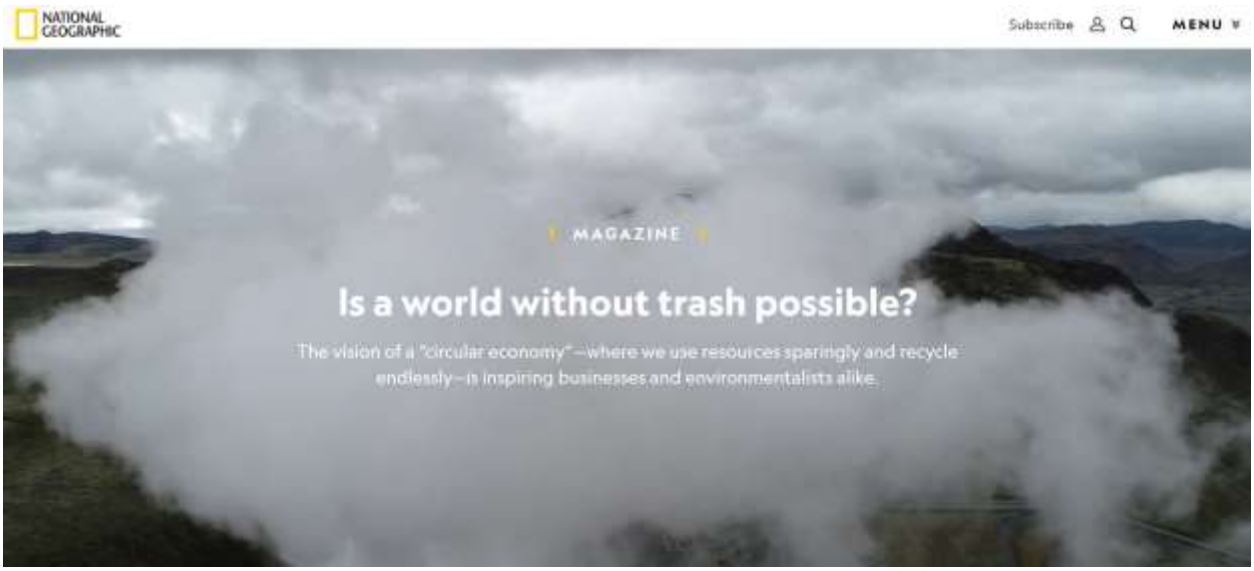

Switching from fossil fuels to renewable energy, such as the geothermal heat from magma beneath Iceland's lava fields, is an essential step toward a circular economy—one that would produce no waste of any kind.

By **Robert Kunzig**

Photographs by **Luca Locatelli**

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In Amsterdam I met a man who revealed to me the hidden currents of our lives—the massive flows of raw materials and products deployed, to such wonderful and damaging effect, by 7.7 billion humans. Our shared metabolism, you might say. It was a crisp fall morning, and I was sitting in a magnificent old brick pile on the Oosterpark, a palace of curved corridors and grand staircases and useless turrets. A century ago, when the Dutch were still extracting coffee, oil, and rubber from their colony in Indonesia, this building had been erected as a colonial research institute. Now it houses assorted do-gooder organizations. The one Marc de Wit works for is called Circle Economy, and it's part of a buzzing international movement that aims to reform how we've done just about everything for the past two centuries—since the rise of the steam engine, "if you need to pinpoint a time," de Wit said.

De Wit is 39, genial, bespectacled, a little disheveled, a chemist by training. He opened a pamphlet and spread out a diagram he called "an x-ray of our global economy." Unlike natural ecosystems, which operate in cycles—plants grow in soil, animals eat plants, dung replenishes soil—the industrial economy is largely linear. On the diagram, fat, colored currents of the four types of raw material—minerals, ores, fossil fuels, and biomass—surged from left to right, splitting and braiding as they became products that met seven human needs. Sand went into

concrete apartment towers on six continents. Metal ore became ships, cars, and also combine harvesters—in a single year we harvested 22.2 billion tons of biomass, just to feed us all. Fossil fuels powered those vehicles, kept us warm, became plastic, became all kinds of things. The total flow into the economy in 2015 was 102.3 billion tons.

The Hellisheiði Power Station, Iceland's largest geothermal plant and the world's third largest, produces electricity as well as heat for homes. Geodesic domes over the wells help reduce the visual blot on the landscape.

All good so far; amazing even, if you're the type to be amazed by human effort and ingenuity. It's what happens next, after our needs are met, that's the problem—the mother of all environmental problems, in fact. De Wit pointed to the gray fog on the right edge of the diagram. The gray fog is waste.

In 2015, he explained, about two-thirds of the material we scratched from the planet slipped through our fingers. More than 67 billion tons of hard-won stuff was lost, most of it scattered irretrievably. Plastic trash drifted into rivers and oceans; so did nitrates and phosphates leaching from fertilized fields. A third of all food rotted, even as the Amazon was deforested to produce more. Think of an environmental problem, and chances are it's connected to waste. That includes climate change: It happens because we burn fossil fuels and scatter the waste—carbon dioxide—into the atmosphere.

(Plastic isn't the enemy, but plastic waste in the ocean and elsewhere is a global plague. Are biodegradables and recycling the cure? Staff writer Laura Parker considers what a circular economy for plastics might look like.)

This may sound ridiculous, but as de Wit walked me through the numbers that morning, it felt like an epiphany. There was a unifying, exhilarating clarity to that wonky diagram, to the way it defined the task. Sure, it said, the threats we face are multifarious and overwhelming. Sure, they're planetary in scale. But really, to get along on this Earth, we must do just one thing: Stop wasting so much of it. De Wit pointed to a thin arrow that circled back, from right to left, along the bottom of the diagram, representing all the material we'd managed to capture through recycling, composting, and so on. It was only 9.3 billion tons: just 9 percent of the total.

At Iceland's Blue Lagoon, geothermal water that has already generated electricity at the Svartsengi Power Station and is no longer scalding is used to create a popular tourist attraction. The water's high silica content keeps it from leaching into the lava field and gives it an appealing aqua tint.

The "circularity gap," as de Wit and his colleagues dubbed it when they presented their report at the World Economic Forum in Davos in 2018, is relatively new in human history. It dates to our industrial use of fossil fuels in the 18th century. Until then, most of what humans did was done with muscle power, whether human or animal. Growing things, making things, shipping things took hard labor, which made them valuable. Our limited physical energy also restricted how big a dent we could put in the planet. It kept most of us very poor, however.

Cheap fossil energy, concentrated by geologic time and pressure in seams of coal or pools of oil, changed all that. It made it easier to extract raw materials anywhere, ship them to factories, and send the merchandise everywhere. Fossil fuels exploded our possibilities—and the process keeps

intensifying. In the past half century, while the world's population has more than doubled, the amount of material flowing through the economy has more than tripled.

"Now we're reaching the limits," de Wit said.

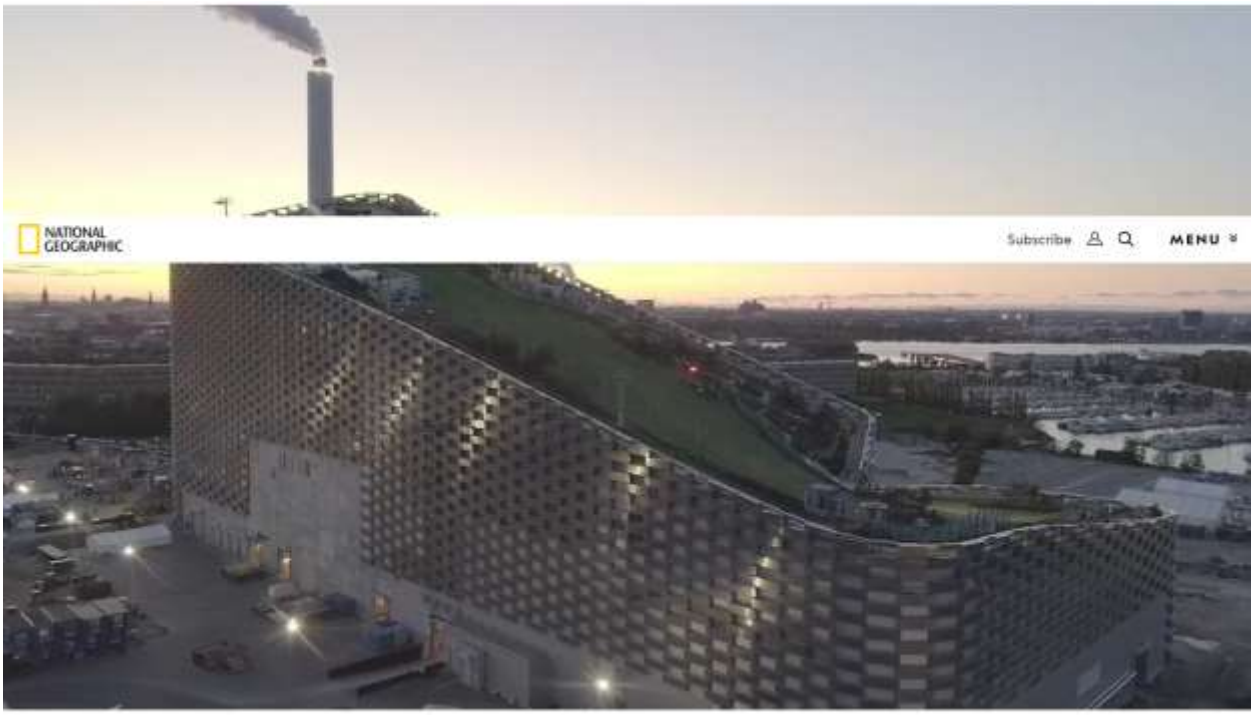
In Copenhagen, Denmark, skiers descend the sloping roof of the Amager Bakke incinerator, which converts 534,600 tons of municipal waste a year into energy—enough to electrify 30,000 homes and heat 72,000. The plant doubles as a recreational destination, with an all-season ski slope, a tree-lined hiking and running trail, and a 280-foot climbing wall, the world's tallest.

For that same half century, environmentalists have been warning of limits to growth. The new "circular economy" movement is different. It's a collection of strategies—some old, such as reducing, reusing, and recycling, and some new, such as renting rather than owning things—that together are meant to reshape the global economy to eliminate waste. The circular economy doesn't aim to end growth; it aims to bend how we do things back into harmony with nature, so that growth can continue. "Prosperity in a world of finite resources," as European environment commissioner Janez Potočnik once put it, in the foreword to an Ellen MacArthur Foundation report. It said the circular economy could save European businesses up to $630 billion a year.

The idea is catching on, particularly in Europe, that small, crowded, rich but resource-poor continent. The European Union is investing billions in the strategy. The Netherlands has pledged to go fully circular by 2050. Amsterdam, Paris, and London all have plans. "It must happen,"

said Wayne Hubbard, head of the London Waste and Recycling Board, when I asked whether the circular economy could happen.

One man who definitely thinks it could happen, and whose work has proved revelatory to many others, is American architect William McDonough. With German chemist Michael Braungart, he wrote the visionary 2002 book *Cradle to Cradle*, which argues that products and economic processes could be designed such that all waste becomes fodder for something else. Before setting off for Europe, I made a pilgrimage to McDonough's office in Charlottesville, Virginia. Our conversation ricocheted from his childhood in Tokyo, through Plato, Aristotle, and Buckminster Fuller, to some new compostable blue jeans he was excited about, before I finally managed to ask him the nagging question: Is all this talk of an end to waste just pie in the sky?



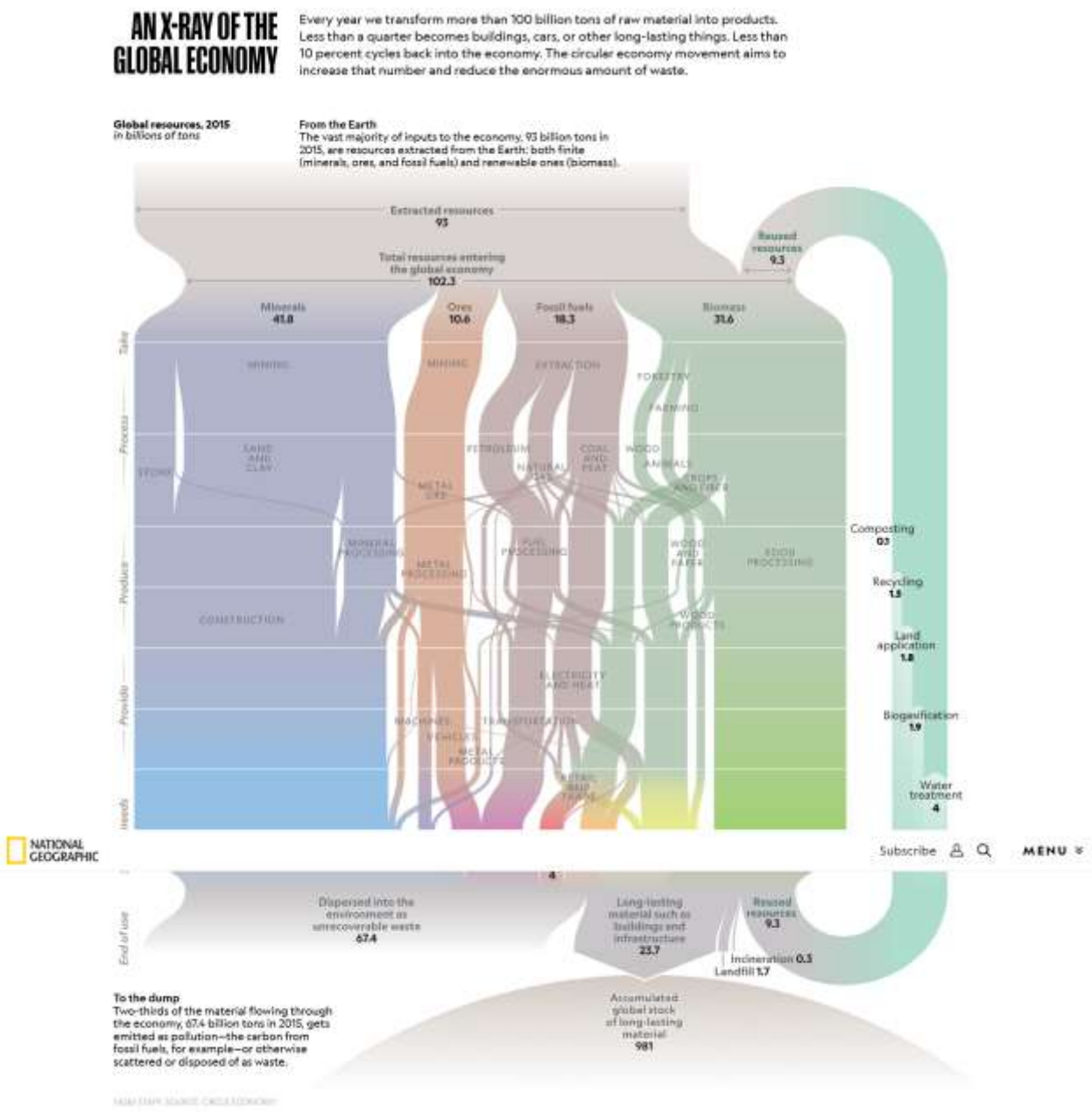
The green slope of Copenhill, as the Danish incinerator is also called, conceals a silo that can hold more than 24,000 tons of trash, which is mixed by an automatic crane to help it burn cleaner. Equipment to filter the smoke takes up much of the plant's interior. A clean-burning, energy-generating incinerator is a better end for trash than a dump—but the circular economy aims to end trash by not producing it at all.

"It's absolutely pie in the sky, no question about it," McDonough said. "You need pies in the sky to help us go forward. Because remember what Leibniz said."

I didn't remember much about that German philosopher.

"Leibniz said, 'If it is possible, therefore it exists.' And I'm saying, 'If we can make it exist, it's therefore possible.' "

Was that tautological? Was it wise? Did Leibniz really say that? It was intriguing, in any case. Not long after that, I took my busted old roller bag to be repaired (very circular, compared with buying a new one), packed the certified cradle-to-cradle jeans that McDonough had given me, and headed out to see what evidence of possible existence I could find for the circular economy.



Metals

The first small breaks in our natural circularity actually predate the 18th-century industrial revolution. The Romans, besides tossing broken amphorae around in an uninhibited way, pioneered a fraught invention: sewers. That is, they channeled human waste into rivers, instead of returning it to fields where, as any circularity maven will tell you, those nutrients belong. As a young boy in Tokyo in the 1950s (his parents were in the occupying American Army), McDonough recalls waking at night to the sound of farmers collecting the family's night soil. His mother would soothe him with lullabies about poop, sometimes in Japanese with an Alabama accent. It made a permanent impression.

The Romans, like the Phoenicians before them, also mined copper from the rich deposits at Río Tinto in Spain. But they recycled too: They melted down bronze statues from conquered peoples to make weapons. Copper has always been a prime target for recyclers. Compared with sewage, it's scarce and valuable.

In the yard at the Aurubis copper smelter in Lünen, in the Ruhr region of western Germany, a large bust of Lenin stands in a flower bed—a souvenir of the many bronze Lenins melted here, from towns around communist East Germany, after East and West were reunited in 1990. Aurubis, Europe's largest copper producer, is also the world's largest copper recycler. When the Lünen plant was built in 1916, at the height of World War I, copper for artillery shells was in short supply, and Germans were pulling bronze bells out of church towers. "Since that day, this plant has exclusively done recycling," said Detlev Laser, the deputy plant manager.

Nearly 3,300 decommissioned planes and helicopters are stored on Davis-Monthan Air Force Base in Tucson, Arizona, where there's little humidity to cause corrosion. Nicknamed the Boneyard, it's the world's largest aircraft dismantling and repurposing facility and the sole repository of out-of-service aircraft from all branches of the U.S. government.

Copper, unlike plastic, say, can be recycled indefinitely without loss of quality—it's a perfect circular material. The Lünen plant still processes bulk copper, mostly pipes and cables, but it has had to adapt to waste with much lower concentrations. As Europe has replaced landfills with

municipal incinerators, a lot of slag is showing up containing bits of metal—"because someone threw their cell phone in the trash" instead of the recycling bin, Laser said.

With Hendrik Roth, the plant's environmental manager, I watched an excavator drop bucketloads of electronic debris, including laptops, onto a sloping conveyor that carried it toward a shredder—the first of more than a dozen steps in the bewildering and deafening sorting process. At one station, a conveyor raced by, carrying hand-size shards of circuit boards. Some fell into an abyss; others leaped as if by their own volition onto a belt above. A camera system, Roth explained, was deciding whether each shard contained metal—and if not, activating an air jet under it at just the right instant.

Aurubis sells the aluminum and plastic it recovers to those industries; copper and other nonferrous metals go into its own ovens. In the tidy yard, the dust is swept daily and fed to the smelter. "We have no waste here," Laser said.

Left: At Davis-Monthan, personnel with the 309th Aerospace Maintenance and Regeneration Group recover usable parts from helicopters and other aircraft.
Right: In Roswell, New Mexico, Cavu Aerospace operates a civilian counterpart to the Tucson base, dismantling aircraft for major airlines. Valuable parts are resold, while others are recycled for raw materials such as aluminum.

Worldwide, only about a fifth of all electronic waste is recycled, according to a 2017 UN report. Aurubis even takes shipments from the United States. "But I do wonder sometimes why such a highly industrialized country would give up such resources," Roth said. "They're sitting on billions." That's starting to change. Apple, for example, encourages customers to trade in old iPhones; an intelligent robot in Texas dismantles them and extracts materials for new devices.

But copper exemplifies a general challenge: There's a limit to what even aggressive recycling can accomplish. At Aurubis, recycled copper accounts for only a third of production; the rest still comes from mines. World copper production has quadrupled in the past half century and is still growing. The technologies we need to get off fossil fuels require a lot of copper; a single giant wind turbine uses about 33 tons.

"Demand is growing," Laser said. "You'll never cover that with recycling." The circular economy is going to require other strategies.

The aircraft at Davis-Monthan are sprayed with a protective coating, which can be removed when they are scavenged for parts or returned to service. Reusing machinery is a time-honored strategy for reducing waste.

Clothes

The emblem of the Ellen MacArthur Foundation, a set of nested circles, was on Dame Ellen's teal hoodie when we met in her headquarters, an old sailmaker's loft on the Isle of Wight. In 2005, at age 28, MacArthur finished sailing around the world on a 75-foot trimaran in a record time of just over 71 days—alone. She had packed 72 days' worth of food. She had raced storms off Antarctica and fixed a broken generator. She arrived home, having survived a microcosm of Spaceship Earth, with a visceral awareness of limited resources.

Why wasn't everyone talking about that? she wondered. She gave up competitive sailing and instead traded on her fame and access to corporate boardrooms—"it would be a waste not to use it," she told me—to establish an organization that has done more than any other to promote the circular economy, using a hierarchy of strategies. The best is the simplest: Waste less stuff by keeping it in use.

That choice hits many people most acutely in their closets. From 2000 to 2015, while the world population grew by a fifth, clothing production doubled, according to an Ellen MacArthur Foundation report, thanks to the explosion of "fast fashion." With so many cheap clothes, the report estimated, the average item was worn a third fewer times by 2015. That year, the world threw away more than $450 billion worth of clothes.

In Prato, Italy, where the textile industry has thrived since the 12th century, about 3,500 companies employing 40,000 workers process discarded textiles, especially wool. Skilled workers handle the first step, sorting garments by hand into fine gradations of color.

A carbonizer uses sulfuric acid to burn away cellulose and contaminants such as cotton stitches, which could compromise the quality of the recycled wool.

Jorik Boer makes a living rescuing some of them as head of the Boer Group, a Dutch family business that began a century ago on the streets of Rotterdam with his great-grandfather collecting rags, metal, and paper in a cart. Today, from his base in Dordrecht, Boer runs five plants in the Netherlands, Belgium, France, and Germany. Together they collect and sort—and resell for reuse or recycling—up to 460 tons of discarded clothing a day.

People have the wrong idea about what happens when they drop clothes into a donation bin, Boer said; they think the clothes are given directly to needy people. What usually happens instead is that companies like Boer buy donated clothing, sort it, and resell it—all over the world.

"You need a lot of experience to know where you can sell and reuse a piece of clothing," Boer said. Through the window behind him, I could see the rapid but practiced movements of women pulling clothes from conveyors, examining each item briefly, then pivoting and tossing it into one of 60 or so bags. Each woman sorts about three tons a day, Boer said. Sorters must have an eye for fashion—especially for the best stuff, just 5 or 10 percent of the total, which makes most of Boer's profit. In Russia and eastern Europe, prized items such as women's underwear can fetch up to five euros a kilogram ($2.50 a pound). Most lower quality material gets shipped in 55-kilogram bales to Africa, where it's sold for as little as 50 cents a kilo.

At one point Boer eyeballed my gray sport coat, which I felt quite confident of; he couldn't see the ink stains on the inside pocket. "We cannot sell your jacket anywhere," he volunteered cheerfully. "No one in the world wants to buy it." Boer said he would actually have to pay someone to take my unfashionable garment away.

But they buy used underwear? I was miffed.

Wool that has been sorted by color, washed, shredded, and vigorously blown with hot air sits at the bottom of an industrial dryer.

“That’s clean, used underwear,” Boer said. People normally don’t donate dirty clothes.

He gets more clothing these days than he can handle, mostly from Germany, which collects 75 percent of its discards: Town governments have gotten into the act. He can’t find enough skilled workers. At the T-shirt grading station, I noticed an older man. “That’s my dad,” Boer explained. Marinus, the retired CEO, still pitches in. He loves the work.

The Boers’ biggest worry is how clothing is changing. Right now the company is able to resell 60 percent of what it collects. Clothes that are kept in service and worn again are better for the planet—the material and energy that went into making them don’t have to be replaced—and also for Boer. “It’s what’s financing this whole business,” he said.

The other 40 percent, the clothes no one wants, are recycled as wipe cloths or shredded for insulation or mattress stuffing. Some are incinerated. The recycled fraction increasingly includes cheaply made, worn-out items. Boer loses money on almost all of it. Fast fashion, he said, could help put him out of business.

There’s one form of recycling he makes a modest profit on. For decades Boer has shipped wool sweaters and other loose knits to companies in Prato, Italy, that mechanically tease the wool apart, recapturing long fibers that can become good-as-new garments. Woven cotton or polyester can’t be recycled that way; the fibers end up too short. Half a dozen start-ups are working on technology to chemically recycle these fibers. To spur its development, Boer thinks the European Union should require new clothes to contain, say, 20 percent recycled fibers.

“In 10 years it will be there,” Boer said. “It has to be there.”

At Ellen MacArthur I heard enthusiasm for a different business model, one that might promote circularity in many economic sectors—a model based on renting rather than owning. Rent the Runway and other online clothes-rental companies make up less than a 10th of a percent of the global fashion market so far, but they’re growing fast.

In theory, renting is more sustainable: If many people share the same item, fewer clothes might be needed overall. In practice, that’s not certain; customers might just add luxury rentals to existing wardrobes. Renting will certainly add to the packaging, shipping, and dry-cleaning of clothes. Writing in *Elle* recently, journalist Elizabeth Cline, author of two books on fast fashion, tried to sort out the pros and cons. “Wearing what’s already in your closet is the most sustainable way to get dressed,” she concluded.

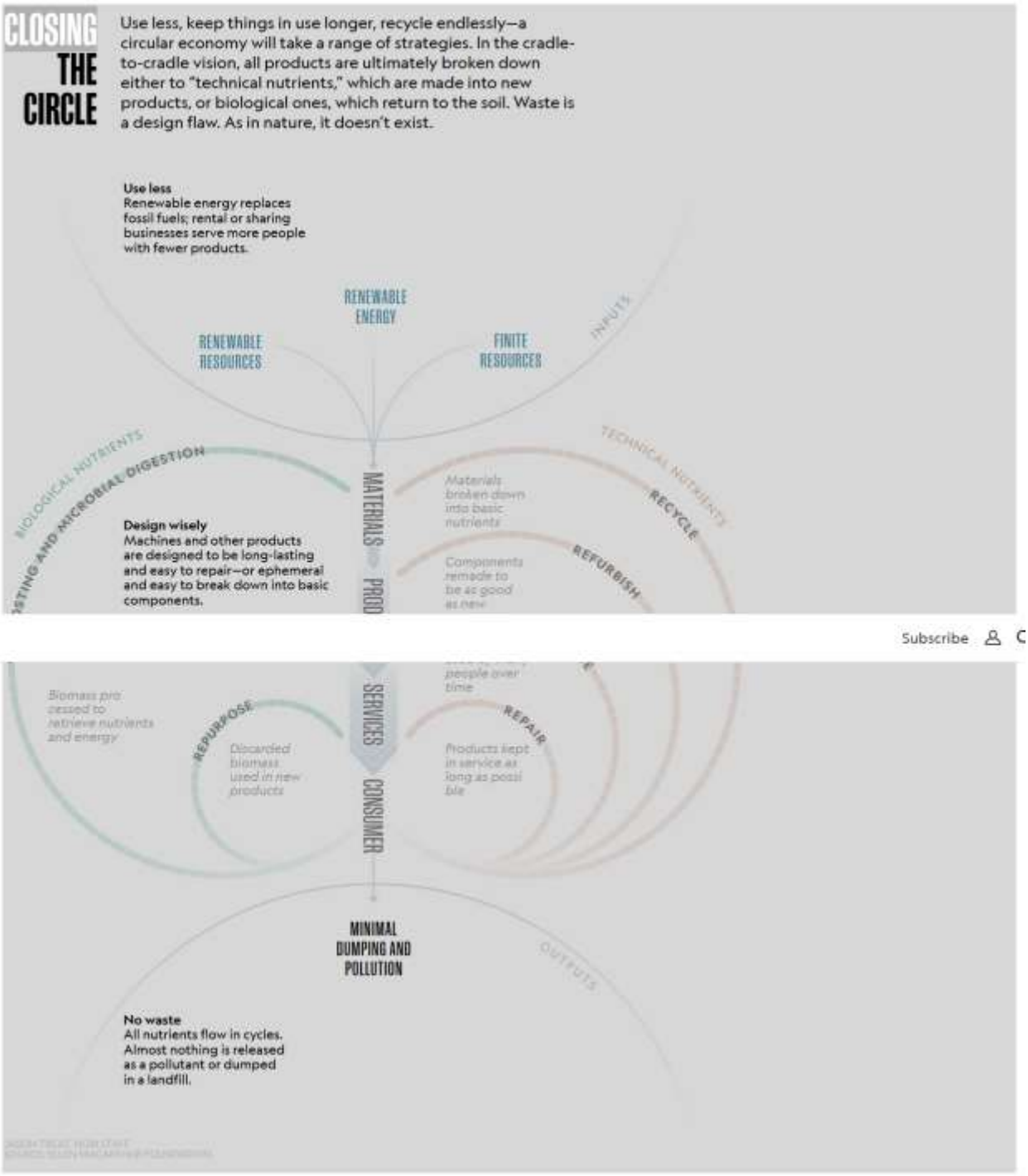
Left: After the shredded wool comes out of the dryer, it is ready to be spun into yarn and made into fabric.
Right: Rose Greenfield models a dress designed by Flavia La Rocca and made from wool recycled in Prato. Only one percent of the world's textile waste is currently recycled into new clothing, according to the Ellen MacArthur Foundation.

Food

People can’t go circular on their own; the system has to change. But individual choices do matter. “It’s about using less stuff in the first place,” said Liz Goodwin of the World Resources Institute.

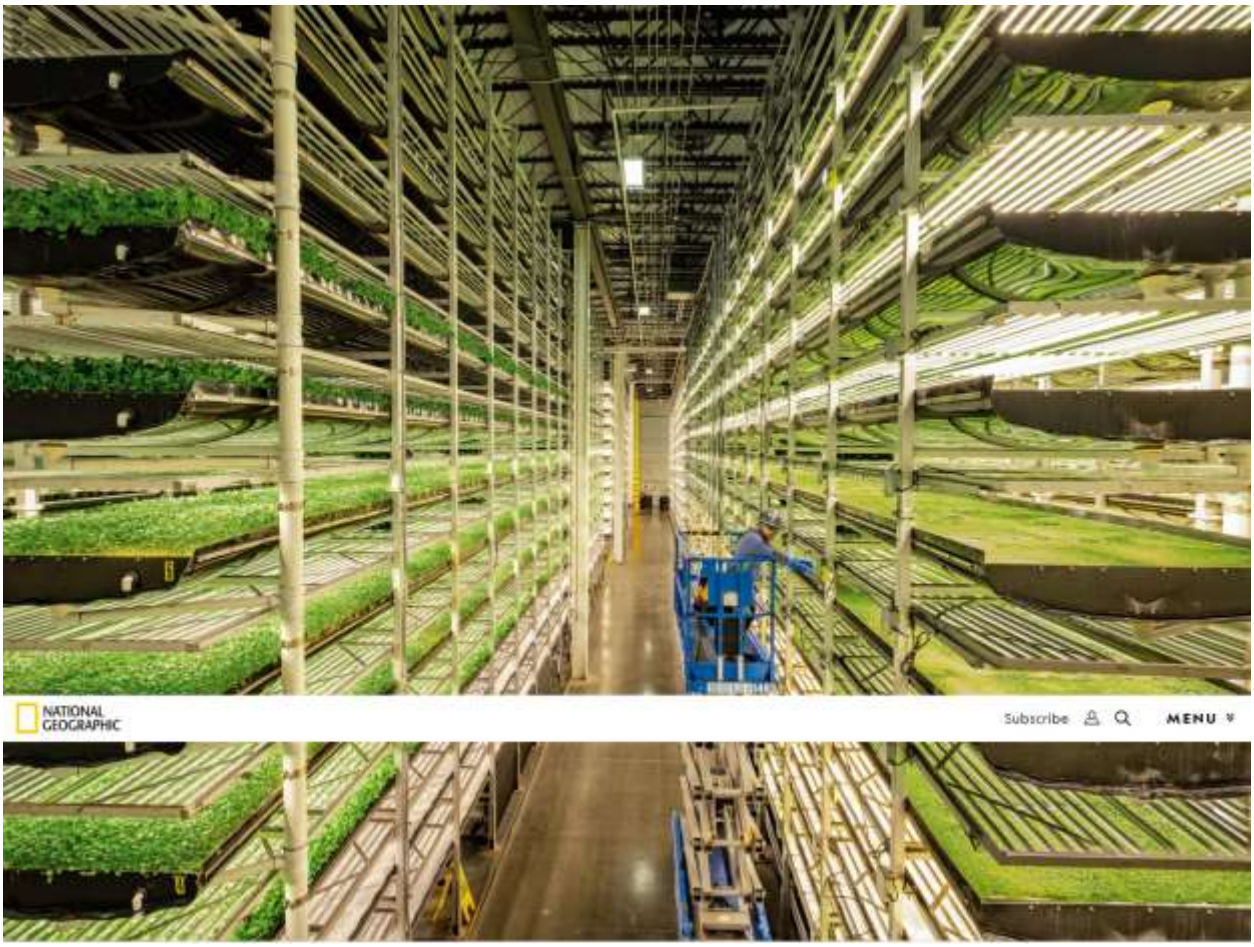
In 2008 the Waste and Resources Action Programme (WRAP), which Goodwin ran then, did one of the first major studies of food waste. The nonprofit surveyed more than 2,100 British families who had agreed to let inspectors paw through their garbage and weigh each food scrap. “Absolutely shocking,” Goodwin recalled. “We found whole chickens in their wrappers.” Nearly half of all salad and a quarter of all fruit was ending up in bins, as were nearly 400,000 tons of potatoes a year. In all, Britons were tossing one of every three bags of groceries.

As it turned out, they’re not exceptional. Roughly a third of all food is wasted globally, at an annual cost of nearly a trillion dollars, WRAP’s global director, Richard Swannell, told me. Over dinner at a restaurant in Oxford, at which we both took care to clean our plates, Swannell explained that before the WRAP study, no one was aware of just how much food—and money—was going to waste in Britain.



WRAP launched a chipper PR campaign ("Love Food Hate Waste"). It worked with women's groups to disseminate food-rescue tips. (A favorite was ways to dress up toast to save stale bread.) It also persuaded grocery chains to adopt some simple measures: Clearer, extended "use by" dates; smaller, resealable packages; an end to "buy one, get one free" sales on perishables. It was boring stuff, forgotten common sense, but it worked. By 2012 the amount of edible food wasted in Britain had fallen by a fifth. "We've had massive progress," Swannell said.

The progress has stalled lately, but no one ever thought common sense alone would end food waste. Artificial intelligence may be required. From a remodeled Victorian furniture factory in the Shoreditch section of London, Marc Zornes, CEO of Winnow, is pitching a high-tech solution that his start-up already has placed into 1,300 restaurant kitchens: smart garbage cans.



The world's largest indoor vertical farm, operated by Aerofarms at its headquarters in Newark, New Jersey, aims to raise vegetables sustainably year-round in the heart of cities. Baby leafy greens are grown on a reusable substrate made from recycled plastic bottles. Water is misted on the roots from below, saving 95 percent of what would be needed outdoors. No pesticides are used. Nutrients and fertilizers are applied only as needed, and the lighting provides the specific wavelength that the vegetables require. The company says its yields are 390 times as high as farming in fields.

Zornes demonstrated one in his conference room, using a plastic chicken leg. Each time a cook or waiter dumps a pot or platter of something into a Winnow can, a scale measures the added weight and a camera snaps a picture. The AI software identifies the new garbage—at Ikea it has learned to distinguish three kinds of meatballs—and displays its cost.

Zornes claimed his clients—AccorHotels, the French multinational, is another big one—routinely cut food waste in half by listening to their garbage cans. Breakfast buffets are notorious, he said; most leftovers are discarded. “When you start measuring the problem, you start managing it,” Zornes said. You make less of what you’re throwing out. I had walked through Winnow’s graffiti-decorated carriage doors expecting grooviness and hype; I walked out wanting to tell my nephew, a Ritz-Carlton chef, about Winnow.

A few days later I had a similar experience in Amsterdam at InStock, a restaurant that makes ambitious cuisine from surplus food. In a spare but cozily lit room, I sat down under a wooden sign that tallied the “rescued food”—780,054 kilograms, or more than 850 tons. One of the founders, Freke van Nimwegen, was at the bar checking the books. She joined me and told me her story as my prix fixe menu ran its courses.

Van Nimwegen was two years out of business school and working for Albert Heijn, the largest Dutch grocery chain, when she discovered the food waste problem. As an assistant store manager she wanted to do something about it, and she couldn’t—food banks might take some bread but not all the produce. She and two co-workers came up with the idea for InStock in 2014 and persuaded the company to support it. It has gone from a pop-up to this restaurant to two others in Utrecht and The Hague, and for van Nimwegen, it was just getting really interesting.

Black soldier flies raised on food waste might replace soy as a protein in animal feed, saving land, according to Entocycle, a British start-up.

“It’s not that we had a dream to start a restaurant chain,” she said. “Not at all. We wanted to do something about food waste.”

My main course arrived: nuggets of “Kentucky Fried Goose.” “Watch out, there can be bullets in the meat,” said the waitress. Schiphol Airport, van Nimwegen explained, employs hunters to dispatch wild geese that might otherwise foul jet engines. The dead birds used to be incinerated; now they come here. The nuggets were chewy but tasty and bullet free. With eggplant chutney and red pepper coulis they went down nicely.

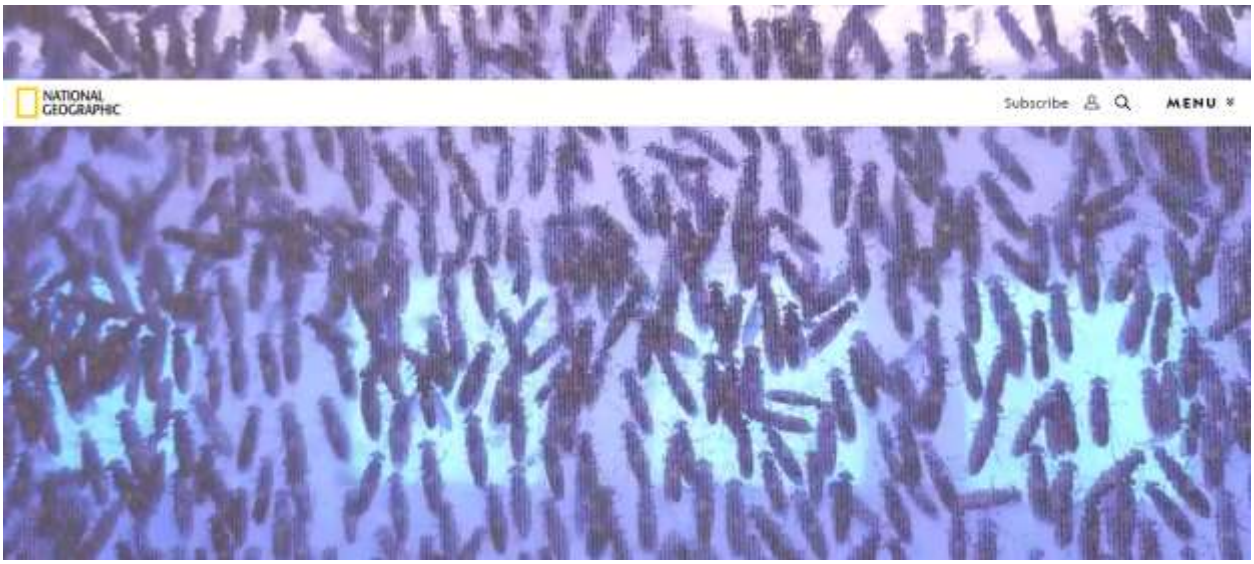
The chefs at InStock improvise with whatever they get. The food comes from Albert Heijn but also from producers, including farmers. “It’s easy to point fingers at the supermarket,” van Nimwegen said. “The whole supply chain, including the customer—everybody wants everything in stock. We’re just spoiled, basically. The companies don’t want to sell ‘no.’ So they’ll always have a little bit too much.”

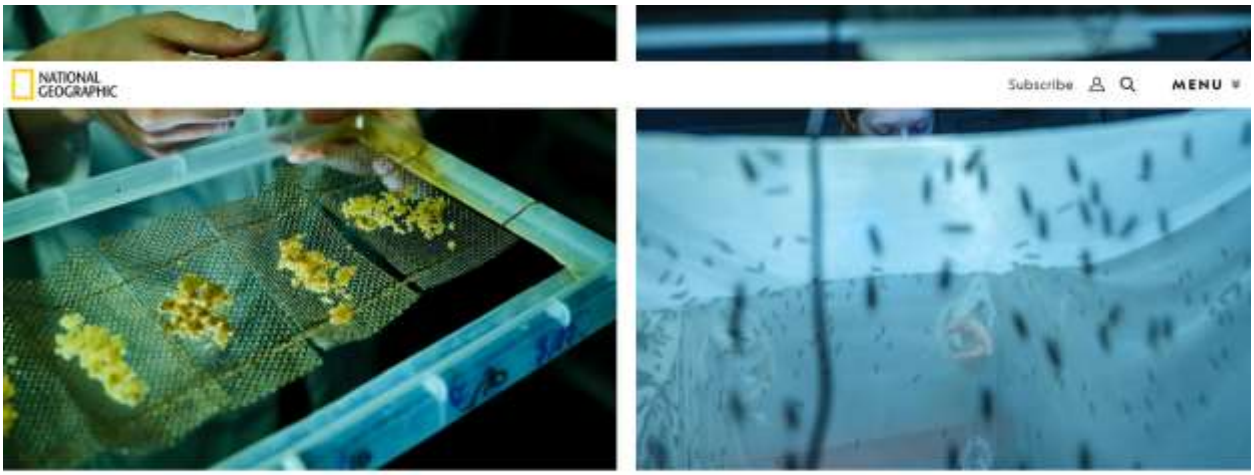
In 2018 InStock started delivering surplus food to other restaurants. Van Nimwegen’s priority now is to get contracts to supply corporate cafeterias. “The most important thing for us is to

make volume," she said. "These kinds of places have a thousand people that need lunch." The Dutch have managed to decrease food waste by 29 percent since 2010, according to a government report, even more than the British.

Dessert was a fabulous foam of berries and cherries poached in red wine, from bottles open too long at the bar. The bill came in a toy shopping cart filled with misshapen fruit: a flat peach and a very skinny pear. I pocketed them to supplement the lunches I'd be rescuing from the breakfast buffet and, feeling a pleasant combination of woke and well-fed, cycled back to my hotel through the misty Amsterdam night.

In my room I found a bat flying in frantic circles. Watching the poor beast search for the open window, I sensed another gift, a metaphor this time. But at first I didn't know what to do with it.





At its London lab, Entocycle tests breeding conditions for black flies (2) and feeds brewery and coffee waste to the larvae. They're harvested after just two weeks (1).

Openings

Getting out of the trap we've entered with the linear economy, and back to an economy modeled on nature's, is going to take a lot of "divergent thinking," as psychologists call it. In Copenhagen I paused to admire the new municipal incinerator, which burns trash for energy and definitely diverges from the norm: There's an all-season ski slope on its roof. But my real destination was the nearby port of Kalundborg, something of a circular economy icon.

There I sat in a cramped conference room with the managers of 11 industrial plants, separate companies all, who have formed an unusual bond: They use each other's waste. The chairman of the group, Michael Hallgren, manages a Novo Nordisk plant that makes half the world's supply of insulin—and along with its sister company, Novozymes, 330,000 tons of spent yeast. That slurry is trucked to a bioenergy plant, where microbes convert it to enough biogas for 6,000 homes and enough fertilizer for nearly 50,000 acres. That's just the latest of 22 exchanges of waste—water, energy, or materials—that make up the Kalundborg Symbiosis.

It wasn't planned, said Lisbeth Randers, the town's symbiosis coordinator; it grew up over four decades, one bilateral deal at a time. A wallboard company came to Kalundborg in part because waste gas from the oil refinery was available as a cheap energy source; it later sourced gypsum from the nearby coal-fired power plant, which made it by scrubbing sulfur dioxide out of its smoke. None of this happened primarily for environmental reasons—but the Kalundborg Symbiosis, Randers said, reduces carbon dioxide emissions by 635,000 metric tons a year, while saving the participants $27 million. Hallgren is now overseeing the construction of an insulin plant in Clayton, North Carolina. "I have a dream that I can make a symbiosis work in Clayton," he said.

In the rolling fields of Westphalia in Germany, home to a famous kind of ham and, not incidentally, many pigs, I met a woman who, with no engineering education, has designed an industrial-scale solution to one of the region's major problems: too much pig manure. Nitrates leaching from overfertilized fields have polluted groundwater in about a quarter of Germany. A typical farmer around the town of Velen, where I met Doris Nienhaus, might spend $40,000 a year to truck nearly 2,000 tons of liquid manure more than a hundred miles away to a field that's not already manured up. "At some point it won't be economically viable," Nienhaus said.

In Kalundborg, Denmark, 11 companies cooperate to convert waste into resources. A bioenergy plant receives 330,000 tons a year of spent yeast slurry from nearby factories that make enzymes and insulin.

Left: Novo Nordisk, the insulin maker, uses steam from a neighboring power plant to sterilize equipment.
Right: At the bioenergy plant, a technician tests a spoonful of yeast slurry. Microbes in large tanks digest the spent yeast, producing enough biogas for 6,000 homes and enough fertilizer for nearly 50,000 acres.

Her solution is a plant that extracts the basic nutrients—phosphorus, nitrogen, and potassium—from manure. Nienhaus, who used to work for the regional agricultural federation and has raised pigs, persuaded 90 farmers to invest $8.4 million. Their farms' manure is digested by microbes, and the resulting biogas fuels a generator that powers the plant, with electricity left over to sell to the grid. Fast centrifuges, a proprietary polymer, and hot ovens separate the digester glop into a brown liquid, rich in nitrogen and potassium, and an ash that is 35 percent phosphorus. All that will be sold; the plant will produce no waste, Nienhaus said. When I visited, it was in its test phase. Nienhaus displayed her first batch of phosphorus in a small white dish, like granules from a gold strike.

Once upon a time, every farmer ran a circular economy, keeping only as much livestock as his or her land could feed, and those animals pooped no more than the land could take. Industrial livestock operations broke that circle. A few years ago, I spent some time on a cattle feedlot in Texas; that's when I started thinking about the circular economy. I watched 110-car trains full of Iowa corn rumble into Hereford, Texas, and I saw hills of manure at the feedlot, waiting to be sent to local farms. Shouldn't that be going back to Iowa to fertilize the corn, I asked? Too expensive, was the answer—but if a plant like Nienhaus's were there, only the nutrients would need to be shipped. Maybe the circle could be unbroken again.

When Eben Bayer invented his new thing in 2006, he was an engineering student at Rensselaer Polytechnic Institute in Troy, New York. He was taking a class in invention, learning to think divergently, and the problem he was pondering—he'd read *Cradle to Cradle*—was the toxic glues in particleboard or fiberglass. Growing up on a Vermont farm, Bayer had spent hours shoveling wood chips into a furnace to make maple syrup. The wood chips often stuck together—because they'd been colonized by mycelium, the dense mesh of microscopic fibers that make up the roots of mushrooms. Bayer wondered: Could mushrooms grow a harmless glue?

In addition to the enzyme and insulin plants, visible here in the foreground, the Kalundborg Symbiosis also includes, grouped around the town's harbor, a wallboard factory, an oil refinery, and a power plant that recently converted from coal to wood chips. Wind turbines loom on the horizon.

The first product he and his partner Gavin McIntyre made at Ecovative Design, the company they founded, was packaging. They inoculated ground hemp fibers or wood chips with small amounts of mycelium, and the tiny white roots filled the spaces between the particles, enmeshing and gluing them. They found the stuff could be grown in molds of any shape. It stops growing when you dehydrate it—and when you're done with it, you can compost it. In the past decade, Ecovative has made more than a million pounds of packaging—packing corners, display molds for cosmetics—for customers willing to pay a little extra to be sustainable.

Lately they've moved on to bigger things—things that are 100 percent mushroom. In soil mycelium grows in layers of mesh, but when it hits the air, it starts forming mushrooms. Ecovative has figured out how to trick mycelium into a hybrid growth pattern, in which it lays down solid microlayers one after another. "It's like a biological 3-D printer," Bayer said. With investment funding and $9.2 million from DARPA, the Defense Advanced Research Projects Agency, Ecovative is expanding a lab to figure out how to grow all manner of things—shoe soles, vegan leather, edible scaffolding for artificial steaks—from mycelium. In 2018 designer Stella McCartney made a handbag out of the stuff and showed it at the Victoria and Albert Museum.

In the cradle-to-cradle vision of McDonough and Braungart, waste doesn't exist even as a concept. Every material is either a well-designed "technical nutrient," capable of being endlessly

recycled, or a biological one, safe to eat or compost. Bayer shares that view—but he's betting most things will be biological in the future. "Biologically derived materials already fit into how Earth works," he said. "Spaceship Earth can digest this stuff."

At the Missoula, Montana, headquarters of Clearas, co-founder Kevin McGraw holds a dish of microalgae—the key to the company's novel system for cleaning municipal wastewater. When wastewater mixed with algae is pumped through well-lit, transparent pipes (aka "vertical ponds"), the algae bloom profusely, soaking up nitrogen and phosphorus—the nutrients that might cause harmful blooms if the water were discharged to a lake or river. The resulting biomass can be recycled for other uses.

Beyond good and evil

All the trash we make is not a sign that we're evil. It's a sign we're a little dumb. When I met Michael Braungart in Hamburg, Germany, he could barely wait for me to open my notebook before making this most essential point. He started his career as a Greenpeace activist, orchestrating protests at chemical companies, and has since consulted for many corporations. "We're fighting with cradle-to-cradle against a cultural heritage that comes out of religious beliefs," he said, meaning monotheistic ones. The legacy they've bequeathed to environmentalism, said Braungart, is the idea that nature is good and humans, in our effect on it, basically evil—the best we can do is limit the damage. To Braungart that's misguided and unambitious. He's an environmentalist who, like chemists and engineers, believes we can improve on nature. He once designed a biodegradable ice-cream wrapper implanted with wildflower seeds; you could litter it, and it would propagate beauty.

Outside Amsterdam I visited a 23-acre office park that McDonough's firm designed and Braungart helped select materials for, called Park 20/20. When the developer, Coert Zachariasse, made his own pilgrimage to Charlottesville a decade ago, he was hoping the guru would reveal exactly how to build a cradle-to-cradle office park. But McDonough demurred. "He said, 'We don't know yet, but we're going to figure it out,' " Zachariasse recalled. The developer felt disappointed at first—then liberated, empowered.

Park 20/20 is about three-quarters built, and it's already a green and pleasant office park. The facades are varied and imaginative, the spaces sunlit and inviting, the energy all renewable, the wastewater treated and recycled on-site. One of its coolest features is less apparent: Instead of the usual concrete-slab floors, the buildings have thinner, hollow, steel-beamed ones. They allow seven stories to fit in the usual height of six, using 30 percent less material overall.

A worker sorts tires at Kargro Recycling, a facility in Vianen, the Netherlands. Every year, more than 1.5 billion tires are discarded worldwide. The company retreads some and recycles others, extracting steel wires and shredding rubber. Another company, Black Bear Carbon, processes the granulated rubber into oil and a solid carbonaceous char. The oil is used for biofuel; the char can be used in tires, inks, coatings, and rubber goods.

In winter, warm water from the neighboring canal, stored underground since the previous summer, flows through pipes in each subfloor, heating the space above; in summer, cool canal water from the previous winter flows through pipes in each ceiling, cooling the space below.

And unlike concrete slabs, the prefabricated floor-ceiling sections are designed to be disassembled and reused, should the building need to be reconfigured or demolished. The Park 20/20 buildings are "material banks"—whereas elsewhere, building materials make up the largest waste stream flowing into landfills.

In McDonough's office I sat on an old Herman Miller chair upholstered with the first product he and Braungart ever designed, a fabric made of wool and ramie, which is made from nettles. Both men insisted it was edible, and had I been a goat, I might have tested that assertion. As McDonough was talking to me about Leibniz and a world of possibilities, I found my mind drifting to an old movie called *Diner,* which I'm more familiar with. "If you don't have good dreams … you got nightmares," Mickey Rourke's character says toward the end, as he and his young buddies are heading off into uncertainty. Maybe they'll grow up successfully, maybe not. And maybe, I thought, our whole species is in that situation—needing a dream to steer toward, in order to avoid the nightmare.

The circular economy is a dream that's inspiring a lot of people to do cool stuff. But—if I may close this journey with a thud—here's the thing: It's not happening. If you look away from the bright lights and at the dull numbers, the ones de Wit showed me, the "circularity gap" is growing, not shrinking. Our use of natural resources could double by 2050. Our carbon emissions are still increasing.

Nestled in a lava field on Iceland's Reykjanes Peninsula, this greenhouse receives geothermal electricity and heat from the neighboring Svartsengi Power Station. The barley plants growing in volcanic pumice absorb carbon dioxide from the air, making the greenhouse carbon-negative. Orf Genetics raises the engineered grain to make human growth factors used in such applications as cosmetics to rejuvenate skin.

(Watch the behind the scenes video of the making of the March 2020 National Geographic cover.)

“Is it moving fast enough? Not really,” de Wit said. “All indicators are in the red.”

Like the other optimists I met, de Wit is counting on time. Building a circular economy will require an enormous cultural shift, on the scale of the industrial revolution. “You need stamina,” de Wit said. “My sense is we can’t do it with the generation in power. It will require a generation to take off.” That was my generation he was hustling offstage; I didn’t take it personally, though. Sure, we’ll be pushing up daisies long before the circular economy arrives. But we’ll be doing our bit for it that way.

Luca Locatelli’s photos of Dutch agriculture in the September 2017 issue are on exhibit at the Guggenheim Museum in New York. Senior editor **Robert Kunzig** wrote about cities in April 2019.

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