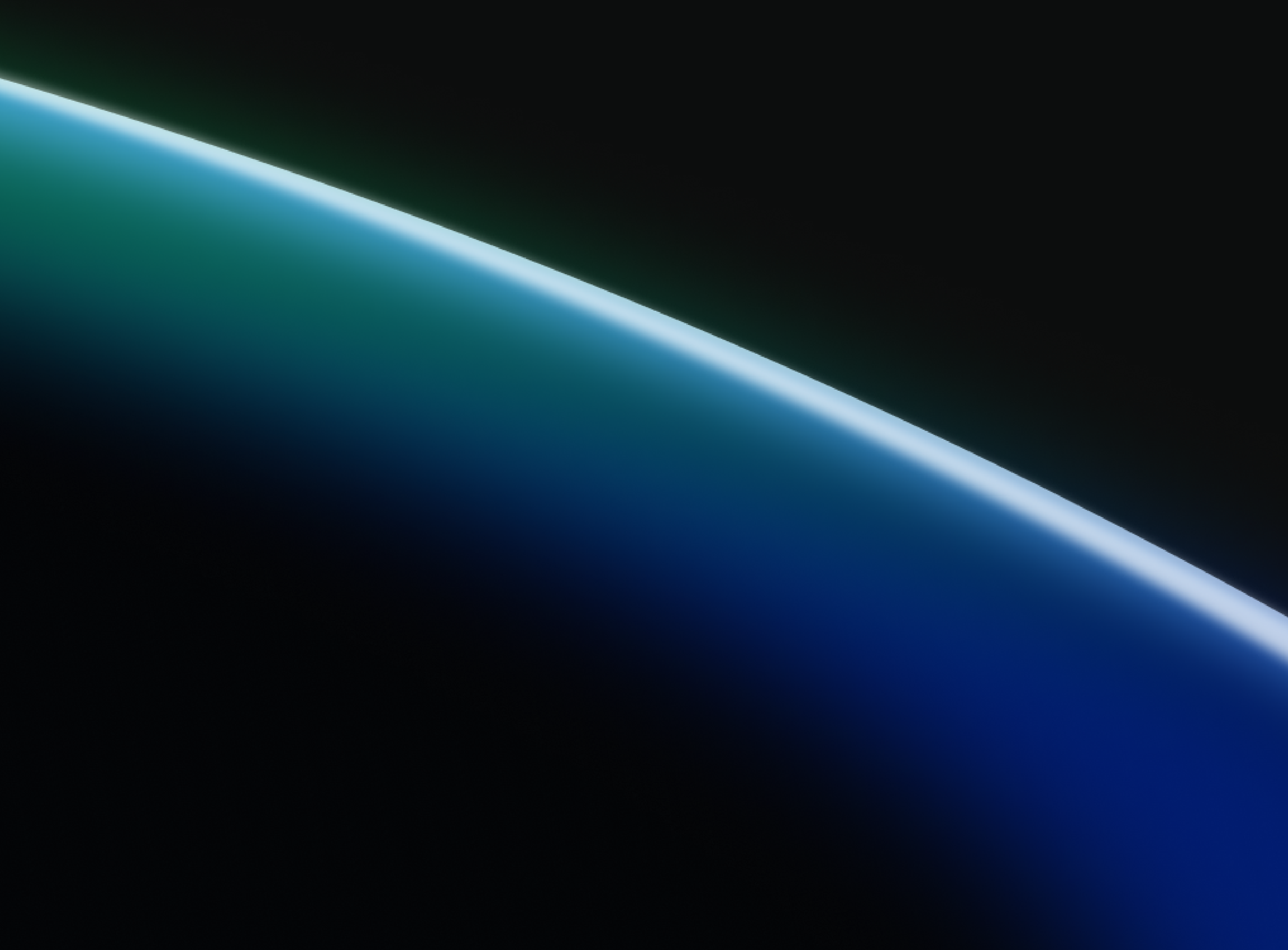
Breakthrough Energy

State of the Transition 2023

Accelerating the Clean Industrial Revolution



breakthroughenergy.org/transition

FOR THE FULL INTERACTIVE EXPERIENCE, PLEASE VISIT OUR REPORT MICROSITE.

UNLESS OTHERWISE NOTED, EVERY COMPANY MENTIONED IS ONE THAT BREAKTHROUGH ENERGY VENTURES – THE VENTURE CAPITAL ARM OF BREAKTHROUGH ENERGY – HAS INVESTED IN.

SOURCES

Foreword

Read a message from our founder, Bill Gates, about the state of the energy transition and why he's optimistic about the road ahead.

Bill Gates

FOUNDER OF BREAKTHROUGH ENERGY

For me, 2023 was a year of climate dissonance.

On one hand, every week seemed to bring another once-in-a-century natural disaster — fires in Greece and Maui, deadly heat waves in India, a drought in Kenya, the sky turning orange in New York — and still, the world pumped more greenhouse gases (GHGs) into the atmosphere than in any year prior.

On the other hand, the year left me feeling more hopeful than at any point in my two decades of working to confront climate change.

Why? One word: Innovation.

FOREWORD

The State Of The Clean Energy Transition

When I founded Breakthrough Energy in 2015, very few people seemed to be talking about how R&D might address the changing climate.

Instead, the world had coalesced around two strategies for reducing GHG emissions. The first was just asking everyone to do less. **Build less. Fly less. Drive less. Buy less.** Not being wasteful is very important, but getting the entire world to pull back on the realities of modern life is not an effective or fair strategy to address climate change. This is especially true for those who don't have enough to begin with — as they often have done the least to contribute to the climate crisis and are struggling to increase basic living standards for their families and communities.

The second strategy was to rely on the limited number of clean electricity technologies we had back then, like wind turbines and solar panels. But electricity only accounts for about a quarter of all GHG emissions. The rest come from factories smelting coal to make steel, farmers laying fertilizer to grow crops, and thousands of other daily activities. **Why,** I wondered, **weren't more people developing new technologies to solve these problems?**

> Eight years later, I am no longer asking that question. The climate innovation landscape has changed completely. It's not an exaggeration to say that we're in the beginning stages of a Clean Industrial Revolution.

Five activities in the global economy — building things, growing food, transportation, generating electricity, and keeping buildings warm and cool — account for 100% of GHG emissions, and in every single one there are new startups developing technologies to decarbonize them.

I call these the "**five grand challenges**," and if I were issuing an innovation report card, each would receive an A or B for the pace and promise of the R&D. In fact, if there weren't so many sources of emissions — if there were, say, one or two grand challenges, instead of five — we'd be on track to achieve a net-zero world in the next decade or two.

Unfortunately, climate change is a bigger and more complex problem than most people imagine — and the problem is still growing faster than our ability to solve it. We need to find new ways to accelerate our efforts — fast-forward buttons for decarbonization.

2023

The following report is a 2023 snapshot of this race to get emissions to zero; a snapshot as seen through the lens of the investors, technologists, policy experts, and innovators at Breakthrough Energy — which means innovation is placed squarely in the foreground.

In many cases, this document provides an update on ideas, technologies, and policies profiled in my 2021 book, **How to Avoid a Climate Disaster.** All are worthy of more investment and attention, but there are three that we're talking more and more about at Breakthrough Energy: **hydrogen, carbon removal, and the electricity grid.**

I wanted you to read about these three technologies first because they could be those decarbonization fast-forward buttons. They can help us abate emissions across many of the grand challenges — and maybe all of them.

ILLUSTRATION OF HYDROGEN MOLECULES

HYDROGEN

There are no silver bullets for climate change, but hydrogen comes close.

The most plentiful element in the universe is pure reactive chemical energy, which means it can replace fossil fuels almost everywhere they're used, from an airplane's fuel tank to many industrial processes. (For this reason, you'll see hydrogen pop up throughout the report.)

1

Many startups have made great strides in producing hydrogen, often through a process called electrolysis. The challenge is less about whether we can supply hydrogen — and more about whether there's demand for it. In theory, hydrogen can play a key role in decarbonizing many sectors of the global economy, especially through seasonal energy storage. To make sure we don't go dark when the sun isn't shining or the wind isn't blowing, electricity can be converted into hydrogen, stored for months, and then converted back to electricity when it's needed. The problem is these markets for hydrogen haven't developed quickly enough.

CARBON REMOVAL

Even if humanity stopped emitting carbon dioxide (CO_2) tomorrow, climate change wouldn't be solved

ROCKEFELLER-ERA OIL SITE

2

— because there'd still be a century's worth of GHGs trapped in our atmosphere. The oil drilled by John D. Rockefeller and the fuel burned by World War II bombers is long gone, but the CO_2 they emitted is still here — in the air around us, keeping our planet warm.

Getting rid of these historic emissions is crucial to addressing climate change, and one way is called nature-based carbon removal — planting trees, preventing deforestation, and managing soil and croplands more efficiently. But nature-based removal doesn't cover nearly enough emissions to be a panacea, and it's notoriously hard to measure.

On the other hand, engineered carbon removal, which includes direct air capture, offers much clearer markers of progress, but it's also prohibitively expensive for most of the world, making it nearly impossible to scale. A hybrid model may be the most promising and cost-effective solution to come along yet.

It's important to understand that carbon removal is not an excuse to keep emitting, or to slow down our transition to a clean energy economy — we need to keep innovating as fast as we can. But it's become clear that carbon removal will be a necessary tool to have in our toolkit.

Still, the whole carbon management industry is very nascent, with technologies that are expensive at best (and ineffective at worst). Investors, innovators, and governments are going to have to keep exploring this field, knowing that they may hit some dead ends. Carbon removal is that important to our future.

ELECTRICITY GRID

3

ELECTRICITY TRANSMISSION

A core component of the world's net-zero strategy is "electrifying everything":

replacing gas-powered vehicles with battery-powered ones, for example, then charging those car batteries up with clean electricity.

The first step of this process is producing lots of clean electricity, and the world has made significant progress, deploying 280 gigawatts of it last year alone — about 23 times the electricity consumption of New York City. It's the second step — transmitting that electricity everywhere — where we're stumbling.

In much of the world, power grids are either unbuilt or woefully obsolete, a problem that limits the impact every new wind turbine, solar farm, or nuclear plant can have. The Inflation Reduction Act (IRA), recently passed in the United States, is projected to cut emissions by roughly a billion tons — so long as there's a functioning grid. If not, the IRA may only achieve 20% of that projection.

In every country, we need to build new, smarter grids — interstate highway systems for power — that can reliably bring high-voltage power from new, net-zero sources to people everywhere.

What's next? A harder, more practical exam

In many ways, electricity transmission foreshadows the next phase in the fight for our climate. New technology can definitely help improve our power grid. Engineers can invent more advanced power lines that transmit more energy. But really, transmission is a scale problem — not an innovation problem:

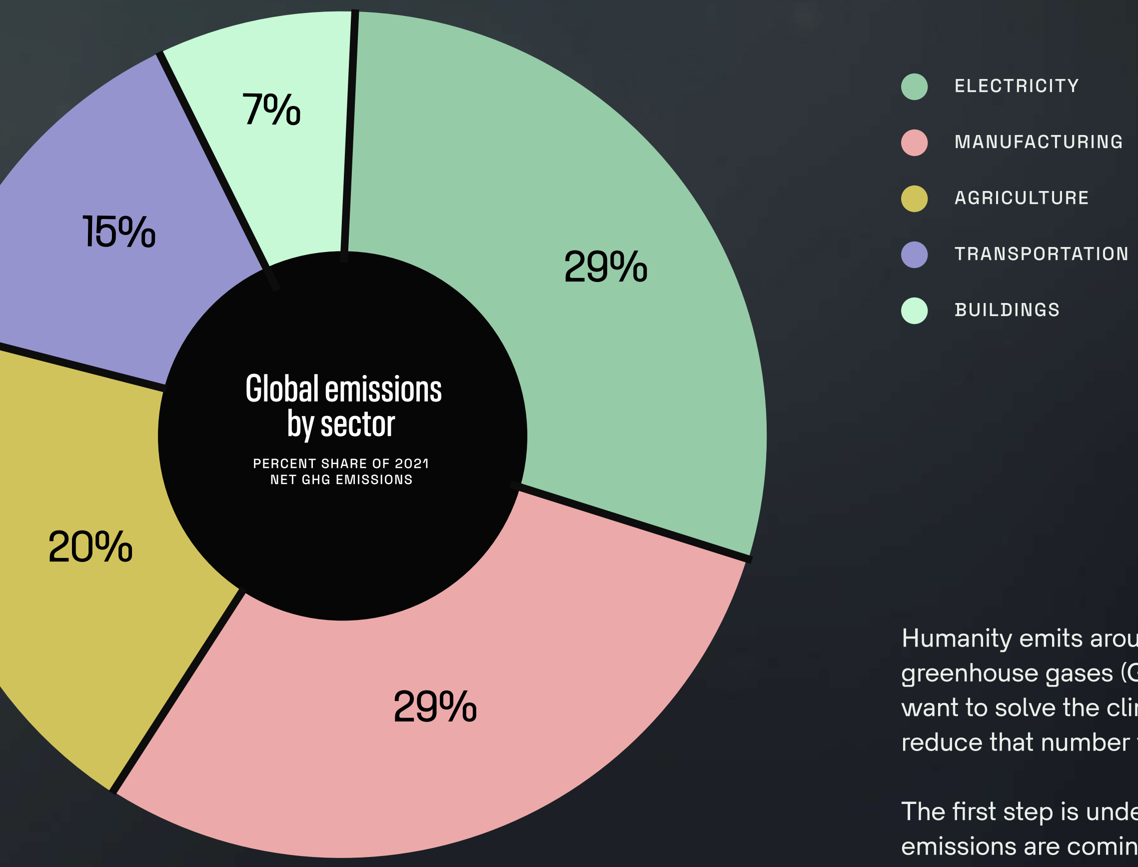
Even if you invent new power lines, how do you get the permits to build them? Will governments make it easier to send electricity across borders?

Questions like this will increasingly determine how bad things will get.

Climate innovators should be given a stellar grade for their work in the lab, but in future years, we'll all face a much harder practical exam — getting those innovations out into the real world.

Bill Gates
FOUNDER AT BREAKTHROUGH ENERGY

The Grand Challenges



SOURCE
Rhodium Group

Humanity emits around 52 billion tons of greenhouse gases (GHGs) every year, and if we want to solve the climate crisis, then we need to reduce that number to zero.

The first step is understanding where these emissions are coming from. Five activities account for 100% of all emissions.

As Bill mentioned, we call the work of decarbonizing these sectors, “Grand Challenges,” and in the following pages, we walk through all five of them, discussing the latest technologies, policies, and challenges in detail.

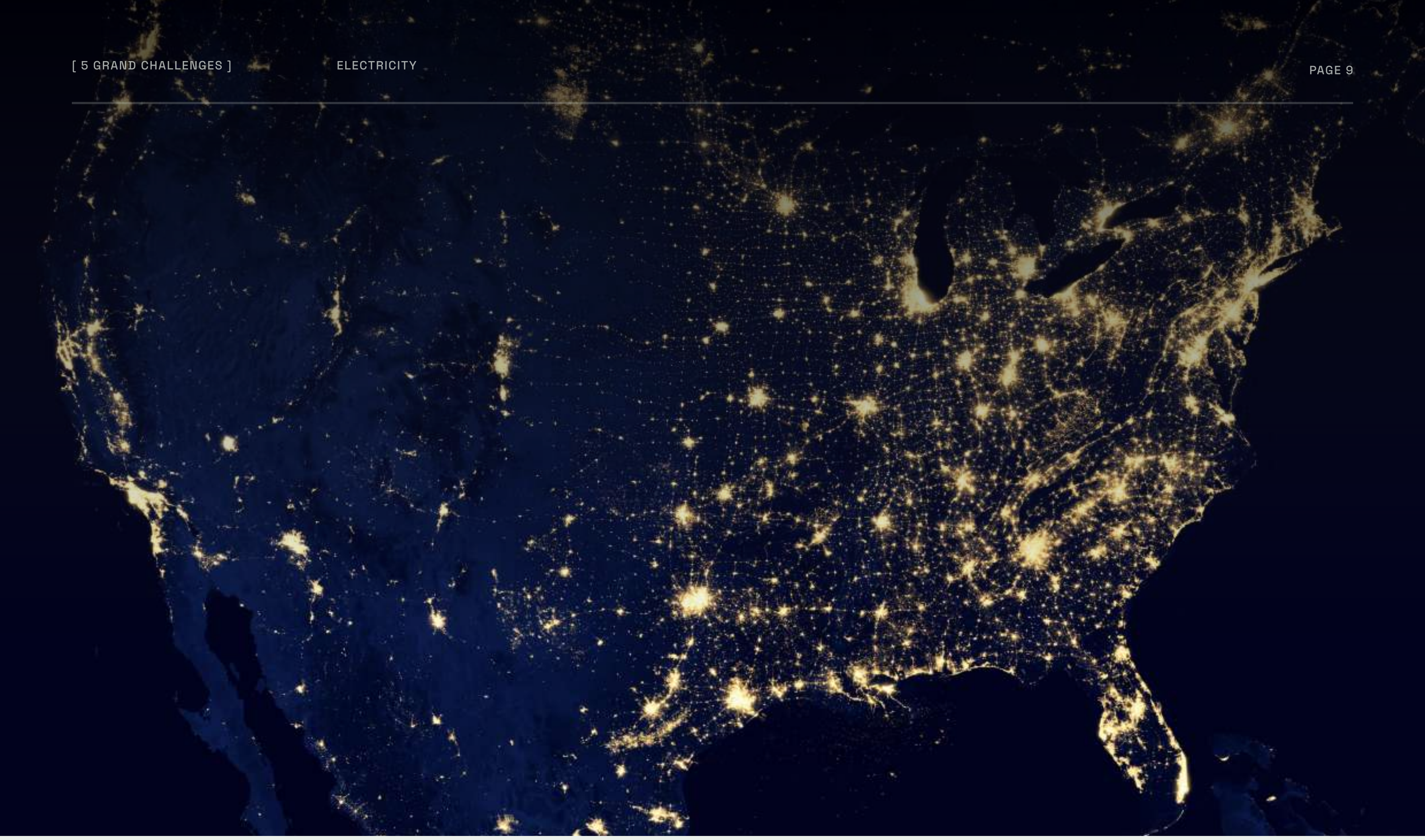
Unless otherwise noted, every company mentioned is one that Breakthrough Energy Ventures — the venture capital arm of Breakthrough Energy — has invested in.

29% of Global Greenhouse Gas Emissions

Electricity

A zero-carbon world won't be one where people use less electricity, but more. Find out why in this section as we explore the latest advancements in renewable energy, electrical transmission and storage, and nuclear power.

1



HOW WE PLUG IN

A VIEW OF THE U.S. ELECTRICAL POWER GRID FROM SPACE

The Electricity Grand Challenge

IF YOU ONLY HAVE BRAIN SPACE FOR THREE THINGS

1 A zero-carbon world won't be one where people use less electricity, but more. Most experts agree that the world will need to triple the amount of electricity we use by 2050. The world is making progress generating this electricity cleanly, but that's meaningless if we can't move it or store it efficiently and affordably.

2 What about nuclear power? Fusion is an innovation on par with the industrial revolution or the discovery of fire. But if we wait for fusion, it may be too late. We have to have a baseload power to rely on, and fission is the best-understood zero-carbon option available.

3 Going forward, the technology is in decent shape, though prices need to come down to incentivize adoption. But we need to rebuild (or build outright) all our electricity grids — and permitting, siting, and general NIMBYism remain significant policy hurdles to that.

Electrify Everything

1

In the early 2000s, the public conversation around climate change often boiled down to a footprint. Conventional wisdom — and several handy calculators and quizzes — told us that we needed to reduce our carbon footprint by using less electricity.

They got the first part right. We do need to reduce our carbon footprint to net zero. But over the last decade, experts have developed a new, counterintuitive understanding of how to get there:

MAJOR CITY LIT UP AT NIGHT

COAL-FIRED POWER STATION AT NIGHT

We don't sacrifice our use of electricity. We expand it.

Here's why: When you run your air conditioner or heat your oven, that usually burns carbon because most homes are connected to a power grid.

At the other end of that grid is often a coal or natural gas plant. Today, those plants account for about a quarter of all emissions globally. To get to net zero, the world needs to replace those carbon-emitting sources of energy with clean ones.

But people also emit a ton of carbon without ever plugging into an outlet or connecting to a grid. They drive cars with internal combustion engines. They make steel using coal or heat buildings using natural gas.

We'll talk about these emissions sources in the following pages, but what they have in common is that often, the best way to decarbonize them is with zero-carbon electricity: replacing your gas-powered car with one that plugs into the wall, for example.

That's why even though carbon-based electricity accounts for about a quarter of all emissions, carbon-free electricity amounts to more than a quarter of the solution. The world has roughly 8,000 gigawatts of installed electricity capacity. It's not just a matter of making sure all 8,000 are produced with wind, or solar, or nuclear. It's a matter of building another 20,000-30,000 carbon-free gigawatts so we can reduce emissions in other areas.

AERIAL VIEW OF A SOLAR POWER PLANT IN THE COUNTRYSIDE

It's also about keeping up with demand. Because as we electrify things, more people will need even more electricity. Estimates suggest that electricity demand could triple by 2050 in order to reach net zero.

2050

Demand will also continue to increase as emerging markets become wealthier. A society's wealth directly correlates to how much energy it has access to. And all nations should be as prosperous as they can be. We'll never build a coalition to fight climate change if the implicit message is that people have to stay poor.

THE GOOD NEWS

Of all the grand challenges, the most progress has arguably been made in electricity, propelled by low-cost and widely available clean energy and batteries.

AERIAL VIEW OF ELECTRIC TOWERS IN GREEN FIELDS

Of course, generating energy and delivering electricity are two different problems. We've gotten a lot better at generating clean electricity over the past decade. Figuring out how to deliver and store it for later use has been a little tougher.

The big challenges with delivery are storage and transmission. How do we get clean electricity to people when and where they need it?

With fossil fuels, it's easy.

You transport coal or natural gas to a power plant, convert it into electricity, and then send the electricity along power lines to the homes and cities that need it.

ARRAY OF SOLAR PANELS IN NEVADAN DESERT

Solar and wind power don't work that way. The sunniest and windiest places aren't the only ones that need electricity, and they're not usually near big cities either. Plus, you can't exactly ship sunlight or wind in a railcar or a pipeline.

Storing and transmitting clean electricity will require big, modernized, and interconnected electric grids. Right now, those don't exist. In some countries, the grids are too small, old, and fragmented — in other countries, they don't have grids at all.

We'll get to all of these issues in the sections below. But let's start at the beginning of the electricity process: Where do we get the energy?

RENEWABLES

The Winds — and Rays — of Change

2

Since Breakthrough Energy was founded eight years ago, the proliferation of wind and solar power has been astonishing.
Last year alone, the world deployed 280 gigawatts of renewables — enough to supply about 23 times the annual electricity consumption of New York City. And as we've gotten more efficient at building them, these sources have also become more affordable. Solar cells were 10 times cheaper in 2020 than in 2010.

AN ILLUSTRATION OF FOUR OFFSHORE WIND TURBINES

We've also seen growth and innovation in geothermal and hydropower. In fact, hydropower is the biggest source of renewable energy in the United States — and new technologies are creating ways to access it in different circumstances than the traditional large-scale dams we're used to. And if we can find a cost-effective way to tap into Earth's vast reserves of deep geothermal heat, we have a huge opportunity to provide large amounts of zero-carbon power: experts estimate more than 1,000 gigawatts are readily available in the United States alone.

For example, **Fervo**, a Breakthrough Energy Ventures company, uses new drilling technologies to drill horizontally into geothermal reservoirs. Not only does this open up new, untapped reservoirs of power, but it also lowers our carbon footprint by allowing us to drill multiple wells from the same location.

A FERVO GEOTHERMAL
DRILLING SITE

A MOTION-BLURRED PHOTO OF OFFICE BUILDINGS IN A BUSINESS DISTRICT

But it's still not enough — especially given the ongoing challenges, including that nearly half of the wells dug for geothermal power turn out to be duds.

Most people — even those who run big utility companies — haven't fully grasped just how much energy we actually need. It's a huge amount. In order to meet the 2050 net-zero goals, the International Energy Agency (IEA) estimates that we will need to start deploying renewable energy at least three times faster.

Right now renewables are scaling rapidly to meet that challenge. And several companies are working to accelerate the pace and address the cost and logistical hurdles that renewable energy generation faces.

For example, **Aikido**, a company led by three Breakthrough Energy fellows, is developing a self-upending, semi-submersible platform designed specifically for floating, offshore wind turbines. It can fold up so the turbine and the platform can fit through relatively small spaces and unfold like a fan when it reaches its target spot in the ocean.

The bigger issue with renewables, though, is intermittency. People need electricity on demand even when the wind doesn't blow or the sun doesn't shine. But what if the grid wasn't dependent on the weather?

The most efficient way to handle the intermittency challenge is through a combination of storage and transmission. These two solutions would allow us to move electricity through time and space. Let's start with storage.

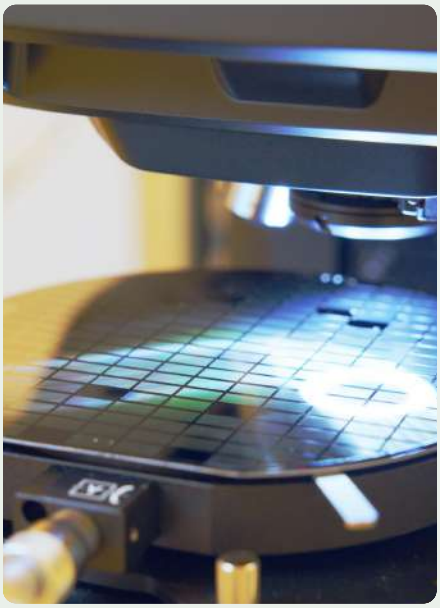
AN ILLUSTRATION OF A MALTA ENERGY STORAGE SITE

STORAGE

Energy When We Need It

3

Generally, when you make electricity from solar and wind power, you get it when they give it, unless you can store it for another time. That's why storage — one of the biggest challenges the world faces in the energy transition — has been such a significant area of investment for Breakthrough Energy and innovators throughout climate tech. It's central to building a clean and reliable grid. And it is key to fulfilling the promise of renewable energy — ensuring that it can be stored so that it's available on demand.



ANTORA ENERGY'S THERMOPHOTOVOLTAIC CELL

In the short term, the best way we have to store this electricity is through batteries. While this technology has improved in recent years, it is still incredibly expensive.

Researchers are continuing to work on ways to extend their duration and make them more cost effective. But some of the most exciting developments we've seen have come in long-duration energy storage (LDES) technologies.

A BATTERY BUILT BY FORM ENERGY

A holy grail for LDES would be hydrogen. As Bill wrote in this report's foreword, hydrogen could be a key way to store renewable energy that powers cities where the sun isn't shining or the wind isn't blowing. That's because hydrogen is the key ingredient in fuel cell batteries, and these batteries, unlike wind or sunlight, can be boxed up and shipped and stored for years before they're converted back into energy.

The challenge is cost. It's expensive to manufacture hydrogen without emitting carbon dioxide (CO_2). Fortunately there are other ways of producing LDES technologies — mechanical, thermal, chemical, and electrochemical methods that can operate for at least 10 hours.

100 HRS

One promising company is **Malta**, which takes electricity from the grid and converts it with a heat pump to thermal energy by creating a temperature difference. The heat produced by this process is stored in molten salt, while the cold is stored in a chilled liquid antifreeze coolant. When the grid needs power, the temperature difference is converted back into electrical energy by a heat engine.

Form Energy has come up with another method. Founded by the former head of Tesla's stationary energy storage program, it stores electricity for up to 100 hours in what's known as an iron-air battery that converts iron into rust and then reverses the process on demand.

AN ILLUSTRATION OF FORM ENERGY'S BATTERY ONE FACILITY

FORKLIFT MOVING CARBON BLOCKS

In addition to storing electricity for a longer period of time, LDES could also enable the decarbonization of other sectors, such as industrial heating processes. **Antora** is working on exactly that, storing renewable electricity from sources like wind and solar as heat in solid carbon blocks. These are just some of the innovative companies working to solve the storage problem. But we also have to focus on scaling and deploying these technologies.

Scaling LDES presents several challenges. Most LDES manufacturers are either startups or newly-public companies with limited experience in large-scale production. It's also hard to monetize these technologies, as most markets prioritize shorter duration storage.

What's more, there's no clear standard for defining LDES or measuring its performance. And since lithium-ion batteries already dominate the energy storage market, it could restrict the need for LDES, especially for storage needs below eight hours. The low market penetration of renewables presents another limitation, as LDES only becomes essential if and when renewable sources represent the majority of the energy mix.

For long-duration energy storage to be deployed at scale, the market must recognize and compensate for the unique benefits these technologies provide, such as supplying power during peak demand or maintaining grid stability during periods of high variability.
LDES is pivotal for the decarbonization of the US and international power grids. And moving forward, governments need to enact more policies that catalyze the deployment of LDES and create demand.

TRANSMISSION

Energy Where We Need It

4

So, we've discussed storing energy. But how do we move it?

Let's use the United States as a case study. Last summer, the United States Congress passed the Inflation Reduction Act, investing billions in clean energy and taking a historic step towards building the economy needed to meet the goal of decarbonizing the power sector by 2035.

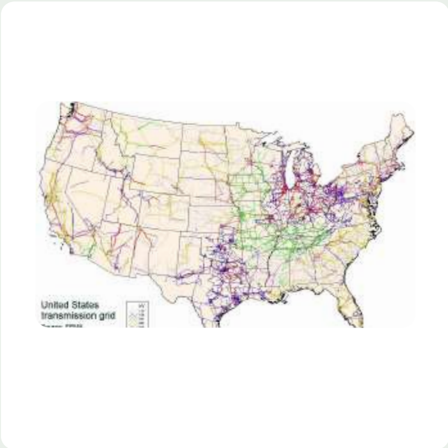
THE FLOW OF ELECTRICITY

But there's a problem: The United States' power grid isn't ready for it.

Right now, the United States' outdated power grid is creating a bottleneck effect — they have the energy, but it has nowhere to go. In fact, 80% of the IRA's emissions reductions will go unrealized if the United States doesn't increase its grid's transmission capacity by over 60% by 2030 — and at least double or triple it by 2050.

Most of the power lines you see today in the United States were built between the 1950s and the 1970s. In terms of electricity infrastructure, it's downright ancient, and these power lines were only meant to last 50 years in the first place.

In fact, the United States doesn't really have one grid, but a messy patchwork of many grids, which makes it essentially impossible to send electricity beyond the region where it's made. It's also fairly dumb. Systems don't talk to each other well and are slow to adapt to change.



A TRANSMISSION GRID OF THE UNITED STATES

The U.S. power grid wasn't designed with a net-zero world in mind. It relies on railroads and pipelines to move fuel over long distances to centralized power plants, where that fuel is turned into electricity and transmitted over short distances to the cities that need it. This system doesn't work for wind and solar, which are intermittent and often far from where people live.

That's why the United States needs to upgrade the grid, build more high-voltage transmission lines that can carry electricity long distances, and use those transmission lines to better connect regions and communities to one another.

In other words, an interstate highway system for electricity needs to be built that can bring power to every corner of the country (on land and offshore), with the digital systems to make it smart, adaptable, and efficient.

A VIEW OF THE U.S. ELECTRICAL POWER GRID FROM SPACE

This is no small task. It took the United States more than a century just to build the fragmented grid it has today.

And in order to reach its climate goals, the United States needs to replace the existing wires and at least double the size of that grid in less than 30 years.

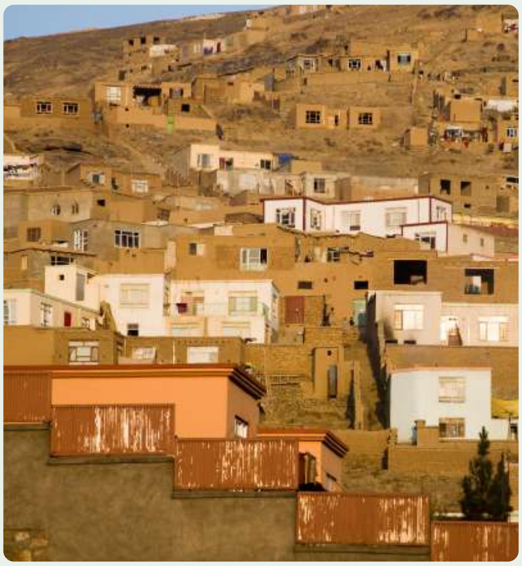
Unlike a lot of the other issues we'll discuss, transmission is primarily a policy problem, not a technological one. The technology, for the most part, already exists.

But in the United States, it's hard to build new power lines. The current permitting process is long and convoluted. You need available, connecting parcels of land and communities that are willing to have power lines running through their parks and neighborhoods. To put this in perspective, a transmission project carrying wind power from Wyoming to California took 18 years to fully permit. We just don't have that kind of time.

GREEN AND RED AURORA OVER
A FIELD WITH POWER LINES

This isn't just a U.S. problem. Grid challenges are global. From getting permits to finding connecting land, most nations are facing similar obstacles to expanding and updating their grids.

In fact, Europe presents more complicated challenges than the United States; instead of 50 states, you're dealing with over 20 countries. And a third of the European Union's grids are already over 40 years old — by 2030, half will be.



AN IMAGE OF A NEIGHBORHOOD ALONG A DESERT HILL

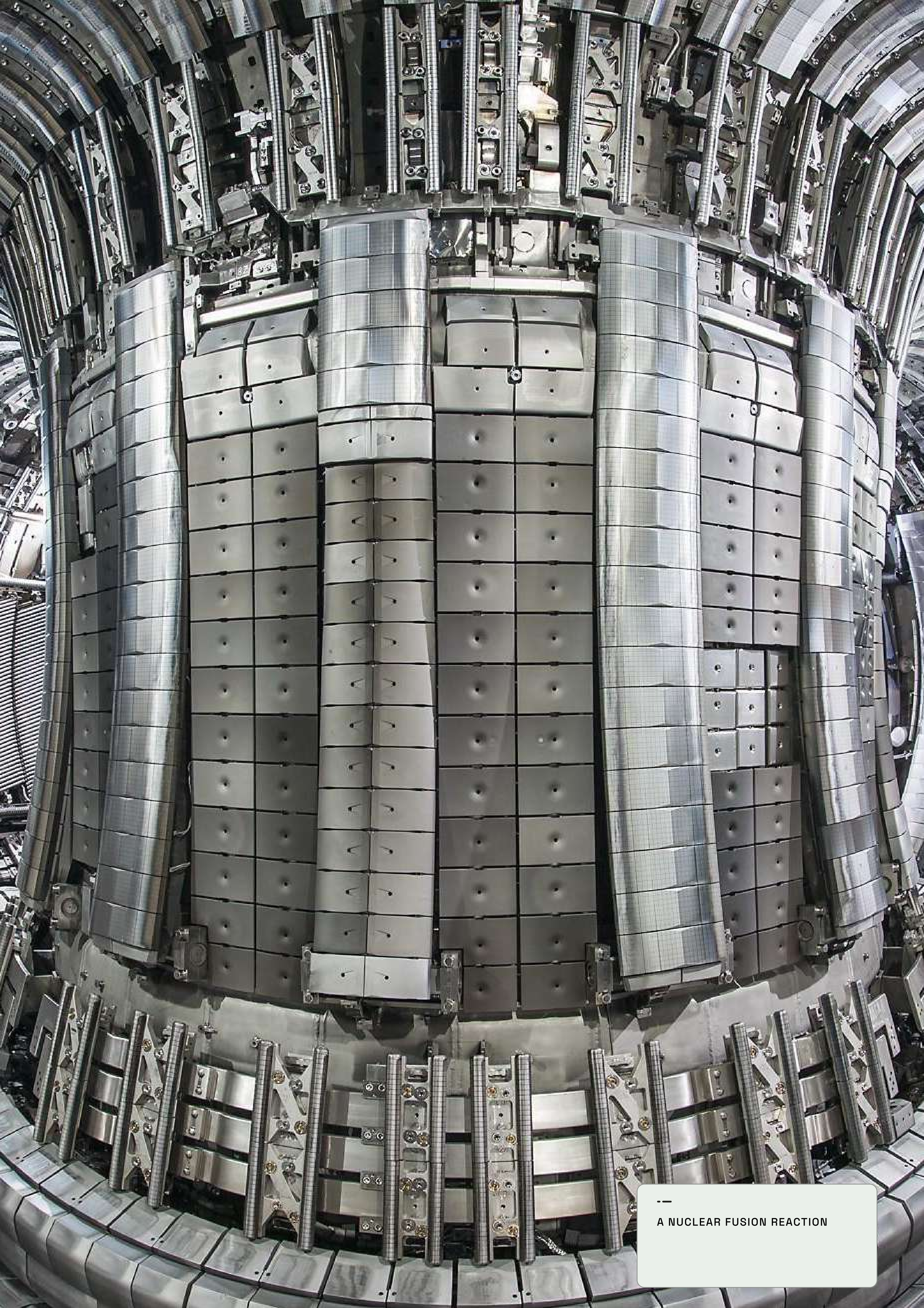
The issue is even more acute in low and middle-income countries where fiscal constraints make it very difficult to connect.

Even in places like China, where companies have been able to build ultra-high voltage transmission lines faster than anywhere else, the country faces challenges making new DC lines interoperable with its regional AC grids, and balancing supply and demand to prevent blackouts and reduce electricity waste.

In regions like Sub-Saharan Africa, where half the population lacks access to electricity, the primary issues with upgrading and expanding the grid are access to capital and governance. In the interim, smaller-scale solutions such as microgrids can help expand energy access, as these places continue to develop and invest in large-scale grid infrastructure.

Although transmission is primarily a policy problem, innovation will help too. For example, what if we could take existing power lines and transmit more electricity through them? This could help build out electricity capacity while working through the permitting process of building new transmission lines.

There's no transition without transmission.



A NUCLEAR FUSION REACTION

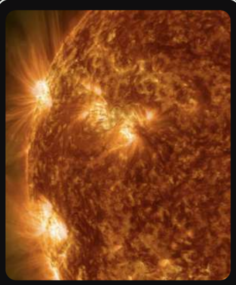
NUCLEAR

Fission, Fusion, and the Future

5

We need every tool at our disposal to fight climate change, because almost every energy source presents tradeoffs. We've talked about wind and solar, storage, geothermal, and hydropower — all critical technologies. But we haven't yet discussed the elephants in the room: nuclear fission and fusion.

SMOKE RISING FROM A NUCLEAR PLANT IN FRANCE



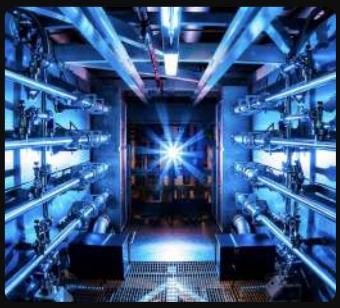
THE SURFACE OF THE SUN

The simple answer is they're going to be vital, but in different ways. Fission — the one you think about when you hear the phrase "nuclear power" — is created by splitting atoms. And it's already an important source of clean energy for countries around the world. Just ask France, which currently gets 70%of its power from it, or Ontario, which gets more than 50%.

That's because fission can deliver a lot of power with a limited footprint, day and night, all year long, anywhere on earth. No other clean energy source can reliably do that.

There are several organizations working to build next-generation fission reactors that produce far less waste and don't pose the same risks as older reactors. In fact, with the help of supercomputers, we can now game out digital simulations of different reactor designs to make sure we're building the safest reactor possible. These new designs inherently prevent the kind of accidents people tend to associate with fission power. Advanced fission designs have ameliorated some of the cost concerns, too, and companies using these designs will be commercial this decade.

There's another "nuclear" in this story though. It's called fusion, and it holds even greater promise than everything we've discussed so far.



INSIDE OF A NIF PREAMPLIFIER SUPPORT STRUCTURE

While fission takes atoms apart, fusion pushes them together — or, fuses them. This is the same process that powers the sun, and here on Earth, scientists replicate it with lasers or pushing plasma around inside a big magnet. If the scientists replicate it with lasers or by pushing plasma around inside a big magnet., the fusion process stops. There is no potential for a runaway chain reaction or meltdown.

Researchers have actually been doing fusion reactions since the early 1900s. But for the last century, fusion had a problem: fusion reactors always took in more energy than they put out. That is, until last year.

In December of 2022, researchers made a historic breakthrough. Scientists at Lawrence Livermore National Laboratory outside of San Francisco achieved the first fusion reaction in history to generate more energy than it took in.

The best analogy here might be Kitty Hawk — both in its importance and infancy. The Wright Brothers' plane changed history, but it was a far cry from commercial production when it launched into the air.

That's where fusion is today; still in the research and development stage, where it's only done in labs, but beginning to move to the domain of real companies putting energy out into the world.

WILBUR WRIGHT GLIDING DOWN A SLOPE IN KITTY HAWK, NORTH CAROLINA

So why don't we just forget about the rest and focus on fusion?

First off, while the advancements we've made in fusion are astounding, there's still a lot of uncertainty.

And second, it will be too late. The first fusion power plant will likely hit the US grid by 2030. But the technology probably won't be ready for widespread adoption for years after that. We can't wait that long. Fusion could have a profound, positive impact on humanity — providing energy abundance for the world over, but we'll have to rely on other technologies to ensure that the world is still livable by the time we can make good on fusion's promise.

29% of Global Greenhouse Gas Emissions

Manufacturing

There's no path to net zero without improving how we build things. In this section, we discuss the challenges and opportunities of changing the way we make cement, steel, and other materials that make up our world.

2

MAKING THINGS BETTER

AN AERIAL VIEW OF A CONSTRUCTION SITE

The Manufacturing Grand Challenge

IF YOU ONLY HAVE BRAIN SPACE FOR THREE THINGS

1 Cement and steel are the most widely used materials in the world, responsible for 10% of global greenhouse gas (GHG) emissions. But they're actually among the lowest emissions-intensive building materials that we have today — we just use them at incredibly high volumes.

2 Given the challenges of replacing these materials — which are ubiquitous and have unique advantages — our main focus should be on making improvements to their process and supply chain, while also developing high performance substitutes where possible.

3 Going forward, there's a lot of opportunity for technological innovation in this sector. But we also need to aggressively incentivize the use of clean steel and cement through public procurement, tax credits, demo project funding, and other methods. More funding and confidence in promising technologies can help move the needle on this notoriously hard-to-decarbonize industry.

STEEL AND CEMENT

The Hardest Decarbonization Challenge (pun intended)

A WORKER AT A STEEL PLANT

1

So far, this report has avoided rank-ordering our carbon problems — because that's pretty much impossible. What's harder to decarbonize: the world's electricity grid or our transportation sector? Or what about our food supply?

There's no real consensus, with one salient exception: manufacturing.

That shouldn't scare us off, though. If anything, it should motivate us. Because in the face of the toughest challenge, we've already started making inroads.

Today, 29% of all (GHG) emissions come from how we make things. And this may be the most difficult chunk of carbon to get rid of.

Why? Because of the two most commonly manufactured materials on Earth: steel and cement. (How common are we talking? Concrete, the mixture of cement and water, is the second-most consumed material **on the planet**, after water.)

TEMPLE OF PALLAS, ROME

The majority of cement and steel emissions comes from the high-heat processes that create these materials themselves. Cement is made by heating up calcium carbonate to nearly 1,500°C, and steel is formed by reducing iron ore in massive blast furnaces that can get as hot as 2300° C. Most of these operations are not currently electrified.

That's partly because these processes far predate electricity; they have been honed over thousands of years. Cement dates back to the Romans, and people were refining steel at the same time wooly mammoths walked the earth. Countless generations have perfected the science of making these materials cheaply, abundantly, and relatively efficiently.

Both cement and steel are, pound for pound, among the lowest carbon dioxide (CO_2) emitters among common building materials. We just use them in such enormous quantities that they end up having this outsized impact on the climate.

How can we find a cheaper, greener option for materials that are already cheap, that are already low-carbon, and that are so abundant that they literally compose the foundation of our world?

An important first step would be "electrifying everything" that we are able to as we outlined in the previous chapter: innovative electrification technologies will be required to cut down on the energy footprint of cement and steel manufacturing.

Then, with the innovative technologies at our disposal, and sufficient investments in them, we can improve nearly every step of both these processes, from cleaner component parts of cement to the way iron ore is reduced into steel. For the final stretch, we need to harness public policy, regulations, and behavioral change to actually increase uptake of these innovations in industries that are often set in their ways.

ROLLS OF STEEL SHEET
STACKED IN A FACTORY

CONCRETE JUNGLE

Reinventing Cement

2

Today, the global cement market is worth nearly $900 billion. About 60% of cement emissions come from the "process," whereby carbon dioxide is released from limestone to form calcium oxide. The other 40% come from energy, or the heat that makes things like mining and limestone processing possible.

It's hard to displace cement, because most alternatives, like clay bricks, have higher emissions per unit, cost more, or don't have the same broad functionality.

A CEMENT MIXING TRUCK

WORKERS MIXING CEMENT

So how should we think about decarbonizing cement? We can start with different approaches or chemistries to make cement.

The vast majority of cement used today is "Portland cement," a mixture of limestone, clay, and other minerals typically burned in a kiln, a recipe first developed in the 19th century. But innovators are finding ways to make cement that do not emit so much CO2. We already have some promising options.

For example, there's **Brimstone**, a startup that has developed a process to make Portland Cement in a new way – from calcium silicate rocks, which have no embedded CO_2, instead of the traditional limestone. These rocks fit almost seamlessly into the existing cement supply chain, creating just one extra step.

EXTERIOR OF A BUILDING
MADE OF CONCRETE

A second approach is to stretch cement further. In traditional formulas, cement constitutes about 10% to 15% of concrete. But what if we could get that down to five percent? Or even lower?

Turns out, that's eminently possible. We just have to add other ingredients known as "supplementary cementitious materials," or SCMs. We already have several SCMs that can help reduce the amount of clinker (the stony pieces left behind after coal is burned) in cement: fly ash, slag cement, silica fume. One company working in this space is **Terra CO2**, which makes SCMs from widely available silicate-based raw materials found near existing aggregate mines.

Another case study is the company **Ecocem**, an emerging startup in Breakthrough's investment portfolio in Europe, which has invented ingenious new concrete formulations using finely ground binders and fillers to achieve concrete with only four percent ordinary Portland cement (OPC). In a sign of its widespread potential, Ecocem is already building out facilities for next summer's Paris Olympics.

Conveniently, all these stretching measures are also cost-saving measures, because cement is the most expensive component of concrete.

One team working on this problem from an entirely different angle is a Breakthrough Energy Fellows project called **Chement**, which has pioneered a new room-temperature electrochemical process that provides an extremely energy efficient way to produce cement with renewable electricity.

AN ILLUSTRATION OF A CEMENT PLANT

Another potential intervention is carbon capture and storage, or CCS. Since cement is already so cheap per unit, the "Green Premium" here is pretty high, and a CCS surcharge can often mean almost doubling the price of cement. And retrofitting existing plants may not make great economic sense, because a new CCS plant costs almost as much as a cement plant — but it's a good option to have on hand for new construction, especially in emerging markets.

None of these piecemeal solutions are sufficient in and of themselves, because the industry is already so large and established, and these interventions all take a long time to implement.

On the flip side, many of them work well together, and we should consider stacking them wherever possible.

A NEW LOOK

Green Steel

3

3000 years after we started making steel, this strong and cheap alloy of iron and carbon represents over 90% of all the metal used in the world. It's also the single most emissive manufactured good on earth — responsible for roughly 2.5 gigatons of carbon dioxide (CO_2) emissions each year, excluding the emissions from generating electricity used in steel production (those are included in the electricity section).

That's about five percent of all global greenhouse gas emissions.

A STEEL FURNACE

Carbon isn't just a source of energy in steelmaking, but also the most common reducing agent that helps rip the oxygen off naturally-occurring iron ore to make steel. 70% of today's steel is made in blast furnaces, a technology invented in the 18th century to reduce steel using huge quantities of carbon.

Decarbonizing steel is hard, due to the metal's extremely broad functionality, but we do have two broad paths to try and do so. The first is by decarbonizing the primary steelmaking process itself, and the second is by increasing the quality and quantity of recycled secondary steel.

A PICTURE OF RECYCLED STEEL

DIRECT REDUCED IRON

The first pathway centers on Direct Reduced Iron, or DRI, which arose from the discovery that you don't have to melt iron ore to turn it into iron; if you just keep it hot enough with certain fuels — like natural gas, coal, hydrogen, or biofuels — you're left with the same metal. Today's DRI uses natural gas, so there is still a carbon dioxide byproduct — albeit less of it than with traditional steel — but, in the future, DRI using green hydrogen can have a CO_2 footprint of steel as low as zero. (That being said, hydrogen makes the reducing reaction endothermic, which requires more energy on the front end.)

So why don't we just use DRI for everything? For starters, alternative reducing agents like hydrogen also cost far more than natural gas; green hydrogen can be over five times the price of the latter. So in the short run, hydrogen DRI simply costs more than ordinary steel. But as we drive down the cost of hydrogen and alternative fuels, we can expect wider applications.

DRI also typically leaves behind other metals like aluminum and silicon that need to be melted again, so you can only use it on high-grade ores without too many contaminants. It's currently only about six percent of the global iron supply — and is becoming even more expensive and rare — so we need a hydrogen solution that can work on a wider range of ores. One Breakthrough Energy Fellows project, **Hertha Metals**, is working on this very challenge. Hertha is developing an iron and steel manufacturing technology that converts any grade of iron ore into ultra-low carbon footprint iron and steel through a hydrogen-electric approach.

RECYCLING SECONDARY STEEL

The second major pathway for driving down steel emissions is recycling secondary steel — essentially, remelting and reshaping it. Secondary steel already accounts for about 24% of global steel production and is the least energy- and emissions-intensive process we have for making steel today. The major constraint is that, over time, recycled steel accumulates impurities again — which is why recycled steel has fewer applications over time, like in the automotive industry, which mandates high-purity steel.

Several companies today are exploring better ways to separate recycled iron from contaminants, so we can expand the secondary steel market beyond the place where it has plateaued in recent years.

Further down the road, carbon capture, utilization, and storage (CCUS) can also help decrease the energy needed to manufacture steel. To date, we haven't shown that we can achieve a sufficiently high rate of capture (90% or more) to make it worthwhile, and, like with cement, it would likely come at a high price. But it's something to keep in our arsenal for a time when we've maximized the other solutions at hand.

BEYOND INNOVATION

Policy & Consumer Choice

4

These are all incredible, cutting-edge technologies, many of which were unimaginable just a decade ago.

But technology isn't the whole story. Imagine, for instance, that you're a contractor. You're putting in your proposal for a new bridge that has to be built. What do you choose? A design that uses the normal recipe for cement that you've used your entire career — the formula that local building regulations say is approved? Or do you propose using a different kind of carbon-free cement that, while just as strong, isn't specifically approved by the government, meaning if something breaks, it's on you?

BRIDGE UNDER CONSTRUCTION

A BUILDING CONSTRUCTION SITE WITH STEEL GIRDERS

It doesn't matter if we make greener steel and cement if we ignore the way it gets into the ground.

We need to incentivize that aggressively, through public policy, regulation, public procurement, and education. Officials at every level of government should expand the regulatory incentives and support for the use of green manufacturing alternatives.

Public procurement — the process by which public authorities purchase goods and services from companies — can play a huge role in the early movement of markets. Getting national and state governments to be among the first major customers for clean alternatives to cement and steel can radically disrupt these markets over time.

We need to incentivize that aggressively, through public policy, regulation, public procurement, and education. Officials at every level of government should expand the regulatory incentives and support for the use of green manufacturing alternatives.

Public procurement — the process by which public authorities purchase goods and services from companies — can play a huge role in the early movement of markets. Getting national and state governments to be among the first major customers for clean alternatives to cement and steel can radically disrupt these markets over time.

A MODERN, STATIONARY
CONCRETE BATCHING PLANT

When it comes to building codes, we should move from prescriptive (i.e. conservative) standards to performance-based standards that encourage innovation.

Both functional and regulatory barriers have prevented the wider uptake of innovations to ordinary Portland cement. Portland cement has exactly the right pH to prevent the corrosion of reinforcing steel, which is the main reason concrete structures fail; this is one of its hardest functions to replicate. What's more, there's huge economic inertia towards these alternatives, because of the sunk costs — nearly a trillion dollars — in old-school Portland cement.

Something that can help move the needle on uptake and regulation is more funding to promising technologies to demonstrate its use at scale, which can motivate regulatory changes and create a virtuous cycle. More broadly, financial incentives like demo project funding and tax credits can help overcome the Green Premium for producers. One great example of this is the Bipartisan Infrastructure Law (BIL) passed in the United States in 2021, which earmarked over $500 billion for precisely such purposes.

UNFINISHED CEMENT AND STEEL STRUCTURES

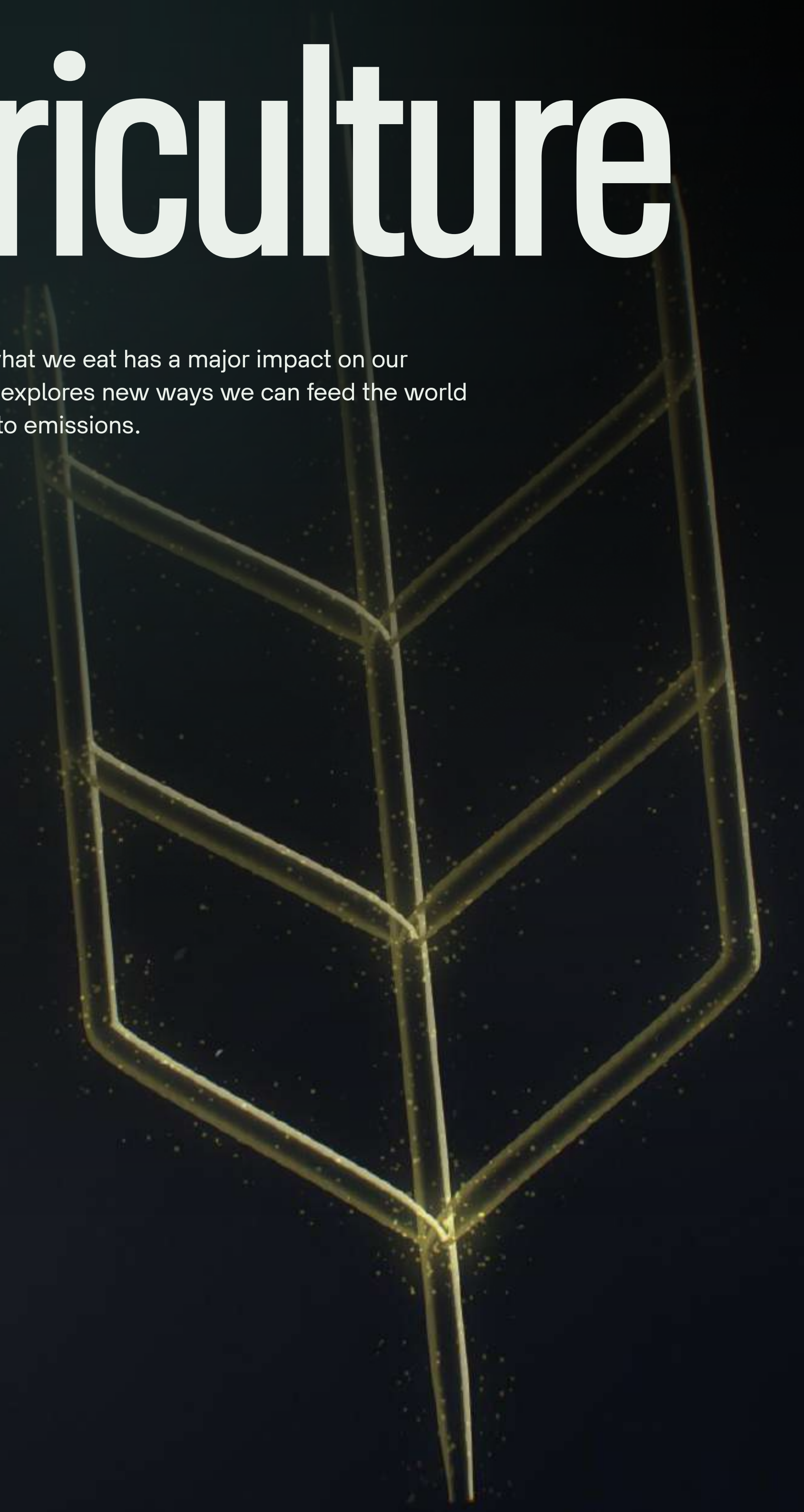
Due to the complex value chains of steel and cement, we need leadership from industry players who are willing to scale technologies. This isn't like electric vehicles, where manufacturers can sell directly to consumers who are open to paying a Green Premium. A new supplementary cementitious material, like **Terra CO2**, sells its product to a concrete producer, who sells it to a builder, who may then interface with a consumer, who may or may not want to shoulder the largely-invisible Green Premium. That's why it's crucial that establishment and emerging companies alike commit to scaling new technologies, which has been relatively slow to date, particularly in cement.

There's no silver — or steel — bullet when it comes to solving the emissions puzzle in manufacturing. But the sheer scale of these industries promises that these solutions, if we make sincere efforts to implement them, will be well worth it.

20% of Global Greenhouse Gas Emissions

Agriculture

From rice to cattle, what we eat has a major impact on our climate. This section explores new ways we can feed the world without contributing to emissions.



3

HOW WE GROW THINGS

An Update On Agriculture

WOMEN PLUCKING LEAVES IN SRI LANKA

IF YOU ONLY HAVE BRAIN SPACE FOR THREE THINGS:

1. Food demand will only increase as our population grows. We need to find ways to feed the world without contributing to emissions. That means finding better ways to fertilize plants, raise livestock, conserve water, and reduce food waste.
2. Methane from cows and livestock is the dominant driver of agriculture emissions. By 2050, there could be an additional 500 million cows roaming the planet. Just in the last few years, numerous companies have been founded to tackle enteric emissions. New technologies like cow vaccines and methane-reducing feeds could help significantly.
3. Going forward, the challenges here are as much geographical and cultural as they are technological. But while there's no one-size-fits-all solution, it's clear we need more public R&D funding so we can continue to develop better ways to feed the world without contributing to emissions.

We Are What We Eat

1

Did your parents ever tell you, “You are what you eat”? Maybe they were trying to scare you off of that cinnamon roll or guilt you into putting some broccoli on your plate. Whatever it was, the message was clear: What you put in your body affects your health. Turns out, it also affects the health of our planet.

AN AERIAL VIEW OF ACRES OF CROPLAND

The food and agriculture sector accounts for 20% of global greenhouse gas (GHG) emissions. Two thirds of that comes from crop and livestock activities, while the rest comes from landfills, deforestation, and land use change.

But it’s not just the size of agriculture’s emissions that makes it hard to tackle, it’s the source. The majority of emissions come from GHGs other than carbon dioxide (CO_2) like methane and nitrous oxide, both of which are more potent warming agents than CO_2. Methane warms the atmosphere approximately 28 times more than an equivalent amount of CO_2 over a century. Even worse, nitrous oxide’s global warming potential is about 300 times that of CO_2 over the same time frame.

Other factors also make these sources harder to tackle than CO_2. For example, technology to capture CO_2 in the air is far more advanced than methane or nitrous oxide capture. Methane and nitrous oxide also originate from a variety of natural sources like wetlands, livestock, and rice farming.

Another challenge of decarbonizing the agriculture sector is that agricultural emissions manifest differently around the world. They’re influenced by geography, which determines what crops can grow where, as well as by cultural attitudes toward food production and consumption. In other words, what works in the United States may not work elsewhere, and vice versa.

India, for example, has the largest cattle herd in the world, due to the cultural significance of cows. In Indonesia, deforestation for palm oil can account for more emissions than the nation’s entire energy sector. In Brazil, deforestation and cattle farming account for the majority of emissions. And in the United States, fertilizer application and nitrous oxide lead the emission profile.

CROPLANDS DAMAGED BY SEVERE DROUGHT

What's more, agriculture is arguably the sector most impacted by climate change. This creates a vicious cycle: Climate change has caused lower yields from crops, in turn increasing fertilizer use and deforestation, which raises emissions and exacerbates climate change even further.

Whatever we do, one thing is clear: The status quo is unsustainable. Not only would inaction mean continued increases in emissions, but it would also lead to dire levels of food insecurity, which has already increased dramatically due to climate shocks and supply chain disruptions.

And yet, up to this point, the resources devoted to decarbonizing the agriculture sector simply don't reflect its outsized impact on climate change. From 2002 to 2019, total public agriculture R&D spending in the United States, which includes federal, state, and private sector funding of public institutions, declined by about a third, largely due to a reduction in state funding. Although the FY2023 bill increased funding for USDA agencies, bringing it close to early 2000s levels, the American Association for the Advancement of Science states that it was still about six percent lower in 2022 compared to 2003, indicating waning state support for public agricultural research.

Other large nations have outpaced the United States. China, the largest importer of U.S. agricultural goods, and Brazil, a major international competitor with the United States in agricultural exports, both increased their agricultural R&D funding over the past two decades. India, another country with a large agricultural sector, has also increased its public R&D spending.

To make matters worse, the two largest sources of emissions in the agricultural sector — enteric methane and synthetic fertilizer — have received disproportionately low levels of research funding.

A DRIED-UP RICE PADDY IN
SOUTHERN CHINA

Over the past year, we've collaborated with climate groups to champion greater funding for several key agricultural programs, including the National Institute of Food and Agriculture, which supports innovations that curb enteric methane emissions without cutting back on beef and dairy outputs; the Agricultural Research Service, another USDA branch, which delivers valuable information to the public on nutrition, food safety, crop protection, conservation, and more; the Foundation for Food and Agriculture Research, a nonprofit established by the 2014 Farm Bill, which ensures that federal funds for agricultural research are matched from private sources; and the Agriculture Advanced Research and Development Authority (AgARDA), which focuses on high-risk, high-reward projects that conventional funding sources overlook but could usher in the next wave of agricultural advancements.

As we advocate to better fund and expand all of these programs, we recognize that the future of agricultural policy in every part of the world must be proactive. Through increased investment, bold incentives for farmers and consumers, and revolutionary innovations in livestock management, fertilizer production, and plant-based alternatives to meat, we can feed the world and mitigate climate change at the same time.

A PORTRAIT SHOT OF A COW

HOLY COW:

Tackling Livestock Emissions

During the COVID-19 pandemic, the race for a vaccine consumed our world. Scientists and innovators put their heads together to find, test, scale, and mass deploy mRNA vaccines to the globe's nearly eight billion people, one of the greatest feats of ingenuity in human history.

2

What if we told you there could be a “vaccine” for climate change? Well, at least for a big part of it. Let's explain.

We know burping is impolite. But when it comes from cows, it also imperils our planet. That's because cows digest food differently than humans do.

COWS FEEDING IN A BARN

Arkea Bio

In a process called enteric fermentation, bacteria inside a cow's stomach breaks down food, ferments it, and produces methane, which the cow then mostly burps out. Methane is a much stronger warming agent than CO_2, and the methane cows burp and fart out (known as "enteric emissions") accounts for four percent of global emissions alone.

That's a serious problem, because cows are a vital part of our global food system. They contribute about 34% of our diet's protein and 16% of its calories. And as the world's population and food demand grow, there could be an additional 500 million cows roaming the planet by 2050, according to projections by the United Nations Food and Agriculture Organization.

That's where the vaccines come in. In fact, the word vaccine is derived from the Latin word for cow. We've invested in a company called **Arkea Bio**, which uses a cutting-edge, multivalent vaccine that delivers antibodies to the rumen, a compartment of the cow's stomach, to reduce methane production.

There's a high scientific risk here and it may not work. But it's hard to overstate the potential impact of this vaccine. We know this technology is highly scalable. Look no further than the massive effort to administer nearly 14 billion COVID-19 vaccines in three years. If successful, Arkea Bio's vaccine could become one of the most important climate breakthroughs.

Rumin8

Rumin8, an Australia-based company, is tackling this problem in a different way. In recent years, farmers discovered that bovine methane production can change based on what cattle consume. A seaweed diet, for example, has been shown to significantly reduce the production of methane in cows. Only problem is, transporting seaweed to cow farmers just doesn't make economic or logistical sense, not to mention the fact that cows just don't like the salty taste of seaweed very much.

Rumin8 has created a workaround, taking the active ingredient in seaweed and using it to target enzymes in the cow's stomach to reduce methane production. If Arkea Bio's technology works like a vaccine, Rumin8's works more like a probiotic that can be administered in cow feed.

Of course, the simplest way to reduce livestock's impact on the climate is to stop eating them. But reducing demand for beef has proved harder than we imagined.

Plant-and cell-based alternative meat companies have exploded in recent years, but Americans' hunger for meat alternatives has plateaued. Plant based meat is still only about one percent of the meat market in the United States. The Green Premium for plant-based beef remains absurdly high, and most surveys show consumers still find the taste lacking. And internationally, beef demand is expected to increase as low- and middle-income countries get wealthier, since per capita meat consumption is strongly correlated with per capita GDP.

That doesn't mean we should give up. Breakthrough Energy is working with several companies focused on accelerating the adoption of plant-based alternatives to meat. Take **Savor**, for example, which creates zero-carbon fats using a thermochemical process. Most fat used today comes from palm oil, which is in nearly half of all packaged goods, and which, as we've discussed, is a major driver of deforestation.

Fat is critical to a food's flavor and texture. If companies like Savor can improve the way we make plant-based meats by replacing palm oil and animal fats, it could help shift consumer preferences and significantly reduce emissions.

Nobell is another company working in this space. Founded by a Lebanese immigrant looking for better vegan cheese, Nobell helps farmers create dairy-free products using soybeans to grow the dairy protein casein, which gives cheese its gooey texture. Accelerating consumer adoption of plant-based alternatives would have a cascading effect on emission reduction. Not only would it help reduce the emissions from livestock themselves, but it would also free up land currently used for livestock feed such as corn and soy.

However, even if the plant-based alternative market continues to grow, we could still have more cows on Earth by 2050 than we do today. That means we need to focus our efforts on decarbonizing the world's cattle herd and other livestock.

Policy can play a critical role here by incentivizing the uptake of new and innovative approaches that improve animal nutrition and feed efficiency. It can also accelerate the adoption of new practices, like Arkea Bio's vaccine.

But tackling methane emissions from livestock requires a nuanced approach, given the pivotal role livestock play in global nutrition and economies. Livestock, particularly dairy, is a lifeline for about a billion people worldwide, providing sustenance and economic stability. We need to approach this challenge with farmer-centric innovations in feeding, manure management, and general farming practices.

Moreover, we need to streamline regulatory standards for methane-reducing products. Investments in these areas will not only mitigate methane emissions but also support farmers in adopting sustainable practices.

A HERD OF CATTLE

FERTILIZE THIS

Sustainable Crop Production

3

Meat isn't the only farming activity contributing to or being impacted by climate change. After livestock, deforestation and land-use change account for the largest source of agricultural emissions.

Feeding the world is a tall order, and climate change has only made things harder. At our current crop yield rates, we will need an additional 500 million acres of cropland — the size of Argentina — by 2050 to meet rising demand for food. That's going to be a huge driver of deforestation and, in turn, emissions.

AN AERIAL VIEW OF CROPLANDS

To address these challenges, we must seek innovative solutions that reduce emissions, increase crop yields, enhance resource efficiency, and build climate resilience.

The best way to reduce deforestation while still meeting rising food demand is to improve the amount of food we produce per acre. That starts with tackling the emissions and inefficiencies of the most important product farmers use to grow their crops: synthetic fertilizer.

AN AERIAL VIEW OF CROP FIELDS

For the last century, farmers have used synthetic fertilizer to dramatically increase yields for wheat, rice, corn, and soybeans, helping feed people and animals the world over. In fact, wheat and rice alone account for about 40% of global caloric consumption.

Farmers use synthetic fertilizer to provide their crops with nitrogen, an indispensable element for life on Earth. The more nitrogen crops have, the more they grow, the greater a farmer's yield. But this process is having serious effects on our environment — from air and water quality to human health and ozone-depletion.

Synthetic fertilizer production accounts for approximately two percent of the world's energy use and contributes to one percent of its (GHG) emissions.

N2O

Nitrous oxide is the toxic byproduct of nitrogen fertilizers. You may know nitrous oxide as laughing gas, but in the context of climate change, there's nothing funny about it. Nitrous oxide is nearly 300 times more potent than CO_2 and is now the world's dominant ozone depleting substance.

Then there are the geopolitical concerns, as the majority of nitrogen production comes from the Middle East, China, and Russia, where we've seen conflict significantly disrupt the nitrogen supply chain. Before the Russian invasion, Ukraine was a crucial agricultural trade partner to the European Union, supplying significant shares of animal, vegetable oils, and cereal crops. Additionally, the European Union relies significantly on Russian imports of ammonia and urea, both processed forms of natural gas, for fertilizer production. This disruption has caused food and natural gas prices to skyrocket throughout Europe and other parts of the world.

AN AERIAL VIEW OF A CORN FIELD

A TRACTOR SPREADING FERTILIZER

Nitrogen fertilizer is also remarkably inefficient. About 50% of nitrogen fertilizer applied to soils is actually lost to the environment.

If we can manage nitrogen more efficiently by delivering it to crops with less energy, emissions, and run-off, we can enhance food security and reduce our dependence on imports.

One of the most promising strategies comes from **Pivot Bio**, a California-based company that uses nitrogen-fixing bacteria to give plants the ammonia they need to grow. Pivot Bio uses microbes in the soil to create a symbiotic relationship with the roots of crops. The microbes consume root exudates, a sugar product expelled by the crop, which gives them the energy they need to convert hydrogen from the air into ammonia.

This process could displace the need for synthetic fertilizer entirely, providing more or less nitrogen to the crop as needed without washing away during severe weather. Unlike current methods of producing ammonia, the energy source for this process comes at no cost. In other words, these microbes create a built-in fertilizer factory in the soil.

AGRICULTURAL SPRAYER WORKING ON A FARM

AN AMMONIA PRODUCTION PLANT

ReMo Energy goes after a different part of the fertilizer process: production. In order to make synthetic fertilizer, we have to produce ammonia. A critical step in this process is converting natural gas to hydrogen, known as the "water-gas shift reaction," which produces GHGs.

ReMo is developing ammonia plants fueled by renewable electricity to deliver nitrogen fertilizer at prices competitive with natural gas-fueled supplies. The renewable electricity is used to run electrolyzers that make hydrogen from water rather than from CO_2. This process works especially well in the American Midwest, where we see both high ammonia demand and abundant renewable electricity.

A FARMER SCATTERS FERTILIZER IN A FLOODED RICE PADDY

We can incentivize better practices through policy, such as offering reduced crop insurance rates for sustainable nutrient management or subsidies to counter potential yield reductions.

A decarbonization roadmap, developed in partnership with experts, could also guide stakeholders towards a climate-conscious fertilizer industry that reduces emissions and ensures a sustainable future.

But the agriculture sector's reliance on nitrogen isn't its only problem. It's also using up water at an unsustainable rate.

THE COLORADO RIVER, WHICH IS CURRENTLY EXPERIENCING A SEVERE DROUGHT

In the American Southwest, which is experiencing a severe drought, 55%of the Colorado River's water is used for cattle feed. And in Southeast Asia, water demand is heavily driven by rice irrigation; in India, for example, over 60% of water demand comes from rice fields. Growing rice in flooded fields contributes significantly to global methane emissions; in fact, rice is the world's most greenhouse gas-intensive crop on a per acre basis.

It's also not going anywhere. Just as meat is a vital part of American food culture, rice is a critical component of diets in Southeast Asia and many other parts of the world. And by 2050, rice demand is expected to increase 50%.

That's why water resiliency has become critical to sustainability efforts, not only to ensure food security but to reduce the emissions that come from excessive water use.

To accelerate low water-use, low-methane rice cultivation technologies, Breakthrough Energy Ventures co-founded **Rize**. Rize works with rice growers to accelerate the adoption of a water-saving irrigation technique called Alternate Wetting and Drying (AWD).

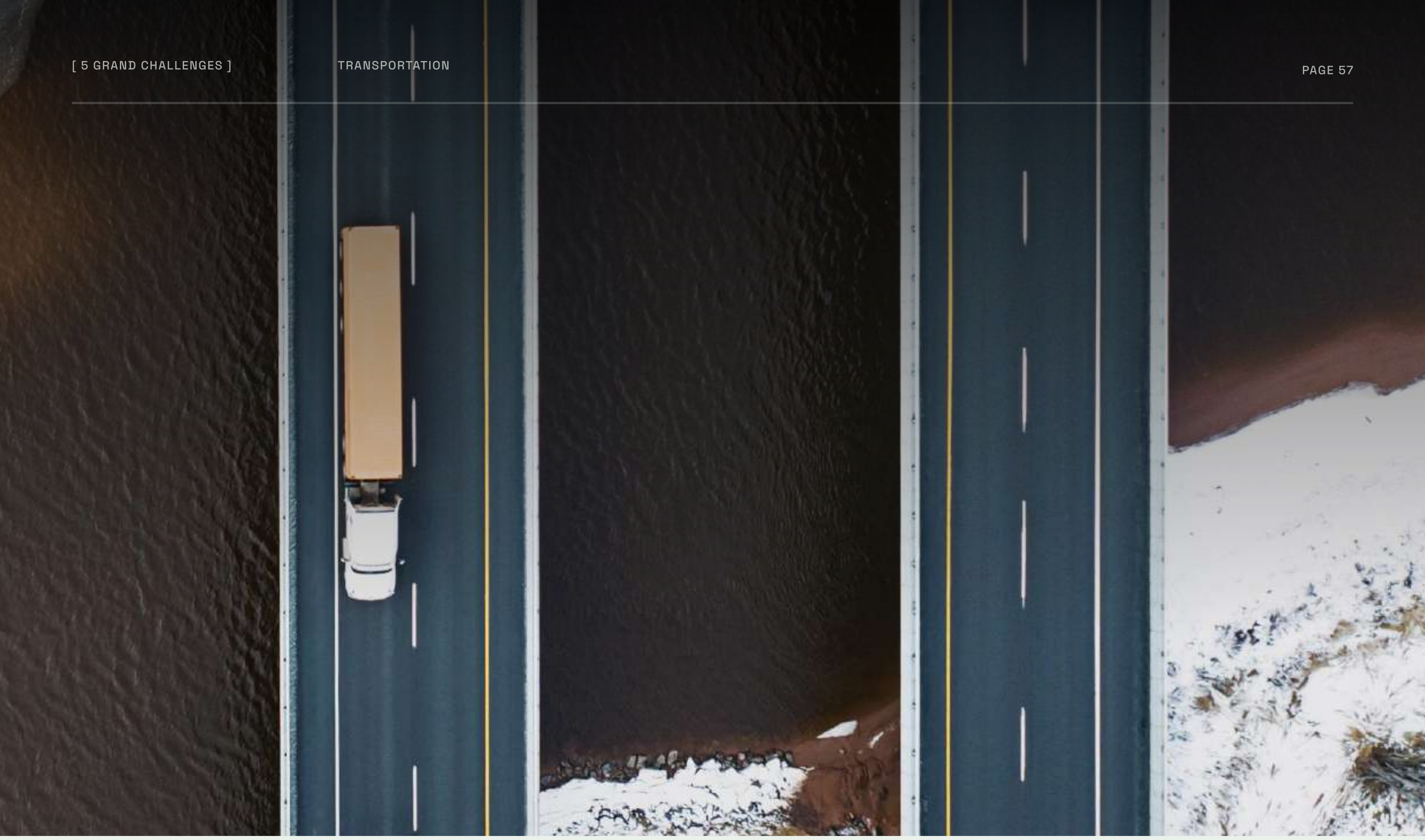
Using what's called a piezometer to measure water levels, farmers can optimize water usage for rice by alternating between cycles of wetting and drying, reducing their water consumption by roughly 30% and methane emissions as well as by producing more with less, we can spare the need for land clearing to feed a growing, more affluent population.

15% of Global Greenhouse Gas Emissions

Transportation

From electric vehicles to sustainable aviation fuel, our modes of transport need to change rapidly to achieve our net-zero goals. This section looks at the barriers and breakthroughs in modernizing how we get around.

4



HOW WE GET AROUND

The Future Of Zero-Carbon Transportation

AN AERIAL SHOT OF A TRUCK DRIVING OVER A BODY OF WATER

IF YOU ONLY HAVE BRAIN SPACE FOR THREE THINGS:

1 Electric vehicles (EVs) have come a long way. They are now roughly as cheap and can travel just as far as regular cars. And by 2035, some projections show they could account for half of the new vehicles sold in the United States.

2 The minerals that power batteries are in jeopardy. Not only are we potentially running out of some of them, but most of the world's current lithium, cobalt, and nickel production is concentrated in just a few places, meaning conflict or natural disaster could cause significant supply disruptions.

3 Going forward, long-distance and heavy-duty transportation will be the biggest technological hurdle. We need better public and private collaboration not only to incentivize the uptake of batteries and e-fuels but to improve their performance, endurance, and affordability.

A LARGE TRUCK DRIVING
THROUGH THE DESERT

A POSTCARD ILLUSTRATION OF AN UNDERWATER WHALE BUS, WHICH WAS COMMISSIONED FOR THE 1900 WORLD'S FAIR IN PARIS.

For the 1900 World's Fair in Paris, a series of 87 postcards were commissioned, each envisioning what France would look like in the year 2000. Most were pictures of transportation — absurd transportation.

Policemen wear winged uniforms, directing traffic in midair while transatlantic travelers sit in undersea buses hitched to humpback whales.

A POSTCARD ILLUSTRATION OF FLYING POLICEMEN, WHICH WAS COMMISSIONED FOR THE 1900 WORLD'S FAIR IN PARIS.

Presumably, the postcard artists never paused to ask some basic questions. Like, how would one domesticate a large sea mammal so it can pull a bus? Or why would it be more efficient to elevate traffic 10 meters off the ground rather than leave it on Champs-de-Élysées?

For those of us trying to help usher in zero-carbon ways of moving around, the Paris postcards are a good reminder: Visions of the future are a dime a dozen. But if you haven't figured out the science or the economics yet, you'll look foolish.

Fortunately, there's one aspect of zero-carbon transportation where both the engineering and the economics are just about solved: electric cars and light vehicles.

Today, road transportation accounts for roughly 75% of all transportation-related emissions, and passenger cars are responsible for half of that. Electrifying the Earth's fleet of cars would be an enormous achievement, and many of the cost and engineering barriers have already been overcome. The remaining challenges involve building out charging infrastructure, improving battery safety and the supply chain to make them, as well as the time it will take to turn over the current fleet of vehicles.

AN ELECTRIC VEHICLE

It's the other postcards — ships, planes, and heavy-duty trucks that need to travel long distances — that are still a little fuzzy.

These modes of transportation are simply much harder to electrify than passenger vehicles. They're heavier; they require more energy and must cover more distance; and they're far more expensive.

We do know what the general picture should look like, and it's not whale-powered underwater boats or individual propeller planes. In fact, the outline looks a lot like it does today: fuel.

Just without the carbon. Unfortunately, that's a lot harder than it sounds. Bio- and electrofuels are potential substitutes, but today, the Green Premium of these products is much too high to widely commercialize them.

The science and economics of creating carbonless liquid fuel just aren't mature yet. And it's going to take huge investment, historic innovation, and major policy changes to get there.

Electric vehicle adoption is still in its infancy, but like an infant, it’s expected to grow fast: According to a recent report by Bloomberg New Energy Finance, EVs could be 75%of all global passenger vehicle sales by 2040.

A SHIP TRANSPORTING HUNDREDS OF CONTAINERS

BATTERY FIRES AND RARE METALS

The Remaining Roadblocks for Electric Vehicles

1

Electric vehicle adoption is still in its infancy, but like an infant, it's expected to grow fast: according to a recent report by Bloomberg New Energy Finance, EVs could be 75% of all global passenger vehicle sales by 2040.

Over the past decade, auto and policymakers have taken a jackhammer to the roadblocks that previously stood in the way of mass EV adoption. Some EVs, today, are nearly as cheap as their internal combustion engine counterparts.

AERIAL VIEW OF THE SKOURIOTISSA COPPER MINE IN CYPRUS

With one battery charge, they can travel about as far as a traditional vehicle does on a tank of gas. And when the battery is low, there are thousands more places to plug in. In the United States, the number of charging stations nearly doubled between 2019 and 2022, and the Inflation Reduction Act could triple the current number, adding an estimated 500,000 EV chargers by 2030. We still have a ways to go to make EV charging as widespread, seamless and fast as filling up a gas tank, but our progress is undeniable.

And yet, as these roadblocks have started to crumble, two new ones have appeared.

The first roadblock to EV adoption involves battery materials.

AN AERIAL VIEW OF AN OPEN-PIT IRON MINE IN KAYSERI, TURKEY

Today, most batteries are powered by lithium while nickel and cobalt are also crucial components. Current mining and processing of these three minerals is not evenly distributed across the planet.

In fact, more than half the world's cobalt mining is in the Democratic Republic of Congo while China accounts for 40% of the world's chemical lithium production — and nearly 80% of the cathode production for batteries. Now imagine what happens if one of those countries experiences a major crisis, like a war, a natural disaster, or trade restrictions.

If the concentration of so many critical minerals in so few places exposes the battery supply chain to geopolitical risk, how can the future of road transportation be battery-powered vehicles?

400

MILES

One answer is **battery recycling**. Another is developing batteries that use far **less nickel and cobalt** — or even none at all. There are a handful of possible configurations, but a promising one is a lithium-iron phosphate battery, or LFP.

LFPs don't use any nickel or cobalt and while they pack less energy than a standard lithium-ion battery at a cell level, they have higher safety properties. That means you can pack more cells in a smaller space and basically provide the same range you get with a nickel cobalt manganese (NCM) battery. In February, a company called **Our Next Energy** outfitted a BMW with their LFP for a test drive. The BMW made it 400 miles on a single charge.

Both innovations — battery recycling and batteries with less critical minerals — are still years away from widespread use. But they will need to be critical pieces of our strategy as the world's lithium, nickel, and cobalt resources begin to wane.

The other roadblock is battery safety — or more specifically, battery fire safety. EVs are actually more fire safe than traditional vehicles. Generally speaking, for every one EV that catches fire, there are 35 regular cars that go up in flames. Still, fires involving lithium-ion batteries tend to burn hotter and longer than fires fueled by gasoline.

For car makers, addressing battery fires isn't just a matter of protecting lives; it's also a matter of preventing bankruptcy-threatening recalls, factory fires, and loss of inventory in transit. Today, two percent of the cars on the road are electric. If an automaker has to recall two percent of its fleet because of a battery defect, that's a big financial problem. But it's not company-ending. The math changes, however, when electric cars are 100% of the vehicles a carmaker sells.

CHARGE DECLINED!

Why batteries won't work for planes, ships, and trucks at long distances — and what to do about it

2

Of the five "grand challenges" discussed in this report, transportation is the only one where people have to lug their energy around with them. The problem is that — as far as power sources go — it's hard to find something better to lug than gasoline. It's shelf stable, cheap, and energy dense.

Per gallon, gas costs about as much as bottled water and packs more energy than a stick of dynamite. The best lithium-ion batteries, by comparison, contain 35 times less energy pound-for-pound, meaning that to get the same amount of energy as a gallon of gas, you'll need batteries weighing 35 times heavier.

SHIPPING CONTAINERS AT A PORT

There are some modes of transportation — like cars — where the battery-for-gasoline tradeoff makes sense.

But as we start talking about vehicles that need to drive longer distances and carry heavier loads than a family sedan, the rationale for batteries breaks down. An electric cargo truck capable of driving 600 miles in a single charge would need to carry so many batteries, it would have to haul 25% less cargo. And that's saying nothing of ships that need to stay afloat and planes that need to stay aloft.

Good news is, trucking and aviation are changing. A higher percentage of flights are short, which means more flights can be electrified or hydrogen-powered, especially cargo fleets and regional passenger travel. And trucks are more volume-limited than weight-limited these days, meaning they can use more of their weight-carrying capacity for batteries.

A CLOSE-UP SHOT OF
LIQUID FUEL

But for the full decarbonization of these modes, we will likely need a solution other than batteries. And the best way we've found is to create a fuel that approximates what's used now — something that can be used in existing infrastructure and looks like gasoline, works like gasoline, but doesn't emit carbon dioxide (CO_2) like gasoline. That's the key innovation challenge for transportation: clean, liquid fuels.

Biofuels

AERIAL VIEW OF AN ALGAE BIOFUEL PROJECT

One pathway is biofuels, which are fuels synthesized from plants, crops, and waste materials.

Biofuels aren't new. In the United States, they're actually old enough to have a complicated reputation because every non-electric car that runs on gasoline includes at least 10% ethanol — a biofuel that, depending on how it's produced, could emit more CO_2 than it saves. Growing the corn to make ethanol requires fertilizer, and eventually, as you grow more and more ethanol crops, that means cutting down forests or overtaking space that could otherwise be used to grow food for humans.

There are ways of making biofuel that don't require heavy agriculture or mass deforestation — like algae. It's a great source of lipids, which are hydrocarbons — the building blocks of any liquid fuel.

A company called **Viridos** believes they can produce algae so lipid rich, they can grow fuel in ponds as cheaply as oil companies drill it from the ground.

Electrofuels

A FIREFIGHTER BATTLING A BLAZE

Another option is to leave plants aside and make the hydrocarbons ourselves using clean electricity.

Engineers do this by pulling carbon out of the air with direct air capture technology, then combining that carbon with hydrogen, which can come from splitting apart the H from the H20 molecules in seawater, from natural hydrogen deposits in the Earth's crust, or from myriad other ways of making clean hydrogen.

These fuels are called **electrofuels — or e-fuels** — and the manufacturing process is exactly as complicated (and expensive) as it sounds. According to analysis by the Rhodium Group, sustainable aviation fuel is currently three to five times more expensive than regular jet fuel.

Over the next three decades, a trillion dollars is needed to help the fuel industry scale and reduce its Green Premium — and that's just for commercial planes. Fuel for ships and trucks will require even more.

In fact, clean hydrogen will be especially vital to the shipping industry, which is notoriously difficult to decarbonize and accounts for three percent of all emissions. Right now, the fuel ships use is dirt cheap, meaning there's little incentive to switch. What's more, conventional container ships can carry far more cargo and go much longer distances than electric ships.

Figuring out how to transform it into a fuel that's easy, cheap, and safe to transport in cargo ships will require more innovation and public-private collaboration.

OFFSHORE WIND TURBINES

Human beings are going to need liquid fuels for a long time — longer, certainly, than anyone reading this will be alive. And government support will be critical for lowering costs.

The European Union, for example, is well-positioned to be an e-fuel leader. The North Sea is packed with windmills producing clean electricity to power the hydrogen-splitting electrolyzers, and Europe's carbon pricing scheme is an extra force pushing down the Green Premium for sustainable fuels. Now, fuel suppliers must ensure that two percent of fuel made available at EU airports is SAF in 2025. This rises to 20% in 2030 and 70% by 2050. 35% of fuels must also be synthetic fuels, which are made using captured CO_2 emissions, by 2050.

Meanwhile, the United States first tried to tackle clean fuels for passenger vehicles through the creation of the "Renewable Fuel Standard" in the early 2000s. Unfortunately, this policy has not yielded significant emissions reductions in the transportation sector and has failed to incentivize the production of innovative low-carbon liquid fuels.

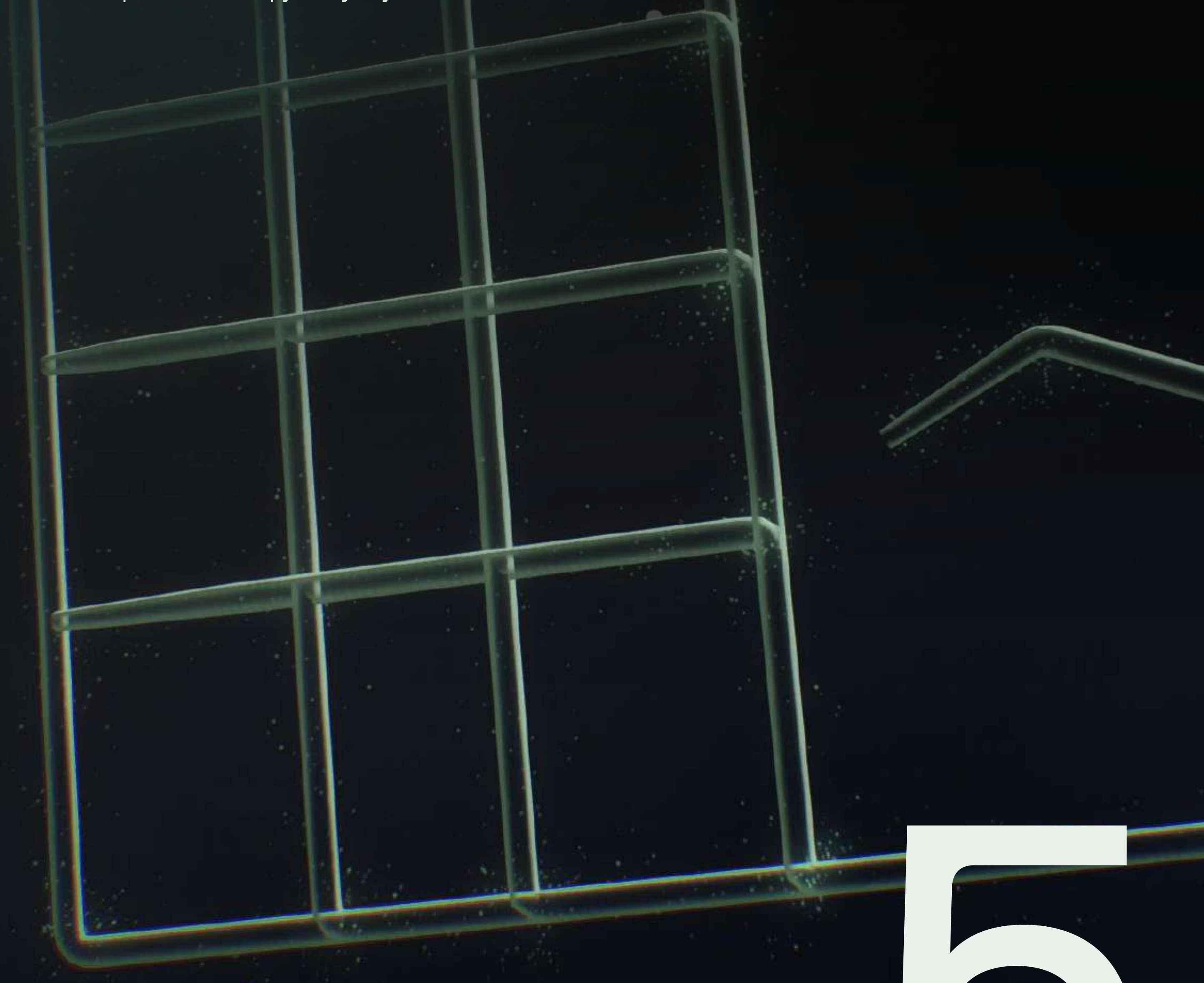
To truly stimulate innovation in the fuels space — especially for use in long-distance planes and ships — we need better policy that doesn't pick winners and losers and instead rewards fuel makers for producing increasingly cleaner fuels.

California, Washington, and Oregon all have a state clean fuel standard program that can serve as models.

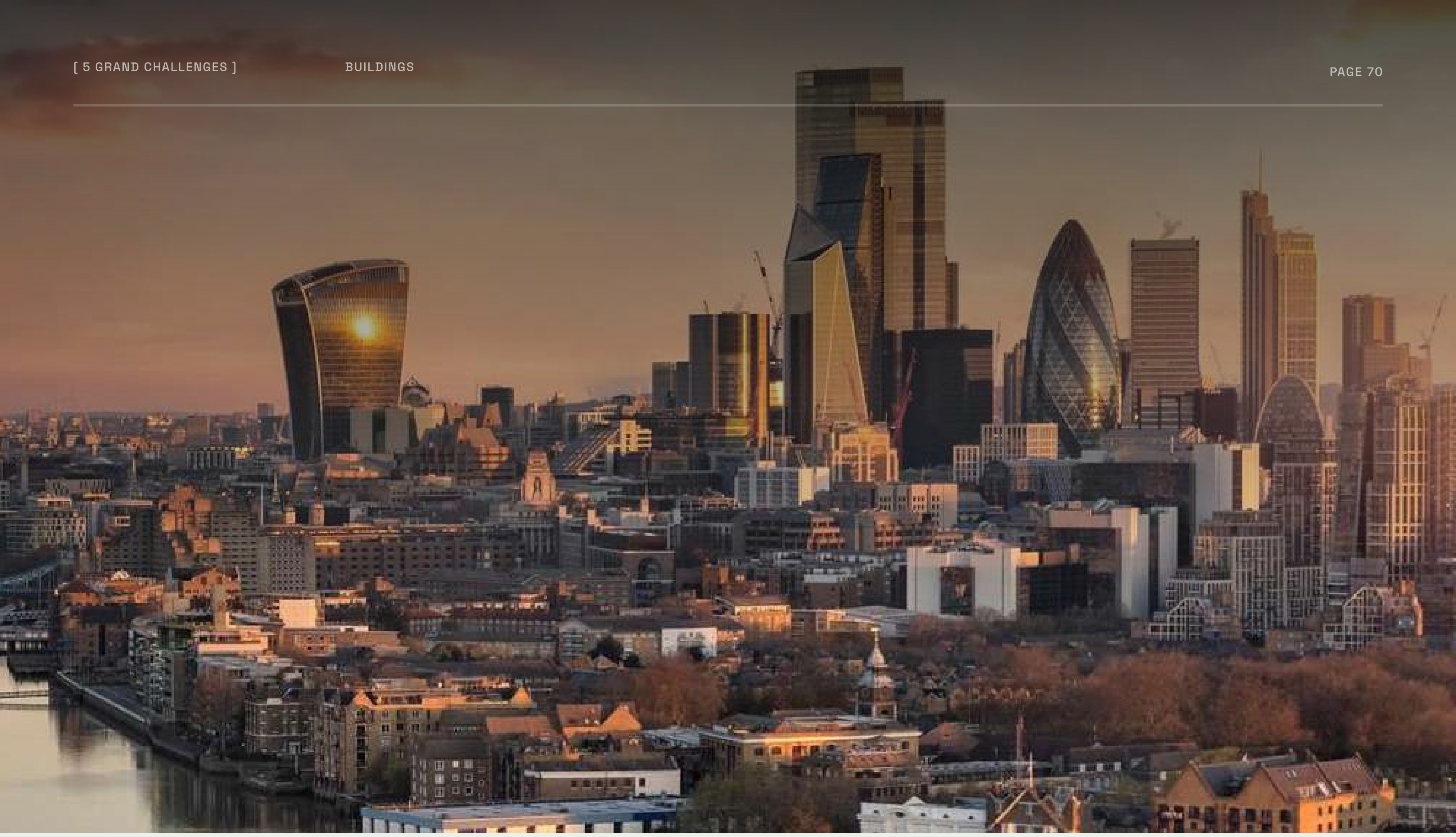
7% of Global Greenhouse Gas Emissions

Buildings

Heating and cooling our homes and workplaces takes a lot of energy. This section details the latest innovations that will help decarbonize the spaces we occupy every day.



5



HOW WE STAY WARM AND KEEP COOL

LONDON'S BUSINESS DISTRICT

An Update On Buildings

IF YOU ONLY HAVE BRAIN SPACE FOR THREE THINGS:

1 Buildings last a long time. The ones we build today will likely still be emitting carbon dioxide (CO_2) long after we're gone. As we noted in the steel/cement chapter, it takes a lot of carbon to construct them. But it also takes a lot to operate them. That's why we need to make them far more energy efficient and electrified.

2 Cooling demand is rising rapidly. Of the five billion A/C units expected to be in operation around the world by 2050, roughly 40% have already been installed. We have the technology to decarbonize this boom by using more efficient A/C units and heat pumps, plugging leaky ducts, and changing out single-pane windows, but mass deployment is a challenge. Buildings waste a lot of energy.

3 Going forward, behavioral changes will be key to decarbonizing this sector. The technology is here and the Green Premiums are lower than for other grand challenges. Now we need governments, corporate buyers, and other consumers to buy in.

AERIAL VIEW OF BARCELONA

Old Buildings, New Ideas

1

The median age of a building in New York City is 90 years old. In Europe, over 85% of today's buildings will still be standing in 2050, and the majority were built before energy efficient standards existed.

Point is, buildings last a long time. The buildings our grandparents constructed are still emitting CO_2 today. And the ones we build today will likely keep emitting CO_2 long after we're gone.

AN OLD BROWNSTONE IN NEW YORK CITY

What's more, the updates we make to buildings rarely make them more efficient. In Europe, for example, 10% of buildings are renovated every year. But only one percent of those renovations have a positive impact on the building's energy usage.

This is a major climate challenge. Buildings account for seven percent of global emissions, and that's just measuring on-site energy usage. Taken together with source energy (i.e. the total amount of raw fuel needed to operate buildings, including transmission, delivery, and production losses) and embodied carbon, they account for approximately 40% of global CO_2 emissions, which makes buildings the largest contributor of all the sectors we've discussed.

But since we've already covered the majority of embodied CO_2 emissions caused by using cement and steel in building construction, we're going to focus this section on the carbon footprint of **operating** homes and buildings.

Through air conditioners, furnaces, and water heaters, heating and cooling today's buildings consumes a lot of energy and emits a lot of CO_2 in the process. Buildings also waste much of the energy these devices produce. Our structures are essentially leaky containers, filled with single-pane windows and uninsulated, leaky ducts that let energy out. In fact, as much as 40% of heated or cooled air leaks out of the typical building.

Here's the good news: Compared to some of the other sectors we've discussed, the technologies we need to decarbonize heating and cooling already exist for the most part — from heat pumps and smart controls to energy-efficient air conditioners and double- or triple-glazed windows.

The main issue is deployment. We've already built a lot of buildings, and as we've discussed, they last a long time. It's going to take a colossal effort not only to update the way we construct our homes and offices, but to retrofit the buildings we already have to make them more energy efficient. We need to update building regulations to allow for the use of new materials and processes, and encourage building and home owners to make the changes needed.

EVERYTHING UNDER CONTROL

Raising a Commercial Building's IQ

2

In 1999, Disney released an original film called Smart House about a futuristic home that develops a mind of its own, with controls for everything imaginable. Sentient homes that turn evil aren't quite what we're going for, but building automation is a key piece of the decarbonization puzzle. Because the better you can control a building's energy usage, the better you can limit its emissions.

That's the idea behind companies like **75F**, which is working on advanced building controls for small-to-medium sized buildings that often get overlooked by automation advances. We know that building intelligence can have a major impact on efficiency.

We've already seen this progress in other areas of our lives. For example, when you get in a car these days, there's a button, lever, or dial at your fingertips for just about everything: A/C, seat-heaters, defrost, music, GPS, gas levels. Buildings should be the same. There's no reason a four-story condo building should have fewer controls than a two-passenger car.

A GREEN BUILDING FACADE

KEEPING OUR COOL

Innovations for the Coming A/C Boom

3

One of the most frustrating paradoxes of climate change is that, as the world gets hotter, our main method of cooling down could make climate change even worse. Not only do air conditioners increase CO_2 emissions, they also leak an even more harmful substance: refrigerants. Known as F-gases, refrigerants cause thousands of times more warming than an equal amount of CO_2.

EXTREME HEAT IS ACCELERATING THE A/C BOOM, CREATING A VICIOUS EMISSIONS CYCLE.

We have to break this vicious cycle, because the demand for cooling isn't going anywhere but up. Global heating demand is nearly 30 petajoules per year. To put that in perspective, that represents more than 780,000 years worth of electricity for the average American home. But cooling is projected to surpass it before the end of the century. More than 90% of American homes already have an air conditioner, compared to just 12% of homes in India. But as temperatures in already hot places like India continue to increase, more people will want access to air conditioning.

By 2050, there will be more than five billion A/C units in operation around the world — more than twice the amount in use today. Air conditioners will consume as much electricity as all of China and India do now.

AN ILLUSTRATION OF HVAC UNITS

Several companies are exploring ways to meet this cooling demand in an energy efficient way. Take Blue Frontier, for example, which has developed a liquid desiccant that behaves like a battery for your air conditioner. **Blue Frontier** uses this liquid desiccant to store energy as "dehumidification potential." Combined with evaporative cooling, their technology can pull moisture out of the air in your home and make it cooler. This not only cools your home without the use of harmful refrigerants, but it also reduces peak energy demand by allowing you to store electricity at its cheapest and deploy it when costs are high.

The technology was actually first discovered as a way to kill anthrax, not unlike the original concept for air conditioning, which was developed as a (misguided) way to treat malaria.

Blue Frontier is just one example of several companies working to revolutionize the air conditioning space. **enVerid** is another innovator in this space. enVerid's solution pulls CO_2 and other gaseous contaminants out of indoor air, which allows you to recycle more air and lower the load on your A/C. This especially helps in hot summer and cold winter months; it also allows you to use a smaller A/C unit.

But even as these technologies get better, consumers aren't taking advantage of them. According to the International Energy Agency (IEA), the typical A/C unit sold today is only half as efficient as what's widely available. That means they either don't have the information or the incentives to make energy efficient choices. We need to change that.

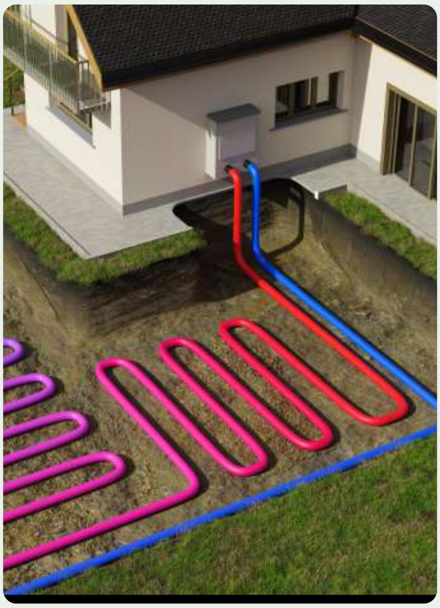
SOME LIKE IT HOT

Why Heat Pumps Are Key to Decarbonization

4

Even as temperatures rise, winter is still coming. And just as we're exploring ways to cool down our homes without warming our planet, we also need clean and efficient ways to stay warm when things get frosty.

Today, furnaces and water heaters account for a third of all emissions that come from the world's buildings. And unlike A/C units, they don't all run on electricity. They're typically powered by oil, natural gas, or propane, which means just cleaning up our electricity grid won't solve the problem.



AN ILLUSTRATION OF A GROUND-SOURCE HEAT PUMP SYSTEM USING GEOTHERMAL ENERGY

That's where heat pumps come in. Because heat pumps run on electricity, they move us away from needing fossil fuels to heat our homes.

There are many different heat pump designs, but the process is similar in all of them: transferring heat from your home to an outside source to cool it down, or transferring heat from the outside source into your home to heat it up. It's the source that changes from design-to-design. For example, air-source heat pumps use the air outside your home. Air-water pumps use reservoirs of water with steady temperatures.

A company called **Dandelion** uses a powerful geothermal heat pump to replace your home's entire HVAC system. This heat pump takes advantage of the stability of the Earth's temperature ten feet underground, which remains 55 degrees Fahrenheit during both winter and summer. During the warmer months, the heat pump takes heat out of your home and puts it in the ground. Once winter rolls around, it takes heat from the ground and puts it back inside your house.

Heat pumps aren't without their flaws.

For example, they struggle to operate at full capacity in extremely cold weather. But they have improved enormously in recent years. 30 years ago, heat pumps were only effective down to about 32 degrees Fahrenheit, or freezing. Today, we have heat pumps that are effective at -15 degrees Fahrenheit. Despite this progress, we still have work to do. And we'll need continued heat pump innovation and other solutions, like e-fuels, for areas of the world where heat pumps aren't fully effective.

Nevertheless, heat pumps will be a key piece of the decarbonization puzzle. In fact, we need an estimated 400 million more heat pumps installed this decade to reach our net-zero target.

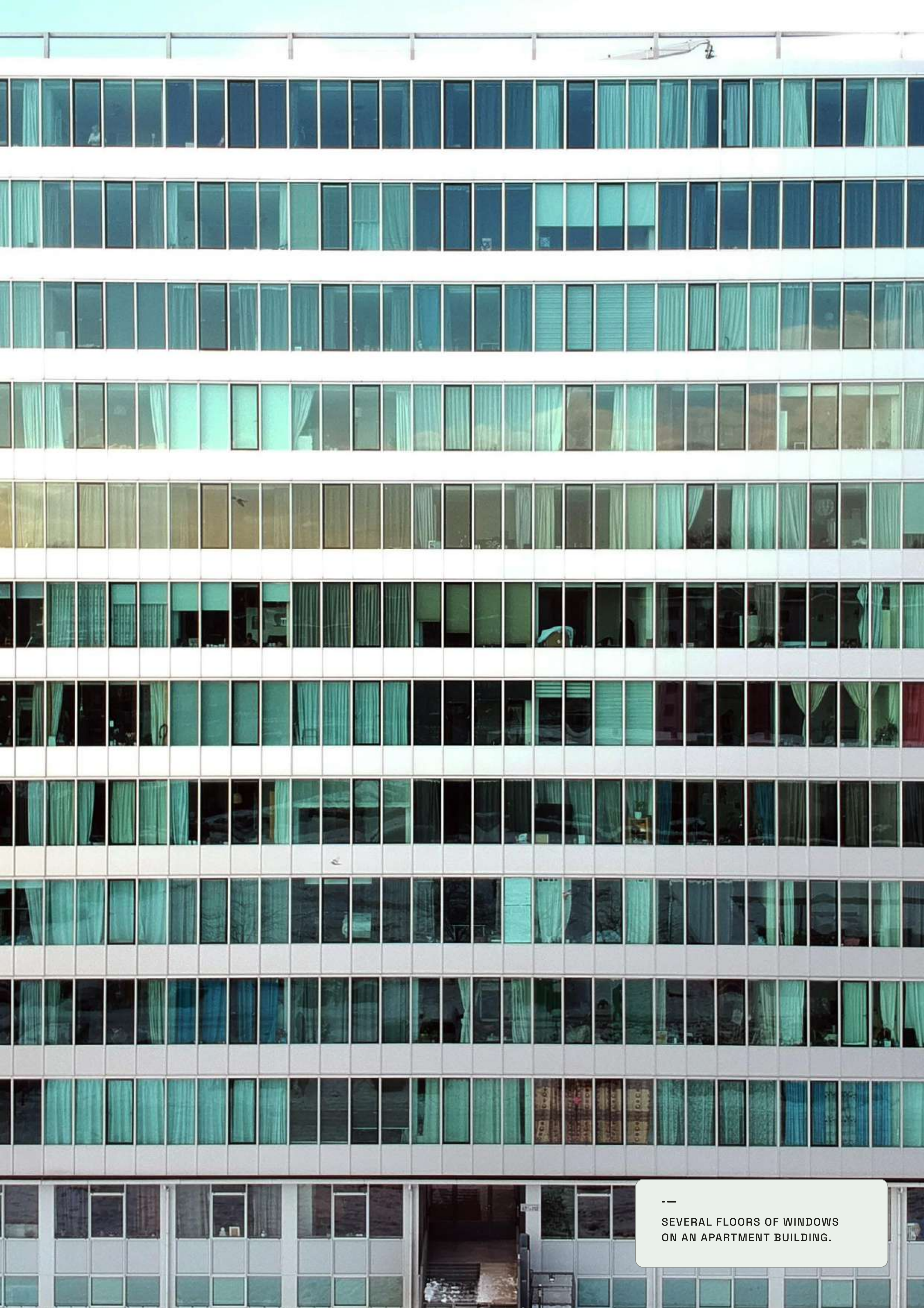
A GEOTHERMAL HEAT PUMP

Of course, it doesn't matter how efficient a heat pump is if no one buys it or if it doesn't work right. Right now, the upfront cost of heat pumps deters many customers. And while heats pumps typically provide 50% energy savings, they use 30% more energy than they should if they're installed incorrectly.

A company called **Conduit Tech** is trying to fix this bottleneck by streamlining the ordering and installation process. Conduit enables HVAC professionals to more easily identify homeowners that are good candidates for electrification and support them through the product lifecycle — design, installation, and maintenance.

30%

The recent Inflation Reduction Act is helping, too, by heavily subsidizing heat pumps, with tax credits up to 30% of the purchase cost.



SEVERAL FLOORS OF WINDOWS
ON AN APARTMENT BUILDING.

WINDOW OF OPPORTUNITY

Breaking Up with Single-Pane Glass

5

Look out your window and you'll see another way your house may not be as efficient as it should be. No, we're not talking about what you see from the window. We're talking about the window itself. The window glass in most of the world's homes and buildings is single-pane, which means a lot of the heat from your house is leaking out, forcing your HVAC system to work harder, cost you more money, and emit more CO_2 into the atmosphere. In fact, windows are the number one source of heat gain in the summer and heat loss in the winter.

AN OPEN WINDOW LOOKING OUT AT THE COUNTRYSIDE ON A FOGGY DAY

FACADE OF GLASS SKYSCRAPER

LuxWall is trying to change that with an incredibly efficient next-generation window. It consists of two specially coated glass panes with a vacuum between them, and it retains four times as much heat as a single-pane window. Think of it like the insulated coffee mug you use in the morning. It keeps things warm on your way to work a lot better than the average cup.

These windows also don't require a lot of installation labor. Without even taking apart your window frame, an installer can switch out three of your single-pane windows for double-pane ones in the same time it takes to bake a frozen pizza.

As with heat pumps, the challenge here is mass deployment. The world currently has 17 billion square meters of single-pane windows. In South America, Africa, Australia, and much of Asia, more than 80% of windows are single-pane.

Replacing all those windows is a daunting task, to say the least. But it's more than worth it. Because as long as we continue to use single-pane glass, we are quite literally throwing energy out the window.

-—

A BEDROOM IN A MODERN HOME

DUCT, DUCT, LOOSE

Sealing Your Home

6

Another way your home is losing energy is through what developers call a “leaky envelope.” In addition to windows, your home often has loose ducts and cracks in the walls that allow air to leak out. Plugging these leaks can help lower energy usage and save you money on your next energy bill.

A ONE-STORY HOME

A WORKER INSTALLING A VENT DUCT

Aeroseal, an Ohio-based company, deals with all the air leakage not involving windows. They’ve developed a harmless polymer fog that’s light enough to float in the air. To seal up a building, they close all the doors and windows, blow air into the building to raise the pressure inside, and then release a fog of these polymers. As the air heads for leaky spots in the air ducts and walls, it carries the polymers, and they build up in the cracks and crevices, making them air-tight.

This can be done at a fraction of the cost — and time — of the traditional manual process. And thanks to deals with several large homebuilders and developers in the United States and Canada, Aeroseal has already sealed over 250,000 buildings.

Unfortunately, sealing your ducts and updating your HVAC system just isn’t as sexy to homebuyers, renters, or real estate agents as redoing your kitchen or adding an extra bathroom.

A FLOWER BOX OUTSIDE A HOME
WITH CRACKS AND PEELING PAINT

Right now, it just doesn't affect the home value as much. As we've seen with the other grand challenges, many of the necessary changes don't affect comfort, quality, or functionality for the consumer, so it's difficult to convince them to accept the Green Premium.

What's more, there's a split incentive problem at play when it comes to big apartment complexes and commercial buildings: If the renter is paying the electricity bill, the landlord has little incentive to retrofit the building with more energy efficient appliances, such as an improved HVAC system or better-insulated windows. These behavioral challenges are at the core of the decarbonization challenge in the buildings sector.

So this will be an uphill battle, but the technology is already here. The Green Premiums are lower than for other grand challenges, and in some cases even negative. And the impact on our climate could be a game-changer.

How Breakthrough Energy Works

Innovation is, by its very nature, unpredictable — but it often follows a well-trodden sequence.

1. **Discovery**: Who are the most promising researchers and innovators out there? Often they're not where you would think, but working in a garage, or university lab, and the idea of a company is barely a glimmer in their eye.
2. **Development**: How can these innovators build companies and actually commercialize their ideas?
3. **Deployment**: How do we make sure those products find lots of willing buyers and users in the real world?

These steps have been broadly true for every major breakthrough in climate tech. But there's an additional twist in this sector: there's no natural market for zero-carbon products, no matter how exciting the technology is. So we also need policy and advocacy to help these products along at every stage.

At Breakthrough Energy, our organization mirrors this process — including that unique last piece — so we can give the world's best climate innovators exactly what they need, no matter where they are in their journey.

How Breakthrough Energy Works

Discovery

Where do climate innovators and innovations come from? This section details the work Breakthrough Energy is doing at the discovery stage.

PAUL ALLEN AND BILL GATES
WITH MICROCOMPUTERS, 1980

Discovery

In 1975, long before Microsoft was a household name, Bill Gates and Paul Allen were just two guys workshopping their ideas in an Albuquerque garage.

Forty years later, when Bill founded Breakthrough Energy, he wondered: Where were the climate tech equivalents of him and Paul Allen? Where were the garages and laboratories populated by young innovators with big ideas?

Finding — and supporting — these people is the first, critical step in the journey for any good innovation, which is why we call this stage, “discovery.”

TAKACHAR'S PROTOTYPE, THE "TAKAVATOR," A PORTABLE MACHINE THAT TURNS CROP WASTE INTO BIOFUELS, CARBON-BASED FERTILIZER BLENDS, AND OTHER VALUABLE BIOPRODUCTS

At Breakthrough Energy, we try to identify great ideas, long before they are associated with a company, founder, or even a catchy name — and long before they have attracted serious funding.

Why? Because we need to improve on existing technology by an order of magnitude — and we don't even know yet what that will look like. It's estimated that nearly half of all emissions reductions in 2050 will come from technologies that have yet to reach the market. The sky-high stakes of the climate emergency mean that we **must** jump-start innovation at the earliest stages, so that ideas can get into the world faster than they would under normal market conditions.

We do this through three programs:

Fellows

1

Breakthrough Energy's Fellows program has some similarities to well-known incubators like Y Combinator and TechStars, but there are key differences. First, our program is focused on technology. The highly technical space we work in requires a highly sophisticated vetting and selection process. We do rigorous technical diligence up front, which also helps derisk technology down the line for our Fellows' future investors. Second, our Innovator Fellows — world-leading scientists and engineers with a critical climate technology to commercialize — work with a dedicated Breakthrough Energy management team that helps identify a specific set of technical milestones and checks in regularly on their progress, providing guidance and advisory support.

FURNO'S MODULAR CARBON-NEUTRAL CEMENT KILN TECHNOLOGY

We also offer an unprecedented level of support for commercialization and growth through our Fellows business advisors program, which is unique in the field. These experienced industry leaders rotate from team to team, advising innovators one-on-one, on topics from fundraising and techno-economic modeling to navigating pilot opportunities and discovering customers.

Even with all this support, some of these highly risky technologies will hit a dead end — and that's okay. We also consider human capital development as a goal in itself: our overall program curriculum is designed toward cultivating talent and empowering scientists to keep innovating in the climate space.

There's no blueprint for a BE Fellow, but here are a couple of examples of Fellows and their journeys:

GURINDER NAGAR
FURNO, FOUNDER AND CEO

Gurinder Nagra was a Stanford PhD student when he founded a company called **Furno Materials**, with an idea to leverage oxyfuel combustion for a more compact, modular, "green" cement kiln, a far more energy-efficient alternative to the average cement plant. Nagra was clearly an innovator, but he had no business experience, no prototypes, and no experiments to show that this would actually work. Still, we bet on his idea in our first Fellows cohort. He quickly hired some great teammates, through introductions from our Business Fellows, and used our R&D funding to set up an independent lab to run initial experiments. Just two years later, he has a working green cement kiln in his lab in Mountain View — one that is already shipping products to customers.

SARAH LAMAISON AND DAVID WAKERLEY
DIOXYCLE, CO-FOUNDERS

Sarah Lamaison and David Wakerley co-founded a French startup called **Dioxycle**, developing a novel device that uses low-temperature electrolysis to directly convert carbon emissions into common chemicals and feedstocks. When they applied for Breakthrough funding, in the middle of the pandemic, they spent all their time in a tiny lab in Bordeaux. Our funding got them out of emergency mode, and into a bigger lab in Paris with a team of nearly two dozen people, where they succeeded in hitting all of their early technical milestones. They recently closed an impressive round of Series A funding, and are engaged in conversations with industry and key utility partners to work towards a small-scale pilot.

Through three cohorts, we've already supported 90 Fellows, across 41 projects and 13 countries, in areas including cement, hydrogen, long-duration energy storage, steel, electrofuels, and carbon capture. We are continuing to scale and grow the program.

A COHORT OF BE FELLOWS

Explorers

2

There are some ideas that are too early even for Innovator Fellowships: ideas that are not yet out of the lab, let alone spun out into a company. That's something we realized after Fellows' first year — which is why, during Cohort Two, we added the Explorer program. Explorers are working on research at universities that might lead to a company down the line. Their ideas are not just at an earlier stage, but often also carry higher technical risk than those of our full-time Fellows.

A BIOLOGIST EXAMINING A PLANT IN A GREENHOUSE

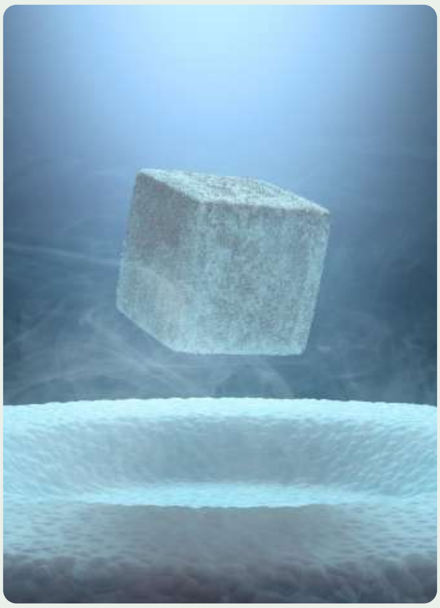
Explorers are primarily academics. We enable them to spend a year at their home institutions, doing commercially-focused research that wouldn't get funded by traditional sources. An example of an Explorer is a plant biologist who has developed a way to decrease the emissions footprint of staple crops, and can see a path to commercialization. We guide them to work on a specific set of experiments, and to get the "technology readiness level" of their research as high as possible — like, for instance, expanding experiments from a model species to commodity crops like corn and soybeans.

If their experiments work, they're ready for the next stage and have a pipeline to become Fellows. Some Explorers from last year have already joined us as Innovator Fellows in Cohort Three.

Workshops

3

The final, and newest, piece of our work at the Discovery stage are workshops. These are intended for us to gain insight into the critical, but often overlooked areas of scientific discovery that could unlock some holy grail solutions. Our workshops bring together scientific experts on some of the most cutting-edge subfields, like high temperature superconductors and hydrogen storage applications, to identify, at the earliest possible stage, if there are ideas or concepts that we can eventually scale up to an Explorer or Fellows project, or even straight to a company that's ready for investment.



AN ILLUSTRATION OF A SUPERCONDUCTOR

This September, we brought together experts, researchers, and startup founders to specifically discuss metal hydrides as a new hydrogen storage option. Why? Hydrogen is a prime energy carrier — a potential replacement for fossil fuels — but safely storing hydrogen at high efficiency and low cost remains a major challenge.

Metal hydrides are a unique potential solution. They can store hydrogen inside a solid-state material using only temperature and pressure. In addition, metal hydrides have potential applications for other energy systems such as heat pumps, cooling, thermal storage, and heat upgrading.

With that in mind, we asked questions to some of the field's leading scientists like: What kind of applications are possible if they do work? What ancillary technology might we need to make that possible? What else should we be researching around this subject? Our hope is, no matter which of these theoretical technologies work out, or when, we'll be in a good place to develop a commercial ecosystem around it.

WIND TURBINES AT SUNRISE

THE HORIZON

Today, some of the most promising companies in climate tech are just ideas in universities and laboratories, far from Silicon Valley, in the minds and on the work benches of brilliant scientists and engineers.

Our discovery programs find and foster the people working on those critical, yet high-risk, technologies, and help them develop their ideas before soliciting conventional scaling capital.

Across our first three cohorts, we're working to help derisk a portfolio of high-potential technologies so that more capital can follow our trail to the most exciting climate solutions of tomorrow.

How Breakthrough Energy Works

Development

How do we turn great ideas into great companies? This section details the work Breakthrough Energy us doing at the development stage.

AN AERIAL VIEW OF SILICON VALLEY IN THE 1970S

Development

The best way to build technologies is with tech companies, and for almost 50 years, the surest way to build tech companies has been with venture capital.

The first venture firm signed a lease on Silicon Valley's Sand Hill Road in 1972, and ever since, the playbook for building a very big technology company very quickly has followed four steps: identify a unique way to solve a large problem using technology; secure a venture investment; use the money to hire smart people; and build a successful company.

But there's always been an unwritten caveat to these instructions: they don't apply if the company you're building has something to do with the Earth's changing climate.

Venture capital has always had a climate problem.

THE SAN FRANCISCO-OAKLAND BAY BRIDGE LIT UP A NIGHT

Unlike VC and software, or VC and search engines, or VC and social media, VC and climate tech never fit very well together — partially because of a skills gap. Climate tech is a relatively new field, and there aren't many people with both a hard science background and expertise in building startups.

Successful entrepreneurs often became venture capitalists while chemists and biologists became, well, chemists and biologists, leaving an absence of people who might make informed investments in nuclear fusion or carbon-free cement.

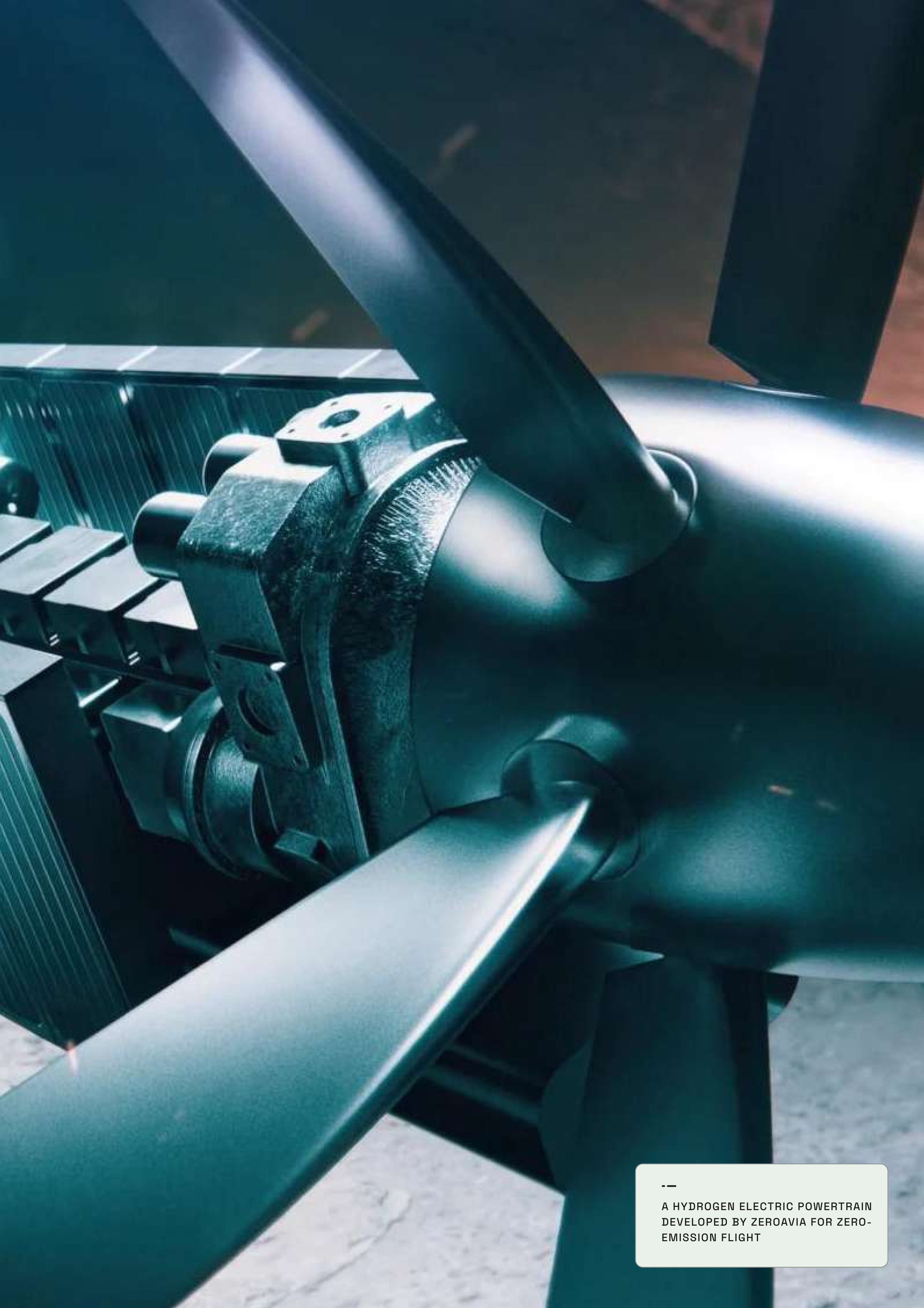
Timing was another square peg in a round hole. Most venture capital firms invest in startups hoping they'll make their money back within a decade, a reasonable expectation when you're investing in software. Roughly twenty-six months elapsed between Microsoft's hiring of its first Windows programmer and when the first Windows 1.0 floppy disks hit the shelves.

A FUSION MAGNET MANUFACTURED BY COMMONWEALTH FUSION SYSTEMS USING A NEW HIGH-TEMPERATURE SUPERCONDUCTOR

But fusion power plants are not lines of code. Nor are carbon-free steel factories or advanced car batteries. These technologies can take years, even decades, to translate from cutting-edge science to deployable and scalable solutions.

Climate tech is also typically "tough tech" — applications of science and technology to the world's biggest problems — and has similar structural obstacles to getting off the ground. Namely, pretty slim margins, which are usually not compatible with a VC firm seeking huge returns for a small slice of their portfolio.

These kinds of tech also have fewer intermediate checkpoints to make sure they actually work. Think of an industry like pharmaceuticals, which has a standard progression of four different trial phases — there's nothing really comparable for tough tech. It's often difficult to tell how well a company will do until it's literally on the market.



A HYDROGEN ELECTRIC POWERTRAIN DEVELOPED BY ZEROAVIA FOR ZERO-EMISSION FLIGHT

ZEROAVIA HYPERTRUCK GROUND RIG TESTS IT'S HYPERCORE MOTOR TECHNOLOGY

For all these reasons, by the mid-2010s, Bill Gates and Breakthrough Energy's founding team realized that, if climate tech was to benefit from the company-building, scaling power of VC, then it would need to be a pretty different kind of VC.

It would have to be a VC operation that was built for the specific purpose of supporting decarbonization technologies, which meant it would have to be far more patient, and more technical. Any VC firm investing in climate would also need to get comfortable taking enormous risks and be prepared to deal with the policy and capital intensity specific to climate tech.

A CEMENT BLOCKED CREATED USING BRIMSTONE'S CARBON-NEGATIVE PROCESS

Of course, all VC firms are comfortable with some measure of risk. They recognize that only a small fraction of their portfolio companies will return a profit. But climate venture capital is different from the rest in one important respect: There's a big invisible countdown clock hanging over its work like a specter. Investors and their startup companies aren't trying to meet an artificial financial deadline; they're racing against a real climate deadline, as more and more greenhouse gas (GHG) emissions are released into the Earth's atmosphere.

Given the narrow window we have to solve climate change, it doesn't make sense to invest resources in a company that will abate a small amount of GHG emissions — even if their technology is a surefire bet. We need to make big (albeit well-informed) bets. At Breakthrough Energy Ventures, we concluded that any startup worthy of investment needed a conceivable pathway to reducing 500 megatons per year of GHG emissions — roughly one percent of all global annual emissions.

Six years later, Breakthrough Energy Ventures has invested nearly two billion in over 100 such companies. It's still too early to measure how much emissions these companies, individually or collectively, have abated. (We plan to include those metrics in future versions of this report). But much of the anecdotal evidence we have shows that our model is working.

CASE STUDY

Antora Energy

When Breakthrough Energy Ventures first met with **Antora**, the company employed 15 people and had just moved out of their first office at Lawrence Berkeley National Laboratory.

“Office,” in fact, was a generous term. Antora was working out of a trailer.

Andrew Ponec, Justin Briggs, and David Bierman had started Antora with a single question: What is the most important solution to climate change that no one else is building? Their answer: a modular thermal battery capable of outputting zero-emissions heat and power to decarbonize manufacturing, the single largest source of global emissions.

ANTORA’S TECHNOLOGY PRODUCING THERMOPHOTOVOLTAIC CELLS

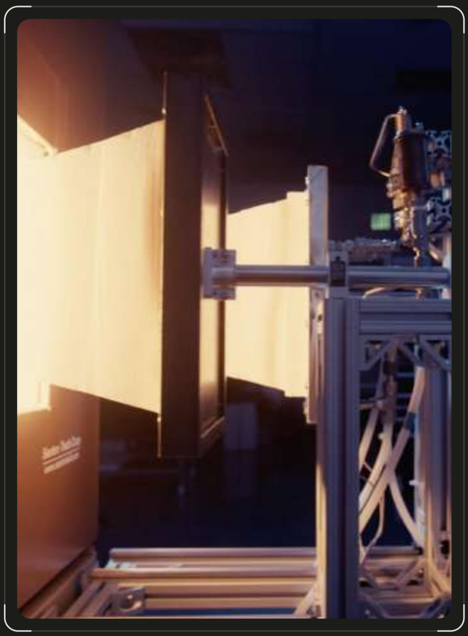
ANTORA’S THERMAL ENERGY STORAGE SITE IN FRESNO, CALIFORNIA

At the time, Antora had recently broken the world record for efficiency in thermophotovoltaics—a groundbreaking technology for converting heat to power.

And the scrappy team had built a prototype that demonstrated the basic operational principles of their thermal battery, receiving seed funding from the U.S. Department of Energy’s Advanced Research Projects-Energy (ARPA-E), the Office of Industrial Decarbonization and Energy Efficiency (IEDO), the National Science Foundation (NSF), and the California Energy Commission (CEC).

It was immediately clear to the BEV team that Antora had a powerful idea for a rapidly scalable product, an enormous market opportunity to decarbonize industrial heat and power, and an exceptional team with world-class technical expertise. What they needed was private capital and support to take their game-changing idea from a prototype to a commercial-ready product. That is what Breakthrough Energy Ventures delivered, co-leading Antora's Series A and bringing total funding up to $50 million

BEV's Christina Karapataki, who joined Antora's board, and Sila Kiliccote, a former startup CEO, who joined as a board observer, are now trusted partners to Andrew, Justin, and David on all aspects of the business, including product development and the commercial roadmap. They have connected Antora with major renewable power suppliers, marquee customers, and critical commercial and financial partners. And the robust policy and communications support that Breakthrough offers has helped Antora navigate the intricacies of the energy and industrial sectors.



ANTORA'S PROCESS HEATS CARBON UP TO 2,000 DEGREES CELSIUS, ONE-THIRD THE TEMPERATURE OF THE SUN.

Two years after leading Antora's Series A, the catalytic impact of our investment is clear.

This fall, Antora launched its first commercial-scale thermal battery at an industrial site outside Fresno, California, which Bloomberg called "a major step toward its goal of weaning heavy industry off fossil fuels."

With BEV's support, Antora is now ready to scale. They recently opened a thermal battery manufacturing facility in San Jose, California that will have its first battery modules rolling off the line in 2024 to serve major industrial decarbonization projects. And they have additional customers lined up for a proven product that's poised to decarbonize industrial sites across the United States and around the world.

What's next for BEV?

What are the kinds of companies the climate needs built next?

Last year, at Breakthrough Energy's inaugural summit, Eric Toone, BE's Chief Technology Officer, laid out three categories of problems that need addressing:

1. The challenges we didn't see in in 2015, when we were founded;
2. The challenges we did anticipate, but still haven't solved;
3. The challenges that didn't exist in 2015, but now do because the world has changed.

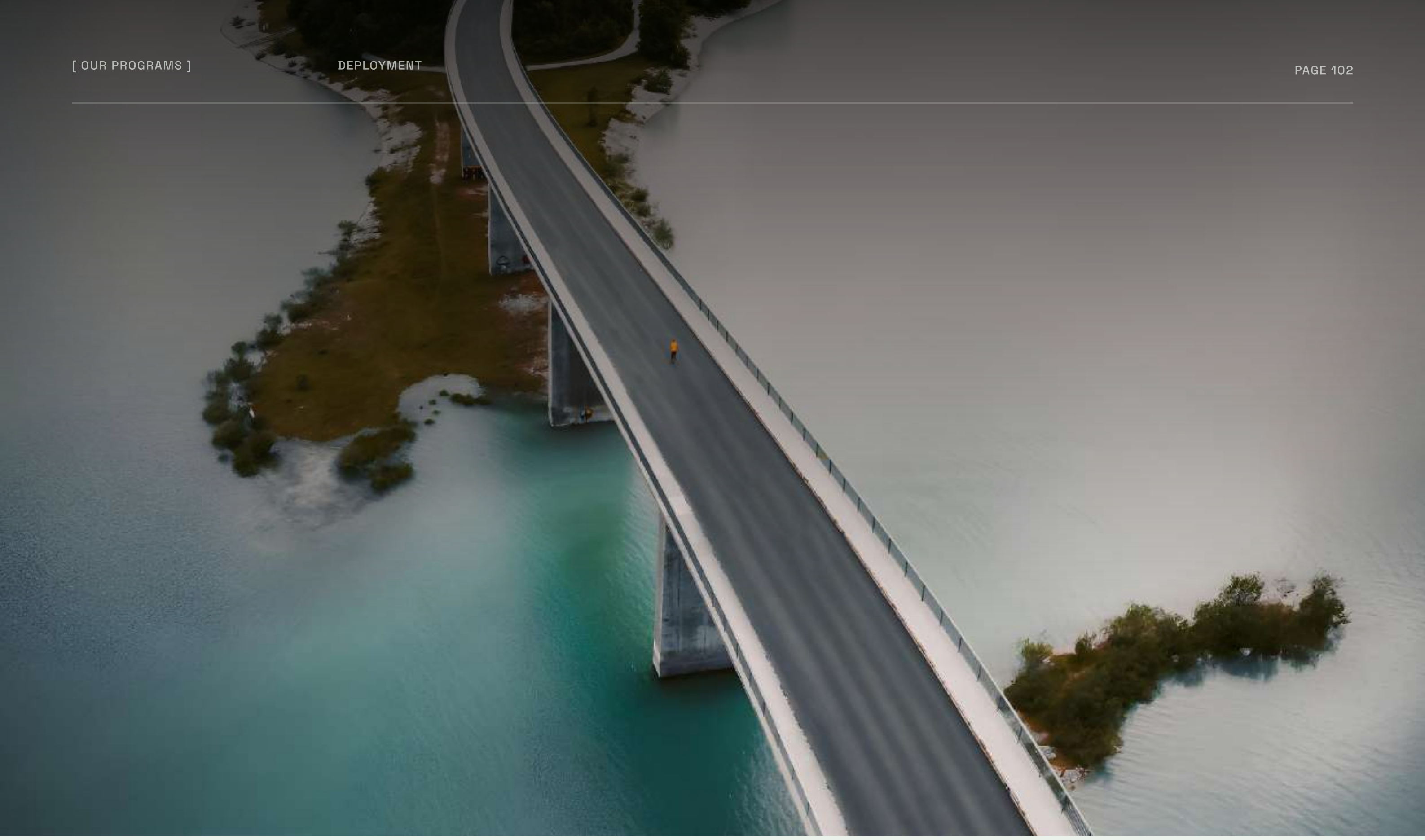
Those questions are informing the future of Breakthrough Energy's work at this development stage, as we look at funding new early-stage companies — and continue to help the ones already in our portfolio.

BEV'S ERIC TOONE DELIVERS REMARKS AT THE BREAKTHROUGH ENERGY SUMMIT

How Breakthrough Energy Works

Deployment

How do we help innovators get their tech out in the world at scale? This section details the work Breakthrough Energy is doing at the deployments stage.



DEPLOYMENT

Breakthrough Energy Catalyst

A BRIDGE CROSSING A LARGE BODY OF WATER, WITH FOREST AND MOUNTAINS IN THE DISTANCE

Imagine you're an innovator working on emerging climate technologies. You pour your blood, sweat, and tears into developing the technology. Once you get it to work, investors will surely be knocking on your door. Right? Unfortunately, it's not that simple.

For a new technology to draw investors, it needs to be "derisked." That means more than just proving the technology can work. It means proving it can work at scale — and be cost competitive with fossil fuel alternatives.

BADWATER BASIN IN DEATH VALLEY NATIONAL PARK, INYO COUNTY, CALIFORNIA

All new technologies need to be "derisked," but especially new climate technologies. Often a company's first commercial-scale project seems too risky for traditional infrastructure investors. These projects require huge sums of funding, and have highly uncertain returns.

In short, there is a treacherous gap between technology development and technology deployment at large scale. Innovators sometimes call this, "the valley of death." Most new technologies being deployed in first-of-a-kind (FOAK) projects never make it across.

But what if we could help build a bridge across the "valley of death?" That's where Breakthrough Energy's deployment program, Catalyst, comes in.

ROBOTIC ARMS ASSEMBLING AN EV BATTERY PACK AT A COMMERCIAL SCALE PLANT

By using its capital alongside our team's energy-infrastructure-investing and project-development expertise, we work with innovators to advance their projects from the development stage to funding and ultimately, to construction — starting the derisking process and reducing the technology's green premium to increase the chances it will make it to the other side of the valley.

If our Discovery-stage work helps accelerate the earliest-stage of innovation through Fellows, Explorers, and Innovation Workshops, and our Development work accelerates climate-tech company-building through groundbreaking venture funds, then you can think of our Deployment work as accelerating late-stage innovation — what's often called learning-by-doing, which is what happens when projects get developed and built, processes improve, and costs come down over time.

Because at this stage, innovators need more than just financing. They need expertise.

Innovators need people who understand how to get sites, permits, easements, interconnections, and regulatory approvals. They need business development people looking for customers, securing critical feedstocks and power. And they need people advancing the project design, engineering, procurement, and construction plans, including identifying key equipment and contractors.

Finally, they need the team to execute complex construction while adhering to timelines and strict budgets. Catalyst provides not only critical funding, but also this infrastructure expertise to lower the engineering and other operational risks of promising technologies. And we unite companies with key stakeholders such as investors, off-takers, and governments to enable demonstrations or build commercial-scale projects.

SUNRISE IN BEIJING'S CENTRAL BUSINESS DISTRICT

Our criteria for the projects and technologies we support focus on two main attributes: impact and replicability.

Not every project is a fit for Catalyst, but we let innovators know why they fall out of our scope. For example, we wouldn't support a conventional investment in wind or solar energy, which can usually attract funding elsewhere. Nor would we support a project that can only work in the American Southwest.

What we take on must be scalable around the world, including and especially in emerging markets. Certain technologies may have already achieved some level of success — via pilot projects or a technical demonstration — but require additional funding for much larger FOAK projects to prove that they can scale up.

What We've Achieved (So Far)

1

Catalyst has identified five areas that were ripe for our unique derisking approach: clean hydrogen, long duration energy storage (LDES), sustainable aviation fuel, direct air capture, and manufacturing.

These are areas where new technologies have emerged from the discovery and development phases but are not yet mature enough to attract capital from typical infrastructure investors. They're also areas where the technologies are more expensive than fossil-fuel alternatives.

LANZAJET'S ALCOHOL-TO-JET BIOREFINERY IN SOPERTON, GEORGIA

Over the past year, the Catalyst team has tried to home in on technologies in these areas. We're looking at ones that will reduce the most emissions and will be easily replicable. We've also attracted projects that are geographically diverse, with one-third of our investments happening in Europe. Here are some updates:

• Clean Hydrogen

Catalyst's focus continues to be on electrolytic hydrogen production, particularly via technologies like Alkaline Water and Proton Exchange Membrane (PEM) electrolysis.

• Long Duration Energy Storage

Catalyst continues to back as many viable storage technologies as possible. If we want to dispatch renewable energy 24/7, the world needs options, including technologies that don't rely on lithium-ion batteries and are capable of "intraday energy shifting" — around 10 hours of energy storage — or "multi-day shifting," which is about 100 hours of storage. This work builds on grants we've made in the past, like the $20 million for Xcel Energy to support the deployment of two multi-day, long-duration energy storage projects.

Sustainable Aviation Fuel

Catalyst is prioritizing new SAF technologies that can scale globally with a near-term focus on "Power-to-Liquids" projects. We're also supporting the scale-up of e-fuels production by working with projects to de-risk conventional electrolyzer technology and prove end-to-end process integration at an unprecedented scale. This work builds on the successful grants we've made, including $50 million to Lanzajet. With the money, they are completing construction of their alcohol-to-jet fuel Freedom Pines Fuels plant in Georgia.

Direct Air Capture

In the carbon removal space, we continue to analyze a number of engineered carbon removal solutions, like carbon mineralization, solid sorbent, and liquid solvent.

Manufacturing

Catalyst added manufacturing as a focus this year — specifically the manufacturing of cement, steel, plastics, textiles, and fertilizers.

EUROPEAN COMMISSION PRESIDENT URSULA VON DER LEYEN DELIVERS REMARKS

Catalyst also began operationalizing its €840 million partnership with the European Investment Bank and the European Commission. We also previously announced a similar partnership with the United Kingdom to be made operational and are closely collaborating with the U.S. Department of Energy.

HYDROGEN FUEL STORAGE WAREHOUSE

What We've Learned (So Far)

2

If there's one thing we've learned over the last year, it's that this is hard work. All of these technologies will face obstacles related to financing, technological reliability, standardization, and regulation. So how can they avoid the common pitfalls of scaling up? Here are five things the Catalyst team has learned so far.

THE SHADOW OF A PLANE AGAINST AN ARRAY OF SOLAR PANELS

First, these companies need a marketplace that sets them up for success. That means securing strategic anchor investors and long-term offtake agreements for their products under terms that will eventually attract infrastructure investors.

Take the airline industry, for example. We know we need to cut emissions from plane travel. One avenue is through sustainable aviation fuel (SAF). It is one of the most straightforward decarbonization stories given that, for the most part, infrastructure and airplanes do not need to be replaced — just the fuel. Unfortunately, airlines typically only buy fuel stock for months at a time, not multiple years ahead. That is far too short of an offtake for emerging SAF companies to attract investment and guarantee revenue. It's critical that aviation fuel buyers agree to offtake agreements of no less than ten years in order to give investors the confidence they need to invest capital in production. Catalyst has helped explain this to forward-thinking airlines, and those airlines are signing long-term agreements for some of the projects we are backing.

We've seen this work before. The solar and wind power revolutions were built on the backs of 20-year offtake agreements with utility companies. This gave investors the confidence to support these technologies, helping them scale and ultimately change the landscape of the electricity industry.

A CONSTRUCTION SITE AT SUNSET

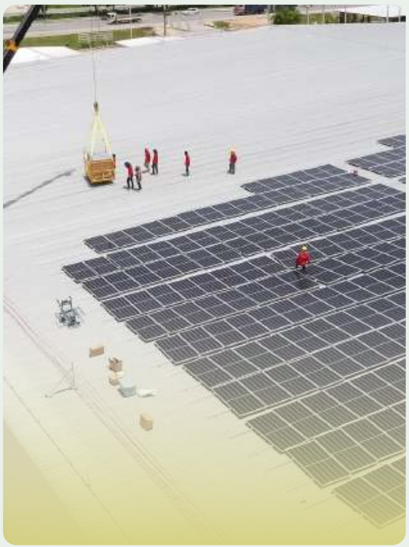
Second, it's vital for developers and investors to structure construction and equipment contracts that isolate risk, incentivize high performance, and ensure tech reliability and replicability. New projects can often face delays and unexpected costs, especially during the physical construction phase. In fact, only about 10% of capital projects come in on time and on budget.

To put investors at ease, those developing FOAK projects should insist on engineering, procurement, and construction (EPC) contracts that create clear accountability for quality, costs, and risks among qualified contractors, as well as build in incentives and adequate resources (such as time and dedicated funds) for on-time and on-budget execution. There needs to be a very strong risk sharing framework that allows all parties to be able to rely on these contracts and have a high certainty that the project will be built.

Third, while developers of these projects should court early customers, they should be careful about locking in pricing until the design of their project is mature and the full costs are known. As mentioned earlier, project costs typically increase as the design matures, and this must be considered before a final investment decision can be made.

Fourth, projects need to show reliable access to feedstock and clean electricity supply. It's impossible to attract long-term investors to projects that can't show they have a stable supply of the raw materials necessary to make the technology work. What's more, it's not worth investing in a climate project that negatively impacts the environment. That's why it's critical for these technologies to be supported by clean electricity.

AERIAL VIEW OF ELECTRIC SUBSTATION



WORKERS INSTALLING SOLAR PANELING ON THE ROOF OF A LARGE WAREHOUSE

Finally, developers should look at how all the pieces of the project fit together and ask themselves, “Can this support my nth project?” This goes back to our first lesson: Set yourself up for long-term success.

Emerging climate tech should not be a business of one-offs. By definition, we need technology and agreements that can scale and go the distance, shifting markets and modeling success for other players. Emerging technologies should try to share information, standards, and best practices where possible. This helps ensure broader industry success by improving tech reliability and preventing other companies from making avoidable mistakes.

WHAT’S NEXT

Expand, Expand, Expand

As we head into the new year, Breakthrough Energy is focused on expansion across all areas of our deployment work. How do we expand funding to projects beyond our current pipeline of projects? How do we reach deeper into the decarbonization of industry? How do we expand our reach to support projects in other markets around the globe? How do we expand our partnership base and draw in new investors to help lift up these critical technologies?

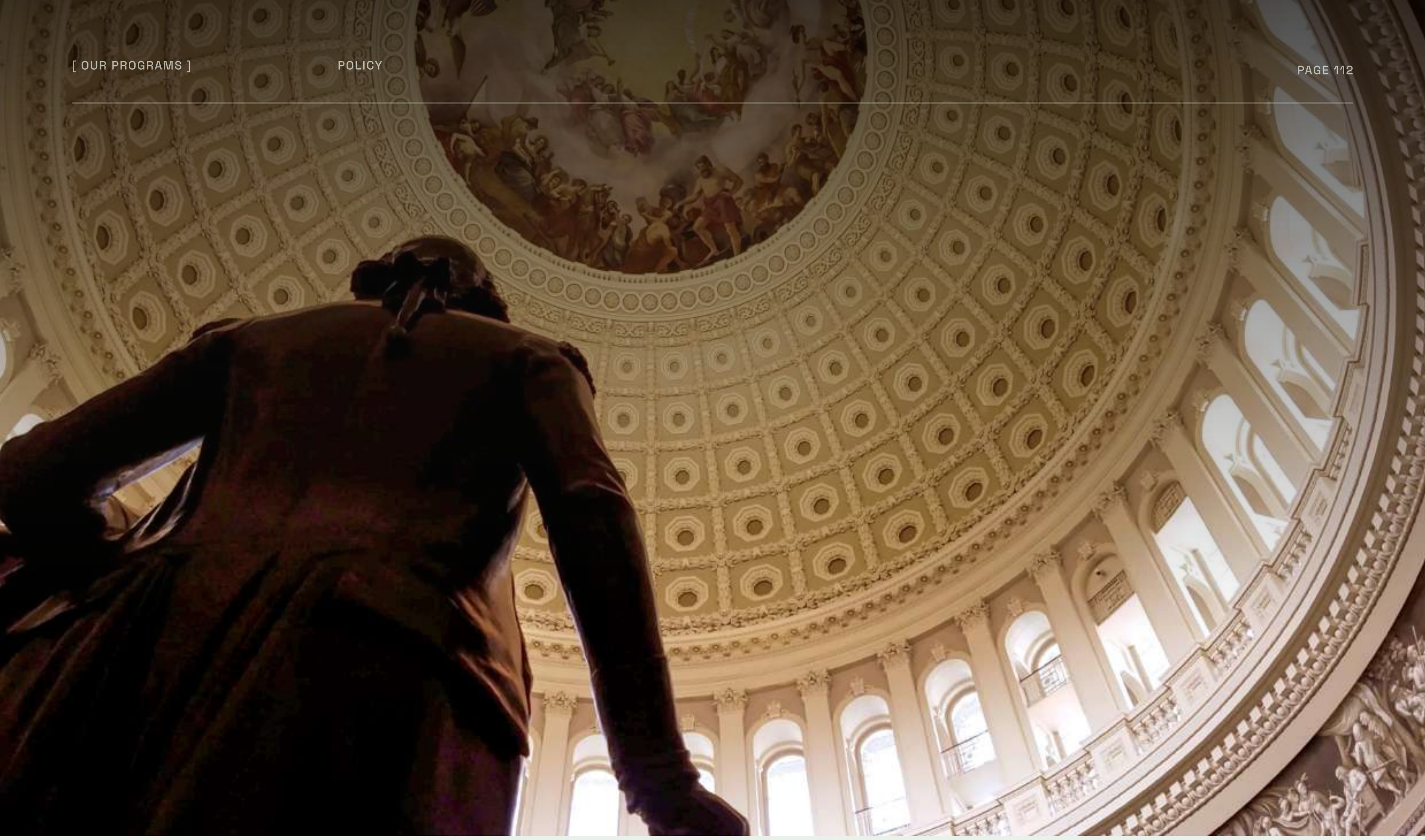
ROWS OF PIPELINE AT SUNSET

If we’re going to meet our climate goals, we need to catalyze innovation all around the world. With the right capital solutions and expertise, cleaner alternatives can displace carbon-intensive technologies and help us reach net zero.

How Breakthrough Energy Works

Policy

This section looks at how Breakthrough Energy is supporting policy-making around the world.



A VIEW OF THE U.S. CAPITOL DOME'S CEILING

CROSS-CUTTING

Policy

When the first modern electric cars hit the market in the late 1990s, interest was limited. The first people to buy them were either very rich, very climate-conscious, or both.

It wasn't until the 2010s that electric vehicles (EVs) finally found something like a mass market. Why? Batteries became much cheaper, and EVs became far more affordable — but another key factor was that the government intervened. In 2009, the United States implemented a federal EV tax credit, giving a $7,500 rebate to anyone who purchased a qualifying EV. One 2018 study found that every $1,000 offered as a rebate or tax credit increases average sales of EVs by 2.6%.

STARTUP HELIOGEN USES FIELDS OF AI-CONTROLLED MIRRORS TO HARNESS THE POWER OF THE SUN.

This is the perfect example of why climate innovation doesn't happen in a vacuum: Technology is important, but policy is often what moves the needle on adopting them at scale.

Even if new green technologies are perfect — which the first electric cars certainly weren't — they have their limits. The fundamental challenge of inventing zero-carbon products, from EVs to green cement to sustainable jet fuel, is that there's no natural market for them. Sure, you might get a few wealthy climate advocates to buy them, but without some extra incentive, they won't catch on.

That's why the people historically tasked with fixing broken markets — policymakers — are as important as innovators and scientists in achieving a zero-carbon world.

At Breakthrough Energy, we support this policy-making around the world, drawing on our technical expertise across all the different sectors you just read about.

PRESIDENT BIDEN SIGNING THE INFLATION REDUCTION ACT AT THE WHITE HOUSE

Of course, every country's journey to net zero will be different, and so will the policies they need. But at the highest level, when we think about climate policy from a global perspective, it can be divided into three parts.

1. The first is the highly-industrialized, high-income countries, like the United States and many European countries, where a lot of innovation is happening, and where governments are wealthy enough to help fund the transition to lower sources.
2. Then there are the middle-income countries — like Brazil, India, and China — who often have higher real-time emissions, but are also the largest markets for adopting those technologies.
3. Finally, there are low-income nations across the Global South, which don't have the money to pay for these things, but still need them — arguably the most — because their populations are the most vulnerable to extreme climate change.

United States

1

The United States is the second-largest greenhouse gas (GHG) emitter in the world. As the United States moves to meet its climate goal of reducing emissions by 50% in 2030, it can simultaneously inspire and incentivize the energy transition in the rest of the world.

USPA VICE PRESIDENT, ALIYA HAQ ON STAGE WITH PRESIDENTIAL ADVISOR JOHN PODESTA

First, the good news: American climate policy in recent years has been a rare bright spot in our field.

The Energy Act of 2020, the Bipartisan Infrastructure Law of 2021, the CHIPS and Science Act of 2022 (CHIPS), and the Inflation Reduction Act of 2022 (IRA) — all signed into law, three of them with bipartisan support — will help reduce U.S. emissions and drive down green premiums for emerging clean technologies. Together, these bills will invest at least $500 billion in clean energy — with the potential for the total investment over 10 years to climb to over one trillion, depending on how much demand is created in the private sector.

But much more work remains to ensure that these laws are implemented successfully, as well as to ensure progress in future climate policy. Our U.S. Policy & Advocacy Team aims to cut through it by leveraging our in-house team of experts, our uniquely strong network, partnerships forged through grantmaking, and a longer-term view than workaday politics can often afford. Looking to 2024 and beyond, our policy team is focusing on multiple fronts. We're helping agencies implement new funding and tax credits, advocating for more long-distance transmission lines to accommodate increased electrification, focusing policy work on "hard to abate" sectors like agriculture and aviation, and driving the conversation forward around technology-neutral performance standards for electricity, fuels, and manufactured products — to name just a few tracks in which we work.

Europe & the United Kingdom

2

In 2019, the United Kingdom (UK) became the first G7 economy to commit by law to net zero by 2050. Soon after that, the European Union (EU) became the world's first multinational bloc to set a legally binding net-zero emissions target, dubbed "Fit for 55," referring to its 2030 target of reducing emissions by 55% (compared to 1990 levels), through reforms covering everything from renewable energy and energy efficiency to green hydrogen mandates.

A GEOTHERMAL POWER STATION IN ICELAND

FROM LEFT TO RIGHT: RAMYA SWAMINATHAN (CEO, MALTA), ANN METTLER (BE VP, EUROPE), FATIH BIROL (IEA EXECUTIVE DIRECTOR), BILL GATES (BE FOUNDER), AND URSULA VON DER LEYEN (PRESIDENT OF THE EUROPEAN COMMISSION)

But, on a practical level, both the United Kingdom's and the European Union's overall net-zero transitions require far more effective mechanisms to unlock investment.

In short, industry and investors need a business case: one supported both by demand for green products and services, and by targeted interventions to stimulate investment. BE is supporting Europe's journey to become a climate tech leader and meet its ambitious climate goals in a number of ways.

In these regions, we're focusing on key roadblocks to scaling up promising technologies, like long-duration energy storage (LDES) and green steel. We're also bringing attention to regulatory bottlenecks and slow permitting; forging partnerships, including with the European Commission, the European Investment Bank and the UK government; and addressing key scaling challenges, such as with LDES and e-fuels. We're also working to reduce overall transition costs in an era of high inflation by leveraging private finance, tapping into institutional investors' capital, and working to increase the availability of public risk capital for emerging climate technologies.

It remains important to work across all fronts, because progress is never linear. The Ukraine war and subsequent energy crisis have slowed progress on electrification, which remains the cheapest decarbonization pathway in Europe — just one example of why, even in a region with exemplary climate leadership, it's crucial to constantly evaluate and adjust our strategies.

Low- and Middle-Income Nations

3

The key problem with getting the green premium on promising new technologies to zero is that initial production, with a new process and high learning curve, is often expensive, as evidenced by precedents like solar power and lithium batteries. So countries in a position to lower that either through procurement policies or tax credits, can send a helpful market signal for the rest of the world.

WIND TURBINES OVERLOOKING A RURAL ROAD

Once we have the kind of better-performing alternatives incubated by organizations including Breakthrough Energy, our goal is to help roll out those products at scale — making them affordable enough to deploy in such large, middle-income countries as India and Brazil, and allowing millions, if not billions, of people to reduce emissions while still improving their quality of life. We rely on our evolving global network to make this happen, constantly expanding partnerships with philanthropic actors, lawmakers, advocates, and activists.

One common type of policy hurdle around the world is bureaucratic.

For instance, emerging technologies in methane-reduced feed for cows have huge potential to decrease emissions. But across countries with the biggest cattle inventory, it's harder to get new kinds of food approved for animals than for humans, which makes it nearly impossible to scale these technologies. We are working globally to solve such policy obstacles, taking into account country-specific challenges and concerns at every step.

NEXT STEPS

What guides our policy efforts, both in the United States and internationally, is that they're all stops along the global pathway to net zero. Though it requires complex navigation of local partnerships and political realities, our policy work is conducted with an eye towards accelerating innovation around difficult problems, and getting solutions into the real world as fast as possible over the next decade.

Carbon Management

Removing carbon from the air will be vital to our clean energy future. This section explores the different methods of carbon removal and management, and why they're not an excuse to keep polluting.

CARBON MANAGEMENT

A BATHTUB OVERFLOWING

An Update On Carbon Removal & Direct Air Capture

When making the case for net zero, climate experts often refer to the "bathtub analogy." The atmosphere is like a bathtub that's slowly filling up with water. (In this case, the water is carbon dioxide (CO_2). Even if we slow the flow of water — or CO_2 — to a trickle, the tub will eventually fill up and water will come spilling out onto the floor. What makes this process even more complex and challenging is that there are multiple spigots — electricity, transportation, buildings, manufacturing, agriculture — so you can't simply turn one knob.

That's why it will be extremely difficult to shut off all the water before the bathroom floods. So in addition to turning off the spigots, we also need to mop up the spilled water on the floor.

That's where carbon capture, storage, and removal come in. Most of this report focuses on how to reduce our emissions by switching to renewable energy, decarbonizing steel and cement, and fostering innovation in technologies like hydrogen and fusion and other promising technologies. But that still won't be enough to completely avoid disaster, because there's already too much carbon in the air.

A CARBON REMOVAL FACILITY

Before we go any further, we need to make one thing clear: Carbon capture is not an excuse to keep emitting greenhouse gases (GHGs).

Many climate experts worry that this technology gives people the wrong idea: Why stop emitting carbon when we can suck it out of the air? This is neither practical nor economically efficient. But over the last decade it's become abundantly clear carbon capture is one necessary tool, in a larger tool kit, we can use to achieve net zero.

There are many ways to capture or remove CO_2 from the air. The oldest technological capture method is called point-source capture, which involves new builds or retrofitting industrial sites and power plants with special devices that capture the CO_2 before it even reaches the atmosphere.

Direct air capture (DAC) is a new method, which can remove CO_2 from the air anywhere, not just at the site of emission.

Of course, engineered removal methods are not the only option. Nature offers avenues as well. Natural carbon removal includes planting trees, preventing deforestation, and managing croplands more efficiently.

Finally, there is a hybrid option that brings together the benefits of engineered and natural carbon removal strategies. This involves burying biomass that would otherwise decay and emit carbon. While point-source capture has been around a long time, these devices are expensive to buy and operate. And unless mandated by law, companies have little incentive to use them.

We've seen some progress in lowering the costs and carbon footprint in this space. Companies like **Mantel**, a BE Fellow, have found innovative ways to do point-source capture using less energy and less heat than typical methods, lowering the cost of this technology.

The most promising advancements in this space, however, have come from the carbon removal methods. In addition to preventing CO_2 from entering the atmosphere, we can remove CO_2 already in the air. All three of the aforementioned removal strategies, which we will discuss in detail below, are vital to reducing CO_2 in the atmosphere and reaching our climate goals.

But cost remains the biggest barrier. Today several companies are pursuing practical direct air capture; some of those approaches could have cost entitlements below $100/ton. Yet, while there is some market for carbon capture and sequestration at those levels, widespread willingness to pay is likely significantly lower than that. That means we need more options for carbon removal.

THE TAKING TREE

Nature-Based Carbon Removal

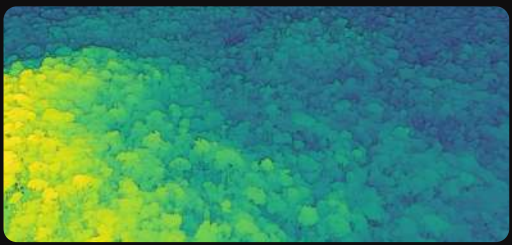
1

There are several natural ways to remove CO_2, from planting trees and preventing deforestation to managing soil more efficiently and seeding algal blooms with iron. Currently, these methods remove about 30% of annual emissions. They're relatively inexpensive, globally scalable, and have added co-benefits like increased crop yields.

AERIAL VIEW OF A FOREST DAMAGED BY FIRE

But nature-based removal has some challenges. For starters, it's not permanent. Forests and croplands are prone to wildfires and other natural disasters, which would quite literally send all the carbon they trap up in smoke and back into the atmosphere.

Nature-based removal is also hard to measure. How do we know that what is happening is actually additive? Would a tree have grown naturally in a similar spot even without sending someone to do it? What's to stop people from taking money in exchange for protecting forests in their area that they were never planning to cut down in the first place?



PACHAMA'S FOREST MAPPING HELPS BRING TRANSPARENCY TO CARBON MARKETS

These problems have plagued nature-based removal strategies for years, inviting skepticism from climate experts and investors. But new tools and technologies are resulting in far more rigorous monitoring, reporting, and verification.

Pachama, a company BEV has invested in, uses remote sensing and satellite mapping to develop forest carbon projects and ensure the credibility of carbon credits, harnessing the power of AI to build a modern, scalable, and transparent carbon market.

Soil carbon sequestration has shown great promise as well, but it also struggles with inaccuracies and transparency. Another company we're working with, **Yard Stick**, deploys handheld probes and spectroscopy for nearly instantaneous carbon measurement reporting verification. The cost-effectiveness of this method allows for a significant increase in the number of samples taken and may help address the signal-to-noise challenge that's been inherent in soil analysis.

Preventing deforestation is also critical to limiting our emissions. Carbon credits are one way to disincentivize deforestation. But what if the deforester you're dealing with is Mother Nature? **Data Blanket**, a BEV company, uses AI drone technology to give firefighters an upper hand against wildfires and prevent even further destruction and carbon release.

LAYERS OF SOIL

Nature-based carbon removal is the only tool we have that's scalable today, and we need it in order to manage land use change emissions over the next decade.

And yet, for all its affordability and scalability, it doesn't provide the permanence of engineered solutions. Nature-based solutions can be a stopgap, but we need advanced engineering and technology to take us the rest of the way.

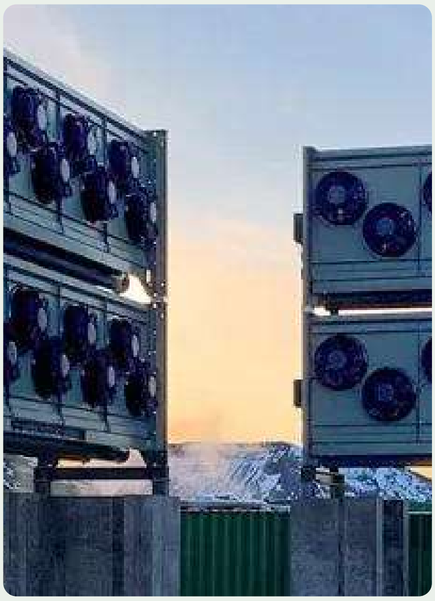
DIRECT AIR CAPTURE

Engineered Carbon Removal

2

The concept of engineered direct air capture (DAC) is simple: We take carbon directly from the air and store it safely underground permanently. No risk of wildfires or tornadoes coming along and reversing all of our progress. And unlike nature-based removal, the benefits of DAC are highly quantifiable; in other words, we know exactly how much CO_2 we're pulling out of the air.

It's also permanent. Once we inject CO_2 into things like concrete or underground reservoirs, it stays there. Or in climate terminology, it's "durable."



CLIMEWORKS' DAC+S FACILITY "ORCA" IN ICELAND

So what's the problem? Well, there are a few. DAC isn't cheap.

In fact, it's some of the most expensive technology out there, coming in at above $1,000 per ton of CO_2 for individual buyers and more than $750 per ton for corporate or bulk buyers. That's partly why at the moment, there are only two commercial-scale facilities in operation in the world, one in Iceland run by a company called Climeworks (which is not part of the BEV portfolio) and another that was just opened by **Heirloom** in November 2023. But like point-source capture, no matter how much the cost of direct air capture comes down, it will always cost more than doing nothing. Without policy intervention, there is little incentive for companies to pursue it.

DAC is also highly energy intensive. And no nation wants to take precious clean electrons to remove carbon instead of providing power to its people and businesses. Then there are the legal issues. To put things in the ground, you need to go through siting, permitting, and other regulatory hurdles that can take years.

-—

A CLOSE-UP OF DARK GRAY STONE

CO_2

Heirloom, a San Francisco-based company, is trying to get around some of these obstacles. Heirloom uses a process called carbon mineralization. They grind up limestone, put it on larger baking-esque sheets, and let it passively pull CO_2 out of the air. Once it's fully saturated with CO_2, they put it inside an electric kiln, heat it up to release the CO_2 that was absorbed, and put the carbon underground. Because of the limestone's passive properties, this method uses significantly less heat and power than traditional direct air capture technologies.

-—

Once you capture carbon, however, you need a place to store it. Companies like **44.01** work with DAC companies to do exactly that. 44.01's process takes captured CO_2, combines it with water, and injects it deep underground into a rock called peridotite.

Because this rock in particular is very reactive with CO_2, it accelerates the process of mineralization, turning CO_2 into a solid in a matter of years, compared to traditional CO_2 storage, which can take thousands of years to mineralize.

These innovations hold a lot of promise and potential, and direct air capture may well be the way of the future. But most DAC options are too expensive, energy intensive, technologically complex, and regulatorily fraught to scale globally.

THE HYBRID WAY

Carbon Casting

3

There is a third option, a hybrid of the first two we've discussed that combines the strength of nature-based approaches with the lasting impact of engineered removal.

Graphyte is one company exploring this area. Incubated by Breakthrough Energy Ventures, **Graphyte** has developed a carbon dioxide removal approach that is permanent, affordable, and immediately scalable.

INERT CARBON BLOCKS CREATED BY GRAPHYTE TO STORE BIOMASS.

Foresters and farmers already capture billions of tons of CO_2 each year in the form of timber and crop residues that are left to decompose into CO_2 and methane. But what if carbon-rich biomass can be transformed into permanently sequestered carbon? That's what Graphyte does with its Carbon Casting technology. This process dries the biomass to remove microbes and the water they depend on, then creates inert carbon blocks protected by an impermeable barrier to ensure the biomass decomposition does not restart. These blocks are stored in monitored, underground storage sites that provide a further layer of protection and enable robust long-term monitoring.

This new technology provides an immediate pathway to low-cost carbon removal with durability over 1,000 years. Combining photosynthesis with practical engineering enables Graphyte to meet long-term cost targets in the near term, whereas other approaches hold the promise of achieving these targets over many years, contingent on future innovations.

The Carbon Casting process preserves nearly all the carbon stored in the biomass while also consuming less energy than other removal approaches (an order of magnitude less than the leading direct air capture solutions). In addition, the use of a purpose-built sequestration site enables comprehensive monitoring of the sequestered carbon, making Graphyte's approach the only permanent negative-emissions technology that can be monitored directly.

By making high quality carbon removal affordable to companies and governments today, Graphyte accelerates progress toward the billions of tons of carbon removal needed to meet the IPCC's projected path. It also broadens the opportunity to areas in the Global South that are rich in biomass but simply can't afford expensive and energy-intensive DAC solutions. Graphyte collaborates with farmers and foresters who sustainably manage agriculture and timber lands across the world, and turns their unused biomass into permanent carbon removal. As we work to accelerate the clean energy transition, climate leaders should consider this important addition to the toolkit to deliver higher volumes of permanent removals at an affordable price today.

Policy and Persuasion

4

Innovation is key, but we can't scale these technologies without proactive policy and public funding. This past summer, the United States saw a major breakthrough on that front when the Department of Energy announced its first round of awards for Direct Air Capture hubs, the single largest investment in the history of DAC. These hubs can bring together multiple DAC companies within the same facility to access shared infrastructure so they can scale their technology faster and do it at a lower cost.

A VISUALIZATION OF A RURAL DIRECT AIR CAPTURE FACILITY SOURCE: THIRD WAY

Policy isn't the only tool in our arsenal. We also need to increase understanding about these technologies. For example, direct air capture remains relatively unknown among the public. But when people understand it better it gains support, especially when they learn about its potential to create jobs and address emissions.

Again, carbon removal shouldn't be an excuse to keep emitting. We must continue our efforts to decarbonize every sector of the global economy. In other words, we still need to turn off the spigot, even if we can drain some of it.

But the bottom line is, carbon management needs to be an option that remains on the table. Despite its drawbacks, it's a vital tool for the future. And no one's ever solved a problem faster with fewer tools at their disposal.

Glossary Of Terms

Algal Blooms	Natural phenomena with ecological consequences, algal blooms, while visually striking, can disrupt aquatic ecosystems, underscoring the delicate balance in nature.
Anchor Investors	Strategic backers who provide stability to projects, offer credibility and confidence, and attract additional investments.
Biomass	Organic materials converted into energy, biomass showcases nature's potential as a renewable energy source, highlighting the importance of sustainable resource management.
Carbon Credits	These are tradable permits encouraging emission reduction efforts. They promote environmental responsibility, while fostering a collective approach to combating climate change.
Desiccant	These substances, which absorb moisture from the air, are vital components of technologies ensuring our living spaces remain dry and comfortable.
Decarbonize	Organic materials converted into energy, biomass showcases nature's potential as a renewable energy source, highlighting the importance of sustainable resource management.
Electrify Everything	A new understanding of how we get to net-zero. Instead of having to sacrifice our electricity usage, we expand it, make it cleaner, and use it to electrify other industries that rely on fossil fuels.
Electrolysis	Electrolysis is a process where an electric current is passed through water, splitting it into hydrogen and oxygen. The hydrogen gas is then collected, providing a clean and renewable source of energy.
Embedded Carbon Dioxide	These are the unseen emissions tied to the products we use daily, stemming from their production and transportation. For example, the steel beams in your office building aren't emitting carbon right now – but they did when steel factory workers smelted coke and iron to create them.
Feedstock	Essential raw materials, feedstock includes biomass and other natural resources, forming the foundation for various industries, from energy to manufacturing. Stable feedstock is critical for emerging climate startups, giving investors confidence that the company has enough supply of the necessary materials to produce at scale and over the long-term.
Global South	A term encompassing developing regions, the Global South embodies diverse cultures and economies, shaping the world's future through innovation and collaboration. Since these nations are often clustered around the equator, they are experiencing the worst effects of climate change.

Green Premium

Organic materials converted into energy, biomass showcases nature's potential as a renewable energy source, highlighting the åThis term reflects the additional cost associated with zero-carbon choices. If a regular cement costs $135 a ton, and "clean" cement costs $200, cement's green premium is $65 dollars. Reducing this green premium to zero — for cement and every product – is the most important thing the world can do to solve the climate crisis.
of sustainable resource management.

High-Income Countries

Nations like Japan, Germany, or the United States. The World Bank defines high-income countries as having a per capita income of at least $13,845 (in US dollars). In the context of the climate crisis, these are the nations that have emitted the most greenhouse gases historically, but they're also where most of the innovation is happening—and where governments are wealthy enough to help fund the transition to lower sources.

High-Purity Steel

A highly refined variant of steel that typically has higher strength and hardness with lower environmental impact.

Low-Income Countries

Nations ranging from Pakistan to Chad to Vietnam, which are still facing considerable challenges to industrialization and economic development —though many still demonstrate resilience and resourcefulness. Their populations are also among the most vulnerable to climate change, so it's crucial that there is global support for their equitable development. According to the World Bank, these nations have an average per capita income of under $1,136 per year.

Metal Hydrides

Scientific wonders, metal hydrides are compounds storing hydrogen, holding potential for cleaner energy solutions and reduced dependency on fossil fuels.

Middle-Income Countries

Nations like Brazil, India, and China, whose economies are rapidly growing and developing. The World Bank splits these countries into two groups – upper middle-income countries and lower middle income countries. People living in these nations have an average per capita income anywhere from $1,136 and $13,845 (USD). NatIn the context of the climate crisis, these nations represent some of the biggest markets for the clean tech being piloted and prototyped in high-income countries.

Off-Take Agreements

These agreements assure the market for renewable energy producers, fostering confidence among investors and enabling the growth of sustainable energy projects. For example, a sustainable aviation fuel company may secure an off-take agreement with an airline to ensure it has a buyer for the fuel when it comes to market.

Public Risk Capital

Funding from governments supporting high-impact projects, public risk capital plays a vital role in driving innovation and addressing societal and environmental challenges.

Venture Capital

Venture capital: This is a type of financing often used to support early-stage companies. Since climate tech can be riskier and require longer-term investments than other technologies, it often has trouble attracting traditional VC investors.