DISCOVERY REPORT

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Beating the heat

How chemistry can decarbonize the economy and stall global warming

Published by
c&en

$39.99

Decarbonizing the economy of the future

The year 2050 may seem far away, but time is of the essence with climate change. That's the year when the United Nations–led Race to Zero campaign would like to see businesses, cities, institutions of higher education, and others achieve net-zero carbon dioxide emissions. That same campaign encourages an interim goal of halving emissions by 2030, 9 short years from now. The task is monumental.

We love to call chemistry "the central science," and it's easy to see chemistry's central role in reducing the global economy's carbon footprint. In the second quarter of 2020, C&EN's Discovery Report covered battery advances to support a grid powered by renewable energy. In the fourth quarter of 2020, the report focused on reimagining agriculture, a sector that accounted for about 18% of global greenhouse gas emissions in 2016.

Those are just two pieces of a complicated pie. Transportation, energy use in buildings, and industry—including the chemical industry—are also major greenhouse gas contributors. This report examines how chemists are addressing greenhouse gases in chemical equations key to economic activity—whether removing them from the product side or converting them to reagents that then become useful materials. In the following pages, you'll meet entrepreneurs commercializing concrete and steel manufacturing processes with fewer CO_2 emissions, pulling CO_2 directly from air, building proteins and diamonds from CO_2, and more.

Contributing editor Carmen Drahl, who has covered organic chemistry and green chemistry for C&EN, edited this report. It includes a reading list of papers and patents curated by our sources, as well as by information scientists at the CAS division of the American Chemical Society.

As an ACS member, you get exclusive access to the Discovery Report, a quarterly publication bringing you cutting-edge research defining the chemical sciences and our industry. Look for the next one in the first quarter of 2022.

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INSIDE

Published by
c&en

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CHEAT SHEET

5 questions and answers about chemistry’s role in decarbonizing

Q.

What does decarbonizing mean?

» **The dictionary definition of *decarbonizing*** is “to remove carbon from.”

» **Decarbonizing has a more precise definition** in conversation among chemists and entrepreneurs. The word encapsulates the process of sustainably reducing carbon dioxide emissions and compensating for emissions that are unavoidable.

» **In practice, decarbonizing is about making changes to chemical processes** that underpin the economy. Next-generation processes will require fewer fossil fuels and emit less CO_2 and other greenhouse gases.

Q.

Why is it important to decarbonize the economy?

» **Decarbonizing is important to minimize climate change.** Once in Earth’s atmosphere, CO_2 traps heat, contributing to the greenhouse effect.

» **In 2015, nearly 200 countries committed to the Paris Agreement,** an international treaty that aims to control greenhouse gas emissions. The agreement sets global temperature goals and will require countries to report on their climate mitigation efforts.

Q.

How is chemistry playing a role in decarbonizing?

» **Chemistry is critical to decarbonizing.** The chemical industry makes modern life possible but emits about 6% of CO_2 globally. Start-ups are upscaling green ways to make high-volume chemicals such as ammonia and ethylene and are converting CO_2 into feedstocks.

» **New routes to steel and concrete,** materials that together account for about 10% of global CO_2 emissions, are emerging from chemistry-focused entrepreneurs.

» **Strong, light materials** will cut fuel consumption in transportation. Chemists are envisioning a future with hydrogen rather than fossil fuel and with renewable energy stored in batteries.

» **To capture CO_2 emissions before they reach the atmosphere,** chemists have devised membranes, metal-organic frameworks, and other tools.

Q.

What are the challenges of decarbonizing?

» **Implementation will cost companies extra money, at least in the short term.** Those costs will in part be transferred to clients and consumers, putting decarbonizing companies at an economic disadvantage compared with firms doing business as usual.

» **The Paris Agreement is insufficiently binding,** according to critics. The Donald J. Trump administration withdrew the US from the accord until the Joe Biden administration reversed the decision, potentially setting a precedent for other major emitters to leave.

» **Climate change affects marginalized communities disproportionately.** Countries will need to ensure that financial and environmental gains from decarbonization don’t leave those people behind.

Q.

What’s next for decarbonizing?

» **New pilot-scale efforts** to transform CO_2 into ethylene, nitrogen fertilizer, and other products are coming online in the next year; those efforts will inform industry watchers how efficient and cost effective the technologies are.

» **At the 26th UN Climate Change Conference (COP26) in Glasgow, Scotland** this fall, for the first time, nations explicitly mentioned moving away from coal power and fossil fuel subsidies in their pact. Data show that while humanity has cut emissions since the Paris Agreement, the progress isn’t enough to forestall major impacts of climate change, such as flooding and heat waves.

8 experts identify opportunities for chemistry to help decarbonize itself and the economy

Fiona Beck

» Senior research fellow, Australia National University

"Australia has some of the best renewable energy resources in the world, both wind and solar," Fiona Beck says. The country is rapidly decarbonizing its coal-dominated domestic electric grids. It has enough extra renewable energy to export, but that is more challenging.

As an isolated continent, Australia cannot easily send renewable power to neighbors. One way is to use renewable power to manufacture energy-intensive products, such as steel or fertilizer, and export those, Beck says. Another way is to split water with electricity from renewables and send the resulting hydrogen overseas. Japan, Australia's top buyer of coal, has pledged to phase out coal power by 2030 and has invested heavily in hydrogen vehicles and refueling stations.

But converting renewable power to hydrogen and then using hydrogen fuel to generate power has an efficiency rate of just 30%, before considering losses from compression and transport. Beck is working to streamline fuel creation through direct photochemical hydrogen production.

Beck and her colleagues reported earlier this year 20% efficiency in solar-to-hydrogen energy conversion by pairing low-cost perovskite solar cells with nickel-based catalysts. The researchers estimate that hydrogen produced this way could cost under $3 per kg. The cost of hydrogen from electrolysis is in flux, but they estimate photochemical hydrogen could be comparable.

Australia is also piloting exports of cheap hydrogen made using coal as a feedstock, but Beck is concerned that this would lock in the need for carbon capture and storage. "We should be using capture and storage for processes that we really can't decarbonize," she says.

> "Australia has some of the best renewable energy resources in the world, both wind and solar."

Elizabeth Biddinger

» Professor, chemical engineering, City College of New York, and deputy director, Center for Decarbonizing Chemical Manufacturing Using Sustainable Electrification (DC-MUSE)

For Elizabeth Biddinger, true decarbonization in chemical manufacturing requires a paradigm shift. Chemical reactions and purifications powered by burning fossil fuels must instead run on renewably powered electricity. But the chemical sector also consumes fossil fuels as raw materials. These feedstocks must be displaced as well—by sourcing carbon from above ground rather than below.

Biddinger is developing electrochemical methods for upgrading biomass-derived molecules into useful products. She names furfural as a promising example because it can be obtained from woody biomass that doesn't compete with food and feed. Biddinger hopes to convert furfural in one electrochemical step into 2-methylfuran, a potential antiknocking additive or gasoline alternative, and furfuryl alcohol, which can be further transformed into polymers and adhesives.

Electrochemical upgrading of biomass-derived molecules is still largely confined to the laboratory, where researchers like Biddinger race to probe the reactions' fundamental mechanisms. Meanwhile, she and her colleagues at DC-MUSE are also attempting to electrify a top carbon dioxide–emitting chemical reaction: the production of ethylene.

The big challenge is establishing electrochemical, biomass-based processes in time to meet 2050 climate goals, Biddinger says. "Thirty years is actually really close if we're talking about transforming the chemical industry."

CREDIT: COURTESY OF INSTITUTION UNLESS NOTED; CITY COLLEGE OF NEW YORK (BIDDINGER)

Michael Dosier

» Chief technology officer, Biomason

“Concrete is the second-most-consumed material in the world following water by mass,” Dosier says, and it accounts for about 8% of the world’s carbon emissions.

An intermediate, Portland cement, drives most emissions. It’s made by baking quarried calcium carbonate at 850 °C, a process that generates carbon dioxide and calcium oxide. Mixing the latter with water and loose aggregate material such as sand or crushed stone yields concrete.

Biomason CEO Ginger Krieg Dosier looked to nature for alternative ways of making concrete. Organisms combine calcium and carbonate ions to build coral reefs and other structures out of calcium carbonate. Such structures rival or even surpass synthetic constructs in strength and durability—and become a means to store carbon.

Seeking to copy nature, the duo identified a marine microorganism strain that efficiently precipitates calcite, the most stable form of calcium carbonate. From there, they developed a mixed consortium of bacteria that generates calcium carbonate and binds loose aggregate material in seawater. The result is Biomason’s thin, tile-sized building materials, which can be used indoors or out. “Oddly enough, the planet gives us the answer,” Michael Dosier says.

> **“Concrete is the second-most-consumed material in the world following water by mass.”**

Robert Hagemann

» Cofounder and chief marketing officer, Aether Diamonds

“Historically, the mined diamond industry has been disastrous for the environment,” Robert Hagemann says. Every carat of mined diamond displaces up to 250 metric tons (t) of earth and generates 65 kg of carbon emissions from heavy machinery running on fossil fuels, he says.

With too much carbon in the atmosphere, Aether’s cofounders decided to make diamonds from emissions. “Every single atom of carbon in Aether’s diamonds comes from the atmosphere,” Hagemann says. The company uses carbon dioxide from Climeworks, a direct air capture company based in Switzerland. Another firm converts the CO_2 to hydrocarbons. Aether’s diamond reactors then grow large diamonds from the hydrocarbons via chemical vapor deposition.

Aether uses zero-emission energy throughout the process, Hagemann says. The company is working on carbon accounting with a third-party assurance provider, SCS Global Services; Aether is committing to removing—through a combination of direct air capture, reforestation, and other efforts—20 t of CO_2 from the air for each carat of diamond it produces. An average US resident generates 16 t of carbon emissions every year, according to the Nature Conservancy.

Metals are another big pollution source in the jewelry industry. “We can’t wear diamonds without having it set into something, so metals are necessary,” Hagemann says. Aether currently uses sustainably mined gold, but electronic waste is a potential treasure trove—if chemists and chemical engineers can figure out how to extract the materials sustainably, he says.

Jalaal A. Hayes

» Professor, chemistry, Lincoln University, and founder and CEO, Elyte Energy

Hydrogen is poised to play a starring role in a decarbonized world. Jalaal A. Hayes has spent 10 years researching ways to transport and store hydrogen, and he thinks safety is a major obstacle to that future. Liter for liter, hydrogen carries far less energy than gasoline. To compensate, hydrogen is compressed and ferried around in a big tank—an intimidating sight, since some people might associate hydrogen with the hydrogen bomb, Hayes says. “That’s not a good look for the public.”

Hayes is developing lithium amide–magnesium hydride powders to address the volume challenge. “The powder is like a sponge,” he says. When pressurized with hydrogen gas, the powder absorbs the hydrogen and retains it even when the pressure is released. Applying heat releases the hydrogen as needed. The system packs in more hydrogen for a given volume than standard pressurization and eliminates pressurized transport and storage. “Instead of having a big tank, you can have one-tenth of that tank, so to the eye it looks much safer,” Hayes says.

Through his start-up, Hayes is working on a prototype that combines a fuel cell with hydrogen storage. The fuel cell component draws from the stored hydrogen to produce electricity. With about 10 g of hydride material, the refillable prototype charges an iPhone from 10% to 30% in about 15 min. Hayes envisions a larger prototype—a “briefcase-sized power station”—that could be used for off-grid applications like recreational vehicles or emergency power.

CREDIT: LINCOLN UNIVERSITY (HAYES)

Klaus Kümmerer

» Professor, sustainable chemistry and material resources, Leuphana University

For Klaus Kümmerer, the laws of thermodynamics point to a hard reality for decarbonizing chemical manufacturing: the industry must reduce everything, including complexity of target molecules, number of synthetic steps, waste generated, and product output.

The chemical sector is the largest industrial consumer of oil and gas. Every action consumes energy and generates waste, which cannot be recovered without expending more energy. “The more materials that we are moving and circulating and using, the bigger the price we have to pay in terms of energy, environmental pollution, and loss of material,” Kümmerer says. “We can only behave wisely to lose as little as possible.”

Kümmerer advocates for alternative business models that transform sellers of chemicals into sellers of chemistry-driven services, which he says could promote better stewardship of chemicals. For example, hospitals must maintain a high standard of hygiene to keep infection rates low but are not obligated to apply large volumes of disinfectants, Kümmerer says. A provider could achieve the same level of hygiene by using disinfectants more precisely or designing equipment and rooms to be as easy as possible to clean. In this way, chemists and chemical companies could be paid for their knowledge instead of just their products, according to Kümmerer.

“The challenge is doing more in terms of service with less in terms of chemicals and energy,” he says.

> **“The challenge is doing more in terms of service with less in terms of chemicals and energy.”**

Karthish Manthiram

» Professor, chemistry and chemical engineering, California Institute of Technology

Few chemical reactions are as energy intensive as the Haber-Bosch process. Karthish Manthiram aims to make ammonia electrochemically instead.

Manthiram says it’s already possible to somewhat decarbonize this essential chemistry by switching the hydrogen source: chemists can obtain hydrogen with electrochemical water splitting powered by renewable energy instead of traditional production from methane involving hot, pressurized steam.

But when it comes to feeding that hydrogen into the traditional Haber-Bosch process, Manthiram says “the challenge is one of scale mismatch.” Electrochemical water splitting works best at small scale, with operations distributed to minimize transport and storage costs. The Haber-Bosch process itself requires high temperature and pressure, so facilities tend to be massive and centrally located.

Making ammonia electrochemically would eliminate the mismatch. Although the technology is nowhere near commercialization, it has advanced rapidly in the last few years. When Manthiram began studying electrochemical Haber-Bosch in 2017, the Faradaic efficiency—the percentage of electrons from electricity that winds up in the ammonia product—was in the single digits.

By 2020, Manthiram’s group achieved 35% Faradaic efficiency. This June, an Australian team hit a huge milestone by reaching 69% Faradaic efficiency while operating the process for 3 days continuously, Manthiram says.

When he started in the field, Manthiram used to say that electrochemical synthesis was 20 years away. “Five years later, I feel like maybe it’s 5 years away.”

Jenifer Shafer

» Program director, Advanced Research Projects Agency–Energy (ARPA-E)

The 1.86 billion metric tons (t) of crude steel produced in 2020 accounts for some 7% of the world’s greenhouse gas emissions, and production is expected to hit 2.5 billion t per year by 2050. “In order to mitigate or manage this, we need, basically, a clean sheet,” Jenifer Shafer says.

Existing methods for decarbonizing steel, such as adopting green hydrogen or carbon capture, add costs.

ARPA-E held a workshop this August discussing ideas that could achieve net-zero emissions and scale up to make 100 million t of steel per year at $400 per ton, which is also the approximate cost of traditional crude steel.

One approach is redesigning the reactor. A makeover could mean electrification to reduce iron ore with green electricity instead of fossil-based agents. Another up-and-coming idea is reduction with hydrogen plasma, which unlike the traditional process is exothermic, Shafer says.

A second strategy is finding resources that use less energy to mine and process, including scrap metal, fine oxide powders, or iron-containing industrial waste. Shafer is also intrigued by the possibility of skipping the reduction step and using iron oxides directly to make high-value steel products.

Shafer thinks that staying open to ideas is key. “I would be surprised if there was a silver bullet solution,” she says. ■

CREDIT: PERSONAL PHOTO (SHAFER)

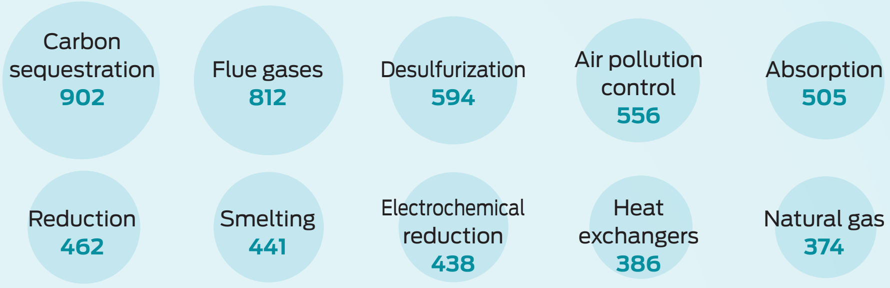
BY THE NUMBERS

Understand trends in decarbonization

Multipronged approach

The most common topics indexed in patents illustrate the variety of approaches and sectors involved in controlling greenhouse gas emissions.

Number of Patents



Who's who

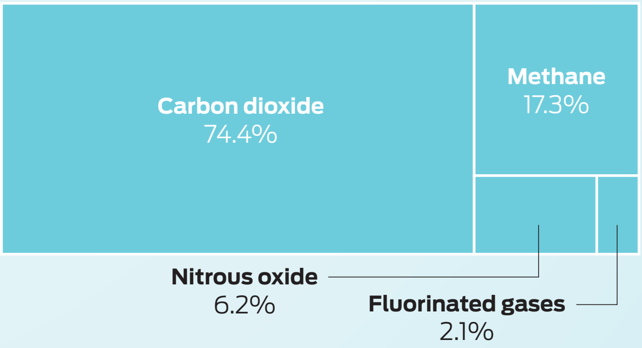
We found the companies and institutions most active in filing patents that mention decarbonization alongside three strategies of interest.

Absorption		Electrochemical reduction		Carbon sequestration	
Assignee	**Number of Patents**	**Assignee**	**Number of Patents**	**Assignee**	**Number of Patents**
Alstom Technology	30	Dalian Institute of Chemical Physics, Chinese Academy of Sciences	26	Sinopec	17
IFP Energies nouvelles	23	Siemens	23	IFP Energies nouvelles	15
Siemens	16	Toshiba	8	Toshiba	11
Sinopec	11	Zhejiang University	8	Tianjin University	8

Supporting Cast

Carbon dioxide is not the only greenhouse gas. Here is how much key gases contribute to warming, taking into account their different warming impacts and lifetimes in the atmosphere.

Carbon dioxide equivalents, 2016



Decarbonization stats

Boost your knowledge with our selection of facts and figures.

46%

Proportion of global decarbonization patents and applications from China during 2000–2020.

$800 million

Funds raised from January through September 2021 by companies using carbon dioxide to make products, a threefold increase from 2020.

386%

Increase in patents involving both electrochemical reduction and decarbonization, 2015–20.

5.8%

Proportion of global greenhouse gas emissions produced in 2016 by the chemical industry

50 billion

Metric tons of carbon dioxide equivalents emitted globally each year

75%

Percentage of carbon dioxide equivalents emitted by the world's top 10 emitting countries

Sources: CAS Content Collection, Climate Action Tracker, Our World in Data, Reuters.

Notes: CAS information scientists searched patents and publications containing the concept of decarbonization from 2000 to 2020. The topic of reduction in the CAS Content Collection refers not only to reduction reactions but also to general strategies for reducing carbon dioxide levels. General Electric purchased Alstom Technology's energy division in 2015. Sinopec patents are indexed under China Petroleum & Chemical Corporation. Greenhouse gas emissions are converted to carbon dioxide equivalents by multiplying each gas by the amount of warming it would create relative to CO_2 over 100 years. Fluorinated gases include hydrofluorocarbons, chlorofluorocarbons, perfluorocarbons, and sulfur hexafluoride.

The race for green steel

MARK PEPLOW, SPECIAL TO C&EN

If the steel industry were a country, its carbon dioxide emissions would rank third in the world, below China and the US and above India. Aside from churning out 1.86 billion metric tons (t) of steel in 2020, steelmakers generated over 3 billion t of CO_2, corresponding to an astonishing 7–9% of all human-made greenhouse gas emissions, according to the World Steel Association. No other industrial material has a greater climate impact.

With global steel demand expected to rise to 2.5 billion t per year by 2050 (*Metals* 2020, DOI: 103390/met1009117), that environmental burden is growing. Yet an analysis of the overall reduction in worldwide carbon emissions needed to limit global warming to a maximum of 2 °C above preindustrial levels—the goal of the 2015 Paris climate agreement—suggests that the steel industry's annual emissions must fall to about 500 million t of CO_2 by 2050 (*Metals* 2020, DOI: 10.3390/met10070972).

Achieving that target will require the industry to reduce its carbon intensity from about 1.85 t of CO_2 per metric ton of steel to just 0.2 t. That will take nothing less than a revolution in steelmaking technology, backed by hundreds of billions of dollars in investments.

CREDIT: SHUTTERSTOCK

At first glance, changing the trajectory of this leviathan business looks like an almost impossible task. Steelmaking has annual sales of $2.5 trillion, according to the World Steel Association, and relies on heavy infrastructure, such as the gigantic blast furnaces that are used to make iron, which can last 20–40 years. “It’s quite difficult to shift a market like steel because there’s so much sunk cost in a blast furnace,” says Michael Lord, an expert adviser to Beyond Zero Emissions, a climate think tank.

Yet a growing number of companies are taking up this daunting challenge, including both established steel majors and disruptive innovators. They are piloting a flurry of technologies that could curb steel’s carbon emissions, largely by using new ways to reduce iron oxides into iron. Some approaches rely on hydrogen from electrolyzers powered by renewable electricity; others use that power directly in electrochemical reactions.

Steelmakers have flirted with these methods for decades, but industry insiders say the business case for transformation is now stronger than ever. Advances in chemistry, metallurgy, and engineering have significantly improved the efficiency of these alternative routes to steel. “They’re also associated with renewables, hydrogen, and other technologies that are on a pretty relentless cost-reduction pathway,” says Thomas Koch Blank, senior principal of the Breakthrough Technologies program at RMI, a nonprofit focused on the clean energy transition. “That’s going to fundamentally challenge the structure of the industry.”

Many of the most ambitious approaches are being pursued in Europe, which makes about 10% of the world’s steel. Rising carbon taxes set by the European Union threaten to squeeze companies’ profits if they fail to decarbonize, and this policy is spurring billions of euros of investment in green steel.

This investment could seed change elsewhere. Although some steel companies may be pursuing these projects as a way to burnish their environmental credentials, Lord says, they are also laying the groundwork for a low-carbon future. “I think they’re getting involved so that they’re ready to switch.”

Beyond coke

Humans have been extracting iron from its ores since . . . well, since the dawn of the Iron Age, over 3,000 years ago. Smelting traditionally took place in bloomeries, small furnaces filled with burning charcoal and iron ore containing hematite (Fe_2O_3) or magnetite (Fe_3O_4). Bellows forced air through the furnace to make carbon monoxide, which reduced iron oxides to form a solid, porous mass of metal called sponge iron. After knocking off the crust of silicates and other impurities, known as slag, people could hammer the metal into wrought iron. Heating this on a bed of charcoal added roughly 2% carbon, creating an alloy commonly known as steel. For thousands of years, carbon has played these three vital roles in steelmaking: a fuel for heating, a reducing agent, and an alloying agent.

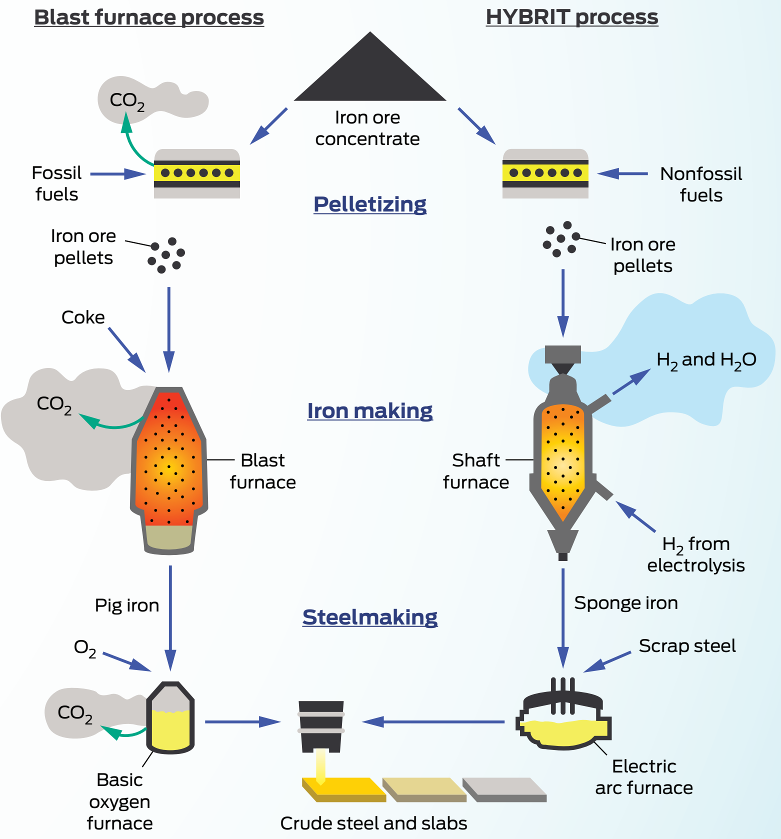
Today, iron is largely made inside blast furnaces running at 2,000 °C or more, where ore, coke, and limestone meet a blast of hot air, creating molten pig iron with a high carbon content—roughly 4–5%. Coke, the crucial carbon source for modern steelmaking, is manufactured by heating crushed coal to drive off tar and gases. The process makes this concentrated source of carbon strong enough to support the huge weight of ore in cavernous furnaces. The world’s largest single blast furnace, at Posco’s Gwangyang steelworks in South Korea, is 110 m high and produces over 5 million t of pig iron per year.

Traditional, coke-based steelmaking

$$2C + O_2 \longrightarrow 2CO$$

$$2Fe_2O_3 + 3C \longrightarrow 4Fe + 3CO_2$$

$$Fe_2O_3 + 3CO \longrightarrow 2Fe + 3CO_2$$



Recipe for reduction

The Hydrogen Breakthrough Ironmaking Technology (HYBRIT) process aims to replace the coke and other fossil fuels used in traditional blast furnace–based steelmaking and instead relies on hydrogen created with renewable electricity. The process should lower carbon dioxide emissions in all stages of steelmaking, including pelletizing iron ore, reducing iron oxides to iron, and producing crude steel.

CREDIT: ADAPTED FROM HYBRIT

Because of its relatively high carbon content, pig iron is brittle, so it must be processed in a basic oxygen furnace. This furnace delivers pure oxygen through a water-cooled lance, driving off carbon as CO_2 along with other impurities to leave crude steel. Secondary refining then fine-tunes the alloy's metallurgy to make high-grade steel. Roughly three-quarters of the world's steel is produced through this blast furnace–basic oxygen furnace route. Processing iron ore into pellets and making coke are responsible for about 20% of this route's CO_2 emissions, with the blast furnace itself responsible for about 70%.

Despite huge advances in steelmaking technology, the underlying chemistry has remained essentially unchanged for millennia, and it won't be easy for the industry to curb its dependence on coke. Some of the largest players in the industry—including the top two producers, ArcelorMittal and China Baowu Steel Group—are planning to retrofit existing furnaces with carbon-capture systems so that CO_2 released during steelmaking can be stored underground or used to manufacture chemicals like methanol. But carbon capture is an expensive Band-Aid for an intrinsically unsustainable technology. "Carbon capture fundamentally means doing what you did before, but adding cost," Koch Blank says. "It's going to be virtually impossible for that route to be cost competitive."

There are already commercial alternatives to coke, however. Well over 100 iron-making furnaces, which mostly rely on processes known as Midrex and HYL-Energiron, instead use natural gas to produce direct reduced iron (DRI), a kind of sponge iron. These plants convert natural gas into syngas, a mixture of hydrogen and CO, both of which reduce solid iron oxide to solid iron inside a shaft furnace at around 1,000 °C. The DRI that emerges several hours later typically contains 1–4% carbon and can be converted into steel in an electric arc furnace, which uses electricity to melt the metal. Carbon and oxygen may also be added in this furnace to remove impurities and adjust the steel's carbon content. Bolstered by cheap shale gas, a growing number of DRI plants help supply over 100 million t of steel per year, more than 5% of global output, and arc furnaces are already widely used to recycle scrap steel.

Overall, this DRI–arc furnace route has 35–40% lower CO_2 emissions than conventional steelmaking (*Berg- Huettenmaenn. Monatsh*. 2020, DOI: 10.1007/s00501-020-00975-2. Crucially, DRI plants could also act as a stepping-stone to even lower emissions because green hydrogen, made via electrolysis, can be blended into the feed gas to reduce the need for natural gas. Many of the world's biggest steelmakers plan to transition DRI facilities to use more hydrogen in the mix or build new DRI plants that run almost entirely on green hydrogen.

Direct reduction with syngas

$Fe_2O_3 + 3H_2 \longrightarrow 2Fe + 3H_2O$ Endothermic

$Fe_2O_3 + 3CO \longrightarrow 2Fe + 3CO_2$ Exothermic

The HYBRIT consortium will use green hydrogen to reduce iron ore at its pilot plant in Luleå, Sweden.

CREDIT: HYBRIT

> **"It's quite difficult to shift a market like steel because there's so much sunk cost in a blast furnace."**

Hydrogen hope

One of the leading efforts to adopt hydrogen as a reducing agent is in Sweden, where a project called HYBRIT (Hydrogen Breakthrough Ironmaking Technology) is attempting to decarbonize every step of the steelmaking process. HYBRIT is a collaboration between the mining company LKAB, steelmaker SSAB, and energy company Vattenfall that kicked off in 2016. It will rely on cheap and plentiful wind power in northern Sweden to electrolyze water, generating vast amounts of hydrogen.

In 2020, HYBRIT finished building a pilot DRI plant in Luleå, Sweden. Until recently, it was running on natural gas, but in May, it started the first trials with hydrogen and will produce about 1 t of DRI per hour during 2-to-4-week campaigns. Over the next 3 years, these trials should answer a range of scientific and technical questions raised by the switch to hydrogen. "We need to find out what are the best operating conditions," says Martin Pei, SSAB's chief technology officer.

Syngas's reduction of iron oxide involves two key reactions. The reduction with CO is exothermic, and that released energy helps drive a parallel endothermic reduction by hydrogen. Switching to a hydrogen-only system significantly changes this thermodynamic balance, so the hydrogen must be preheated before it enters the furnace, which HYBRIT aims to achieve with an electric heating system. Upping the hydrogen content also increases the volume and velocity of gas flowing through the shaft furnace and changes the composition of the DRI (*Metals* 2020, DOI: 10.3390/met10070922). HYBRIT researchers will study how the composition of this iron compares with DRI made with natural gas and whether it is suitable to pass on to an electric arc furnace.

Meanwhile, HYBRIT is exploring alternative ways to produce the iron ore pellets that feed the DRI plant. This process currently uses fossil fuels, but HYBRIT has tried a bio-oil by-product from papermaking instead, and plans to test hydrogen-based heating to make the pellets.

HYBRIT is already planning a larger demonstration plant in Vitåfors, Sweden, which would reach commercial-scale continuous production of 200 t of DRI per hour. Pei says that this plant should help deliver fossil-free steel—which should have a carbon footprint less than 5% of that of conventional steel—to the market in 2026. SSAB plans to replace all its blast furnaces in Sweden and Finland so that it is entirely fossil-free by 2045.

Back in 2017, HYBRIT estimated that its steel would be 20–30% more expensive than that produced by the traditional coke-based route. But the economic equation has changed since then, thanks in part to the European Union Emissions Trading System. This cap-and-trade system sets ever-tightening regulatory limits on industry's CO_2 emissions while enabling companies that reduce their emissions below this cap to sell spare carbon allowances. In 2017, an allowance to emit a metric ton of CO_2 was priced at less than €10 (about $11), but by spring of 2021 it had soared above €50 (about $57) in anticipation of the EU further strengthening its emission reduction commitments.

If the cost of green hydrogen fell from today's $3–$6 per kilogram to $1 per kilogram, today's carbon price would be enough to make hydrogen-based steelmaking cost competitive with traditional methods, according to BloombergNEF, an energy consultancy. Nel, a Norwegian electrolyzer maker, says it is already targeting a hydrogen cost of $1.50 per kilogram by 2025.

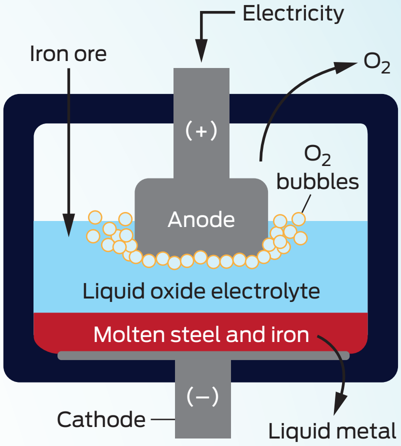
The result is that low-carbon technologies like HYBRIT could soon have a growing commercial advantage over traditional steelmaking. "We believe that in the long run, this will become even more competitive, since we know that emission costs will go up," Pei says. "Society is really pushing in that direction, and we believe there is a good business case."

Iron ore must be converted into pellets before undergoing direct reduction with syngas or hydrogen.

CREDIT: LKAB (PELLETS); ADAPTED FROM BOSTON METAL (ELECTROLYSIS)

Bright spark

Molten oxide electrolysis uses electricity to reduce iron ore to molten metal while generating copious amounts of oxygen.



Turning up the heat

HYBRIT's partners are not the only steel companies targeting hydrogen. Swedish start-up H2 Green Steel is planning to build a hydrogen-based DRI plant in Boden, just 30 km from Luleå, and will begin production in 2024. And other companies aim to feed hydrogen directly into traditional coke-fueled blast furnaces, making use of existing infrastructure to achieve more modest emission reductions. In 2019, for example, Thyssenkrupp began trialing this approach at one of its coke-burning blast furnaces in Duisburg, Germany. This approach could eventually reduce blast-furnace CO_2 emissions by about 20%.

Austria's Voestalpine is involved in a more radical project, called SuSteel, that aims to use hydrogen plasma to reduce iron ore. "The advantage of this concept is that you go in one step from iron ore to crude steel," says Johannes Schenk of the University of Leoben, one of the project leaders.

SuSteel's hydrogen plasma smelting reduction technology uses electricity to shred hydrogen gas as it passes through a hollow graphite electrode into a conical reactor. This process creates a stream of hydrogen atoms, ions, and molecules at temperatures over 20,000 °C. The plasma melts and reduces finely ground iron ore to create a pool of liquid steel (*Metals* 2018, DOI: 10.3390/met8121051). Pelletizing is unnecessary, and the graphite electrode adds just enough carbon to the metal to form crude steel, so the metal can avoid a trip through an electric arc furnace and proceed directly to secondary steel refining. SuSteel's pilot plant at Donawitz, Austria, will start running in the summer and eventually produce 50–100 kg of steel per batch.

One constraint shared by most hydrogen-based methods is that they need to be fed with hematite because magnetite is far less porous and so has a much slower reduction rate inside a shaft furnace (*Steel Res. Int.* 2019, DOI: 10.1002/srin.201900108). That means steelmakers that rely on magnetite ore must first oxidize it to hematite before it can be reduced in a furnace.

An approach called flash ironmaking technology (FIT) promises to avoid this redox roller coaster because it is well suited to reducing purified magnetite. FIT uses oxygen to partially burn a stream of natural gas or hydrogen inside a reactor, creating a gas mixture that reduces a cascade of iron ore particles less than 100 µm wide (*Metals* 2021, DOI: 10.3390/met11020332). Thanks to their small size, these particles can be reduced much faster than iron ore pellets, says Hong Yong Sohn of the University of Utah, who developed FIT. The reaction is so fast, Sohn says, that “even in a large industrial-sized reactor, the maximum reaction time is maybe 10 s.”

Up to 70% of iron and steel produced in the US starts from a low-grade magnetite ore called taconite, and the existing purification process produces fine particles that can go directly into a FIT reactor. In 2017, Sohn’s team built a 2 m high reactor that can make about 10 kg of iron per hour, and the researchers calculate that running the system on green hydrogen could offer up to 96% lower CO_2 emissions than a blast furnace. Sohn is now looking for an industrial partner to build a FIT reactor at a larger scale and estimates that a 35 m high FIT reactor could produce 1 million t of iron per year.

Power play

Despite improvements in the efficiency of electrolyzers, some scientists argue that it could be more economical to skip the hydrogen and use renewable electricity itself to reduce iron oxides. Massachusetts Institute of Technology spin-off Boston Metal, for example, is pioneering a process called molten oxide electrolysis. “Our goal is to make steel that is no more expensive than steel made by the conventional route,” says Donald R. Sadoway of MIT, who cofounded the company in 2012.

The electrochemical process happens inside a squat, 2 m wide steel vessel lined with alumina-based bricks, with an anode poking down through the top and a horizontal cathode on the base. Inside the vessel, iron oxides are dissolved in a mixture of molten metal oxides such as silica, magnesia, and quicklime, all heated to about 1,600 °C by an electric current. At the cathode, this current reduces iron ions to form a pool of liquid iron that can be sent to an electric arc furnace. The energy-intensive step of pelletizing the ore is unnecessary, and Sadoway says the reduction process is more energy efficient than hydrogen-based routes.

Molten oxide electrolysis

Anode: $6O^{2-} \longrightarrow 3O_2 + 12e^-$

Cathode: $2Fe_2O_3 + 12e^- \longrightarrow 4Fe + 6O^{2-}$

A key breakthrough behind this technology came in 2013, when Sadoway developed a 90:10 chromium-iron alloy anode that could withstand the extreme conditions inside the reactor without corroding or reacting with oxygen or the molten electrolyte (*Nature* 2013, DOI: 10.1038/nature12134). During the process, the alloy forms a thin oxide coating that protects the underlying metal but still allows electron transfer.

One challenge is that the electrochemical reaction releases copious amounts of oxygen at the anode, which reduces the conductivity of the melt. “If you landed from Mars and saw this thing, you’d say this is an oxygen-producing facility,” Sadoway says. The company has developed engineering solutions to remove this oxygen as quickly as possible. Boston Metal has also tailored the mixture of metal oxides to ensure that it melts at a reasonable temperature, remains stable, and is not too viscous, so oxygen can escape from the mix (*J. Electrochem. Soc.* 2014, DOI: 10.1149/2.0451501jes). In January, Boston Metal raised $50 million in investment funding, and it plans to have its first demonstration plant running by 2025. “There are fantastic challenges in front of us, but the electrochemistry is sound,” Sadoway says.

Other research groups are pursuing a low-temperature electrochemical process called electrowinning. In France, a project called Siderwin has built a 3 m long pilot plant that will host finely milled hematite ore particles suspended in a highly alkaline aqueous sodium hydroxide solution at about 110 °C. When a current passes through the electrolyte, iron metal grows on the surface of the cathode, while oxygen gas is liberated at the anode. The iron plate is then removed and fed into an electric furnace to make steel.

Low-temperature electrowinning

Anode: $12OH^- \longrightarrow 12e^- + 3O_2 + 6H_2O$

Cathode: $2Fe_2O_3 + 6H_2O + 12e^- \longrightarrow 4Fe + 12OH^-$

Thanks to the low-temperature conditions, the process uses 31% less energy than traditional steelmaking and reduces CO_2 emissions by 87%, according to the Siderwin team. Compared with hydrogen-based routes, electrowinning also relies on less infrastructure, says Hervé Lavelaine de Maubeuge, a researcher at ArcelorMittal who coordinates the Siderwin project. “There is a long journey to industrial scale, but theoretically we have a strong advantage in terms of capital costs,” he says. Siderwin’s pilot plant began tests in September, with a goal of producing 100 kg of iron in every 2-day shift.

Ready for revolution?

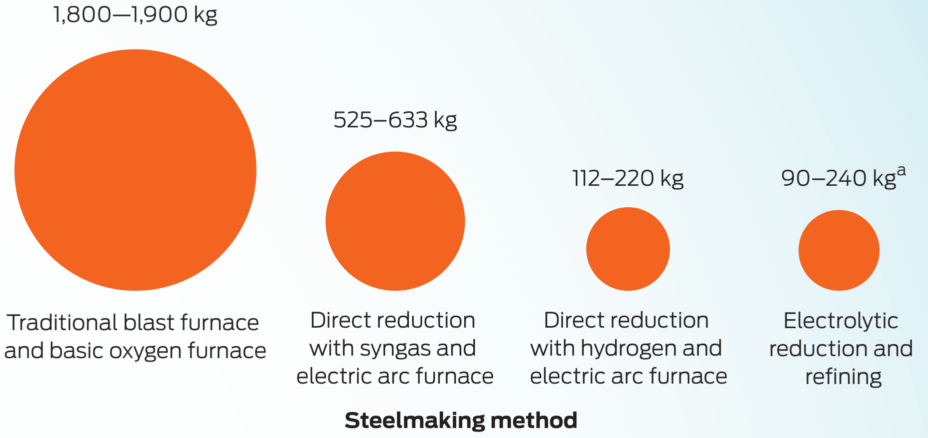
Despite the promise of new steelmaking technologies, they currently operate on a scale that is eclipsed by traditional blast furnaces. And although the prices of renewable electricity and green hydrogen are falling fast, the capital costs of setting up new plants—and shuttering old ones—are still a major barrier to change across the industry. Beyond Zero Emissions' Lord and RMI's Koch Blank agree that most steel companies are not yet committing the level of investments in new technologies needed to completely decarbonize by 2050.

Meanwhile, an industry-wide shift to these technologies would require eye-watering quantities of solar and wind power. Researchers at K1-Met, a research center in Linz, Austria, that is involved in green hydrogen and steel projects, calculate that if hydrogen-based DRI replaced all of Europe's current steel production, the industry's electricity demand would increase at least fivefold, to 400–500 TW h per year. That additional demand is equal to about 18% of total current EU electricity consumption and would require an additional 50,000 wind turbines (*Steel Res. Int.* 2020, DOI: 10.1002/srin.202000110). Large-scale hydrogen-based steel production would also need enormous amounts of electrolyzer capacity. The largest electrolyzers currently operate at about 20 MW, but a DRI plant making 2 million t of iron per year would need about 1 GW of hydrogen-generating capacity.

Carbon emissions

Producing steel with blast furnaces and basic oxygen furnaces releases significantly more carbon dioxide than newer steelmaking methods.

CO_2 emissions per metric ton of steel produced



Sources: *Steel Res. Int.* 2020, DOI: 10.1002/srin.202000110 (blast furnace and direct reduction methods); Siderwin (electrolytic).

a Electrolytic numbers are based on developers' predictions of carbon dioxide emission reductions.

Note: The size of each circle represents the midpoint of the emission ranges shown.

Yet Koch Blank points out that the industry has managed similar revolutions in the past. During the 1960s and 1970s, the basic oxygen furnace largely replaced its predecessor, the open-hearth furnace, because it offered much lower capital costs and required far fewer workers. "It took about 20 years to replace literally every steel asset in the world with a new technology," he says.

Environmental legislation could help tip the balance in the newcomers' favor. The EU has committed to at least a 55% reduction in CO_2 emissions by 2030 relative to 1990 levels, and the bloc is considering a carbon tax on imports such as steel, which could help domestic low-carbon technologies stay competitive.

In the US, the Buy Clean California Act of 2017 requires state-funded building projects to use construction materials that meet certain carbon-intensity limits, which should give low-carbon manufacturers an advantage. Those limits come into effect in 2022, and they mandate that hot-rolled steel, for example—which is used in construction beams—must have a carbon intensity below 1.38 t of CO_2 per metric ton of steel, less than the global average carbon intensity of the metal today. Similar green public procurement programs operate in countries like Japan, South Korea, and South Africa. Perhaps the biggest policy questions are in China, which produces about half the world's steel. Although reports earlier this year suggested that the government plans a 30% cut in steelmaking emissions by 2030, the road map to achieve this target is unclear.

Other trends in steelmaking should help lower the material's carbon footprint. Recycling currently provides about 30% of the world's fresh steel, but that is expected to reach 50% by 2050, which would open up more opportunities for renewable-powered electric arc furnaces to produce steel (*Metals* 2020, DOI: 10.3390/met10091117). Meanwhile, metallurgists are developing stronger, lighter steel alloys that could help meet demand with less metal.

Alongside changes in technology and regulations, international supply chains may also need to adapt. "It would make more sense to locate the bulk of green steel production in places where it's a lot easier to produce renewable energy," Lord says. And while thermal technologies benefit from economies of scale, electrochemical methods may be better suited to smaller steelmaking units located close to customers, Koch Blank says.

For now, it's still unclear which of these technologies will emerge as winners. "Hydrogen-based direct reduction is arguably further ahead in commercialization, but I think it's largely up for grabs," Koch Blank says. In the next few years, though, the pilot plants now springing up around the world could provide an answer.

Mark Peplow is a freelance science journalist based in Penrith, England.

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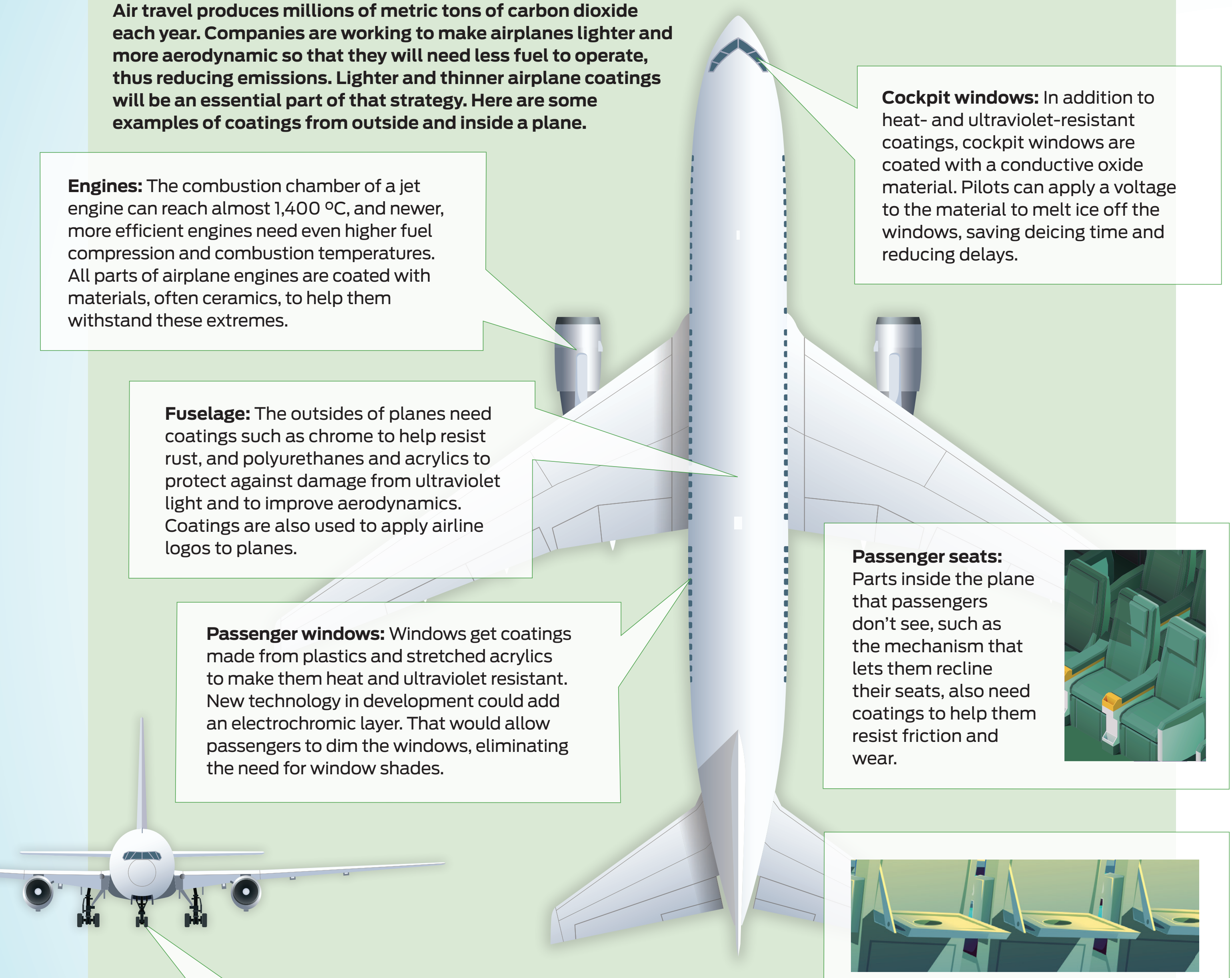
ANALYSIS

Decarbonizing the friendly skies

LEIGH KRIETSCH BOERNER, C&EN STAFF

Air travel produces millions of metric tons of carbon dioxide each year. Companies are working to make airplanes lighter and more aerodynamic so that they will need less fuel to operate, thus reducing emissions. Lighter and thinner airplane coatings will be an essential part of that strategy. Here are some examples of coatings from outside and inside a plane.



Cockpit windows: In addition to heat- and ultraviolet-resistant coatings, cockpit windows are coated with a conductive oxide material. Pilots can apply a voltage to the material to melt ice off the windows, saving deicing time and reducing delays.

Engines: The combustion chamber of a jet engine can reach almost 1,400 °C, and newer, more efficient engines need even higher fuel compression and combustion temperatures. All parts of airplane engines are coated with materials, often ceramics, to help them withstand these extremes.

Fuselage: The outsides of planes need coatings such as chrome to help resist rust, and polyurethanes and acrylics to protect against damage from ultraviolet light and to improve aerodynamics. Coatings are also used to apply airline logos to planes.

Passenger seats: Parts inside the plane that passengers don’t see, such as the mechanism that lets them recline their seats, also need coatings to help them resist friction and wear.

Passenger windows: Windows get coatings made from plastics and stretched acrylics to make them heat and ultraviolet resistant. New technology in development could add an electrochromic layer. That would allow passengers to dim the windows, eliminating the need for window shades.

Tray tables: Plastic tray tables get coatings to prevent food stains, kill viruses and bacteria, and resist damage from cleaners used 10–15 times a day. These polymer materials have embedded nanoparticles or are treated with nonstick coatings and quaternary ammonium compounds.

Landing gear: Protection against rust and impact resistance are especially important in the landing gear, critical parts of the aircraft that have to withstand harsh conditions and intense forces. Coatings for landing gear include chrome; hard, diamond-like carbon; and anodized metals.

A version of this infographic was published on cen.acs.org on Sept. 3, 2021, and in C&EN’s print magazine on Sept. 6, 2021, on page 33.

We choose 20 promising companies innovating for a low-carbon future

aether

» **aether Diamonds**

» **aetherdiamonds.com**

» **Based:** New York City

» **Publicly launched:** 2018

» **Money raised in start-up funding rounds:** $2.6 million

» **Publicly traded:** No

» **Key partnerships:** Climeworks

» **Strategy:** Aether's partners extract excess carbon dioxide from air and convert it to a hydrocarbon gas. Aether pipes the gas into chemical vapor deposition reactors to grow diamonds (see page 5). The gems are equivalent to those from mines—without the humanitarian or environmental toll.

» **Why watch:** The company debuted its jewelry in December 2020 with spreads in *Vogue* and elsewhere, and it currently has over $3 million in pending sales.

BOSTON METAL

» **Boston Metal**

» **bostonmetal.com**

» **Based:** Woburn, Massachusetts

» **Publicly launched:** 2012

» **Money raised in start-up funding rounds:** $76 million

» **Publicly traded:** No

» **Key partnerships:** Companhia Brasileira de Metalurgia e Mineração (CBMM)

» **Strategy:** Boston Metal uses its molten oxide electrolysis process to produce steel with lower CO_2 emissions compared with conventional production (see page 12). Renewable electricity powers the process, which reduces iron oxides from ore into liquid iron, which can then be alloyed into steel.

» **Why watch:** The company plans to introduce its first demonstration plant in 2025.

BREATHE

» **Breathe Applied Sciences**

» **breathesciences.com**

» **Based:** Bengaluru, India

» **Publicly launched:** 2016

» **Money raised in start-up funding rounds:** Not disclosed

» **Publicly traded:** No

» **Key partnerships:** Not disclosed

» **Strategy:** Breathe develops materials that transform CO_2 emissions from coal and natural gas power plants to methanol and other useful chemicals. The company, a finalist for the 2021 NRG COSIA Carbon XPRIZE, has commissioned a pilot plant that can convert 300 kg of CO_2 per day.

» **Why watch:** India imports about 80% of its methanol from other countries. If scalable, Breathe's technology could increase the homegrown methanol supply.

c16 BIOSCIENCES

» **C16 Biosciences**

» **c16bio.com**

» **Based:** New York City

» **Publicly launched:** 2017

» **Money raised in start-up funding rounds:** $24 million

» **Publicly traded:** No

» **Key partnerships:** Culture Biosciences

» **Strategy:** C16 harnesses microbial fermentation to build a sustainable alternative to palm oil, a vegetable oil commonly used in the food, beauty, and fuel industries. Environmental organizations criticize palm oil cultivation for destroying forests and other habitats, as well as alleged human rights abuses.

» **Why watch:** The company's backers include Breakthrough Energy Ventures, which was founded by Bill Gates.

CarbonBuilt

» **CarbonBuilt**

» **carbonbuilt.com**

» **Based:** Los Angeles

» **Publicly launched:** 2020

» **Money raised in start-up funding rounds:** $10 million

» **Publicly traded:** No

» **Key partnerships:** US National Carbon Capture Center, Stripe

» **Strategy:** CarbonBuilt has developed a greener formula for concrete. Instead of using emission-heavy Portland cement as the concrete binding agent, the company opts for portlandite, which absorbs waste CO_2 from power plant emissions as it hardens.

» **Why watch:** CarbonBuilt was one of two winners of the NRG COSIA Carbon XPRIZE, which comes with a $7.5 million award.

CARBON COLLECT

» **Carbon Collect**

» **mechanicaltrees.com**

» **Based:** Dublin

» **Publicly launched:** 2018

» **Money raised in start-up funding rounds:** Not disclosed

» **Publicly traded:** No

» **Key partnerships:** Arizona State University

» **Strategy:** Carbon Collect calls its proprietary machines "mechanical

trees" because they capture CO_2 from air without any energy input. The tree-like towers are 10 m tall when fully extended and contain sorbent tiles to collect circulating CO_2.
» **Why watch:** The firm is discussing partnership possibilities with players in the aviation (see page 14), food and beverage, and energy industries.

CEMVITA FACTORY

» **Cemvita Factory**
» **cemvitafactory.com**
» **Based:** Houston
» **Publicly launched:** 2017
» **Money raised in start-up funding rounds:** Not disclosed
» **Publicly traded:** No
» **Key partnerships:** BHP, Oxy Low Carbon Ventures
» **Strategy:** Cemvita Factory engineers microbes to be more productive at transforming CO_2 into valuable molecules such as ethylene, a precursor to numerous polymers. By giving the microbes a particular banana gene, the company can make ethylene without fossil fuel or plant sources.
» **Why watch:** Cemvita's microorganisms can also be used to clean up heavy metal and acid pollution from mining.

circa

» **Circa Group**
» **circa-group.com**
» **Based:** Parkville, Australia
» **Publicly launched:** 2006
» **Money raised in start-up funding rounds:** Not disclosed
» **Publicly traded:** Yes, IPO 2021
» **Key partnerships:** GazelEnergie, Norske Skog, Wood
» **Strategy:** Circa changes waste biomass into biobased chemicals. Its solvent, dihydrolevoglucosenone (Cyrene), is an alternative to the established solvents *N*-methyl-2-pyrrolidone (NMP) and dimethyl formamide (DMF). Both solvents come from fossil fuels and have suspected toxicity issues.
» **Why watch:** In September, the company chose the site for its first commercial facility, a former coal-fired power plant in France.

Compact Membrane Systems

» **Compact Membrane Systems**
» **compactmembrane.com**
» **Based:** Newport, Delaware
» **Publicly launched:** 1993
» **Money raised in start-up funding rounds:** $54.6 million
» **Publicly traded:** No
» **Key partnerships:** Braskem, PBF Energy
» **Strategy:** Compact Membrane Systems, a DuPont spin-off, makes membranes by coating a porous substrate with fluoropolymers. The polymers can be tailored for multiple applications, including nabbing CO_2 from a plant's emissions before they exit a smokestack.
» **Why watch:** The company says that because its technique relies on cartridges the size of a container of spray paint, it can be used to capture carbon from smaller sources that would not be compatible with established technology.

COOLBROOK

» **Coolbrook**
» **coolbrook.com**
» **Based:** Geleen, Netherlands
» **Publicly launched:** 2011
» **Money raised in start-up funding rounds:** Not disclosed
» **Publicly traded:** No
» **Key partnerships:** Brightlands Chemelot Campus, Oxford Thermofluids Institute, Schmidtsche Schack, University of Cambridge
» **Strategy:** Coolbrook produces ethylene, an important chemical feedstock, without high-heat, CO_2-emitting steam cracker furnaces. Its reactor is instead powered by renewable electricity that generates thermal energy with high-velocity rotor blades.
» **Why watch:** Coolbrook has received $14.5 million in grants to build a pilot plant by April 2022. It soon plans to announce partnerships with major oil companies.

enVerid
Energy savings. Air quality.

» **enVerid Systems**
» **enverid.com**
» **Based:** Westwood, Massachusetts
» **Publicly launched:** 2010
» **Money raised in start-up funding rounds:** $24.7 million
» **Publicly traded:** No
» **Key partnerships:** Massachusetts Institute of Technology, National Renewable Energy Laboratory, US Department of Energy, University of Southern California
» **Strategy:** enVerid lowers the carbon footprint of heating and cooling commercial buildings. The company's synthetic sorbent efficiently captures CO_2 and other contaminants from indoor air, reducing the need for outside air and consequently lowering energy use and carbon emissions.
» **Why watch:** The filtration platform has been deployed in schools and child care centers in Washington, DC; Philadelphia; and elsewhere.

Heirloom

» **Heirloom Carbon Technologies**
» **heirloomcarbon.com**
» **Based:** San Francisco
» **Publicly launched:** 2020
» **Money raised in start-up funding rounds:** Not disclosed
» **Publicly traded:** No
» **Key partnerships:** Stripe
» **Strategy:** Heirloom Carbon Technologies turbocharges the process by which natural minerals such as magnesium oxide absorb CO_2 from the air. The gas can then be released into underground storage, freeing up the minerals for reuse. The process involves repeated cycles of spreading oxide minerals in thin layers and continually exposing them to open air.
» **Why watch:** Heirloom's technology was coinvented by Jennifer Wilcox, whom the Joe Biden administration has since appointed principal deputy assistant secretary for the Office of Fossil Energy at the Department of Energy.

hydrogenious
LOHC TECHNOLOGIES

» **Hydrogenious LOHC Technologies**
» **hydrogenious.net**
» **Based:** Erlangen, Germany
» **Publicly launched:** 2013
» **Money raised in start-up funding rounds:** $77.9 million
» **Publicly traded:** No

» **Key partnerships:** Clariant, Eastman Chemical, Hyundai Motor
» **Strategy:** Hydrogenious LOHC Technologies develops benzyltoluene as a carrier medium to safely handle hydrogen in the existing fuel infrastructure. Hydrogen fuel produces water rather than CO_2 when consumed.
» **Why watch:** In July, it announced the founding of a joint company with Østensjø, an international shipping company.

» **Infinium Holdings**
» **infiniumco.com**
» **Based:** Sacramento
» **Publicly launched:** 2020
» **Money raised in start-up funding rounds:** Not disclosed
» **Publicly traded:** No
» **Key partnerships:** Amazon, Mitsubishi Heavy Industries, Neuman & Esser
» **Strategy:** Infinium buys waste CO_2, adds green hydrogen produced from water by renewable electricity, and then uses its proprietary catalyst to convert the mixture to syngas. An additional step produces fuels for planes, ships, and trucks.
» **Why watch:** The company plans to add direct-air capture as a source of its CO_2.

» **LanzaTech**
» **lanzatech.com**
» **Based:** Skokie, Illinois
» **Publicly launched:** 2005
» **Money raised in start-up funding rounds:** $280.4 million
» **Publicly traded:** No
» **Key partnerships:** Argonne National Lab, India Glycols, Shougang Group, Twelve (see page 18), Unilever
» **Strategy:** LanzaTech captures carbon monoxide and uses proprietary microbes to transform it into fuels, textiles, and even proteins for the animal feed industry.
» **Why watch:** In 2020,the company spun out renewable jet fuel firm LanzaJet, which has already attracted $64 million.

Note: Companies were included because of the novelty and potential of their methods, amount of capital raised, number of partnerships, and number and identity of investors.

Sources: Crunchbase (accessed October 2021), company websites, news reports.

» **Monolith**
» **monolith-corp.com**
» **Based:** Lincoln, Nebraska
» **Publicly launched:** 2012
» **Money raised in start-up funding rounds:** $64.3 million
» **Publicly traded:** No
» **Key partnerships:** Mitsubishi Heavy Industries, Nebraska Public Power District
» **Strategy:** Monolith superheats methane from natural gas rather than burning it. This technique, powered by renewable electricity, breaks methane's bonds to form carbon black, a critical automotive material, and hydrogen, which can be used as fuel or to produce chemicals.
» **Why watch:** The firm is scheduled to begin construction on an expansion facility in the fourth quarter of 2021 that will produce green ammonia with the hydrogen from its methane pyrolysis process.

» **Nitricity**
» **nitricity.co**
» **Based:** San Francisco
» **Publicly launched:** 2018
» **Money raised in start-up funding rounds:** $6 million
» **Publicly traded:** No
» **Key partnerships:** Fresno State Center for Irrigation Technology
» **Strategy:** Nitricity constructs devices on farms so that farmers can produce their own nitrogen fertilizer on-site. The proprietary process requires only air, water, and renewable electricity, in contrast to the emission-intensive route to ammonia.
» **Why watch:** The company's commercial-scale pilot is underway, producing nitric acid and nitrate-based fertilizers for green peppers.

» **Solugen**
» **solugen.bio**
» **Based:** Houston
» **Publicly launched:** 2016
» **Money raised in start-up funding rounds:** $435.2 million
» **Publicly traded:** No
» **Key partnerships:** AkzoNobel, Diamond Wipes, Nanotronics, Xytel
» **Strategy:** Solugen uses engineered enzymes and chemical catalysts to construct valuable molecules such as hydrogen peroxide from sugars, air, and CO_2.
» **Why watch:** The team raised money from existing investors to focus on a zero-carbon route to glucaric acid, which is an alternative to the environmental pollutant phosphate as a corrosion inhibitor for water treatment facilities.

» **Svante**
» **svanteinc.com**
» **Based:** Burnaby, British Columbia
» **Publicly launched:** 2007
» **Money raised in start-up funding rounds:** $195 million
» **Publicly traded:** No
» **Key partnerships:** LafargeHolcim, Total
» **Strategy:** Svante incorporates its materials—which are tailored to catch and release CO_2 quickly—into a turntable-like device. In one 360-degree revolution, the machine provides concentrated CO_2 for safe storage or other applications and regenerates the adsorbent.
» **Why watch:** Svante received US $20 million in July from the Canadian government to scale operations.

» **Transform Materials**
» **transformmaterials.com**
» **Based:** Riviera Beach, Florida
» **Publicly launched:** 2014
» **Money raised in start-up funding rounds:** Not disclosed
» **Publicly traded:** No
» **Key partnerships:** Chart Industries, DSM Nutritional Products
» **Strategy:** Transform's proprietary microwave plasma reactor energizes methane to an ionized state. Without any combustion, the ions recombine to form hydrogen, which is a clean fuel, and acetylene, which is a valuable chemical for vitamins, flavors, fragrances, and plastics.
» **Why watch:** In May, Transform's pilot plant met a crucial productivity milestone in its agreement with DSMa

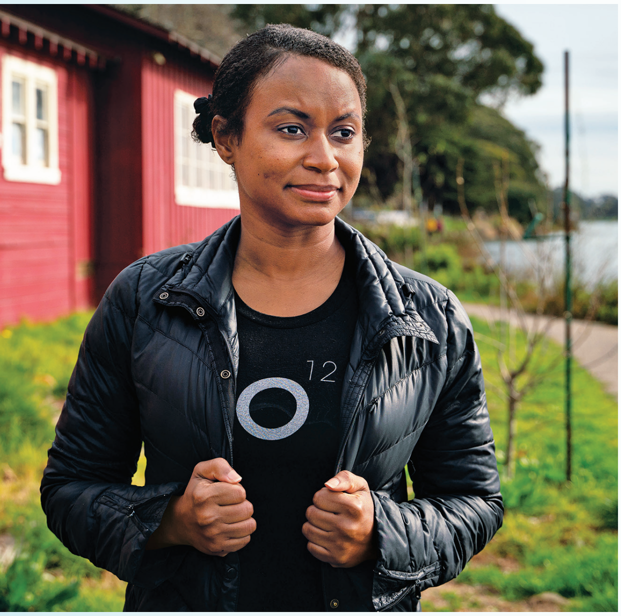
Twelve: Converting greenhouse gases into materials and chemicals

FRIEDA WILEY, SPECIAL TO C&EN

Etosha Cave's sense of adventure has taken her to the McMurdo Station in Antarctica to do research and sustained her through cofounding a company in 2015.

Cave is the chief science officer of Twelve, a start-up company specializing in recycling the greenhouse gas carbon dioxide into valuable chemicals. The company's core technology is based on her PhD research. "We convert carbon dioxide gas into useful products such as plastics, diesel fuel, and household cleaners," Cave says.

Twelve makes reactors that use electricity and water to convert carbon dioxide into useful chemicals; transition-metal catalysts speed up the process. The key to the company's electrochemical system is a unique ionic polymer membrane electrode. At the reactor's anode, water is oxidized to generate protons that are transported by the membrane and used in further reactions. The catalyst reduces gaseous CO_2 into molecules such as carbon monoxide, methane, and ethylene.



Twelve cofounder and chief scientific officer Etosha Cave

"Our main competitor is the status quo, as in most places it is still free and inconsequential to throw CO_2 into the atmosphere," Cave says. "We also are taking advantage of low-cost renewable electricity, which could make our method of CO_2 conversion much cheaper as time goes on."

Other companies are also striving to transform carbon dioxide into useful materials. Cave says Twelve's key advantage is the ionic polymer membranes in its reactors, which allow for high power densities and a robust system design that operates at relatively low temperatures.

Twelve's partners include the California utility Pacific Gas and Electric and the luxury vehicle manufacturer Daimler.

Cave's quest for adventure has remained a constant source of inspiration in her life. Before moving to Stanford to start her doctoral program in engineering, she spent 5 months working on an atmospheric chemistry project in Antarctica at the McMurdo Station. In addition to being the trip of a lifetime, the field research supported her career goals. "Antarctica is one of the analogs of living on Mars, and I'd like to be an astronaut someday," she says.

She notes that Twelve's technology for converting an abundant gas into useful chemicals would be particularly useful on Mars or the moon.

Cave says she fantasizes about retiring to a martian colony one day—the ultimate adventure. "Ninety-five percent of Mars's atmosphere is CO_2," she says. "I would love for our technology to be featured on a spaceflight."

Frieda Wiley is a licensed pharmacist and former chemist turned freelance science and medical writer.

Twelve at a glance

» **Launched:** 2015
» **Based:** Berkeley, California
» **Strategy:** A unique ionic polymer membrane electrode underpins reactors that use electricity and water to convert carbon dioxide into useful chemicals.
» **Funding:** $68 million

SOURCE: CRUNCHBASE

This article is reprinted with permission from C&EN. A version of this article was published in C&EN on Feb. 22, 2021, on page 68.

CREDIT: SARAHBETH MANEY

CO_2 capture drives metal purification

MARK PEPLOW, SPECIAL TO C&EN

CO_2 from a car exhaust reacts with diethylenetriamine to isolate lanthanum from nickel in solution.

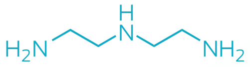
CREDIT: *NAT. CHEM.*

Capturing the carbon dioxide emitted by fossil fuel power stations or industrial plants offers a vital way to reduce greenhouse gas emissions. But carbon-capture technologies are still considered too costly for widespread deployment.

Chemists at the University of Lyon have now developed a method to capture CO_2 while simultaneously purifying mixtures of metals. Coupling these two processes, they argue, means CO_2 capture can generate value in the form of purified metals, potentially making carbon capture more economically viable (*Nat. Chem.* 2020, DOI: 10.1038/s41557-019-0388-5).

Current carbon-capture systems often use amines that react with CO_2 in flue gas to form carbamates. These compounds can be separated and heated to release a stream of pure CO_2, regenerating the amine so that it can be cooled and reused. But the huge temperature swings involved make the approach costly.

Meanwhile, the CO_2 released from the amines is sometimes used to help displace oil from underground reserves. "The oil-extraction process is effectively paying for the price of capturing CO_2," says Julien Leclaire from the University of Lyon. This process ultimately leads to more carbon emissions when the oil is burned, however.



Diethylenetriamine

So Leclaire's team looked for an alternative way to add value to carbon capture. They settled on a polyamine called diethylenetriamine (DETA), which reacts with CO_2 to produce monocarbamate or dicarbamate anions, along with inorganic bicarbonate anions. Mixed with metal chlorides, the amine, carbamates, and bicarbonates can act as ligands or counterions to form a range of metal complexes.

Most of these complexes are in reversible equilibriums with one another and interconvert by ligand exchange. But some complexes are insoluble, and under the right conditions they form solid precipitates that contain a single metal compound. "The idea is that each metal can find its ideal combination, in terms of ligand and counterion, that allows each of them to be separated," Leclaire explains.

As a proof of principle, the researchers prepared a mixture of lanthanum chloride and nickel chloride in water, added DETA, and then bubbled CO_2 directly from a car's exhaust through the solution. This triggered a series of ligand exchange reactions that created insoluble lanthanum carbonate, $La_2(CO_3)_3$, which the team removed by centrifugation.

"If you can get a process that selectively picks out individual metals, you have the start of a very exciting industrial symbiosis," says Peter Styring, who works on carbon-capture, utilization, and storage technologies at the University of Sheffield. "This makes absolute sense."

Leclaire and his colleagues are now using their method to purify the metals found in rare earth magnets, which are widely used in wind turbines, and they hope to collaborate with metal-recycling companies to develop the technology further.

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> **"If you can get a process that selectively picks out individual metals, you have the start of a very exciting industrial symbiosis."**

READING LIST

Our picks of the patent and journal literature on decarbonization

2021

» Svante. **"Adsorptive Gas Separation Process and System."** US Patent 11,148,094, filed March 31, 2017, and issued Oct. 19, 2021.

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» Wang, Yuan, Astha Sharma, The Duong, Hamidreza Arandiyan, Tingwen Zhao, Doudou Zhang, Zhen Su, et al. **"Direct Solar Hydrogen Generation at 20% Efficiency Using Low-Cost Materials."** *Adv. Energy Mater.* 11, no. 34 (Sept. 9, 2021): 2101053. https://doi.org/10.1002/aenm.202101053.

» Dbt-Ioc Centre For Advanced Bio-Energy Research, LanzaTech New Zealand. **"Fermentation Process for the Production of Lipids."** US Patent 11,111,510, filed Dec. 20, 2019, and issued Sept. 7, 2021.

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» Suryanto, Bryan H. R., Karolina Matuszek, Jaecheol Choi, Rebecca Y. Hodgetts, Hoang-Long Du, Jacinta M. Bakker, Colin S. M. Kang, Pavel V. Cherepanov, Alexandr N. Simonov, and Douglas R. MacFarlane. **"Nitrogen Reduction to Ammonia at High Efficiency and Rates Based on a Phosphonium Proton Shuttle."** *Science* 372, no. 6547 (June 11, 2021): 1187–91. https://doi.org/10.1126/science.abg2371.

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» UT–Battelle. **"Guanidine Compounds for Carbon Dioxide Capture."** US Patent 10,583,387, filed May 14, 2018, and issued March 10, 2020.

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Note: This list was chosen by experts who work in the field, CAS information scientists, and C&EN editorial staff.