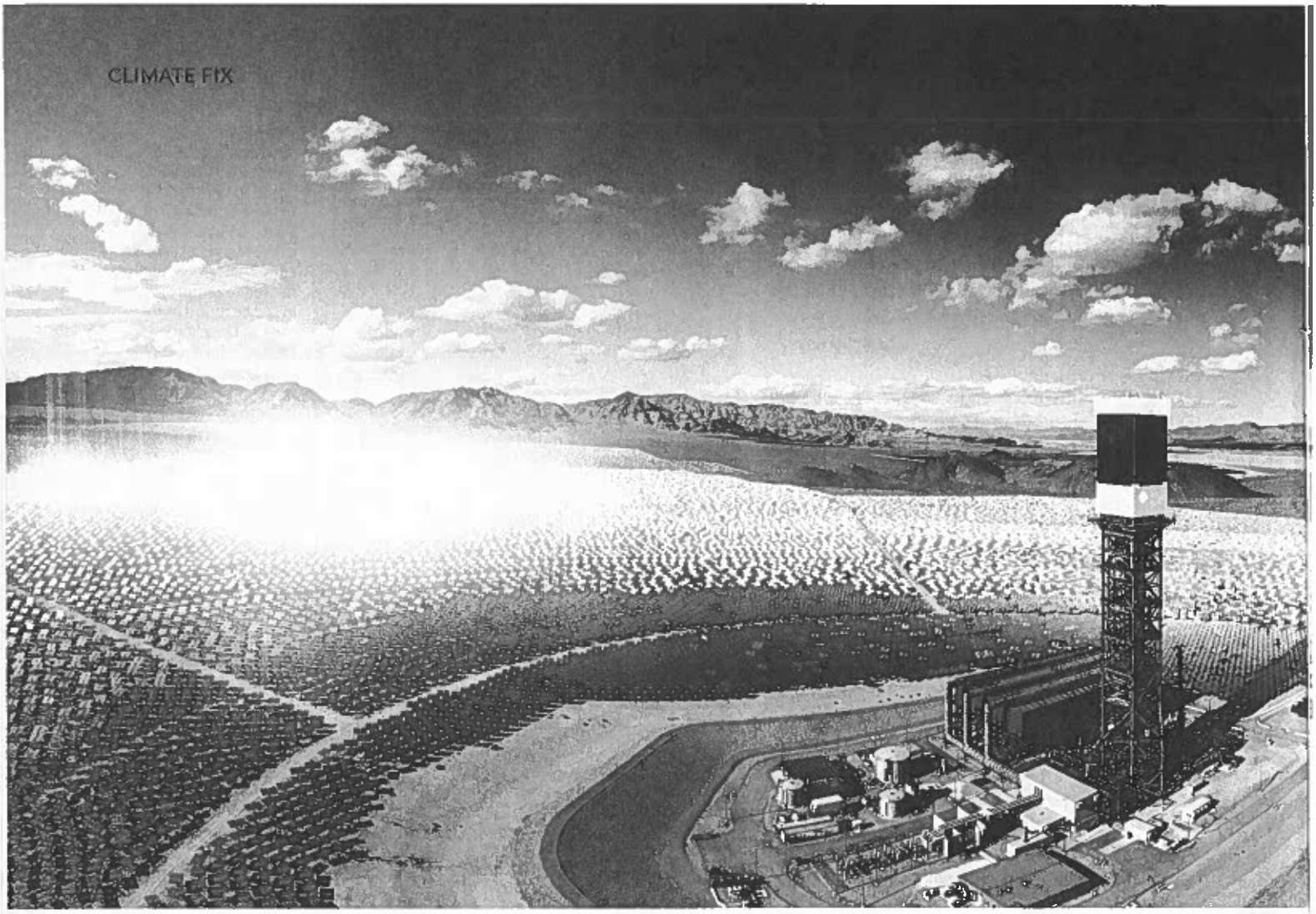


The Road to NET-ZERO

How we can cut emissions to curb climate change

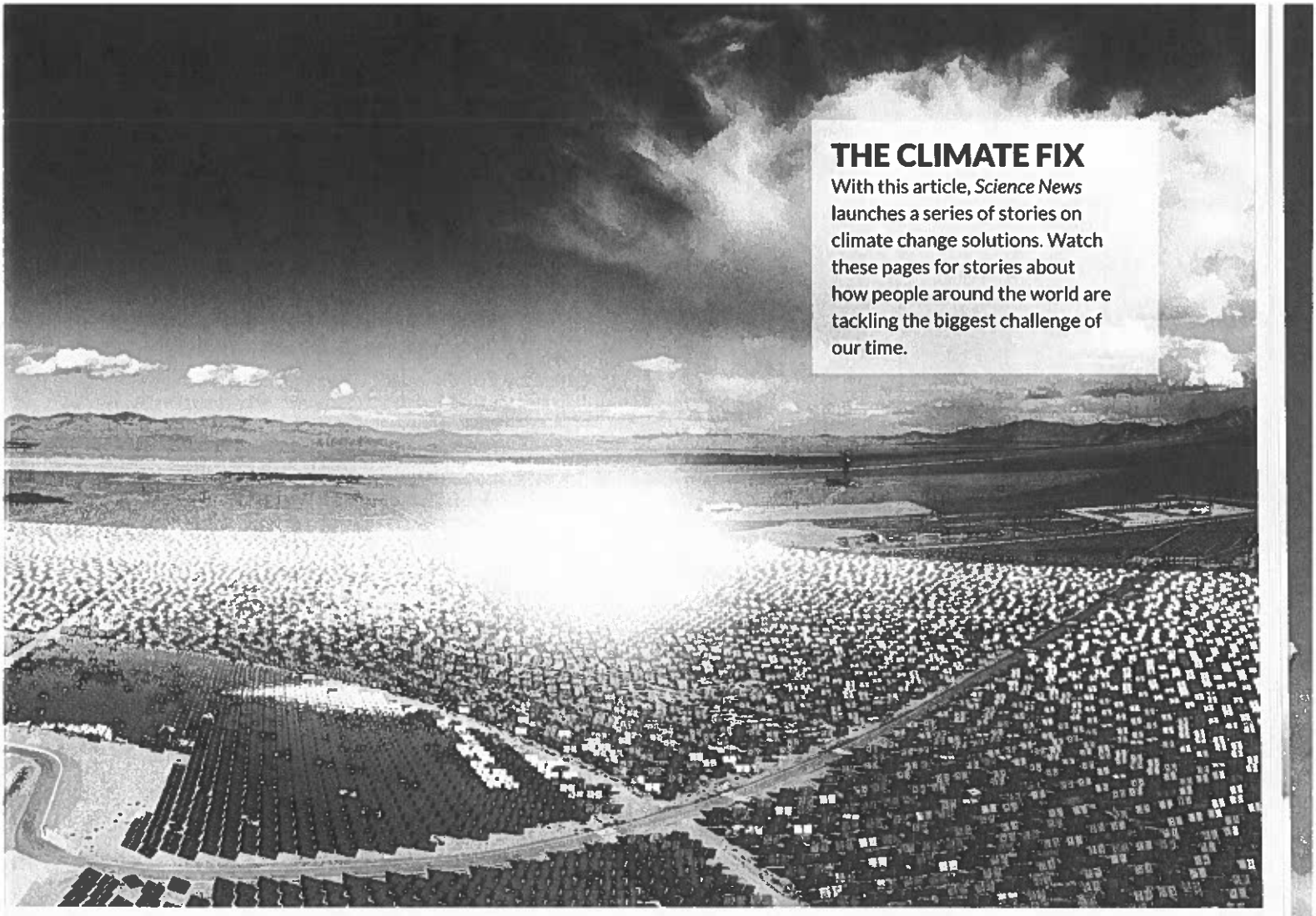
By Alexandra Witze

A lot of the technology needed for a future with fewer carbon dioxide emissions is already available. The Ivanpah Solar Electric Generating System in the Mojave Desert focuses sunlight to generate steam. That steam spins turbines to make electricity.

ADAMKAZ/E+/GETTY IMAGES

Patricia Hidalgo-Gonzalez saw the future of energy on a broiling-hot day last September. An email alert hit her inbox from the San Diego Gas & Electric Company. "Extreme heat straining the grid," read the message, which was also pinged as a text to 27 million people. "Save energy to help avoid power interruptions."

It worked. People cut their energy use. Demand plunged, blackouts were avoided and California successfully weathered a crisis exacerbated by climate change. "It was very exciting to see," says Hidalgo-Gonzalez, an electrical engineer at the



THE CLIMATE FIX

With this article, *Science News* launches a series of stories on climate change solutions. Watch these pages for stories about how people around the world are tackling the biggest challenge of our time.

University of California, San Diego who studies renewable energy and the power grid.

This kind of collective societal response, in which we reshape how we interact with the systems that provide us energy, will be crucial as we figure out how to live on a changing planet.

Earth has warmed at least 1.1 degrees Celsius since the 19th century, when the burning of coal, oil and other fossil fuels began belching heat-trapping gases such as carbon dioxide into the atmosphere (*SN*: 3/12/22, p. 16). Scientists agree that only drastic action to cut emissions can keep the planet from blasting past 1.5 degrees of warming—a threshold beyond which the consequences become even more catastrophic than the rising sea levels, extreme weather and other impacts the world is already experiencing.

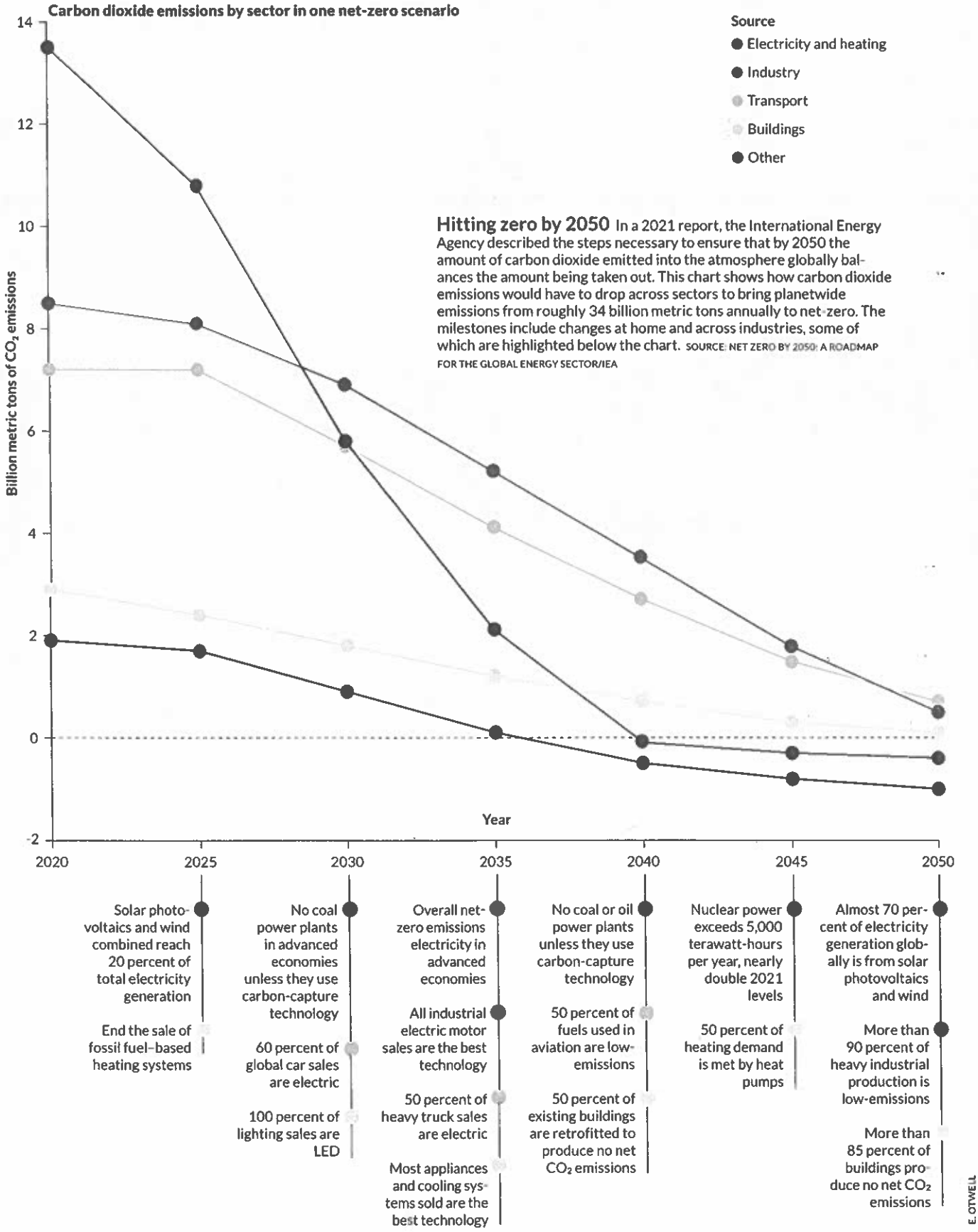
The goal is to achieve what's known as net-zero emissions, where any greenhouse gases still entering the atmosphere are balanced by those being removed—and to do it as soon as we can.

Scientists say it is possible to swiftly transform the ways we produce and consume energy. To show the way forward, researchers have set out paths toward a world where human activities generate little to no carbon dioxide and other greenhouse gases—a decarbonized economy.

The key to a decarbonized future lies in producing vast amounts of new electricity from sources that emit little to none of the gases, such as wind, solar and hydropower, and then transforming as much of our lives and our industries as possible to run off those sources. Clean electricity needs to power not only the planet's current energy use but also the increased demands of a growing global population.

Once humankind has switched nearly entirely to clean electricity, we will also have to counterbalance the carbon dioxide we still emit—yes, we will still emit some—by pulling an equivalent amount of carbon dioxide out of the atmosphere and storing it somewhere permanently.

Achieving net-zero emissions won't be easy. Getting to effective and meaningful action on climate change requires overcoming decades of inertia and denial about the scope and magnitude of the problem. Nations are falling well short of existing



Hitting zero by 2050 In a 2021 report, the International Energy Agency described the steps necessary to ensure that by 2050 the amount of carbon dioxide emitted into the atmosphere globally balances the amount being taken out. This chart shows how carbon dioxide emissions would have to drop across sectors to bring planetwide emissions from roughly 34 billion metric tons annually to net-zero. The milestones include changes at home and across industries, some of which are highlighted below the chart. SOURCE: NET ZERO BY 2050: A ROADMAP FOR THE GLOBAL ENERGY SECTOR/IEA

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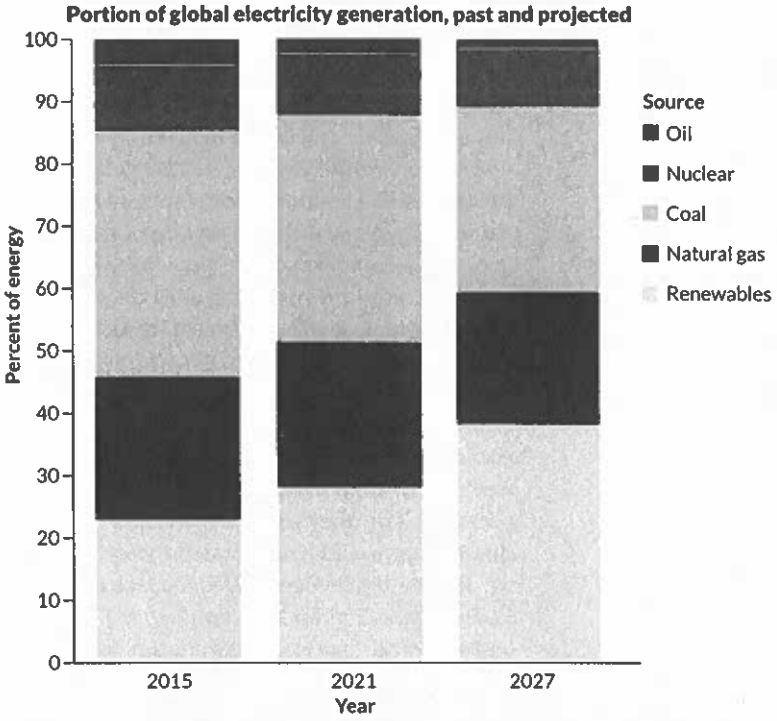
pledges to reduce emissions, and global warming remains on track to charge past 1.5 degrees perhaps even by the end of this decade.

Yet there is hope. The rate of growth in CO_2 emissions is slowing globally – down from 3 percent annual growth in the 2000s to half a percent annual growth in the last decade, according to the Global Carbon Project, which quantifies greenhouse gas emissions. There are signs annual emissions could start shrinking. And over the last two years, the United States, by far the biggest cumulative contributor to global warming, has passed several pieces of federal legislation that include financial incentives to accelerate the transition to clean energy. "We've never seen anything at this scale," says Erin Mayfield, an energy researcher at Dartmouth College.

Though the energy transition will require many new technologies, such as innovative ways to permanently remove carbon from the atmosphere, many of the solutions, such as wind and solar power, are in hand – "stuff we already have," Mayfield says.



A growing share Renewable energy sources, such as solar, wind and hydropower, account for a larger share of global electricity generation today than they did in 2015 (28 percent versus 22.8 percent). The International Energy Agency predicts they'll account for more than 38 percent by 2027. SOURCE: IEA

The current state of CO_2

Of all the emissions that need to be slashed, the most important is carbon dioxide, which comes from many sources such as cars and trucks and coal-burning power plants. The gas accounted for 79 percent of U.S. greenhouse gas emissions in 2020. The next most significant greenhouse gas, at 11 percent of emissions in the United States, is methane, which comes from oil and gas operations as well as livestock, landfills and other land uses.

The amount of methane may seem small, but it is mighty – over the short term, methane is more than 80 times as efficient at trapping heat as carbon dioxide is, and methane's atmospheric levels have nearly tripled in the last two centuries. Other greenhouse gases include nitrous oxides, which come from sources such as applying fertilizer to crops or burning fuels and account for 7 percent of U.S. emissions, and human-made fluorinated gases such as hydrofluorocarbons that account for 3 percent.

Globally, emissions are dominated by large nations that produce lots of energy. The United States alone emits around 5 billion metric tons of carbon dioxide each year. It is responsible for most of the greenhouse gas emissions throughout history and ceded the spot for top annual emitter to China only in the mid-2000s. India ranks third.

Because of the United States' role in producing most of the carbon pollution to date, many researchers and advocates argue that it has the moral responsibility to take the global lead on cutting emissions. And the United States has the most ambitious goals of the major emitters, at least on paper. President Joe Biden has said the country is aiming to reach net-zero emissions by 2050. Leaders in China and India have set net-zero goals of 2060 and 2070, respectively.

Under the auspices of a 2015 international climate change treaty known as the Paris agreement, 193 nations plus the European Union have pledged to reduce their emissions. The agreement aims to keep global warming well below 2 degrees, and ideally to 1.5 degrees, above preindustrial levels. But it is insufficient. Even if all countries cut their emissions as much as they have promised under the Paris agreement, the world would likely blow past 2 degrees of warming before the end of this century.

Every nation continues to find its own path forward. "At the end of the day, all the solutions are going to be country-specific," says Sha Yu, an earth scientist at the Pacific Northwest National Laboratory and University of Maryland's Joint Global Change Research Institute in College Park, Md. "There's not a universal fix."

But there are some common themes for how to accomplish this energy transition – ways to focus our efforts on the things that will matter most. These are efforts that go beyond individual

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consumer choices such as whether to fly less or eat less meat. They instead penetrate every aspect of how society produces and consumes energy.

Such massive changes will need to overcome a lot of resistance, including from companies that make money off old forms of energy as well as politicians and lobbyists. But if society can make these changes, it will rank as one of humanity's greatest accomplishments. We will have tackled a problem of our own making and conquered it.

Here's a look at what we'll need to do.

Make a lot more clean electricity

To meet the need for energy without putting carbon dioxide into the atmosphere, countries would need to dramatically scale up the amount of clean energy they produce. Fortunately, most of that energy would be generated by technologies we already have — renewable sources of energy including wind and solar power.

"Renewables, far and wide, are the key pillar in any net-zero scenario," says Mayfield, who worked on an influential 2021 report from Princeton University's Net-Zero America project, which focused on the U.S. economy.

"Renewables, far and wide, are the key pillar in any net-zero scenario."
ERIN MAYFIELD

The Princeton report envisions wind and solar power production roughly quadrupling by 2030 to get the United States to net-zero emissions by 2050. That would mean building many new solar and wind farms, so many that in the most ambitious scenario, wind turbines would cover an area the size of Arkansas, Iowa, Kansas, Missouri, Nebraska and Oklahoma combined.

Such a scale-up is only possible because prices to produce renewable energy have plunged. The cost of wind power has dropped nearly 70 percent, and solar power nearly 90 percent, over the last decade in the United States. "That was a game changer that I don't know if some people were expecting," Hidalgo-Gonzalez says.

Globally the price drop in renewables has allowed growth to surge; China, for instance, installed a record 55 gigawatts of solar power capacity in 2021, for a total of 306 gigawatts or nearly 13 percent of the nation's installed capacity to generate electricity. China is almost certain to have had another record year for solar power installations in 2022.

Challenges include figuring out ways to store and transmit all that extra electricity, and finding locations to build wind and solar power installations that are acceptable to local communities. Other types of low-carbon power, such as hydropower and nuclear power, which comes with its own public resistance, will also likely play a role going forward.

Get efficient and go electric

The drive toward net-zero emissions also requires boosting energy efficiency across industries and electrifying as many aspects of modern life as possible, such as transportation and home heating.

Some industries are already shifting to more efficient methods of production, such as steelmaking in China that incorporates hydrogen-based furnaces that are much cleaner than coal-fired ones, Yu says. In India, simply closing down the most inefficient coal-burning power plants provides the most bang for the buck, says Shayak Sengupta, an energy and policy expert at the Observer Research Foundation America think tank in Washington, D.C. "The list has been made up," he says, of the plants that should close first, "and that's been happening."

To achieve net-zero, the United States would need to increase its share of electric heat pumps, which heat houses much more cleanly than gas- or oil-fired appliances, from around 10 percent in 2020 to as much as 80 percent by 2050, according to the Princeton report. Federal subsidies for these sorts of appliances are rolling out in 2023 as part of the new Inflation Reduction Act, legislation that contains a number of climate-related provisions (SN: 12/17/22 & 12/31/22, p. 28).

Shifting cars and other vehicles away from burning gasoline to running off of electricity would also lead to significant emissions cuts. In a major 2021 report, the National Academies of Sciences, Engineering and Medicine said that one of the most important moves in decarbonizing the U.S. economy would be having electric vehicles account for half of all new vehicle sales by 2030. That's not impossible; electric car sales accounted for nearly 6 percent of new sales in the United States in 2022, which is still a low number but nearly double the previous year (SN: 12/18/21 & 1/1/22, p. 28).

Make clean fuels

Some industries such as manufacturing and transportation can't be fully electrified using current technologies — battery powered airplanes, for instance, will probably never be feasible for long-duration flights. Technologies that still require liquid fuels will need to switch from gas, oil and other fossil fuels to low-carbon or zero-carbon fuels.

One major player will be fuels extracted from plants and other biomass, which take up carbon dioxide as they grow and emit it when they die, making them essentially carbon neutral over their lifetime. To create biofuels, farmers grow crops, and

others process the harvest in conversion facilities into fuels such as hydrogen. Hydrogen, in turn, can be substituted for more carbon-intensive substances in various industrial processes such as making plastics and fertilizers—and maybe even as fuel for airplanes someday.

In one of the Princeton team's scenarios, the U.S. Midwest and Southeast would become peppered with biomass conversion plants by 2050, so that fuels can be processed close to where crops are grown. Many of the biomass feedstocks could potentially grow alongside food crops or replace other, nonfood crops.

Rein in other greenhouse gas emissions

Greenhouse gas emissions other than carbon dioxide will also need to be slashed. In the United States, the majority of methane emissions come from livestock, landfills and other agricultural sources, as well as scattered sources such as forest fires and wetlands. But about one-third of U.S. methane emissions come from oil, gas and coal operations. These may be some of the first places that regulators can target for cleanup, especially "super emitters" that can be pinpointed using satellites and other types of remote sensing.

In 2021, the United States and the European Union unveiled what became a global methane pledge endorsed by 150 countries to reduce emissions. There is, however, no enforcement of it yet. And China, the world's largest methane emitter, has not signed on.

Nitrous oxides could be reduced by improving soil management techniques, and fluorinated gases by finding alternatives and improving production and recycling efforts.

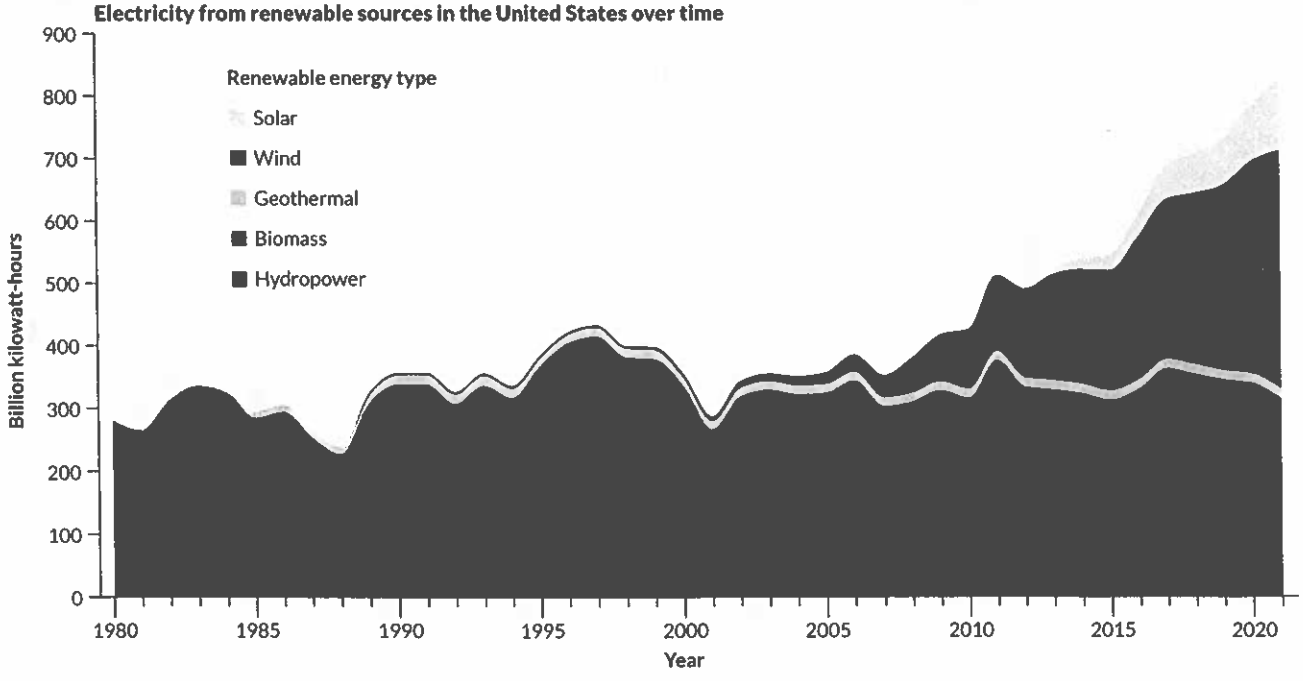
Sop up as much CO_2 as possible

Once emissions have been cut as much as possible, reaching net-zero will mean removing and storing an equivalent amount of carbon to what society still emits.

One solution already in use is to capture carbon dioxide produced at power plants and other industrial facilities and store it permanently somewhere, such as deep underground. Globally there are around 35 such operations, which collectively draw down around 45 million tons of carbon dioxide annually. About 200 new plants are on the drawing board to be operating by the end of this decade, according to the International Energy Agency.

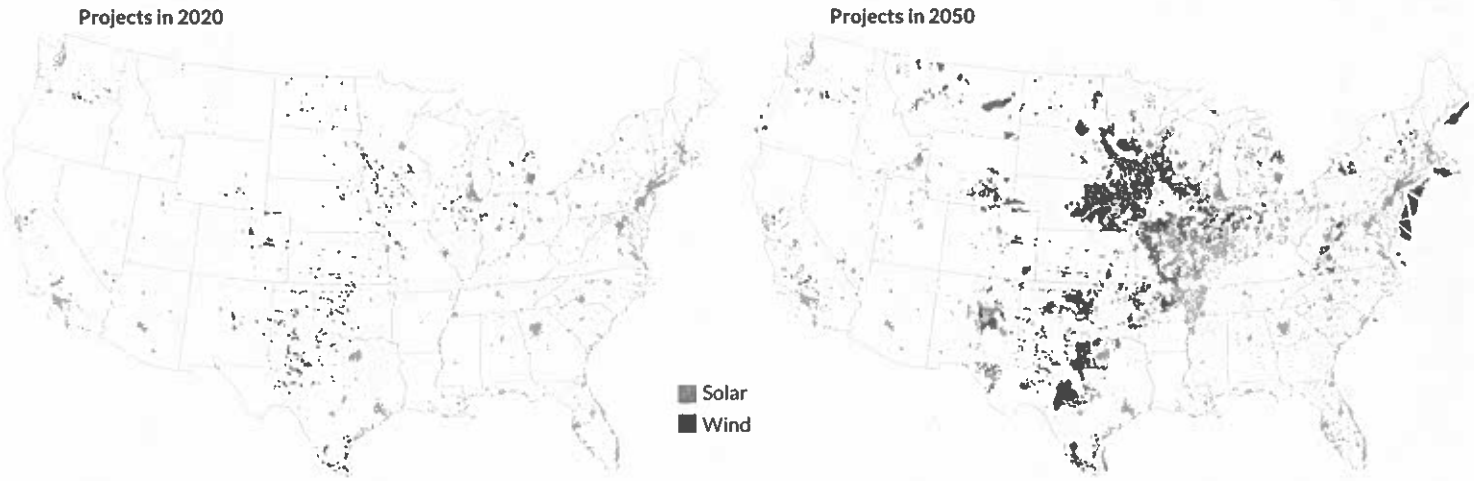
The Princeton report envisions carbon capture being added to almost every kind of U.S. industrial plant, from cement production to biomass conversion. Much of the carbon dioxide would be liquefied and piped along more than 100,000 kilometers of new pipelines to deep geologic storage, primarily along the Texas Gulf Coast, where underground reservoirs can be used to trap it permanently. This would be a massive infrastructure effort. Building this pipeline network could cost up to $230 billion, including $13 billion for early buy-in from local communities and permitting alone.

Another way to sop up carbon is to get forests



E. OTWELL

Catching sun and wind The amount of electricity generated from wind and solar power in the United States has surged in the last decade. The boost was made possible in large part by drops in the costs of producing that energy. SOURCE: U.S. ENERGY INFORMATION ADMINISTRATION



Power up Achieving net-zero would require a dramatic increase in solar and wind power in the United States. The maps above show the footprint of existing solar and wind infrastructure in the contiguous United States (left) and a possible footprint for a midrange scenario for 2050 (right). Gray shows population density of 100 people per square kilometer or greater.

and soils to take up more. That could be accomplished by converting crops that are relatively carbon-intensive, such as corn to be used in ethanol, to energy-rich grasses that can be used for more efficient biofuels, or by turning some cropland or pastures back into forest. It's even possible to sprinkle crushed rock onto croplands, which accelerates natural weathering processes that suck carbon dioxide out of the atmosphere.

Another way to increase the amount of carbon stored in the land is to reduce the amount of the Amazon rainforest that is cut down each year. "For a few countries like Brazil, preventing deforestation will be the first thing you can do," Yu says.

No time to waste

The Princeton team estimates that the United States would need to invest at least an additional $2.5 trillion over the next 10 years for the country to have a shot at achieving net-zero emissions by 2050. Congress has begun ramping up funding with two large pieces of federal legislation it passed in 2021 and 2022. Those steer more than $1 trillion toward modernizing major parts of the nation's economy over a decade — including investing in the energy transition to help fight climate change.

Between now and 2030, solar and wind power, plus increasing energy efficiency, can deliver about half of the emissions reductions needed for this decade, the International Energy Agency estimates. After that, the primary drivers would need to be increasing electrification, carbon capture and storage, and clean fuels such as hydrogen.

The trick is to do all of this without making people's lives worse. Developing nations need to be able to supply energy for their economies to develop. Communities whose jobs relied on fossil fuels need to have new economic opportunities.

Julia Haggerty, a geographer at Montana State University in Bozeman who studies communities that are dependent on natural resources, says that those who have money and other resources to support the transition will weather the change better than those who are under-resourced now. "At the landscape of states and regions, it just remains incredibly uneven," she says.

The ongoing energy transition also faces unanticipated shocks such as Russia's invasion of Ukraine, which sent energy prices soaring in Europe, and the COVID-19 pandemic, which initially slashed global emissions but later saw them rebound.

But the technologies exist for us to wean our lives off fossil fuels. And we have the inventiveness to develop more as needed. Transforming how we produce and use energy, as rapidly as possible, is a tremendous challenge — but one that we can meet head-on.

For Mayfield, getting to net-zero by 2050 is a realistic goal for the United States. "I think it's possible," she says. "But it doesn't mean there's not a lot more work to be done." ■

Explore more

- Net-zero America: Potential pathways, infrastructure, and impacts. Princeton University. 2021.
- Net zero by 2050: A roadmap for the global energy sector. International Energy Agency. 2021.

E. LESLIE, A. PASCALE, J.D. JENKINS/PRINCETON'S NET-ZERO AMERICA STUDY. ANNEX D: SOLAR AND WIND GENERATION TRANSITIONS