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Pioneers winners chosen by BNEF in 2023

Climate-Tech Startups to Watch in 2023: BNEF Pioneers

The winners of BloombergNEF's Pioneers 2023 award were announced on April 17. The annual competition searches for game-changing technologies or innovations with the potential to accelerate global decarbonization and halt climate change. This note profiles each of this year's 12 winners, describing how the technologies work, the maturity of each company and the reasons behind BNEF's decision-making process.

- BNEF has run the Pioneers competition since 2010. Since then there have been 141 winners, including this year's Pioneers. These companies have cumulatively raised $14.9 billion. In 2023, BNEF received applications from 348 companies in 42 countries.
- Challenge 1 — Accelerating the deployment of clean hydrogen: The winners of this challenge are developing electrolyzer technologies for the production of hydrogen (SunGreenH2's electrode technology and H2Pro's electrochemical and thermally-active electrolysis) and equipment that can run on hydrogen (Mainspring Energy's linear generator).
- Challenge 2 — Sustainable metals and materials for an electrified future: The winners of our metals challenge are developing novel methods of extracting metals (Jetti Resources' catalyst for recovering copper from stranded ore), recycling batteries (Li-Cycle's hydrometallury process) and metals processing (Nth Cycle's electroextraction process).
- Challenge 3 — Building a net-zero food production system: The winners of the agriculture challenge are developing ways to improve crop farming (Precision AI's drones for herbicide application), produce low-carbon proteins (MicroHarvest's microbial fermentation of proteins) and reduce emissions from animals (FutureFeed's seaweed feed ingredient).
- Wildcards: The wildcards category is open to any climate-tech innovation outside of the challenges listed above. This year's winners are applying electrochemistry in novel ways in the cement (Sublime System's lime production process), steel (Electra's low-carbon ironmaking for steel) and carbon removal (Travertine's acid and base production) industries.

Figure 1: BNEF Pioneers 2023

Source: BloombergNEF

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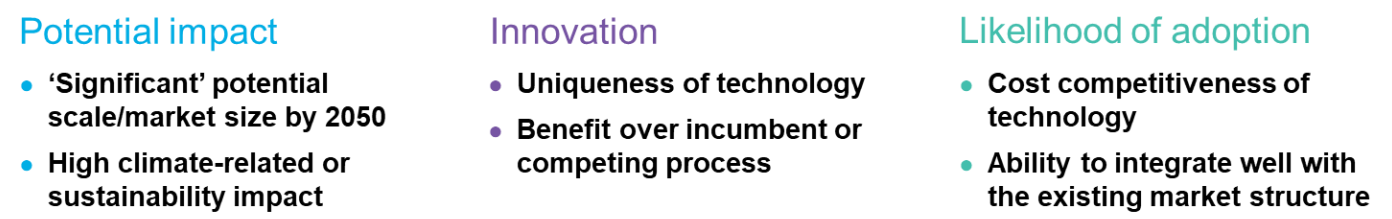
1. How does BNEF choose its Pioneers?

Each year, BNEF awards the Pioneers prize to innovators addressing three pre-selected challenges, and also recognizes a few 'wildcard' winners outside of these challenge categories. BNEF chooses its Pioneers in a four-step process:

1. **Choosing the challenges:** BNEF chooses its challenge areas each year through discussions with each of our sector teams. The themes focus on topics where there is a lack of a clear technology solution to an urgent climate challenge. These technology gaps emerge from BNEF's long-term outlooks on energy, industry and transport such as the *New Energy Outlook* (web | terminal) and *Electric Vehicle Outlook* (web | terminal).
2. **Finding the applicants:** BNEF searches for potential applicants using its own startup databases and published research, as well as analyst knowledge. We solicit applications from our analysts, network of clients and research contacts. About half of the 250-300 applications that BNEF receives each year are solicited, while the other half come from our open application portal. Winners are often chosen from the pool of unsolicited applications.
3. **Choosing the finalists:** Each application is read and scored by a relevant sector analyst based on the dimensions of potential impact, innovation and likelihood of adoption (Figure 2). Top-scoring companies are put through as finalists. BNEF attempts to represent a diverse range of technologies with the finalists, rather than relying solely on quantitative scores.
4. **Choosing the winners:** BNEF conducts a full day of finalist judging, where an analyst champion pitches each finalist, using a prepared presentation and written profile. The judges are the BNEF management committee, which uses a voting and discussion process to determine the winners of the competition.

Figure 2: Scoring dimensions for BNEF Pioneers applicants



Source: BloombergNEF

2. Challenge 1: Accelerating the deployment of clean hydrogen

Clean power and carbon capture are not enough to fully decarbonize all sectors. Renewable, or clean, fuels will also be essential. Hydrogen, made from renewable power, has the potential to play a significant role in reaching net-zero emissions, both as an energy storage medium and as an energy-dense fuel. Grey (fossil-fuel based) hydrogen is already used in making fertilizer, oil products and chemicals. If green hydrogen can replace grey hydrogen, and also scale to help decarbonize steel, petrochemicals and heavy transportation sectors, the demand for it could reach 500 million tons, according to BNEF's NEO Net Zero scenario (from 100 million tons today). However, green hydrogen currently costs three times that of grey hydrogen to make and has an immature supply chain. Because of this, despite significant investments in electrolyzer manufacturing, the green hydrogen demand market has not materialized. This chapter profiles the three Pioneers winners developing technologies to accelerate the deployment of clean hydrogen.

2.1. SunGreenH2

Table 1: SunGreenH2 company details

Name	HQ	Founded	Funding	Technology
SunGreenH2	Singapore	2020	$3.5 million	Nanostructured electrodes for electrolyzers

Source: BloombergNEF, SunGreenH2

Why is innovation needed to make electrolyzers more efficient?

The core technology of producing green hydrogen is water electrolysis. In this process, an electrolyzer uses carbon-free electricity to split water into hydrogen (H_2) and oxygen (O_2). For more information, see *Electrolysis Primer: An Old Technology Adapts for New Uses* (web | terminal).

Even though the technology is over a century old, H_2 production via electrolysis is a nascent industry, and electrolyzer technologies need to improve if zero-carbon H_2 is to scale. Production efficiency is a key area of improvement. Currently, making a kilogram of H_2 via electrolysis requires 57.8 kWh of electricity. This kilogram contains 39.4 kWh of energy, an efficiency of 68%. Beyond 2035, electricity accounts for over 70% of levelized H_2 costs.

Electricity will be the biggest cost component for H_2 production in the future.

The Net-Zero Scenario of BNEF's New Energy Outlook 2022 estimates that nearly 21,000 TWh of electricity will used by electrolyzers for H_2 production in 2050, accounting for 29% of global power demand. Because electricity will be the biggest cost component of H_2 production in the future, making electrolyzers more efficient would have a significant impact on H_2 costs and reduce the need to build out additional renewable power capacity. For more information, see *New Energy Outlook 2022* (web | terminal).

What is SunGreenH2's technology?

SunGreenH2 has developed, and is patenting, nano-structured electrodes for use in electrolyzers. Electrodes are where the chemical reactions occur and H_2 and O_2 are produced. The nanostructure of SunGreenH2's electrodes increases their surface contact area with the water that is being electrolyzed. This increases the current density and H_2 output per unit surface area of the electrode. This means more H_2 is produced for the same size electrolyzer, and energy consumption per unit of H_2 output is decreased.

Why is SunGreenH2 a Pioneer?

SunGreenH2's electrodes boosts power consumption efficiency.

SunGreenH2's technology addresses multiple bottlenecks in the H_2 electrolysis industry. The first of these is cost. The firm states it can reduce plant stack capex by 50% primarily through increasing H2 output while reducing the use of precious metals. Simultaneously its technology boosts power consumption efficiency by 10%, lowering the operational cost of electricity.

On top of its impressive technical performance, SunGreenH2's technology has another key advantage: it can be implemented on existing manufacturing lines. SunGreenH2 uses industrially-established low-cost, high-throughput manufacturing methods. This is advantageous for new electrolyzer technologies because the market for manufacturing lines will be oversupplied in the coming decade. Electrolyzer production capacity will exceed expected demand by a factor of 12 at the end of 2023 based on existing capacity announcements. SunGreenH2's technology can be used across all electrolyzer technologies, so it is well-positioned despite the oversupply.

How mature is SungreenH2?

SunGreenH2 is in the early stages of product development and has two patents pending. The company developed a prototype in 2022 and is trialing electrodes with Molymet, a metals processor, and others in Chile. It will deploy its first commercial electrolyzer product with Naturgy Innovahub in Spain and other partners in Singapore and Australia in 2023. SunGreenH2 has raised $3.5 million in total funding to date from SGInnovate, SOSV, Cap Vista and others. The company has also been awarded grant funding from Shell and the Energy Market Authority in Singapore.

2.2. H2Pro

Table 2: H2Pro company details

Name	HQ	Founded	Funding	Technology
H2Pro	Israel	2019	More than $100 million	Electrochemical and thermally-activated electrolysis

Source: BloombergNEF, H2Pro

Why is innovation needed to make electrolyzers cheaper?

Electrolysis will become the cheapest option for hydrogen production.

Hydrogen is produced today through carbon-intensive methods, mainly via steam reforming of methane or gasification of coal. Releasing few or no greenhouse gas emissions, electrolysis is one of two ways to produce low-carbon hydrogen. Today grey hydrogen costs $2 per kilogram to make, compared to the as high as $12 per kilogram cost of green hydrogen production.

BNEF expects hydrogen production costs in most countries to drop to $1.50-2.00/kg by 2030 as electrolyzer technologies improve. The faster cost declines for electrolysis occur, the faster it can become the primary method of producing hydrogen and enabling decarbonization in several hard-to-abate industries. For more information, see *2H 2022 Hydrogen Levelized Cost Update: Trending Higher* (web | terminal).

What is H2Pro's technology?

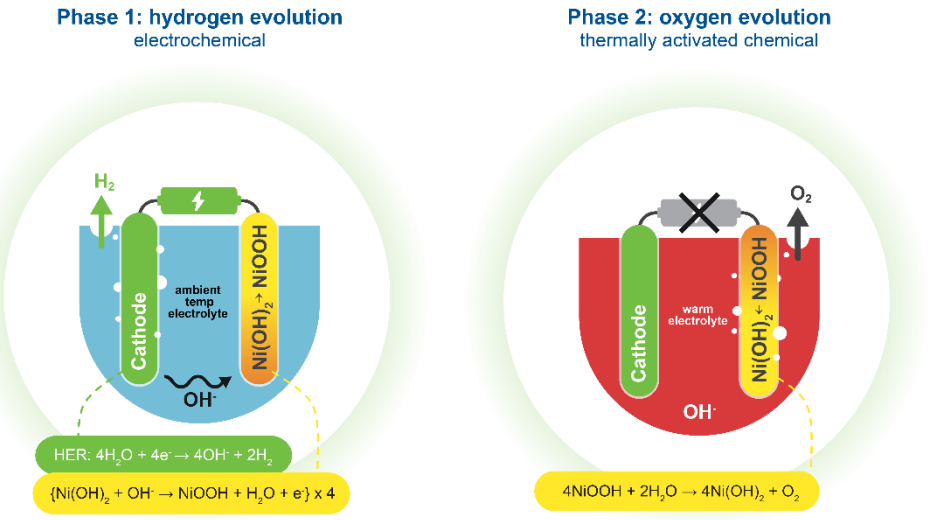
H2Pro has created an electrolyzer which uses a combination of electrochemical and thermally-activated chemical reactions (E-TAC). The E-TAC system uses a two-part process to create hydrogen.

H2Pro's electrolyzer uses a two-part process to create hydrogen.

The first phase of E-TAC is electrochemical. Electricity is applied to the electrolysis cell, and H_2 is generated at the cathode. The unique aspect of H2Pro's technology is that O_2 is not simultaneously generated at the anode like in a traditional electrolyzer. Instead, the anode is oxidized and transformed from nickel hydroxide ($Ni(OH)_2$) to nickel oxyhydroxide (NiOOH). The electrons from this oxidation reaction close the electrical circuit.

To complete the water-splitting cycle, the anode must be returned to its initial state so that the process can be repeated. In this second phase, the power is turned off and a warm electrolyte is introduced. This accelerates the spontaneous self-discharge reaction of the NiOOH, which is accompanied by a chemical-oxygen-generation reaction in which O_2 is released, and the anode transforms back to $Ni(OH)_2$ (Figure 3).

Figure 3: Schematic of hydrogen production via e-TAC electrolysis



Source: H2Pro. Note: Yellow oval indicated anode.

Why is H2Pro a Pioneer?

H2Pro's process eliminates the need for an expensive membrane to keep hydrogen and oxygen separate.

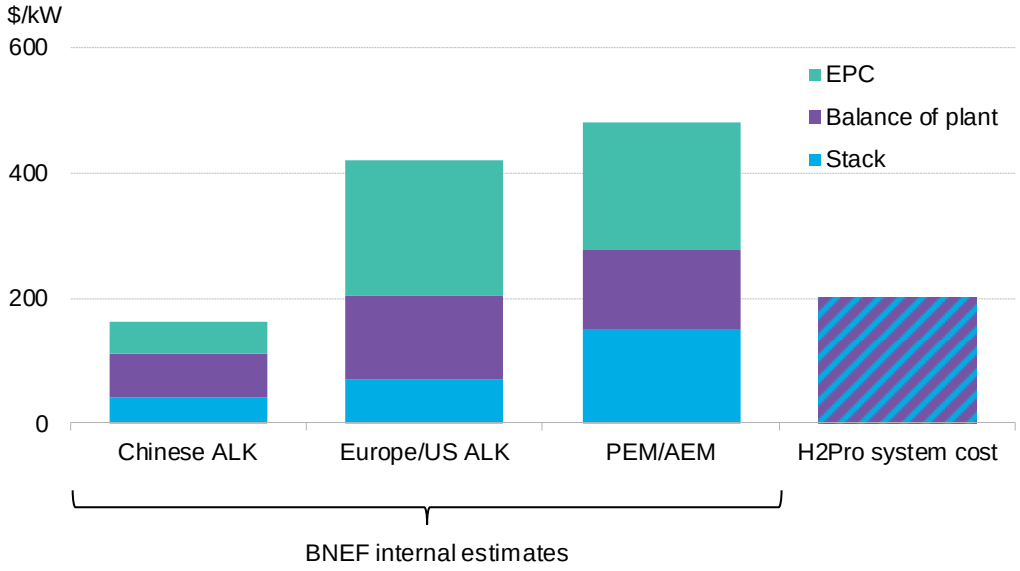
The decoupling of the H_2 and O_2 production in H2Pro's electrolyzer means that one of the most expensive components of an electrolyzer – the membrane separating the two produced gases – can be removed. Because the gases are produced separately, there is no risk of explosive mixing. H2Pro says that it will build electrolyzers for $200/kW by 2030. This cost is lower than BNEF estimates for proton-exchange membrane and anion-exchange membrane electrolyzers, and in line with alkaline electrolyzers in the US and China (Figure 4).

H2Pro also states that it is more energy efficient to produce O_2 in an electrolyzer using thermal energy, rather than using electricity as in an alkaline or PEM electrolyzer. In a Nature Energy study, H2Pro demonstrated a lab efficiency of 98.7% compared with 68% seen in today's standard equipment.

The target capital cost of H2Pro's electrolyzer alongside its impressive efficiency would, if realized, make hydrogen produced from its electrolyzers among the cheapest energy molecules available, taking into consideration US and European subsidies.

Moreover, H2Pro's two-step process makes its electrolyzers suitable for ramping production up and down. With the improved ramp speed, H2Pro's electrolyzers could match hydrogen production to when renewable power plants are generating electricity, making the hydrogen produced "greener" than that from electrolyzers that run at high capacity factors and therefore require power from the grid even when fossil fuels are powering it.

Figure 4: 2030 project capital costs of electrolyzers



Source: BloombergNEF, H2Pro. Note: H2Pro system cost includes both stack and balance of plant. ALK = alkaline, PEM = proton exchange membrane, AEM = anion exchange membrane, EPC = engineering, procurement and construction.

H2Pro's process is suitable for ramping hydrogen production up and down.

How mature is H2Pro?

H2Pro is building a demonstration plant in 2023 capable of producing 73 tons of H_2 per year. It is planning its first commercial deployment for 2025 and aims to have gigawatt-scale manufacturing capabilities by 2030.

To date, most of H2Pro's credibility comes from patents and its scientific publications. The company has five patents and has a publication in peer-reviewed scientific journal Nature Energy discussing the E-TAC process. The company also won Shell's New Energy Challenge in 2020 and has raised over $100 million to date, including backing from established climate-tech investor Breakthrough Energy Ventures.

2.3. Mainspring Energy

Table 3: Mainspring Energy company details

Name	HQ	Founded	Funding	Technology
Mainspring Energy	US	2010	$531 million	Fuel-agnostic linear generator

Source: BloombergNEF, Mainspring Energy

Why is innovation needed in generator technologies?

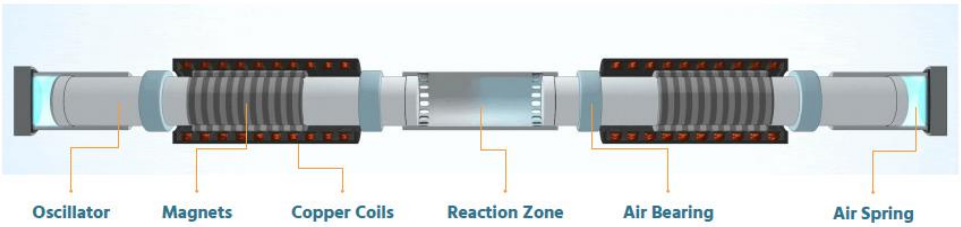
One main use case for H_2 is as a carrier of energy. But turning H_2 back into electricity is also difficult. Engines, turbines and fuel cells that are built to produce electricity from H_2 are expensive and inefficient.

What is Mainspring Energy's technology?

Mainspring's linear generator can utilize multiple fuels.

Mainspring has developed a new kind of power generator technology that is different from engines, turbines and fuel cells. Its linear generator product creates a flameless reaction of air and fuel in the central chamber (Figure 5). The reaction moves oscillators covered with magnets through two copper coils. Air springs at the ends of the generator move the oscillators back to the original position, and the cycle of motion produces electricity.

Figure 5: Diagram of Mainspring Energy's linear generator



Source: Mainspring Energy

Mainspring's generator can accommodate multiple fuels (H_2, ammonia, biogas, others) by varying the oscillator position and fuel chamber compression. This design, combined with Mainspring's adaptive control software, enables full dispatchability and switching between fuels. The company says efficiency across all fuels ranges from 43-50%, which is similar to a fuel cell (40-60%) and higher than simple gas turbines (30-40%).

Why is Mainspring Energy a Pioneer?

Mainspring sells its product to commercial and industrial customers.

Mainspring Energy's generator is more flexible on fuel sources than competing technologies and prevents sites where a unit is installed from being locked into a single decarbonization route. Because Mainspring Energy's generator is fuel agnostic, customers can switch across different low- or zero-carbon fuels depending on costs and availability. This flexibility will be valuable to companies as they would be able to adapt to changing commodity prices and keep carbon emissions low without installing additional equipment. Additionally, as distributed generation, the generators could provide power to industrial users as a supplement to variable renewable generation.

Mainspring Energy's generator also emits less NO_x emissions compared with a diesel generator. NO_x emissions contribute to climate change and are potent air pollutants. The generator uses a flameless reaction to avoid NO_x and the need for an expensive flue gas scrubber.

How mature is Mainspring Energy?

Mainspring Energy's first pilot project occurred in 2014-2016. The company's first commercial project began in 2020, and it has deployed tens of units at customer sites to date. Mainspring Energy is selling its generator to commercial and industrial customers. It is currently producing 0.25 MW generators.

3. Challenge 2: Sustainable metals and materials for an electrified future

The scale-up of clean energy, alongside the electrification of heating, transport and industrial activities, will require a five-fold increase in demand for key metals if we are to reach net-zero emissions by 2050. Metals including copper, lithium, cobalt and nickel are used in the power grid, electric vehicles and in lithium-ion batteries. This will require a rapid escalation in supply and represents a $10 trillion opportunity for the metals sector. However, today there are reduced investment levels in mining and an increasing view that the sector is too risky to support. The amount of capital flowing into raw materials is currently inadequate, leading to supply shortages and higher prices. For more information, see BNEF's *Transition Metals Outlook* (web | terminal).

Innovation will be needed to increase the supply of new materials and to reuse existing materials. Doing so will lower the carbon intensity and environmental impact of the metals sector. This chapter profiles the three winners of this challenge, which are developing new ways to extract, reuse and process metals.

3.1. Jetti Resources

Table 4: Jetti Resources company details

Name	HQ	Founded	Funding	Technology
Jetti Resources	United States	2014	$205 million	Catalyst for extracting copper from stranded ore

Source: BloombergNEF, Jetti Resources

Why is innovation needed in copper mining?

BNEF expects annual demand for refined copper to grow by 58% from 2022 to 2040.

BloombergNEF expects annual demand for refined copper to grow by 58% from 2022 to 2040. This growth in copper demand will mainly be driven by the electrification of transportation and the growth of the power system. Unless new discoveries are brought online, there will be a significant shortage of primary production of copper by 2040. An extended supply crunch could elevate prices over a long period, leading to a slowdown in the deployment and adoption of clean technologies due to higher infrastructure costs and scarcity of raw materials. For more information, see *Global Copper Outlook 2022-2040* (web | terminal).

While essential for decarbonizing the global economy, copper has its own environmental impacts. It is twice as emission intensive as steel, and mines often pollute local water supplies with toxic chemicals. Innovations are needed to reduce the environmental impact of the mining industry as it scales.

Declining ore grades are also a massive problem in the copper mining industry that disincentivizes investment in new capacity and increases the environmental damage per unit of copper produced. BNEF expects the average ore grade to continue to decrease from 0.7% copper in 2020 to 0.5% in 2030.

What is Jetti Resources's technology?

There are two routes for producing copper from ore: pyrometallurgy (where ore is concentrated and smelted at high temperatures) and hydrometallurgy (where ore is piled in a heap and washed in acid to release target minerals). Most copper is produced through pyrometallurgy right now,

despite the fact it is more expensive, energy and emissions intensive. Pyrometallurgy has the benefit of producing copper faster but is only competitive on higher-grade ore.

Jetti's catalyst makes hydrometallurgy economically viable on lower-grade ores.

Jetti has developed a catalyst that aims to make hydrometallurgy economically viable on lower-grade ores, namely chalcopyrite. Low-grade chalcopyrite –the world's largest source of copper –is often discarded as waste because it is too low grade for pyrometallurgy and cannot currently be leached. According to Jetti, copper cannot be leached from chalcopyrite because of a passivation layer that forms on the surface of the mineral, essentially blocking copper from being extracted. Jetti says its catalyst electrochemically alters this passivation layer, making the leaching of low-grade chalcopyrite economically competitive.

The mechanics of how this passivation layer forms has been somewhat up for debate and a challenging question in the field of materials science. Jetti says that its understanding of the mechanism, which it published last year in a peer-reviewed journal article, is evidence of its expertise in leaching.

Why is Jetti Resources a Pioneer?

There are few innovations in the market to boost the capacity of existing copper mines.

Jetti Resources' catalytic technology, which can be implemented at existing mines, is one of few innovations that exist in the market to help boost the capacity of existing copper mines. This is important because the incoming supply crunch for copper could limit the roll out of key technologies that use large amounts of copper, such as EVs, wind turbines and electric grids. Copper mines can take over a decade to come online and the high prices induced by the supply crunch are therefore unlikely to be quickly resolved by new mining capacity. Boosting capacity of existing facilities is one of the best strategies to address supply shortages.

On top of that, Jetti's technology has proven commercially successful with one project generating an IRR of 171%. Jetti also helps solve another non-climate related challenge facing miners: declining grades of ore and rising operating costs.

How mature is Jetti Resources?

Jetti's technology has been proven commercially and is now deployed at two mines, with a third operation under construction. The first deployment was with Capstone Copper at its Pinto Valley Copper Mine in Arizona where, within one year, Jetti was able to double production from a leach area containing hundreds of millions of tons of ore. Jetti began operations at Capstone's Pinto Valley Mine in 2019 and discussions about the potential for expansion are ongoing. Jetti opened its second operation at Freeport-McMoRan's Bagdad mine in 3Q 2022 and expects to commence commercial production at Freeport-McMoRan's El Abra mine in late 2023.

Jetti currently has a pipeline of more than 20 growth projects at various stages of development. This pipeline has translated into fundraising traction. The company closed a $100 million Series D round, which reportedly valued it at $2.5 billion in December of 2022. The company has a research partnership with the University of British Columbia, and investors include Mitsubishi, BHP, Teck, BMW and Freeport-McMoRan.

3.2. Li-Cycle

Table 5: Li-Cycle company details

Name	HQ	Founded	Funding	Technology
Li-Cycle	Canada	2016	$580 million in reverse merger	Hydrometallurgical lithium-ion battery recycling

Source: BloombergNEF, Li-Cycle. Note: Funding indicates amount raised in reverse merger with Peridot Acquisition Corp.

Why is lithium-ion battery recycling needed?

With more than three quarters of the lithium mined today used in energy-transition technologies, mainly batteries, lithium is the metal with the highest share of its demand coming from the energy transition. BNEF expects this share to rise from 79% in 2022 to 95% in 2050. The lithium market will be tight for the next three decades, and the market may be undersupplied.

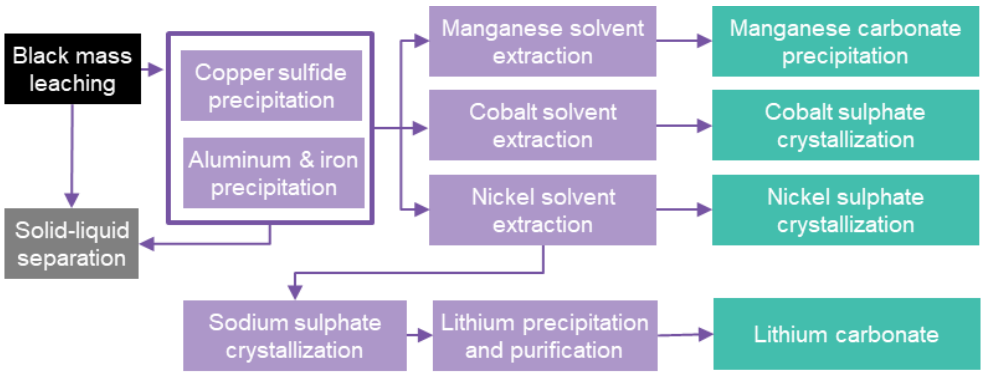
While this shortage will require bringing new lithium resources online, recycling can be a significant source of metals moving forward. As well as providing a secure, domestic supply of critical minerals, recycling can reduce the environmental footprint of those metals. For more information, see *Lithium-Ion Battery Recycling Market Outlook* (web | terminal).

What is Li-Cycle's technology?

Li-Cycle has a network of facilities for collecting and recycling lithium-ion batteries.

Li-Cycle has developed its Spoke and Hub network of facilities for collecting and recycling lithium-ion batteries, battery manufacturing scrap and battery packs. At the Spokes, Li-Cycle processes lithium-ion batteries through a proprietary, submerged shredding process. This converts the material into plastics, copper, aluminum and 'black mass', which contains battery metals. The plastics and metals are sold and shipped off to Li-Cycle's recycling partners, and the black mass is sent to its Hubs. At the Hubs, the second stage of Li-Cycle's resource recovery process, a hydrometallurgical process is used to refine the black mass into high-purity, battery-grade materials including lithium carbonate, nickel sulfate and cobalt sulfate (Figure 6). Hydrometallurgy uses acids and bases to control the pH of leach solutions. This allows for selective dissolution of materials and precipitation of products. These materials are then sold to Li-Cycle's strategic offtake partners.

Figure 6: Black mass to battery-grade materials process at Li-Cycle hubs



Source: BloombergNEF

Why is Li-Cycle a Pioneer?

Li-Cycle's process is less emissions-intensive than mining for new materials.

Li-Cycle's process efficiently recovers metals from lithium-ion batteries, and because it uses hydrometallurgy, a mature technology, the company can make an impact in the near term. The hydrometallurgy process enables up to a 95% recycling efficiency rate, recovering lithium, nickel and cobalt. The company says that this is higher than typical recycling efficiencies/recoveries from existing and emerging processes, which have recovery rates in the range of ~50-70%. In addition to higher recovery rates, hydrometallurgical recycling processes are less energy- and carbon-intensive than thermal processes that other lithium-ion battery recycling companies use.

Additionally, Li-Cycle's process is less emissions-intensive than mining for new materials (Table 6) and the company says that it can reduce water usage by up to 97% (approximately 2 million cubic meters), compared to mining and refining.

Table 6: Comparison of Li-Cycle's process to mining, per metric ton of battery input

Emissions type	Emissions reduction	Percentage emissions reduction
CO2	117,000 metric tons	40-67%
NO_x	495,000 metric tons	86-89%
SO_x	330,000 metric tons	80-86%

Source: BloombergNEF, Li-Cycle

Li-Cycle's business model also reduces the risk the company faces as the battery industry evolves. The firm is focused on producing battery metals as final products, rather than cathode materials. This reduces the risk that changing cathode chemistries could diminish demand for the company's output.

How mature is Li-Cycle?

Li-Cycle's facility have a combined processing capacity of 51,000 metric tons per year.

Li-Cycle is a mature company that went public in 2021, raising $580 million through its reverse merger with Peridot Acquisition Corp. It has a strong customer network, including more than 200 commercial contracts, including with several of the largest global automakers and battery manufacturers for its battery feedstock supply. Its technology is at a commercial-scale in its existing Spoke facilities in Ontario, Arizona, New York and Alabama. Additionally, it has partnerships with LG Chem/LG Energy Solution, Glencore, KION Group and several other global lithium-ion battery participants.

Li-Cycle has four operational Spoke facilities with a total 51,000 metric tons/year processing capacity in North America. In 2023, it plans to expand its total processing capacity across its Spoke network to 81,000 metric tons/year, boosted by its Spoke facility in Germany which will commence operations.

The company also aims to commence commissioning of its first commercial Hub facility in Rochester, New York, where it will process black mass into battery-grade materials. This Hub is designed to have a processing capacity of 35,000 metric tons of black mass per year, which is equivalent to the materials used to manufacture approximately 18 gigawatt-hours (GWh) of lithium-ion batteries.

Li-Cycle recently entered into a conditional commitment with the U.S. Department of Energy (DOE) for a loan of $375 million through its Advanced Technology Vehicles Manufacturing

Program, in support of the Rochester Hub. This strategic financing provides increased financial flexibility to fund Li-Cycle's future global growth plans.

3.3. Nth Cycle

Table 7: Nth Cycle company details

Name	HQ	Founded	Funding	Technology
Nth Cycle	US	2019	$19.3 million	Electroextraction for lithium-ion battery recycling

Source: BloombergNEF, Nth Cycle

Why is innovation needed in metals processing?

Recovering the metals from batteries is important, and BNEF expects that by 2035, there will be over five million metric tons of batteries available for recycling. Currently, hydrometallurgy is the preferred method of battery recycling in Europe, the US and by more environmentally-conscious recycling companies in China. It is increasingly being used in other regions as well. The process has its drawbacks, however, such as the production of chemical waste from the use of acids and bases to extract materials from batteries. Similar shortcomings exist in metals refining. Novel methods for processing various feedstocks are being explored to increase the potential supply while lowering negative environmental impacts and potentially costs. For more information, see *Lithium-Ion Battery Recycling Market Outlook* (web | terminal).

What is Nth Cycle's technology?

Nth Cycle uses electroextraction to process black mass and create battery cathode precursor material.

Nth Cycle has developed a proprietary process, called electroextraction, to process black mass – i.e. the material from shredded batteries that contains many of the valuable battery metals. The black mass is processed to create nickel mixed-hydroxide precipitate, a battery cathode precursor material.

Electroextraction combines multiple separate processing techniques including electrowinning, chemical precipitation and filtration into a single compact and modular unit. To do this, the core technology uses a porous electrode material to increase the effective electrode surface area. This allows for a flow-through system that can dramatically increase throughput per unit time and area, thereby significantly lowering capital costs.

Why is Nth Cycle a Pioneer?

Nth Cycle is developing a new critical-metals recycling technology that, if successful, could impact the scrap recycling and mining industries in the long term. One of the company's advantages is that its process can refine critical minerals from conventional and unconventional sources, or feedstock. These sources range from end-of-life batteries, to metal ore from mining, to slag from steel production. Combined with the technology's modular design, which allow the equipment to be placed at the site of the customer, the wide range of usable feedstocks expands the range of customers who can utilize the company's technology.

Nth Cycle's process has 92% lower emissions than traditional mining and refining processes and 44% lower emissions than more mature critical mineral recycling technologies. The company says it can directly mitigate 5.2 $GtCO_2e$ in emissions cumulatively by 2050 by reducing the embodied emissions of nickel compared with pyrometallurgy and hydrometallurgy.

How mature is Nth Cycle?

Nth Cycle's process has a wide range of usable feedstocks.

Nth Cycle is currently at commercial deployment scale and expects rapid growth given the market demand for critical metals. Nth Cycle's technology has been developed for over five years, and the process and system have been vetted by a third party for emissions reduction potential. The company raised $12.5 million in a Series A round in 2021.

4. Challenge 3: Building a net-zero food production system

The production of food is essential, but unlike the energy and transport sectors, which now have mature decarbonization technologies, the agriculture industry lacks a cost-effective pathway to reduce greenhouse gas emissions and environmental impacts. Agricultural emissions account for at least 23% of annual CO2 emissions. The agriculture sector is driving large-scale changes in the carbon, nitrogen and phosphorous cycles, and the sector will need to learn to produce more food on less land. For more information, see Sustainable Agriculture: The New Green Revolution (web | terminal).

This chapter covers the three winners of this challenge which look to create a more sustainable agriculture system.

4.1. FutureFeed

Table 8: FutureFeed company details

Name	HQ	Year founded	Funding	Technology
FutureFeed	Australia	2020	$19.4 million	Feed supplement to reduce ruminant methane emissions

Source: BloombergNEF, FutureFeed

Why is innovation needed for enteric methane emissions?

Animal farming accounts for around half of greenhouse gas emissions from farms, according to FAOSTAT. Enteric fermentation is the cause of the majority of animal farming emissions, contributing 2.8 gigatons CO_2e. Methane is produced as a byproduct of enteric fermentation, a digestive process found in ruminant animals such as cattle, sheep, goats and buffalo. Enteric fermentation means that proteins and fats products derived from ruminants are carbon-intensive.

Asparagopsis can be used as a feed supplement to reduce enteric-methane emissions by 80% or more.

The most impactful strategy for lowering the emissions footprint of meat and dairy would be to substitute for other products derived from plants, non-ruminant animals, or produced in an artificial setting. These low-carbon alternatives have yet to meaningfully displace ruminant products, so solutions that abate emissions from ruminants will play an important near-term role. Technologies that reduce the levels of emissions produced by animals have the potential to impact emissions trends without requiring significant changes to food consumption patterns. For more information, see *Tech Radar: Decarbonizing Beef and Dairy Production* (web | terminal).

What is FutureFeed's technology?

FutureFeed holds the rights to the patent for reducing methane emissions using Asparagopsis, a red seaweed that produces a bioactive chemical called bromoform. Asparagopsis can be used as a feed supplement for cattle to reduce enteric-methane emissions by 80% or more. The seaweed works because the bromoform is structurally analogous to methane and inhibits one of the proteins in the methane production process. Adding five grams of the feed ingredient in its freeze-

dried form per kilogram of dry food is enough to have the desired impact. FutureFeed does not produce the seaweed itself but licenses independent seaweed growers (Figure 7). The nine licensees to date are turning the seaweed into a feed supplement that can be given to cattle and sheep.

Why is FutureFeed a Pioneer?

Few interventions for methane emission from cattle are available today, and of the ones that are being commercialized, the bromoform in FutureFeed's seaweed produces the highest emissions reduction. The 80% emissions reduction is higher than reduction from competing feed supplements (Table 9), and one of the licensees hopes to reach 150 million cattle by 2030.

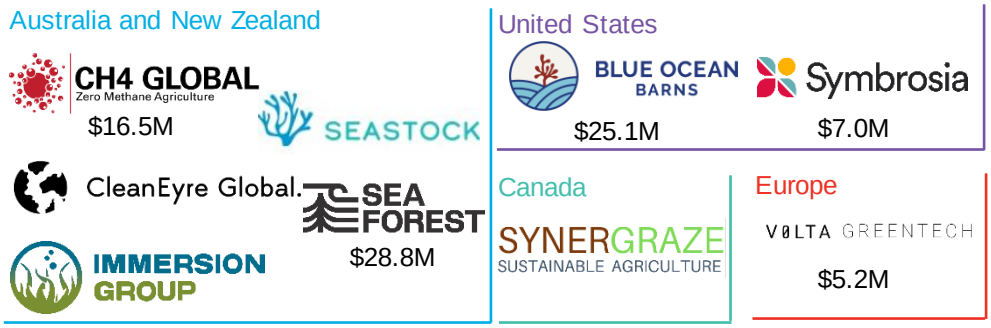
The feed supplement also has other potential benefits to the farmer. The seaweed may also make the cattle more productive as cattle currently lose as much as 12% of energy intake to methane production. Studies are underway to validate and quantify this effect.

Table 9: Efficacy of dairy cow feed additives on reducing methane emissions

Feed additive	Methane reduction
Bromoform	45-99%
3-NOP	25-90%
Tannins	13-30%
Saponins	7-23%
Essential oils	8-22%

Source: BloombergNEF, Global Warming and Dairy Cattle: How to Control and Reduce Methane Emission, DSM. Note: Data are from academic studies, and results seen in the field may vary.

Figure 7: FutureFeed's licensees by location and disclosed funding



Source: BloombergNEF, FutureFeed, CB Insights. Note: Data as of February 8, 2023.

How mature is FutureFeed?

FutureFeed was spun out of the Commonwealth Scientific and Industrial Research Organisation, an Australian government agency, in 2020 to commercialize the seaweed feed supplement. The feed ingredient has been subject to various scientific studies, and FutureFeed says ten peer-reviewed studies since 2016 demonstrate its efficacy. The company is currently working on a digital tool for the measurement and verification of methane emissions reductions from use of the feed ingredient.

The supplement has received different types of regulatory approvals in different jurisdictions. A freeze-dried product and an oil-based product received regulatory approval in Australia, and CH4 Global, one of the licensees, completed the first commercial sale of a feed product in June 2022. Asparagopsis is also approved for sale in California and the EU.

A proof-of-concept project for FutureFeed's 'Farmed to Lower Methane' trademark is about to start and will be used on consumer products including red meat, dairy products, wool and leather. FutureFeed plans to operationalize use of the trademark by 2024.

4.2. MicroHarvest

Table 10: MicroHarvest company details

Name	HQ	Year founded	Funding	Technology
MicroHarvest	Germany	2021	$9 million	Microbial fermentation of proteins

Source: BloombergNEF, MicroHarvest

Why is innovation needed in alternative proteins?

Microharvest uses microbial fermentation to grow proteins.

Alternative proteins are an important part of the transition to a low-carbon food system. Animal farming produces greenhouse gas emission through enteric fermentation, manure and land use change. Even with improved farming practices, eliminating all emissions from animal farming is difficult.

Many new and established companies are attempting to develop viable technologies that produce low-carbon proteins at scale, though there is no clear front-runner. With lower emissions, land use and water usage, alternative proteins have multiple environmental benefits. For more information, see *Alternative Proteins: Fake It Till You Make It* (web | terminal).

What is MicroHarvest's technology?

MicroHarvest uses microbial (or biomass) fermentation to grow proteins from bacterial strains in a growth medium inside a bioreactor. The company grows bacteria that are 60-79% protein, using its own bacterial strain and growth medium made of sugar derived from agricultural and food byproducts. A fermentation process allows for exponential growth of biomass, which is then separated and harvested from the cells. Selective breakdown and dehydration of the biomass increases the final protein's stability and shelf-life. The resulting powder is added to feed, pet food and human food as a nutrient-dense protein source.

Why is MicroHarvest a Pioneer?

MicroHarvest believes its product reduces land use by 99% and CO_2 emissions by more than 70%.

MicroHarvest's microbial fermentation can significantly reduce emissions. From a preliminary lifecycle analysis, MicroHarvest believes its product reduces land use by 99% and CO_2 emissions by more than 70%, relative to beef-derived protein. Through process optimization and intensification, it expects the latter to increase to more than 80% by 2028. Moreover, the flexibility of MicroHarvest's process to alter the type of sugar input and use byproducts from other industries also reduces its overall emissions footprint.

MicroHarvest's technology is also an improvement over other alternative protein technologies. The company says that its aerobic production process is more efficient than those that work in an anaerobic environment and less energy intensive than producers using CO_2 or methane as a feedstock. It also produces its food output on daily rather than monthly or annual cycles, boosting food supply resiliency compared to its competitors.

How mature is MicroHarvest?

MicroHarvest completed bench- and pilot-scale tests in 2021-2022. The company scaled to a production rate of 300 kilograms per day in 2023, with successful application tests for shrimp feed proving deployment in an operational environment. Having these verified results, MicroHarvest expects to begin its first commercial deployment of extract in Q4 2023. The company is focused on producing proteins for animal feed first, thereby avoiding the loop of catching fish to feed fish

and providing non-animal-based ingredient for pet food. MicroHarvest plans to produce proteins for human consumption in a couple of years.

4.3. Precision AI

Table 11: Precision AI company details

Name	HQ	Founded	Funding	Technology
Precision AI	Canada	2018	$16 million	Fixed-wing drones for precision herbicide application

Source: BloombergNEF

Why is innovation needed in pesticide application?

The agriculture sector has many environmental impacts. In addition to accounting for a quarter of global carbon emissions, the sector is a leading driver of biodiversity loss, as well as nitrogen and phosphorus pollution. One cause of this is pesticide usage. An estimated 95% of herbicides reach a destination other than the target species.[1] This is a major driver of extinction for insects, which provide essential pollination services to 75% of crops. Innovations are needed to avoid the overapplication of pesticides, thereby lowering adverse biodiversity impacts and emissions. For more information, see *Technology Radar October 2022: Precision Agriculture* (web | terminal).

What is Precision AI's technology?

Precision AI's drones reduce herbicide usage by up to 95%.

Precision AI sells a fixed-wing drone for crop spraying (Figure 8). The drone is equipped with cameras, and the company has developed software so that the drone can autonomously fly over fields, identify weeds and accurately apply herbicide. By applying herbicide only to weeds, rather than all crops, usage is reduced by up to 95%.

Figure 8: Precision AI's fixed-wing drone

Source: Precision AI

[1] Hendrichs, J. et al, Area-wide Integrated Pest Management, Development and Field Application, CRC Press, 2011.

Why is Precision AI a Pioneer?

Precision AI's drone has a dual sustainability benefit. First, it reduces the use of herbicide by up to 95%, as only areas where weeds are identified are sprayed (as opposed to the traditional process of blanket applications). This reduces chemical production and protects the health of the environment surrounding the farm. Second, the use of drones, rather than on-ground vehicles, to apply pesticides reduces soil compaction on farms. Reduced soil compaction leads to increased crop yields and thus reduced land-use per calorie produced.

Precision AI's drones reduce soil compaction, which in turn reduce land-use per calorie produced.

BNEF estimates that a 95% reduction in the use of pesticides and a 6% increase in yield through reduced soil compaction (resulting in lower land-use emissions) would amount to approximately 70 $MtCO_2e$ in emissions reductions annually. The likelihood of adoption for the technology is high. Big-acre farms have been keen adopters of digital technology to boost crop yields, and Precision AI makes a convincing business case with its proposed costs and benefits.

How mature is Precision AI?

Precision AI says it has received deposits on orders worth $6 million in a pre-order campaign. The company aims to have 24,000 acres under management by 4Q 2024 and 100,000 acres under management by 4Q 2025. The company raised $16 million in 2021.

5. Wildcards

Each year, BNEF Pioneers looks for wildcard applicants. These companies are developing technologies to address other challenges in the transition to a net-zero future. This year's BNEF Pioneers wildcards winners are innovating in the fields of steel, cement and carbon removal.

5.1. Electra

Table 12: Electra company details

Name	HQ	Year founded	Funding	Technology
Electra	US	2020	$85 million	Low-carbon iron production for steelmaking

Source: BloombergNEF, Electra

Why is innovation needed for steel production?

Steel is the most widely used metal in the world and essential in buildings, infrastructure, vehicles, tools and packaging. The sector accounts for 8% of global emissions and almost 30% of industrial emissions. Despite slowing demand in China, steel production will continue to rise to serve growing economies in India and Southeast Asia.

Iron is the biggest component of steel and its greatest source of emissions. Iron ore is processed at high temperatures to remove impurities and oxygen. In direct reduction-electric arc furnaces (DR-EAF), one of two primary steel production processes, iron-making accounts for 41% of energy consumption and around 90% of CO_2 emissions. Decarbonizing steelmaking will be expensive. Doing it by 2050 will require an additional capital expenditure of $278 billion. It involves the use of new green fuels for high temperature heating, increasing the use of recycled scrap, creating new production pathways and/or the use of carbon capture. Innovation is needed to lower costs and create technologies that can be easily adopted in the industry. For more information, see *Decarbonizing Steel: Technologies and Costs* (web | terminal).

What is Electra's technology?

Electra has developed an aqueous electrolysis process to refine lower-grade iron ore into high purity iron plates at low temperatures (approximately 60°C) using low-cost intermittent renewable power to eliminate emissions from ironmaking.

Electra produces low-carbon, high-purity iron that can be used for steelmaking.

Electra produces its zero-carbon iron by leaching iron ore with an acid. It then uses an electrochemical process on this acid solution to electroplate iron, creating plates of iron which will be sold as Electra's product. This low-temperature iron can then be fed into electric arc furnaces to manufacture steel. The electric arc furnace is already a mature technology that is used to recycle scrap steel. Electra's innovation is for producing iron.

Why is Electra a Pioneer?

Electra's iron-making process does not use fossil fuels as a chemical reactant and so it can be powered solely by zero-carbon electricity. Its process would save about 1.4 tCO_2e per ton of iron if benchmarked with current mainstream coal-based ironmaking process.

Additionally, Electra's process has advantages over other decarbonization technologies for steel. The process takes place at 60°C, which means it can efficiently ramp up and down, making it easier to integrate with low-cost renewable power. It is also particularly suited for processing more abundant low-grade iron ore, which would alleviate a constraint in metals demand. This is a key differentiator from H_2 direct reduction, another decarbonization pathway for steel production.

How mature is Electra?

Electra is currently scaling from lab to pilot. The company has demonstrated the success of its process in a lab, producing iron plates of 400 cm^2 in area. It is aiming to construct a pilot plant in 2023 that will produce plates that are 1 m^2 in area. Additional plans include building a demonstration plant with a renewable energy partner in 2025 and commissioning its first commercial-scale deployment in 2027. Electra plans to build small modular factories co-located with iron ore mines, rather than the large integrated factories that are common in steel production today.

5.2. Sublime Systems

Table 13: Sublime Systems company details

Name	HQ	Year founded	Funding	Technology
Sublime Systems	United States	2020	$50 million	Electrochemical production of lime for cement making

Source: BloombergNEF, Sublime Systems

Why is innovation needed for cement production?

Cement production is responsible for 8% of global emissions.

Cement production is responsible for 8% of global emissions. Cement is currently made by heating limestone above 1,400°C using coal, gas or waste plastic as fuel. In addition to the emissions from the fuel needed to reach that high temperature, there are direct emissions that the limestone produces CO_2 when it decomposes into lime – a key step in cement production. BNEF believes cement demand will rise from four billion tons today to almost six billion tons by 2050, so abatement technologies are needed to avoid rising emissions (Figure 9). Decarbonizing cement is difficult because alternative green fuels for providing the high temperatures required are limited,

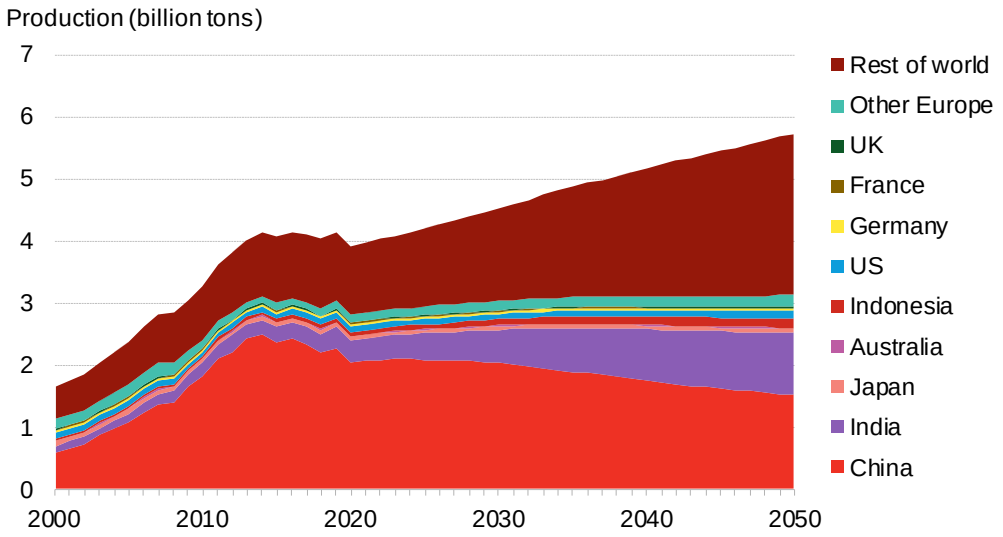
and avoiding the direct emissions from limestone decomposition requires expensive equipment replacements. For more information, see *Tech Radar: Low-Carbon Cement* (web | terminal).

What is Sublime Systems' technology?

Sublime Systems's electrochemical process replaces the fossil fuel-intensive part of cement production.

Sublime Systems is decarbonizing cement production by using an electrochemical process, powered by zero-carbon power. It produces lime (calcium hydroxide) from materials other than limestone, avoiding both the CO_2 process emissions and the heating emissions. Sublime replaces the industry's legacy kilns – the most energy- and fossil fuel-intensive part of the traditional cement manufacturing process – with an electrochemical process that makes cement at ambient temperatures. Sublime's system uses feedstock containing calcium and adds it into a process where one electrode forms a low pH liquid that dissolves calcium and extracts it from whatever feedstock to which it is bound, and a second electrode produces an alkaline solution where the calcium precipitates. This calcium is now reactive and can perform to the standards of traditional cement. The final product is a drop-in cement replacement for ready-mix concrete.

Figure 9: Cement production, by region



Source: BloombergNEF

Why is Sublime Systems a Pioneer?

Cement's emissions are roughly 0.8 tCO_2 per ton of cement. If Sublime captures its target of 90% of the market by 2050, it will abate up to 3.4 billion tCO_2 per year. The emissions reduction is due to Sublime's technology shifting a thermal process to an electrochemical one. The electrical process does not require high heat and can be run on renewable energy.

Additionally, Sublime's product is chemically identical to today's cement, which is important as there is no benefit to having a differentiator in the cement market. Above all else, buyers want a cement that is the same as what they use now, so there is no risk to a project's safety and no extra steps in design to accommodate a new material. Sublime produces cement with a different feedstock and process route but produces the same final product.

Sublime System's product is chemical identical to today's cement.

Finally, because it can use multiple feedstocks, Sublime's process could help to mitigate the effects of mining on local environments by choosing minerals that are easier to extract such as calcium or available as byproducts of other mines. Sublime can use calcium-silicate rocks or traditional limestone as feedstock. If using the former, this avoids process emissions altogether. If using the latter, this releases a high purity stream of CO_2, which can be more easily and cheaply captured.

How mature is Sublime Systems?

Sublime is currently operating a pilot plant that can produce 100 tons of cement per year. Sublime recently raised a $40 million Series A to ramp up production at its pilot plant, conduct product testing with customers, secure offtake agreements and prepare for the construction of a larger plant. With this funding, Sublime will build a demonstration-scale plant capable of producing up to 40,000 tons of cement per year, which is expected to be commissioned by 2025. At that point, Sublime will be able to fill silos with its cement, which is the minimum quantity needed for ready-mix concrete suppliers to start using Sublime Cement™ commercially. The company has raised a total of $50 million from well-established climate investors including Lowercarbon Capital, Energy Impact Partners, Prime Impact Fund and The Engine.

5.3. Travertine

Table 14: Travertine Technologies company details

Name	HQ	Year founded	Funding	Technology
Travertine	US	2022	$3 million	Electrochemical carbon removal and acid production

Source: BloombergNEF

Why is innovation needed for carbon removal?

Meeting net-zero targets will first and foremost require rapid and deep emissions reductions. But it is becoming increasingly clear that removing carbon dioxide from the atmosphere will also be needed to avoid global warming above 1.5°C. With industrial emissions, for example, carbon removal will be needed to capture the remaining 10% of emissions that evade point-source carbon capture systems. While it is clear that carbon removal is necessary, there are many technologies that could potentially serve this demand, all with various advantages and disadvantages, and no technology has reached mass adoption. For more information, see *Climate-Tech Innovation: Scaling Carbon Removal* (web | terminal).

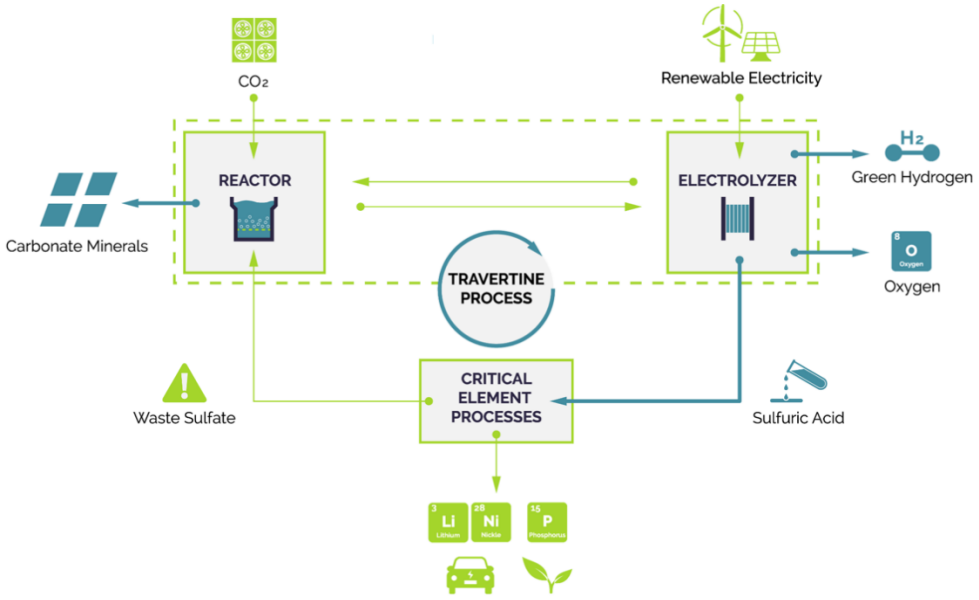
What is Travertine's technology?

Travertine uses sulfate wastes to produce a base for carbon removal and an acid for extractive industries.

Travertine has developed a novel electrolysis process that uses sulfate wastes from mining and fertilizer production as inputs to generate an acid and a base (Figure 10). Carbon dioxide is captured from the air using an air contactor charged with base produced in the electrolyzer. The acid can be used in extractive industries or to create more feedstock for the process.

Water is electrolyzed in the presence of sulfate waste produced during critical mineral extraction or mine tailings leaching, producing sulfuric acid (H_2SO_4) and a base (a hydroxide). The hydroxide serves as a sorbent for carbon removal. It is put into an air contactor where it reacts with atmospheric CO_2, forming a carbonate solution. The solution reacts with the sulfate waste to precipitate solid carbonate minerals that permanently sequester the CO_2.

Figure 10: Example process diagram of Travertine's technology



Source: Travertine

Demand for sulfuric acid is set to increase as it is a key input for mining processes and fertilizer production.

The H_2SO_4 meanwhile has multiple uses. In mining and fertilizer industries, the acid can be used in leaching processes to extract critical elements like lithium and phosphorus, simultaneously producing new sulfate waste to feed back into Travertine's process. In dedicated carbon removal projects (only necessary once the process scales to multi-hundred million tCO_2 scale), the acid is neutralized on mine tailings to produce new sulfates and simultaneously extract residual metals like nickel.

Why is Travertine a Pioneer?

Travertine's carbon-removal technology has several factors that position it well to succeed as a carbon removal technology. Firstly, Travertine's process produces sulfuric acid as a byproduct. Demand for sulfuric acid is set to increase in the coming decades as it is a key input for mining processes and fertilizer production. Supplies of sulfur are simultaneously set to decline as most sulfur is sourced from desulfurization processes in oil refineries. Travertine's process could therefore alleviate a supply shortage of a key material.

Secondly, the cost of Travertine's carbon offsets can be subsidized through the sales of sulfuric acid to industrial consumers. Based on historical prices of sulfuric acid, Travertine could generate $160-$490 in revenue per tCO_2 removed from the atmosphere. This could, however, go higher. Today's acid prices are effectively subsidized because sulfur is produced as a byproduct of oil refining. There are also many new technologies for solving the energy transition that could use acid as a process input, boosting demand for the product. Jetti Resources and Electra, for example, use acid for their processes, though it is not necessarily sulfuric acid.

Finally, Travertine's process removes many of the costliest steps of carbon removal when compared with direct air capture. The hydroxide used in Travertine's process as a sorbent for carbon is akin to the amine materials that are used to strip carbon from the air in direct air capture plants operated by companies such as Climeworks. But because the hydroxide is cheap, new

material can be used and discarded without regenerating the sorbent to be used again. Regeneration is often the most energy-intensive step of other carbon-removal processes. Travertine can also avoid the need to transport and store supercritical CO_2 by storing the CO_2 in solid carbonate minerals.

How mature is Travertine?

Travertine's carbon removal is subsidized through acid sales and avoids costly steps.

Travertine is an early-stage company. The technology was developed at the University of California, Berkeley, and the company has funding from ARPA-e, Grantham Environmental Trust, Clean Energy Ventures Fund and Bidra VC. Travertine expects to reach commercial scale by 2028 and aims to deploy four plants by 2030. This timeline is behind other leading carbon removal companies by a few years. Travertine has received a pre-purchase agreement from the Frontier Climate Fund, a leader in serving as a validating customer for carbon-removal startups.

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