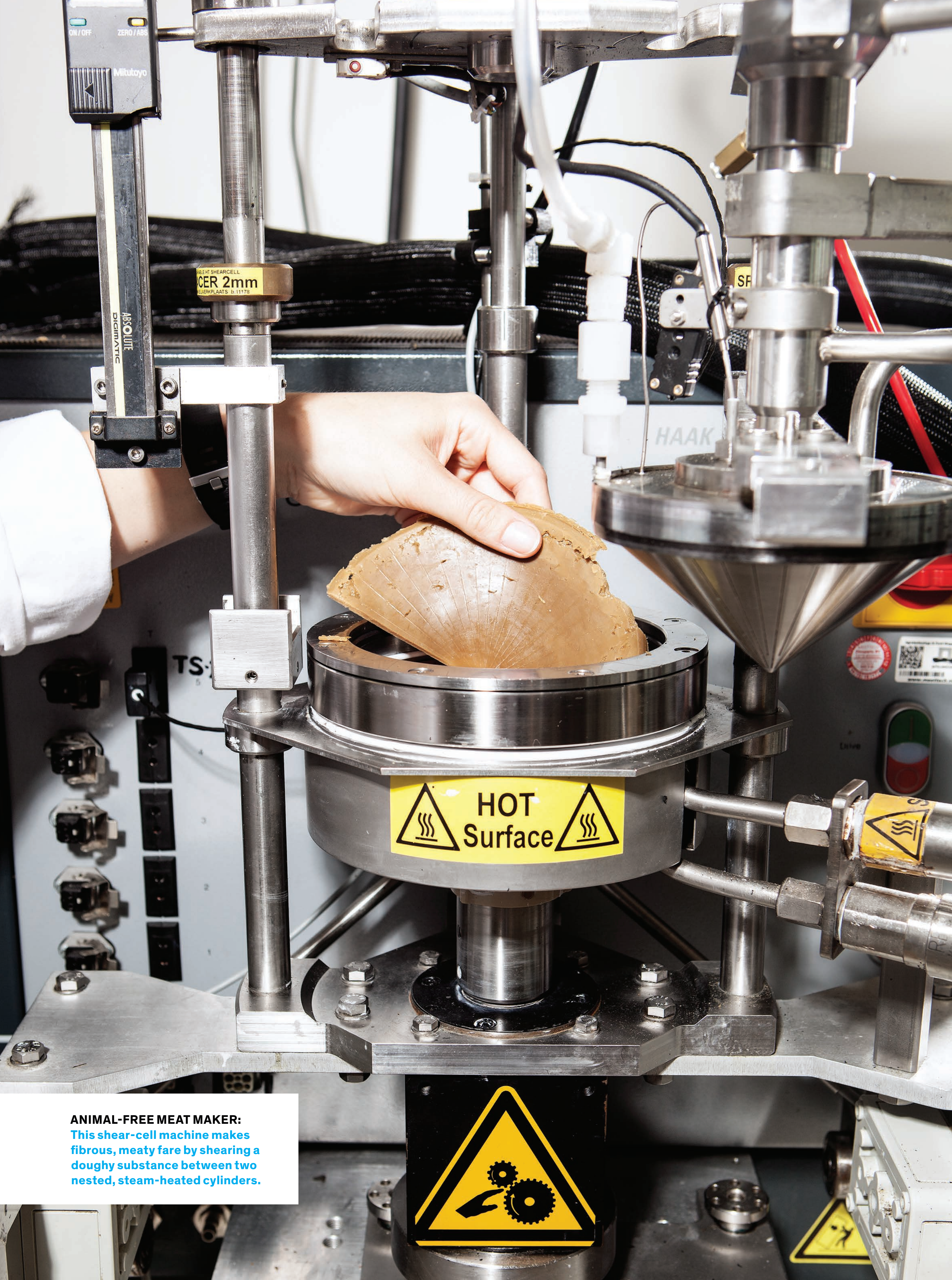
ILLUSTRATION BY MCKIBILLO



ANIMAL-FREE MEAT MAKER:
This shear-cell machine makes fibrous, meaty fare by shearing a doughy substance between two nested, steam-heated cylinders.

BLUEPRINTS *for a* MIRACLE

PART 3: FOOD

What Will the Food Miracle Be?

A really good fake steak could cut greenhouse gas emissions. That's the point of a Dutch inventor's radical meat-making machine BY DOUGLAS HEINGARTNER

ATZE JAN VAN DER GOOT removes a laptop-size slab from a refrigerator and deposits it on a table with an icy thump. It's a reddish-brown mass, with clearly visible fibrous striations. And though it's half frozen, it's still pliable: You can pick away small pieces with your fingers, but it retains its shape, just like a hunk of frigid raw beef would. • This is no ordinary fake steak. For one thing, it has attracted the interest–and money–of some of the world's leading food conglomerates, including Unilever, the Swiss flavor maker Givaudan, and Avril Group, the Paris-based agro-industrial concern. Then, too, it was not made with an ordinary food extruder, like most meat substitutes on the market today. Rather, it was produced with a new and radically different kind of machine. This machine was designed by Van der Goot to do one thing extraordinarily well: turn vegetable-based ingredients into something so similar to meat that it can grab a healthy share of the fast-growing market for meat substitutes, which was estimated at US $4 billion last year by the research firm Visiongain, in London.

There's more than money at stake here. The global meat industry is the source of about 15 percent of greenhouse gas emissions, or roughly as much as what comes from all the vehicles on the planet. Producing the beef in just one hamburger creates about the same amount of greenhouse gases, in carbon-dioxide equivalents, as driving a Mazda Miata 60 kilometers.

And it's going to get worse. The United Nations predicts that as the global population grows from 7.6 billion today to 9.8 billion by 2050, more countries will industrialize, and food production will soar by 60 percent. At the same time, global meat consumption will surge because as people become more prosperous, they tend to consume more meat and dairy. In 2014, about 315 million metric tons of meat were produced worldwide, and the U.N.'s Food and Agriculture Organization (FAO) figures that will increase to 455 million metric tons by 2050.

"Using animals as a technology for food production worked when we had millions of people, maybe up to a billion people," says Nick Halla, the chief strategy officer of Impossible Foods, of Redwood City, Calif., whose plant-based burger has been rolling out to favorable reviews in the United States. "But it doesn't work now that we have 7 billion going on 10."

COWS ARE A REMARKABLY inefficient food source. Barely 4 percent of the calories a cow eats becomes beef that people

NIELS BLEKEMOLEN

WHERE'S THE BEEF? It's not here in the laboratory of Atze Jan van der Goot, a professor at Wageningen University & Research, in the Netherlands. Van der Goot [right] and an assistant have produced a vegetable-based meat substitute, visible on the bench at left.

NIELS BLEKEMOLEN

can eat. Producing 1 kilogram of protein from beef uses about 18 times as much land, 10 times as much water, 9 times as much fuel, 12 times as much fertilizer, and 10 times the amount of pesticides as producing the same amount of protein from kidney beans. And beef production occupies almost 60 percent of the world's agricultural land, even though it accounts for less than 2 percent of the calories consumed by the world's population.

"It would be hard to imagine a more inefficient means of producing protein," says Liz Specht, a biologist with the nonprofit Good Food Institute. "Raising animals for food," she declares, "is one of the top contributors to every single one of the most severe environmental problems plaguing us."

Scores of organizations, including startup companies and multinational conglomerates, are now pursuing alternatives to meat in general and beef in particular. The work isn't part of an organized effort to lower greenhouse gas emissions, but if it succeeds, it will have that effect.

Plant-based meat analogues are a growing business—the global market is expected to swell to $5.8 billion by 2022, according to the market research firm Million Insights. Across the board, production of these surrogates is associated with much lower greenhouse gas emissions than actual meat is, according to an analysis of 39 meat substitutes conducted by the Federation of American Societies for Experimental Biology.

Replicating meat convincingly, however, is no mean feat. Meat consists of muscle, fat, water, connective tissues, amino acids, and minerals, all of which have to be created and blended with exquisite precision to produce flavors, textures, aromas, and cooking properties to which many people have become accustomed. Companies such as Impossible Foods and Beyond Meat are selling generally well-regarded ground-beef substitutes, so the race now is to the next logical step: a product that has both the taste and springy, fibrous mouthfeel of genuine muscle meats, such as beefsteak.

A fake steak is much more difficult to produce than a good stand-in for ground meat. Researchers are pursuing two main avenues: cultured meat, and vegetable-based meat substitutes. Cultured meat is also known as lab-grown meat, cellular meat, in vitro meat, or, as its adherents like to say, "clean meat." To produce it, researchers start with self-renewing cells, such as embryonic or pluripotent stem cells, from animal tissue. They then create genuine meat by culturing and multiplying those cells in a nutrient mix in a bioreactor.

Cultured meat was thrust into the media spotlight in 2013 when Mark Post, a professor at Maastricht University, in the Netherlands, unveiled his cultured meat burger, which cost about $330,000. A pair of taste testers found it underwhelming. Nevertheless, three companies—San Francisco-based Just and Memphis Meats, and MosaMeat in the Netherlands—have announced plans to bring cultured meats to market in the near future. A fourth company, SuperMeat, in Israel, recently raised $3 million in seed funding.

Just (known until recently as Hampton Creek Foods), which already sells a range of plant-based foods, is the most specific about its near-term plans. The company's head of communications, Andrew Noyes, said in April that Just plans to have a cultured-meat product for sale by the end of this year.

Cultured meat has a lot going for it. Unlike real meat, its production wouldn't generate toxic runoff, and it wouldn't spawn bacterial superbugs. Producers could precisely control the proportion and type of fats in the product, tweaking its flavor and nutritional content. And unlike plant-based analogues, cultured meat actually is meat, so in theory, it wouldn't require consumers to adapt to new flavors, textures, or cooking methods.

But against these advantages must be weighed some sobering difficulties. One of the biggest technical challenges is choosing the nutrient mix in which the muscle cells are cultured and encouraged to grow into muscle fibers. Most of the work so far has used fetal bovine serum, which is harvested from cow fetuses. It's expensive and not at all compatible with the sustainability and ethical imperatives driving the development of meat alternatives.

So researchers are now investigating a wide assortment of nonanimal serum alternatives–for example, ones based on algae or mushroom extracts. These solutions, or "substrates," contain varying proportions of oxygen, sugar, vitamins, minerals, and, typically, compounds selected from a vast array of amino acids, growth factors, and other biological agents. At the Swiss Federal Institute of Technology (ETH), in Zurich, food technologist Alexander Mathys says it would be "a clear game changer" if another kind of medium could be successfully developed.

Just, Memphis Meats, and SuperMeat all insist they are close to solving the serum problem, but they decline to give any details.

Another problem is the very high costs of cultured meat. Memphis Meats CEO Uma Valeti claims that the company's production costs have dropped "dramatically" since mid-2017, when the costs had fallen below $2,400 per pound ($5,300 per kilogram).

In terms of sustainability, there's no guarantee that the production of lab meat will use less energy than animal-grown meat. The few analyses that have been carried out so far have been inconclusive. In a 2015 study in the *Journal of Integrative Agriculture*, Carolyn S. Mattick and her colleagues considered the type of energy inputs that might be needed for a full-scale cultured-meat production facility: The facility itself would need to be built, large quantities of growth media would need to be produced and heated to the right temperature, the massive bioreactor tanks would need to be frequently cleaned and drained, various materials would need to be shipped in, and much of the water involved in the production process would need to be sterilized. Although cultured meat will certainly use less land and water than livestock production, "those benefits could come at the expense of more intensive energy use," the authors wrote.

Specht, at the Global Food Institute, cautioned that the life-cycle analyses that have been done so far "are based on cell-culture operations for biopharma production, which may be of little relevance to food applications." Cultured meat is also expected to beat conventional meat on greenhouse gas emissions, but mostly because of the absence of methane production (cows and sheep belch quite a lot, it turns out).

LARGER REDUCTIONS in greenhouse gas emissions would come from a wide embrace of vegetable-based meat sub-

FAKE STEAK: The current version of the Couette-cell machine in Van der Goot's laboratory can produce meatlike, fibrous slabs nearly 3 centimeters thick.

ROBIN UTRECHT

DINNER IS SERVED: Atze Jan van der Goot holds the most recent version of his plant-based steaks, which are produced from soy protein and wheat gluten.

ROBIN UTRECHT

stitutes, which are now a hotbed of tech innovation. Though puny when compared to global meat sales, the multibillion-dollar market for meat substitutes is growing briskly and has attracted interest from technologists, researchers, and venture capitalists.

Van der Goot, whose academic career began in fluid-dynamics research, has been developing his machine for more than a decade, together with colleagues at Wageningen University & Research and at Delft University of Technology, both in the Netherlands. He calls it a Couette-cell machine, and it looks like a shiny makeshift version of the meat slicer you'd find at your local deli, with duct-taped tubes connecting various cylindrical parts.

When the project started, few people were interested and even fewer companies, Van der Goot says. But after the prototype machine was unveiled in 2015, companies started lining up. In 2017, a consortium called Plant Meat Matters was launched to commercialize the technology, with partners currently including Givaudan, Unilever, and Dutch meat-analogue maker The Vegetarian Butcher. The consortium now has a waiting list. The prototype was designed together with TU Delft, but new machines will be built, a bit ironically, by Meyn Food Processing Technology, a Dutch manufacturer of poultry-slaughtering equipment.

Van der Goot's machine updates a method called extrusion, which is how most plant-based meat replacements are made today. Food extruders, which have been producing breakfast cereals, pasta, snacks, and pet foods for decades, use high pressures and temperatures to squeeze a doughy mixture through a tube. A cooling step then causes the smooshed proteins to solidify, eventually rolling out of the device as crumbly pieces. The most popular variant, known as high-moisture extrusion cooking, blends the ingredients together while the water-rich mixture is heated to 130 to 180 °C.

The Couette-cell machine is a stripped-down version of an extruder. It has two nested cylinders, one of which spins while the other is fixed. This motion creates linear shearing as the "dough" is stretched out between them. The spinning pulls the proteins in a single direction, causing meatlike fibers to appear spontaneously. These fibers are key to replicating the look and texture of muscle meats, as opposed to ground meats.

In addition to creating a more realistic, meatlike product, the shear-cell machinery uses less power than does traditional extrusion. Both processes require thermal energy to heat the machines and materials and mechanical energy to shear or mix the materials (and, in the case of traditional extrusion, to push them through a die). In fact, traditional extruders use slightly less thermal energy, but the Couette machinery uses 90 percent less mechanical energy, Van der Goot says, and that's where the technology's main energy and cost savings come from. "If the process requires less mechanical energy," he says, "then we need a smaller engine, and the wear on the shear-cell motor will be far less." The upshot is cheaper equipment and lower maintenance costs.

Van der Goot shows me one of his recent creations: a slab that looks stunningly like beefsteak. It's about 3 centimeters thick, 60 cm long, and 25 cm wide. Although the lab was not set up for a tasting on the day I visited, Van der Goot's team insists that the slab cooks and cuts like an actual steak. If true, that would be a big improvement over essentially all of the plant-based beef analogues currently in supermarkets, which mimic ground beef rather than steak and take the form of tiny chunks that have been smooshed together to form a patty or meatball.

To make the steaklike slab, Van der Goot starts with a mixture of soy protein isolate (a highly purified form of soy protein), water, and wheat gluten, which is required to create the fibrous structures. The water and soy isolate are mixed together and left to rest for about 30 minutes, as this "prehumidification" period enhances the later protein structuring. The gluten is added last, to prevent globules from forming.

This water/soy isolate/gluten mixture is then quickly poured into the Couette device through a tube, until the space between the two cylinders (known as the shearing zone) is completely filled with the mixture. The material is then heated to 95 °C and spun at a modest 30 rpm for about 15 minutes, as the heat helps to solidify the fibrous structures created during the shearing. Experiments have found that these fibrous structures won't appear at temperatures higher that 100 °C or lower than 90 °C.

"It's mild and simple," Van der Goot says of the shear-cell process, "and that is also why it can be very inexpensive." He envisions a scenario where the local butcher shop would have a small version of the machine on a countertop to create artisanal blends at will. His team has experimented with alternative mixtures of peas or lupines, but so far getting the right texture has proved difficult. That's why one of the goals of the Plant Meat Matters consortium is figuring out how ingredients other than soy can be used in such mixtures.

Van der Goot acknowledges that his latest machine is not yet ready for commercial production, but he's confident it will be within a couple of years. Biologist Specht, of the Good Food Institute, thinks the machine could be well received. "The capital expenditure associated with the high-moisture extruders that many plant-based meats use is a significant bottleneck," she says, "so a lower-cost production strategy can certainly democratize access to plant-based meat."

THOUGH MEAT-FREE OPTIONS are steadily improving in quality and growing in number, expanding their availability beyond upscale outlets such as Whole Foods in the United States isn't going to be easy. A Finnish study from February 2018 found that while messages pointing out the negative health and environmental consequences of meat had some effect on people who already believed that meat is unhealthy and unsustainable, they had hardly any effect on everyone else.

And yet, the need to cut back on the amount of energy used in producing protein is becoming increasingly urgent. Besides the emissions, raising billions of animals for food takes up 26 percent of the planet's ice-free surface, land that could otherwise be used for CO_2-absorbing forests or to grow more efficient high-protein plants.

Ultimately, there will probably be not one large food miracle but many small ones. Plant-based and cultured meats will coexist. "I believe that 30 years out, both will be on the market and will occupy significant fractions of market share," says Specht. "Visionaries like Bill Gates are investing in both plant-based and clean meat, as are huge companies like Tyson Foods. They see this as a two-pronged solution."

Another possibility is that people will start eating more chicken and eggs rather than cows and lambs, notes Peter Alexander, a land-use researcher at the University of Edinburgh. Alexander recently authored a study that hailed plant-based meat substitutes and insects (yes, insects) as the most sustainable long-term food solutions, but also noted that similar environmental benefits would accrue if people simply ate a lot more chicken and eggs and a lot less beef.

"Sure, there are potentially transformatory changes that we could have," Alexander says, "but in order to achieve those, we have to imagine consumers radically altering their preferences, which just doesn't seem likely."

"Our goal is to drastically reduce the impact of our agriculture system on the world," says Halla of Impossible Foods, capturing the driving motivation of the bustling new industry growing up to produce meat alternatives. "If we can create better products than animals can, and that people like better–and we are approaching that–then it will be an easy choice for consumers to switch. We can create a much more sustainable food system." ■

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SMIL SAYS...

Eating less meat (above all, less beef) and wasting less food are environmentally less burdensome and healthier than producing meat substitutes.

ILLUSTRATION BY MCKIBILLO

It'll Be Harder Than We Thought to Get the Carbon Out

Even if the proposed ways to reduce greenhouse gases work, they'd need decades to make a real difference

BY **VACLAV SMIL**

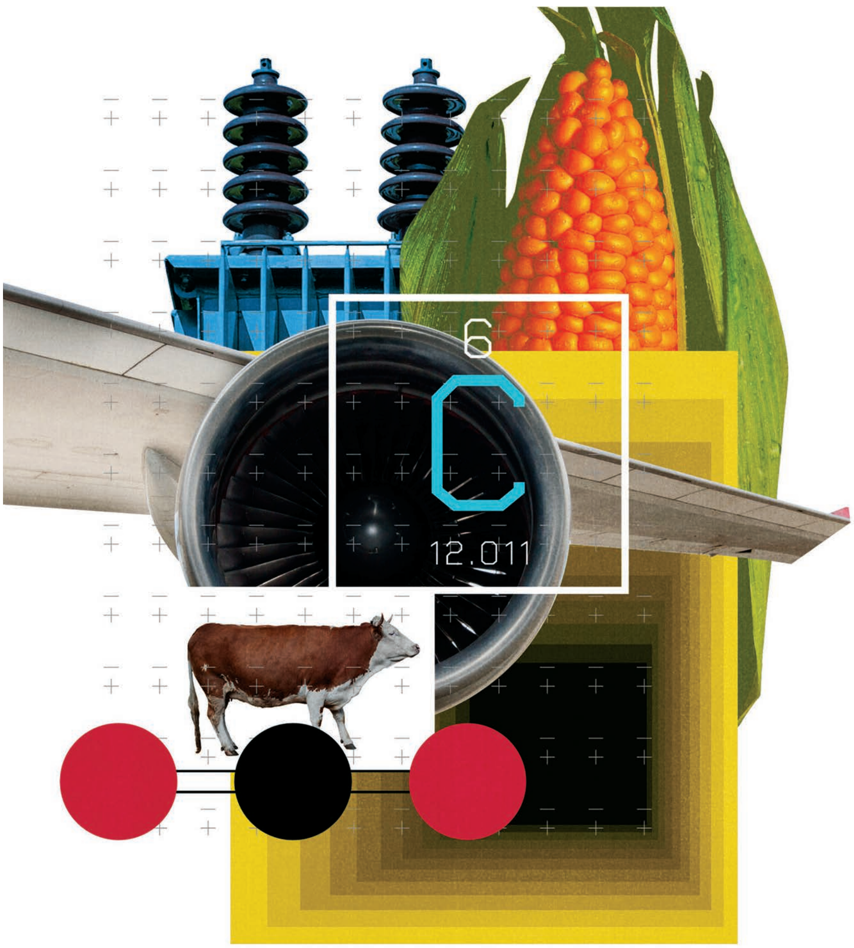
WHEN A BRIGHT NEW idea comes along, it's easy to imagine a fantastic future for it. Perhaps the best example of this is Ray Kurzweil's Singularity, scheduled to arrive in 2045, which will supposedly bring "immortal software-based humans, and ultrahigh levels of intelligence that expand outward in the universe at the speed of light." Not to be left behind, a former Google X senior executive says that "everything you see in sci-fi movies is going to happen." Not just something, mind you, but *everything*.

• Compared with such utterly ahistorical visions, unmoored from reality, the articles gathered in this issue are actually quite tame. They promise only a long-lasting supply of affordable and clean energy—either through nuclear fission or through electricity derived from burning (yes, burning) CO_2—and a surfeit of food from a variety of sources: vertical farms based in cities, crops that will need almost no fertilizer, and environmentally friendly meat substitutes.

Of course, these claims of impending innovation may be seen (although they are not labeled as such) as being largely aspirational—but the benefits would be great if even just a fraction of their goals were realized during the next generation.

At the same time, these claims should be appraised with unflinching realism. I would not presume to offer specific, in-depth critiques of proposed innovations even if I had 300 instead of three pages to work with. Instead, I will just point out some nontrivial complications pertaining to specific proposals, and above all, I will stress some fundamental systemic considerations that are too often ignored. These are not arguments against the need for some form of the techniques that are promoted here but rather cautionary reminders that many of today's ambitions will not become tomorrow's realities. It's better to be pleasantly surprised than to be repeatedly disappointed.

Human beings have always sought innovation. The more recent phenomenon is this willingness to suspend disbelief. Credit this change to the effect that the electronics revolution has had on our perceptions of what is possible. Since the 1960s, there has been an extraordinarily rapid growth in the number of electronic components that we can fit onto a micro-



chip. That growth, known as Moore's Law, has led us to expect exponential improvements in other fields.

However, our civilization continues to depend on activities that require large flows of energy and materials, and alternatives to these requirements can't be commercialized at rates that double every couple of years. Our modern societies are underpinned by countless industrial processes that have not changed fundamentally in two or even three generations. These include the way we generate most of our electricity, the way we smelt primary iron and aluminum, the way we grow staple foods and feed crops, the way we raise and slaughter animals, the way we excavate sand and make cement, the way we fly, and the way we transport cargo.

Some of these processes may well see some relatively fast changes in decades ahead, but they will not follow microchip-like exponential rates of improvement. Our world of nearly 8 billion people produces an economic output surpassing US $100 trillion. To keep that mighty engine running takes some 18 terawatts of primary energy and, per year, some 60 billion metric tons of materials, 2.6 billion metric tons of grain, and about 300 million metric tons of meat.

Any alternatives that could be deployed at such scales would require decades to diffuse through the world economy even if they were already perfectly proved, affordable, and ready for mass adoption. And none of the innovations presented in this issue fits fully into that category. In fact, these three critical prerequisites are notably absent from nearly all of the innovations presented in this issue.

Most of the articles do acknowledge that difficulties lie ahead, but the overall impression is one of an accelerating advance toward an ever more remarkable future. That needs some tempering. Today, we can fly for up to an hour in a two-seat, battery-powered trainer plane; in a decade, perhaps we'll fly in a battery-assisted regional hybrid plane. The savings in energy use and in carbon emissions will be modest–and we are a very long way from all-electric intercontinental airliners.

The traveling-wave nuclear-fission reactor [p. 30] has many obvious advantages over the dominant pressurized water reactor, including remarkably safe operation and the ability to use spent nuclear fuel. But our experience with developing fast-breeder reactors, which are cooled with molten sodium, indicates how extraordinarily challenging it can be to translate an appealing concept into

PHOTO-ILLUSTRATION BY Stuart Bradford

a commercially viable design. Experimental breeder prototypes in the United States, France, and Japan were all shut down many years ago, after decades of development and billions of dollars spent.

Vertical farms [p. 50] in cities can produce—profitably—hydroponically grown leafy greens, tomatoes, peppers, cucumbers, and herbs, all with far less water than conventional agriculture requires. But the produce contains merely a trace of carbohydrates and hardly any protein or fat. So they cannot feed cities, especially not megacities of more than 10 million people. For that we need vast areas of cropland planted with grains, legumes, and root, sugar, and oil crops, the produce of which is to be eaten directly or fed to animals that produce meat, milk, and eggs. The world now plants such crops in 16 million square kilometers—nearly the size of South America—and more than half of the human population now lives in cities. The article in this issue acknowledges that vertical farms can't substitute for much farmland, and that the claims made for it have been exaggerated.

Crops that get their nitrogen by fixing it from the air [p. 62] would largely eliminate the need for synthesizing and applying the most important plant macronutrient. Today, only legumes (and some cultivars of sugar cane) coexist with symbiotic nitrogen-fixing bacteria; imparting this symbiotic ability to staple grains would be a feat rivaling the outcome of a long evolutionary process. But symbiosis does not come free, and bacterial nitrogen fixation is not as reliable as fertilizer application. Legumes pay a considerable price for sharing their photosynthetic products with bacteria. The average yield of U.S. corn is now about 11 metric tons per hectare, and it needs about 160 kilograms of nitrogen per hectare; U.S. soybeans yield 3.5 metric tons per hectare while receiving only a small, supplemental application of about 20 kg of nitrogen per hectare. When at last we make grain crops symbiotic with nitrogen-fixing bacteria, will they maintain their high yields? And how uniformly will future engineered microbes perform in different soils and climates, and with different crops?

Meat substitutes and cultured meat [p. 66] are meant to reduce the environmental burdens associated with meat production. But a better, less burdensome solution would simply be to moderate our eating of meat. Good nutrition does not require annually consuming nearly double your weight in meat—100 kg per capita in some developed countries, such as the United States. Producing just 30 kg per year for 8 billion people could be done with well-managed grazing and by feeding herds the residues from crop and food processing, together with some of the enormous quantity of food that's now wasted.

Using emitted carbon dioxide in fuel cells [p. 22] and burning supercritical CO_2 to run turbines [p. 26] constitute the latest in an increasing array of techniques aimed at reducing emissions of the leading greenhouse gas. These efforts at carbon capture and storage began decades ago and have increased since 2000, but all operating projects and those under construction have an annual capacity equal to just 0.3 percent of annual emissions from stationary sources (less than 40 million metric tons compared with some 13 billion metric tons). This is another perfect illustration of the scale of the challenge. All of the carbon-capture projects now scheduled to start operating at various dates during the 2020s would not even double today's minuscule rate of carbon capture.

Electric vehicles [p. 46] are the latest darling of the media, but they run into two fundamental constraints. EVs are meant to do away with automotive carbon emissions, but they must get their electricity somehow, and two-thirds of electricity worldwide still comes from fossil fuels. In 2016, electricity produced by wind and photovoltaic solar still accounted for less than 6 percent of world generation, which means that for a long time to come the average electric vehicle will remain a largely fossil-fueled machine. And by the end of 2017, worldwide cumulative EV sales just topped 3 million, which is less than 0.3 percent of the global stock of passenger cars. Even if EV sales were to grow at an impressive rate, the technology will not eliminate automotive internal combustion engines in the next 25 years. Not even close.

Battery- or fuel-cell-powered designs for small ferries and river barges (see "The Struggle to Make Diesel-Guzzling Cargo Ships Greener" online) offer a transport capability orders of magnitude below what's required to propel the container ships that maritime trade depends on. Compare these little boats with the behemoths that move containers from the manufacturing centers of East Asia to Europe and North America. The little electric vessels travel tens or hundreds of kilometers and need the propulsion power of hundreds of kilowatts to a few megawatts; the container ships travel more than 10,000 kilometers, and their diesel engines crank out 80 megawatts.

Battery-powered jetliners [p. 42] fall into the same category: The big plane makers have futuristic programs, but hybrid-electric designs cannot quickly replace conventional propulsion, and even if they did, they wouldn't save vast amounts of carbon emissions. If you compare a small, battery-powered trainer with a Boeing 787 and multiply capacity (2 versus 335 people), speed (200 vs. 900 kilometers per hour) and endurance (3 vs. 17 hours), you'll see that you need batteries capable of storing three orders of magnitude more energy for their weight to allow for all-electric intercontinental flight. Since 1950, the energy density of our best batteries has improved by less than one order of magnitude.

The human craving for novelty is insatiable, and in a small matter you can meet it in no time at all, particularly when Moore's Law can help you. It took a single decade to come up with entirely new mobile phones. But you just can't replicate that pace of adoption with techniques that form the structure of modern civilization—growing food, extracting energy, producing bulk materials, or providing transport on mass scales. While it is easy to extoll—and to exaggerate—the seductive promise of the new, its coming will be a complicated, gradual, and lengthy process constrained by many realities. ■

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That's just a small fraction of the CO_2 emitted by the facility. To put things in perspective, a typical 500-MW coal plant emits about 3.3 million metric tons of carbon dioxide per year—which works out to about 9,000 metric tons per day—and so capturing 90 percent of those emissions would require about 400 MW of fuel cell capacity.

That's a lot of fuel cells. In terms of capital investment, fuel cell power is three to four times as expensive as conventional coal power. With a carbonate fuel cell, the cogenerated heat and electricity could boost the host plant's power output by 80 percent. Advocates point out that when full life-cycle costs are taken into account, along with the difficult-to-quantify environmental benefits, the balance begins to favor such a combined cycle.

STACK OF CELLS: **Each fuel cell module consists of 400 individual carbonate fuel cells. A 2.8-megawatt unit contains two such modules.**

BOB O'CONNOR

AT THE MOMENT, though, the partners on the Barry project are a long way from building such a system. For starters, in order to integrate carbon-capturing fuel cells with a coal-fired plant, you need a way to fuel the fuel cells. Regular coal isn't suitable, so you'd have to gasify it first, which adds complexity and cost.

So, paradoxically, FuelCell Energy's coal exhaust experiment will be fueled by natural gas, which is one of the reasons that the Barry plant was selected as the host site. A hybrid coal/natural gas facility, the plant is itself a bellwether of U.S. energy trends. As built in 1954, the station was an all-coal operation, and by 1971 its original two generators had been joined by three more coal-fired units. Then, in 2000, Southern installed five natural-gas-fired units, and in succeeding years, it moved to phase out coal, shutting down one coal unit in 2015 and converting two others to gas.

SMIL SAYS...

All the projects that are now in advanced and early stages of development would not even double the current minuscule rate of carbon sequestration.

Another attraction of the Barry plant is that it's already hosted a demonstration of carbon capture and sequestration. In partnership with the DOE, Southern used Mitsubishi Heavy Industries' amine process to chemically fix the carbon from coal-fired exhaust and then pipe it for storage in an oil field 19 kilometers away. The project, which ran from August 2012 to September 2014, sequestered about 104,000 metric tons of CO_2. (Another coal plant, operated by Southern in Kemper, Miss., was supposed to showcase a different method of carbon capture, but last year the company announced that the site would simply switch to natural gas without capturing any of the emissions.)

In a second phase of the project involving ExxonMobil, FuelCell Energy will adapt its technology to decarbonize natural gas exhaust. That will entail a somewhat different process, which the energy giant will help sort out. Tim Barckholtz, an ExxonMobil senior science advisor, says that when his company first heard about FuelCell Energy's pioneering work in carbon capture, it proposed a collaboration, which began in 2014.

In principle, it's simpler to capture carbon from natural gas exhaust than from coal exhaust, Barckholtz says. "Gas turbines have half as much CO_2 per electron as a coal-fired power plant does, so your job is half as big."

In practice, though, integrating the fuel cells with any type of power plant brings surprises. "In the stand-alone mode, the carbonate fuel cell is operating in ideal conditions," Barckholtz explains. "But when you couple it to a big power plant, it's kind of the tail wagging the dog." A delicate "balance of plant" must be maintained when working with combined cycles like this. Otherwise, the plant can trip off. Ironing out such issues will occupy ExxonMobil scientists and engineers in the months to come.

In the meantime, says FuelCell Energy's Leo, his company is focused on building the coal exhaust portion of the experiment. When ready for operation in early 2019, the fuel cell system will run for about six months before switching to natural-gas exhaust. If history is any guide, expect incremental developments instead of breakthroughs.

That such a project is taking place at all, though, testifies to a shifting view of electricity that sees climate change and greenhouse gas emissions as unacceptable consequences of business as usual. And that shift is driving interdisciplinary collaborations at the frontier of industrial research.

"When I got into this [project], I had to spend the first six months reteaching myself a whole lot of electrochemistry," admits Barckholtz, who holds a doctorate in inorganic chemistry. FuelCell Energy and ExxonMobil are each experts in their own fields and accustomed to operating at very different scales. "So putting the two together has really led to some interesting ideas of how to improve and optimize our systems."

And for companies like FuelCell Energy that have struggled for decades to challenge the cheap-energy-at-all-costs paradigm, that is progress. ■

↗ **POST YOUR COMMENTS** online at https://spectrum.ieee.org/carbonatefuelcell0618

ILLUSTRATION BY MCKIBILLO

THIS POWER PLANT RUNS ON CO_2

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also depends on the captured carbon dioxide being used productively. Right now, one growing market for CO_2 is using it to drive hard-to-access oil out of the ground. Pipelines already stretch through Colorado, New Mexico, and Texas to deliver naturally occurring supplies of the gas to oil companies. Occidental Petroleum Corp.'s CO_2 use in West Texas alone amounts to about 100,000 metric tons a day, equal to the output of 45 NET Power plants, the oil company says.

While it might seem counterproductive to use a zero-emission technology to help push more fossil fuel out of the ground, experts point out that even in a low-carbon world, we'll still need oil as the key feedstock for the petrochemical and plastics industries. And it may be only a matter of time before there is a price for carbon that will make such uses less economical. Already in the United States, a recently passed law offers tax credits worth $50 per metric ton of CO_2 buried but only $30 per metric ton used for oil production.

Assuming such industrial gas sales materialize, the net effect would trim the NET Power plant's levelized cost of electricity (LCOE), a proxy for the price that the plant must receive for its output over its lifetime to break even. On paper, the first plant should have a base LCOE of around $50 per megawatt-hour, according to NET Power. That puts it in the same ballpark as a combined-cycle power plant with no CO_2 capture. Once multiple plants are built to scale and with all industrial gas sales factored in, the company forecasts LCOE to fall to around $42/MWh (even without the new tax credits).

As a result, NET Power's backers say that by the time its 30th plant is on line, the technology could match the construction cost and efficiency—about $1,000 per kilowatt and 50 percent—of today's combined-cycle power plants. And with no on-site emissions.

But technology doesn't stand still, and existing turbine designs are evolving to address carbon emissions. For example, in March, Gasunie, Statoil, and Vattenfall tapped Mitsubishi Hitachi Power Systems to convert a 440-MW combined-cycle power plant in the Netherlands to burn hydrogen by 2023. Mitsubishi claims that a gas turbine it is developing has used a 30 percent hydrogen fuel mix. That mixture resulted in a 10 percent reduction in CO_2 emissions, compared with natural-gas-fired power generation.

With Allam's technology being tested for only the first time, it's probably too early to speak with confidence about price, says a chief technology officer with a global turbine manufacturer who asked not to be named. For one thing, the CTO says that air-separation is an expensive, mature technology with little opportunity to eke out much cost savings.

NET Power acknowledges that the air-separation unit is a big expense. But it claims that the cost is largely a wash because the Allam cycle cuts out multiple pieces of equipment that otherwise would be needed to run a conventional combined-cycle plant.

SMIL SAYS...

It's supercreative, but we'll need to divert more than 3 billion metric tons of CO_2 every year to make a dent in global emissions.

The CTO also marvels at the high pressure that the Allam cycle operates under and its impact on the turbine. "It's an order of magnitude higher than conventional technology," he says. NET Power CEO Bill Brown responds that Toshiba showed no concern over the high turbine pressures and that the most substantive modifications to the turbine design were to provide additional coatings on the turbine blades and more layers of insulation.

NET POWER IS NOT ALONE in exploring supercritical CO_2 for energy production. Another approach is called indirect firing, explains the DOE's Weiland. Indirect firing takes heat from a standard turbine's exhaust and uses it to heat and compress supercritical CO_2 for use in what is an otherwise conventional steam cycle. That added process should boost the efficiency by 2 to 4 percentage points over that of a regular steam turbine. So a 550-MW supercritical CO_2 plant would save enough fuel to energize 17,500 to 35,000 more homes per year than a 550-MW state-of-the-art steam power plant, based on average annual U.S. household use of 10,800 kWh.

Akron, Ohio-based Echogen Power Systems has designed an 8-MW generator that uses supercritical CO_2 to turn waste heat derived from a gas turbine or engine into electricity. A heat exchanger drives the CO_2 conversion, and the process yields roughly 20 percent more power than a gas turbine alone.

Supercritical CO_2 technology is also being explored with an $80 million facility funded by the DOE project called STEP, or Supercritical Transformational Electric Power. The pilot plant, about 10 MW, will be an indirect-fired system that uses the Brayton cycle (typical of internal combustion engines). Researchers will use the facility to test components and technologies such as heat exchangers, compressors, and turbines for use with supercritical CO_2. The San Antonio, Texas, facility is slated to open in 2019.

Meanwhile, NET Power's parent, 8 Rivers, and its partners are working on a variation of the Allam cycle that would run on syngas (carbon monoxide and hydrogen) derived from coal. The goal is to build a 100- to 300-MW power plant by the early 2020s, most likely in North Dakota, where the CO_2 could be used to push oil out of the Bakken Formation.

Even as testing gets under way in LaPorte, NET Power is scouting sites for a commercial-scale facility. CEO Brown says that eight locations are under consideration, in the United States, the United Kingdom, Qatar, and the United Arab Emirates. The key will be local demand for industrial gases and pipeline-quality CO_2 for oil production. Greenhouse gas emission rules like those in the European Union may favor the Allam cycle, too.

Expectations are high for success at LaPorte, and Brown is eager to see precisely what this potentially revolutionary technology can do. ■

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ILLUSTRATION BY MCKIBILLO

THE PRIUS OF THE SKY

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internal-combustion engine, with its hundreds of parts and countless complex mechanical interactions.

Gram-by-gram work gives way, eventually, to a revolutionary improvement. A big one came in the early 1980s, when General Motors and Sumitomo Special Metals separately introduced superpowerful neodymium magnets in motors. For the next game changer, look to machines whose electromagnets are wound with superconducting wire.

A motor-generator would lose almost no energy as waste heat if it had superconducting windings—a dream that could be entertained only after the advent of high-temperature superconductors. These ceramic materials superconduct at -135 °C, some 100 °C "warmer" than the original metal superconductors did. So, rather than cooling them with liquid helium, at a bare whisper above absolute zero, designers can rely on liquid nitrogen.

Siemens has been working on this concept for nearly two decades. It originally planned to put superconducting motors aboard ships at sea, where space and weight are at a premium. Even so, the company's current version of the machine (used as a generator) is a piece of furniture bigger than a grown man. So the company's engineers are now miniaturizing the machine for use in aviation. Its immediate power-density goal is 10 watts per gram. Siemens won't show me this stuff, just a picture of the bigger supercooled machine with a diagram of the future aviation version superimposed on it. The drawing is maybe a tenth the size of the image.

Other companies are also on the hunt. GE Aviation is working on cryogenically cooled machines for NASA, but about this GE won't say much either. All these companies are tight-lipped; perhaps they're loath to tip their hands, or maybe they haven't got much yet to show. In any case, NASA estimates that passenger planes using cryogenic systems of 30 MW and up won't be ready to fly until the mid-2030s.

To take full advantage of such a superconducting motor—and, in a hybrid system, a superconducting generator as well—you'd want superconducting power inverters, too. NASA has a contract with GE to produce one that can handle 19 kW/kg at 99 percent efficiency.

Integrating the motor into a hybrid design—probably using a gas turbine to spin the generator—is still in the works. Siemens engineers are first modeling everything in silico, an interactive simulation I'm shown just a glimpse of, on a computer screen. And the glimpse I'm given is of the current iteration, of a normally cooled machine. "It's a series hybrid, and this tells us how the power distribution will work," Balázs tells me.

Today gas-turbine generation is used most commonly as backup power for the grid, where the weight of the components matters not at all. However, plenty of military aircraft now flying pull electrical power from turbines powered either by the jet engine's compressors or from airflow produced by the forward motion of the plane.

↗ **POST YOUR COMMENTS** online at https://spectrum.ieee.org/hybridairplane0618

It may seem like a great deal of work to save just a few kilos, but every bit counts. A kilo saved on the motor gives you precious extra kilos for the batteries. When United Airlines recently began printing its in-flight magazine on lighter-weight paper, saving 28 grams (1 ounce) per issue or about 5 kg (11 pounds) per flight, it calculated the move would save the company 640,000 liters of fuel every year, worth US $290,000.

That's why new airliners, such as the Boeing 787, include so much carbon-fiber reinforced polymers. So does the 330LE: One guy is all it takes to pull the plane out of a hangar.

Okay, let's fast-forward to the finished product. It's a dozen years from now, and airlines are operating hybrid planes that are so quiet they can fly at night over cities. Thanks to their swiveling props, they can take off from shorter runways, perhaps even a runway right inside a city. They save energy because they're lighter and more efficient. That means they cost less to run and therefore to own—the inverse of the situation with commercial aircraft today, where operating costs dwarf the purchase price.

One caveat: In the midterm, a decade or so hence, mere hybrids will be only slightly "greener" than conventional aircraft. The big improvement will come after experience and economies of scale with hybrids allow the industry to make the transition to pure-electric planes, perhaps in the 2030s. "We see energy savings of from 4 to 20 percent" through hybridization, says Otto Olaf, head of sales and business development in Siemens's Munich office. "If we fully electrify the plane, there are even bigger savings."

Just as compelling to the airlines is the associated reduction in the greenhouse gas emissions. "The European Union's Flight Path 2050 aims to reduce emissions by a factor of more than 2," says Siemens's Anton, "but by then passenger travel is expected to double, so we'll need at least a fourfold improvement."

It isn't clear just how these numbers are to be calculated. The easy way is to compare exhaust emissions against passenger-miles. The more honest way is to estimate "well to wake" effects, taking into account the expected source of any electricity that might be generated on the ground and stored in batteries for later use in the air. This calculation would also have to account for how much energy is used to make the batteries, the motors, the ultralight carbon-composite airframe parts, and all the rest.

That same EU program also aims to reduce aircraft noise by half by 2050. And that, it turns out, is the greatest motive of the airline industry right now. Just to get around restrictions on nighttime flights, airlines sometimes spend money to muffle their older, louder planes, a job called "hush kitting."

"That was the biggest surprise when Siemens started talking to airlines," Anton says. "I was always mentioning quiet operation as the third thing, after energy and emissions. Now it's the first thing."

This wouldn't be the first green technology to succeed for reasons having little to do with global warming. People bought the hybrid Prius to save on gas; they buy the Tesla to out-accelerate a Porsche. Airlines will buy hybrid-electric airplanes for their quiet operation, and lower greenhouse gas emissions will come almost as a side effect. But they will come. ■

Faculty Positions
Centre for Nano Science and Engineering, Indian Institute of Science, Bangalore

Centre Description: The Centre for Nano Science and Engineering (CeNSE) was established in 2010 to pursue interdisciplinary research on the nanoscale. It is a full- fledged department with its own masters and PhD programs. Science to systems to society is our motto. We have electronics engineers, material scientists, physicists, chemists and mechanical engineers collaborating internally and working with the rest of the Institute on a diverse array of problems. The Centre has a state of the art nano-fabrication facility and a characterization facility for evaluating the electrical, mechanical, structural and optical characteristics of materials and devices. We are looking for device engineers working in the emerging areas of post-Moore memory, logic, system on-chip/in-package architectures, neuromorphic architectures, devices for quantum computing, RF electronics, internet of things, multimodal sensing and cyber physical systems to come and join our team.

Position Description: The faculty member will be expected to set up a device program that can either interface with the current activities or develop a new branch altogether. It is expected that this program will leverage the extensive device fabrication facilities created in CeNSE. He/She will have the exciting opportunity to work in a collaborative research environment. CeNSE currently has very mature research threads in areas related to CMOS and post-CMOS electronics, power electronics, integrated opto-electronics, MEMS/NEMS, systems scaling, 3-D packaging and molecular sensing.

Qualification: We invite applications for the position of Assistant Professor. The candidates should have an excellent academic and research record with at least 3 years of post-PhD research experience preferred. The candidate should preferably have a background in physics or electronics engineering. He/she should preferably have clean room device fabrication experience. Exposure to device modelling and simulation, integrating new materials platforms, testing systems performance and to collaborative research programs are desirable.

Salary/Benefits: The position is a tenure track position and will be governed by the norms of the Institute.

To Apply: Interested candidates should send the application packet to fsc.cense@iisc.ac.in. CeNSE is also looking for faculty applicants in other areas. Details regarding the method of application, the procedure followed by the Institute and other areas open for applications can be found on our website at **http://www.cense.iisc.ac.in/content/careers**.

FACULTY POSITIONS
School of Information Science and Technology (2018)

The School of Information Science and Technology (SIST) at Fudan University invites applications for several tenure-track or tenured faculty positions at the associate and full professor levels. Interested research areas include (but not limited to) the following areas:

- **Micro-nano Systems:** neuromorphic computing and artificial intelligence, wireless sensing and smart electronics, Microelectronic and Photoelectronic Devices, microwave and RF power electronics, flexible and printable electronics, micro-nano fabrication and integration, navigation and positioning technology
- **Circuits and Systems:** Complex network and system control, sensor network and signal processing, intelligent image and information system, human dynamics and social computation, swarm intelligent system, unmanned aircraft control theory and engineering
- **Biomedical Engineering:** digital health techniques, medical ultrasonics, medical imaging and image processing, ECG or EEG analysis and processing, medical electronic system, body sensor networks, physiological and behavioral data sensing and processing
- **Physical Electronics:** solid state lighting, organic light-emitting electronics, nanophotonics, wide-band-gap semiconductor materials and devices, facility agriculture, vision and ergonomics, healthcare lighting, plasma technology and application, thermal management of LED, energy Internet, smart electronics, power electronics
- **Communication:** optical communication and sensing, wireless multimedia, space and satellite communication, software defined networks, underwater communication, communication signal processing, and smart cities applications
- **Optical Engineering:** precision optical manufacturing, optical measurement opto-mechanical design & FEA, bio-photonics such as single molecule detection & 3D imaging, VR/AR, space solar energy, digital optics, Ultra-precision Optical Manufacturing, Opto-electronic Device and System
- **Electromagnetic Field & Wave:** microwave remote sensing, computational electromagnetics, radar signal processing, image processing & information sensing, wireless power transmission, space communication, microwave circuit and systems

Successful candidates must have a Ph.D. degree from a reputed university, a demonstrated strong research expertise in their discipline, excellent communication skills and a commitment to graduate and undergraduate teaching.

Fudan University is a top-ranked university in China. The SIST consists of Departments of Electronics Engineering, Optical Science and Engineering, Communication, Lighting Engineering and Micro- Nano systems. The school has developed a strong educational system covering undergraduate, graduate and the professional degree programs, and centers of excellence for electromagnetic wave, micro-nano systems, medical electronics, and advanced lighting etc. More information can be found at **http://www.it.fudan.edu.cn/En/Default**

Fudan University offers highly internationally competitive salaries and benefits. Candidates interested are invited to provide a Curriculum Vitae, research and teaching statements and the names/email addresses of three references to it_renshi@fudan.edu.cn

A BETTER MAILBOX

In the United States in the 1870s, letter boxes were still a new phenomenon, and many people, accustomed to hand-delivered mail, weren't sure what to make of them. How would they know if they'd received mail? Thus was born the electric mailbox: Depositing letters in the box closed a battery-powered circuit, which rang a bell inside the house. Ephraim E. Weaver, an inventor in Philadelphia, saw room for improvement. Parcels that wouldn't fit in the box wouldn't trigger the bell, he realized. His 1885 patent added an external key, which the postman used to close the circuit manually. Think of it as "You've got mail!" for the 19th century. ■

↗ **For more on early electric mailboxes, see https://spectrum.ieee.org/pastforward0618.**

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