able year-round, and it is much denser than light grasses, making it easier to move around.)

Though thermochemical systems have the advantage of being able to handle a range of feedstocks without having to remix the enzymes and organisms for each, the biocentric companies remain unconvinced. “It takes billions to build a Fischer-Tropsch plant,” says Jack Newman of Amyris. “You have to amortize those costs over the amount of energy the plant will ultimately make, which turns out to be too expensive. You’re in effect simulating the forces that made biomass into petroleum in the first place, that intense pressure and heat. But the original forces were tectonic: the weight of mountains plus the core heat of earth. We can just retrofit an ethanol plant, which costs orders of magnitude less.”

John Howe of Verenium concedes that “the approach we’re taking is costlier right now, no doubt, but there’s a lot more room for improvement given that F-T [Fischer-Tropsch] is pretty mature while industrial biotech is still in its early stages of development.” He also believes that fuels made with enzymes will ultimately have a much better net energy-and-carbon balance. By definition, enzymes lower the energy required for a chemical reaction to take place. That’s their function in organisms, and “that’s their magic,” says Howe, “in making biofuels.”

There may be biofuels magic of a very different sort in a process far removed from Verenium’s experiments with enzymes. To see one of the most unlikely, and potentially most transformative, biomass-to-fuel experiments, you could visit Phoenix, Arizona. The trip itself provides a quick review of the current strategies for producing energy, and of the mark they leave on the land. Flying in from the north, over the Four Corners region where Utah, Arizona, Colorado, and New Mexico meet, you look
down on mile after mile of broad desert mesas, each one’s top scraped flat and bare and all linked together by a web of rutted and barren roads. It might take a minute to understand what you are seeing: coal-bed methane rigs atop each denuded mesa, furiously pumping up the natural gas that will soon be burned to make electricity. The seemingly endless sprawl of Phoenix, lights blazing, air-conditioners churning, provides a further review—of where that electricity goes.

But the most surreal part of the journey begins thirty miles west of the city, where brand-new housing developments and emerald-green golf courses give way to saguaro cactus and dusty mesquite. Here, in this desiccated landscape, is one of the greatest electricity-generating hubs in the world. First to rise up on the horizon is the nation's second-biggest power plant, the Palo Verde nuclear facility, each of its three 1,270-megawatt reactors marked by a hulking cooling tower. A bit farther on, Duke Energy’s 500-megawatt natural gas plant emerges, then Sempra Energy’s 1,250-megawatt plant and another 1,000-megawatt facility operated by the town of Gila Bend. Altogether, more than 9,000 megawatts of electricity is generated in this bleak reach of the Sonoran Desert. Overhead, massive towers strung with 500-kilovolt lines carry a big chunk of that electricity straight to Southern California.

At first glance, the four smokestacks of the Redhawk power plant, the 1,000-megawatt natural gas–fired facility run by Arizona Public Service (APS), seem indistinguishable from the rest. Except that there is a big greenhouse at their feet, and a pipe running from the top of one smokestack into that greenhouse. Rather than venting the carbon dioxide–rich stack gases into the atmosphere, the power plant feeds those gases to a growing family of well-loved creatures. They could be tulips: at the Shell Pernis Refinery outside Rotterdam, engineers use waste carbon dioxide as fertilizer for flower farms, which “adds new meaning,” as the Guardian quipped, “to the term ‘greenhouse gas.’”*

Here, at Redhawk, a far less lovely crop is grown: algae. Beyond a few manufacturers of cosmetics and nutritional supplements, who value them for their high levels of beta-carotene and omega oils, few recognize algae as an object of desire worthy of such hothouse care. Even at Redhawk, facility engineers invest enormous time and ingenuity killing the hundreds of species of algae that invade the cooling towers; because they adapt so quickly, the engineers must regularly cook up a new toxic brew.

Under the right circumstances, however, these microscopic single-cell creatures turn out to be a dream feedstock for making liquid fuels. They are the fastest-growing plants on earth—doubling their mass in a few hours’ time. They are the most adaptable, thriving not only in cooling towers but also in sewage, boiling water, ice, Antarctica, and the Dead Sea. They are the richest in high-energy oils ideal for making biodiesel—producing thirty times more vegetable oil per acre than sunflowers or rapeseed—and are rich in carbohydrates that can become ethanol and proteins for animal feed. They filter many air pollutants, neutralizing acids and splitting nitrogen oxides—precursors to smog—into harmless nitrogen and oxygen. Most important, they are the world’s most efficient converters of carbon dioxide to oxygen and biomass. Algae have few higher-order functions: They don’t need to leaf, flower, produce seeds, or bear fruit. All they do is consume carbon dioxide and divide. “It is photosynthetic life reduced to its essence,” says Ray Hobbs, who runs APS’s Future Fuels program.

It was their appetite for carbon dioxide that first caught the attention of Isaac Berzin, the chemical engineer who cofounded

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* Guardian, August 12, 2006.
GreenFuel Technologies and began this experiment at APS. A graduate of Ben Gurion University in southern Israel, Berzin was working on a postdoctoral degree at MIT in the lab of Professor Robert S. Langer, a biomedical engineer with more than five hundred patents who was presented the National Medal of Science in 2007. As part of work the lab was doing for the International Space Station, Berzin was growing algae inside a small bioreactor and began thinking about new uses for algae on earth.

While working on his terrestrial system, Berzin was visited in his basement laboratory by a friend, who brought along a friend of his own—a Russian immigrant named Leonard Blavatnik. Then number eighty-seven on Forbes magazine’s list of the four hundred richest people (by 2007 he had moved up to the forty-fifth place and was worth $7.2 billion), Blavatnik had made his first fortune acquiring stakes in newly privatized Russian companies, including the Tyumen Oil Company, which he later merged with British Petroleum into Russia’s second-largest oil company. After seeing what Berzin was doing, Blavatnik offered to write a check on the spot for $100,000. “I’m sorry I can’t take your money,” Berzin said. “I need at least a million to get this thing from the basement to the roof.” “Well,” said Blavatnik, “that will take a little longer.” After completing due diligence, he returned to Berzin. “Isaac, you asked for $1 million but after looking at all you have to do, I think you’d better take $2 million.” So GreenFuel was born. Blavatnik’s Access Industries has continued to support the company, along with other venture investors.

Berzin has an unusually affectionate relationship with his algae. “They’re not pond scum. They’re the sweetest creatures,” he told a reporter at National Public Radio in January 2006. He keeps a video of the microscopic creatures on his laptop. “Belly dancing around, they have a little mustache. They touch each other with the mustaches. . . . My kids ask me, ‘Oh Daddy, it’s so cute. It’s like pets. So, what do you do with them in the end?’ I say, ‘Uh-oh . . . I burn them.’”

In 2004 GreenFuel was ready for its first real-world test of the algae’s ability to eat stack gases. On the roof of MIT’s 20-megawatt cogeneration plant, Berzin filled 30 nine-foot-high triangles of clear pipe with a kind of algae soup. The experiment proved a great success: Bubbling the plant’s flue gases through the mixture removed 82 percent of the carbon dioxide on sunny days and 50 percent when clouds were overhead (photosynthesis, like solar cells, works only when the sun is shining). Night and day, it cut nitrogen oxide emissions by 85 percent. So GreenFuel took the next jump: in 2005 it built its Emissions-to-Biofuel (E2B) algae bioreactor at APS’s Redhawk plant.

The first challenge was to find the right algae; most of GreenFuel’s patents, in fact, are for species selection and adaptation. “We look all over the world for nature’s finest,” says Cary Bullock, GreenFuel’s vice president for business development. To protect local ecosystems, the company relies on indigenous varieties or saltwater species (if marine algae were to escape into freshwater, the osmotic pressure would crush them to death, preventing any damage from the alien invasion). They then adapt the algae by gradually shifting their living conditions—the water supply, the chemical makeup of the gas—to match those the algae will encounter inside the farm. The goal is to have algae that reproduce so prolifically—the “local hero,” APS’s Ray Hobbs calls it—that they crowd out any zooplankton or other algae that might try to move in. A few rival companies are working to genetically engineer a race of superalgae, bigger and fatter and even quicker to reproduce, but Hobbs thinks that is a bad idea. “They want big fat guys they can fish out with a net. But given the dangers of unleashing a GMO [genetically modified organism] that adaptable and prolific, they’ll delay themselves fifteen years getting through the regulatory process.
And with twenty thousand species to choose from, why would you need to engineer a new one?"

Arizona, GreenFuel discovered, is great for algae, not least because of the nitrates polluting the Phoenix wastewater, which is used both in the greenhouse and to cool the power plant. For ecosystems, the nitrates are a problem, causing algal blooms that deplete oxygen and create vast dead zones in estuaries and bays. But the same nitrates are great for bioreactors, where an algal bloom is precisely what is desired. Hobbs also wanted to use the nitrogen in the stack gases as fertilizer, skipping the costly pollution-control technology used to remove the nitrogen oxides and instead running the pipe directly to the algae, but regulators wouldn't allow it. "We see algae as agriculture; they see it as power-plant operations. So we had to spend research money on duct work and cranes, and then buy and add nitrogen fertilizers."

The next challenge, which nearly sank the company in 2007 and could still bring it down, is how to configure the bioreactor to allow the algae to get just the right amount of light. Too little is fatal, so either algae on the bottom must be stirred to the top or light must be brought inside the growing thicket. Lots of experiments have gone awry. In Japan, already a commercial producer of algae for supplements, researchers tried lacing fiber-optic cables throughout the tanks to bring light into the depths. The experiment failed: the algae piled onto the tips of the cables and blocked all the light.

Too much light also spells the algae's doom. On a typical 100°F August morning, the sunlight is as intense here as anywhere on the planet. "This much light can burn them to death," says Hobbs. "Algae need rest, like all of us. It has to take in the photon and then rest."

For GreenFuel's first pilot, from August 2005 through November 2006, Berzin solved the problem of "photomodulation" by building giant test tubes lined up in a rack; at the base of each, a spigot could be opened every couple of days to harvest a fraction of the slurry. So how did they mix things up and keep algae from growing on the surface and blocking all the light? "Yeah," says Hobbs, "how about that?" (He can't say more, he says, without revealing protected intellectual property.)

He can say even less about the most recent experiment, called "the 3D matrix system," except to describe its goal: to achieve the highest possible growth per square meter. Outside the greenhouse, the racks still stand where the "seeding culture" was started inside hanging plastic tubes, like giant baggies, which filled with a dark green slime. The algae were then moved inside the secret recesses of the greenhouse itself.

The potential yields from algae dwarf those of any other biofuel crop. Some seventeen hundred U.S. power plants, GreenFuel estimates, have enough land (most of which nobody else wants) for both algae greenhouses and on-site refineries, plus enough waste heat to power both. Unlike soybeans and corn, which can be harvested just once or twice a year, algae multiply so fast they can be harvested daily ("like milking a cow," Berzin says). While an acre of soybeans yields about 60 gallons of biofuels and oil palms about 600 gallons, an acre of algae could yield 5,000 gallons of biodiesel and ethanol a year. At present, only 20 percent of U.S. petroleum consumption is in the form of diesel. But if half of all U.S. cars ran on diesel, as they do in Europe, replacing all of it with soy diesel would require 1.5 billion acres of fertile land, three times the total cropland in the country. Algae could do it in 47 million acres, on land not suited for agriculture. And though they require huge amounts of water, they can tolerate wastewater—and clean power plant emissions along the way.

The potential scale of that carbon cleanup is also immense. In their first configuration, says Hobbs, the algae at Redhawk absorbed 150 tons of carbon dioxide per acre per year. In the newest version,
says Berzin, the algae are adding 100 grams of weight per square meter per day, which means they are absorbing 200 grams of carbon dioxide; at scale, that would take up about a ton of carbon per acre per day. At that rate, says Hobbs, algae grown on 1,000 acres of land available at Redhawk would absorb half the carbon dioxide the plant emitted in 2005 and then could be converted to fuel (a coal-fired plant of similar size would require nearly 2,000 acres—a lot of real estate in some regions of the country). If GreenFuel can get to a competitive price for those fuels, he adds, algae farmers will want as much carbon dioxide as they can get their hands on. Hobbs gestures at the landscape around him: empty except for roads and the seemingly endless colony of power plants. “Two thousand- or ten thousand-acre greenhouses; they don’t really intimidate me.”

When the fuel is burned, the carbon will be released to the atmosphere, but its energy will have been harvested twice, and it will have displaced an equivalent amount of fossil fuels.

“Carbon dioxide is a big risk hanging over the head of utilities,” says Berzin. “After Al Gore, they feel like everyone sees them as villains. But they need to provide more electricity, because we all keep adding demand. So what do they build? If they build coal, in five years when they have to pay to clean up their carbon they’ll look like idiots. If they build natural gas, which is expensive, they’ll look like idiots now. But what if they clean up their carbon dioxide, and for every ton of carbon dioxide they get half a ton of algae worth $300 in biofuels? Well, now they’re American heroes. If they clean up 20 percent of the carbon dioxide effluent from every power plant in the country, they’ll create enough fuel to replace 20 percent of imported oil.”

In mid-2007 everything was going swimmingly. GreenFuel had run successful field tests on a small exhaust gas stream from NRG’s Big Cajun II 1,500-megawatt coal-fired plant in Louisiana and the Sunflower coal plant in Kansas. (The algae “really voted for Kansas,” says Berzin. “And the land: you want 1,000 acres? 10,000 acres? No problem.”) In Arizona GreenFuel was setting world records for algae productivity, a fact confirmed in an independent 2007 report by Otto Pulz, president of the European Society of Microalgal Biotechnology. At all three plants the company had successfully produced transportation-grade fuels, and Hobbs was running several APS vehicles on algae diesel.

And then disaster. First came the news that a South African company that had purchased the bioreactor from the MIT roof, claiming it was launching an algae biofuels company and would soon be buying more GreenFuel technology, had in fact used that pilot reactor to con investors to sink money into a company that didn’t exist. By the time GreenFuel realized it was never going to get paid, and that its name had been damaged, the fake South African company was facing charges of police bribery and involvement in a carjacking syndicate.

Worse, at Redhawk, the algae had begun growing faster than they could be harvested, choking off light and nutrients and causing them to die. In July 2007 the company’s lead investor, Robert Metcalfe of Polaris Venture Partners, stepped in as CEO, shut down the greenhouse, and laid off half the staff. “Harvest was just one of the issues,” says Hobbs. “The underlying problem was that this little start-up was growing really fast and had a communications breakdown between the scientists and the guys on the ground.” Jennifer Fonstad, from Draper Fisher Jurvetson, another backer, became chairman of the board; Berzin remained chief technology officer. Metcalfe, who in the 1970s invented the Ethernet for local-area networking and cofounded the billion-dollar networking company 3Com, called the breakdown a “success failure” typical of efforts to commercialize emerging technologies. To keep the company going, he raised more funding. “I keep asking the trillion-dollar question that led to the founding of GreenFuel,” he
explained, “Why expensively sequester carbon dioxide when it could be profitably recycled?”

Perhaps more than any other cutting-edge green technology, algae arouses intense passions, including intense skepticism; several of the Web sites that track clean technology had great fun with the GreenFuel setback and claimed vindication of their doubts. Maligned it to the collapse a decade ago of the U.S. government Aquatic Species Program, which beginning in 1978 had conduct algae research for nearly twenty years. Using open ponds rather than closed bioreactors (a strategy now being pursued by several GreenFuel rivals), the federal algae farmers had been overrun by wild species that outcompeted their obese, domesticated cousins.

In 1996 the Department of Energy concluded that algae fuels were too expensive to produce at large scale and shut down the program. (Late in 2007, with oil prices topping $90 a barrel, the National Renewable Energy Laboratory announced that the government had changed its mind and would resume research into algae.)

Berzin believes the Energy Department made a fatal mistake by not taking its research to a power plant to make use of wastewat flue gases, and the waste heat available for drying and refining the algae. “They never had that complement, were never exposed to that potential for integration,” he says. Ray Hobbs is more sarcastic. “Oh well, I guess if the government can’t do it, then nobody can.”

Hobbs also does not acknowledge defeat. “GreenFuel jumped in scale too fast, to a thousand-square-meter greenhouse, and we caught unprepared. But when Isaac [Berzin] regrouped and recast it to a hundred square meters, it worked like a charm. When you learn why something doesn’t work and you fix it, that’s a successful experiment, not a failed one. It’s like Edison. After 999 filaments he found the one that worked. And he also found all the ones that don’t work. If you succeed the first time, you won’t really understand why!”

The venture capitalists who are backing GreenFuel have given the company one more chance to prove the technology, imposing a discipline Berzin finds bracing. “They don’t care whether something is intellectually interesting,” he explains. “They want to know if it works. If you’re an academic, you’re like a medical doctor. If you make a mistake, your patient dies. But if you’re a start-up, you’re like the pilot of a small plane. If you make a mistake, you die.”

Even if GreenFuel crashes, Hobbs is prepared to pick up the wreckage. “If GreenFuel in its current form folds because the VCs [venture capitalists] lose patience, I just see us regrouping. The company might go under, but not the idea. APS is 120 years old. If we have to go this alone, with the utility capability, we will. Their interest is the profits to be made by making fuel and competing with oil; our interest is in a better way to capture carbon.” That level of commitment, says Berzin, has made all the difference. “There were many Issacs before, but there was never a Ray before. APS was the first commercial energy company to open these doors.”

By late 2007, GreenFuel had begun deployment of a sixth system Berzin calls a “horizontal thin film,” which uses more land but promises to cut capital costs enough to beat oil at $60 a barrel. He is also working on cheaper ways to separate the algae from the water and extract the oils to be made into fuel. He has partnerships with leaders in global “algaculture,” including an Israeli company that was among the first to use flue gases, but all those partners grow high-value algae that sells for $5,000 a ton or more. For fuel, Berzin needs to cut that price by an order of magnitude. That means he cannot afford to pressurize the carbon dioxide to bubble it through the algae, or to use a centrifuge to separate the algae from the water. But “after $26 million and six years of growing gray hairs,” he says, he has invented most of the operational units he requires, albeit quietly. “If you’re a scientist who makes a breakthrough you want to run naked through the streets shouting. If you’re in business, you keep your mouth shut and run to your patent lawyer instead.”
Hobbs sees the extraction problem as relatively trivial. "You add a little methanol and a catalyst, you get glycerins and methylesters. You hydrogenate the methylesters, you get diesel fuel. We'll partner with GE Water or 3M Filtration Systems. We're not three guys in a lab. We're going to do this like we do things. Then we'll ship the leftovers to shrimp farms for feed, or ethanol plants. Both have already come knocking."

The multiple iterations, explains Berzin, are not a matter of discarding old experiments for new, but rather the development of a portfolio of options to address differing circumstances. In Europe, where land is expensive, power plants could use the more expensive "matrix" to maximize productivity per acre. Where land is abundant and cheap, as at most U.S. power plants, they could use the thin-film technology to maximize returns.

GreenFuel will now tackle one of the largest sources of global warming pollution in the West: the Four Corners Power Plant west of Farmington, New Mexico, owned by APS and five other utilities. On a return flight from the moon, Apollo astronauts reported seeing two human structures from space—the Great Wall of China and the plume from this 2,000-megawatt coal-burning plant. The Environmental Integrity Project ranks it the very worst among power plants for total nitrogen oxide emissions and eighteenth for carbon dioxide emissions. Before feeding the flue gases to the algae, GreenFuel may also need to do extra scrubbing of sulfur dioxide, which acidifies in water and might corrode the duct work, and to select algae that do not absorb heavy metals like mercury. "Algae enjoy a nice coal flue gas," says Hobbs. "It has lots of nutrition, and they have an amazing capacity to handle contamination. But it might be too much, and we don't want the dangerous stuff."

The Four Corners algae project is a partnership among seven utilities in four states: APS, El Paso, the Los Angeles Department of Water and Power, Southern California Edison, Tucson Electric, Salt River, and Public Service of New Mexico. The land is being leased from the Navajo, who have a hundred thousand acres under irrigation but have not yet found the ideal crop to grow. The carbon cap in California, which extends to out-of-state power suppliers, has pushed the project forward, says Hobbs. Arizona itself is part of the Western Climate Initiative, along with California, New Mexico, Oregon, Utah, Washington, and the Canadian provinces of British Columbia and Manitoba; all have agreed to cut carbon emissions across the region 15 percent below 2005 levels by 2020.

The effort to make fuels from algae fed on stack gases is not Hobbs's first foray into alternative transportation. Almost twenty years ago, working as an engineer on APS power plants, he persuaded his boss to let him build an electric race car. His team converted a Honda, and when in 1991 it won the inaugural Solar and Electric 500 at the Phoenix International Raceway, it made the foldout in Popular Science. "That set a fire in Detroit. The car companies were bitterly resistant. They feared that GE or Siemens would move in on them with their huge financial muscle. They didn't want to have to remake their manufacturing lines and retrain their dealers. And mostly they didn't like getting told what to do."

"GM was especially hostile toward us. But everyone told me they were the key to moving the industry, so the next car we converted was a Saturn. Motorola had asked if they could develop our electric drive. Those first brainstorming sessions with them just blew me away. I wasn't used to a competitive industry; at utilities we just kind of hmmm-hmmm along."

Again, the electric Saturn dusted the rest of the field, accelerating from 0 to 60 miles an hour in 4.7 seconds. In 1994 the team beat that record again, converting an Indy car and hitting 60 in 3.2 seconds. "That one was scary to drive—like a silent rocket,"
says Hobbs. “It had maximum torque at zero rpm, so it cornered amazingly. The first time it came past us at 120 miles per hour, we heard a weird chirping noise. We finally realized it was the tires on the pavement, which no one had ever heard before because of the engine roar.”

Lately, Hobbs has stayed away from the racetrack. “We got way ahead of the car companies, which was never our intent. Rockefeller helped develop the internal combustion engine to increase demand for oil. We just wanted to make a market for our off-peak assets.”

In fact, Hobbs’s motivation for his experiments seems much deeper. “We’re able to live the way we do now because the decisionmakers in our parents’ and grandparents’ generations thought about us and built the infrastructure we would need,” he says. He likens the present generation to the grasshopper in Aesop’s fable—singing all summer while the ant stored up food, then starving when winter came. “When did we become grasshoppers?” he asks.

“Every human takes care of the generations behind them.”

Hobbs’s optimism occasionally deserts him. “If we all fail, and we might, the rich and strong will have the last safe places on earth. And the billions of poor people will either figure out a way to take those places back, or they will die.”

But against that despair Hobbs marshals a deep reverence for nature. He is awed by algae. “You are looking at the origins of life, an organism that has survived for three and a half billion years and created the conditions for other life to emerge. They are the root of the food chain. And so elegant. Single-celled algae can crack water with a photon into hydrogen and oxygen, then metabolize that hydrogen with carbon dioxide to sugar. We can’t do that. We can’t even fully understand it. You just have to be mesmerized and humbled.”

Like Metcalfe, Hobbs thinks the idea of sequestering carbon underground is both wasteful and risky. “Carbon dioxide is danger-

ous in large quantities,” he explains. “We spend enormous amounts of money to dig holes to get carbon out of the ground, and the best fix we can come up with is to dig more holes and put it back in? That’s something your dog might think to do.

“Given all we invest to get carbon in the first place, shouldn’t we think of ways to use it again? The tomatoes in my sandwich come from greenhouses where they burn natural gas just to make carbon dioxide to feed the tomatoes. We have a valuable raw material coming out of that smokestack, and we’re just throwing it away.”

Hobbs spends a lot of time thinking about the carbon cycle and how it has operated since the emergence of life on earth: carbon moves from the atmosphere into living organisms and the oceans, then into sediments and rock, and only very slowly out of the rock and back into the atmosphere. That cycle was in balance until humans started digging up and burning deeply buried reservoirs of ancient carbon; without our thirst for those fossil fuels—the fossilized remains of plants and animals that predated the dinosaurs—that ancient carbon would have cycled back into the atmosphere very slowly, over many eons.

“The answers are right in front of us,” Hobbs argues. “Algae is nature’s building block—it’s now carbon was managed on the planet for hundreds of millions of years. Can’t we seize that example? By digging up fossil fuels that were stored over millions of years, humans accelerated the front end of the carbon cycle. So we’re accelerating the back end, the uptake part of the cycle. From the time we burn the carbon in the power plant to the time we get oil out of the algae is a matter of a few hours. We get that carbon back in a few hours. And we keep thinking about just how many times we could get that same carbon to play. After a while, you could lose the coal entirely. You could grow the algae, burn the algae in the power plant, capture that carbon dioxide and pump it back into the greenhouse, and grow more algae. Dried algae has as
many BTUs per pound as coal. You'd have a completely renewable power plant.

"You have to gather it all up in your arms, think of it as a whole system. We throw away heat. We need to use it. We throw away flue gas; we need to use that too. But these ideas will only work when carbon dioxide has monetary value. Without a price on carbon dioxide, the economics will always pressure you to burn fossil fuels. No one knows how to give that up, it's our economic universe.

"And if you don't get long-term policies in place, the political momentum we've got going right now will just dump out the other end. If we get this, the oil companies will go nuts, because it's distributed, which means they can't control the supply. They'll send their lawyers and lobbyists in, just like they did with the electric car. The political allies we have now won't be there long enough. I lived through the zero-emissions mandate—and saw the government fold under pressure.

"You need a way for people to make money. Forget wisdom. We have to play off greed. A carbon cap will be the turning point. You can't stack the deck against these scientists and innovators. Society has to stand with them. And utilities are nothing more than instruments of public policy.

"I have a devout belief in God, and I believe God put carbon in the bank for us to use at the right time, but that we have to rise to the challenge to manage it."