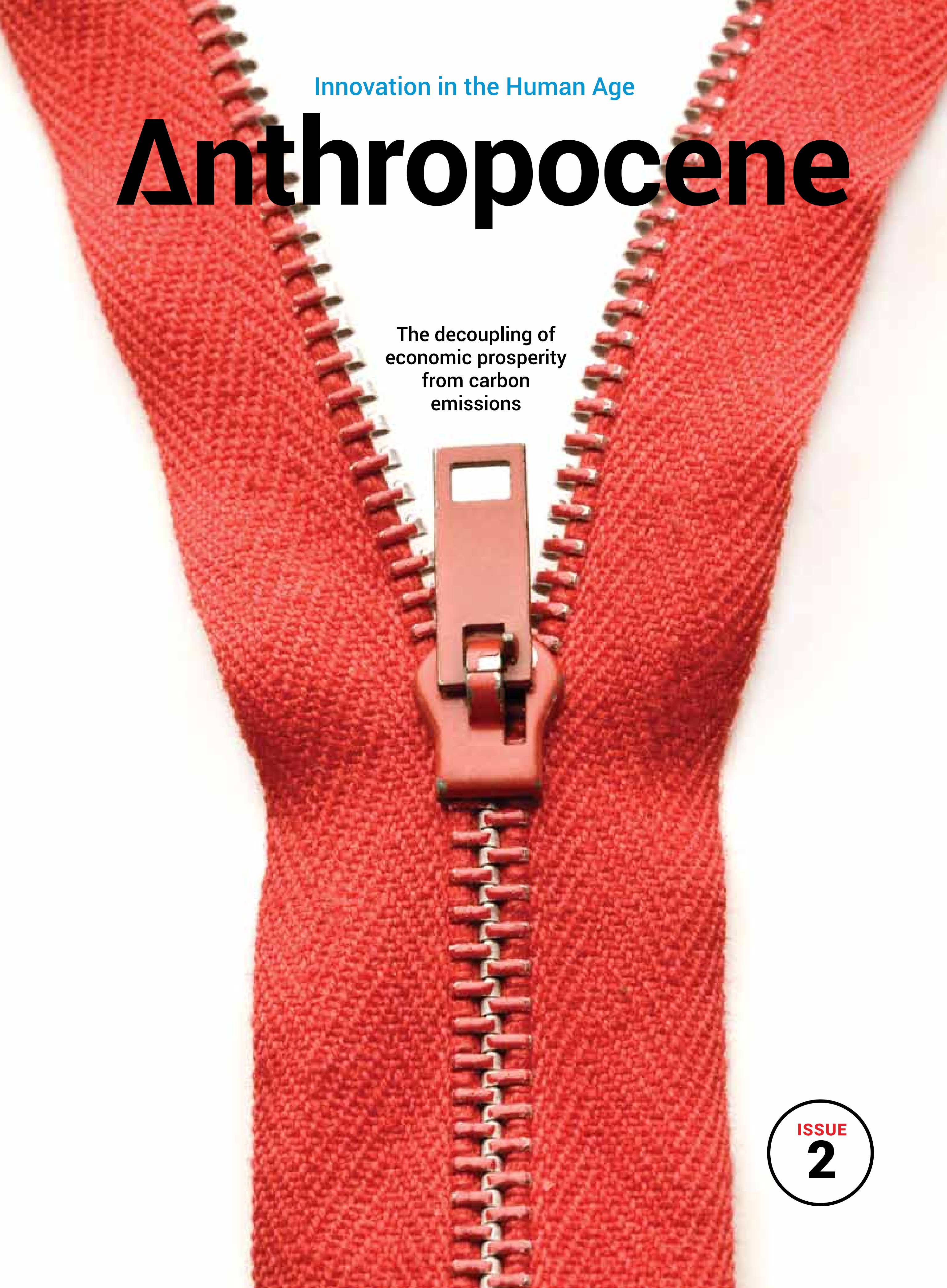
Innovation in the Human Age

Anthropocene



The decoupling of economic prosperity from carbon emissions

ISSUE 2

We are a digital, print, and live magazine in which the world's most creative writers, designers, scientists, and entrepreneurs explore how we can create a sustainable human age we actually want to live in.

Anthropocene

published by futurearth

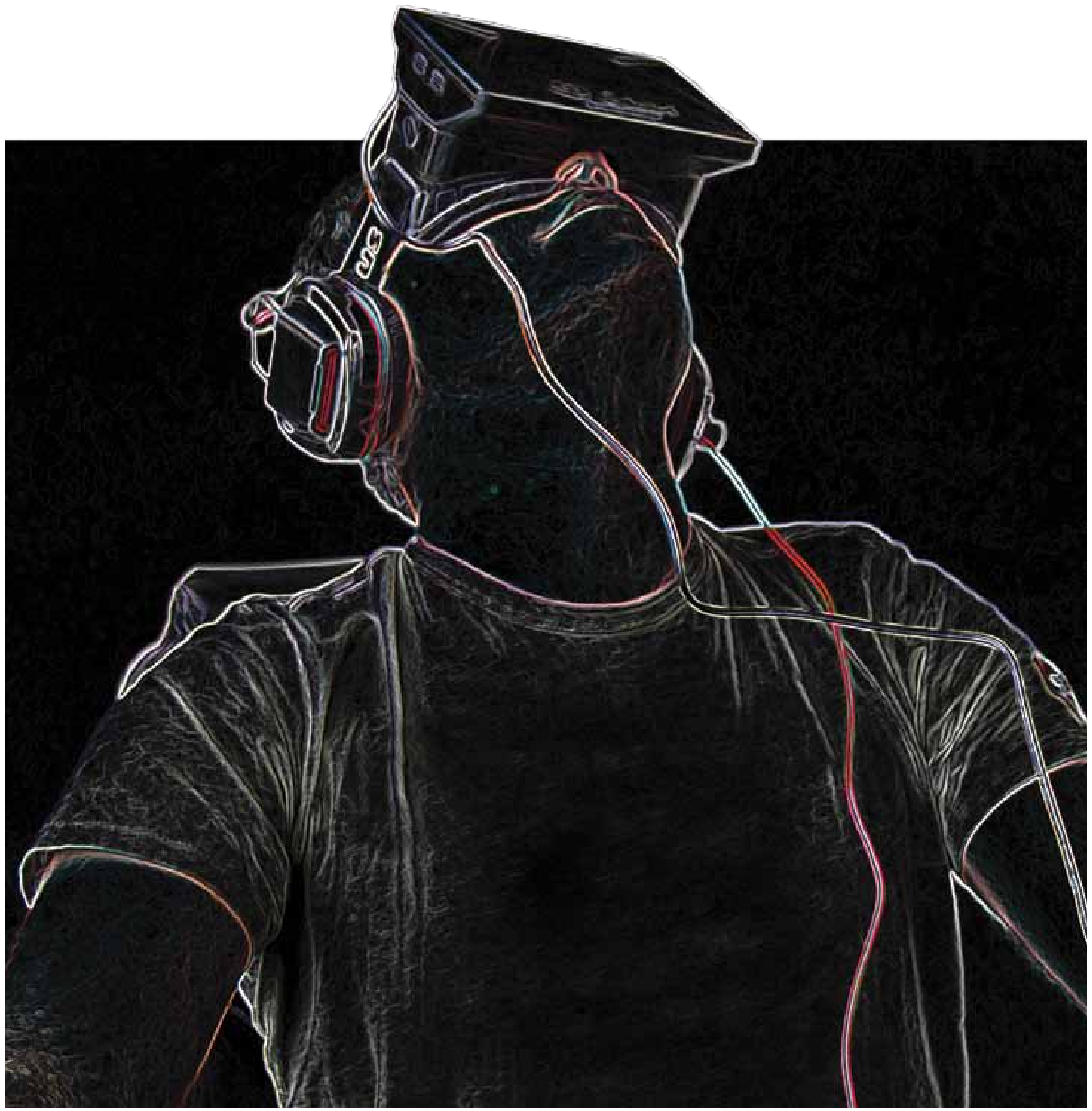
Future Earth connects science, innovators and local communities to accelerate the transformation to a more sustainable world

futurearth
research for global sustainability

Photo ©Abbie Trayler-Smith/Panos Pictures/Department for International Development

Anthropocene

Perspective



Look up. Try turning an old idea upside down and even inside out. To solve a wicked problem like decarbonization of the world's economies, it behooves us to search out new vantage points—and to stretch a little, intellectually.

In this second issue of *Anthropocene*, that's precisely what we've tried to do. Veteran writer and *Economist* editor Oliver Morton takes the lead on page 66. Solar geoengineering, he says, demands a new and often troubling way of looking at our home planet. In the 1970s, Apollo missions gave us a God's-eye view of the Earth and helped launch the environmental movement. Now we're faced with the daunting task of keeping global warming below 2 degrees Celsius. It is in this context that Morton deftly coaxes us to confront the godlike powers of geoengineering. It is problematic. It has potential. And it represents an irrevocable change in the human relationship to the planet that can't be ignored.

Then, on page 76, Robinson Meyer, a staff writer for *The Atlantic*, flips our usual way of looking at the decarbonization problem on its head. In debates over how best to treat our fossil fuel addiction, there seems to be an almost magnetic pull to the demand side of the classic economic equation. Often we try to curtail consumption by making things we want less of—in this case, carbon-spewing fuels—more expensive. But policies such as taxing carbon are politically precarious right now. So Meyer asks, what if we *also* exerted pressure from the supply side of the equation? Drawing on the work of Matt Frost and Bård Harstad, Meyer wonders whether we might make some headway toward decarbonization through a remarkably simple plan. Small groups of nations, or even super-wealthy individuals, could buy coal and other fossil fuel reserves—and not mine them. True, it is no panacea. But when you find yourself in a hole, it is time to stop digging.

And while we're challenging assumptions, don't miss Wayt Gibbs's article on energy equity on page 46. The short answer to the question posed in the title of the article, "How much energy will the world need?" is: a lot more than you think. Take your best guess and triple it. As the world gets ever closer to eliminating extreme poverty, the global appetite for energy will skyrocket. Gibbs walks through some complex numbers on energy demand to arrive at a simple conclusion. The challenge before us is not to do more with less, but rather to do more with more.

Technology will be pivotal. And one technology that is crashing headlong into almost every aspect of modern life is artificial intelligence. Technology writer Mark Harris provides a fascinating glimpse into how AI could make electrical grids vastly more efficient by making millions of tiny "turn it on or off" decisions that human beings would never bother to make.

If there is a theme for this issue, I'd say it is all about the lens through which we peer at our predicament. Change its curvature, and a whole new set of possibilities comes into focus.

Kathryn Kohm
Editor-in-Chief

Issue 2.

July 2017

1.

Idea Watch

People and projects pushing the boundaries of sustainability

IDEA WATCH

Instead of Trump's Wall, Let's Build a Border of Solar Panels

By Homero Aridjis and James Ramey

Donald Trump has repeatedly called for Mexico to build a wall between our countries. There is indeed a way that Mexico could create a barrier between the US and Mexico, one constructed exclusively on the Mexican side, with substantial benefits for both countries and the planet: a solar border.

Sunlight in the northern deserts of Mexico is more intense than in the US Southwest because of the lower latitude and more favorable cloud patterns. And construction and maintenance costs for solar plants in Mexico are substantially lower. Thus, building a long series of such plants all along the Mexican side of the border could power cities on both sides faster and more cheaply than similar arrays built north of the border.

Solar energy is already being generated at lower prices than those of coal. With solar plants along vast stretches of the almost 2,000-mile US-Mexico border on the Mexican side, a new high-voltage direct-current (HVDC) grid could be set up to transmit energy efficiently from that long, snaking array to population centers along the border. HVDC power lines lose exponentially less energy over long distances than traditional power lines. Cities that could immediately benefit include San Diego, Tijuana, Mexicali, Tucson, Phoenix, El Paso, Ciudad Juarez, San Antonio, and Monterrey.

If one were to construct the equivalent of a strip of arrays one-third the width of a football field south of the entire US-Mexico border, wider in some areas and narrower in others, with a wide berth allowed for populated areas and stretches of rugged terrain, sufficient energy might be produced to also supply Los Angeles, Las Vegas, Albuquerque, Dallas, and Houston. For the US cities, it would be a way to obtain cheaper and cleaner energy than they could from other sources.

A solar border would alleviate a range of binational problems. For one, it would have a civilizing effect in a dangerous area. Since solar plants use security measures to keep intruders out, the solar border would serve as a de facto virtual fence, reducing porousness of the border while producing major economic, environmental, and security benefits on both sides. It would make trafficking drugs, arms, and people all the more difficult for criminal cartels. In Mexico, the solar border would create a New Deal–like source of high-tech construction and technology jobs all along the border, which could absorb a significant number of would-be migrant workers on their way to cross into the US illegally, at great physical risk.

Rendering of a solar wall on the US-Mexico border. Architect Ronald Rael explores this and other concepts for the border wall that unite rather than divide in his new book, *Borderwall as Architecture* (borderwall-asarchitecture.com). Image ©Rael San Fratello

Most importantly, it would make a significant contribution to the global battle against carbon emissions, since the electricity generated would be carbon-neutral, and the purchase of so much solar technology would bring its price down further. The plants would be built using environmentally sensitive techniques for avoiding habitat loss for desert species.

Electricity exports from Mexico to the US have existed for over a century and have burgeoned in recent years, which should make international long-term loan guarantees for solar plants relatively easy to obtain.

Additionally, the grid could extend to the coasts, where ecologically sensitive desalination plants could be built for the production of fresh water to be pumped inland to those cities and agricultural areas along the border that suffer from water shortages—phenomena bound to worsen as the effects of global warming increase desertification. This would reduce tension and food security concerns that have vexed bilateral relations for decades because of the disputed water supply of the Rio Grande and other shared water sources.

Once the solar plants are installed and prove successful, additional areas in Mexico could be added to the grid, building on the accumulated know-how generated in the new workforce by the initial construction experience. Mexico has immense potential as a solar-producing country—especially in its high, central plateau deserts, which provide the most favorable combination of dry, unclouded, low-latitude, and relatively cool climate for solar generation. Potentially, all of Mexico could be solar-powered one day.

How to pay for it? Although it would be a major investment, the price of industrial solar generation continues to drop quickly, and because Mexican solar power is cheaper to build and maintain than comparable facilities north of the border, international investors would have strong incentives. Fortuitously, Mexico's recent constitutional reforms encourage foreign and domestic investment in the electric-power sector. Construction of the solar border would go a long way toward helping Mexico achieve its mandated climate change goals, which include 35 percent renewable electricity generation by 2024. Electricity exports from Mexico to the US have existed for over a century and have burgeoned in recent years, which should make international long-term loan guarantees for solar plants relatively easy to obtain.

If the initiative were framed as a big, charismatic project that has the full backing of the Mexican government, garnering the admiration of the rest of the world, it would position Mexico as an exemplary world leader in combating climate change. Mexico and the US would be connected by a truly beautiful wall—a symbol of unity, visible even from space.

Homero Aridjis is an award-winning Mexican poet, novelist, diplomat, and environmentalist. **James Ramey** is a professor at Metropolitan Autonomous University, a member of Mexico's National System of Researchers, and a documentary film producer.

This article was originally published in the *Huffington Post/World Post* on December 19, 2016, and received 1 million Facebook Likes.

Art ©Guido Daniele (guidodaniele.com)

IDEA WATCH

Human-Driven Evolution Is a Hallmark of the Anthropocene

By Lizzie Wade

During World War II, Londoners often sought shelter from German bombs in the city's subway tunnels. There, they encountered another type of enemy: hordes of voracious mosquitoes. These weren't your typical above-ground mosquitoes. They were natives of the Underground, born in pools of standing water that pockmarked the underground passageways. And unlike their open-air cousins, London's subterranean skeeters seemed to love biting humans.

Fifty years after the war ended, scientists at the University of London decided to investigate the subway population. They collected eggs and larvae from subway tunnels and garden ponds and reared both populations in the lab. The outdoor mosquitoes fed on birds, but the tunnel bugs preferred mammal blood. And when the scientists put males and females from the different populations into close quarters designed to encourage mating, not a single pairing produced offspring. That sealed the deal: the underground mosquitoes were a whole new species, adapted to life in the subway tunnels people had built.

It's stories like this one that got Joseph Bull thinking. As a conservation scientist at the University of Copenhagen, he hears a lot about how humans are driving other species extinct. If the current rate stays steady, the planet is on its way to its sixth mass extinction, a severe event on par with the meteorite impact that killed the dinosaurs. But he wondered whether there might be a flip side. Certainly people's planet-transforming activities had to be creating new species, too. But how, and how many? Bull decided to see whether he could count all the new species humans had created or were on their way to creating, in a sort of mirror-image of extinction rates and endangered species lists.

First, Bull had to come up with a list of human activities that could create new species. The most obvious one is domestication. By picking out the traits in a wild population that are most beneficial to humans and breeding for them, people can "force evolution in different species," Bull says. Wolves become dogs, nubby grass becomes maize, wild boars become pigs.

As people's environmental reach has expanded and our corresponding sense of responsibility for the planet has grown, we've started applying the principles of domestication to helping wild species, too. For example, several environmental organizations—including The Nature Conservancy and SECORE International—recently joined forces to breed resilient corals, selecting the heartiest parents and raising their offspring in protected pens in the Caribbean. In pilot projects on the island of Curaçao and in Mexico, scientists are currently working on transplanting these born survivors into wild reefs suffering the effects of climate change and pollution. The

The Human Age will be shaped by the species we create and foster as well as the ones we kill off

A version of this story was originally published by *Wired*.

idea is to provide a shot of genetic diversity to the reefs, ensuring they can withstand high temperatures and acidifying oceans without bleaching. Researchers, including biologist Ruth Gates of the Hawaii Institute of Marine Biology, say coral reefs are unlikely to survive much longer without such "assisted evolution." (1, 2)

People's efforts to help species we like can sometimes backfire. The livestock industry pumps antibiotics into animals to keep them healthy in overcrowded quarters and to encourage them to grow more quickly, but such widespread use allows low levels of those antibiotics to leak out into the environment. Such small amounts don't stop the growth of bacteria, but some scientists wondered whether they could affect pathogens in other ways. In a recent issue of the *Philosophical Transactions of the Royal Society B* dedicated to human influences on evolution, researchers exposed colonies of the common bacterium *Pseudomonas fluorescens* to very low levels of the antibiotic streptomycin. Streptomycin kills bacteria by interfering with its ability to make proteins, but at nonlethal levels that same mechanism causes the bacteria to mutate. The researchers discovered that exposure to nonlethal amounts of streptomycin caused *P. fluorescens* to evolve resistance not only to the antibiotic, but also to a common phage—a virus that infects *P. fluorescens* and naturally keeps its population down. (3) Efforts to strengthen livestock via antibiotics, therefore, could actually be doing more to help bacteria.

Humans have relocated 891 plant and animal species and domesticated 743

Humans can also drive speciation in less direct and less purposeful ways. "It's important to think about the creation of new species as a process," Bull says. One of the most dramatic ways people put that process into motion is by moving members of an existing species from one place to another. Sometimes those individuals die in the new environment. Sometimes they hang on and interbreed with native species. And sometimes they take over, like kudzu in the American South or snakes on Guam. Over time, the new environment exerts different pressures on the invasive population, causing it to diverge from its ancestors. The invasive species might also change the game for native species, pushing them in new genetic directions (if, of course, it doesn't just drive them extinct).

Although hunting is one good way to drive a species extinct (just ask the passenger pigeon), it can also spur evolution by removing certain types of individuals from a species gene pool—birds of an easy-to-see color, say, or fish large enough to be caught in a net. No new species is known to have been created through hunting alone, Bull says. But given enough time, it's far from impossible.

Finally, we have the process that created the underground mosquito: people's propensity to create entirely new ecosystems, especially those including cities. Populations of animals colonize these new environments and adapt to their demands—from mosquitoes developing a taste for mammal blood underground to city birds becoming better problem-solvers than their rural relatives. In the same human-directed-evolution issue of *Philosophical Transactions of the Royal Society B*, researchers found that urbanization affected even plankton. After taking samples from 84 ponds in Belgium, located in areas ranging from rural to suburban to very urban, the researchers found that in most cases, the more built-up the pond's environment was, the smaller its zooplankton tended to be. They posit that change in size is due to the fact that cities generate more heat than rural areas, and hotter temperatures mean that oxygen becomes less soluble in water. Animals with small bodies and lower oxygen requirements are therefore better able to survive in urban aquatic environments. That could cause problems, the researchers say, because zooplankton graze on microscopic plants; if the zooplankton shrink too much, the tinier plants could grow out of control. (4)

Lizzie Wade writes about science from her home in Mexico City. She is a contributing correspondent for *Science*, focusing on archaeology, anthropology, and all things Latin America.

Keeping these mechanisms in mind, Bull tallied up humans' impact on species in a paper published last year in *Proceedings of the Royal Society B*. Scientists have recorded 1,359 plant and animal extinctions in the past 12,000 years. Meanwhile, humans have relocated 891 plant and animal species and domesticated 743, for a total of 1,634 species. (5) It seems that human-driven speciation could be as much a mark of the Anthropocene as extinction is.

Of course, extinction, like speciation, is hard to document while it's happening. Many species likely disappear before scientists even know they are there. That's why extinction rates are calculated with extrapolations and models but even so give widely different numbers. That's all to say that many more than 1,359 lifeforms have likely gone extinct in the past 12,000 years. One scientist even estimates that the world has lost 130,000 species of recorded invertebrates alone. (6) It's also possible humans create species without detecting them. Just think of the wild world of antibiotic-resistant microbes, which evolve so fast in response to drugs that it's dangerously difficult to keep up.

Number of species, however, is just one way to measure the effects humans have on nature—and maybe not the best way. Drive keystone predators such as wolves or sharks extinct, and entire ecosystems collapse—no matter how many new species pop up to replace them. What's more, older species can carry millions of years of evolutionary history in their genes; if they go extinct, that diversity is lost. "Anthropogenic species represent a nanosecond of the evolutionary time that many 'natural' species have passed through," says Christopher Dick, an evolutionary biologist at the University of Michigan. "In conservation, there is no comparing a 10-million-year-old tree or turtle species with a decades-old strain of insect or plant." Species whose genomes have been shaped by mere decades or even years of human-driven evolution may have lost the rare genes that aren't particularly helpful in current environments but may regain their usefulness as the world changes. Something like this is currently happening to maize, as the varieties people have bred and planted most intensively can't keep up with the climbing temperatures and longer droughts brought on by climate change. Researchers at the International Maize and Wheat Improvement Center, a seed bank outside Mexico City, are racing to collect the older and rarer maize varieties still grown in remote villages in Mexico—in hopes of finding a constellation of ancient genes that could save the world's supply of corn.

Bull agrees that speciation and extinction don't cancel each other out. "If we only use number of species as a way of measuring progress that someone makes on conservation, then we're missing a load of other important considerations," he says. "We cannot replace something lost with something gained when it comes to nature." Human-driven speciation may turn out to be a calling card of the Anthropocene. But no matter how many species of underground mosquitoes we inadvertently create, they won't make up for what we destroy.

1. van Oppen MJH. et al. Building coral reef resilience through assisted evolution. *PNAS*. 2015.
2. van Oppen MJH et al. Shifting paradigms in restoration of the world's coral reefs. *Global Change Biology*. 2017.
3. Cairns J et al. Sublethal streptomycin concentrations and lytic bacteriophage together promote resistance evolution. *Philosophical Transactions of the Royal Society B*. 2017.
4. Brans KI et al. Eco-evolutionary dynamics in urbanized landscapes: Evolution, species sorting and the change in zooplankton body size along urbanization gradients. *Philosophical Transactions of the Royal Society B*. 2016.
5. Bull JW and M Maron. How humans drive speciation as well as extinction. *Proceedings of the Royal Society B*. 2016.
6. Régniera C. Mass extinction in poorly known taxa. *PNAS*. 2015.

The Circular Economy Made Real

In more and more pockets of the industrial landscape, the byproducts of one process are becoming the raw materials for another, trash is getting a useful second life, and waste is becoming a thing of the past

By Lindsey Doermann

©Fruitleather Rotterdam

©Adidas

Food waste turns into fashion

In the Netherlands, an innovative startup is using principles of the circular economy to cut down on two environmental scourges—food waste and leather production. Fruitleather Rotterdam (facebook.com/fruitleather.rotterdam) is deseeding discarded fruit and then mashing, boiling, and drying it into a leather-like material. From there, it's used for footwear, fashion accessories, and upholstery; the team recently produced a chair for Dutch Design Week. What began as a design school project is now a nominee for the Henri Winkelman Award for entrepreneurial designers.

Plastic trash from the ocean becomes running shoes

For Adidas and the nonprofit Parley for the Oceans, cleaning plastic out of the oceans is a mere first step in combating waste at sea. Together they're making shoes and other apparel out of ocean plastic. The composition of the "upper" of the UltraBOOST Uncaged running shoe is 95 percent recycled plastic from deep-sea gillnets and from trash harvested from the waters off the Maldives. Adidas sold 7,000 pairs of these ocean-plastic shoes last year and has committed to making 1 million more pairs by the end of 2017. It has also incorporated the recycled material into T-shirts, shorts, flip-flops, and professional soccer jerseys.

Plastic waste becomes low-cost building blocks

In Bogotá, Colombia, plastic is sent to the landfill by the ton. Architect Oscar Andres Mendez Gerardino is looking to change this—and simultaneously create low-cost housing options for city residents. His company, Conceptos Plásticos, is melting and molding plastic and rubber waste into LEGO®-like bricks and pillars that can be assembled into buildings. Four people can construct a single-family home in just five days, according to the company. In 2015, Conceptos Plásticos turned 120 tons of plastic waste into shelter for 42 families displaced by violence in Guapi, Cauca, near the Pacific coast of Colombia. Company founder Gerardino received a Young Entrepreneurs Award from Unilever in 2016.

Photos ©Unilever

Car dashboards become 3D-printer filament

What becomes of your trusty old car when it's finally consigned to the scrap heap? Dutch company Refil has perfected the process of shredding and melting old plastic car-interior parts, such as dashboards, to recycle them into 3D-printer filament. From there, your old dash can become a vase, a toy, new jewelry, or anything else you can make with a 3D printer.

Brewery wastewater feeds algae, then becomes biodegradable ink

Upslope Brewing in Boulder, Colorado, has piloted a partnership to bring brewery byproducts full circle. Local startups Boom Algae and Living Ink Technologies are using Upslope's waste carbon dioxide, spent grain, and canning rinse water to cultivate algae. The algae then become the base pigment for 100 percent–biodegradable ink. To close the loop, the brewery will use the algae ink to print its menus.

Photo by Jesse Borrell/NOCOAST

Photo courtesy of Refil

Closed-loop food production at The Plant in Chicago

Entrepreneur, artist, and industrial-preservation enthusiast John Edel has been working for the past seven years to transform an abandoned meat-packing facility in Chicago's Back of the Yards neighborhood into a test bed for closed-loop, net-zero energy food production—one that also turns a healthy profit.

©Ria Neri/Whiner Beer Company

Spent grain from Whiner Beer Company's brewery helps fuel the oven of neighboring Pleasant House Bakery, feeds fish in The Plant's aquaponics operation, and serves as a growing medium for an indoor mushroom farm. Whiner makes Belgian- and French-style barrel-aged beers and operates a taproom in the old warehouse. Plans are in place for the spent grain to help fuel The Plant's anaerobic digester when it's up and running—and hence help power the entire building.

©Pleasant House Bakery

Pleasant House Bakery found it could incorporate spent grain from Whiner Beer Company, and coffee chaff from a roastery in the building, into combustible "bio-bricks" for its masonry oven. Testing showed that the briquettes burn hotter and faster than wood, so they may not serve as a fuel substitute while goodies are baking. But they do show promise for maintaining heat in the oven between baking cycles, cutting down on the amount of wood required to reheat the oven from a low temperature.

Amaranth under grow lights ©Plant Chicago

The Plant is raising fish and microgreens in a closed-loop aquaponics system. The microgreens clean the water for the fish, and fish waste provides fertilizer for the plants. Staff and interns are experimenting with supplementing expensive commercial fish feed with the brewery's spent grain. And soon the system's waste will help power the anaerobic digester.

Oyster mushroom ©Phil Norton

Belkacem El Metennani's business, Fruiting Mushrooms, operates out of an old ham freezer in the basement of The Plant. It uses byproducts from agriculture, beer production, and coffee brewing elsewhere in The Plant as a growing medium for gourmet mushrooms—oyster, lion's mane, comb's tooth, and reishi. El Metennani sells his mushrooms locally, of course.

IDEA WATCH

The Carnery

Imagine a culinary future with *in vitro* meat . . .
The real thing may not be as far away as you think

By Isha Datar
and Robert Bolton

Above: A concept for a cultured pork product grown from pig stem cells for the fictional restaurant Bistro *In Vitro*. Image courtesy of Next Nature Network.

Counter Culture, London's latest *in vitro* micro-carnery, proves it's the real thing. The restored 1970s-era English brewpub boasts an expansive bar of reclaimed mahogany and booths upholstered with magnificent *in vitro* leather. Steaks are grown to precision inside giant steel vats decorated (functionally) with illuminated green algae tanks. A disorienting mingling of global spices flavors varieties of exotic and heritage meats like boar and Berkshire, all of which are cultured on site. The large charcuterie board, consisting of mushroom-medium duck *foie gras*, coriander mortadella, and crispy lobes of sweetbread pairs perfectly with a shortlist of probiotic cocktails (try the rum and kombucha).

In vitro meat has the capacity to transform meat production as we know it, not only offering new and diverse types of product but also introducing an entirely new way of thinking about and interacting with food. One day, growing meat may seem as natural as making cheese or beer.

Like a bakery where bread is made, a winery where wine is made, and a brewery where beer is made, the "carnery" is where *in vitro* meat is made.

The farm was long the cultural ground connecting humans to our food and to our labor. Through over 10,000 years of agricultural practice, farming—food and work—was a foundation on which we developed our sense of humanity. From values such as integrity, quality, respect, and stewardship, to experiences of shared knowledge and enjoyment, to developing our relationship with land and species—and gaining a concept of the cyclical passage of time that connects us to the seasons—the farm has been our cultural rooting. Keeping farm animals played an integral role in maintaining the farm. Animal husbandry and crop cultivation were concerted activities. Animals were fed on crop residues after a crop was harvested, or on pastures that were unfit for farming. Manure was used to replenish soils. Animals were slaughtered and shared. Meat was honored and savored.

To meet and exceed consumer demands for food, the farm has been a site of cutting-edge breakthroughs in mechanical engineering, genetics, and chemistry. The craft of tending the herd evolved into processes of automation and directives. Meat production scaled to a point where it can no longer fit into a cyclical and sustainable farming system. Today most meat is produced on industrial farms where animals are bred, raised, and slaughtered for the principal purpose of producing food for human beings. Crops that could feed humans are instead fed to meat animals. Fertilizer is produced in such quantities that it spoils soils rather than nourishing them. In many ways animals are treated as living, meat-producing bioreactors with human food as an input, polluting waste as an output, and various drugs, hormones, and genetic manipulations added to make the process more "efficient." Price is the defining product characteristic, and minimizing this incurs vast external costs to the environment, animal welfare, and public health.

Further, meat is defined as a small handful of species, presented by a smaller handful of corporations. Few players, little product diversity, and a very narrow, inexpensive price range characterize the meat-production industry status quo.

In light of population increase, food insecurity, volatile food prices, environmental concerns, and changing value systems around food, it is clear that current modes of production cannot persist. For meat production to take place responsibly, we will have to significantly diversify our eating habits—and with them, our production habits. *In vitro* meat is one promising alternative. We don't know enough about it yet. But we know we can make it. And we are responsible for exploring what it will mean not only for our health and environment, but also for our culture and our sense of humanity. How should we feel about interacting with lab-grown meat?

If we're comfortable treating meat animals like bioreactors, and engineering them strictly for the purpose of maximal protein production, then perhaps we can go a step further. Meat is simply a collection of muscle, fat, and connective tissues. Rather than raise an entire complex organism only to harvest these tissues, why not start at the basic unit of life, the cell, to produce meat? *In vitro* meat is meat, created in a bioreactor rather than in an animal.

A few things are required for making meat *in vitro*: a cell line, a medium to feed the cells, a bioreactor where cell growth can take place, and a structure upon which the cells can attach and grow. Each of these elements allows for limitless variations of technique and process. The room for deviation bridges science with craft, enabling *in vitro* meat makers to create unique products with unique characteristics and features. At the fictional *in vitro* meat restaurant Counter Culture that begins this essay, the boar meat could be made with adult stem cells collected from wild boar, cultured in an algae medium. Grown in a rotating wall bioreactor on a tubular scaffold, the cell stretches to produce a lean, grained meat. The mushroom-medium duck *foie gras* could be made from a co-culture of duck fat and liver cells in a mushroom-based medium, 3D-printed onto a bioabsorbable scaffold to produce a fatty, smooth, and cruelty-free *foie gras*. The flexibility of *in vitro* meat production can change and diversify the ways people consume and interact with their food.

As it stands today, a thick interface separates the experience of eating from the process of food production. Industrial farms are located far from the eyes of consumers, and knowledge of what occurs in these farms is limited in the wider public. While consumers are mostly disconnected from the realities of where their food comes from, marketers continue to romanticize the ideal farm of yore, substituting images of agriculture in place of ones of industry, dropping visual cues to the rural farm on packaging, advertising, and in retail displays. These signifiers remind us of the core human values and sense of community that we've historically associated with the farm. Indeed, when done well, you can taste the crafted freshness. In the eyes of diners and marketers alike, the distinction between fantasy and reality is apparently trivial, if not entirely nonexistent. We buy into rustic theaters of "artisanal," "small-batch," and "hand-crafted" cuisine, though the associations we have with these words may bear no resemblance to the actual back-end production processes. The theater of branding is effective enough that we're relieved of our responsibility to confront the truths of our food. *In vitro* meat may play into this theater—fitting among the existing symbols, textures, and cues that make us comfortable with artifice—while breaking down its fourth wall, chipping away the layers, so that like the farmer, the baker, the butcher, and the brewer, we can interface directly with the realities of food production.

The science and art of culturing cells to produce meat has been called "carniculture." Like a bakery where bread is made, a winery where wine is made, and a brewery where beer is made, the "carnery" is where *in vitro* meat is made. Carniculture might be dressed with similar connotations and aesthetics to the craft-brew and farm-to-table movements.

We have to ask not only how *in vitro* meat products nourish our bodies, but how the process of making them nourishes human culture and fits in with our sense of a modern humanity. How, going forward, can the manufacturer of *in vitro* meat achieve the symbolic status of the farmer, the baker, and the small-batch brewer? How can the carnery, like the bakery, the winery, or the brewery become an impetus for human culture? Though it uses mammalian cell cultures rather than yeast cultures, a carnery has the potential to look very similar to these facilities—beer breweries in particular.

> For meat production to take place responsibly, we will have to significantly diversify our eating habits—and with them, our production habits.

At the carnery of the future, large stainless-steel tanks house the biological processes that are transforming organic ingredients into food products. Conditions such as temperature and pressure are controlled and manipulated. Inputs and outputs are carefully measured. The work environment is clean and safe. But it doesn't feel like sterile science. It feels crafted, artisanal—because it is.

As with beer, the basic production scheme for producing *in vitro* meat can be modified and adapted in endless ways to make products that vary in appearance, aroma, taste, and mouthfeel. This makes for an industry comprised of many diverse products and players, and production on many different scales. A brewery can be massive with several stories–tall bioreactors, located near city limits—or it can be smaller and situated in urban areas. A brewpub restaurant may choose to brew seasonal offerings in-house, while a DIY enthusiast may wish to try his or her hand at making the ultimate personalized brew with a home-brewing operation.

Imagine that within the stainless-steel tanks at a brewery, microbrewery, brewpub, or basement, meat—rather than beer—is being brewed.

Low-cost, mass-produced meat is cultured in massive carneries in rural areas. Because the risk of bacterial contamination and viral epidemics is far decreased without the use of animals, the meat production business is no longer at risk of recalls, workers are no longer at risk of health issues, and the local rural environment is no longer at risk of water and air pollution.

Mid-range *in vitro* meat is made in local carneries in urban areas. These carneries host school and travel tours, educating the public on the art and science of carniculture. Because growing meat *in vitro* does not require the large tracts of land that factory farms require, this carnery is located in a skyscraper that once contained office space. Algae tanks surround the outer surface of the tower, reaping the unshaded sun available several stories up from ground level.

High priced meats are "micro-cultured" in trendy neighborhoods at boutique carnery pubs such as the fictional Counter Culture described at the beginning of this essay. These small-batch facilities create various seasonal offerings, depending on which media ingredients are available and which cell cultures and nutrient profiles are in vogue. Forward-thinking restaurants offer signature meats cultured in-house, paired with a house wine. Some chefs focus on nutrition profiles, some focus on traditional "heritage breed" lines and others focus on biomolecular gastronomy. They test the limits of carniculture by culturing rare or extinct species, co-culturing multiple cell types or developing unique, never-before-seen cell lines.

Communities of home carniculturists, who began as foodies and DIY bio enthusiasts, swap techniques and recipes at cultured-meat cook-offs, fairs, and night markets. Carniculture bloggers post photography, data, and other media documenting their materials, methods, and meals online. The home carnery movement spawns carniculture specialty shops, cell-culture babysitting services, protocol-swapping websites, cell banks, and special-interest magazines. Hobbyists seeking to turn their passion into a profession have a variety of certification and apprenticeship programs to choose from to help them join a major carnery or start one of their own.

In contrast to industrial farming, meat-production methods go from secretive to celebrated. Meat-production facilities go from vast to vertical. The meat-production industry moves from the hands of few to the hands of many. And people grow more authentically connected to the origins and creation stories of what they eat.

For this new industry to exist, some conditions have to be met in the early days of discovery and development.

The science has to remain fairly open, transparent, and publicly accessible. With a population of scientists scattered about the planet interested in making *in vitro* meat a reality, an "open source" approach to it will accelerate development of the technology. Intellectual property protection has a place in the industry at some point, but heavy, prohibitive patent protection early on could stunt this new industry before it has a chance to flourish. Culturing *in vitro* meat involves a level of "art" and technique that comes only with experience and familiarity with processes and materials. As such, patent protection will be complemented by trade secrets, secret recipes, and the carniculturist's distinct artistry and prowess.

Development needs to coincide with public conversation about meat, meat production, carniculture, and food science. Consumers need and want to know about the origins of their food. The new science of carniculture must be developed responsibly, driven by discourse from the beginning. This is much more likely to happen if research is funded and conducted publicly, openly engaging researchers, DIY bio enthusiasts, and students to address scientific hurdles. Creating a food politic that tackles resource use, the environment, public health, and animal welfare should be a cooperative movement.

In vitro meat is simply meat created outside the animal. Cultured meat and carcass meat are the same product, though created through different processes. The potential for carniculture to introduce a more humane and sustainable meat industry is undeniably compelling. With the right set of conditions in place during the development of cultured-meat science, carniculture can reduce the need for, or entirely displace, factory farming. By embracing transparency and creating a culinary attitude, the *in vitro* meat industry can become more diverse, responsible, and viable than the current meat industry. A new set of food values emerges, unique from and yet akin to those we associate with the family farm. A future with *in vitro* meat is indeed a cultured future.

Isha Datar is executive director of New Harvest and a pioneer in the field of cellular agriculture.
Robert Bolton is a Canadian writer and a senior strategist at the global innovation firm, Idea Couture.
This essay was originally published in *The In Vitro Meat Cookbook,* 2014. Reprinted with permission.

IDEA WATCH

To Upcycle Fast Fashion Melt Down Clothes

By Lindsey Doermann

Fast fashion—affordable clothing that tends to be tossed after only a handful of wears—takes a hefty environmental toll. Growing cotton, for example, requires copious amounts of water and pesticides. And in the landfill, textiles release greenhouse gases as they degrade. What's more, many of today's clothes are made of difficult-to-recycle fabric blends.

Now chemical engineers in Finland have devised a way to break down cotton-polyester-blend fabrics and reuse some of the material. They presented their research at a recent meeting of the American Chemical Society. Using an ionic liquid (i.e., a liquid salt), they can dissolve or "melt" the cotton out of the fabric. The resulting cellulose solution can then be spun into new fibers.

Next, the team is investigating whether it can turn the recovered polyester into usable fibers and reuse dyes from the old clothes.

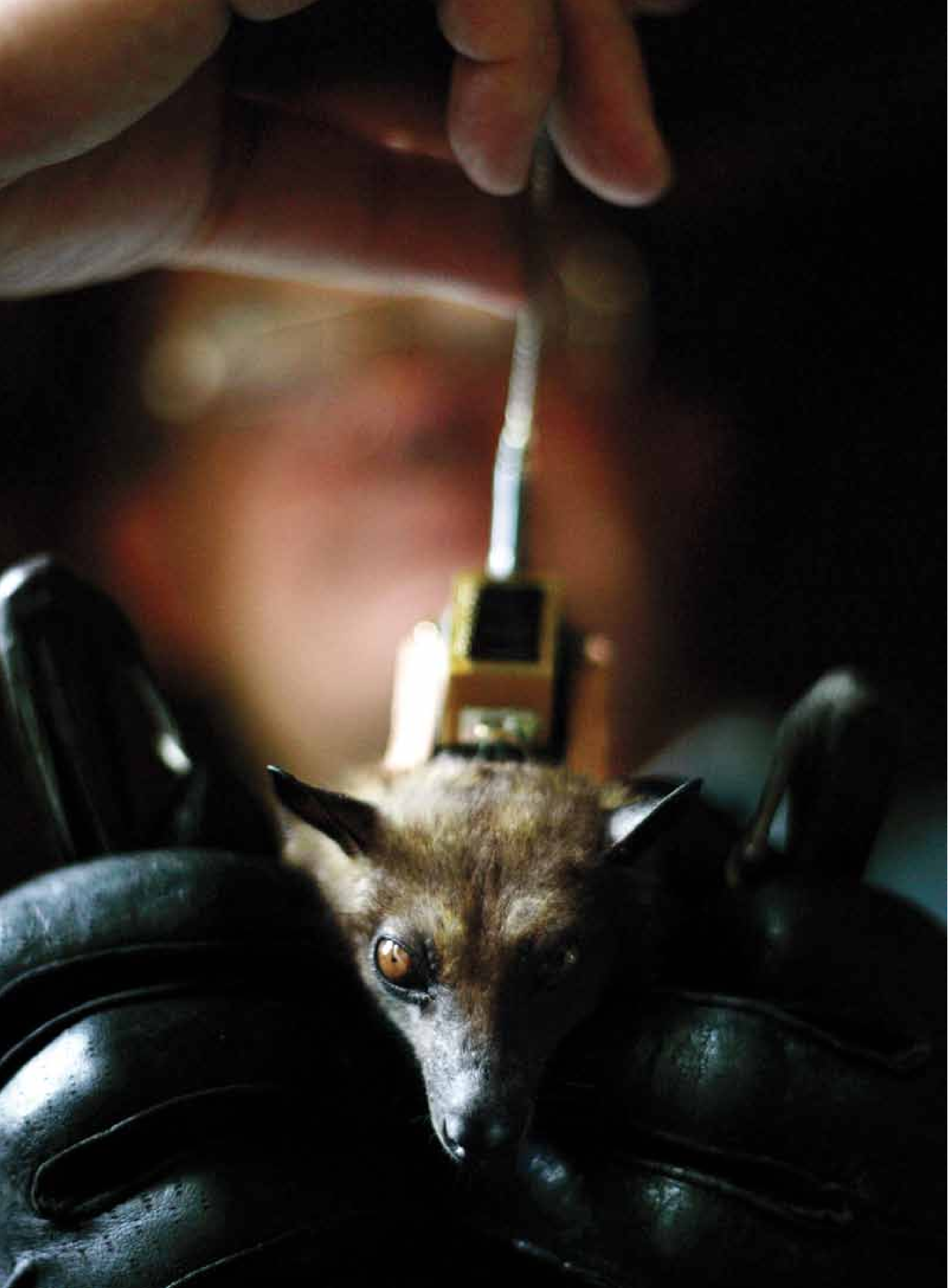


Photo ©Kieran Dodds/Panos

IDEA WATCH

An Internet of Wings

Researchers will track migratory animals from the International Space Station to predict the next pandemic

By Jane C. Hu

Renowned naturalist John James Audubon noticed that each winter, local birds disappeared for a few months and reappeared in the spring. But were these birds the same as those from the previous year, or a new crop? To find out, he conducted the first bird banding study in 1803 by attaching silver string to an eastern phoebe's leg. He found that it came back to the same nesting site year after year.

Two centuries later, zoologist Martin Wikelski has taken up Audubon's charge, albeit with far more sophisticated tools. Wikelski is director of the International Cooperation for Animal Research Using Space (ICARUS), a collaboration between scientists and the German, Russian, and European space agencies. Instead of string, ICARUS researchers are attaching GPS sensors, some the size of a euro one-cent coin and weighing a mere 5 grams, to bats, geese, and other animals. Since the project's start in 2002, scientists from all over the world have collectively tagged more than 2,000 animals representing 600 species. Armed with data from this network of roving wildlife, scientists can see in unprecedented detail where they go, how they live, and perhaps even how they transmit disease—all from space.

The Centers for Disease Control estimate that more than six out of ten infectious diseases are zoonotic: passed between animals and humans. Previous research has shown that outbreaks of diseases such as avian influenza tend to track with migration routes, and birds that travel long distances and reconvene once a year have the highest risk of transmitting the disease.

Using ICARUS, scientists will track the travel routes and health of fruit bats, mallards, and geese, creating what Wikelski calls "a heat map of life and death." In one recent project, ICARUS researchers implanted a handful of Swedish mallards with sensors that recorded not only location but also body temperature to monitor the spread of avian influenza. Those temperature readouts could identify infected individuals; a higher-than-average body temperature reading likely indicates infection. By comparing an individual's data with their travel history, scientists can piece together where animals contract and transmit diseases.

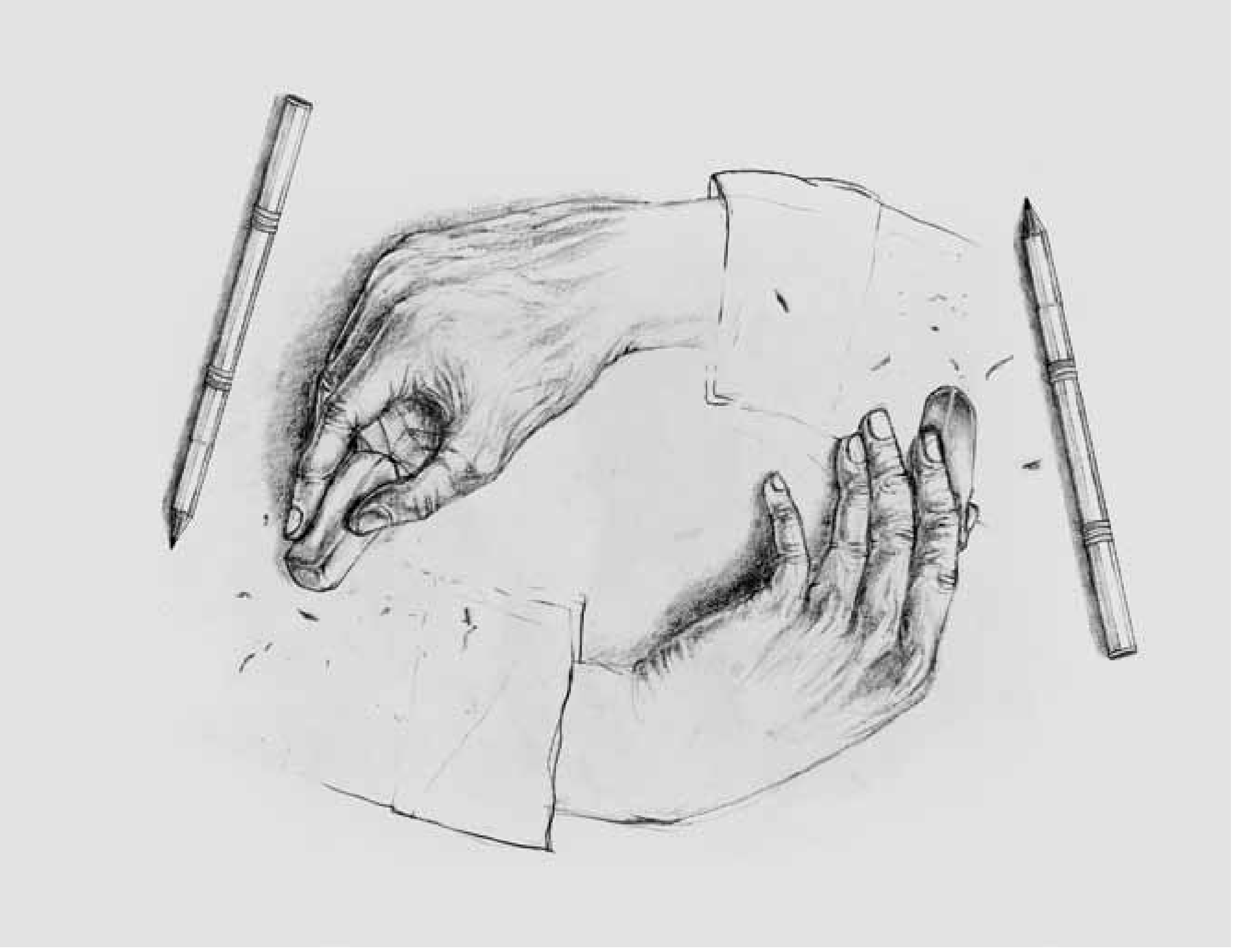
The data can also indicate how virulent a particular strain is and how likely it is to spread to other species. "If you have a body temperature increase, then you know that some low-path[ogenic] avian influenza is coming through—or if you have a massive fever and the animal dies, you know you have high-path[ogenic] avian influenza," he says.

Currently, that data can be collected only from base locations on the ground, close to where tagged animals live. But this October, the ICARUS team will install a receiver on the International Space Station, making it easier than ever to collect data from animals anywhere on the planet. Wikelski describes the receiver as similar to a cell tower: as the ISS orbits the earth, passing above tagged animals, ICARUS's receiver will signal animals' sensors to transmit their data.

Wikelski's next step is to correlate this information with even richer data from blood samples, for example, which would reveal how animals carry and spread antibodies. The team's long game is to create better models of disease transmission, which will lead to improved accuracy in predicting outbreaks and, potentially, the ability to intervene.

Drawing parallels to the "Internet of Things" made up of "smart" technology embedded in everyday objects such as cars and thermostats, Wikelski calls ICARUS the "Internet of animals" or the "Internet of wings." Standing upon Audubon's shoulders and those first silver strings, it allows us to see the world as never before.

Jane C. Hu is a Seattle-based science journalist. Her writing has appeared in *Slate, Scientific American, Nautilus,* and other publications.



©Tang Yau Hoong

IDEA WATCH

Rewritable Paper

Print. Erase. Repeat.

By Prachi Patel

E-readers and tablets seem to be all the rage, but most people still find good-old-fashioned paper books hard to beat. A Pew Research Center survey found that 65 percent of Americans had read a print book in 2016, as opposed to 28 percent who had read an e-book. However, our paper habit takes a toll on the environment.

A rewritable paper made by researchers at the University of California, Riverside, could help. The researchers "print" the paper using ultraviolet light instead of ink, and the text stays legible for five days before fading away. "You wouldn't want to use it for writing contracts," says chemist Yadong Yin, who led the work. "But it would be ideal for things like newspapers and posters." The paper can be reused 80 times and could be recycled after that, he says.

Conventional paper costs pennies but leaves a huge footprint. About 4 billion trees are cut every year to make paper or cardboard, using a process that consumes immense amounts of electricity and water. The paper and pulp industry is the world's fifth-largest energy consumer. It uses the most water per ton of product and is a major polluter. Even paper recycling pollutes.

Yin and his colleagues set out to crack the code of low-cost, low-toxicity reprintable paper. They coated conventional paper with nanoparticles of two commonly used materials: the compound titanium dioxide, which is used in sunscreens and makeup, and the paint pigment Prussian blue.

The paper starts out entirely blue. Placed under ultraviolet light, the titanium dioxide particles get excited and produce electrons that they donate to the neighboring Prussian blue particles. This makes the blue pigment lose its color and turn white. Over time, oxygen from the air absorbs the extra electrons, changing the pigment back to blue. Heating the paper to 120 degrees Celsius speeds up the process and erases the paper in ten minutes.

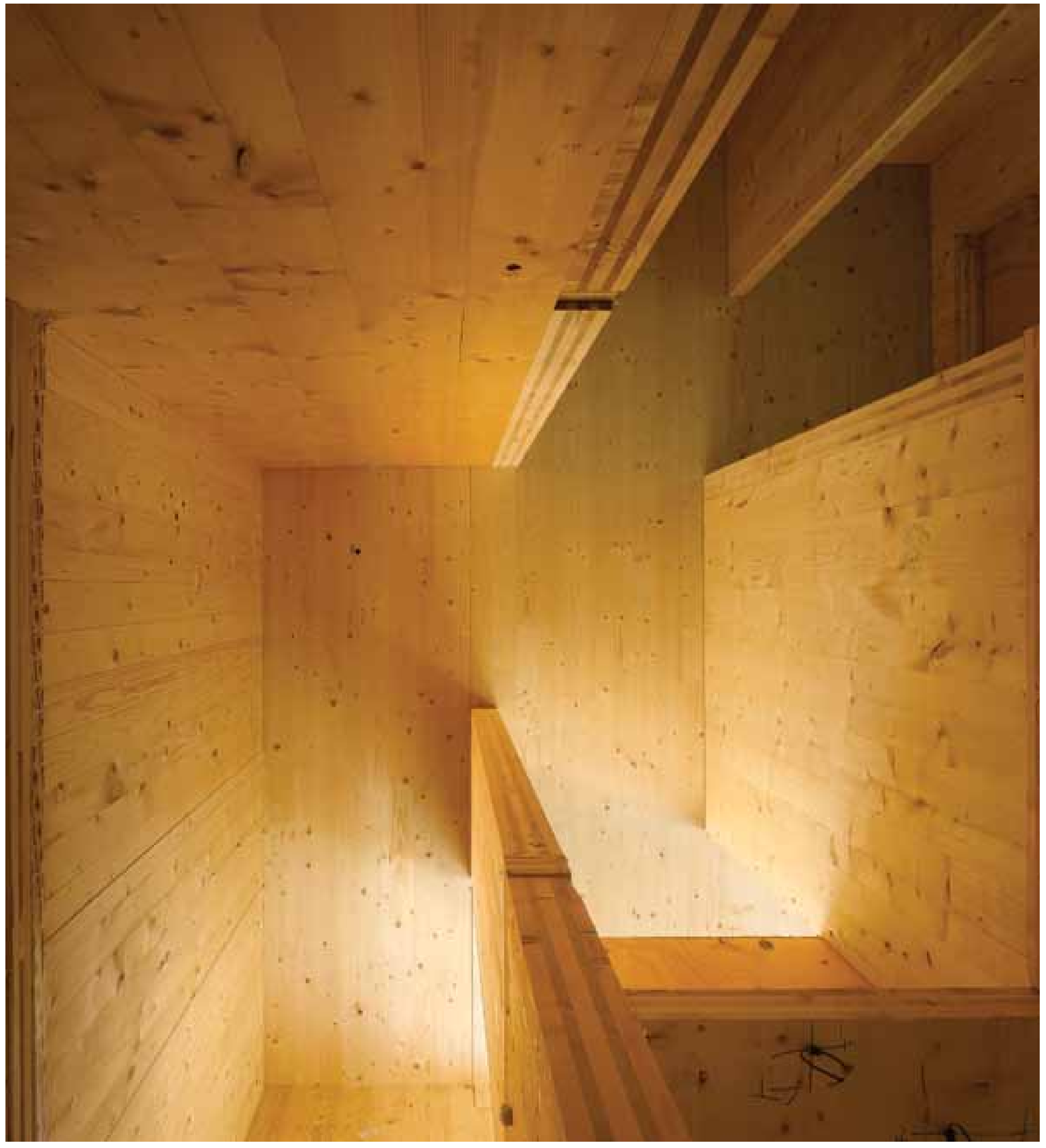
To "print" on the paper as a proof of concept, the researchers used a rudimentary process involving masking. They inkjet-printed text with black ink onto a transparent sheet, which acted like a mask when they shined UV light through it. Parts of the rewriteable paper under the black ink remained blue, while the surrounding areas turned white.

For commercial printing without a mask, a UV laser could be used to scan the paper surface on areas that need to remain white, Yin says. This would work similarly to the way today's laser printers do.

The researchers report that they can print patterns at incredibly high resolution—as small as 10 micrometers, or ten times smaller than our eyes can see. And as for cost, their coated paper should be comparable to regular paper. Both titanium dioxide and Prussian blue can be produced by the ton and are inexpensive. In fact, titanium dioxide is already used to make bright white paper, Yin says.

The team is now thinking about how to make a commercially viable printing technique and multi-colored paper.

Prachi Patel, originally from Nagpur, India, is now based in Pittsburgh. She writes about energy, biotechnology, nanotechnology, and computing. She is a contributing editor at *IEEE Spectrum* and her work can also be found in *Scientific American* and *Technology Review*.



Waugh Thistleton Architects ©Will Pryce

©Lever Architecture

©reThink Wood

Left: Murray Grove, completed in 2009, is a nine-story apartment building in London constructed entirely of prefabricated solid timber. **Top right:** The 130-foot-tall Framework building in Portland, Oregon, is one of two competition winners of the US Tall Wood Building Prize, cosponsored by the US Department of Agriculture in 2015. **Bottom right:** Cross-laminated timber panels consist of lumber boards glued and pressed together in alternating directions to resist compression and boost strength.

IDEA WATCH

The Rise of the Wooden Skyscraper

New, mass-timber engineering could transform the twenty-first-century city from a carbon source into a carbon sink

By Susan Moran

The building materials that have defined and fueled the great urban migration of the twentieth and early twenty-first centuries are brick, steel, and concrete. The building blocks of low-carbon cities of the future may, ironically, be a much older, time-honored material—wood.

The carbon footprint of steel and concrete is enormous. Manufacturing and transporting concrete alone accounts for roughly five percent of global carbon dioxide emissions. Wood, however, is both renewable and a carbon sink. According to researchers at the University of Canterbury in Christchurch, New Zealand, construction of a mid-rise building made of steel or concrete results in emissions of roughly 1,600 metric tons of CO_2. By contrast, a similarly sized building constructed from a new generation of engineered woods known as mass-timber products has a zero carbon footprint—and can even sequester up to 600 metric tons of CO_2.

If we use mass-timber products "to help satiate the world's imminent demand for housing," says Alan Organschi, "a city becomes a bank, storing carbon." Organschi, a partner at Gray Organschi Architecture in Connecticut, is among a growing group of pioneering architects exploring the potential for mass-timber products replacing steel and concrete in everything from skyscrapers to bridges to mid-rise urban buildings.

Unlike standard two-by-fours, mass-timber products are made from smaller pieces of wood that are laminated together to create panels up to seven layers thick and up to 64 feet long and eight feet wide—making them ideal for tall buildings. The most established mass-timber product is cross-laminated timber (CLT). The panels are engineered to be pound-for-pound stronger than steel—and at least as fire-resistant. That's because the panels are so thick that under the stress of fire, typically only the outside layer chars—forming a protective layer for the rest of the member.

Organschi's firm has launched a research initiative called Timber City to tease out the potential for an ecological-economic win-win—in which dense cities, healthy forests, and robust rural economies all work in sync.

Mass-timber panels, for example, can be made from blemished wood, such as bark beetle–damaged pine trees or small-diameter trees left in the wake of decades of fire suppression. Instead of decaying in the forest—or going up in smoke—and releasing huge quantities of carbon, the wood stores that carbon neatly in buildings. Using low-grade, small-diameter timber for CLT and similar products could also open up new markets for timber companies, helping to offset the decline in demand for paper.

A key caveat is that tall-timber structures will sequester carbon only as long as the building lasts, or as long as the wood is reused after the building is torn down, rather than being trucked to a landfill. As it turns out, tall-wood pioneers such as Michael Green have taken this into consideration in their designs. His firm engineered the Wood Innovation and Design Centre, an eight-story, mass-timber structure in British Columbia, to use no concrete or "wet" materials above the ground floor so that the wood components might be disassembled and reused.

In Europe, architects began using this new generation of mass-timber products in the mid-1990s, but the movement is just gaining a toehold in the United States. Portland, Oregon, will soon be home to the first high-rise timber structure in the US. Set for completion sometime next year, the office and apartment building, called Framework, will be a 12-story structure designed by Lever Architecture. Gray Organschi Architecture has designed smaller mass-timber buildings in New York and New Haven and is working on several others. In Bergen, Norway, the modular design of the 14-story Treet (Norwegian for "tree") apartment tower was inspired by the country's timber bridges. The tallest wood structure in the world is Brock Commons, a recently completed 18-story student apartment building on the University of British Columbia campus.

At the moment, the number of buildings is small, but the potential is huge. If the construction industry were to replace steel and concrete with CLT and other mass-timber materials, it could take a significant bite out of global CO_2 emissions.

Two-thirds of the human population will live in cities by 2050, according to United Nations projections. In that urban world, says Organschi, it's time to start thinking about producing "carbon sinks in two landscapes versus one: in forests and in cities."

Susan Moran is a journalist whose work has been published in *Popular Science, Discover, The New York Times*, and other publications. She is a host and producer of *How On Earth*, a weekly science radio show in Colorado.

Illustration by Kevin Van Aelst

LANGUAGE OF THE ANTHROPOCENE

Biophony

Soundscape ecology plunges us into a wilder world beyond the mundane and merely visual

By Bernie Krause

When I first wandered into a forest with a recorder and a pair of microphones, in 1968, I was scared to death and literally clueless about how to listen and capture the sounds of the woods. I was on a blind mission—initially drawn there to hear and capture natural ambiences to include as part of an orchestration for an electronic music album and, in the process, find a location that produced something other than the din of human noise. There were no clearly defined goals. No mentors. No teaching guides. Protocols for taping whole natural habitats, whether on land or under the sea, were virtually unknown. Conceptual ways of perceiving and expressing most aspects of field recording were nonexistent, let alone the language for describing the phenomena revealed through sound. Humans had yet to realize the numinous epiphanies that would clarify the associations between the sounds produced by nonhuman organisms and our diverse cultures.

For most of us, the acoustic world has always been an elusive one—an indistinct amorphic entity, unseeable and intangible—and listening is the "shadow sense." Outside of musical literature, few words in English exist to explain the vast range of attributes that sounds express, especially in the emerging world of bioacoustics, the study of the sounds living animals produce.

In the late 1970s, the Canadian composer and naturalist R. Murray Schafer coined the word *soundscape* to refer to the multiple sources of sounds that reach the human ear. Combining this with the word *ecology*, I use the resulting term, *soundscape ecology*, to describe new ways of evaluating the living landscapes and marine environments of the world, mostly through their collective voices.

The soundscape concept consists of what I call signature sources, meaning that each type of sound, from whatever origin, contains its own unique signature, or quality, one that inherently contains vast stores of information. That individual signature is unlike any other. So, also, is the natural soundscape unique in its collective state, especially as it becomes the voice of an entire habitat. With my colleague Stuart Gage from Michigan State University, I have introduced new language meant to describe the three primary acoustic sources that make up a typical soundscape. The first is *geophony*, the nonbiological natural sounds produced in any given habitat, like wind in the trees or grasses, water in a stream, waves at the ocean shore, or movement of the earth. The second is *biophony*, the collective sound produced by all living organisms that reside in a particular biome. And last is *anthropophony*, or all of the sounds we humans generate. Some of these sounds are controlled, like music, language, or theater. But most of what humans produce is chaotic or incoherent—sometimes referred to as noise.

It is important to keep in mind the substantial impact each of these components may have on one another and how they interrelate.

Surrounding our home in rural northern California, the sounds my wife, Katherine, and I have come to know consist of year-round aural traceries of birds, squirrels, amphibians, and insects in the mid-field, the personal conversations we share or the pleading voices of our cats, Barnacle and Seaweed, to be fed or released from indoor bondage to the wider world, the chatter of the TV or the whispered hum of the refrigerator compressor heard from the near field, and the sometimes irritating intrusion of commercial and light aircraft flying overhead combined with the far-off hushed drone of vehicular traffic from two miles away in the far field. The daily and seasonal sounds that define Wild Sanctuary, our home, convey a unique sense of place, one we've come to know as much by listening as by seeing.

The phenomenon of the soundscape usually consists of signals arriving from all directions on the horizontal plane and vertically from the sources overhead—a dome of 3D sound and combinations of any or all of the three main sources mentioned earlier. Whether we're conscious of them or not, we're completely surrounded by acoustic elements coming at us from all directions. Active signals generally consist of biophonies and anthropophonies. Passive elements, such as wind and other weather-related signals, make up the rest. The impact of these sounds can be quite pervasive, depending on the environment. Sound, pressure waves transmitted through the air from a source to some type of receiver, can define the boundaries and structural properties of a room, a particular landscape. The soundscape not only reveals the presence of vocal organisms that inhabit wild biomes, but defines the acoustic detail of floral and geographical features—think of the effects of wind in the trees or grasses, or water flowing in streams and by the lake or seashore. Soundscapes also expose the imbalance sometimes caused by changes in the landscape due to human endeavor or natural causes such as invasive organisms, weather, or movement of the land. One of my lifelong interests has been to find new ways to read, comprehend, and express these sources of information.

Schafer's idea of the soundscape defines events as all the audio signals that reach our ears at any given time. The same goes for the acoustic receptors of nonhuman creatures. With the introduction of new descriptive language, such as geophony, biophony, and anthropophony, I was able to flesh out in greater detail the basic sources of sound. We have now cleared a path for a range of understanding in both science and culture that leads to fresh ways of experiencing and understanding the living world.

One of the most thrilling aspects of my work has been the discovery of the *niche hypothesis*, an early stage of the biophony concept—the collective and structured sound that whole groups of living organisms generate in a biome at any given moment. The term, originally proposed by my colleague Ruth Happel, became clear between 1983 and 1989 and led to the observation that the makeup of wild soundscapes was primarily a form of expression where each type of organism evolved to vocalize within a specific bandwidth—based on either frequency or time. That, in turn, shed light on the bioacoustic relationships between all of the organisms present in a particular biome. In other words, in order to be heard, whether in urban, rural, or wild habitats, vocal organisms must find appropriate temporal or acoustic niches where their utterances are not buried by other signals.

More recently, we have begun to explore the interactions between biophony and the other sources of sound: geophony and anthropophony. For example, several studies, particularly those in process by Nadia Pieretti at Italy's Urbino University, have shown that birds alter their vocalizations to accommodate themselves to urban noise. And killer whales (*Orcinus orca*) do the same with boat noise in their marine environments. Other studies have led to the observation that the music and language produced by a few remaining indigenous cultures can be directly tied to the intricate soundscapes of the natural world that defined their respective habitats, in a rare instance of human biophonic expression.

Gary Snyder, the American eco-poet elder, has pointed out that human language is wild, organizing and reorganizing itself independently of human will. My efforts have shown that, in much the same way, the communicative structures in certain undisturbed biomes form a basis for that paradigm, a constantly changing, reflexive synthesis of correlated sound and its subsequent harvest. Our current understanding of the natural world soundscape necessarily pinpoints "acoustic niches," the special ways different species in a single soundscape use to jostle for sonic territory. By recognizing the function of this partitioning, or formation of acoustic and temporal niches, a creative and important realization emerges: that soundscape ecology is no less crucial than spatial or landscape ecology for our understanding of ecosystem function. Animal communication turns out to be as significant a factor in defining material or acoustic real estate, habitat, and ecological integrity as, say, trophic structure—the feeding and nourishment relationships of all organisms in a specific environment. In fact, territory, habitat, and ecological integrity may no longer be broadly definable in three spatial dimensions alone. The addition of soundscape ecology adds a fourth.

In order to be heard in urban, rural, or wild habitats, vocal organisms must find acoustic niches where their utterances are not buried by other signals.

With our cultural focus primarily on visual experience and manifestation, we seem to have lost the delicate balance informed by incorporating all of the senses in our awareness of place. Nevertheless, it is imperative that we engage with wildness through its multiple dimensions. In that way, our inclusion of the holistic acoustic model enlarges our sense of the wild by literally expanding the boundaries of perception. It also rivets us to the present tense—to life as it is—singing in its full-throated choral voice and where each singer is expressing its particular song of being. It is my goal to encourage us to take a deeper plunge into a wilder world beyond the mundane and merely visual, suggesting that the natural wild is both more complex and more compelling than meets the simple eye. As I always remind my students, "A picture may be worth a thousand words, but a natural soundscape is worth a thousand pictures." ⓐ

Bernie Krause is an American musician and soundscape ecologist. In 1968, he founded Wild Sanctuary, an organization dedicated to the recording and archiving of natural soundscapes. This article was adapted from his book *Voices of the Wild*, published by Yale University Press, with permission.

2.
Deep Dives

The Great Decoupling

The story of energy use, economic growth, and carbon emissions in four charts

By RB Jackson, JG Canadell, P Ciais, C Le Quéré, and GP Peters
Data visualization by Nigel Hawtin

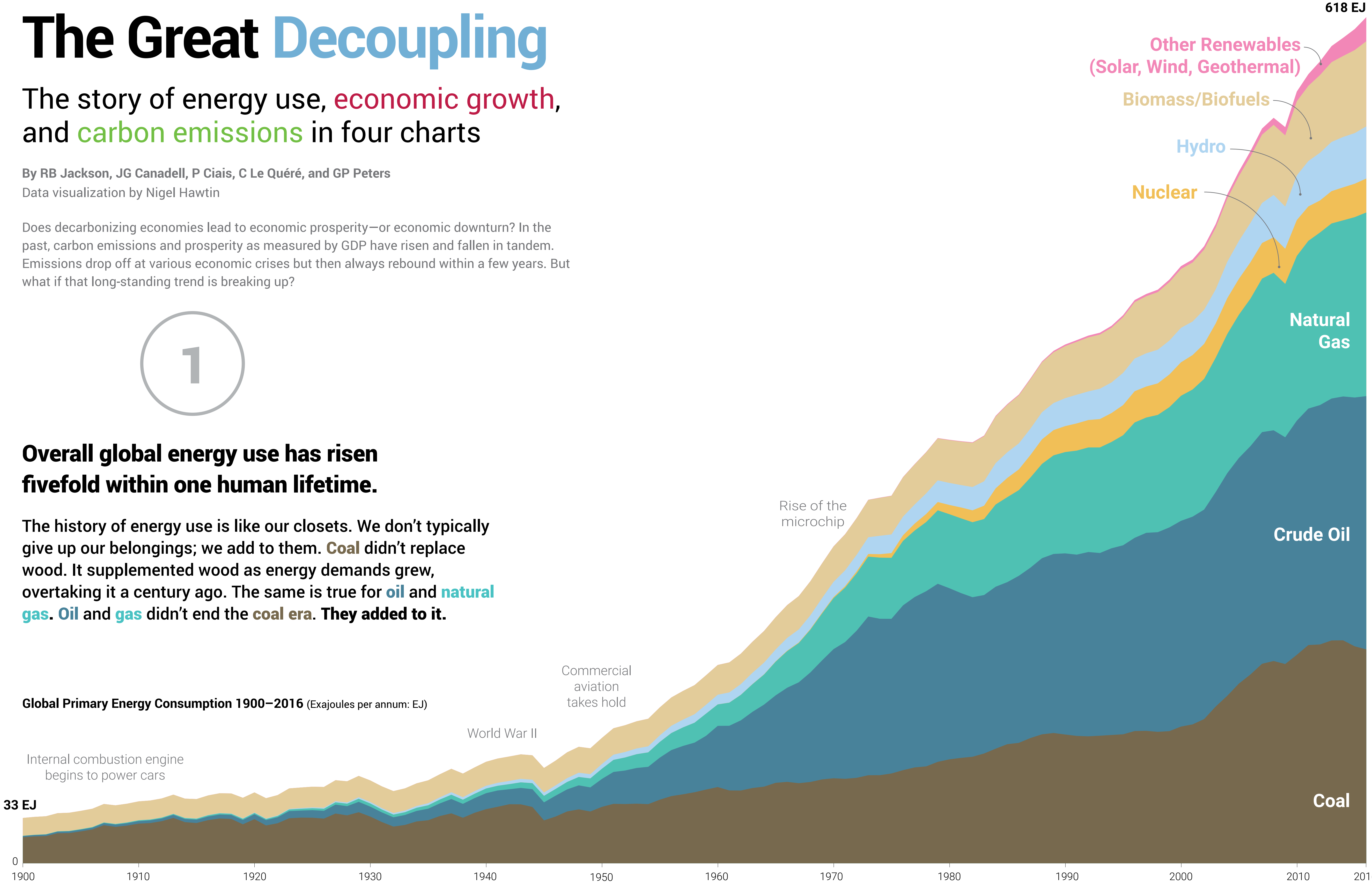
Does decarbonizing economies lead to economic prosperity—or economic downturn? In the past, carbon emissions and prosperity as measured by GDP have risen and fallen in tandem. Emissions drop off at various economic crises but then always rebound within a few years. But what if that long-standing trend is breaking up?

1

Overall global energy use has risen fivefold within one human lifetime.

The history of energy use is like our closets. We don't typically give up our belongings; we add to them. Coal didn't replace wood. It supplemented wood as energy demands grew, overtaking it a century ago. The same is true for oil and natural gas. Oil and gas didn't end the coal era. **They added to it.**

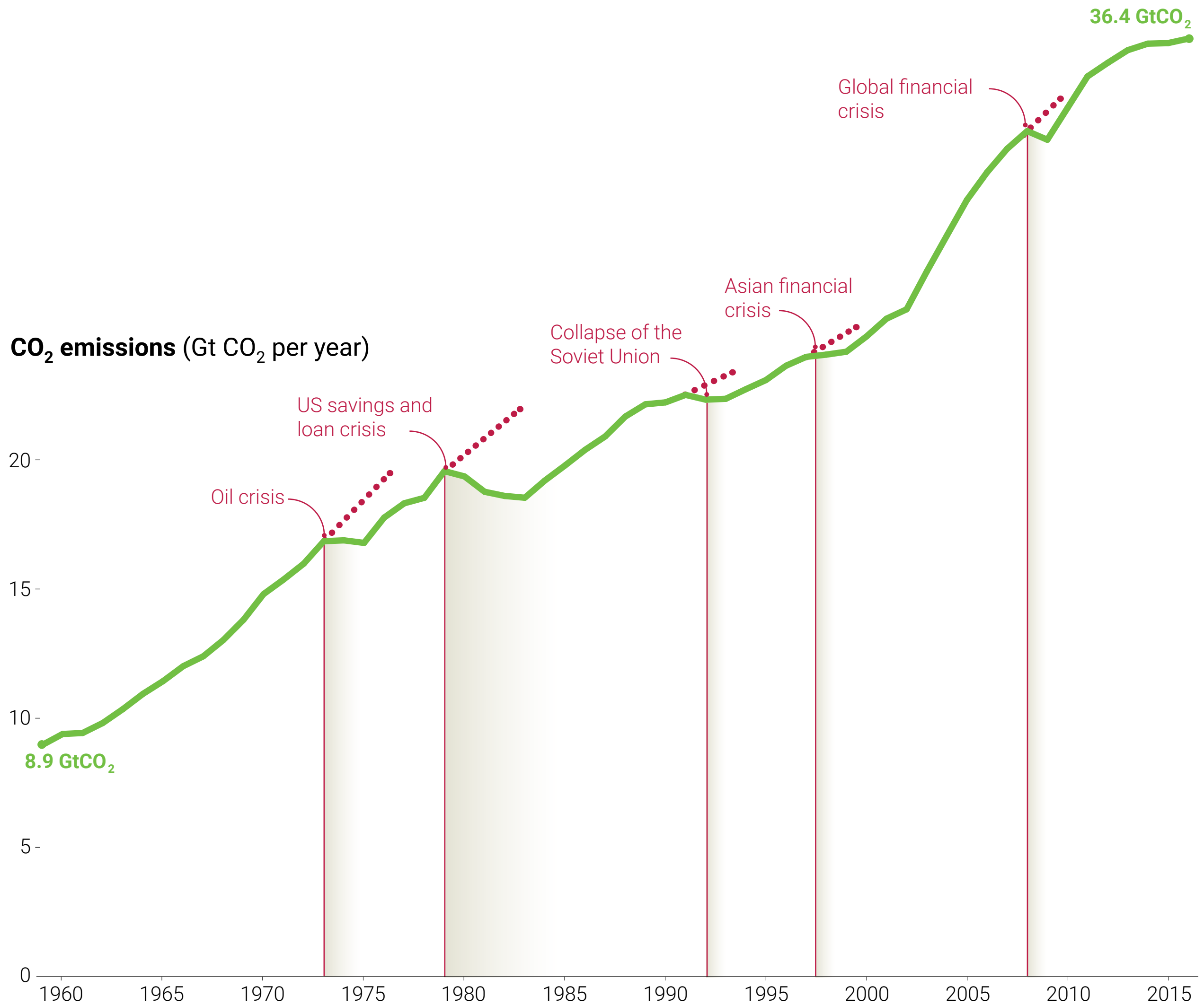
Global Primary Energy Consumption 1900–2016 (Exajoules per annum: EJ)



Data sources: BP Statistical Review of World Energy and the Global Energy Assessment

2

Like energy use, carbon emissions historically have marched resolutely upward—in lockstep with a robust global economy. Economic crises have slowed the rise in emissions at times but haven't stopped it.



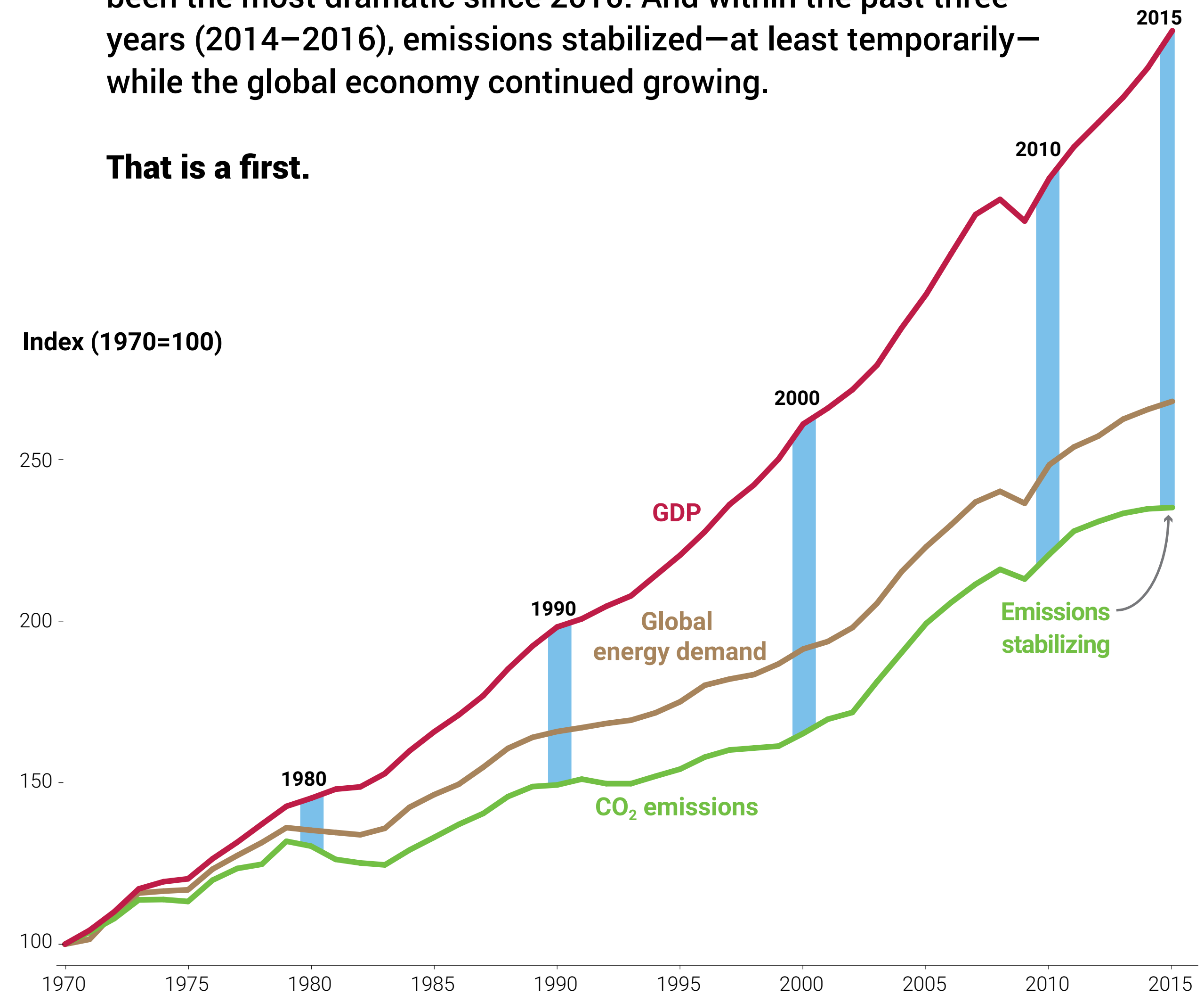
Source: Global Carbon Project

3

Now those trendlines are starting to diverge.

For the past 15 years, global economic growth rose twice as fast as global energy demand and CO_2 emissions. The changes have been the most dramatic since 2010. And within the past three years (2014–2016), emissions stabilized—at least temporarily—while the global economy continued growing.

That is a first.



Sources: Global Carbon Project and the World Bank

4

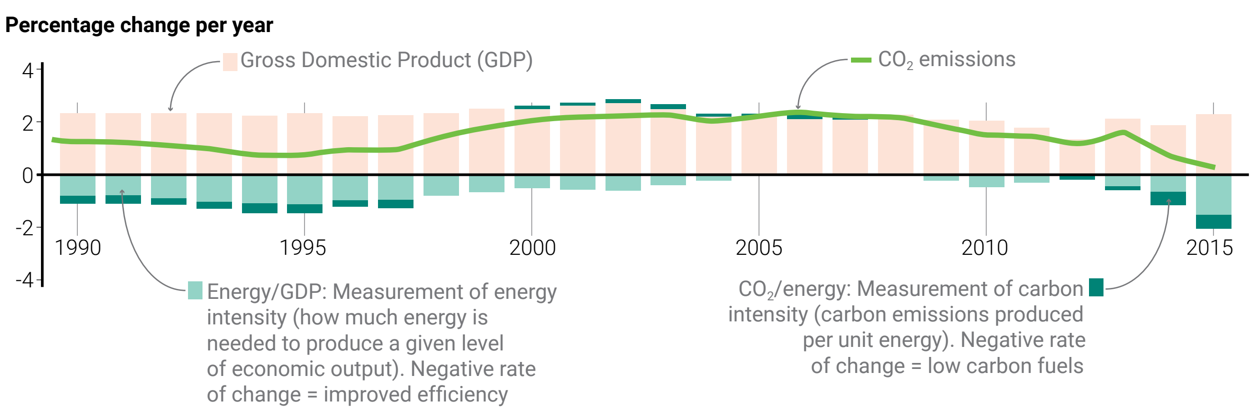
Decoupling, however, is not a foregone conclusion.

Our trajectory is good. **Energy efficiency** is responsible for most of the decoupling to date. But the transformation to **zero carbon fuels** must dramatically accelerate to keep up with growing energy demands and increasing world population.

Only then will decoupling be complete.

World

Energy efficiency improvements, growth in renewables, and reduced coal use in the past couple of years stabilized industrial emissions while GDP continued to grow.



The Kaya Identity

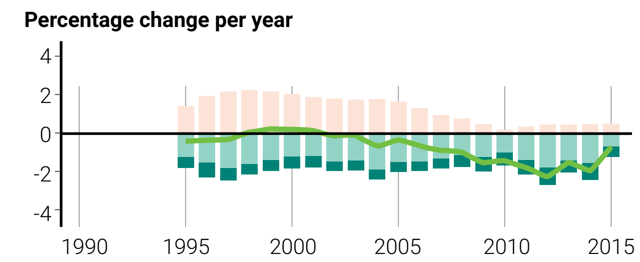
These charts display different factors in the Kaya Identity. Developed by Japanese engineer Yoichi Kaya, the formula provides a way to calculate total CO_2 emissions based on population size, GDP per capita, energy consumed per unit of economic output, and emissions per unit energy. The IPCC used the Kaya Identity to develop its future emissions scenarios by looking at a range of projections for these four driving forces of emissions.

Source: Peters GP et al. Key indicators to track current progress and future ambition of the Paris Agreement. *Nature Climate Change*. 2017.

Rob Jackson is a widely published photographer, poet, and author. He is also chair of the Stanford Department of Earth System Science and a senior fellow with the Stanford Woods Institute for the Environment and the Precourt Institute for Energy. In addition, he chairs the Global Carbon Project, where he works with coauthors Josep Canadell, Philippe Ciais, Corinne Le Quéré, and Glen Peters.

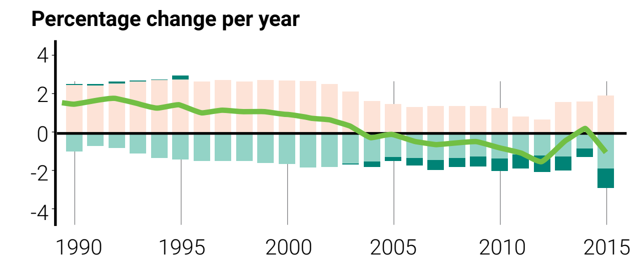
European Union

Along with continuing improvements in energy efficiency, the growing share of renewables in the EU energy mix is reducing carbon intensity. Similar signs of lower carbon energy sources are apparent in China, the US, and the world, especially in the past five years.



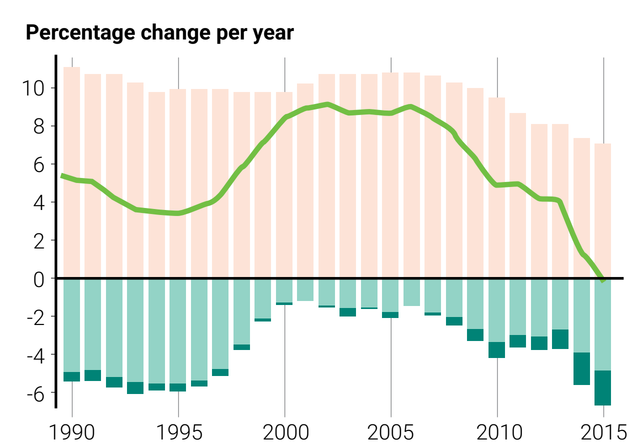
United States

In the US, emissions declined from 2005 to 2012. This is attributable to replacing coal with natural gas, increased renewables, and somewhat slower economic growth.



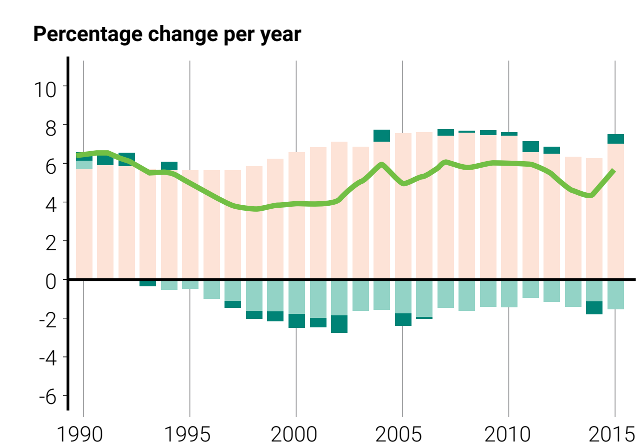
China

In China, rapid emissions growth of ~10 percent per year for a decade has plummeted. The decreased share of coal along with rapidly growing renewables is exerting downward pressure on CO_2 emissions.



India

India's emissions have grown steadily by 5–6 percent per year over the past decade with no clear sign of decoupling—yet. India has pledged to build 3x more solar capacity within the next 5 years than is currently deployed in the US. Turning pledges into action will be critical for India and for all nations.

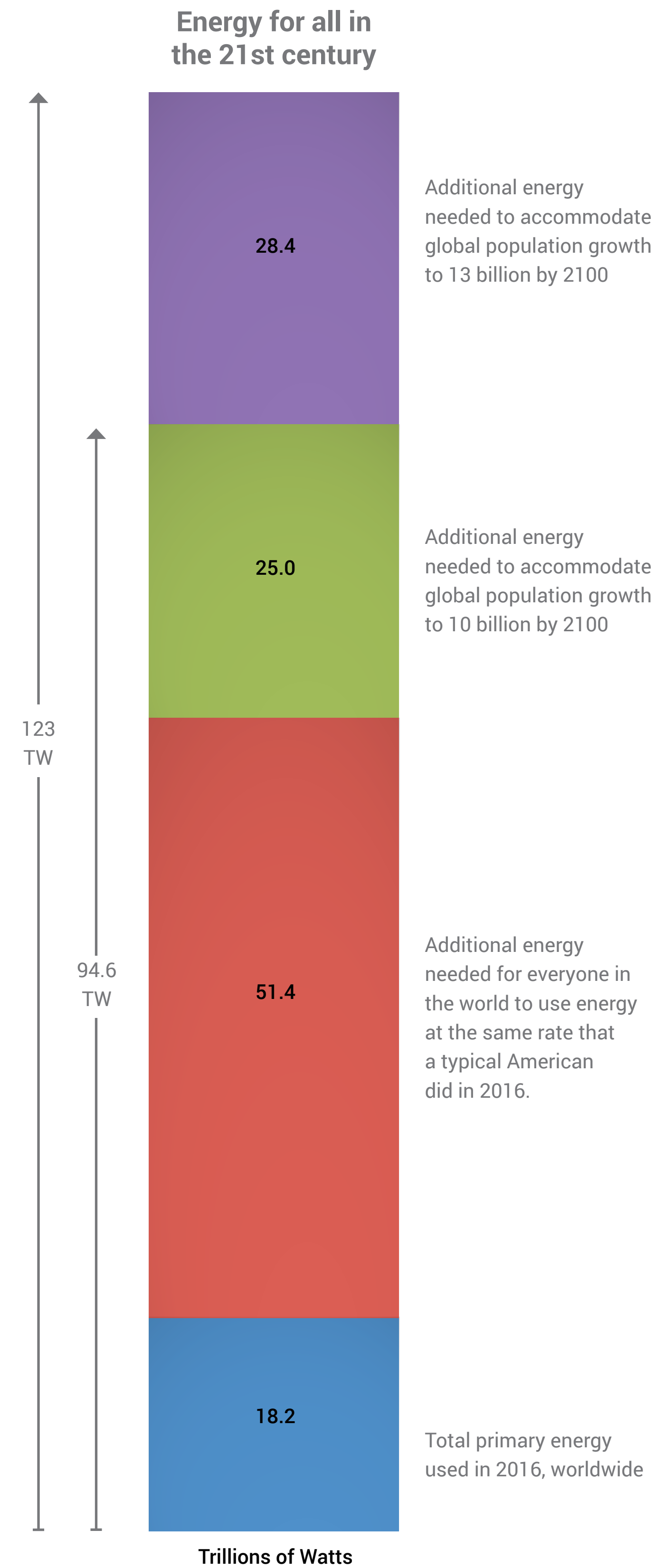


How Much Energy Will the World Need?

Any climate plan that doesn't consider this question is bound to fail

By W. Wayt Gibbs

Photo ©Mathieu Young /mathieuyoung.com



Source: BP Statistical Review of World Energy, 2017

Consider a simple thought experiment. Imagine that by the end of this century, everyone in the world will use energy at the same rate per person that a typical American does today: a steady stream of 9.5 kilowatts (kW), averaged over the year. That's roughly the power consumed by 18 electric-stove burners running nonstop on high, all day, every day.

Does that assumption seem unreasonable? It shouldn't. This is what economic progress looks like. According to energy historian Vaclav Smil, Americans used just one-fifteenth as much useful energy per capita in 1860 as they do today. And during the twentieth century, he observes in his book *Energy Transitions*, annual energy use rose 17-fold globally while economic output soared by a factor of 16—even though nations had to invent and then build the enormous infrastructure needed to extract, process, and transport oil, gas, and electricity.

Now in this new century, technology, information, and wealth speed around the planet faster than ever before. Since 1990, 1.1 billion people have escaped from extreme poverty, with more than 140 million entering the burgeoning middle class every year. The ranks of the newly affluent are also swelling at an accelerating pace. History suggests that as these citizens of the world find more money in their pockets, they will spend much of it—directly or indirectly—on energy.

Add to these upward trends the steadily expanding number of people on Earth and the rapid increases in urbanization and car ownership, and it's a safe bet that the great majority of people, no matter where they were born, will continue to work, vote, protest, and migrate in ways that tend to improve their standard of living over the long run. The future will doubtless see its share of economic downturns and periods of slow growth. But over the course of generations, the mission of humanity has been to enrich itself. There is no reason to expect it to fail now at that mission—or give up on it—after so much past success.

> Since 1990, 1.1 billion people have escaped from extreme poverty, with more than 140 million entering the burgeoning middle class every year . . . History suggests that as these citizens of the world find more money in their pockets, they will spend much of it—directly or indirectly—on energy.

It's natural for those concerned about the pace and risks of global climate change to hope that somehow these trends will change—that the poor can be persuaded to forego the energy-rich lifestyles that the wealthy have enjoyed, or that they will pay extra for clean energy even when dirty forms are cheaper and easier to get.

But such hopes are misplaced. Just as the farmers and laborers of America and Europe did in the nineteenth and twentieth centuries, the urbanizing middle classes of India, China, Brazil, Nigeria, and so many other countries are buying cars, refrigerators, water heaters, and air conditioners almost as soon as they can afford the gas and electric bills. They are eating more meat and taking more long trips. No one has the power—let alone the right—to tell them not to. And any bold plan for saving the climate that fails to meet a massive increase in energy demand during this century is very likely to fail.

So how much energy will the world consume as the twenty-first century unfolds? Following our thought experiment, if average per capita energy demand rises to current US levels by the year 2100, we're looking at some very big numbers.

Maybe the most important among them is this one: 18 trillion watts. In 2016, that was roughly the power needed to keep human civilization humming around the clock. This figure comes from BP's annual report on primary energy use, a report which encompasses all commercially traded fuels and renewable sources.

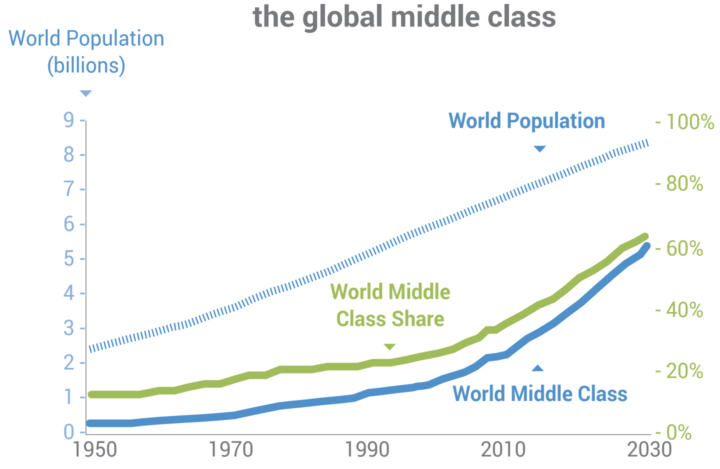
The astounding size of that number is the main reason that meaningful change in the global energy system is grueling. Any new, clean technology must have a power rating with lots of zeros behind it or must be adopted at an explosive rate (and preferably both), or it will simply be too little, too late to make much difference to climate change.

Big as 18 terawatts (or TW, shorthand for 1 trillion watts) may be, humanity's energy intake will almost certainly be bigger tomorrow, and bigger still the day after that. The real action will happen in developing countries as incomes, population, and individual energy use all rise simultaneously.

Start with incomes. As recently as 1990, more than three out of every nine people in the world lived in extreme poverty, on less than US$1.90 per day. By 2013, fewer than one in nine did, and in that year alone 114 million more people (mostly children) escaped that precarious existence. The elimination of desperate destitution is in sight, and it will be one of the signal achievements of human civilization.

Lifting people from extreme poverty to stable subsistence actually costs relatively little energy. The trickle of electricity used by the poor is tiny compared to the gushing streams consumed by the rich. In fact, the International Energy Agency (IEA) has calculated that extending universal access to electricity, heating and cooking gases, and

The expansion of the global middle class



Source: Kharas, H. The unprecedented expansion of the global middle class: An update. Brookings Institution Working Paper 2017.

other modern forms of energy by 2030 would increase overall carbon dioxide emissions by less than 1 percent. That is a cheap price for all the suffering it would prevent and the enormous human potential it would unlock.

But few people are content to stop there—they naturally set their sights on a middle-class lifestyle. Already about 3.2 billion people have achieved that and enjoy annual household incomes between about $15,000 and $150,000, according to a recent analysis by Homi Kharas of the Brookings Institution. The rate of entry into middle class-dom is accelerating, particularly in Asia, and will likely lift total membership to 5 billion by 2030, Kharas forecasts.

Economic security for all, beyond basic poverty alleviation, will come at a steep price in energy. Per capita energy consumption today averages just 2.5 kW worldwide. Lifting all of humanity to the current US standard of living by 2100—an average of 9.5 kW per person, probably a conservative projection—thus means generating more than 51 TW of energy on top of everything we already produce today.

In our thought experiment, the year 2100 will thus see demand reach a mind-boggling 70 TW. Take every coal-fired generator, nuclear power plant, wind turbine, and solar farm and then multiply it by four. The scale of the challenge should be starting to sink in.

But we're not done yet. We haven't accounted for two major factors: population growth and urbanization. Let's look first at the global headcount.

The number of people alive swept past 7 billion in 2011, on its way to probably 11 billion by the end of this century, according to the latest forecasts made by the United Nations Commission on Population and Development. That latter number is uncomfortably squishy because of uncertainty about how quickly fertility rates will continue to fall. Since the 1970s, population has not grown exponentially, as many feared it would, but instead has followed an essentially linear track. Women in China, Indonesia, and other fast-growing Asian economies rapidly reduced the number of children they bore through 2000—and those in India and many parts of Africa continue to do so. The current fertility rate in the US, at 1.9 children per woman, is now below the replacement rate; in India, it is around 2.4 and falling.

> **Although some efficiencies do kick in when people live and work in higher-density buildings, higher incomes swamp that effect.**

As a result, an inflection point is coming in the long arc of humanity's growth. The timing of that change in direction matters a lot: global population could hang at 10 billion or explode to nearly 13 billion by this century's end. Factor population growth into our thought experiment, and global energy use undergoes another big bang, to an astonishing 95–123 TW annually. The span of that range, due to the uncertainty in population growth, is far bigger than the entire global energy system is today.

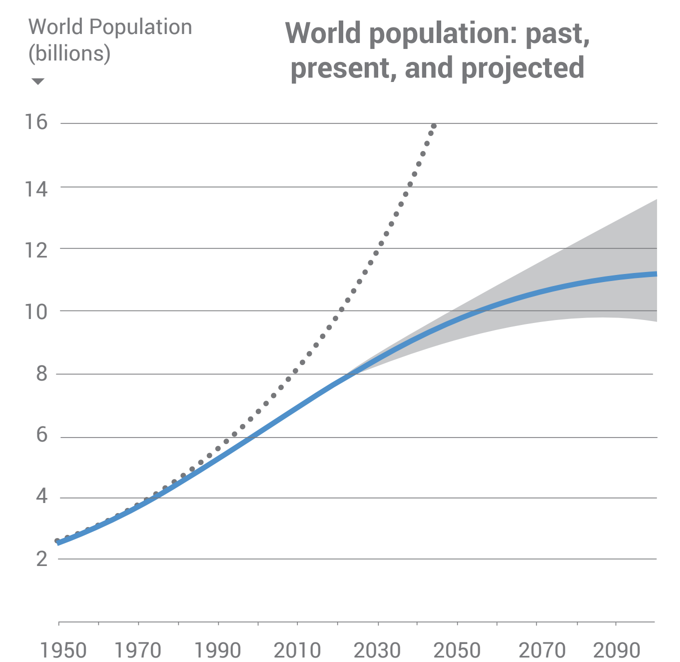
Crossing the 7-billion milestone in world population got a lot of attention, but humanity actually crossed an arguably more important threshold two years earlier. In 2009, for the first time in human history, a majority of the human population was living in cities. This trend toward increasing urbanization looks unstoppable for the foreseeable future, and it has big implications for energy use.

In poorer parts of the world, moving to the city means easier access to electricity, gas for heating and cooking, roads, retail centers, and energy-intensive products (such as computers) and services (such as restaurants). City dwellers tend to have higher incomes, so they consume more energy on average than their rural counterparts. Although some efficiencies do kick in when people live and work in higher-density buildings, higher incomes swamp that effect. So the mass migration of the rural poor into cities—to the tune of 1.6 billion urban residents added over the past 25 years—is boosting individual energy use.

Urbanization is also spurring the disaggregation of households. An extended family of 11 once would commonly share a single house in the country. Now families are much smaller, and kids tend to move out and live solo in an apartment. Despite a dramatic collapse in the fertility rate in China, the billion or so children born in the peak years are now inhabiting many more dwellings, each with its own kitchen, laundry, lighting, heating, and cooling systems. This pattern is occurring in almost every emerging economy. And it contributes to yet another huge factor in energy demand: the explosion of car ownership.

In 2009, China surpassed the US as the world's largest market for new cars. Last year, over 24 million cars were sold there—about 3.5 times as many as in the US. The growth curve looks almost parabolic, and it's anyone's guess where it plateaus. The US has four cars for every five people; in the EU, it's just under three cars. India and

World population: past, present, and projected



Because fertility rates around the world have fallen steeply since the 1960s—with Chinese women bearing fewer children than American women since the mid-1990s—global population (blue) has grown linearly since the 1970s, rather than exponentially (dotted curve) as it would have, had fertility rates stayed constant. The UN now projects that world population in this century will reach 10 to 13 billion, with a median projection of 11.2 billion, in 2100. The wide range of uncertainty in these projections (gray region) has big implications for energy demand in the latter half of the 21st century.

Source: United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects 2017.

China could together host almost 2 billion cars by mid-century if they follow the same path.

Let's hope those vehicles are electric, so that their emissions come from factories and power plants rather than tailpipes. The road to that goal, however, looks long. Last year, just 750,000 EVs were sold worldwide, and only 2 million or so are now in service, according to the IEA.

As with renewable energy sources, it's difficult for the new entrants to keep up with surging demand. Analysts estimate that 1.2 billion cars are now on the road worldwide, and the International Monetary Fund projects that the number will reach 3 billion by 2050. So even though most countries have all but stopped using oil to make electricity—so that they can use it instead for gasoline, diesel, jet fuel, and plastics—experts still think it is likely that we will burn as much oil over just the next 30 years as we did in all of the previous years since 1869.

Even as the number of humans gradually levels off and perhaps begins to slowly dwindle late in the century, more people will be living alone or in small households, more will live in cities, and many more will be driving and flying. So overall energy use per person seems likely to rise quickly—certainly much faster than efficiency improvements can be found to rein it in.

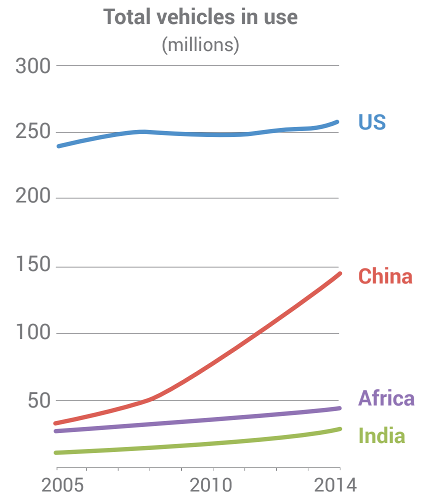
This puts the onus to save the climate squarely on decoupling economic growth from emission growth. That means undertaking a massive and very rapid transformation of the energy-production system to scalable emissions-free sources such as solar, wind, and nuclear. It also means smartly designing twenty-first-century cities to minimize vehicle transport and energy used for heating and cooling.

If your reaction to all this is "It can't be done," you've missed the point. The lesson of the past 200 years is that something like this very likely *will* be done, absent a nuclear war, a runaway plague, a massive meteor impact, or some other catastrophic societal collapse. As is already happening in China, people will organize, institutions will bend, and investors will deploy capital to generate the energy needed to power economic growth. The reason for this may be hard to remember for those of us who already spend our days juggling multiple computers and think nothing of boarding a jet. But it is simple: energy is an indispensable ingredient to a life of basic human dignity.

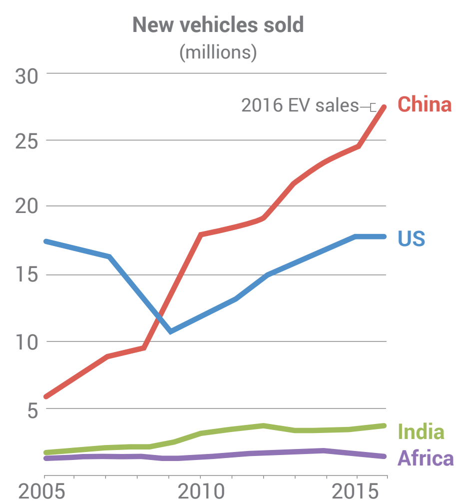
Without sufficient energy, poor farmers cannot get the fertilizer they need for their crops. A complete lack of access to electricity still prevents a billion people from getting good medical care, running refrigerators, and turning on reading lights and radios. Most of the 2 billion poorest people still burn wood, charcoal, dung, or leftovers from farming to cook their food. Those open fires cause respiratory problems that kill 4 million every year, mainly women and children. Affordable electricity could put an end to that—and solve so many other problems as well.

Driving Demand

Car and truck ownership in China has exploded, and within a decade or so there will likely be more vehicles in China than in the US. As the middle class blossoms in India and Africa, car sales there are all but certain to skyrocket as well.



Sales of electric and plug-in hybrid cars are growing quickly, but so far these still make up just 2 percent of the vehicles sold in China. Regardless of whether the hordes of new vehicles end up running on gas, biodiesel, hydrogen, or electricity, the energy to power them will have to come from somewhere.



Source: International Organization of Motor Vehicle Manufacturers

So the question looming over this century is not *whether* energy use will expand dramatically, but *how*—how will all of this new energy be produced? And what can those of us in rich economies do to prevent the coming energy expansion from wrecking the climate?

It's tempting for high-tech societies to focus foremost on transforming their own energy systems to be as clean and efficient as possible. Certainly, it's important to set a good example.

But it's also important to realize that, to a first approximation, all the new energy to be created as this century unfolds will have to be generated in the poorer parts of Asia, Africa, and South America—because that's where the people are who will use it. Transformation of the North American and European energy systems is not irrelevant, but it becomes increasingly less relevant as energy use in currently low-income regions catches up to that of the high-income nations.

Over the long term, the best thing the rich and emerging economies can do is to push better energy technology forward as far and as fast as possible so that it can be deployed globally in the decades to come. Unfortunately, our track record to date is not great.

Fifteen years ago, a group of far-thinking physicists, energy experts, and engineers published a seminal article in *Science* laying out various ambitious paths for developing emissions-free technologies to generate the 25 TW of clean power they estimated would be needed by 2050 or so. They surveyed a range of challenging but technically plausible approaches, including fusion reactors, space-based solar plants, and schemes to capture and permanently store carbon dioxide emissions from power stations.

Now we are a third of the way down that road to 2050. Energy use is up 50 percent, but unfortunately only 0.9 TW of the 5 TW added since 2002 came from renewable energy sources, and half of that was hydropower. Fusion and space solar are still stuck in the experimental stages, and research into carbon sequestration is starved for funding. Due to declines in nuclear energy production, the fraction of global energy provided by fossil fuels is about the same today (86 percent) as it was in 2002.

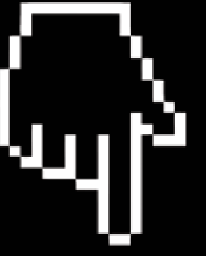
Transformation of the North American and European energy systems is not irrelevant, but it becomes increasingly less relevant as energy use in currently low-income regions catches up to that of the high-income nations

Clearly, we must do better to produce, demonstrate, and perfect cheap new technologies for creating, storing, and transmitting emissions-free energy. We also need to push hard to improve energy efficiency everywhere possible so that energy use grows more slowly than income—and so that emissions don't increase at all but actually start to fall. As Robert Jackson describes on page 44, the two longest levers we have for applying the brakes to emissions and keeping warming in check are how cleanly we make energy and how efficiently we use it to support our standard of living.

That is why we need breakthroughs in energy to help people in modernizing societies enjoy the basics that those in the richer parts of the world have long taken for granted. We keep saying we need to do more with less. No. We need to do more with more: make a lot more energy—a lot more cleanly—and use it a lot more efficiently for the benefit of a lot more people.

W. Wayt Gibbs is a freelance science writer and editor based in Seattle. He is a contributing editor with *Scientific American* and editorial director at Intellectual Ventures. His work has appeared in *Science*, *Nature*, *Discover*, *IEEE Spectrum*, and *The Economist*.

Throw Software at the Problem



carbon dioxide

The world today is powered by wasteful and inflexible electricity grids that stand in the way of deep cuts to greenhouse gas emissions. But new experiments are pushing artificial intelligence and sensor networks into the grid—and into factories, data centers, and transit systems—in order to pull fossil fuels out.

By Mark Harris

A smooth-running electrical grid finely balances resources against need at superhuman speed, day in and day out. Pulling that off in the midst of a massive shift from giant coal and gas plants able to run 24/7 to scattershot arrays of wind turbines and solar panels fluctuating by the minute is a tough problem. But it is exactly the kind of problem that artificial intelligence (AI) should be good at.

Grids are vast, interconnected systems, and they already rely heavily on old-school automation to manage the ever-shifting dance of power generation and consumption among thousands of variables and millions of users. But that centralized, hardwired kind of automation has its limits.

In England, for instance, where I grew up, there has been much hand-wringing over the carbon footprint of the 60 billion nice cups of tea we drink each year. Terrific debates have raged over how much eco-friendlier loose-leaf is than packaged teabags, and over the damage that a milky cuppa does to the climate (thanks to habitually flatulent cows). Often overlooked, however, is the peculiar national phenomenon of "TV pickup." After a big soccer match, a huge surge in demand saps energy from the grid as people switch on their electric kettles and open their fridges. In 1990, the nail-biting climax of the World Cup semifinal created a record TV pickup of 2.8 gigawatts—more than the output of two nuclear power stations.

Grid operators dread such spikes. When supply fails to match demand, the frequency of the alternating current swerves. In the United States, even a little dip from the standard 60-Hz frequency of electricity can make wired clocks run slow. Severe deviations can damage televisions and crash computers, so utilities typically resort to rolling blackouts in such cases. Earlier this year, for example, a heat wave in South Australia caused people to crank up their air conditioners, forcing network operators to pull the plug on tens of thousands of customers.

Utilities hold extra generators in reserve to react to TV pickup, heat waves, and other predictable surges in demand. But the swiftest response is rarely the greenest. Boil water for tea on a normal day, and you might use clean power from Britain's offshore wind farms. Boil it after the FA Cup final, and you will likely tap electricity from a much dirtier source, such as "diesel farms" or natural gas–fired "peaker" generators.

The cost for this reliability is measured in both dollars and tons of carbon dioxide. EnerNOC, an energy software company, estimates that 10 percent of all generating capacity in the United States is there just to meet the last 1 percent of demand. "Some gas power stations operate for only 100 to 200 hours a year, but they have to be kept open and staffed," says Valentin Robu, an assistant professor in smart grid systems at Edinburgh's Heriot-Watt University. "They're extremely expensive." And they are increasingly common, as many countries shift their power mixes to include more wind and solar farms, whose output can vary from minute to minute even on the briskest and sunniest days.

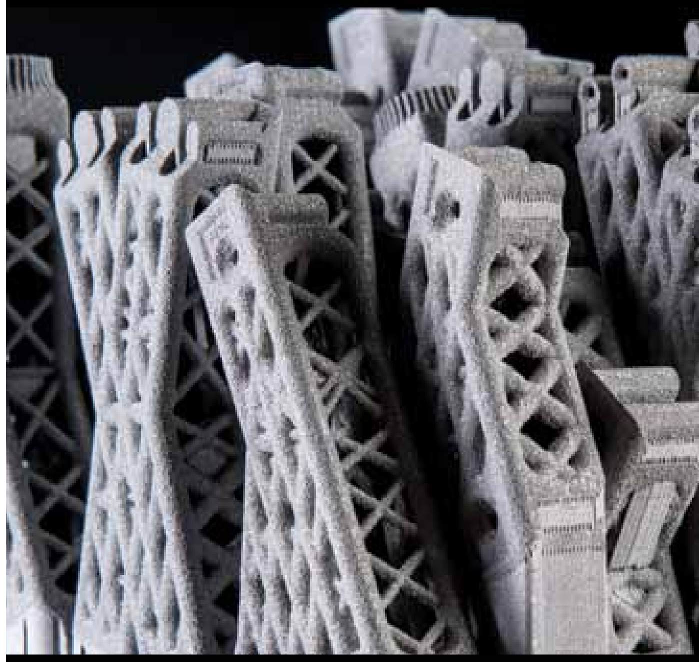
Utilities could get by with fewer back-up power plants—reducing costs and emissions simultaneously—if they could flatten the peaks and troughs of electricity demand on a national scale. But to do that efficiently and quickly enough, grid managers would need superhuman abilities to see spikes coming and to coordinate myriad complex adjustments. They also need better ways to store energy cheaply and to push some power uses from surge times to lulls.

Our attention spans are short. Our wills are weak. But software that can tirelessly observe and subtly intervene in our daily lives promises to achieve what decades of nagging have not.

Luckily, technology may offer an answer: put AIs in charge of our grids. Algorithms and software are already capable of weighing thousands of variables and making millions of tiny decisions a day. AI is also increasingly able to blend customer preferences with inferences about how customers usually behave—to anticipate when people will adjust their thermostats or switch on their washing machines, and even to do it for them. Some see in this technology the potential for a revolution in the way we organize the generation and delivery of energy.

A revolution of this kind is badly needed. The demand for energy—and electricity in particular—is all but certain to rise substantially throughout the first half of this century, even as carbon emissions must decline precipitously to avoid accelerating global warming even further. Researchers now think that handing over control of electricity grids to AIs could curb our carbon footprint without destroying our way of life. "Timing is critical," says Robu. "This is exactly where we need AI."

The search for greener ways to meet surges in demand has led utilities to try some creative solutions. One is to build what amount to giant capacitors: systems that can fill up gradually with energy during quiet periods and then discharge it quickly when demand spikes. Where geography



How AI Can Suck Carbon Out of

Design & Manufacturing

Experts project that by 2050 emissions from aviation will consume about a quarter of the world's remaining carbon budget. AI offers a way to slash airplanes' weight—and do the same for their emissions.

Aircraft manufacturers are now experimenting with generative design, which mimics natural evolution in the way it arrives at an optimal plan for a part. The process starts with engineers' inputting design goals for an engine component or a wing spar into software. Given the specified materials and structural requirements, the AI software then quickly generates many alternative designs. It simulates the performance of each candidate and calculates its weight and cost. Equally important, the AI learns from each iteration which aspects of each design work and which don't. In the time it takes a human designer to come up with one idea, an AI can spin through thousands to home in on the optimal solution.

The results often look bizarre—organic shapes that bend and gape like skeletons or ancient trees—but the cost and weight savings can be remarkable. An aircraft part that Airbus designed last year using AI was 45 percent lighter than the best a human could manage.

Photo: A bionic partition separating the seating sections in an airplane.
Image courtesy of Autodesk.

allows, power stations can pump water uphill into dams (or compressed air down into caverns), then discharge it to spin generator turbines at tea time. Other storage options include massive flywheels and even giant versions of the lithium-ion batteries that power your laptop. But the giant scale needed to smooth out the tallest peaks of demand poses tough economic and engineering challenges for all these approaches.

A smarter idea, Robu says, is to leverage high-capacity batteries that consumers are already connecting to the grid, such as those in fancy new electric vehicles (EVs) or in some houses equipped with rooftop solar panels. "First of all, you coordinate charging so you don't charge cars at all when there's high demand," he says. "Then you could support the grid by partially discharging their batteries at these critical times. Of course, people who own these EVs would get paid for that." The trick is getting everything to work together seamlessly. No one wants to finish their morning cuppa and head out to work, only to find that their EV's battery is flat.

This system would reach into thousands of homes during peak events and switch off, say, all the tumble dryers for an hour until demand subsides.

Enter artificial intelligence. AI is a blanket term for computer software that mimics a few of the smarter things that humans can do, including learning, reasoning, pattern recognition, and problem solving. AI can already surpass humans at selected tasks, such as ingesting mountains of data from millions of devices (such as car batteries) and quickly figuring out the most efficient way to charge and discharge them. At other jobs, AI is less capable than an infant. Computers still struggle to understand the simplest social relationships, for example, and they often come to ridiculous conclusions when they try to make deductions that require common-sense knowledge about the world.

Where machine learning has succeeded most impressively—such as in recognizing faces or responding helpfully to certain kinds of spoken commands—it works not because the computer has learned to do the task the way a human would, but because the software continually changes its own processes to reach the desired outcome. With AI based on this kind of machine learning, the more data it ingests, and the more widely and often it is used, the more accurate it becomes.

While Amazon, Google, and other tech companies were hoovering up AI experts to make smarter speakers and self-driving cars, Robu left his native Romania to work as a researcher at Harvard, Microsoft, and several European universities with the hope of putting AI into the grid. He envisions a scheme, based on game theory, in which an AI absorbs the preferences of thousands of EV owners, matches them each second to the needs of the grid, and prices everything fairly. Some owners may insist that their car battery always remain at least 75 percent charged. Others may be willing to let it drop lower overnight, as long as it is full in the morning. "The system will find the best time to charge and discharge, and owners would get some share of the payment," Robu explains. "People who are more patient are likely to be paid better because the system has more flexibility in when to charge."

Such vehicle-to-grid systems sound great, but repeatedly charging and discharging lithium-ion batteries reduces their capacity. In 2015, even the forward-looking chief technology officer of Tesla said that vehicle-to-grid is "something that I don't see being a very economic or viable solution—perhaps ever, but certainly not in the near term." Future improvements in battery technology could change that calculus. In the meantime, there are other options.

AI could give new life to an older, simpler idea: encouraging people to shift some electricity use to quieter times. Utilities call this approach demand response, and they have already signed up many large industrial customers, such as aluminum smelters, to reduce demand when necessary in return for discounted prices. But for demand response to put peaker plants out of business, it must gain far wider adoption. In high-income countries, residential homes (together with commercial users) consume the lion's share of electricity—40 percent in the United States, compared to about 20 percent in China.

Utilities have enticed household customers to help them manage demand before. When I was growing up in Britain in the 1980s, many homes had thermal-storage heaters—basically ceramic bricks warmed by electric heating elements—that operated only during the off-peak hours overnight. Some of my friends woke up toasty warm every winter morning but crawled into chilly beds each evening. Given such trade-offs in comfort, the hassle of needing a special electricity meter, and the gradually shrinking fraction of household spending going toward utility bills, the scheme never really caught on.

But Robu and others believe that technology has now evolved to the point that a demand-response system could appeal to

How AI Can Suck Carbon Out of

Traffic

Every minute your car sits idling, it pumps CO_2 out the tailpipe. Now a startup, Rapid Flow Technologies, is trying to use AI to ease congestion in cities. The company employs a system known as Surtrac that was developed at Carnegie Mellon University to bring more intelligence to traffic lights. Radar sensors and cameras monitor car flow and wait times at intersections. The AI then adjusts the timing of the lights to move vehicles through as efficiently as possible.

Although the AI at each intersection works individually (to prevent mass outages), the smart systems can share data with others nearby. A pilot test at nine intersections in Pittsburgh reduced average travel times by one-fourth and average wait times by 40 percent. Surtrac systems are now running at 50 intersections in the city, with plans to expand to 150 more in the next three years. Where the smart lights are in place, travel times have dropped by 25 percent, braking by 30 percent, and idling by more than 40 percent.

Meanwhile, Google is putting AI to work on the problem of parking. Cars hunting for a space can account for one-third of all traffic in the most congested downtown areas—wasting time, burning fuel, and spewing greenhouse gases. Google Maps for Android phones can now predict parking availability near a destination in 25 US cities. Hopefully, the app will persuade drivers to park and ride instead.

AI doesn't mind sweating the details. The grid will have to make multiple split-second decisions and weigh tiny barters of solar power and battery space that would just annoy a person.

enough consumers, and cover enough appliances, to reach the necessary scale. Beyond just remotely controlling a few megawatt-munching smelters, this system would reach into thousands of homes during peak events and switch off, say, all the tumble dryers for an hour until demand subsides.

It's a tempting idea, but it faces several hurdles. The first challenge is understanding what you can switch off—and when. The low-hanging fruits are power-hungry appliances such as ovens, fridges, washing machines, and clothes dryers. The system will need to draw on a database of both user preferences and appliance specifications to know whether it is acceptable to turn off a dryer at any point in its cycle, or whether a washing machine should be shut down only after it has drained. Some refrigerators and freezers could be driven to cooler-than-usual temperatures during the day and then turned off at peak demand—but only for so long, to avoid spoiling food inside.

Using AI is essential, Robu argues, because there's no way humans could look at all the relevant data. "Once you instrument a fridge, you can sample it every five minutes and get a lot of information from it—and you might have 10,000 fridges," he says. Software is also the only way to coordinate such a diverse collection of machines, some available for only brief windows, so that too many don't turn back on at the same time and create a rebound peak.

Tech companies are already selling some of the many components needed to translate this vision into action. Smart meters now wirelessly transmit data on home electricity use to the cloud and receive signals in response. AI-enabled energy monitors pinpoint appliances in use by sensing their distinctive power signatures. Many of the latest domestic appliances offer remote control by smart-home software. Wi-Fi-networked outlet adapters add energy monitoring to older devices and put them under remote control, even by voice-activated gadgets such as Amazon's Echo. And Robu and other researchers are developing AI-powered software to manage the whole process.

Reimagining a country's entire electricity grid, daunting as that seems, is necessary but not sufficient. To make demand response work on a massive scale, engineers also have to surmount an even bigger obstacle: people.

Not many people today care enough about cutting their household emissions or energy bills to opt into conventional demand-response systems, says Long Tran-Thanh, who has been studying possible solutions to that thorny problem. Tran-Thanh's background allows him to see a bigger picture. Born in Vietnam, he moved with his family to Hungary when he was just seven years old. He went to university in Budapest before relocating again to Britain, where he is now an assistant professor in AI at the University of Southampton. "People here [in the UK] are aware of the disadvantages of high energy usage, and they are quite open to new technologies and new ways of thinking," he says. "But in Hungary, they don't have this kind of mindset yet." Though popular thinking is slowly shifting worldwide, even in Britain, he notes, "You can offer someone a very good plan to improve [energy] usage, but they're not really interested in changing their habits. That's why they're called habits."

Some have tried the obvious: offering customers financial incentives to adjust their behavior. "We thought this would be very useful, but in practice it's not," Tran-Thanh says. "The total of amount of savings you can offer is £20–£30 ($25–35) per year. If you show someone annual savings of £20, they just laugh."

Although any individual's savings are likely to be small, the potential benefits of demand response add up when multiplied across large populations. The US Energy Information Administration calculates that demand response could save a typical American household $40 and 100 kilowatt hours annually. If adopted nationwide, the practice could cut $5 billion a year from power bills and nearly 9 million metric tons of carbon dioxide from greenhouse gas emissions. Even more impressively, according to 2014 calculations by Alexander Smith, an energy researcher then at the Georgia Institute of Technology, by 2040 demand response could save the US up to $28 billion in infrastructure costs and avoid construction of 150 gigawatts' worth of power stations, most of them fossil-fueled.

Tran-Thanh has now turned to AI in the hope of overcoming the people problem. He is developing a system called interactive demand response (IDR) that can realize the financial and environmental gains of demand response without asking people to do their laundry or drink tea in the middle of the night.

IDR teaches machines to understand how people typically use electricity. Tran-Thanh and his colleagues at the University of Southampton developed algorithms to extract patterns from a large dataset on household energy use that was assembled at M.I.T. The AI learns in a surprisingly similar way to humans, exploiting a software technique known as a neural network. No programmer decides in advance how to mathematically translate various kinds of consumption data into distinct demand profiles.

Instead, developers train the neural network by showing it examples. Gradually, it learns by experience—much like a child learning to distinguish pictures of cats from those of dogs. The more examples it sees, the more accurate its output. Young children soon understand that images of dogs and cats represent animals that can move and make noises. But the

How AI Can Suck Carbon Out of

Data Centers

If you want to be really green, ease up on social media. Data centers consume about 2 percent of all the electricity in the US, and that share grows every year. Most of that energy is dedicated to actual computation—serving up all those ads and streaming video—but around one-third is spent on cooling the servers to prevent them from overheating.

Last year, at one of its data centers, Google set loose on the pumps, chillers, and cooling towers AI software developed by its DeepMind subsidiary. The AI spent several months observing thousands of sensors within the center and learning the complex, non-linear interactions among the cooling devices. It then took control and was able to consistently achieve a 40 percent reduction in the amount of energy used for cooling. Google now plans to roll out the algorithms to its other data centers—and share the technology so other tech firms can reduce their carbon footprints, too.

Photo: Insulated pipes running through a Google data center neural network is not able to understand how its learnings correspond to the real world, and that proved to be an important limitation.

The Southampton team's AI system was able to turn electricity consumption data from any household into a reliable prediction of that home's future demand. But homeowners hated it.

The system failed, Tran-Thanh realized, because it was too passive. "Machine learning collects the current data and learns patterns, but it cannot infer possibilities," he says. "You can see only what the user is doing. You don't know whether he is willing to deviate from that behavior." To find out which activities users were comfortable shifting and which were sacrosanct, the software would have to ask them.

"But asking questions is also a problem," Tran-Thanh found. "Every time you ask a question or require a user to interact with the system, it's an annoyance—what we call the 'bother cost.' If you ask too many questions, a percentage of people will just not use it anymore."

His solution to this weakness of AI was . . . more AI. The team folded into IDR a powerful sequential decision-making process called Pandora's Rule to optimize the number of user interactions and minimize the bother cost. Pandora's Rule is a mathematical model tailored for scenarios, such as house- or job-hunting, where you must decide when to stop looking and just make a choice. Adding that model to IDR enabled the system to track the accumulating bother cost and do a quick calculation before asking each user about her preferences, which are gathered via an iPad app. If the risk of asking another question outweighs the energy-saving benefits likely to be obtained, IDR quits while it's ahead.

Tran-Thanh used a reserved portion of the M.I.T. consumption data (data that had not been used for training) to simulate human responses and compare the performance of the AI-enhanced system to that of previous, less "intelligent" algorithms. His conclusion: IDR reliably generated 35 percent greater financial savings for users.

But would these savings be reflected in actual use, or would yet another unexpected problem rear its head? Testing IDR in a community is tricky. "It's hard to wire up old houses, and it's not that efficient," Tran-Thanh says. "It's easier to equip new-build homes—but it might not be cheap." A field trial would have to be large enough to generate good statistics on the benefits (and problems) of IDR, yet small enough to remain affordable.

Demand response could save a typical American household $40 and 100 kilowatt hours annually. If adopted nationwide, the practice could cut $5 billion a year from power bills and nearly 9 million metric tons of carbon dioxide from greenhouse gas emissions.

Luckily for Tran-Thanh, just such a development is taking shape now in the Netherlands. It is a remarkable new community that promises to resemble a floating village of the kind that might become more common on the coasts as sea levels rise.

Rising from a canal in a heavily polluted industrial quarter of Amsterdam, the Schoonschip ("clean ship" in Dutch) project is building a floating neighborhood of 46 new homes connected by dock-like sidewalks. More than 100 residents will soon move into permanently anchored houses made from recycled materials and topped with plant-covered or translucent roofs to capture rain and sunshine. Water will be filtered and recirculated. Electricity generated by 500 solar panels will run 30 heat pumps to provide hot water and climate control.

As a tightly integrated, sustainable community, Schoonschip could be an ideal testing ground for AI-enabled, smart-grid technology. Last year, the builders linked up with Grid-Friends, a demand-response research group led by Michael Kaisers at Centrum Wiskunde & Informatica (CWI), the Netherlands' national research institute for mathematics and computer science.

"I want to do new and original work in smart grids, but I want it to be feasible," Kaisers tells me on a Skype videocall from the Dutch capital. "I've seen a number of research projects reach for a very innovative idea that either is nowhere close to the current situation or has not identified who would actually use it," he says. Schoonschip seems to have avoided those pitfalls. Oversubscribed and with construction about to begin, the community aims to use an AI grid from the outset to achieve zero net carbon emissions, measured over the year. Although Schoonschip homes will draw power in the winter from the Dutch national grid, the community's solar panels will generate excess power in summer months, and that clean energy will flow onshore for others in Amsterdam to use.

This kind of "net metering" is now familiar to homeowners who have rooftop solar panels and pay their utility only for the difference between the power they use and the power they generate. What is unique about Schoonschip is that the entire community will share a single connection to the national grid, with just one electricity meter. Behind that meter, Schoonschip will run its own mini smart grid, tying together the solar arrays and batteries of each house and intelligently coordinating the flow of energy from home to home.

Even a grid of just 46 homes quickly gets complex. With no central authority, every homeowner must decide for himself how much to invest in equipping their house to conserve energy or make its own.

How AI Can Suck Carbon Out of

Factories

Systems do not get much more complicated and interconnected than factories filled with precisely choreographed robots and assembly lines. General Electric thinks that AI has a role to play here, in what it calls "brilliant manufacturing."

An AI manager inhales data from supply chains, design teams, production lines, and quality-control checkpoints. The AI can then order new supplies just before they run out, monitor problems on the production line, and minimize electricity usage. Procter & Gamble says that its use of GE's system has helped the company cut unplanned downtime by 10–20 percent. Because idle factories still run heating, ventilation, and lighting—accounting for around one-third of the entire electricity bill for a car assembly plant—less downtime translates directly into reduced emissions.

"There were long discussions about whether to build bigger terraces or leave more room on the sunny side for harvesting renewable energy," Kaisers says. "In the coordination mechanisms for the automated intelligent control, we will have to take into account the people who made a sacrifice for an additional square meter for solar." Even in this communal village, everyone will pay his fair share for the electricity used.

AI will be baked into Schoonschip's grid from the very start. Kaisers's team is building algorithmic AI "agents" to represent the users in demand-response negotiations among households. The algorithms will base their actions on predictions generated by learning each home's generation and consumption patterns. The system will also use tablet computers to collect homeowners' preferences, such as the minimum charge they want to keep in their batteries at various times of day. "AI agents can be better than humans in reaching good win-win outcomes, making sure that households don't rip each other off but instead collaborate in a positive way," says Kaisers. "Plus, lots of people hate haggling."

AI also doesn't mind sweating the details. The grid will have to make multiple split-second decisions and weigh tiny barters of solar power and battery space that would just annoy a person. "Human time is very expensive," Kaisers says. Schoonschip will probably use Long Tran-Thanh's research to work out the optimal times to ask for users' input; Kaisers suspects owners will be asked no more than five questions a week.

By next summer, Schoonschip should be populated enough to turn off its connection to the national grid for a few weeks, to see how well the AI can run things. But that is just the start. "The big utility companies make good money the way things are going right now. They need an incentive to move, and that incentive is going to be self-sufficient local entities such as Schoonschip cutting into their business. These residential communities could be pivotal entities to put energy transition into practice, Kaiser says.

Schoonschip model ©space&matter

Whether that happens could hinge in part on economics. An AI-controlled smart grid comes at a price above that of the solar panels and heat pumps alone. Each house will likely have an extra smart meter or two, plus computers and sensors. Kaisers expects the bill to come in at less than $500 per household, with a small annual fee for the AI management software. These prices will likely fall as the technology improves—and by locating many of its innovations behind the meter, Schoonschip is not relying on conservative utility companies to drive innovation.

Schoonschip might seem like an insignificant thumb in the dike of climate change, but this bottom-up effort is being watched around the world. Nothing stops environmentally conscious towns in the US from following Schoonschip's model. A community in Germany is already planning to roll out CWI's Grid-Friends technology. And if the system can be proven in cloudy northern climes, it could be applied to even greater effect in poorer, sunnier parts of the world where existing power generation is more carbon-intensive. A 2010 McKinsey report noted that 70 to 80 percent of the India of 2030 is yet to be built. With cities and electricity grids that are still unrealized, developing nations—especially software-savvy ones like India—are well positioned to put lessons learned from pilot tests of AI into action.

What is unique about Schoonschip is that the entire community will share a single connection to the national grid, with just one electricity meter. Behind that meter, Schoonschip will run its own mini smart grid, tying together the solar arrays and batteries of each house and intelligently coordinating the flow of energy from home to home.

Long Tran-Thanh sees great potential for the land where he was born. "Vietnam is still struggling with its basic electricity supply," he says. "It still has daily planned blackouts because it cannot provide electricity to the whole country. But I know some researchers there have already started talking about smart grids. It's at a very theoretical level only, but smart grids can definitely help Vietnam. We have the tools. We have the AI."

Huge challenges remain, the biggest of which is the mind-boggling cost of retrofitting a planet full of dumb houses with the smart sensors and switches needed to let AIs take control. But if the past 30 years have taught us anything, it is that hardware gets smaller and cheaper, and software more powerful, by the month.

The beauty of adding artificial smarts to our grids is that it saves us hidebound, stick-in-the-mud humans from having to change our ways. Our attention spans are short. Our wills are weak. But software that can tirelessly observe and subtly intervene in our daily lives promises to achieve what decades of nagging have not: a meaningful reduction in our energy use that still lets us enjoy a hot cup of tea after every soccer game.

Mark Harris is an investigative science and technology reporter originally from the UK but now based in Seattle, with a particular interest in robotics, transportation, green technologies, and medical devices. He is a contributing editor at *IEEE Spectrum* and writes for a wide range of outlets including *The Economist*, *The Guardian*, and *Wired*.

Cutting Loose the Climate Future from the Carbon Past

A God's-eye view is one thing, but what about a godlike power? Geoengineering demands a new way of looking at the world—one that can be troubling.

By Oliver Morton

There will come a point, somewhere above Arizona, where—in the words of John Gillespie Magee Jr.'s much-quoted poem "High Flight"—you slip the surly bonds of Earth. Rising "where never lark, nor even eagle, flew . . .

with silent lifting mind," you transcend the world below to tread the "untrespassed sanctity of space." Higher than the sky is blue, decoupled from the Earth curved out below, you can appreciate everything within which you live with a new outsider wonder.

A Tucson-based startup called World View Enterprises is offering to sell its customers this cut-adrift communion for about $75,000 a flight when, a few years from now, its services are up and running. Like its rivals in the tourism of the untrespassed, Jeff Bezos's Blue Origin and Richard Branson's Virgin Galactic, World View reckons that there is a tidy profit to be made taking people who yearn for the sublime.

The difference between World View and its better-known rivals is that it does not plan to launch its passengers into the great beyond with rockets, but rather to loft them under vast balloons. Less drama, more duration—a stratospheric sojourn that lasts for hours rather than a pistoning, parabolic rise and fall. The ability to linger has attractions for other applications, too. If you want to put a communications package over

Space balloon
©World View
Enterprises Inc.

a particular site without the expense of a satellite, World View will in time be happy to offer you a "stratollite" that does the job. And if you want to do something to the stratosphere's thin air and see what effect your intervention has, the company can provide a platform for that, too.

It is that last possibility that brought Frank Keutsch and David Keith, two Harvard professors, to the Tucson firm. In 2018 they plan to use a package slung beneath a WorldView balloon to create a trail of tiny particles in the stratosphere and then investigate the particles' physical effects. They call the effort SCoPEx, the Stratospheric Controlled Perturbation Experiment. In time they hope to investigate the effects such particles have on the chemistry of the stratosphere, too, particularly the finely balanced reactions continually producing and destroying its precious ozone.

No one denies that geoengineering presents risks. The questions that matter are how they stack up against the risks of not geoengineering.

SCoPEx will be the first experimental venture of Harvard's new Solar Geoengineering Research Program, which is devoted to looking at ways to slightly reduce the amount of sunlight that reaches the surface of the Earth. Common sense suggests that this would lessen the effects of global warming; climate models confirm that. Placing into the stratosphere reflective particles of the sort that SCoPEx will investigate—at a rate of a million metric tons a year or so rather than SCoPEx's few kilograms—is the most obvious way this might be carried out.

Keith, whom I came to know while writing a book about geoengineering and whom I now count as a friend, has been the driving force behind this new project and is the Harvard program's first director. He believes that if geoengineering of this sort were to prove safe, and were to be appropriately governed, it could do a great deal to reduce the damage being done by the greenhouse gases that humans have pumped into the atmosphere. His program has attracted millions of dollars in funding from Bill Gates, among others. It represents the most ambitious research program into the practical possibilities of geoengineering to date.

Setting aside its balloon-based logistics, the dramatic and divisive global possibilities of geoengineering might seem to have little in common with the individualized, near-space, epiphany-tourism World View plans to sell. I think they share quite a lot. A big part of what will draw people to see the planetary curve of the Earth against the blackness of space is the expectation that the sublime beauty of the sight will deepen and even transform their feelings about the planet—that they will undergo a personalized recapitulation of the deep effect that the Apollo program's pictures of the Earth had on the burgeoning environmental consciousness of the 1970s. Geoengineering offers, and perhaps demands, a similarly changed perspective. And it is one that can be troubling.

The new way of looking at the Earth that the Apollo images provided was double-edged. As anthropologist Tim Ingold wrote in his influential essay, "Globes and Spheres: The Topology of Environmentalism," seeing the Earth from outside did not just expand people's notion of the environment—it undercut it. Environments are things you find yourself inside; seeing one from outside abolishes that situating self-discovery, opening new estrangements instead. In Ingold's words, "The notion of a global environment, far from marking humanity's reintegration into the world, signals the culmination of a process of separation." When the Earth itself, rather than its human and nonhuman inhabitants and our individual relationships to them, became the object of concern, the nature of environmentalism changed. It moved away from practice and the lived experience of joys and constraint and toward the realm of pure ideas.

I don't for a moment doubt that the world needs ways of understanding the Earth objectively and as a whole—or that those ways of understanding have revealed profound risks to the health and happiness of many millions of humans, not to mention other species. But I still find Ingold's analysis insightful. I worry that an environmentalism that focuses on "saving the planet" runs a pernicious risk of pitting those abstract needs against the interests of people whose voices are not heard enough—specifically, the global poor, desperately in need of modern energy services and commercial opportunities to lessen their misery. I also fear that framing environmental issues in terms of nothing less than the fate of the planet has an alienating, disempowering effect. Anticipating the spectacle of disaster on a geological, even astronomical, scale can offer a perversely liberating—even feckless—powerlessness; what could my or anyone's action accomplish in the face of such sublime immensities?

These worries about the planet's post-Apollo objectification are not, I have found, very widely shared. Most environmentalists seem to think "planet in peril" rhetoric is a matter of imagery and inspiration and that's all. No such insouciance greets mention of geoengineering—almost everyone who talks about it, whether pro or con, thinks it matters a great deal. And that seems strange. For what is geoengineering but an operationalization of that Apollo worldview, one that takes the small step from seeing the Earth as a thing in itself to treating it as a thing to be manipulated, from objectification to instrumentalization? In the iconography of geoengineering—the images seen on posters for meetings or placards protesting them, as well as in illustrations for articles and the like—those Apollo images of the Earth turn up again and again. But they are routinely reinterpreted as a nut with a wrench turning it, or as a thermostat dial being adjusted by a vast and disembodied hand.

Environmentalism that focuses on "saving the planet" runs a pernicious risk of pitting those abstract needs against the interests of people whose voices are not heard enough.

The god's-eye view is a necessary precursor to the godlike power. But that does not mean the power does not matter in itself. Geoengineering may grow out of a view of the world that in other circumstances seems to most people unproblematically inspiring. But it would be silly to deny that it brings new problems with it. Who would wield its power, and in whose interests? And what would it do to people's personal motivations for environmental action? Most environmentalists seek or enjoy a particular sense of what it is to care about nature and protect it. If environmental action is something that comes from outside, uncoupled from any change in the way we lead our lives, does it still deliver what the environmentalist spirit craves?

Similar questions are familiar from other conflicts within environmentalism. "Ecomodernists" such as Stewart Brand, Ted Nordhaus, or Erle Ellis argue for saving the environment through an intensification of human activity: more intensive—meaning genetically modified—farming, more intensive—meaning nuclear—energy sources, more intensive—meaning urban—lifestyles. The human footprint becomes deeper but smaller; space is saved for the wild.

It was through such thinking that the term "decoupling" entered the environmental vocabulary. Previously largely a term of art in physics, it was imported by Jesse Ausubel to express what has become the core of ecomodernist belief: that continuing economic growth no longer requires increased environmental impact, and that this decoupling can be encouraged until it becomes more or less complete.

These ideas sound reasonable—indeed, inspiring—to their proponents. They provoke strident resistance elsewhere. Some simply refuse, on the basis of history, human nature, or both, to believe that humans enjoying ever greater and more concentrated technological power will use it as wisely and immaterially as the ecomodernists want; many see no hope for an environmentalism that does not seek fundamental limits on consumption and economic growth.

There is also a deeper feeling that ecomodernism misses the point; that if it were to succeed, it would be by decoupling not just the economy from the environment, but also people from the nature they need. Nuclear-powered, LED-lit, hydroponically nourished, carbon fiber–skeletoned, skyscraper farms might be wonderful things; but these are not the wonders, by and large, that people join the Sierra Club for.

Geoengineering makes seemingly similar promises in a concordant technocratic key—and provokes similar fears. It does not suggest merely that human activity can be decoupled from environmental harm. It suggests that the future can be cut loose from the past—that the legacy of warming stacked up in the atmosphere, molecule by molecule and gigaton by gigaton, might perhaps be set at naught. There is a grandeur in this, and a liberation—just as there is a grandeur, and a liberation, in looking out from the edge of space at the curved Earth set out below. But is there not, also, a deep irresponsibility in seeking to clean the slate? How much transcendence can a conscience bear?

There is an odd irony here. It is true that solar geoengineering of the sort Keith is researching feels essentially deracinated, top-down, technocratic, and—for all those reasons and more—dangerous. But at the same time, it offers something that most current environmentalism, including that of the ecomodernists, does not: a plausible path toward the reduction of near-term harm to people and the natural environment.

At the UN's 2015 Paris summit, the nations of the world committed themselves to keeping global warming "well below" 2 degrees Celsius and, ideally, as low as 1.5 degrees Celsius. This is by no means ideal. A two-degree rise will do a lot of damage and hurt a lot of people. It could render some currently semi-arid and excessively hot places uninhabitable; it will deeply disrupt Arctic ecosystems; it may well, in the long run, doom the Greenland ice cap. And though two degrees is what Paris aspires to, it is not what it looks likely to deliver. The specific cuts in greenhouse-gas emissions to which the nations signing the agreement actually committed themselves were not remotely ambitious enough for that.

The Trump administration's petulant and nihilistic withdrawal from Paris probably damages its prospects further. That does not mean there is no hope. As renewable technologies grow cheaper and transport is increasingly electrified, the rate of progress on emissions reduction may increase faster than the current Paris pledges would suggest, whatever the US federal government does.

Solar geoengineering feels essentially deracinated, top-down, technocratic, and—for all those reasons and more—dangerous. But at the same time, it offers something that most current environmentalism does not: a plausible path toward the reduction of near-term harm to people and the natural environment.

But the degree to which progress needs to speed up if the Paris goals are to be met remains extraordinary. A determinedly optimistic scenario put forward by the Carbon Tracker Initiative, an NGO, suggests that if renewables continue to grow faster than generally expected (as they have been doing), there might be a fifty-fifty chance of no more than 2.4 degrees Celsius of warming. But even if policies became much more ambitious and people, within a few decades, started pulling carbon dioxide down out of the air and storing it away permanently, the risk of breaking the two-degrees barrier would still be more than 50 percent.

For a good chance of limiting global warming to 1.5 degrees Celsius, the world would need even more ambitious reductions in emissions and, in the second half of the century, a truly vast drawdown of carbon dioxide. There may be ways to do this in a clean, efficient way. But as yet they are unproven. Policy analysts currently tend to assume that a carbon drawdown will involve burning biomass to generate electricity and pumping into deep storage the carbon dioxide produced in the process. The biomass presumably would be grown on plantations or through vast ocean-farming systems. But most such discussion ignores the sheer size of the interventions required; to get into the right ballpark, you need plantations across an area bigger than India. If the creation of plantations on such a scale were politically feasible (I think it isn't), the sacrifice of arable land or wilderness would be a terrible cost.

None of this is to say that the world cannot, over the coming century, drastically reduce its emissions or indeed start to reverse them. But the realistic chances of doing so in time to stave off real harm to the people who suffer most from climate change—poor people in hot countries—are very thin. Unless, that is, you add another form of action to the agenda. That is where solar geoengineering comes in.

Note that it is indeed an addition, not a replacement. Neither Keith nor, as far as I know, any of the other researchers looking at the feasibility, side effects, and safety of solar geoengineering sees it as a possible alternative to reducing greenhouse gas emissions. For long-term climate stability, fossil-fuel greenhouse gas emissions have to be brought down to zero; they need to come down to zero to put an end to ocean acidification, too. What geoengineering might do is slow and/or limit the warming which will take place in the time it takes for that global zero to be reached. A layer of fine particles in the stratosphere, capable of reflecting away enough sunshine to cool the planet by just 1 degree Celsius, could be the difference between meeting the most ambitious goal envisaged in Paris and crashing through its upper limit.

That immediately poses the question of what else such a layer of fine particles might do. One possibility is that it might damage the ozone layer. Particles in the stratosphere

Stratosphere cloud layer ©NASA

tend to catalyze ozone-destroying reactions. It is the presence of clouds in the stratosphere around Antarctica that accounts for the ozone hole there; the sulphate particles produced after large volcanic eruptions reduce ozone levels as well as cool the planet (Such episodes of natural volcanic cooling are one of the reasons for thinking that solar geoengineering can have a cooling effect, though they are not a precise analogue). One of the main purposes of SCoPEx is to see whether it is possible to find potentially planet-cooling particles which damage the ozone layer less—or perhaps even replenish it.

Then there are the effects on the climate itself. The cooling triggered by particles in the stratosphere and the warming created by greenhouse gases are not perfect opposites. Greenhouse gases work day and night, summer and winter; they have different effects at different altitudes, warming the middle layers of the lower atmosphere and cooling the stratosphere itself. Stratospheric solar geoengineering works by day only thus it does little to, say, Arctic winters. It cools the surface more than the air above it, and it actually warms the stratosphere. These differences mean that the weather patterns in a world where some greenhouse-gas warming is countered by stratospheric aerosols would not be those of a world where that greenhouse warming never took place, even if the average temperatures were the same.

Experiments such as SCoPEx can tell you what solar geoengineering particles will do to the chemistry of the stratosphere. However, they can't tell you what a veil of particles spread round the world would do to the climate—any more than spraying carbon dioxide into a little patch of the atmosphere would tell you the impacts of greenhouse gas warming. You can't do experiments at the scale of the Earth without, well, doing experiments at the scale of the Earth. But you can use the models built to understand greenhouse gas warming to look at worlds in which geoengineering takes place, too—what I call "doubly altered climates." Such modeling is imprecise, and probably far from reliable when looking at specific regions. But the same is true of models that tackle the effects of greenhouse gases alone—which is to say, the models on which the limits and aspirations of the Paris agreement are based.

Such studies strongly suggest that a couple of degrees of geoengineering would reduce climate impacts over much of the world. Weather patterns would still change: "doubly altered" is not completely canceled out. Altering stratospheric circulation would influence jet streams and hence surface weather. Rainfall patterns would change, though that would not necessarily mean more droughts and might mean fewer floods.

If you had a utilitarian choice between a world with 3 degrees Celsius of greenhouse warming or a world with the same amount of greenhouse gases but enough solar geoengineering to limit the increase in temperature to 1.5 degrees Celsius, and you had only modeled climate impacts to go on, it would be pretty much a no-brainer. The 1.5-degree world would be better for almost everywhere—lower average and peak temperatures and thus less heat stress for humans and ecosystems, lower sea levels, less ice loss, fewer extreme events.

The problem is that climate impacts in a particular scenario are not the only thing at play. People and politics matter, too. Model studies strongly suggest that, for any significant level of geoengineering, some regions would benefit from adding further particles to the stratosphere while some others would not. Such tensions could drive the world toward more geoengineering than is optimal, or toward large-scale international conflict, or both.

There is also an obvious risk that geoengineering might prove a victim of its own success. If it looks like it is actually doing the good it seems to promise—or even if it just looks plausible that it might—then incentives to keep on with the vital work of reducing greenhouse-gas emissions will start to weaken. The world might let itself go.

To imagine that humans can simply stop being a planet-changing force is unrealistic. Thinking that we might find a way to act responsibly may be just as daft. But it seems to me a better foolishness.

If today's energy optimists are correct, that may not matter too much. If green-energy progress really is now unstoppable, and if technologies for pulling carbon out of the atmosphere on a large scale really are going to become available, then emitting a bit more carbon dioxide in the meantime might not be the worst thing. But those are big ifs—especially if the relaxation follows from the promise that solar geoengineering looks plausible, rather than from a demonstration that it actually helps.

Worries such as these are real, serious, and widespread. They lead some wise and cautious people to think that solar geoengineering is best left off the table. They judge that the potential political harm outweighs any promise. And because it is easier not to discuss something than to discuss it—this inertia-through-*omerta* has won out.

No policy wonk, activist, or politician pays a price for not discussing solar geoengineering when talking about how the planet might meet the Paris goals. No one makes a career in geoengineering research: Keith is the only high-profile scientist currently devoting almost all of his research efforts to it. Just one researcher whose doctorate dealt with geoengineering has so far gone on to a tenured university position. A study of geoengineering carried out by the Royal Society in 2009 suggested that perhaps as much as one-tenth of climate research should be devoted to examining such ideas. The actual figure is closer to one one-thousandth, and the rate of publication on the subject is dropping.

Which is why I think SCoPEx matters. A real experiment, up in the stratosphere, will focus attention. That may be uncomfortable for Keith and his colleagues; many will see their high flights not as a quest to touch the face of God but as an attempt to besmirch it. The public engagement programs Keith would like to set up around it may reveal deep and unshifting antipathies. It's a fair bet there will be lawsuits and demonstrations, both by environmentalists concerned that it crosses a stratospheric Rubicon and by "chem-trailers" who believe that the upper atmosphere is already being deliberately manipulated as part of a vast government conspiracy. Good faith will be questioned; tempers will flare; the online threats made against Keith and others who express views on the subject will increase.

Through all this, though, the wider debate may get the real airing it still needs. No one denies that geoengineering presents risks. The questions that matter are how they stack up against the risks of not geoengineering and how they can be managed. That second question is the purview of the other big, recent development in this small, important field: the creation of the Carnegie Climate Geoengineering Governance Initiative led by János Pásztor, a diplomat who previously worked as a climate adviser to Ban Ki-moon. Pásztor and the team he is putting together hope to provide frameworks in which the political, legal, and ethical issues geoengineering raises might be addressed. Their work should help clarify what matters when considering SCoPEx and subsequent research, and to whom it matters. It should also help ensure that the voices of the poor, who are at greatest risk from climate change, are in fact heard.

It may be that geoengineering really does raise more risks through politics than it reduces by scattering sunshine. And perhaps the consensus on this will be so strong that no nation will choose to run those risks and geoengineer anyway. The world would then be left with emissions reductions, adaptation efforts, and the harm that follows when those are insufficient—as they all but surely will be. It seems to me, though, that it is worth trying hard to find out whether a form of geoengineering that is safe, just, and governable might also be politically feasible, rather than assume that it isn't.

This is not just because there is a moral duty to try to reduce the harm climate change is doing. It is also because those images of the Earth from space, that view of "nature" made possible only by the highest of technologies, resonate with a genuine and irrevocable change in the human relationship to the planet.

As Ingold's writing and many worries about geoengineering attest, this change is far from an unmixed blessing. Nor is it an adamantine curse. As those yearning for the view from the windows of a pressurized microhabitat slung below a World View balloon may yet learn, it is both a new breach and a new connection. It is problematic; it has potential.

Humans, spread across the planet's face, tied by trade across its oceans, lifted up into its skies, are now the Earth's environment, as the Earth is ours. We shape each other. In our mutual embrace, we both deserve respect and care. But only one of us is capable of expressing that duty and acting on it. If the world can't bring itself to talk about such care—even if it is to conclude that its wise exercise is beyond human judgment or perhaps human technology—then it is failing both itself and the rest of the planet.

To imagine that humans can simply stop being a planet-changing force is unrealistic. Thinking that we might find a way to act responsibly may be just as daft. But it seems to me a better foolishness.

Oliver Morton is a senior editor at *The Economist*. Prior to that, he was Chief News and Features Editor at *Nature*. His writing has appeared in the *New Yorker*, *National Geographic*, *Discover*, *Time*, *New Scientist*, *The New York Times*, *The Financial Times*, and many other outlets. His most recent book *The Planet Remade* was shortlisted for the Royal Society Insight Investment Science Book Prize.

When You're in a Carbon Hole Stop Digging

Here's a retirement plan for coal that doesn't rely on uninvented technology or science-challenged leaders

By Robinson Meyer

The United States has never had a president as hostile to the theory of anthropogenic climate change as Donald Trump. He has rejected climate change as a hoax, begun to undo years of Obama-era climate policies, and hired an EPA director who questions whether carbon dioxide regulates the temperature of the planet.

It's enough to make the climate-concerned wish for something a little more . . . well, unilateral. In this era when climate leadership seems to buy diplomatic cachet, what could a couple of powerful countries do? What could a wealthy individual such as Bill Gates do to prevent carbon dioxide from being emitted? Even Germany's much-celebrated transition to renewable energy, which has brought down the costs of solar and wind energy worldwide, has reduced its national carbon emissions by only 7 percent. California has found more success: the world's sixth-largest economy has brought down emissions by 10 percent

©Igor Kopelnitsky/ Illustration Source

since 2006. Is there another way to intervene directly in the climate system—and not through internationally dubious geoengineering schemes such as aerosols or sea fertilization, but through simple economics?

There might be. Enter Matt Frost.

I met Frost through Twitter. I knew him first as a witty, curious guy with an unusual collection of interests: mine safety, the statistics software R, the novelist Sigrid Undset, various forms of conservatism. I knew he had five kids and many dogs and that he observed Orthodox Christianity. And I knew he had this plan for keeping coal in the ground.

As I talked to him for this story and began to suss out the realism of what he calls his "coal retirement plan," I learned that during the day, he works in natural-resource management. When you read the EPA's reports on US car-fuel efficiency and air pollution, you're reading his work. So he knows what he's talking about.

Anyway, here's his plan.

Most climate regulations focus on making it more expensive to emit greenhouse gases. The cap-and-trade systems run by both the European Union and, soon, China take this approach: the thing they're capping and trading is emissions.

Frost believes that instead of regulating to limit the burning of fossil fuels, we should just never remove the fuels from earth's crust in the first place. Coal-fired power plants release about 40 percent of global carbon emissions and are a frequent target of climate policies. Frost thinks we should pay the organizations which own underground coal deposits—specifically, the US government—for the right to never mine it.

"The US coal deposits represent a potential store of future CO_2 emissions," Frost told me. "The assumption, the policy assumption, is that they need to be extracted. But what if we just sequester this carbon while it's still in coal form?"

By permanently keeping coal in the ground, carbon dioxide is in turn permanently kept out of the atmosphere. It will never trap heat in the atmosphere or debase the ocean. Thus buying unmined coal constitutes an incredibly cheap form of offsetting carbon consumption. But that's not all it does: sequestering coal from the global market causes coal's price to rise. So coal retirement becomes a voluntary way of pricing in the mineral's considerable climate, environmental, and public-health costs. Coal's price could even rise internationally, weaning other nations off the fuel.

> Buying unmined coal constitutes an incredibly cheap form of offsetting carbon consumption.

In effect, buying coal while it's still in the ground constitutes a very inexpensive, very simple form of geoengineering. It's perfect for climate-concerned billionaires such as Bill Gates or even for international coalitions.

There are several ways to go about it—in the US and around the world. They're both somewhat feasible and a little complicated.

The US is one of very few nations where mineral rights—the ability to mine an area—can be privately held. (In most nations, these rights are public or royal.) But US rights differ, depending on where you are. East of the Mississippi, a property owner typically controls not only the land that he owns a deed to, but also the rights to mine any minerals beneath that land. Particularly in Appalachia, many property owners can (and do) sever those mineral rights from their surface rights and sell them to private companies. Rights get severed and sold by coal seam, so it's possible for multiple companies to own rights for one location, as long as they hold rights to different depths.

"If you ask someone to build a property map of mineral rights in West Virginia, you have to specify which coal seam, because each coal horizon can have a separate owner on the exact same lat-lon coordinates," says Frost. "As you go up and down the mountain, you can run into different ownership."

But west of the Mississippi, things work differently. Especially in Montana and the Mountain West, the government typically holds mineral rights. The Bureau of Land Management now manages those rights, as well as the rights under land that has never left the federal government's ownership. Today, the country's major Western coal deposits—almost 90,000 square miles—are administered by the Bureau of Land Management.

Two different mineral regimes, two different forms that Frost's plan could take.

In Appalachia, no one would have to give a climate-concerned billionaire permission to buy up coal. In fact, Bill Gates or someone else could start buying coal there tomorrow, Frost says.

"The coal industry employs 'land guys' who play a lot of golf with other land guys and strategically assemble viable mining units out of the parcels they can stitch together. A shrewd buyer of retirement coal would apply the same skills, but from the angle of 'sterilizing' as much nearby coal as possible," he wrote to me in an email.

He calls these sterilizing buyers "green-hat land guys." Were a billionaire inclined to hire them, now would be an especially good time. Natural gas has pushed the cost of fossil fuels too low for the old giants to survive. Nearly every major Appalachian coal company has collapsed or filed for bankruptcy, and many national and international banks have fled the industry.

Despite that ease, Appalachia isn't the ideal place to sequester carbon underground. Unless the government changed the tax code, the tracts of unmined coal would continue to be a taxable resource, their price fluctuating with the commodity. There would be no tax benefit to keeping the coal out of the market in perpetuity. In fact, the locked-away seams would present a perpetual tax liability.

So maybe it's better to look to the wide-open West. The Bureau of Land Management controls vast and untapped seams of coal across many Mountain West states. It leases the rights to mine those deposits to interested companies—a program that produces about 40 percent of the nation's annual coal haul.

The BLM began a review of its coal program after the Paris Agreement was drafted, but it was recently canceled by Ryan Zinke, Trump's secretary of the interior. It remains the BLM's statutory imperative to find a fair market price for coal. And anyone who leases federal coal is legally obliged to obtain its "maximum economic recovery"—in other words, they must mine all the coal that is profitable to mine.

Congress could forbid the BLM to lease coal anymore, but in an era of unified Republican control of government, that seems unlikely. So Frost proposes that the BLM alter its policy in one small way: it should let anyone lease its coal. Right now, to lease coal from the BLM, a buyer needs to present a plan to mine it. Frost wants the bureau to trash that requirement. He also wants the government to introduce a kind of perpetual easement—a special kind of long-term lease—that will let individual buyers enter the coal market and sequester carbon without the tax liability.

There are different ways to accomplish this. It may be better for individual buyers to transfer their ownership to a kind of federal carbon trust. This would make carbon sequesterers less liable for events such as underground coal fires. And because natural gas remains economically critical, Frost thinks the trust should not include rights to coalbed methane.

"Let's look at the problem not in the sense of we're burning too much coal, but as: coal is too cheap. What do you do about that?" he told me.

"There's various other kludgy things that have been done in the past, when the government or a special-interest group decided a commodity was too cheap," he says. "How do you prop up the price more? Just as when you pay people not to grow certain crops, why don't we get out of this business of growing coal on our national carbon plantation?"

The best aspect of the coal-retirement plan, as Frost puts it, is that it doesn't require political consensus. "Resources devoted to lobbying for cap-and-trade have yet to directly prevent any CO_2 emissions," he wrote in his original proposal several years ago. "By making one rather esoteric adjustment to US property law, my proposal allows each marginal dollar spent to have some small impact toward increasing the cost of burning coal."

One small change, but a tough one in 2017, when a different administration sits behind the organ of federal rule-making. Frost thinks a coal-retirement clause would be hard to add to the BLM lease in the US, at least during the Trump era. And he doubts that a billionaire could buy coal in West Virginia, at least in a public way. That state's school system relies on income from the severance tax, a fee exacted when coal is removed from the ground.

Previous investments in other parts of the economy, even very big ones, have not managed to substantively reduce emissions. Before the 2014 midterm-election cycle, billionaire Tom Steyer announced he would found and invest heavily in a climate-concerned super PAC. Despite his donating $65 million of his own money to the organization, only three of Steyer's seven candidates went on to win races, most of them in already secure seats. And in 2016, of course, Hillary Clinton seemed to pay a political price over her predecessor's alleged "war on coal," with few apparent electoral benefits. She also lost despite raising nearly twice as much money as Trump.

Buying coal outright seems increasingly more efficient than trying to shape the debate over it.

Climate-concerned countries should form a coalition to purchase buried coal and gas reserves, targeting those that are extraordinarily hard to take out of the ground—for example, the Canadian tar sands.

Frost isn't the first writer to propose the planet keep its coal reserves in the ground. In 2012, Norwegian economist Bård Harstad argued that the best realistic short-term national climate policy was to buy up coal and oil reserves around the world. Not only would this be a very good policy, it is actually the most efficient climate policy imaginable, Harstad thinks.

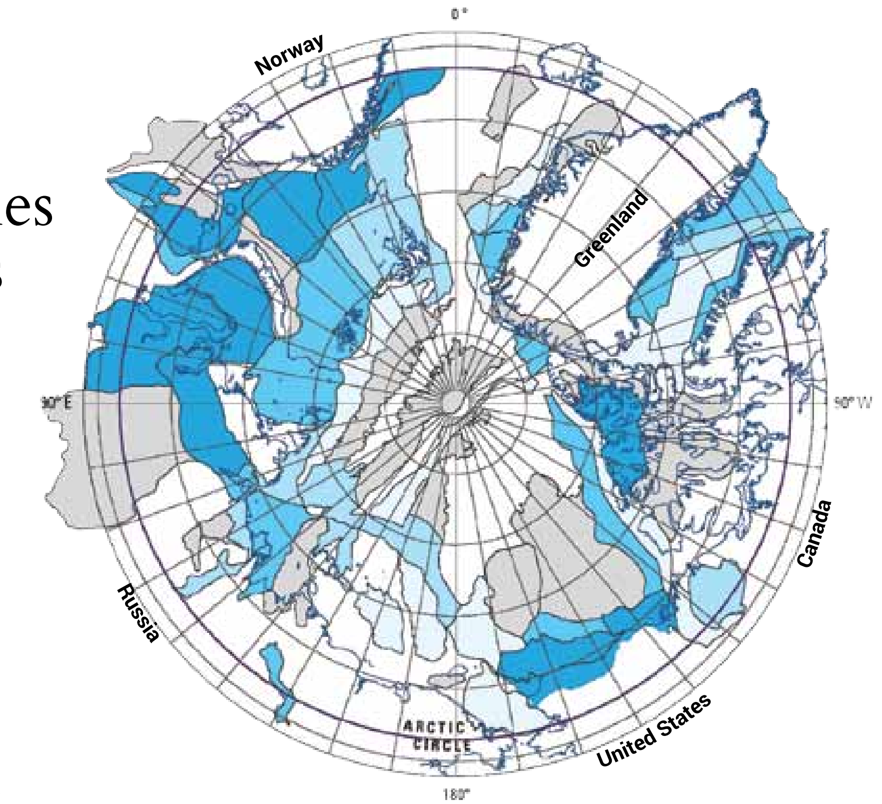
Harstad's policy is meant to solve a problem: some countries will want to take climate action before others do. When those climate-fighting countries impose emissions-limiting policies, they'll burn less coal or oil—and, with global demand down, the price of coal or oil will fall. Other countries, without climate policies, will rush into the fossil-fuel market and burn what they would have burned anyway plus what the first set of nations didn't touch. With even less incentive to invest in renewable-energy sources (because fuels are so cheap!), they'd burn more oil and gas than they would have in the first place.

It constitutes a kind of tragedy of the commons. The virtuous nations would get no reward for their foresight and good stewardship, and meanwhile the planet would still get hotter. Add to all this the reality that almost all the "bad" countries are going to be the poorest ones, places where cheaper electricity lets more families access refrigeration or air conditioning.

Harstad hit upon a strategy similar to Frost's. He thinks climate-concerned countries should form a coalition and proceed as a group to purchase buried coal and gas reserves around the world. This coalition would target reserves which are extraordinarily hard to take out of the ground—for

One place supply-side climate policies could work is the Arctic.

The area north of the Arctic Circle contains an estimated 90 billion barrels of oil and nearly 1,700 trillion cubic feet of natural gas, according to a US Geological Survey report. Approximately 84 percent of these reserves are believed to occur offshore. While these areas are becoming increasingly accessible, drilling there remains a risky and expensive proposition. Experts say these difficult-to-exploit resources should be the focus of coalitions that aim to keep fossil fuels in the ground.



Probability of the presence of at least one undiscovered oil and/or gas field with recoverable resources greater than 50 million barrels of oil equivalent (1)

100% · 50-100% · 30-50% · 10-30%
less than 10% · area of low petroleum potential

1. Circum-Arctic Resource Appraisal: Estimates of Undiscovered Oil and Gas North of the Arctic Circle. USGS Fact Sheet 2008-3049. 2008.

example, the Canadian tar sands. The coalition then has only to pay the relatively meager profit from these reserves to the nation in question, and it can comparatively lock up more coal.

"Note that the world fuel price will be relatively high when the focus is on reducing extraction. This will motivate all companies and countries to economize on energy and to develop green technologies or renewable sources," Harstad wrote in a *Financial Times* op-ed. "Traditional climate policies, by contrast, allow countries that do not co-operate to buy fuel at a low price, and therefore, they face few incentives to adopt or develop green technologies."

Harstad said that his and Frost's plans were generally similar. He was less sure that private buyers, even billionaires, could shift the market in the same way an international coalition could. "An international agreement would be more effective, but also that agreement can (in fact, 'should') focus on reducing coal extraction. The point of my research is to show that such a treaty on extraction is the most effective climate policy," he told me in an email.

He also disagrees with Frost about which coal should be purchased. Harstad thinks that his coalition should lease or purchase the hardest coal to access—in other words, the coal that's most expensive to mine. Then, as demand for coal grows and the price rises—and mining companies start to look at more difficult reserves—they'll find that coal is already locked up.

Now, five years after his op-ed, Harstad is not hopeful about the outlook for supply-side climate policies in most parts of the world. But one place it could work, he told me, was the Arctic. Five different countries make claims to the territory—and, thus, the oil deposits—in the Arctic: Canada, Russia, Norway, the US, and Denmark (via Greenland). All of them are relatively rich, and four of them are relatively progressive.

Harstad believes that all five could decide to permanently set aside the oil in the Arctic in the name of sound climate policy. It would be permanently off-limits—in the same way that 12 countries, including the US and the Soviet Union, decided to set Antarctica aside from military activity in the Antarctic Treaty. Since the oil in the Arctic is already some of the most expensive to mine, setting it aside would not require sacrificing much output.

I've been referring to Frost's plan as geoengineering. His policy tampers with the environment at least as much as our society-wide intervention does.

But if a billionaire (or a large non-profit with similar purchasing power) really wanted to augment its coal-buying efforts and buy the climate more time, they would have to invest in what many people think of as "real" geoengineering and what the UN calls negative emissions technologies (NETs). These are processes that pull carbon out of the atmosphere so it can be trapped on or below the surface. But you could do this without fanciful technology. A recent economic study out of Oxford University found that the most efficient NET over the next 50 years will not be carbon-capturing pumps or artificial photosynthesis, but trees. Afforestation—planting forests where there were none before—is the best, most effective way in the short term to remove carbon from the atmosphere and sequester it.

Were a donor or government to combine the two methods, this could shape the global climate on both ends: removing carbon from the atmosphere while also reducing the influence of future carbon. It could intervene directly into the system. And by raising the price of coal, it could pave the way for a more lasting international commitment—the kind of policy we'll likely need to recover from the next four years.

Robinson Meyer is an associate editor at *The Atlantic*, where he covers technology. This article was adapted from a piece on TheAtlantic.com.

Stories of Innovation in the Human Age

made possible in part by the following organizations

CSE

Centre for Science and Environment is a non-governmental, independent policy research institution based in New Delhi, India. It was founded in 1980 by the late Anil Agarwal. Over the years, CSE has helped shape policies and build public awareness to bring change in areas of pollution mitigation and public health security, low carbon development, natural resource management and livelihood security to make growth sustainable and inclusive. It is currently headed by Sunita Narain.

www.cseindia.org

American Museum of Natural History

Center for Biodiversity and Conservation

The Center for Biodiversity and Conservation at the American Museum of Natural History transforms knowledge—from diverse sources and perspectives, spanning areas of scientific research as well as traditional and local knowledge—into conservation action. We collaborate with partners around the world to increase local and global capacity to address the loss of biological and cultural diversity, and foster connections among diverse practitioners to catalyze conservation on the ground.

www.amnh.org

Stockholm Resilience Centre
Sustainability Science for Biosphere Stewardship

Stockholm University

Stockholm Resilience Centre advances research on the governance of social-ecological systems with a special emphasis on resilience—the ability to deal with change and continue to develop.

www.stockholmresilience.org

SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

The UN Sustainable Development Solutions Network (SDSN) has been operating since 2012 under the auspices of the UN Secretary-General. The SDSN mobilizes global scientific and technological expertise to promote practical solutions for sustainable development, including the implementation of the Sustainable Development Goals (SDGs) and the Paris Climate Agreement.

www.unsdsn.org

3.

Science Shorts

Dispatches from the front lines of sustainability research

Q & A

Is the grass greener on the other side?

Drug legalization could both help and hurt the environment

By Hillary Rosner

Social transformations that once took generations to cement now seem to cover the globe in a matter of years. The legalization of marijuana is a case in point. Uruguay, the Netherlands, Morocco, and a growing list of countries are decriminalizing the forbidden weed. And individual US states are following suit, trailing a wave of public opinion. In a 2016 Pew survey, 57 percent of US adults said marijuana use should be legalized, while 37 percent said it should be a crime. That's nearly the reverse of public opinion on legalizing pot a decade ago.

The reasons for the about-face vary from a desire to curb the violence inflicted by drug cartels, to concerns over vastly uneven criminal prosecution, to access for medicinal uses. Rarely, however, does the list include abating the environmental damage the illegal drug trade wreaks.

But perhaps it should. The ecological impacts of the black-market drug trade are crushing. In Colombia, for example, the cocaine trade was responsible for more than half of all forest loss in the 1990s. (1) According to one study, the spread of coca crops to feed global demand for cocaine "threatens the last repositories of imperiled forest species more efficiently than most other causes of forest fragmentation." And across Central America—particularly in the Caribbean lowland forests of Nicaragua, Honduras, and Guatemala, an area teeming with remarkable plants and animals—drug trafficking is speeding the destruction, lighting a match to the tinderbox built from poverty, illegal logging, industrial agriculture, and weak enforcement, according to research published in 2014. (2)

As cartels push drug crops into increasingly remote areas to avoid law enforcement, the devastation spreads. Herbicides, pesticides, and fertilizers threaten fragile ecosystems. Exact numbers are hard to come by, but one study reported that in 2005, coca growers in Colombia used 81,000 tons and 83,000 barrels of fertilizers and toxic weed and pest killers. (3)

Drug traffickers often launder money and seek to "legitimize" their presence in an area through agriculture—converting even more forests to pasture or oil palm plantations. (2) And the violence that follows cartels into remote areas makes wildlife monitoring and other scientific research more and more perilous.

Even enforcement efforts can deal a blow. In a 2005 trial program, the Colombian government sprayed a deadly herbicide to destroy vast coca crops illegally planted across 13,000 hectares of a national park and surrounding lands. Instead of protecting the park, the government was bombarding it with toxic chemicals. (4)

> Growing 1 kilo of pot generates roughly the carbon emissions of burning 516 gallons of gasoline.

In the US, illegal pot farms have set up shop on public lands with devastating environmental consequences. Some are sucking entire ecosystems dry. Marijuana plants use almost twice as much water per square kilometer as wine grapes, northern California's other major irrigated crop. (5) One study found that water demand for pot cultivation could slash the water available in streams by nearly one-fourth, killing endangered salmon and steelhead trout as well as amphibians. (6)

Terrestrial wildlife takes a hit, too. Several years ago, in forests in northern California and in the southern Sierra Nevada range, scientists began finding a lot of dead Pacific fishers (a forest-dwelling mammal similar to the weasel and a candidate for listing under the Endangered Species Act). Testing revealed that nearly 80 percent of the dead animals, including adults and their kits, contained lethal rodenticides that pot growers use to keep rats from eating their plants and gnawing through their irrigation lines. (7)

All this bad news raises the question: Could legalization offer even a modicum of relief?

Legalizing marijuana in all 50 US states might put drug cartels out of work—solving the public lands problem and even reducing the use of poisons that kill wildlife. But even legal marijuana farming isn't benign. New research shows that indoor pot production—legal and illegal—is a "previously unrecognized source of energy consumption," responsible for as much as 1 percent of total US electricity use. Growing 1 kilo of pot generates roughly the same amount of carbon emissions as burning 516 gallons of gasoline. And out of 20 industries, from textiles to tobacco to plastics, marijuana had the highest energy intensity—more than double any other one except paper. (8) Already, energy demand for indoor pot operations in Washington state—where the drug has been legal since 2012—is projected to double by 2035, according to a report from the Northwest Power and Conservation Council.

Still, legalization done right might offer an antidote. Gina Warren, a law professor at Texas A&M, has looked at drug legalization trends in terms of energy regulation, and she believes that new state licensing regulations offer a chance to limit the greenhouse gas emissions of indoor grow operations. Warren recommends that states and cities should consider energy usage and emissions when granting licenses—and even require pot growers to use only renewable energy. Even without such regulation, simply bringing illicit growers out of the shadows could ease some of the environmental externalities. For example, instead of stealing electricity or running generators, growers would plug into the grid. They could then take part in utility energy-efficiency programs and have a financial incentive to use cleaner, off-peak power. (9)

It's too soon to know what the impact of state-by-state or even countrywide legalization will be—partly because there's virtually no funding to study it. That seems an opportunity lost. Drug policy is flipping right before our eyes. If we paid more attention, perhaps we could make some drugs, particularly the world's most sought-after weed, a little greener.

1. Álvarez MD. Illicit crops and bird conservation priorities in Colombia. *Conservation Biology*. 2002.
2. McSweeney K et al. Drug policy as conservation policy: Narco-deforestation. *Science*. 2014.
3. United Nations Office on Drugs and Crime. World Drug Report 2015.
4. Dávalos LM and AC Bejarano. Conservation in conflict: Illegal drugs versus habitat in the Americas. In: *State of the Wild 2008–2009: A global portrait of wildlife, wildlands, and oceans 2*. Island Press. 2008.
5. Carah JK et al. High time for conservation: Adding the environment to the debate on marijuana liberalization. *BioScience* 2015.
6. Bauer S et al. Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four northwestern California watersheds. *PLoS ONE*. 2015.
7. Gabriel MW et al. Anticoagulant rodenticides on our public and community lands: Spatial distribution of exposure and poisoning of a rare forest carnivore. *PLoS ONE*. 2012.
8. Mills E. The carbon footprint of indoor cannabis production. *Energy Policy*. 2012.
9. Warren GS. Regulating pot to save the polar bear: Energy and climate impacts of the marijuana industry. *Columbia Journal of Environmental Law*. 2015.

Hillary Rosner has covered science and the environment for *National Geographic*, *The New York Times*, *Wired*, *Scientific American*, *Mother Jones*, and many other publications.

Rerouting

Small changes to flight routes could deliver big climate savings

By Lindsey Doermann

With small changes to trans-Atlantic flight routes, airlines could reduce their climate impact by up to 10 percent, according to a new study. These climate savings come with a 1 percent increase in operating costs for airlines.

While planes spew plenty of CO_2, they also contribute to warming by forming contrails and by altering ozone and methane levels. The relationship between contrails and climate isn't straightforward; they generally act to warm the climate, but in some cases they can have a cooling effect. Also, emissions from aircraft flying close to or within the stratosphere have a greater effect on climate than those released at lower altitudes.

An international team of researchers looked at simulations of 400 flights across 85 routes over the North Atlantic for a representative set of summer and winter weather patterns. They found that even small routing changes, to steer clear of regions where emissions would have a large impact, would significantly reduce climate impacts with a minimal increase in cost—mostly from fuel.

The researchers say that climate-optimal routing isn't quite ready for the real world. And cost increases may not fly in an industry with already-slim profit margins. However, they add, market-based measures that account for non-CO_2 climate impacts could offset that additional cost—and set up a win-win for the industry and the atmosphere.

Grewe V et al. Feasibility of climate-optimized air traffic routing for trans-Atlantic flights. *Environmental Research Letters*. 2017.

Reusable or Disposable

Which coffee cup has a smaller footprint?

By Pierre-Olivier Roy

You walk into your local coffee shop, hand the barista your reusable coffee mug, and pat yourself on the back for not using one of those "bad for the environment" single-use cups.

Sounds simple. Right?

Perhaps.

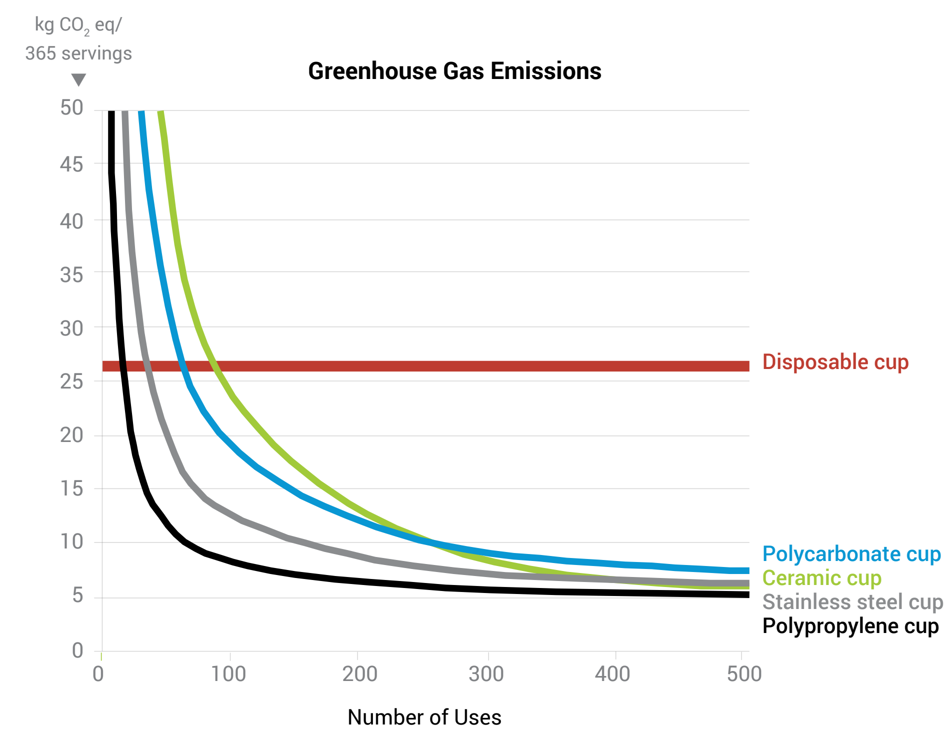
Granted, using a reusable cup lowers the waste-management environmental impacts. But you may not have considered other aspects of the cup's life cycle such as the materials and energy that went into making your sturdier reusable cup, the soap and hot water that will be necessary to wash it, and the energy source behind the heat of this washing water. A recent life-cycle assessment (LCA) by the CIRAIG* tackled those issues. LCAs compile and evaluate the inputs, outputs, and potential environmental impacts of a product or service from material extraction to end of life.

The CIRAIG study compared the potential environmental impacts of a 16-ounce, single-use coffee cup made of a mix of cardboard and polyethylene (with a lid made of polystyrene) to those of a 16-ounce, reusable ceramic cup and to those of a variety of 16-ounce travelers' mugs made of stainless steel, polypropylene, and polycarbonate. Over a one-year span (using one cup a day), the reusable cups scored well in the climate change arena—that is, they were associated with fewer greenhouse gas (GHG) emissions than their single-use counterparts. Likewise, they scored better in the human-health category for things such as toxic emissions, smog, and ozone depletion. They also tended to use fewer minerals and fossil fuels than disposable cups did.

But here's the bitter part. Washing the reusable mugs with hot water and soap puts them at a disadvantage when it comes to ecosystem-quality indicators. These indicators cover issues such as ecotoxicological emissions, acidification, eutrophication, and land occupation.

Perhaps the most important result for the caffeinated among us was that the number of times a cup is used is paramount. Indeed, only with frequent use can one decrease the potential impacts of the reusable cup; it would take between 20 (human health category for a polypropylene travel mug) and more than 1,000 (ecosystem-quality category for all travel mugs) uses, depending on the cup/mug type and the environmental indicator, to make up for the impacts of a single-use cup. If a reusable cup is used fewer times than that, the single-use cup is better for the environment.

What should we do then? Can we help the environment? The answer is yes: by reusing your cup for several years and by limiting the quantity of soap and hot water for washing it, the reusable cup should be the way to go. Limiting your coffee intake could also be something to look at, but that is another problem altogether.



◂ It would take between 20 and 100 uses for a reusable cup to make up for the greenhouse gas emissions of a single-use cup. For ecosystem quality indicators, it could take more than 1,000 uses.

* A center of expertise in life-cycle issues, recognized internationally for its solid scientific research work and its 15 years of applied experience. The International Reference Centre for the Life Cycle of Products, Processes, and Services (CIRAIG) supports industry, governments, organizations, and consumers in their path toward a truly sustainable development supported by life-cycle thinking.

A climate stress test for financial institutions

By Sarah DeWeerdt

In an expansive study published in *Nature Climate Change*, an international team of researchers performed a "climate stress test" of financial institutions. They wanted to know how much the uncertain, delayed, and sudden implementation of climate policies could lead to destabilizing shocks that propagate throughout the financial sector.

The study is part of a larger debate over whether policies designed to help meet the goal of limiting warming to 2 degrees Celsius globally will be good or bad for the economy as a whole. Some past studies have looked at the risk of economic losses from extreme weather events. Others have estimated the value of "stranded assets," fossil fuel reserves that companies wouldn't be able to develop due to carbon regulations. The new study takes a broader view.

The researchers say fossil fuel providers aren't the only firms whose balance sheets will be affected by greenhouse gas regulations. Instead, they define five broad sectors of the economy where climate policy will have an impact: fossil fuels, electric utilities, transport, energy-intensive manufacturing, and housing.

Using a commercial database, the researchers reviewed information on 14,878 EU and US companies and 65,059 shareholders, and reconstructed the portfolio of each shareholder. They found that, although direct holdings in the fossil fuel sector by any one financial institution are relatively limited (4 to 13 percent of portfolios, depending on investor type), the total investments in all sectors of the economy where climate policy could have an effect are extensive, accounting for 36 percent to 48 percent of portfolios.

Moreover, many financial institutions hold equity in the financial sector itself—roughly 13 percent to 25 percent of investments—exposing them to indirect risk. That is, when one bank's balance sheet deteriorates, other institutions that hold its debt also suffer. This was a primary mechanism leading to the collapse of firms during the 2007–2008 financial crisis.

To determine the impact of this interconnection, the researchers conducted a "stress-test" of the 50 largest European banks, modeling what would happen if part of or all the value of a bank's investments in the fossil fuel and utilities sectors were wiped out.

Overall, the top 20 most-affected banks could lose between 8 percent and 30 percent of their total capital in the worst-case scenario. Some banks would suffer little or no direct loss but would be substantially affected by indirect losses stemming from their investments in other financial institutions.

Although none of the top European banks is likely to default solely due to loans in the fossil fuel and utilities sectors, loans in transport, manufacturing, and housing add up to a much more substantial portion of banks' capital. But the available data do not allow these economic sectors to be evaluated in a comprehensive way.

Even so, the researchers say, the results suggest that if financial firms cannot anticipate policy changes, economic shocks will result when fossil fuel investments abruptly lose value. Early and orderly rollout of policies to control carbon emissions and limit global climate change will facilitate financial gains from investments in renewables and help the financial system transition to a green economy. ⓐ

Battiston S et al. A climate stress-test of the financial system. *Nature Climate Change*. 2017.

Climate change researchers don't hide negative results

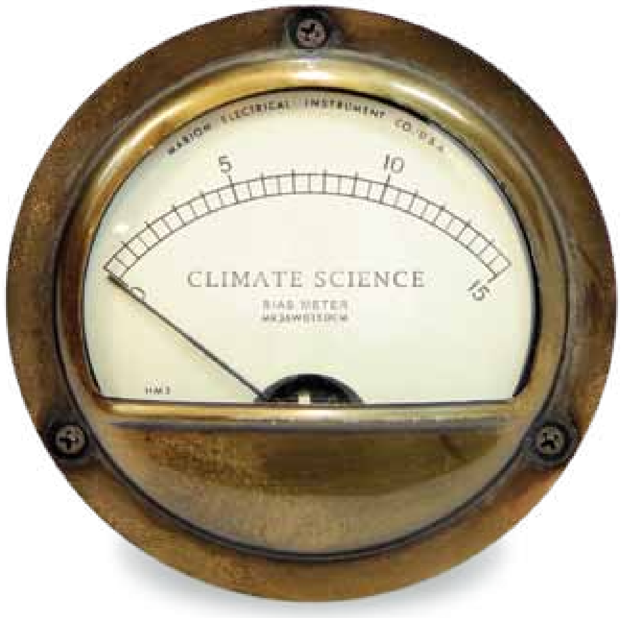
By Sarah DeWeerdt

Researchers don't hide findings that fail to support the prevailing view of human-caused, CO_2-based climate change, according to the first large study to look for so-called publication bias in this branch of the scientific literature. Even so, they may spin results in subtle ways.

Reviews of various scientific disciplines have found that researchers are less likely to report—and journal editors are less likely to publish—studies with negative or nonsignificant results. Two previous studies suggested that the climate change literature does show evidence of this sort of publication bias. But those efforts were small and limited in scope.

In the new study, researchers assessed 1,154 experimental results from 120 studies of the effect

Harlos C, TC Edgell, and J Hollander. No evidence of publication bias in climate change science. *Climatic Change*. 2017.



of climate change on marine organisms. The papers were published in 31 scientific journals between 1997 and 2013.

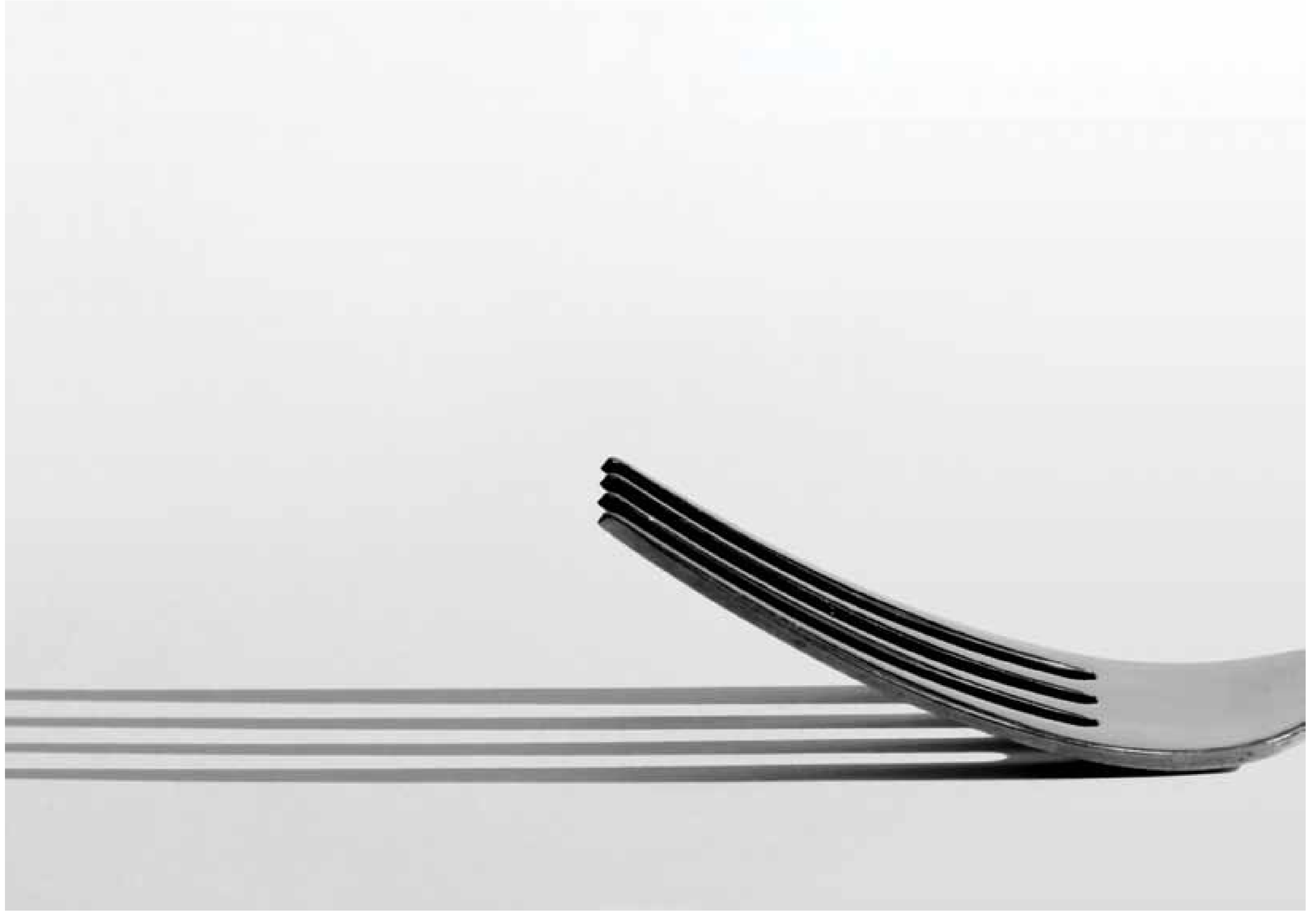
But wait a second. How could the researchers know whether negative results are underreported, if those results might never make it into the scientific literature in the first place? They graphed their data using funnel plots, which take on a characteristic asymmetry when results are skewed. This approach has been used to detect publication bias for at least 30 years. And in this case, the nice, symmetrical funnel plots show no evidence of bias.

However, the researchers did find some evidence of bias—not in *which* results are reported but in *how* they are reported. By analyzing results found in abstracts versus the body of papers, they identified a sort of scientific version of clickbait headlines: abstracts tend to emphasize significant results and the largest effects, while nonsignificant findings and those with a smaller "wow" factor are relegated to the depths of the results section.

In addition, the highest-profile scientific journals tend to publish studies showing the largest effects (and sometimes based on rather small sample sizes). The difference between the results reported in the abstracts and in the bodies of papers is greatest for these top journals.

That could shape the public and scientific debate around climate change. For example, when nontechnical readers look at scientific papers, they may be likely to focus on the abstracts and to look at the most famous journals.

The study isn't designed to identify what's behind these patterns or why scientists and journal editors make these choices. But the results do provide a kind of reality check, an outside view reminding us that "science is a human construct, often driven by human needs to tell a compelling story, to reinforce the positive, and to compete for limited resources," the researchers write.



©Pappaga1

Hitting food-production targets may not be such a stretch

By Emma Bryce

It sounds daunting: By 2050 we'll have to double our food production in order to satisfy the appetite of the planet's rapidly expanding population. In fact, this statistic has become so deeply ingrained that it's being used to shape future agricultural policy. But a group of researchers publishing in the journal *BioScience* has challenged that influential estimate, arguing that it's due for a significant upgrade to bring it in line with recent data.

Their research actually paints a more optimistic picture of the planet's future food needs—while stressing that far more attention should be paid to farming's environmental impact.

Hunter M et al. Agriculture in 2050: Recalibrating targets for sustainable intensification. *BioScience*. 2017.

The oft-repeated "double food production" figure arose a few years ago from some landmark studies carried out by the United Nations and other entities. Their findings relied on both baseline food-production estimates from 2005 and predicted population increase from more than a decade ago. But the new research from Pennsylvania State University, the University of New Hampshire, and Colorado State University used 2014 global food-production data as well as up-to-date global population estimates for 2050 (which were actually higher than those in the original studies). As a proxy for global food demand, they focused on cereals, the planet's most dominant agricultural crop.

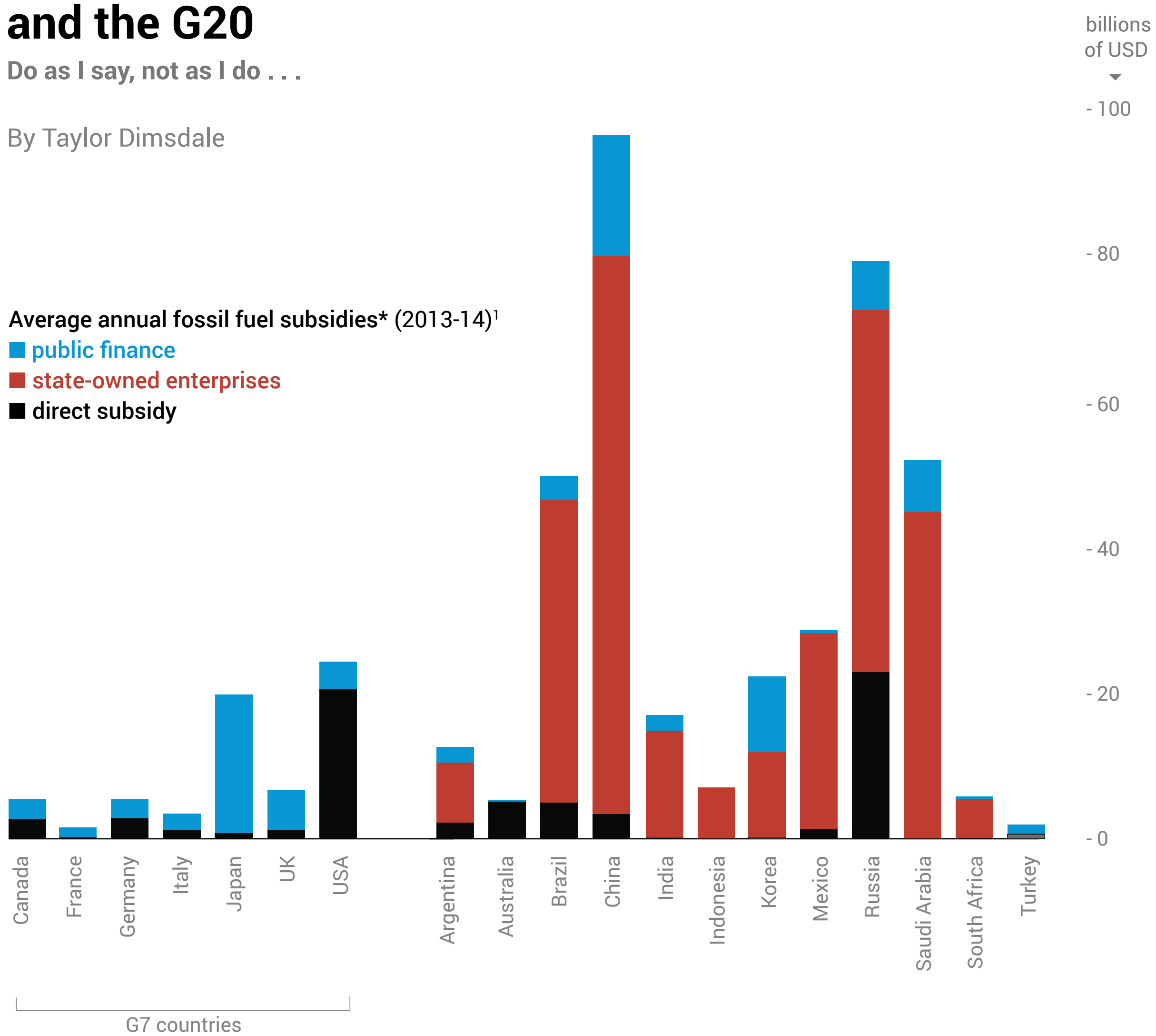
Using these newer data, the researchers found, surprisingly, that a food-production increase of between 25 and 70 percent from current levels (roughly historic rates) would actually be sufficient to meet the world's future food needs. This "recalibrated vision," as they call it, could ease the pressure to use even more fertilizers, pesticides, irrigation, and tillage and to shift some of the focus back to the environment.

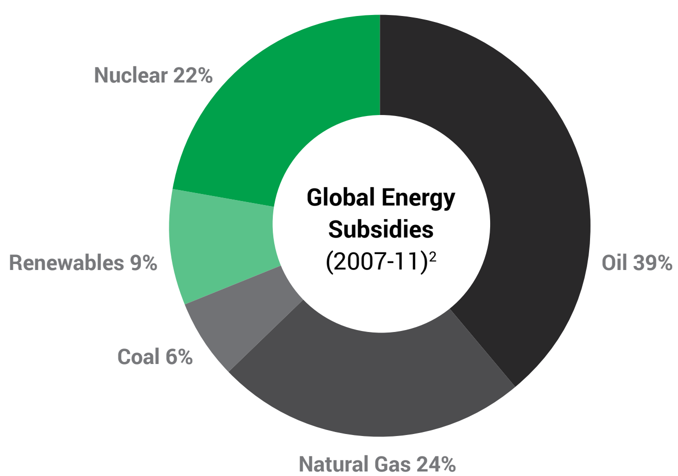
Food production must go hand in hand with specific targets to reduce pollutions, carbon emissions, and other impacts, the researchers say. And that will require more-nuanced studies to figure out the best approaches for different crops in different parts of the world. For now, at least, the new data give us some breathing room to do just that.

Energy subsidies and the G20

Do as I say, not as I do . . .

By Taylor Dimsdale





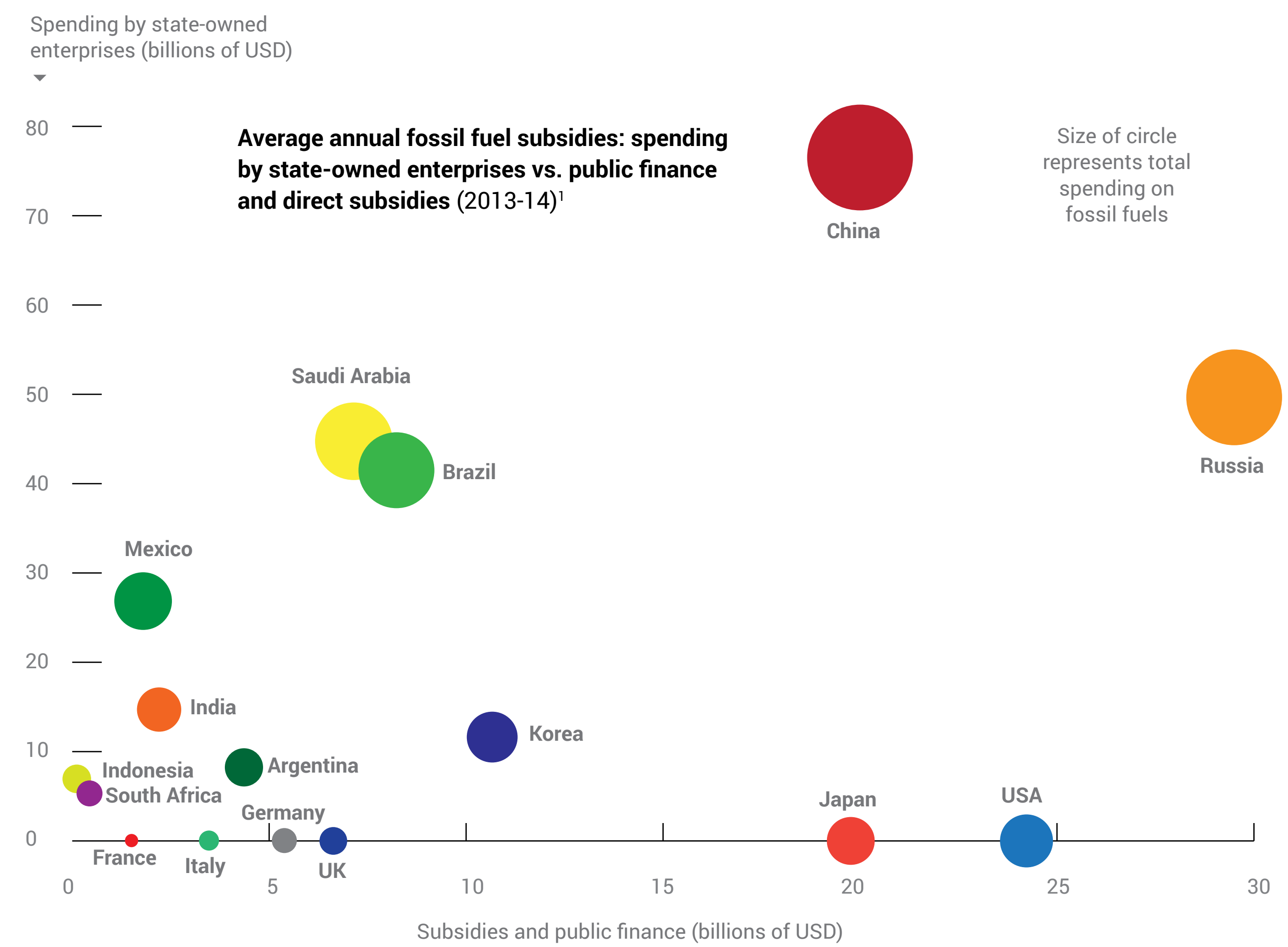
To preserve any chance of keeping the global average temperature well below 2 degrees Celsius, most of the world's coal, oil, and natural gas will need to be left in the ground. A quick look at how the major economies are spending their money, however, shows that government policy has not yet caught up with climate science. The Overseas Development Institute (ODI) and Oil Change International have compiled data showing that the G20 countries are spending over $440 billion annually to support fossil fuel production. (1) Accounting for subsidies is difficult business because countries use different definitions, and accurate data are not always available. To arrive at their own figures, the researchers broke down support for fossil fuels into three categories: direct spending and tax incentives, spending by state-owned enterprises (SOEs), and public finance from development banks or export credit agencies.

The International Energy Agency estimates that the value of fossil fuel subsidies worldwide totaled $493 billion in 2014, up from $390 billion in 2009. Given these trends, it would be easy to forget that in 2009 the G20 agreed to "rationalize and phase out over the medium term inefficient fossil fuel subsidies that encourage wasteful consumption."

While renewable energy has also received public support over the past decade or so through policies such as feed-in tariffs and production tax credits, this is far outweighed by subsidies for oil, gas, and coal.

So how much difference do fossil fuel subsidies make to the climate? According to analysis by the International Institute for Sustainable Development (IISD) and ODI, ending fossil-fuel production subsidies would result in a reduction of GHG emissions by up to 37 Gt by 2050—or roughly 6 percent of the total needed to have a good chance (66 percent) of reaching the 2 degrees Celsius target. (3) Such an approach would mean that 15 percent of all fossil reserves in existing and under-construction oil and gas fields and coal mines in 2015 would be uneconomical to produce.

Progress since the G20 commitment in 2009 has been slow, and the most recent (2016) G20 communiqué failed to make any further commitments on the reform of subsidies or financing for fossil fuels. The G7 took an important step forward last year by urging all countries to eliminate inefficient subsidies by no later than 2025. (4) The G20 will get another chance to make good on its promises when the major economies meet in July in Germany.



* While the researchers made efforts to avoid double counting, it is possible that some government support through national subsidies may also be accounted for in the SOE investment and public finance calculations.

Taylor Dimsdale is head of research at Third Generation Environmentalism (E3G)

Note: The graphs presented here were produced by the author using data from the Overseas Development Institute and Oil Change International. The graphs do not appear in the original report. **1.** Bast E et al. Empty promises: G20 subsidies to oil, gas and coal production. ODI and Oil Change International. 2015. **2.** Koplow D. Global energy subsidies: Scale, opportunity costs, and barriers to reform. Chapter 15 in Halff A, Sovacool BK, and Rozhon J, eds. *Energy Poverty: Global Challenges and Local Solutions.* Oxford University Press. 2014. **3.** Gerasimchuk I et al. Zombie Energy: Climate benefits of ending subsidies to fossil fuel production. IISD, Global Subsidies Initiative, & ODI. 2017. **4.** G7 Ise-Shima Leaders' Declaration. 2016.

©Dan Poole

Is kindness the solution to conflicts with wild dogs?

By Brandon Keim

Killing wild dogs to prevent conflict with humans actually makes matters worse, suggest researchers who analyzed dingo control programs on Australia's Fraser Island. And the lessons learned there, they say, may apply to other species and places, from wolves in Alberta's wilderness to coyotes in suburban California.

On Fraser Island, wildlife authorities have tried to strike a balance between protecting dingoes and keeping their population from growing too large—the idea being that more dingoes means more opportunities for conflict with people. Regular culls of animals considered dangerous began in 1991 and have continued ever since. Tensions boiled over in 2001 when two dingoes attacked and killed a nine-year-old boy. An estimated 120 of the wild dogs now live on the island, with the annual number of dogs killed fluctuating between several and several dozen.

Plot that number against reported incidents of dingo aggression, however, and the killing doesn't seem to have done much good. There are more such incidents now than when the program started. Usually that's blamed on human expansion into once-wild terrain or on dingoes becoming habituated to humans and thus aggressive. But that, say the researchers, isn't necessarily the case.

The alternate explanation: that killing these highly social, intelligent, and emotional creatures leaves individuals traumatized and packs destabilized. Established territories break down; survivors fight for control. Though the total population isn't threatened, the character of its individuals is changed. Aggression might be less about habituation than the psychology of stressed and suffering individuals.

Indeed, surges in dingo-human conflict have tended to follow especially intense episodes of lethal control, says Adam O'Neill, an ecologist with the Dingo for Biodiversity Project and lead author of the study, which was published in *Pacific Conservation Biology*.

"We are not the only social creatures on the planet," he says "but we are alone with the power over all. It's up to us to inspire civility among our fellow species."

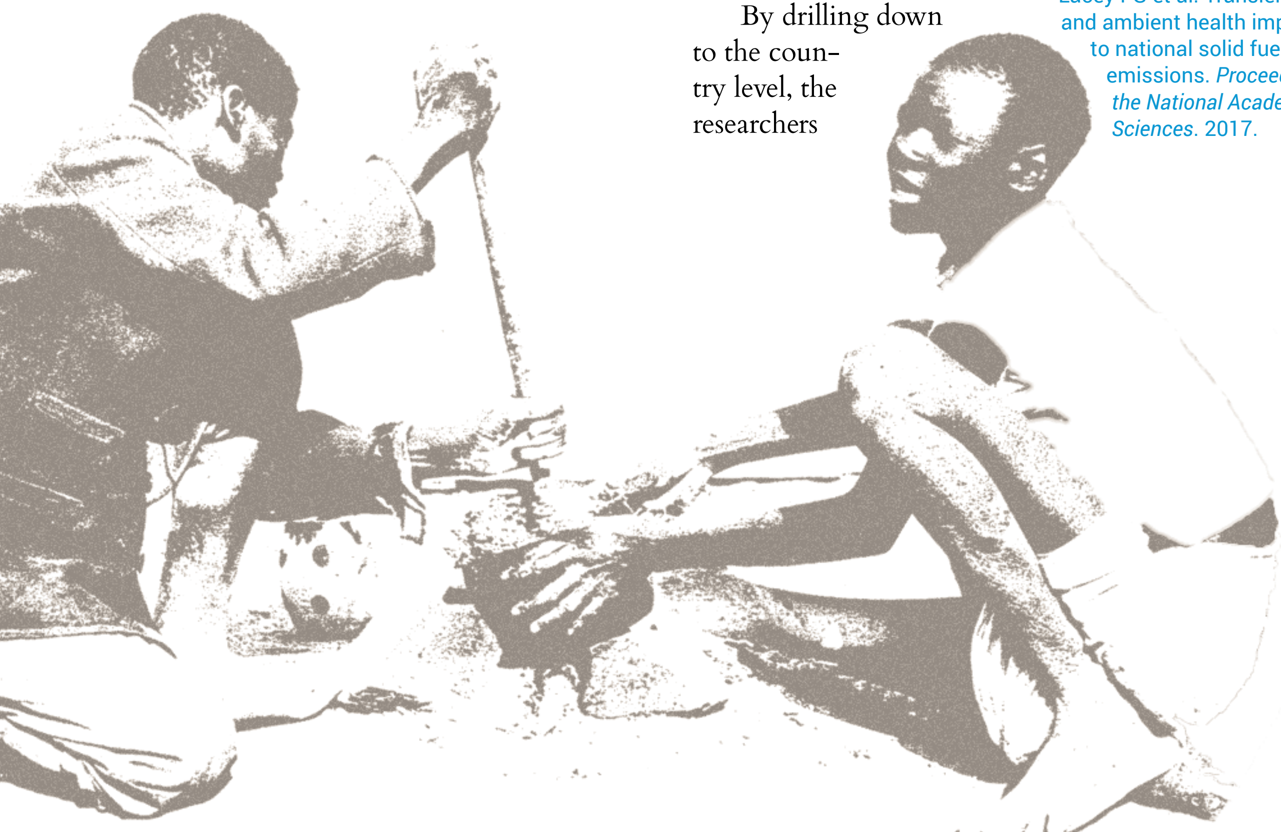
O'Neill A et al. Managing dingoes on Fraser Island: Culling, conflict, and an alternative. *Pacific Conservation Biology*. 2016.

It's not just what we cook, but how we cook that is overheating the planet

By Emma Bryce

There are now 7 billion people on Earth. Every day, nearly half of them prepare their meals over an open flame or on a traditional cookstove, using wood, charcoal, coal, animal dung, and other solid fuels. Collectively, all that cooking produces as much as 2.3 percent of global CO_2 emissions, methane, and an estimated 25 percent of global black carbon emissions. Black carbon, otherwise known as soot, along with other aerosols, causes 4.3 million premature deaths every year due to lung cancer, heart disease, and other ailments.

Such stark realities prompted a team of researchers from the University of Colorado in the US and Dalhousie University in Canada to try out some sophisticated kitchen math.



When they modeled the outcome of a hypothetical 20-year cookstove eradication program in 101 countries, they landed on some striking numbers. First, they found that by 2050, global temperatures would decrease by 0.08 degrees Celsius. That drop occurred primarily because the short-term impacts of aerosols such as black carbon will have played out. By 2100, they saw temperatures decreasing by as much as 0.12 degrees Celsius in a world without solid fuel cookstoves. Considering the Paris Agreement's 2-degrees Celsius warming limit for the globe, that's significant. What's more, researchers estimate that the decrease would also eliminate over 10 million premature deaths by 2050.

By drilling down to the country level, the researchers also saw some salient regional differences. India and China were found to be the biggest cookstove emitters, contributing the most to temperature change. But the amount of emissions didn't always correspond to impact: Azerbaijan and Ukraine, for example, have fewer cookstoves but a large impact on temperature. That's because regional weather patterns in these countries transport emitted soot over Arctic snow—which counteracts its reflective cooling effect.

Eastern Europe and Central Asia aren't places where cookstove interventions are commonplace. But in a more nuanced and strategic approach to tackling climate change from the kitchen, perhaps they should be.

Lacey FG et al. Transient climate and ambient health impacts due to national solid fuel cookstove emissions. *Proceedings of the National Academy of Sciences*. 2017.

Looking for the next miracle drug in city dirt

By Sarah DeWeerdt

Bioprospecting—the search for drugs and other useful molecules produced by living things—often conjures up images of explorers in pith helmets traveling to far-flung locales in search of a miracle cure. But Sean Brady, a microbiologist and biochemist at Rockefeller University, has broken new ground. He started digging—quite literally in the dirt beneath his feet.

Many drugs are based on molecules produced by bacteria. It turns out that soil bacteria in New York City parks produce molecules similar to those in existing antibiotic, antifungal, and antiparasitic medications—and even in anticancer drugs.

Brady and his team extracted DNA from 275 soil samples gathered from parks in all five boroughs of New York City, then used cutting-edge software to pull out potentially interesting genetic sequences from the massively diverse microbial mix. This approach gave them access to the molecules without having to grow soil microbes in the laboratory—which is difficult or impossible in the case of many species.

Charlop-Powers Z et al. Urban park soil microbiomes are a rich reservoir of natural product biosynthetic diversity. *Proceedings of the National Academy of Sciences*. 2016.

Some of the sequences from the New York City soil bacteria encode molecules similar to those in drugs already on the market, hinting that these microbes could be sources of new drugs in existing classes.

But the city park bacteria also contain many DNA sequences that don't match any known ones. Could some of these sequences give rise to totally new classes of antibiotic, anticancer, or other kinds of drugs? Or could they have uses we haven't even dreamed of yet?

The bacterial genetic sequences present in soils vary from park to park. And the urban samples, though distinct from nonurban samples, harbor just as much microbial genetic diversity. The researchers found one sample from Brooklyn's Prospect Park that contained genes encoding more than two dozen molecules previously flagged as potential antibiotics or other medicines. All this suggests that in-depth analysis of city soils could be just as promising as bioprospecting in remote areas.

The work is part of an ongoing citizen science project, Drugs from Dirt, which aims to survey molecules produced by soil bacteria in all 50 US states. So far, Brady's team has collected or received soil from more than 15 states and hopes to receive samples from school groups, naturalists, and other members of the public to fill in the remainder of the map.

Drones deliver less carbon pollution

By Prachi Patel

Online shopping is booming, and unmanned aerial vehicles (aka drones) are expected to take to the skies *en masse* within the next few years to deliver packages. Incorporating drones into the delivery system could be a good thing for the climate, a new study finds.

Engineers at the University of Washington looked at how to best reduce carbon emissions from package delivery in the Los Angeles region. They modeled scenarios in which trucks and drones delivered a range of products to 50–500 recipients.

They assumed that trucks ran on diesel fuel and that drones recharged with fossil fuel–powered electricity. The model also assumed that the aircraft could carry only one parcel at a time and that associated emissions from drones increased with package weight.

The results showed that trucks are better for the climate over longer, multi-stop delivery routes and that drone emissions are fewer when delivering light packages over small distances.

To minimize emissions, the researchers say, a truck would haul packages to a central location from which drones take the packages to homes and businesses. Such last-mile delivery would be especially effective in rural areas, where trucks would not need to venture off main roads.

Goodchild A and J Toy. Delivery by drone: An evaluation of unmanned aerial vehicle technology in reducing CO_2 emissions in the delivery service industry. *Transportation Research Part D: Transport and Environment*. 2017.

GLOBAL RESEARCH PROJECTS

Discover important insights about the planet's atmosphere, oceans, land, and the histories of its climate and peoples. More than 20 worldwide networks of natural and social scientists, which formed under previous international research programs, are now part of Future Earth.

KNOWLEDGE ACTION NETWORKS

Explore our new and innovative research collaborations that are putting the best minds in academia, policy, non-governmental organizations, business, the arts, and more to work on critical issues in global sustainability—from cities to health and finance and economics.

MEDIA LAB

Rethink your place in the world by exploring this incubator for projects at the forefront of visualization, big data, the Internet of Things, virtual reality, artificial intelligence, and beyond. A collaboration with the International Council for Science and Globaïa.

OPEN NETWORK

Join this new online platform to work with professionals and organizations around the world committed to global sustainability. Collaborate on projects, meet new peers, follow international events, and learn about new opportunities and resources.

futureearth.org | network.futureearth.org

How We Pay The Bills

Anthropocene is reader-supported journalism. That means that a significant portion of our operating costs comes from people like you—that is, people who believe that it is time to start talking about sustainability solutions, not just problems. Supporting memberships come with exclusive benefits including high-end print editions (like the one you are holding in your hands), conversations with authors, and networking opportunities.

We also offer sponsorships whereby organizations and businesses can support independent reporting within an editorial beat, such as climate, health, biodiversity, and cities.

For more information:

anthropocenemagazine.org/membership

anthropocenemagazine.org/sponsor

FPO

FPO FPO

FPO FPO

FPO FPO FPO

Innovation in the Human Age

Anthropocene

Editor-in-Chief, Art Director
Kathryn Kohm

Senior Editor, Design Assistant
Lindsey Doermann

Executive Editor
Joshua Tewksbury

Copy Editor
Roberta Scholz

Contributing Editor
Kathleen Snow

Advisory Group
David Biello
Frances Cairncross
James Fahn
Owen Gaffney
Andrew C. Revkin
Denise Young

Editorial Office:

Anthropocene magazine/Future Earth
Sustainability Innovation Lab at Colorado (SILC)
University of Colorado Boulder 608 UCB
Boulder, CO 80309 USA

email: kathy.kohm@futureearth.org

Anthropocene receives support from:

MacArthur Foundation

NSF

Partners:

Sustainability Innovation Lab at Colorado, University of Colorado, Boulder

School of Global Environmental Sustainability, Colorado State University

Earth Journalism Network, a project of Internews

LIGHTEN UP

We know what we are,
but know not what we may be.

—William Shakespeare