**The truth about carbon capture technology**

Climate change is on everyone’s minds this week, as world leaders convene at the 2021 United Nations COP26 Climate Change Conference in Glasgow.

Stronger pollution protections mean focusing on specific communities

There’s a lot of industry talk about whether applying counter carbon technologies and techniques like carbon storage, carbon capture, carbon conversion, and carbon sequestration could make a sizable impact in removing carbon dioxide, the most abundant greenhouse gas emitted today.

Here’s a debrief on what these terms mean, the current state of technology, and what they would look like in practice.

***Carbon capture***

Carbon capture most commonly refers to the process of removing carbon dioxide from various sources like the smokestacks of power plants running on fossil fuels like coal, oil, or gas, as well as from manufacturing and production facilities.

Capture also refers to removing carbon dioxide directly from the atmosphere, called Carbon Dioxide Removal (CDR), or Direct Air Capture (DAC).

However, the flue gas coming out of a smokestack from the chimney of a power plant or industrial facility carries a much heftier amount of carbon, at around 10 to 15 percent carbon dioxide. Meanwhile, the concentration of carbon dioxide in the general atmosphere is around 400 to 450 ppm (parts per million), or about 0.04 percent.

“In the atmosphere, we have carbon dioxide that we’re worried about that’s significant from the point of view of affecting the radiative forcing and climate warming. But it’s very dilute from the point of view of capture,” says Harry Atwater, professor of applied physics and materials science at California Institute of Technology. “So people have to develop ingenious methods for capturing and then concentrating the carbon dioxide as a pure stream.”

The Swiss company Climeworks, for example, is one of the leading companies in the carbon capture space. Across Europe, there are more than a dozen direct air capture facilities that use fan-like machines to filter out carbon dioxide from the air and then heat up the captured molecules to pump them underground.

Another company, like Carbon Engineering, mist a basic chemical like potassium hydroxide to bind and draw down the carbon dioxide (which is acidic) from the air.

“There are multiple technologies for doing direct air capture that are being pursued. There’s also capture of carbon dioxide from the oceans,” says Atwater, like the ARPA-E project he’s working on which received funding from the Department of Energy.

Several National Academies reports indicate that technologies that actively remove carbon dioxide from the atmosphere need to be seriously considered as one of the many climate change combating solutions.

“There has been a lot of work on how to separate that carbon dioxide from other gases,” Peter Kelemen, a professor of earth and environmental sciences at Columbia University, says. “Once you have it, of course, you have to store it someplace.”

***Carbon sequestration and storage***

From Kelemen’s perspective, storage and sequestration are “pretty much synonymous,” except sequestration is used when the storage of the carbon dioxide is “essentially permanent” through methods like geological storage. The Norwegian Sleipner Project in the North Sea, for example, stores dense carbon dioxide fluid under pressure in a pore space under the seabed, Kelemen says.

Carbon sequestration underground has one major flaw, however—the major market for the technology is in enhanced recovery of fossil fuel, Atwater notes, where companies want to pump pressurized carbon dioxide into existing oil and gas reservoirs to get more product out.

For example, someone from the enhanced fracking industry can advocate that they are net carbon negative because they’re technically taking carbon dioxide from the air and injecting it underground. “But of course, what they’re doing is also enhancing the recovery of methane, which is a greenhouse gas, and then carbon dioxide,” he says. So an important question to always ask is whether the whole process a company is employing is net carbon-negative, positive, or neutral.

Iceland is using a combination technology from Climeworks and CarbFix to not only capture the carbon dioxide and pump it underground, but also permanently store it in the form of solids. These carbon-bearing minerals, which are mostly “carbonates” like calcite and magnesite, can store the carbon dioxide for thousands of years.

“If there are favorable strata that allow the conversion of the sequestered carbon dioxide to a solid form, then that renders it much more geologically stable, and we can say that it was safely sequestered without much fear or concern that it’s going to be emitted right back out again,” says Atwater. “CarbFix managed to understand the reaction between the injected carbon dioxide in the mineral strata to create stable carbonates.”

Simply putting extra carbon underground makes less sense than sequestering carbon dioxide into a marketable product that has economic value, says Atwater. Luckily, multiple companies and scientists have turned down this path. Many researchers have considered embedding solid forms of carbon in building materials like steels and cement, an already emissions-heavy industry, says Atwater. “What if we could actually take the carbon dioxide emitted through all the past synthesis of construction materials and then turn it back into materials that we could use like carbon fiber composites and other forms of more benignly stored carbon,” he adds. “That would be an indefinite form of storage.”

In contrast with solid carbon storage, there’s another type of less indefinite form of carbon storage: as fuel.

Fossil fuels, like gasoline (a type of liquid hydrocarbon), combine with oxygen to undergo a combustion reaction in our cars to make carbon dioxide and water. Many scientists have been tinkering with ways of running that reaction backwards, taking carbon dioxide and water and turning it back into fuel and oxygen.

Atwater and Caltech are part of the Department of Energy-sponsored Liquid Sunlight Alliance whose goal is to figure out how to use solar energy to drive that fuel-forming reaction backwards. A big bonus of this method would be the ability to reuse fuel for those tricky-to-decarbonize industries like flight, shipping, and steel production.

“It could be jet fuel you could recycle [and then] reuse in an airplane. It would be zero-carbon in the sense that you would balance the conversion of carbon dioxide into fuel with the combustion of fuel into carbon dioxide,” says Atwater. “That would be a way of producing renewable jet fuel, and that’s something that a lot of airlines are interested in.”

This idea is already well underway. A company based in the Bay Area called Twelve (named after the atomic mass of carbon in the periodic table) is working on converting carbon dioxide back to fuels. A German company called Atmosfair is also making synthetic carbon dioxide-neutral jet fuel by combining hydrogen generated by wind turbines with captured carbon dioxide (its first customer is Lufthansa).

***The cost of carbon***

Over the next few years, experts have to weigh the pros and cons of some of the options we have for cleaning carbon dioxide out of the atmosphere.

Even traditional methods like planting forests and creating natural biomass to store carbon can be challenging to implement and sustain. “Reforestation in the developing world is politically and ethically problematic because the folks who cut down the trees did so for a reason, and may own the land,” Kelemen says. “Afforestation and biofuel production are problematic because they compete with food production for arable land.”

Also, new forests only remove significant amounts of carbon while the forest, or kelp forest in the ocean, is growing, Kelemen explains. “Once they reach ‘steady state’ (a mature forest, for example), the rate of carbon dioxide uptake due to growth is not much larger than the rate of carbon dioxide emissions due to respiration from living plants and decomposition of ‘dead’ biomass.”

To keep a big forest-based carbon sink going, plants will have to be continuously harvested and protected from decay.

Meanwhile, a huge issue for carbon capture and sequestration technology is the price tag. “If you’re simply going to sequester carbon, it requires citizens and leaders of advanced industrial societies to agree to basically tax themselves to underwrite the cost of storing that carbon,” says Atwater. “There’s no worldwide agreed-upon price of carbon per tonne at the moment, which is one of the problems.”

While carbon credit markets are emerging across the corporate sector, right now, there’s a gap between demand and capacity for storage methodologies. “We simply don’t have enough technologies to meet the demand. We’re in a weird moment,” says Atwater. “There’s literally gigatonnes of demand for carbon credits, and there’s only kilotonnes of capacity.”

Most anti-carbon tech are in their infancy. There’s also no large-scale infrastructure supporting their growth and expansion. “Carbon negative technologies, unless you’re going to just pump that carbon dioxide underground that you’ve captured, they’re going to have to create new products like fuels, specialty chemicals and materials,” says Atwater. “The big markets are for things like fuel, cement, and steels. Those are the things that we make at the gigatonne scale.”

These techniques are sometimes shrouded with controversy—namely because many argue that capture and storage lets fossil fuel companies off the hook for their giant carbon footprints. Atwater says “to reach our condition of sustainable level of carbon in the atmosphere below our current levels and back towards pre-industrial levels, we’re going to need to decarbonize and electrify everything that we can.” But for industries that are “almost impossible to decarbonize,” storage opens up an opportunity to put those emissions to good use.

**Need more air in space? Magnets could yank it out of water.**

Humans tend to take a lot for granted, even something as simple as a breath of fresh air. It’s easy to forget how much our bodies depend on oxygen—until it becomes an invaluable resource, such as aboard the International Space Station.

Although astronauts are typically sent to space with stores of necessary supplies, it’d be too costly to keep sending tanks of breathable air up to the station. Instead the oxygen that astronauts rely on for primary life support is created through a process called electrolysis, wherein electricity is used to split water into hydrogen gas and oxygen gas. On Earth, a similar process happens naturally through photosynthesis, when plants use hydrogen to make sugars for food and release oxygen into the atmosphere.

Yet because the system on the ISS requires massive amounts of energy and upkeep, scientists have been looking for alternative ways to sustainably create air in space. One such solution was recently published in NPJ Microgravity, in which researchers found a way to pull gases from liquids using magnets.

“Not a lot of people [are] aware that water and other liquids are also magnetic to some extent,” says Álvaro Romero-Calvo, currently an assistant professor at the Guggenheim School of Aerospace Engineering at Georgia Tech and lead author of the study.

“The physical principle is pretty well known in the physics community [but] the application in space is barely explored at this point,” he says. “When a space engineer is designing a space system involving fluids, they do not even consider the possibility of using magnets to induce phase separation.”

At the Center for Applied Space Technology and Microgravity (ZARM) at the University of Brennan in Germany, Romero-Calvo’s team was able to study the phenomenon of “magnetically-induced buoyancy.” The idea is easier to explain by visualizing a can of soda: On Earth, because the liquid is denser than carbon dioxide molecules, soda bubbles separate and float to the top of the drink when subjected to the planet’s gravity. In space, where microgravity creates a continuous freefall and removes the effect of buoyancy, the substances inside become harder to separate and these bubbles are simply left suspended in air.

To test whether magnets could make a difference, the team took their research to ZARM’s drop tower, where an experiment, once placed in an airtight drop capsule, can achieve weightlessness for a few seconds. By injecting air bubbles into syringes filled with different carrier liquids, the team was able to use the power of magnetism to successfully detach gas bubbles in microgravity. This proved that the bubbles can be both attracted to and repelled by a neodymium magnet from within various substances.

Additionally, the researchers found that through the inherent magnetic properties of various aqueous solutions (like purified water and olive oil) they tested, it’s possible to direct air bubbles to different locations within the liquid. Essentially, it’d become easier to collect or send air through a vessel. Besides being used to create an abundance of oxygen for the crew, Romero-Calvo says the study’s results show that developing microgravity magnetic phase separators could lead to more reliable and lightweight space systems, like better propellant management devices or wastewater recycling technologies.

To demonstrate the magnets’ potential use for research purposes, the team also experimented with Lysogeny Broth, a medium used in to grow bacteria for ISS experiments. As it turns out, both the broth and the olive oil were “significantly affected” by the magnetic force expended on it. “Every bit of effort that we devote to this problem is effort well spent, because it will affect many other products in space,” Romero-Calvo says.

If the next generation of space engineers do decide to apply magnets to future space stations, the new method could generate more efficient, breathable atmospheres to support human travel to other extraterrestrial environments, including the moon and most especially, to Mars. If we were to plan a human mission to the Red Planet, the ISS’s current oxygenation system is too complex to be completely reliable during the long journey. Simplifying it with magnets would lower overall mission costs and ensure that oxygen is abundant.

Although Romero-Calvo says their breakthrough could ultimately help us touch down on Mars, other scientists are working on ways to manufacture oxygen using plasma—a state of matter that contains free charged particles like electrons which are easily excited by powerful electric fields—for fuels, fertilizers, and other materials that could help colonize the planet. And while neither project is up to scale just yet, these emerging advances represent the amazing feats humans are capable of as we keep moving forward, striving to reach beyond our familiar horizons.

**How the most distant object ever made by humans is spending its dying days**

The eyes of the world might be fixed upon Mars, where last week alone, the Ingenuity helicopter took flight and the Perseverance rover made oxygen. But farther—much farther—Voyager 1, one of the oldest space probes and the most distant human-made object from Earth, is still doing science.

The probe is well into the fourth decade of its mission, and it hasn’t come near a planet since it flew past Saturn in 1980. But even as it drifts farther and farther from a dimming sun, it’s still sending information back to Earth, as scientists recently reported in The Astrophysical Journal.

For decades, Voyager has been sailing away at around 11 miles (17 kilometers) every second. Each year, it travels another 3.5 AU (the distance between Earth and the sun) away from us. Now, it’s sending messages home even as it prepares to leave this solar system behind.

There are multiple ways to think about the “edge of the solar system.” One is a boundary region called the heliopause. That’s the frontier where the solar wind (the soup of charged particles continually thrown off by the sun) is too weak to hold off the interstellar medium—the plasma, dust, and radiation that fill the bulk of space.

When Voyager 1 left Earth in 1977, nobody was certain where the heliopause was, according to Bill Kurth, an astrophysicist at the University of Iowa who has been working with Voyager 1 since before it launched. Some scientists then even thought the heliopause was as close as 10 or even 5 AU—around the orbits of Jupiter, which Voyager 1 passed in 1979, or Saturn.

In reality, the heliopause is around 120 AU away. We know this partly because Voyager 1 crossed the heliopause in August 2012, a whole three and a half decades after it departed Earth. That puts the probe well and truly in interstellar space.

Out here, space is filled with interstellar medium—but you’ll not see very much of it. A cube of air at sea level on Earth contains more than a trillion times as many molecules as an equal-sized cube of even the interstellar medium’s densest parts. The region that Voyager 1 is traversing is sparser still. And for the most part, it’s quiet.

But every few years, as Voyager 1 records more data about the plasma and dust out here, it finds something. For instance, in 2012 and again in 2014, Voyager 1 felt a shock. According to Kurth, what Voyager 1 recorded was a magnetic spike, accompanied by a burst of energetic electrons that caused intense, oscillating electric fields. These shocks are the most distant effects of the sun, rippling outwards even past the heliopause.

What Voyager 1 encountered in 2020 was another jump in magnetic field strength, but without those intense electrical oscillations. Scientists instead think it’s a pressure front, a much more subtle disturbance moving out into the interstellar medium. Voyager 1 previously encountered something like it in 2017.

According to Jon Richardson, an astrophysicist at MIT who wasn’t an author on the paper, this latest finding shows that Voyager 1 is still capable of surprising scientists. Normally, he says, the probe would need to experience a shock in the surrounding plasma to measure its density. But with observations like this one, scientists have found a way to use Voyager 1 to continually monitor that density—over 13 billion miles away from us.

Richardson also says the findings show that Voyager 1 continues to feel the sun’s tendrils, billions of miles past the heliopause. “The sun is still having a major effect,” he says, “far outside the heliosphere.”

Meanwhile, Voyager 1 is still within the sun’s gravitational influence. In about 300 years, scientists expect, Voyager 1 will start to enter the inner edge of the Oort cloud, that shroud of comets which stretches as far as several light-years away.

We’ve never actually seen evidence of the Oort cloud, but sadly, Voyager 1 likely won’t be the one to reveal it. The probe is quite literally living on borrowed time. Plutonium-238, the radioisotope that powers the probe’s generator, has a half-life of about 88 years.

As a result, Voyager 1 is starting to lose fuel. Scientists are already having to make choices about which parts of the probe they should keep functional. By the mid-2020s, it’s likely that the probe won’t be able to power even a single instrument.

Still, scientists like Kurth hope they can eke the probe’s life out to 2027, the 50th anniversary of its launch. That, Kurth says, is a milestone that none of Voyager 1’s designers could ever have foreseen.

**Are solar panels headed for space?**

Solar power is a major player in turning the world’s energy from carbon-emitting to climate-friendly—but who says those solar panels need to sit on Earth? The European Space Agency (ESA) has eyed space-based solar power since the beginning of this year. As of August, the agency is considering developing a program to start generating energy with photovoltaics in space.

While space-based energy may sound a little out there, they aren’t the only major organization looking to outer space for our ever-growing clean energy needs. NASA has also taken an interest in generating space-based power. This unique technology might sound like science fiction, but it’s something that could become a significant source of energy in the not-too-distant future.

***How space-based solar power works***

Before rocketing off into space, here’s a quick recap of how photovoltaic panels work. When the sun shines, photolvoltaic cells in the solar panel absorb the energy from light rays. Then, the energy creates a charge that moves inside an electric field within the cell, according to the Department of Energy.

Space-based solar power involves putting photovoltaics in geostationary orbit—the same place where we have weather satellites—and sending the energy they collect back to Earth via a microwave power beam. The microwave power from space-based solar would be received at a power station and used to generate electricity.

Ali Hajimiri, a professor of electrical engineering and co-director of the Space-Based Solar Power Project at Caltech, tells PopSci that space-based solar could be an efficient way of generating solar power. He says it may be even more efficient than putting solar panels on land.

“There is no day and night or seasons or clouds in space. If you look at the total energy that’s available for photovoltaics in space, it’s eight to nine times higher,” Hajimiri says.

Shooting microwave energy at the Earth from space might sound dangerous, but Hajimiri says it’s actually quite safe. “The way the system is designed and built, the energy density that you get is actually less than what you get from standing in the sun,” he says. “It’s actually less harmful than the sun because it’s what’s called nonionizing radiation. A lot of the energy that comes from the sun is ionizing, which is why standing too long in the sun gives people skin cancer.”

Hajimiri says the system could quickly be shut down if something went wrong, such as an electrical issue or if it got damaged.

His team has been developing the hardware needed to generate solar power in space. He adds that these systems could be set up in a modular fashion, which means they could be put together piece by piece. A square of photovoltaics could be sent up to start, and more components could be attached down the line. He says you could have a square kilometer of photovoltaics and generate a gigawatt of energy—enough to power around 750,000 homes.

***Who is getting involved with space-based solar?***

No nation has deployed the technology yet, but space-based solar is gaining interest in areas beyond the US and Europe. China plans to test out space-based solar power in low Earth orbit in 2028, a lower altitude than geostationary orbit. Then, there are plans for the country to try for geostationary orbit in 2030. South Korea and Japan are also taking an interest.

The lucky thing about space is there’s plenty of room to generate energy in Earth’s orbit, and the energy could quickly go wherever it’s needed, Hajmiri says. “You can also almost instantaneously change where the energy is going,” he says. “You can dynamically dispatch power.”

Currently, Earth’s atmosphere reflects about 30 percent of the sunlight that solar panels could collect. While this is important for keeping things from getting too hot on Earth, for energy purposes, that’s a lot of lost potential.

Space-based solar power, theoretically, could generate a lot of energy that’s currently going to waste simply because of where it is.

Many worry about how we’ll keep things running using solar panels when the sun goes down at night. Proposed solutions are often large batteries because they can charge when energy is being generated and discharge when it’s not. But storage wouldn’t be an issue for this type of energy system.

“All of the technologies that are commonplace today are things that were scary or unknown at some point,” Hajimiri says. “We should not let the fear of the unknown dictate where we go.”

**A new power-generating system works like a jet engine**

For a few hours on April 12, engineers at Sandia National Laboratories in New Mexico were able to send electrons back into the Sandia-Kirtland Air Force Base electrical grid using a new type of power generating system. This small proof-of-concept, announced earlier this month, showed the team that their system—which they have been tinkering with since 2007—-was stable, controllable, and able to sync up well to the electrical grid.

The new system, which the team purports could be more efficient than existing power-generating systems, is based off of a thermodynamics process described through a closed-loop Brayton cycle, and works similarly to a jet engine. Most jet engines are powered by an open Brayton cycle. Ambient air is brought in and compressed. Then, it’s heated with fuel and expanded through a turbine. That turbine can then mechanically operate a generator to produce electricity (if you’re ground-based), or thrust (if you’re on an aircraft).

“Previous years, we just made electricity, and put it into resistive load banks. That’s like a huge toaster oven, it turns electricity into heat,” says Darryn Fleming, a mechanical engineer at Sandia National Laboratories who worked on this project. “Being able to put power back on the grid was the main outcome for this program.”

So what engine operations do Brayton cycles describe? “Imagine you take a pipe and you connect the [gas] discharge of the turbine back with the compressor, and you keep the working fluid just in a loop. That’s a closed Brayton cycle,” says Logan Rapp, a Sandia mechanical engineer that was part of the test. “It has the same compressor, turbine, and heat exchange, but the working fluid always stays inside the pipes.”

This system can work with a wide variety of gasses, like air, helium, nitrogen. The Sandia team used carbon dioxide in the supercritical state, which is kind of like a gas, but also kind of like a liquid. “It has a really high density, but it can also be expanded through a turbine like a gas,” Rapp says. “So, we reduced the amount of work needed for compression because it’s so dense, and that allows us to get to higher thermal-to-electric [conversion] efficiencies.”

The electricity that powers most modern day tech is produced through a steam-based Rankin cycle. Fuel like coal is used to heat water to make steam, which is then expanded through a turbine that turns mechanical work into electricity. But the thermal-to-electric efficiency of this system is around 33 percent, says Fleming. By using supercritical carbon dioxide that is above 1,070 psi, and above 88 degrees Fahrenheit, “that’s where you get to the 70 percent density of water, so you get higher efficiencies with your system.” That means it would be able to generate more power with less fuel compared to the steam system.

Plus, Rapp notes that their tech is heat-source agnostic, so it doesn’t have to be coupled with fossil fuels. “There’s been proposals to couple it with natural gas or coal, but we are funded by the Department of Energy’s nuclear energy division. So we are working to couple it with an advanced nuclear reactor,” he says. “We’ve also worked with the solar towers, where the sun is focused using mirrors to heat up a central tower. It works very well in that application.”

They’re also actively investigating whether they can pair the tech with waste heat recovery, where they’re capturing the heat from the exhaust stacks of steel and cement plants to power their Brayton cycle.

In their test, they used an electric heater as their fuel source to power the cycle, and they adapted parts of advanced elevator power electronics into the machine they used to regulate and feed the electricity from their test loop into the grid. Although this time, they consumed more energy than they put back on the grid, Fleming says that it was just a way for them to model the system in action.

As part of the next steps, the team wants to push the machine to higher power levels, higher temperatures, and higher turbine speeds. According to the laws of thermodynamics, amping up those factors will, in theory, allow them to get to higher thermal-to-electric efficiencies. The last test had an efficiency of 35 to 40 percent, but Rapp thinks they can get it to 50 percent with the right configuration. Additionally, the team is also looking to further develop some of the new support infrastructure, like seals and magnetic bearings, needed for a system like this in the coming year.