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

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

BY **VACLAV SMIL**

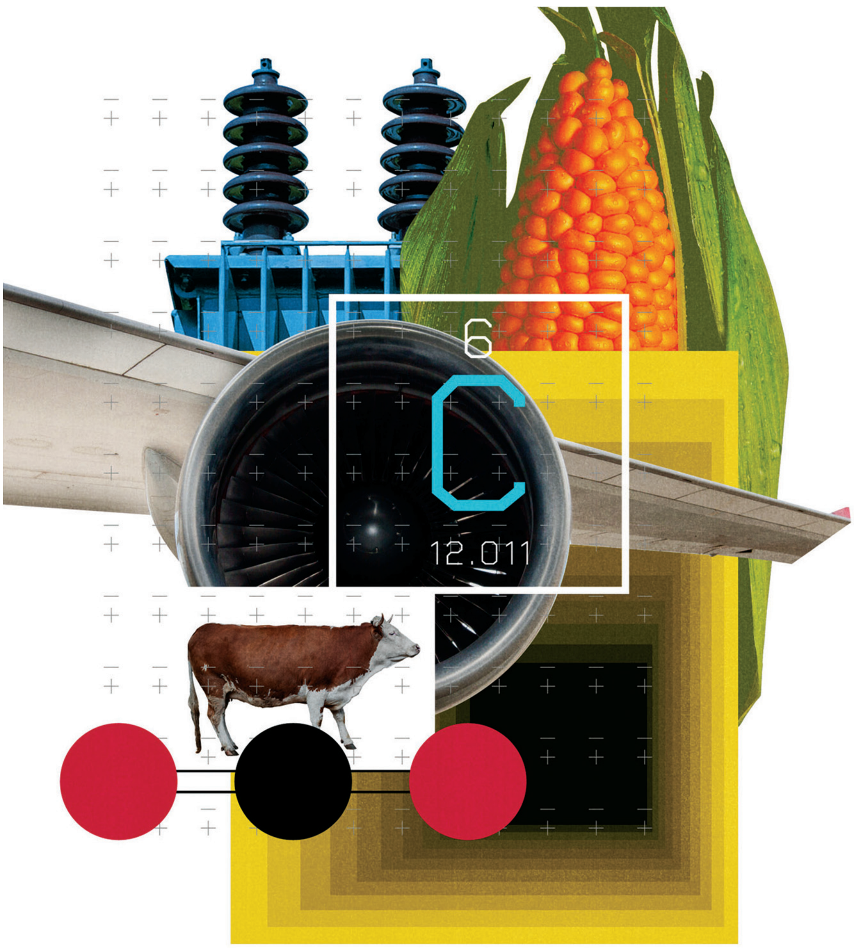
WHEN A BRIGHT NEW idea comes along, it's easy to imagine a fantastic future for it. Perhaps the best example of this is Ray Kurzweil's Singularity, scheduled to arrive in 2045, which will supposedly bring "immortal software-based humans, and ultra-high levels of intelligence that expand outward in the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

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

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

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

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



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

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

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

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

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

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

PHOTO-ILLUSTRATION BY Stuart Bradford

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

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

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

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

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

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

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

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

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

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