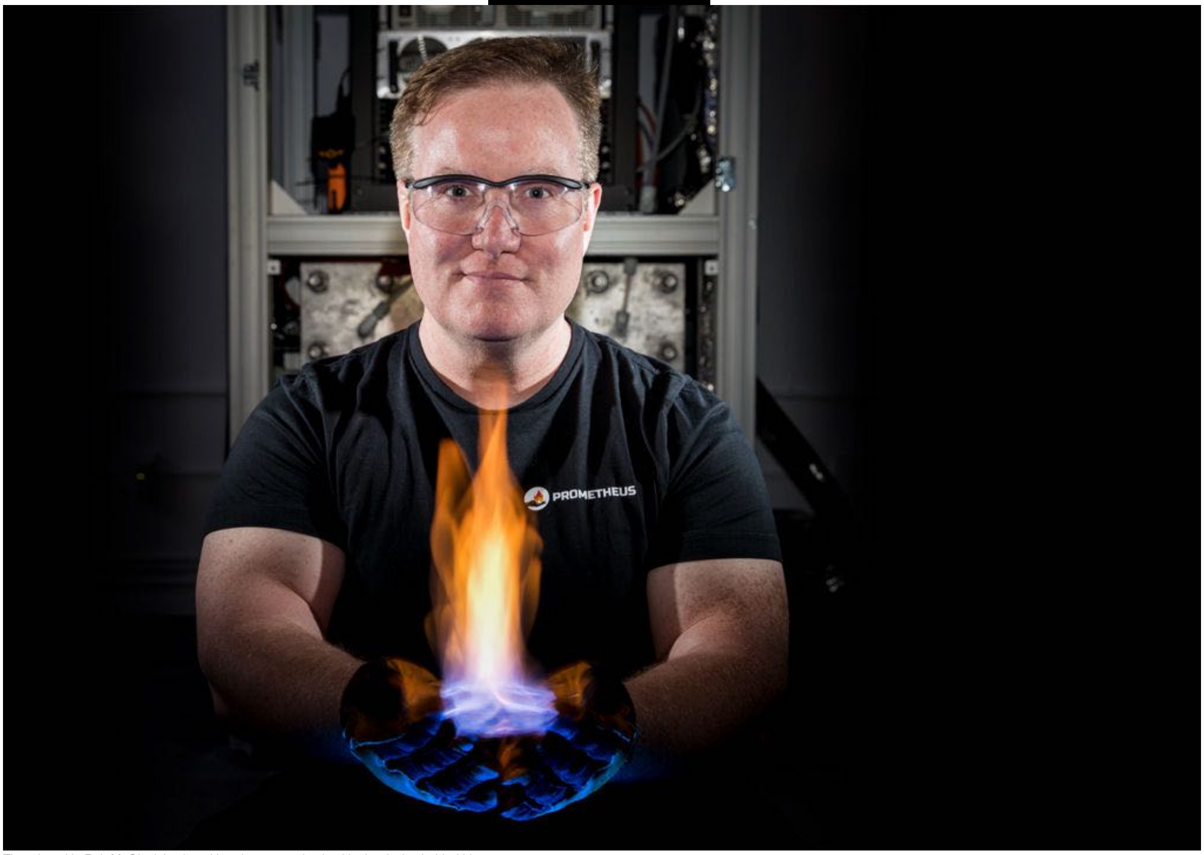
QUEST FOR FIRE



The ethanol in Rob McGinnis's gloved hands was synthesized in the device behind him. LIPO CHING

This former playwright aims to turn solar and wind power into gasoline

By Robert F. ServiceJul. 3, 2019 , 12:00 PM

SAN FRANCISCO, CALIFORNIA—On a warm March day here, you could almost mistake Rob McGinnis for a huckster newly arrived in a frontier town as he delivers a rapid-fire pitch to an audience of thousands of would-be investors. McGinnis, a chemical engineer and entrepreneur, isn't hawking snake oil, however: His elixir is gasoline. Nearly everyone in the developed world is hopelessly addicted to it. Collectively, we use nearly 3 trillion liters every year.

At the pitch fair, McGinnis wears the Silicon Valley entrepreneur uniform of jeans, a black T-shirt, and black leather biker boots. On a theater-size stage, he delivers his spiel, sandwiched between 3-minute presentations for an online personalized clothing store and an outfit that would rent scooters by the month. "We make gasoline from air, water, and electricity," McGinnis announces. "Today, gasoline sells for $3.50 a gallon in California. Next year, we will be selling it for $3 per gallon." Other startups peddling ideas at the fair foresee markets in the billions, but McGinnis aims higher. "We're talking about a $2 trillion [per year] gasoline market," he says.

If all that sounds too good to be true, it might be. "I hope they're right," says Olgica Bakajin, CEO of Porifera Inc., a San Leandro, California, company that has also worked on systems like those at the heart of McGinnis's fuelmaker. But she notes that McGinnis "is a good talker who sells things well."

He has convinced some powerful investors. In December 2018, he received $150,000 from Y Combinator, the Mountain View, California, seed funder hosting the pitch fair, to build a prototype of his air-to-gasoline–maker. The result was a refrigerator-size contraption of catalysts, tubes, electronics, and filters, assembled a week before the pitch fest.

But before the demo, the machine sprang a leak. Although it wasn't operating at the pitch fest, McGinnis's optimism was. He promised audience members that the repaired device would extract carbon dioxide (CO_2) from the air, add it to water, and use a catalyst to rearrange the chemical bonds to make hydrocarbons. The result: fossil fuel without the fossils. "It can sound like magic, but it's really just chemistry," McGinnis told the audience.

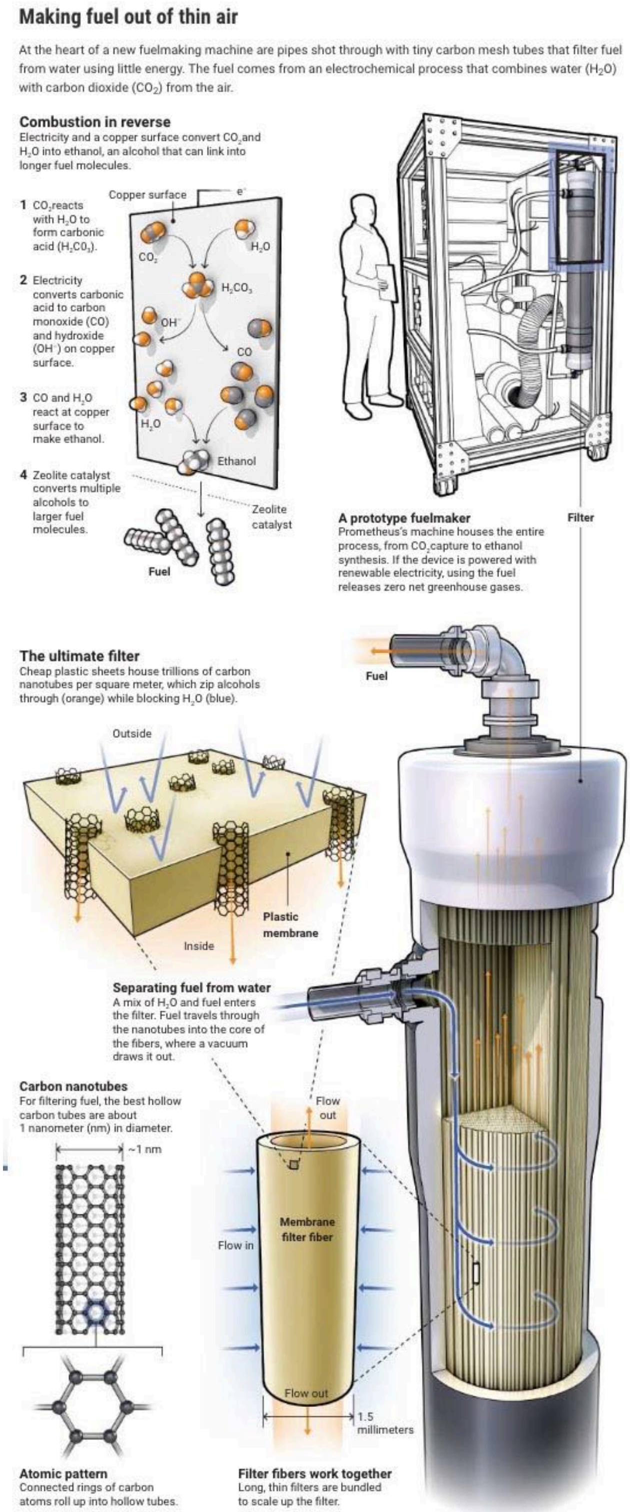
A Promethean project

Synthesizing gasoline, instead of refining it from oil, isn't a new idea. German chemists in the 1920s discovered they could turn coal into carbon monoxide (CO) and hydrogen—a combination known as synthesis gas. Catalysts, along with heat and pressure, could then transform synthesis gas into gasoline and other liquid hydrocarbons.

But McGinnis's setup requires no heat, pressure, or coal. It uses only air, water, and electricity, which can come from the sun or wind. And with those renewable resources becoming ever cheaper, he's betting he can deliver gasoline more economically—and far more cleanly—than companies that must find oil, drill for it, ship it, and refine it.

Several other startups and academic labs are pursuing the same dream. "There has been a lot of progress in the last few years" in turning CO_2 into more-complex compounds, says Peidong Yang, a pioneer in the field at the University of California, Berkeley.

Yet many of those efforts have stumbled over the expensive, energy-intensive steps needed to separate the hydrocarbons from the water they are produced in. Prometheus relies instead on a proprietary carbon nanotube membrane sieve that it says readily parts the hydrocarbons from water. "If they indeed have a low-energy separation process, that solves a big problem," Yang says.



"Rob's approach has a good chance of competing with fossil fuels," says Matthew Eisaman, a physicist at the State University of New York in Stony Brook who consults for Prometheus. Eisaman ran a now-mothballed research program at Google's research arm, Google X, that aimed to turn the CO_2 in seawater into liquid fuels.

Bruce Hinds, a nanotube membrane expert at the University of Washington in Seattle, says McGinnis's published results on his separation technology inspire confidence that the approach could work. "I'm highly encouraged," Hinds says.

McGinnis has long defied expectations. After high school, he enlisted in the Navy, which sent him to Bahrain during the first Gulf War. There, he cleared mines from battlefields and harbors. "I didn't want to do it," he says of his time in the service, but he needed money for school. He enrolled in Cabrillo College, a public community college near Santa Cruz, California, where he dreamed up an energy-efficient approach to desalinating water during a chemistry class. Today, most water desalination uses reverse osmosis, which employs energy to push water through a membrane that excludes salts. McGinnis planned instead to use forward osmosis, which relies on differences in the concentration of compounds on either side of a membrane to move water across; it consumes only about half as much energy. "I prototyped it in my kitchen," he says. "I wanted something to distinguish myself to [transfer] to a really good school."

His school plan worked, and McGinnis moved to Yale University for his junior year. He majored in theater and focused on playwriting. "It was really good training," he says. "A lot of what entrepreneurs do is tell stories."

But he never gave up on science. McGinnis canvassed the chemistry faculty to see whether anyone would let him use lab space in the evenings to pursue desalination. Menachem Elimelech, a Yale chemical engineer, agreed. McGinnis later pursued a Ph.D. in Elimelech's lab, constructed a forward osmosis demonstration, and helped launch a startup company called Oasys Water in Cambridge, Massachusetts, to commercialize the technology. Oasys built five large water treatment plants in China and was eventually bought out by its customer there.

It can sound like magic, but it's really just chemistry.

Rob McGinnis

Even before the buyout, McGinnis felt sidelined from decision-making. He left Oasys in 2012 to explore other ideas for improving membranes for separations, initially looking for even better ways to purify water. He chose to pursue membranes made from thin plastic sheets shot through with myriad carbon nanotubes—tiny hollow tubes made entirely from carbon atoms. Researchers at Lawrence Livermore National Laboratory in California and elsewhere had shown that the tiny channels allow water to pass through while blocking other molecules. But the lab demonstrations employed dime-size membranes; larger membranes leaked and weren't uniform. "Carbon nanotube membranes never lived up to the hype," says Jeffrey McCutcheon, a membrane separation expert at the University of Connecticut (UConn) in Storrs who collaborates with McGinnis.

McGinnis thought he could solve the problem. He formed a company called MatterShift and received lab space in a startup incubator at UConn. After 5 years, he could make uniform membranes the size of a sheet of paper, consisting of carbon nanotubes embedded in a cheap commodity plastic called polyethersulfone.

The key, McGinnis says, was figuring out how to align vast numbers of nanotubes—roughly 2.5 trillion per square meter—so that most pierce the membrane perpendicularly, as ion channels on a cell surface do. Some researchers have speculated that magnetic fields are key to the process, but McGinnis isn't saying. "It's our secret sauce," he says.

In March 2018, he, McCutcheon, and colleagues reported one possible use for their membranes in *Science Advances*: filtering out organic contaminants, such as odor-causing compounds, from water, while applying only a fraction of the pressure used to push water through reverse osmosis membranes. But McGinnis sees that use as a demonstration rather than his primary commercial target.

In the past year, he and his team have come up with a way to transform their membranes from flat sheets into narrow hollow plastic fibers dotted with nanotube pores. The researchers can manufacture those fibers in a continuous process, McGinnis says, cutting them to any length and bundling them to make industrial filters.

"The new piece in the puzzle"

The nanotube filters can perform a far more important feat than removing contaminants, McGinnis says: They separate ethanol from water. Carbon nanotubes of the right diameter—about 1 nanometer—transport ethanol more quickly than water through their interior. McGinnis explains that ethanol's carbons have an affinity for the inside of the carbon nanotubes. So if the starting liquid contains at least 5% to 10% ethanol and a slight vacuum draws it through the filter, the alcohol molecules form a molecular conga line through the nanotubes, excluding nearly all water. The filtered solution winds up containing about 95% ethanol.

McGinnis and his team haven't published those separation results yet. But researchers led by Yang Decai from Dalian University of Technology (DUT) in China reported in August 2018 in *Nano Letters* that a similar carbon nanotube membrane was highly selective and fast at separating ethanol and butanol (another alcohol) from water.

If commercialized, such membranes could benefit biofuel companies that make ethanol from corn, McGinnis and others say. Fermentation leaves a solution of 10% ethanol in water. Today, ethanol producers use heat and 6-meter-tall distillation columns to boil off the ethanol, an energy-intensive process that costs about a third as much as the alcohol itself. McGinnis says his membranes could cut the distillation cost by 90% in an ethanol market worth $50 billion per year in the United States.

If the membranes work as claimed, "That by itself would be big," Peidong Yang says.

This ethanol was produced using only air, water, and electricity. LIPO CHING

McGinnis is working to prove that they do. Last year, MatterShift and partners at UConn received a $900,000 grant from the Department of Energy to demonstrate their ethanol separation technology. Their test uses a 2-meter-high tube with 1400 nanotube-pocked fibers, with results expected this summer.

If either MatterShift's or DUT's membranes prove durable and long-lived, bioethanol producers should represent an eager market, says David Sholl, a chemical engineer at the Georgia Institute of Technology in Atlanta. McGinnis has already founded a company called MatterShift Biofuels to commercialize the technology. But he envisions a bigger future for his membranes: not just filtering ethanol fermented from corn or sugar, but also purifying fuel made from the air itself.

Synthesizing the fuel is the easy part. Peidong Yang's team and groups at Oak Ridge National Laboratory (ORNL) in Tennessee and the University of Illinois in Urbana have published papers in the past 3 years showing that electricity and nanosize copper catalysts can turn CO_2 and water into a mix of alcohols. And startups including a New Orleans, Louisiana, company called ReactWell are pursuing related approaches.

Thus far, the ORNL team has reported the highest efficiency, turning 23% of the electrical energy into fuel. But all the groups using the approach to make alcohols face the challenge of separating the fuel from the water. McGinnis says his membranes are the answer. They are "the new piece in the puzzle no one else has."

In the air-to-fuel machine he hoped to demonstrate at Y Combinator, the membranes filter a liquid that flows from a meter-wide chamber containing two electrodes dunked in water. When air blows through the chamber, the CO_2 it contains reacts with water, producing carbonic acid—the same molecule acidifying the oceans. That acid, in turn, reacts on a copper catalyst coating the negative electrode, or cathode, to create CO. The cathode also strips protons off water molecules, leaving behind negatively charged hydroxide ions. Those ions travel to a positively charged electrode, or anode, where they react to form water and oxygen gas. Meanwhile, at the cathode, multiple CO molecules and protons are transformed into ethanol and other alcohols.

The result is the alcohol and water mixture that goes through the nanotube fibers. Prometheus has repaired its machine since the pitch fair, and it produces "a pretty steady drip" of fuel, McGinnis says: 10 milliliters per hour of alcohol that trickles out a red valve in the back. Over the next month, McGinnis and his colleagues plan to increase the size of their electrodes and catalysts to raise the production rate to 50 to 100 milliliters per hour.

Ultimately, McGinnis plans to add a second catalytic step using commercially available catalysts called zeolites, which would convert the mix of alcohols to the larger hydrocarbon molecules found in gasoline. "All of the pieces of this process have been proved to work. But no one has put them all together," he says. "Until now." He expects the device, when optimized, to produce 20 liters of gasoline per week.

Once the machine is working efficiently, electricity will make up about one-third of its operating costs. Renewable electricity prices around the globe are falling, however, and they already sink near zero at certain times of the day in places where the sun blazes or the wind howls. Prometheus, McGinnis says, could easily ramp its electricity demands up and down to take advantage of the lowest rates, and the machines could be sited wherever renewable power is cheapest. Next year, the company plans to build a $500,000 shipping container–size demonstration plant that can produce hundreds of thousands of liters of fuel per year. And last month, it inked its first deal, to begin to sell carbon-neutral fuel to Boom Supersonic, a Denver company building a supersonic commercial airliner.

Even if all goes according to plan, McGinnis will face a long road to compete with the likes of ExxonMobil. He'll have to prove he can build a fuelmaker cheaply enough to make its gasoline affordable. That could be tough if turning it on makes sense only when renewable electricity prices bottom out. The fuelmaker also works only with a source of clean water. And before he can market his invention, he'll need to prove that his fuels can directly substitute for fossil-derived versions.

At the pitch fair, McGinnis stands next to his prototype and repeats his story for a steady stream of potential investors. "We want to replace all fossil gasoline," he says. "That would make the world a better place." A few hours later, he loads up his wares and moves on in the hope that one day his dreams turn into an energy revolution.

Posted in: **ChemistryTechnology**
doi:10.1126/science.aay5994