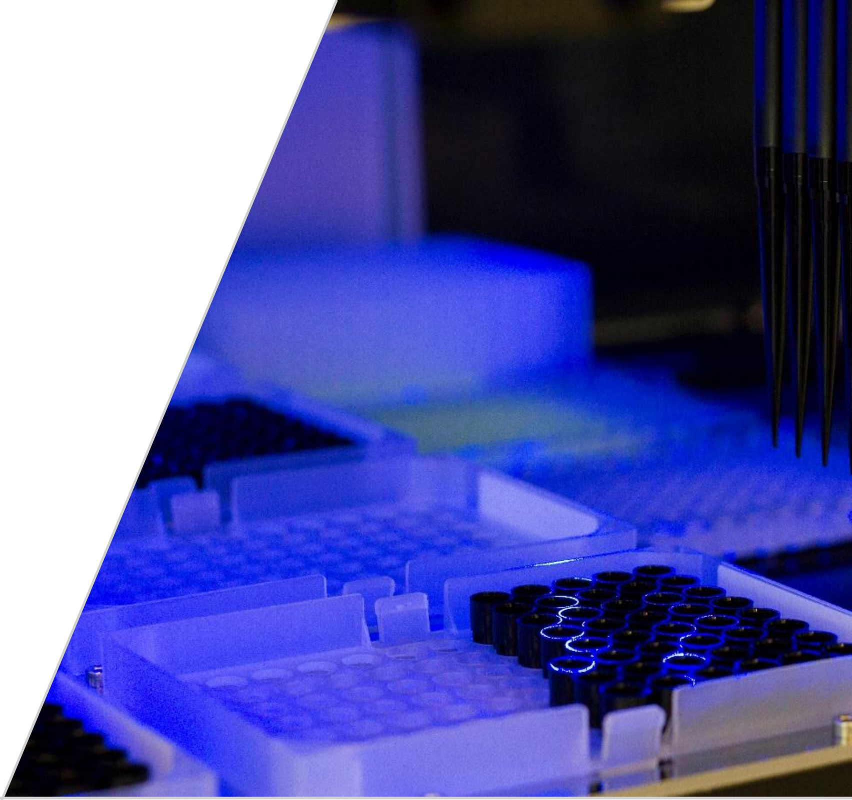

# Advancing Sustainable Materials

## A Climate Technology White Paper


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May 27, 2021

BloombergNEF

# Contents





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# Advancing sustainable materials: an introduction

# Introduction

## Advancing sustainable materials

In this paper we show that there are some important, urgent challenges to decarbonizing materials and products.

Specifically we analyze technology innovations, and the early-stage companies developing them, that would contribute significantly to tackling these problems:

1. **Carbon utilization:** How can we use captured carbon as a feedstock for materials such as concrete and chemicals? (pages 8-14)
2. **Leveraging underutilized biomass:** How can we turn abundant and non-food biomass like wood, waste and algae into useful materials? (pages 15-21)
3. **Closing the loop:** How can we produce virgin-grade material from recycled plastics and batteries? And how can we better track and sort waste? (pages 22-29)

This paper provides data and context on the challenges, evaluates some of the proposed innovations and suggests ways to overcome potential blockers. We highlight 52 startups that are leading the charge in these areas. The final section outlines venture capital investment trends for each of the three technology gaps.

## BNEF Pioneers: hunting for innovation

This is one of three reports to be published following the 2021 BNEF Pioneers awards.

BloombergNEF's annual Pioneers competition identifies and recognizes innovators developing new technologies to tackle some of the most important challenges in the fight against climate change.

Each year, the Pioneers competition focuses on three innovation challenges.

In 2021 the challenges are:

1. Optimizing commercial freight (research note available here)
2. **Advancing sustainable materials (the focus of this research note)**
3. Monitoring and understanding our changing planet (research note available here)

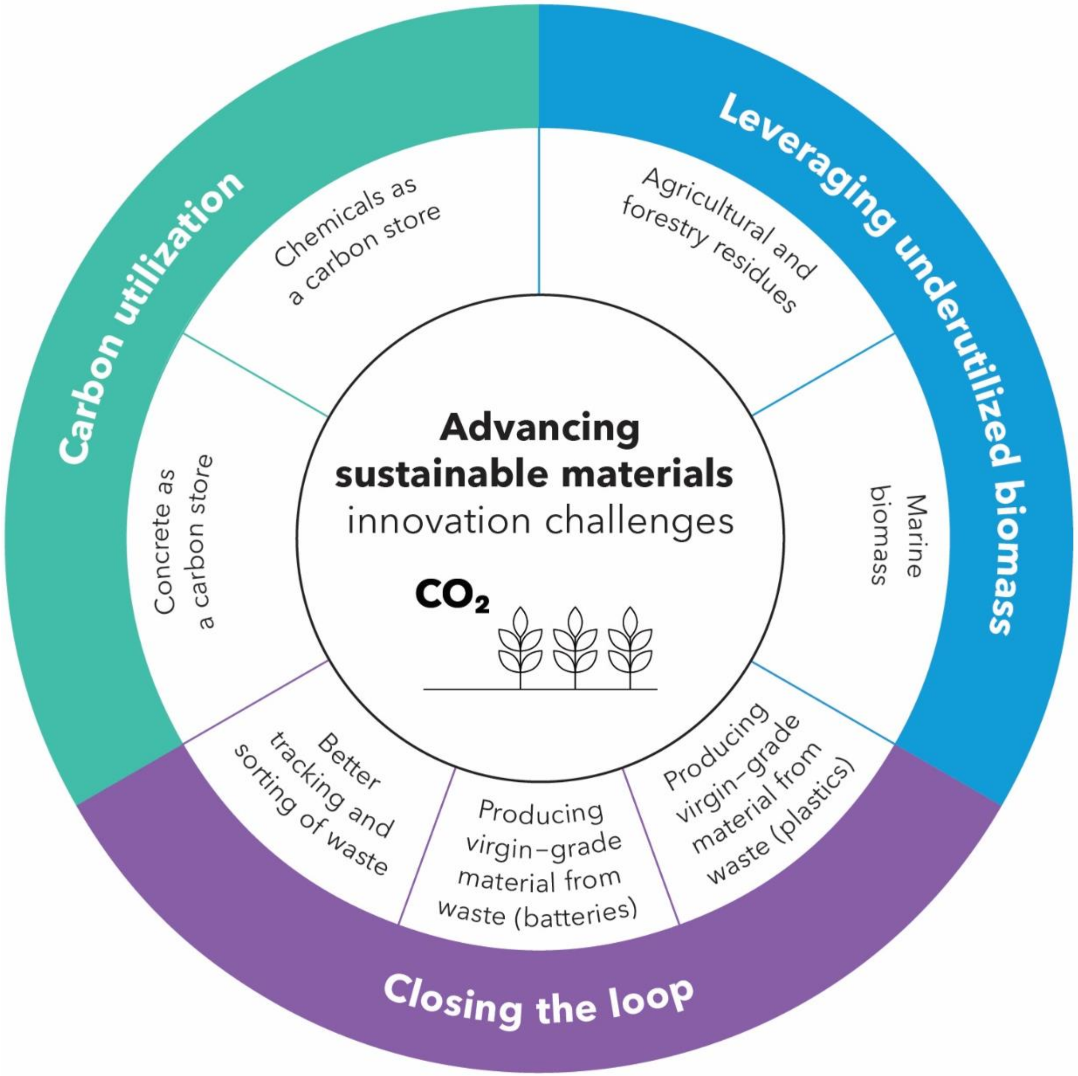
For more information about the Pioneers competition, please visit https://about.bnef.com/bnefpioneers/

# Challenges in making sustainable materials

While the adoption of renewable power and electrification are decarbonizing the economy, our reliance on carbon-intensive materials remains a significant challenge with few easy solutions. Finding sustainable feedstocks is a major challenge in the transition to a net-zero economy.

This report highlights three innovation areas that hold great potential to increase the availability of sustainable feedstocks:

- **Carbon utilization:** Many climate-safe scenarios include negative emissions technologies (NETs) to complement the rapid adoption of low-carbon technologies. The economics of carbon capture remain challenging, but carbon dioxide utilization could support the market for carbon capture and NETs. Converting or trapping CO2 in concrete and chemicals are two prime opportunities.
- **Leveraging underutilized biomass:** Less than half of today's bioenergy is considered sustainable because much of the supply comes from food sources. Other forms of biomass may drive increased land use or deforestation. Finding ways of economically leveraging sustainable biomass resources such as residues, waste and marine biomass could unlock new low-carbon energy and material resources.
- **Closing the loop:** Using a greater share of waste streams as feedstocks is another path to making more sustainable materials. Closing the loop will help reduce the emissions intensity of materials while at the same time preventing ecosystem degradation from raw material extraction and discarded waste. New chemical processes and digital technologies can help boost recycling yields and reduce waste going to landfill.

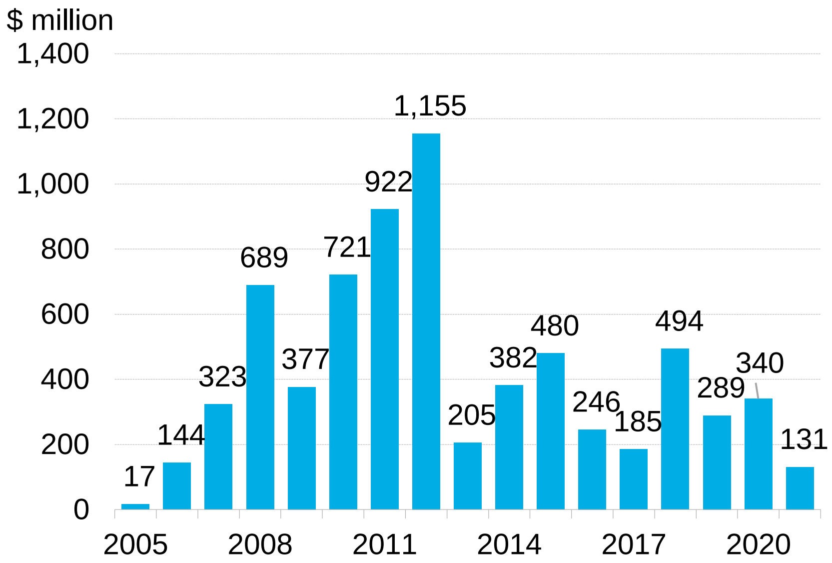


# Companies and funding

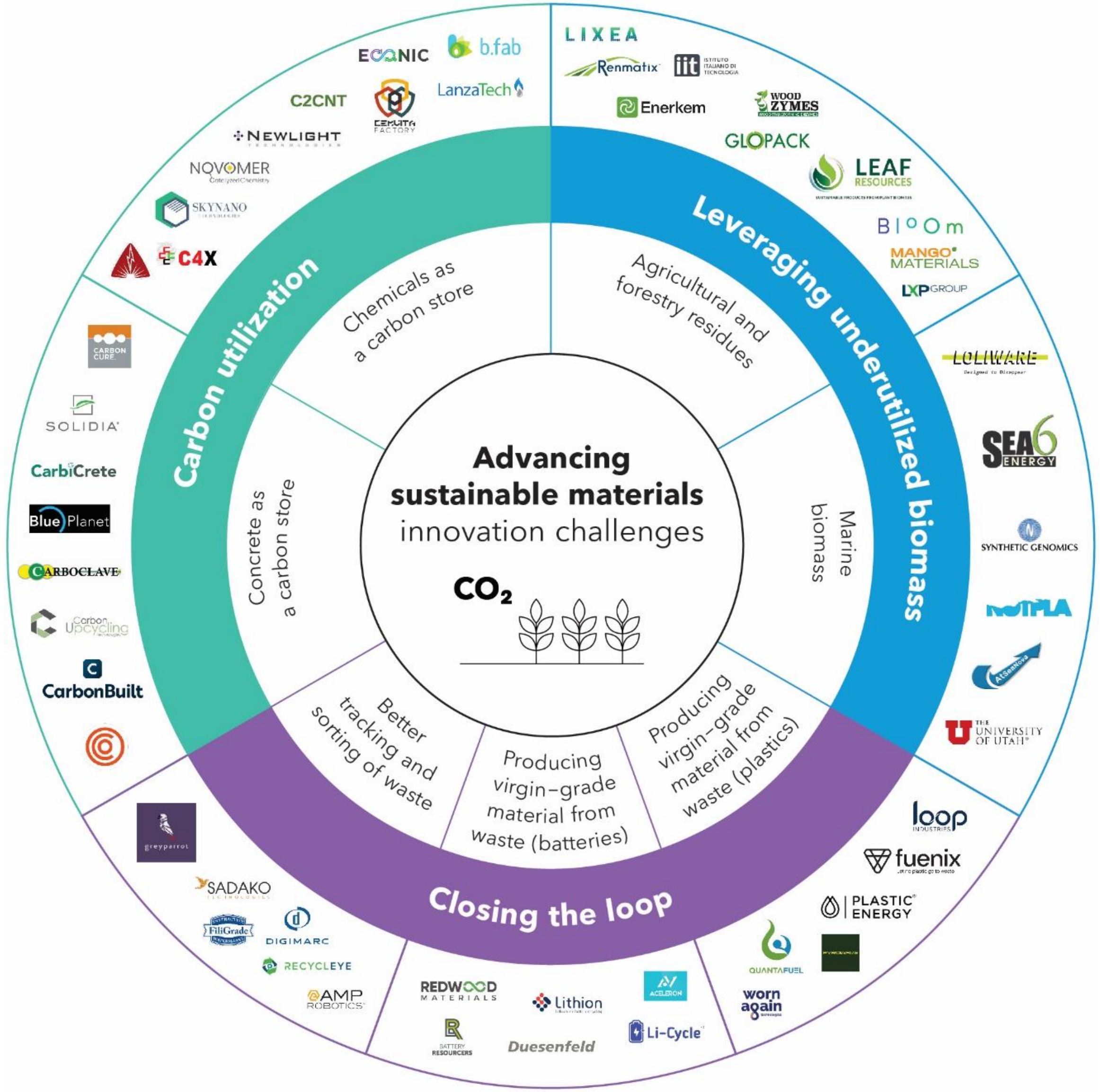
BNEF has identified 104 startups developing technologies in carbon utilization, underutilized biomass and closing the loop. Since 2005, these startups have raised a total of $7.1 billion, with 80% of this investment flowing into bio-based technologies. This is largely due to the maturity of bio-based materials as a sector compared with carbon utilization and recycling.

In this white paper, we profile 52 startups developing these technologies and highlight distinctive characteristics of their business or products.

## VCPE raised to advance sustainable materials (2005 – 1Q 2021)




*Source: BloombergNEF, CB Insights*



# BNEF Pioneers 2021 Winners

## Challenge 2: Advancing materials and techniques for sustainable products

**Tackles the challenge of carbon utilization**

Cemvita Factory engineers microbes that produce precursors for polymers/plastics using carbon dioxide or methane as feedstock. With this, it enables the production of carbon-negative polymers and plastics.

**Tackles the challenge of closing the loop**

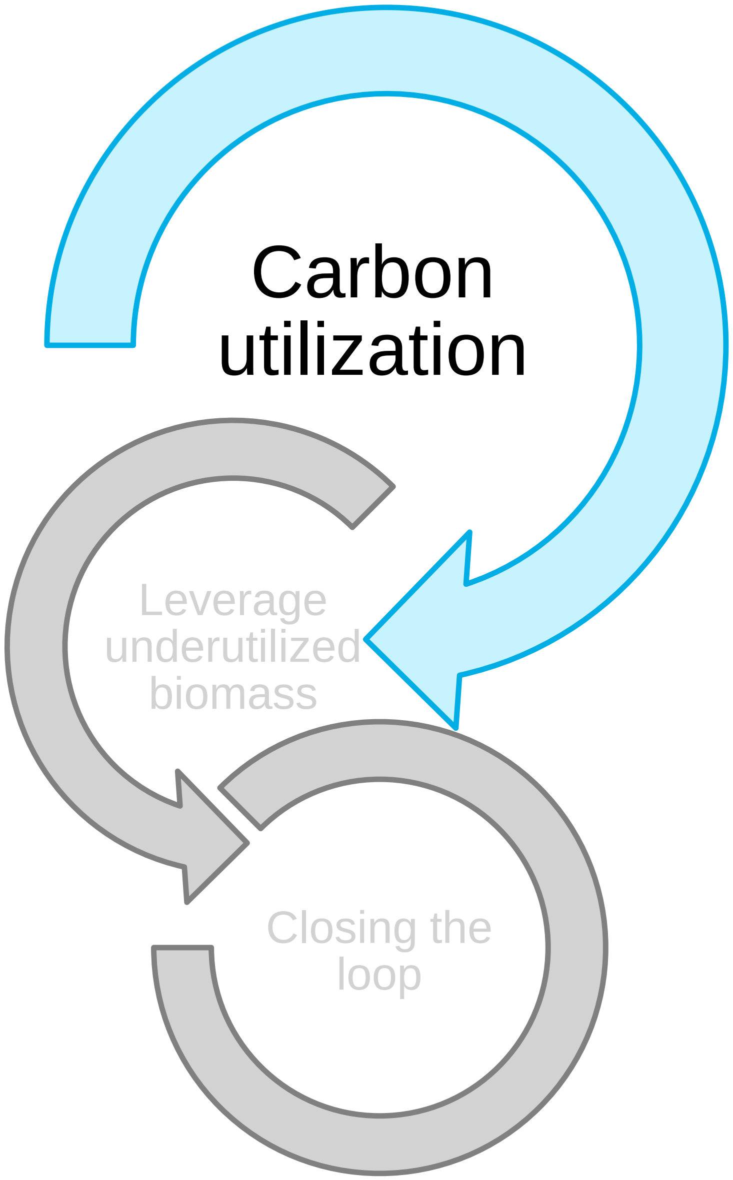
Pyrowave builds equipment that is able to chemically recycle plastics. The pyrolysis technology is able to break plastic down into monomers which can then be reformed as virgin-grade plastic. Pyrowave's technology is focused on polystyrene recycling.

**Tackles the challenge of reducing energy use in manufacturing**

Via Separations has created a graphene oxide membrane with permeability that can be tuned to separate impurities or unwanted byproducts in chemical manufacturing. Its process requires significantly (90%) less energy than existing techniques, and can be applied across a large number of industries, including chemicals, pulp and paper, and food production.

# Technology challenges

## Advancing sustainable materials


Carbon utilization
Leverage underutilized biomass
Closing the loop

# The challenge of carbon utilization

**While half the world's GDP is now covered by some form of net-zero target, this does not bring us onto a 2°C emissions pathway. The IPCC predicts that negative emissions technologies (NETs) will be essential as the world is unlikely to slow emissions output quickly enough to halt global warming. The economics of carbon capture remain challenging, but carbon dioxide utilization could support the market for carbon capture and NETs. Converting or trapping CO2 in concrete and chemicals are two prime opportunities.**

## How big a problem is it?

86% of the IPCC's 400 climate scenarios that have a 50% chance of limiting warming to 2 degrees rely on NETs. The IPCC estimates that 3.3 GtCO2e may need to be captured annually after 2050. Assuming carbon prices in excess of $100/tCO2e, this translates to a market worth over $330 billion per year. Three of the IPCCs seven high-potential NETs require CO2 to be stored, or used, rather than trapping it in the natural environment (such as absorbed by trees):

- Carbon capture and storage (CCS)
- Direct air capture and carbon storage (DACCS)
- Bioenergy with carbon capture and storage (BECCS)

These technologies have yet to scale, and are expensive. Finding a way to utilize the CO2, creating value for it, might incentivize more CO2 capture.

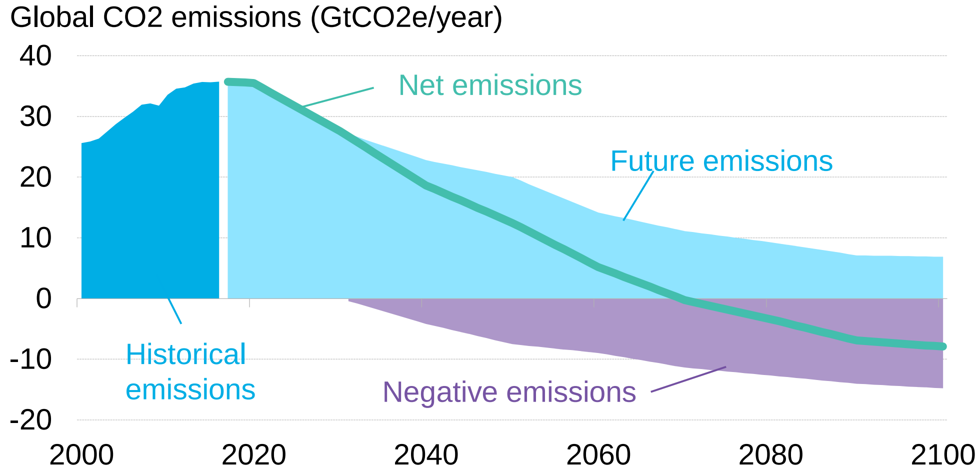
## What should we tackle first?

Large, pure, CO2 streams, such as those from ethanol or gas processing plants, are the easiest and cheapest to capture. If carbon utilization is to scale, then the products it makes should have a large potential market size. This means looking to turn CO2 into bulk commodities, such as chemicals or other materials. However, products most likely to justify a 'green premium', if made from CO2, will be those that are consumer-facing and less price sensitive – that could be smaller volume, higher value specialty chemicals.

## Why is it difficult to solve?

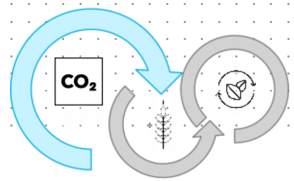
High-volume materials, like concrete and chemicals, offer the greatest opportunity for utilizing carbon. However, these materials are abundant precisely because they are cheap to make. To enable carbon utilization, carbon must first be captured and then additional processes are required to embed it in the product. These processes can require specialized equipment, or additional, expensive inputs, like hydrogen, which add cost. The price sensitivity of these sectors means that policy is needed to enable adoption.

## Slow decarbonization pathways require significant negative emissions to stay within carbon budget




*Source: BloombergNEF, 'The Trouble with Negative Emissions', Anderson and Peters (2016). Note: Adapted from 'The Trouble With Negative Emissions'*

# Concrete as a carbon store




Carbon mineralization is the process by which CO2 turns into a solid mineral. The process has the potential to store billions of tons of carbon in our built environment by trapping mineralized carbon in concrete. Concrete is an ideal carbon store due to the huge volume of material produced and its long lifetime. Higher costs and the need for new building and material standards are hurdles to the adoption of carbon-infused concrete. These limitations could be addressed by creating testing grounds for carbon-infused concrete, through avenues such as government procurement programs.

## New approaches and technologies

There are two main ways of storing CO2 in concrete through the process of carbon mineralization.

**CO2 as curing agent:** CO2 can be used as an input during the mixing of aggregate and cement, either as a strengthening additive, or to reduce the amount of cement needed.

**CO2 as aggregate:** CO2 can be adhered to the aggregate before it is used in concrete. This option has the potential to trap more CO2 per ton of concrete than mineralizing CO2 during the curing or mixing process. This is because CO2 can be stored at quite a high density (up to 44% the weight of the aggregate).

Both of these processes rely on other inputs that react with the CO2 causing it to mineralize. Examples of reactants include fly ash or brines.

## Limitations

**Cost:** Concrete is so widely used because of its low cost. Adding production steps makes it more expensive.

**Flexibility:** Technologies that use CO2 as a curing agent for cement are often only able to produce pre-cast concrete, which is 5-15% of the market.

**Feedstock:** Many of the processes to embed CO2 in concrete also rely on industrial waste streams such as fly ash from coal or steel plants. These waste streams are already highly utilized and would not be available in a future where coal use is eliminated.

**CO2 availability:** CO2 is only captured in small volumes today and many companies developing CO2-based concrete have to pay for manmade CO2 to pilot their technology or wait for the carbon capture industry to scale.

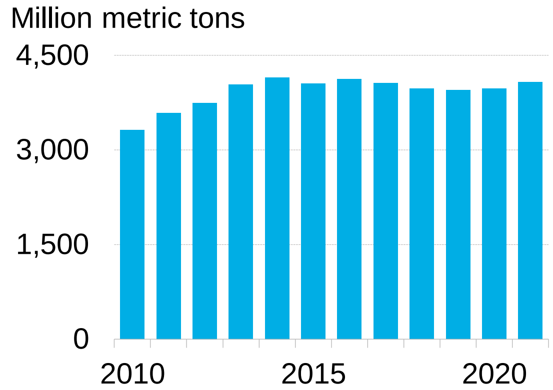
## Potential solutions

**Testing grounds:** Corporate alliances and government procurement policies could provide a fertile testing ground for new concrete mixtures. This would improve confidence in the material.

**Storage efficiency:** Increase the proportion of CO2 in the concrete. CarbonCure’s storage capacity, for example, is only 0.0002 tCO2 for every ton of concrete.

**Cheap carbon:** Cost is the primary concern in producing carbon-negative concrete. Utilizing unpurified carbon streams from flue gas and collocating production with the source of carbon are two methods for reducing costs.

## Global cement consumption




*Source: BloombergNEF, Bloomberg Intelligence, CemNet*

Carbon utilization

# Concrete as a carbon store

## Ready-mix concrete

Carboncure injects $CO_2$ into ready-mix concrete at distributed batch factories. Ready-mix accounts for up to 70% of the concrete market. The technology is also agnostic of $CO_2$ source and does not require waste streams as reactive material. The disadvantage of the technology is that it only stores 0.0002t $CO_2$ per ton of concrete, a fraction of the storage efficiency of other technologies.

## Precast concrete

Solidia's technology cures concrete with $CO_2$ instead of water. It developed its own low-carbon cement substitute that reacts with $CO_2$ to bind concrete.

Carbicrete uses steel slag rather than cement as the binding agent for its concrete. $CO_2$ reacts with the slag to bind concrete.

Carbon Built makes pre-cast concrete blocks that uses carbon from the flue gas of a coal plant as an input. Carbon Built says its concrete has half the carbon emissions of traditional blocks.

## Aggregate coating

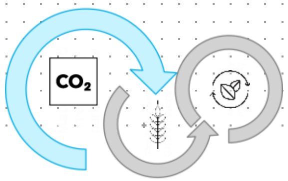
Blue Planet has developed a process whereby ammonium water will absorb $CO_2$ from an emissions point source. This ammonium carbonate water is run over granulated rock and the carbon is gradually deposited in layers over the aggregate. Blue Planet can store 440kg of $CO_2$ per ton of aggregate produced via this method, the highest claimed density of storage of any material discussed.

OCO Technology reacts water, $CO_2$ and industrial waste to produce what it calls manufactured limestone, which can be used as aggregate. The process relies on the reactivity of industrial waste such as fly ash and slag. OCO can store carbon efficiently at rates of up to 250kg of $CO_2$ per ton of aggregate.

## Enhanced fly ash

Carbon Upcycling Technologies embeds $CO_2$ in an enhanced fly ash. This enhanced fly ash can replace a portion of cement in concrete, reducing the emissions intensity of the resultant concrete.

# Chemicals as a carbon store



CO2 can be converted into chemicals, plastics and fuels. These products are unlikely to store carbon for as long as concrete and their storage volume is smaller. However, they can have a higher value than concrete and therefore commercialize carbon utilization with less need for regulation and carbon pricing. Because chemicals, plastics and fuels end up in consumer products (whereas consumers do not directly buy concrete) we think CO2-based versions will be better able to command a 'green premium'. However, the processes are energy intensive and can depend on lower costs for other technologies, such as carbon capture and hydrogen, to become competitive.

## New approaches and technologies

CO2 can be converted to a plethora of industrial chemicals including methanol, ethanol, plastics and fertilizers. CO2 can also be converted into high-value materials such as carbon nanotubes.

**Physical electro-, thermo- and photochemical processes:** These are one of the primary avenues of current research for carbon utilization in chemicals. IP is often based on the catalyst used in the process, which can increase the efficiency of a reaction or create a novel material synthesis route.

**Organic microbial processes:** These are an alternative pathway that have received much funding to date but little success. Some technologies use a hybrid of inorganic and organic processes.

## Limitations

**Smaller market size:** The potential for carbon storage in the chemical market is in the order of one or two million tons of CO2 annually (compared with hundreds of millions of tons in concrete).

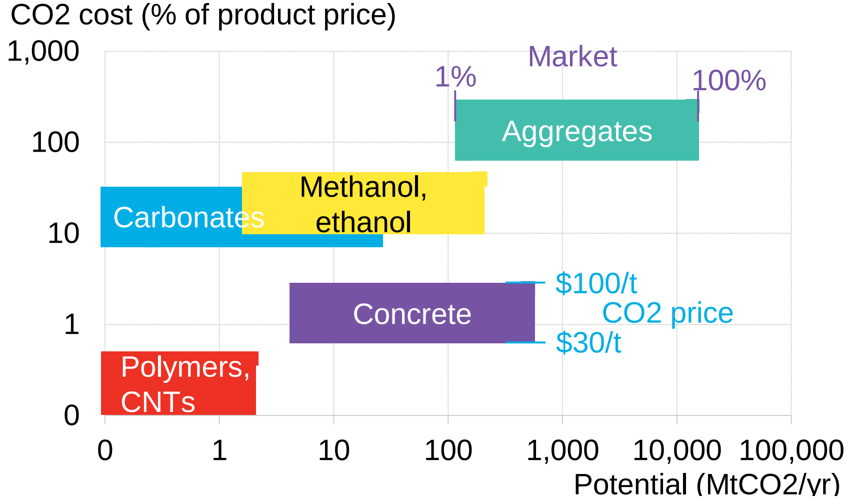
**Clean CO2 source required:** Many technologies for converting CO2 to chemicals are only proven at lab scale and use pure CO2 streams. Catalysts have proven to lack durability and stability at this scale, an issue that would be compounded by the use of industrial CO2 streams.

## Potential solutions

**Ensure resulting products are valuable:** The more value that can be derived from a ton of captured carbon, the more demand there will be for captured carbon. This could be by using large amounts of CO2 to make high volume plastics such as PET or HDPE; or to make smaller volumes of advanced materials like carbon nanotubes that sell for hundreds of dollars per kilo.

**Better catalysts:** Developing catalysts that lower the energy threshold of chemical conversions will make CO2-derived chemicals more competitive, and reduce emissions. Catalysts must also be developed that are more durable and stable.

## Potential CO2 utilization markets and their sensitivity to CO2 prices




Source: BloombergNEF (web | terminal)

Carbon utilization

# Chemicals as a carbon store (physical-chemistry processes)

## Petrochemicals from $CO_2$ using inorganic processes

Around 2010, Novomer developed a process for converting polycarbonate polyols from propylene oxide and $CO_2$. The resulting polyols were 43% $CO_2$ by weight. The firm sold the technology to Saudi Aramco for $75 million in 2016 and has since developed a new catalyst for the production of PHA plastic from ethylene oxide and carbon monoxide.

Econic's catalysts react $CO_2$ with epoxides to make polymers that contain up to 50% $CO_2$ by weight. It can currently produce polyols which are precursors to polyurethane and have applications in foams, coatings, elastomers, sealants and adhesive. Covestro has developed similar technology.

Lectrolyst is developing a two-step electrochemical process to convert $CO_2$ first to carbon monoxide, then to acetic acid and ethylene. The company claims to have the potential to reduce 200 $MtCO_2e$ in emissions if the technology scales globally.

C4X can convert $CO_2$ to methanol and ethyleneglycol. The process relies on hydrogenation and metal-silica nanocomposite catalysts. Its catalyst is highly energy efficient. The process runs at 120-180 degrees rather than the 500 degrees necessary for normal $CO_2$ conversion.

## Carbon nanotubes from $CO_2$ using inorganic processes

C2CNT captures $CO_2$ at a point source to turn it into carbon nanotubes (CNT). Demand for CNT is in the order of thousands of tons annually so unless production from $CO_2$ gets dramatically cheaper this is a relatively small market.

Skynano is also developing the ability to convert flue gas to carbon nanotubes through an electrochemical process. It is currently supported by U.S. DOE funding.

# Chemicals as a carbon store (biochemistry processes)

## Chemicals from CO2 using microbial processes

Lanzatech has developed microbes that consume the flue gas of industrial plants to produce ethanol. The company recently spun off a subsidiary, Lanzajet, that will build facilities for the conversion of ethanol to jet fuel. The project is set to be supplied by Shell's bio-ethanol, however, suggesting its work on carbon capture may be dwindling. On the other hand, it said in September 2020 that it was planning to spin out two new subsidiaries, which could renew its carbon utilization work.

**Lanzatech was named as a BNEF Pioneer in 2012.**

Cemvita Factory develops microorganisms for multiple industrial applications. It has currently identified 30 molecules (chemical intermediates and polymers) it can produce using CO2 as feedstock. It is partnering with Oxy Low Carbon Ventures to convert 1.7 MtCO2e into 0.45 million tons of bio-ethylene annually.

**Cemvita was named as a BNEF Pioneer in 2021.**

Biotech firms have pursued microbial processes for carbon utilization for years. Gingko Bioworks, for example, is a 12-year-old biotech firm valued at over $15 billion. In 2010, it received $6.4 million in funding from Arpa-E to develop e.coli as a mechanism for CO2 utilization. The project ended in cancellation. Joule Unlimited, another example, went bankrupt in 2017 attempting to use cyanobacteria and sunlight to generate fuels from CO2.

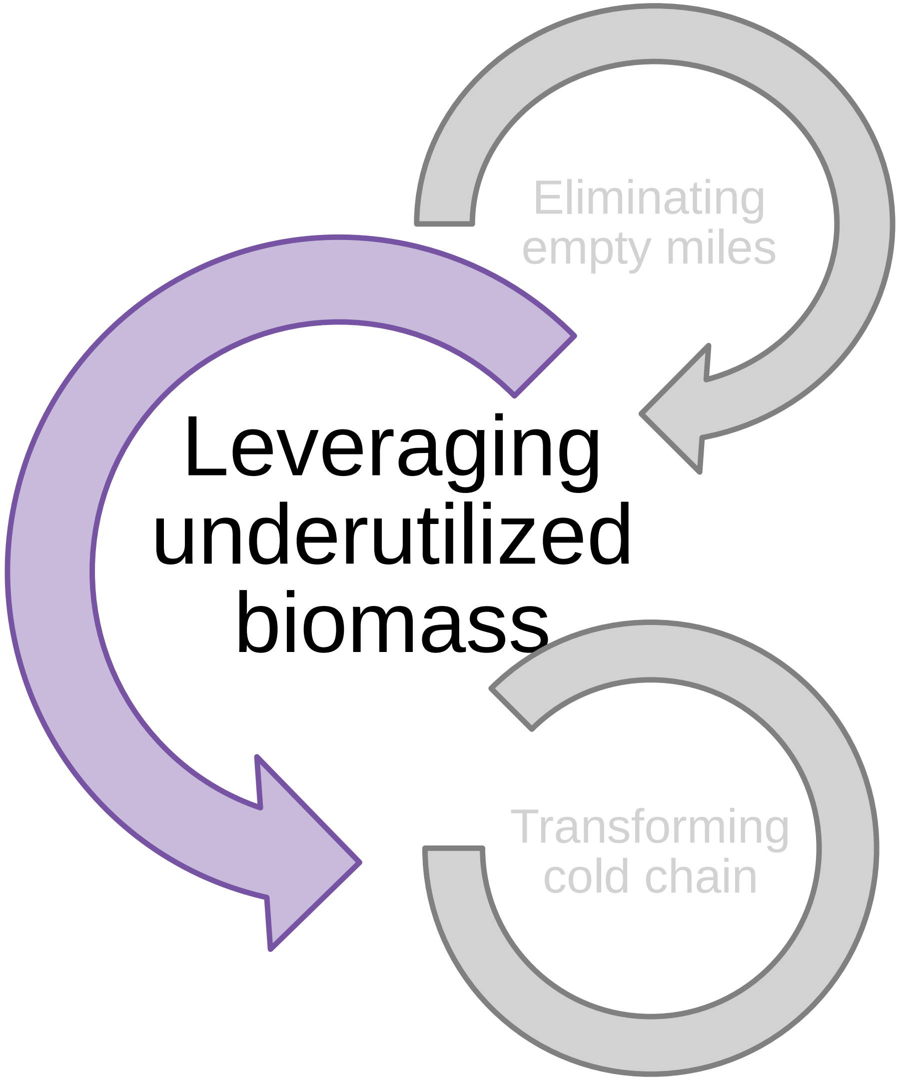
Organic processes are difficult to scale, as the control conditions from labs are difficult to replicate on an industrial scale. Advanced process control technologies enabled by the digitalization of industrial facilities could help these processes expand beyond pilot projects.

## Plastics from CO2 using a biocatalyst

Newlight has developed AirCarbon, a PHA-based plastic generated in a reactor containing methane or CO2 and a proprietary biocatalyst. AirCarbon is 60% carbon and hydrogen by weight. It is a cheaper substitute for oil-based plastics and is certified to be carbon-negative.

## Two-stage hybrid process

B.Fab is developing a hybrid process to make biopolymers from CO2. The technology first produces formic acids from CO2 using electrolysis and then uses microbes to convert the formic acid into useful materials.


Eliminating empty miles
Leveraging underutilized biomass
Transforming cold chain

# The challenge of leveraging underutilized biomass

**Biomass is a low-carbon solution for a number of sectors including transport, industry, buildings, power and materials. Bioenergy already supplies 10% of total final energy consumption, but less than half of this is considered sustainable because much of the biofuel and biochemical supply comes from food sources such as sugarcane and corn. Other forms of biomass may drive increased land use or deforestation. Finding ways of economically leveraging sustainable biomass resources such as residues, waste and marine biomass could unlock new low-carbon energy and material resources.**

## How big a problem is it?

Biomass is one of the best substitutes for fossil fuels and petrochemicals, in terms of its suitability for key demand applications, but increasing the use of biomass puts pressure on land resources and food production. There is a significant amount of potential sustainable biomass (forestry and agricultural residues); waste (organic waste, woody waste) and ocean biomass (algae, seaweed) that could expand biomass supply. However, materials made from these more sustainable types of biomass are less economically competitive for a variety of reasons.

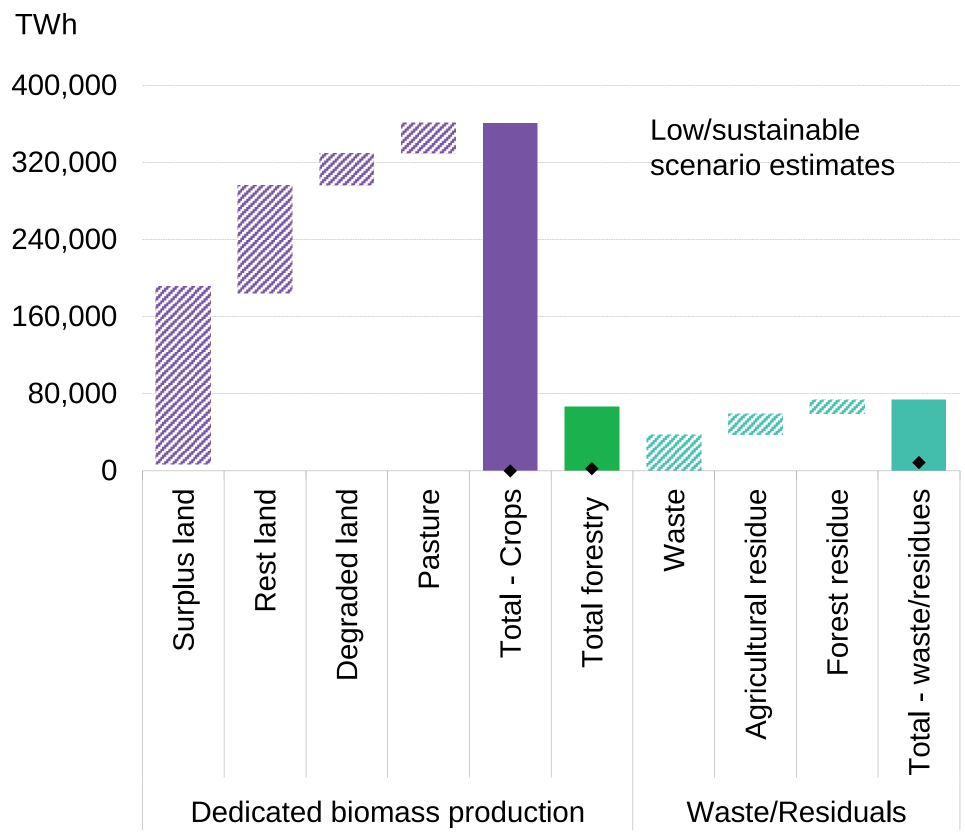
## What should we tackle first?

Because of the higher costs of making products these biomass resources, and the small volumes currently available, it makes sense to target higher value materials and chemicals first, as these could command a green premium.

## Why is it difficult to solve?

Where corn or sugarcane has easy-to-access cellulose, woody biomass and inedible agricultural residues are mostly made up of hemicellulose and lignin. These are complex carbohydrates that are very hard to break into usable sugars. Technologies to do this have proven hard to scale and very expensive. By its nature, waste biomass or ocean biomass is often difficult to acquire or hard to aggregate, making feedstock sourcing challenging.

## Global estimates of biomass potential by feedstock type




*Source:UKERC, BloombergNEF (web | terminal). Note: Estimates are from a range of different studies. Most estimates are for 2050.*

# Agricultural and forestry residues

Agriculture and forestry operations generate waste and residual biomass that are underutilized today. Converting these sources of residual biomass to materials would dramatically expand capacity to produce biofuels and bio-based materials. Lignin and hemicellulose – two plant materials that are currently difficult to process – can account for around half of plant matter by weight. Better processing technologies could expand bio-based material capacity by boosting yields and reducing purity requirements for biomass feedstock. Finished chemicals and materials converted from woody and waste biomass are currently limited to high-value consumer applications such as consumer plastics and cosmetics because of the price premium.

## New approaches and technologies

Lignocellulose – the material in plants and wood that give them structure – is a significant source of underutilized biomass. There are many approaches to breaking down lignocellulose to complex sugars or other products, and then further innovations to turn those sugars into final products:

**Chemical**: Acids, bases and solutions can break down lignocellulose at low temperatures and under low pressure.

**Thermochemical:** More established companies rely on heat, pressure and catalysts to break down lignocellulose.

**Biological**: Enzymes can also break down lignocellulose to sugars. An alternative route is to let anaerobic digestion break down the plant structure to produce methane.

**Physical:** Some research groups are circumventing the need for chemically breaking down the plants by shredding the biomass and using the resultant powder to replace plastic.

**Engineered yeast:** Turning complex sugars (c5) that come from hemi- and lignocellulose into chemicals can be difficult and requires genetically modified or engineered yeasts.

## Limitations

**Feedstock purity:** Many of the technologies for pre-treating and processing lignocellulose rely on homogenous feedstocks. The processes have yet to prove their stability and durability on an industrial scale.

**Cost:** Chemicals made from woody and waste biomass are expensive. The most significant costs are the high capital equipment costs and potential high feedstock costs once demand increases for waste biomass and agricultural residue streams.

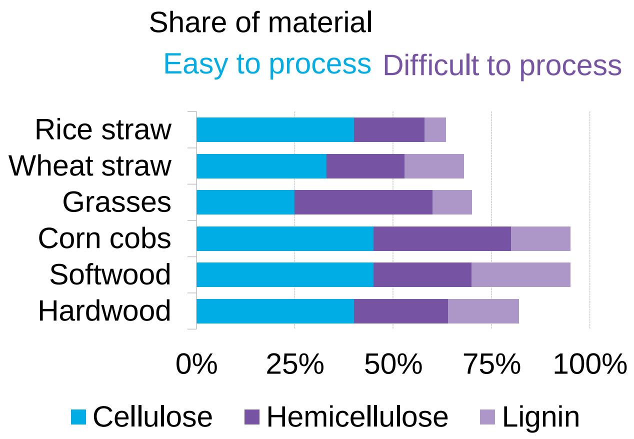
**Feedstock collection:** The production of woody and waste biomass is decentralized. It is difficult and expensive to connect these diffuse points of supply to a centralized processing facility.

## Potential solutions

**Reduce energy requirements:** Innovative catalysts, microbes, or chemical solutions will be essential in reducing the energy requirements and thus costs of these materials.

**Supply agreement:** Securing a supply of feedstock from a large corporate looking to market its sustainability credentials could help a fledgling startup commercialize its technology while avoiding feedstock risks.

## Composition of woody biomass




*Source: BloombergNEF, Science of Alternative Feedstocks. Note: Lower range of estimates shown.*



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# Agricultural and forestry residues (chemical and thermochemical processes)

## Chemical processes

Lixea has developed an ionic liquid that separates lignocellulose. The reaction can take place at temperatures below 200 degrees and also allows for the recovery of metals. Lixea is currently selling cellulose, lignin acetic acid and furfural as outputs of its process rather than processing the outputs itself.

LXP Group has a pre-treatment process for plant biomass to ‘crack’ lignin strands and separate cellulose, hemicellulose and lignin. The process occurs at low temperatures and can therefore use waste heat. LXP Group claims that its process results in separated lignin and hemicellulose that are less contaminated than competing processes.

Bloom Biorenewables has developed multiple processes for the pre-treatment of biomass and processing of lignin into useful materials. Its pre-treatment step uses solvents to break down the lignocellulose. It complements this step by adding aldehydes, which stabilize the lignin produced by the process, making it easier to convert into useful materials. Its current focus is on turning the lignin it produces into vanillin, a cosmetic ingredient with a high value but small market size.

## Thermochemical

Renmatix applies heat and pressure to generate supercritical water that breaks down the lignocellulose in plant matter. Renmatix sells the output of this process as an input for foods, beauty care products and soaps.

**Renmatix was named a BNEF Pioneer in 2014.**

Enerkem has developed a gasification process that produces ethanol and methanol, which can be converted to both fuels and materials. Enerkem markets its gasification process as being particularly robust to heterogeneous feedstock and it can process municipal solid waste as well as woody and waste biomass. Enerkem has been raising multi-million dollar rounds of venture funding and debt consistently since 2010.

# Agricultural and forestry residues (physical and biological)

## Physical

Researchers at IIT research institute in Genoa have developed two methods for turning fruit and vegetable waste into bioplastics. The water-based process relies on dried and powdered ag waste. The first method mixes the powders with biopolymers, resulting in a product that is 70-80% ag waste by weight. In the second process, the powder is mixed with either a solvent or water of a certain pH that breaks down powder and causes it to solidify as a plastic-like material. The properties of the plastic depend on the ag waste feedstock.

Researchers at Montpellier University that are part of the European Glopack project – to develop plastics from ag residues – make plastic pellets by combining PHA with grapevine shoots and wheat straw. The plastic is 100-150% more expensive than polypropylene. The group is looking to build a pilot project by 2021.

## Biological

Woodzymes is an industry-funded research project developing enzymes capable of living in the conditions of a paper processing mill. The enzymes are designed to generate phenols and sugars from lignin and hemicellulose.

Leaf Resources has developed the Glycel process that uses glycerol as a reagent to break down lignocellulose. The process then converts the cellulose into sugars using an enzyme. Leaf Resources then sells lignin, hemicellulose and glycerol as a coproduct rather than trying to process it itself.

Mango Materials does not process biomass directly. Its methane conversion process, however, could use methane from the anaerobic digestion of biomass as a feedstock. Mango Materials use a non-genetically edited microbe to convert methane gas to biodegradable PHA plastic. It is able to produce 1lb of PHA from 2-3lbs of methane gas. The company aims to collocate its plants with methane sources. It has worked for a number of years with Silicon Valley Clean Water wastewater treatment plant. It plans to work with other methane producers such as abandoned coal mines and landfills.

Leveraging underutilized biomass

# Marine biomass

Microalgae and seaweed are two other sources of biomass that, if scaled, could dramatically expand biomaterial capacity. Algae yield per acre is far higher than land-based biomass and it does not compete with food resources. Arpa-E estimates that seaweed-based fuels could meet 10% of U.S. energy demand for transportation. The technology is currently expensive due to the high energy requirements for processing and the labor intensive nature of algae farming. The process of growing algae and seaweed is also difficult to scale. Increasing the efficiency of algae processing and industrializing the production of macroalgae are two paths to reducing the costs of algae-based materials.

## New approaches and technologies

Microalgae and macroalgae (eg, kelp) contain lipids (fats) similar to those found in vegetable oil. These can be extracted to produce petroleum substitutes. Microalgae can be grown in reactors or ponds while macroalgae is grown in seawater on nets and ropes.

**Improving lipid yield:** Companies are increasing the efficiency of lipid extraction from microalgae by using gene editing to increase lipid content and new processes to reduce energy requirements. Others are using genetic modification to make algae produce valuable forms of hydrocarbon exclusively (e.g. jet fuel).

**Industrializing farming:** Some innovators are creating industrial equipment to help reduce the cost of farming.

**Seaweed:** Some startups are using alginate and agar – seaweed extracts – to make single-use biodegradable plastics for consumers.

## Limitations

**Energy intensity:** The process of converting marine biomass to fuels and materials is still expensive due to the energy requirements of refining the materials.

**Scalability:** Photo-bioreactors can either be open or closed. Closed reactors allow for environmental control but are extremely expensive. Open reactors are the more likely candidate for scalable biochemical production but are prone to contamination.

**Labor intensity:** Farming algae and seaweed can also be labor-intensive, making it difficult to scale industrially. In Europe, 85% of harvested seaweed is done so manually.

**Environmental concerns:** Microalgae that is grown in bioreactors can use an enormous amount of water, comparable to some food crops even. Algae also consume fertilizer, a major emissions source.

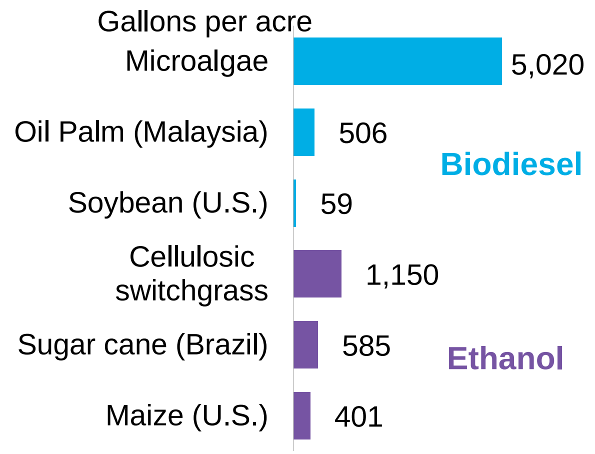
## Potential solutions

**Hybrid bioreactors:** using a combination of open and closed algae ponds could reduce contamination in early-stage growth while maintaining scaling potential.

**Lipid efficiency:** The energy efficiency of algae production can be improved – and thus costs reduced – by increasing the lipid content of algae and reducing the energy required to extract lipids.

**Industrial control systems:** Digital control systems that have become popular in other industrial contexts could be leveraged in algae production to increase the level of environmental control in open algae ponds.

## Land efficiency of biomass




*Source: BloombergNEF, University of Michigan*



BloombergNEF

# Marine biomass

## Increasing lipid yield

Synthetic Genomics has used Crispr gene editing technology to edit genes regulating lipid production in microalgae. It was able to increase oil production by 100% in algae without affecting the growth. It has partnered with Exxon Mobil since 2009. Its current production target is to make 10,000 barrels of oil per day by 2025.

A team of researchers at the University of Utah developed a new kind of jet mixer that shoots solvent at algae. The mixer reduces the energy cost of extracting lipids from algae. The team noted that the process still required more energy than was generated by the extracted fuels but was an improvement on existing techniques.

## Utilizing seaweed

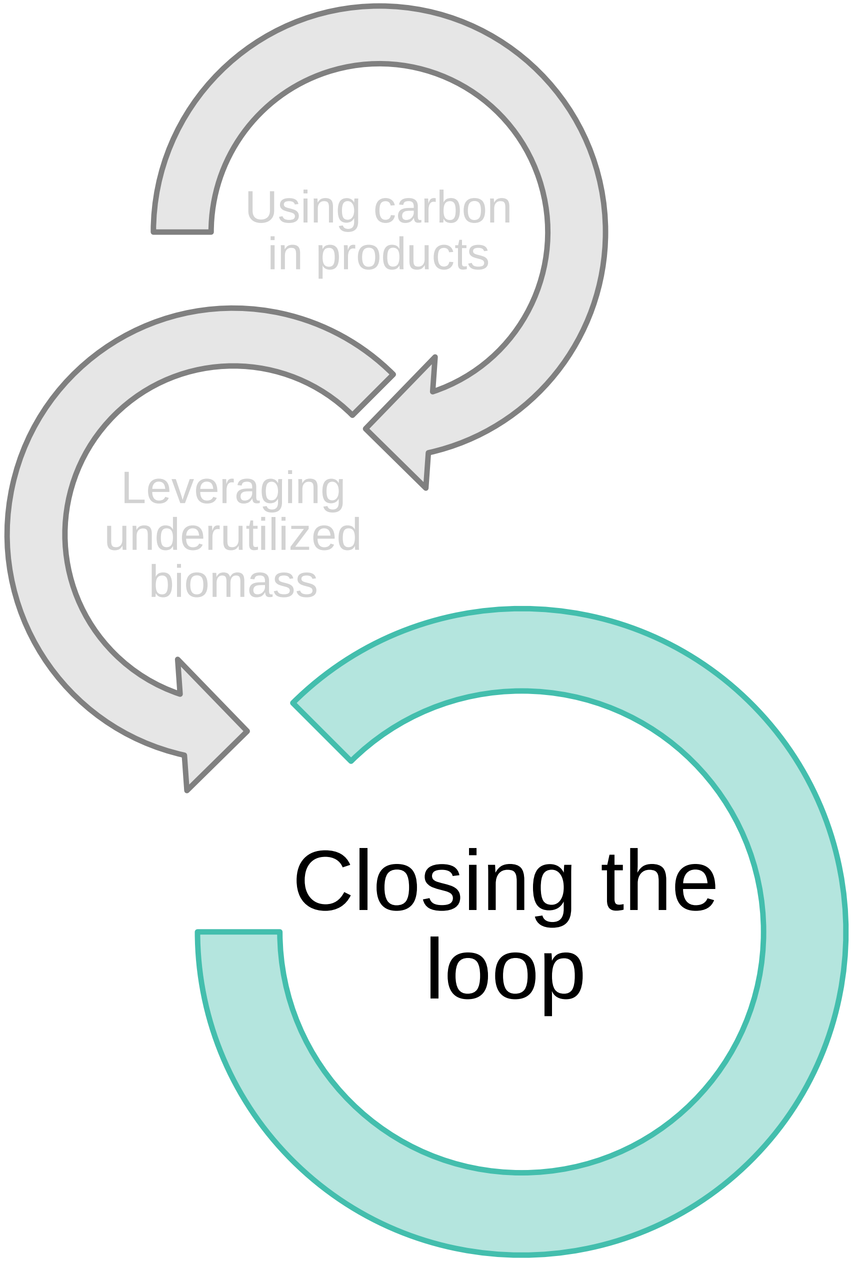
Loliware makes an edible plastic from agar – a component of red seaweed. Its products feel like plastic and are usable for 24 hours after they get wet. The company is currently focused on making straws but plans to expand to cups, lids and single-use cutlery.

Notpla created an edible plastics substitute from alginate that biodegrades in 4-6 weeks. The company makes single-use drinks packaging. The material is produced by mixing a calcium chloride solution with a sodium alginate solution, creating calcium alginate fibers. Notpla has partnered with food delivery service Just Eat to expand to single-use food packaging.

## Mechanized seaweed farming

AtSeaNova sells products and services for industrial scale seaweed farming. It sells harvesting machines as well as substrates (eg, nets, ropes) to encourage seaweed growth. It is also involved in several EU Horizon 2020 projects to develop a more mature seaweed industry.

Sea6 makes infrastructure for industrialized seaweed farming, including offshore platforms and mechanized harvesters and planters.


Using carbon
in products
Leveraging
underutilized
biomass
Closing the
loop

# The challenge of closing the loop

**Closing the loop – or using a greater share of waste streams as feedstocks – is another path to making more sustainable materials. Closing the loop will help reduce the emissions intensity of materials while at the same time preventing ecosystem degradation from raw material extraction and discarded waste. Innovations for closing the loop are focused on hard-to-recycle materials such as certain plastics and batteries. These materials can be difficult to recycle as they become contaminated during use and traditional recycling techniques result in a downgraded product.**

## How big a problem is it?

Current waste management systems produce an enormous amount of waste. Of the 391 million tons of plastic produced in 2014, 42% was discarded, and most of what was collected was incinerated rather than recycled. Recycling this waste could provide huge economic value in two ways. First, closing the loop would prevent discarded materials and raw material extraction from degrading ecosystems. This would also positively impact human health. Second, recycled material is a less emissions-intensive feedstock than virgin material.

## What should we tackle first?

Investment in recycling technology is focused on materials that have intersecting sustainability issues, and not just the most emissions-intensive materials. For plastics, which are a primary focus, the waste crisis, impact on human health and ecosphere, and emissions intensity are key concerns. Battery recycling is another area of interest, particularly given the prevalence of high-value metals and customer sustainability concerns.

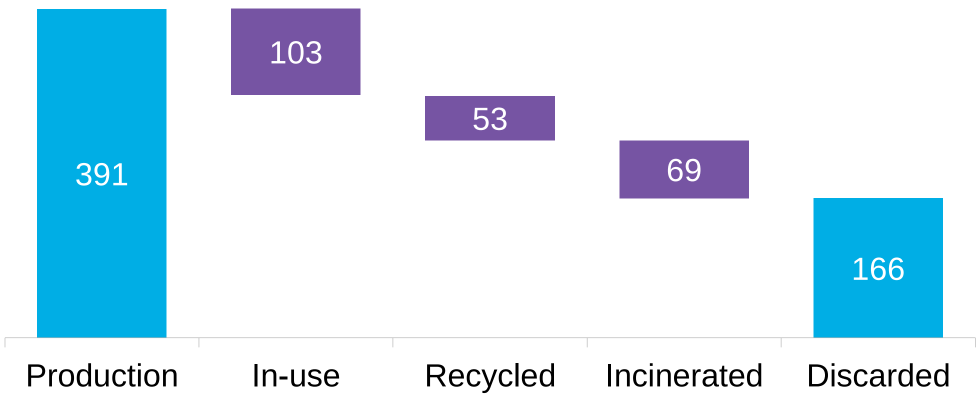
One reason technology development is focused on these markets is because they can be particularly challenging to recycle. There is less need for innovation in other areas like steel for instance, of which 85% is already recycled.

## Why is it hard to solve?

Materials become contaminated in their lifetime, either because they are part of a mixed waste stream (plastics) or because of their design (lithium-ion batteries). This means that material must be collected and sorted, a time consuming and expensive process. Even then, it is not possible to recycle all kinds of materials. There has also been little incentive to recycle many products to date because it is often much cheaper to make new ones.

## Share of waste plastics recycled, incinerated and discarded (2014)

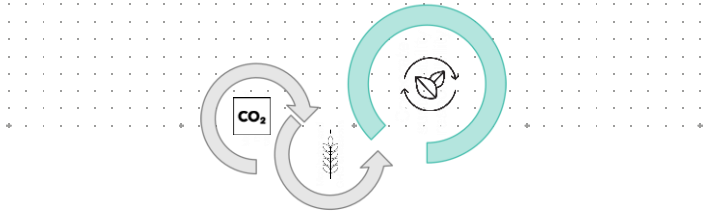
Million metric tons




*Source: BloombergNEF (web | terminal), Geyer, R., J. R. Jambeck and K. L. Law(2017)*

Closing the loop

# Producing virgin-grade material from waste (plastics)




Chemical recycling is the process of breaking plastics down into their precursors to remake material that is of virgin quality. The process leverages cheap waste feedstock to produce virgin-quality petrochemicals at a potentially lower cost than traditional processes. One main benefit of chemical recycling is that it can tolerate more contaminated feedstock, with some processes able to take in plastics that have not been sorted. Chemical recycling is not a catch-all solution for plastics. The process is more energy-intensive than mechanical recycling. It will need to be coupled with complementary low-carbon technologies such as bioplastics and carbon capture to be part of the net-zero economy.

## New approaches and technologies

Most plastic is currently recycled by shredding and melting, which can result in a downgraded material. New approaches reduce plastic to fundamental parts so they can be reformed as virgin-grade material. This is known as chemical recycling and it is has begun to gain steam in recent years.

**Monomer recycling:** Breaks polymers down into monomer precursors using thermal or chemical techniques. Monomer recycling can only support sorted plastic streams. It currently targets PET and polystyrene.

**Feedstock recycling:** Reduces plastic waste to naphtha or diesel, petrochemical precursors to plastics. Pyrolysis is the main process used in feedstock recycling. The main benefit of feedstock recycling is that it can accept mixed plastic waste.

## Limitations

**Emissions:** Chemical recycling is quite energy-intensive and is often fueled by burning the lowest-quality scrap feedstock. While the resulting plastics still have a lower environmental footprint than virgin plastics, the process is more energy-intensive than mechanical recycling, which can run on electricity.

**Limited control of outputs:** Chemical recycling plants have a poor level of control over the composition of their outputs. Similar to refining crude oil, a range of different hydrocarbons are generated, only some of which are high-value. Most processes cannot select for a particular chemical, limiting the overall efficiency.

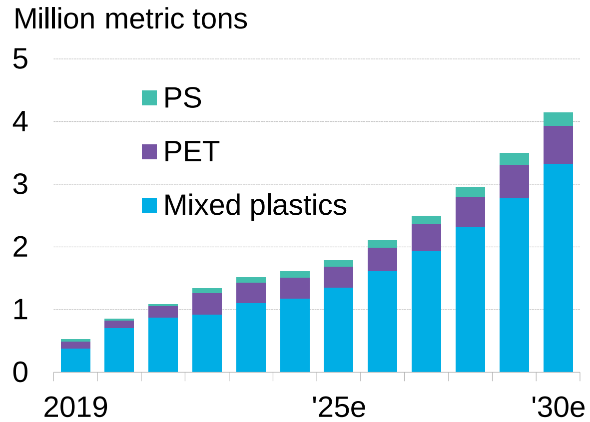
**Competition:** Without policy intervention, market dynamics are likely to divert hydrocarbon products from feedstock recycling of mixed plastics into fuel – and not plastics – applications.

## Potential solutions

**Limit to essential plastics:** Because chemical recycling is more energy-intensive than mechanical, the technology will have the greatest climate impact if limited to plastic waste that cannot be recycled by mechanical means.

**Electrify more processes:** Some chemical recycling processes rely on natural gas and syngas to generate the heat that induces chemical reactions. Switching to electricity as a heat source will be more sustainable as power systems decarbonize.

## Chemical recycling cumulative capacity outlook




*Source: BloombergNEF (web | terminal)*

# Producing virgin-grade material from waste (plastics)

## Monomer recycling – polystyrene

Pyrowave sells equipment that recycles polystyrene using a monomer recycling process, powered by electricity. The process uses microwaves to heat plastic feedstock quickly to 700-800 degrees. Its process has a yield of around 90%, higher than its competitors.

**Pyrowave was named as a BNEF Pioneer in 2021**

## Feedstock recycling

Plastic Energy uses a process called thermal anaerobic conversion (pyrolysis) to break down mixed plastic waste into a hydrocarbon vapour. The vapour is separated in distillation columns to produce a range of products including diesel, naphtha and syngas. Syngas is used as fuel to power the recycling plant. Naphta and diesel are sold to produce virgin grade plastics. Plastic Energy says that plastics made from its feedstock have 55% lower emissions intensity compared with virgin products.

**Plastic Energy was named as a BNEF Pioneer in 2020**

## Monomer recycling – PET

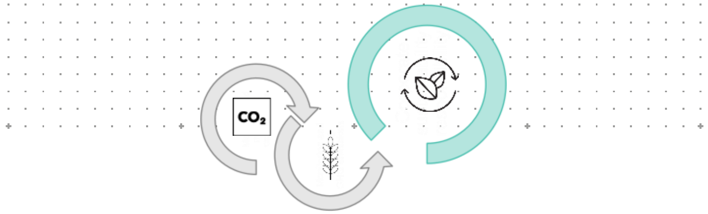
Loop Industries uses a monomer recycling technology to recycle PET. Its process – called methanolysis – uses a proprietary catalyst, methanol and low temperatures to break PET into monomers before repolymerizing it as virgin grade material.

## Monomer recycling - PET and textile recycling

Worn Again Technologies has developed a patented process that converts PET bottles and non-reusable textiles into PET resin and cellulosic pulp. These materials can then be used to create new textiles. The process allows textiles that previously would have been landfilled to be recycled.

Quantafuel also uses pyrolysis to do feedstock recycling of plastic waste. It says that its key IP is a two-stage catalytic process that converts the gas generated by pyrolysis into more desirable hydrocarbons.

# Producing virgin-grade material from waste (batteries)




The volume of used lithium-ion battery packs available for recycling will increase 40 times between today and 2035. At the end of their life, battery packs are dismantled with some cells or modules being repurposed for second-life applications. Those that cannot be repurposed are recycled. Today recycling is simplistic; batteries are mechanically taken apart to recover metals and plastics and the cells re-used, or they are sometimes burnt to extract only one or two more valuable elements. New recycling methods reliant on leaching solutions are more environmentally friendly. These new solutions have lower energy requirements and no toxic emissions. They also face a scaling challenge however, as battery supply chains are only beginning to reckon with and integrate recycling considerations.

## New approaches and technologies

There are two new processes improving the recycling of lithium-ion batteries.

**Pyrometallurgy-hydrometallurgy:** This process relies on heating battery materials to temperatures of 500-800°C to burn off unwanted electrolyte, binders and additives. Battery materials are then selectively dissolved to separate them. This is done using a combination of acids and bases.

**Hydrometallurgy:** More modern recycling processes do not involve a pyrolysis step. Pyrometallurgy is considered the least environmentally friendly element of battery recycling because it is energy intensive and generates toxic emissions.

## Limitations

**Supply chain:** While the supply of used batteries is set to grow, it is still small. Collecting batteries and transporting them to central facilities is also quite expensive and can make recycling uneconomic.

**Economics vary by chemistry:** Not all battery chemistries are created equal. The materials recovered from lithium iron phosphate (LFP) batteries may not sell for as high a price as nickel manganese cobalt (NMC) batteries. Different chemicals may also need to be used in leaching.

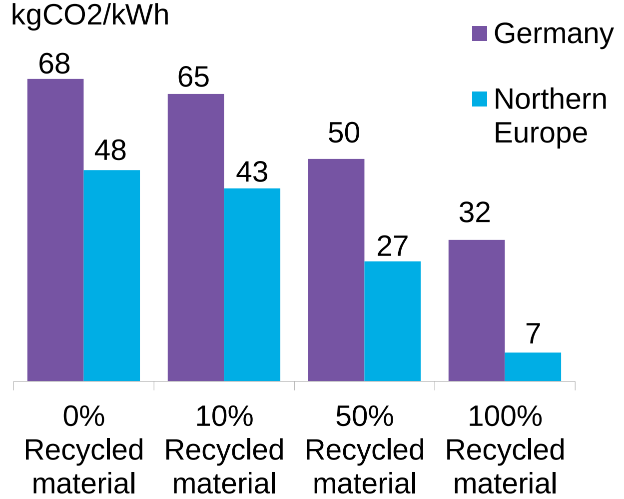
**Design:** Batteries have not typically been designed to be disassembled and it is not yet a priority for automakers compared with reducing costs and increasing energy density.

## Potential solutions

**Distributed model:** Pre-processing batteries at decentralized locations to reduce overall transport costs could ameliorate supply chain issues.

**Access other battery sources:** Rather than relying on the retirement of EVs to fuel growth, battery recycling companies could get a head start by processing materials from cell manufacturing scrap. Accessing unused electronics that have yet to be discarded could be another growth driver.

## Emissions from the production of a 100kWh NMC (622) pack using cylindrical cells




*Source: BloombergNEF (web | terminal)*

Closing the loop

# Producing virgin-grade material from waste (batteries)

## Hydrometallurgical

Li-cycle has developed a two-step 'spoke and hub' recycling process. Spent lithium-ion batteries are mechanically reduced to black mass at 'spoke' facilities before being transported to 'hub' facilities where the black mass undergoes hydrometallurgical treatment. Li-cycle claims it will have recovery rates of at least 95%. Most startups profiled here claim a similar level of recovery. Li-cycle is set to open a facility in Rochester, NY that can process 5,000 tons of spent batteries per year in 2022. Li-cycle is undergoing a reverse merger this year valuing the company at $1.67 billion.

Battery Resources use a hydrometallurgical process to recover up to 97% of metals in lithium-ion batteries. The company recently raised a $20 million series B round to finance a facility with a recycling capacity of 10,000 tons of spent battery per annum.

Lithion has developed a patent-pending hydrometallurgical process that it says is adaptable to all kinds of lithium-ion batteries, including LFP batteries. Lithion is currently operating a pilot plant that has the capacity to recycle the batteries of 350-600 EVs per year. Its planned commercial plant will have the potential to process the equivalent of 4,000 cars per year (2000 metric tons).

Duesenfeld uses a hydrometallurgical process to recycle batteries, claiming to have a yield of 91%. It saves around 4.8 $tCO_2e$ per ton of recycled battery compared with traditional recycling methods. Duesenfeld, like Li-cycle, is creating a model that mechanically shreds and sorts batteries at decentralized locations. Hydrometallurgy is then conducted at its central plant.

## Pyrometallurgy-hydrometallurgy

Founded by an ex-Tesla CTO, Redwood uses a hybrid pyro-hydrometallurgy process to recover up to 95% of nickel, cobalt, aluminum, and graphite in batteries, as well as 80% of lithium.

## Designing for recyclability

Aceleron is an energy services provider and battery maker. The company's Circa platform for battery manufacturing uses compression rather than welding and glue to build battery packs. This design makes the batteries much easier to disassemble during recycling.

# Better tracking and sorting of waste

Understanding the composition of waste streams, and being able to sort them efficiently, is a significant challenge in closing the loop on materials use. Digital technologies are a vital tool in achieving this. Computer vision and digital ID systems are important for analyzing waste streams and are also used for automating the picking and sorting of waste with robots. These technologies can reduce the cost of waste sorting, increase facility throughput and increase the output purity of recycling plants. There are few limitations to the adoption of this technology in the long run but collaboration between material producers and recycling will be essential in ensuring the technology reaches its full potential.

## New approaches and technologies

The most digitalized recycling plants are focused on plastics. Optical sorters are a common technology used in material recovery facilities (MRFs). They use electromagnetic bursts to identify different plastic types. They are increasingly accompanied by newer technologies, such as:

**Computer vision:** Advances in computer vision have generated software platforms that analyze waste streams in sorting plants.

**Robotics:** Computer vision software is often paired with robots that can pick through waste streams more quickly than humans. This reduces the cost of sorting and increases the accuracy.

**Digital ID technology:** New kinds of barcodes and chemical traces are being explored to make it easier for different waste streams to be identified in MRFs.

## Limitations

**Upfront costs:** The more advanced digital technologies such as optical sorters have high upfront costs, which may not be supported by the thin margins in waste processing.

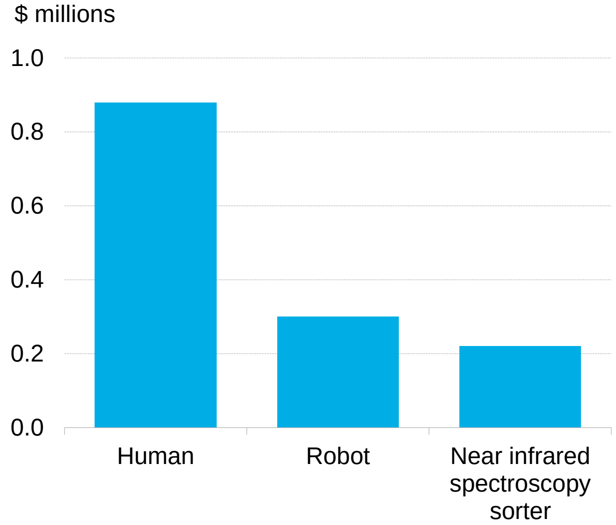
**Difficulty retrofitting:** The implementation of digital technologies in sorting facilities often requires a plant to be reconfigured, as they do not integrate with existing lines.

## Potential solutions

**Value chain collaboration:** The implementation of digital systems would be simplified by the adoption of standard identifying systems. Collaboration between materials producers and recycling stakeholders could help provide standard factors – such as 3D barcodes or chemical tracers – that help identify waste streams.

**Product passports:** A product passport is the concept that every product in the world is associated with some digital file that contains data on its material composition and best practices for end-of-life management. Product passports would be valuable data sources to help MRFs better understand their waste streams. The concept has generated a lot of buzz and the European Resource Efficiency Platform has identified it as an innovation target.

## Cost of recycling methods




*Source: BloombergNEF (web | terminal). Note: Indicative of upfront costs for equipment versus labor costs for 10 years. Costs not adjusted for productivity, inflation or discounting. Includes $100,000 installation and shipping costs for equipment.*

# Better tracking and sorting of waste

### Computer vision and analysis software

Sadako Technologies develops computer-vision technology for industrial applications with a focus on recycling. It has two products. The first is an AI that powers a robot picking machine in MRFs (Max-AI). The other is a monitoring system that tracks waste coming into the facility and creates data streams about the waste composition (RUBSEE).

Recycleye develops software for waste stream analysis and robotic picking. Its WasteNet database contains 2.5 million labelled images of waste for AI training.

### Robotics and computer vision

Amp Robotics develops software that competes with Sadako Technologies. It has an AI platform that powers picking robots as well as software that analyzes waste stream composition. Amp Robotics also builds its own robots. Amp says that its robots can pick 80 items per minute, twice as fast as a human sorter.

### Digital ID technology

Filigrade has made a 3D barcode technology called Curvcode, which is embossed onto plastic products. It has an accompanying optical scanner that can detect the Curvcodes making plastic sorting more accurate. Filigrade currently markets the technology as being most useful in separating food and non-food plastics.

Digimarc has developed an imperceptible watermark that can be imprinted on products. These invisible barcodes can be used to improve sorting in MRFs as well as proving authenticity. They can also create interactive products by allowing customers to view product information by scanning with a smartphone camera. This generates a branding incentive to invest in traceability technology.

# Early-stage investment trends

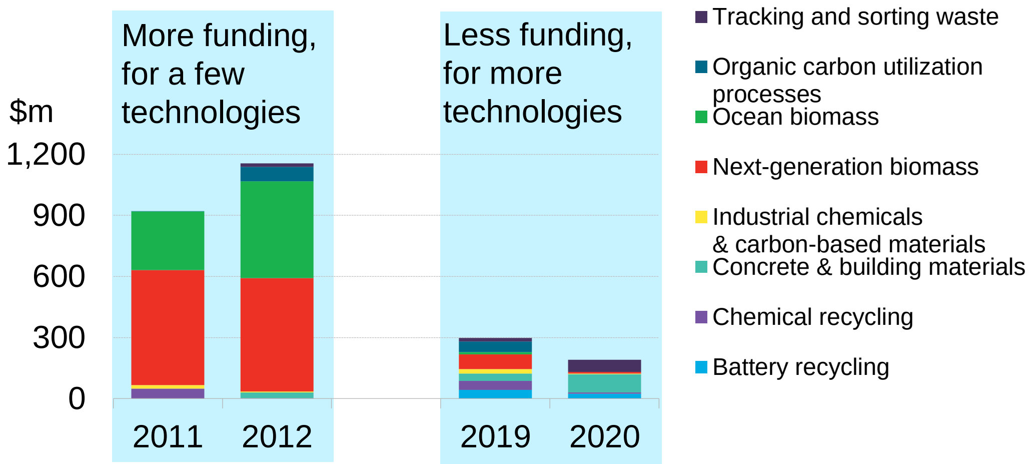
Early-stage investment trends

# A new beginning for VC investing in sustainable products

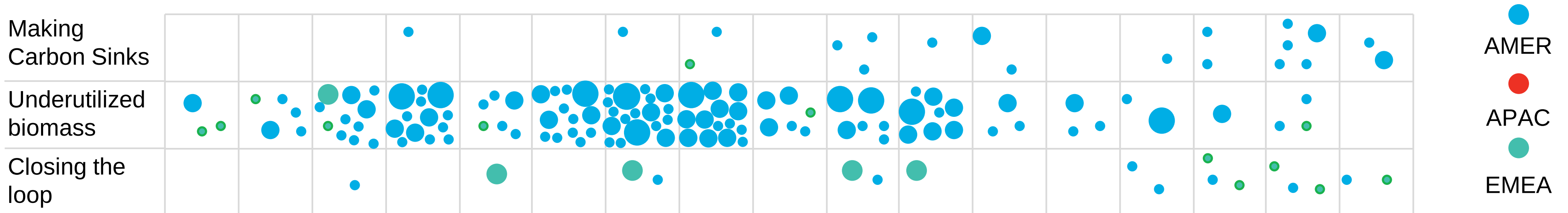
A decade ago, there was high interest from early-stage investors in biochemicals and bioplastics, in part because of U.S. government subsidies and a high oil price. From 2008 to 2012, $3.6 billion went to next-generation biomass and algae startups. But scaling these processes is expensive and takes time. The 2014 oil price crash (plus a few notable startup failures) caused investors to scale back their investment dramatically.

While VC investment in bio-based products (and generally in sustainable materials) has been meager in recent years, there is renewed interest in bioplastics, turning CO2 into materials and new recycling technologies. Often these investment bets are quite small, and the majority of activity (and funding) is coming in the form of asset financing and joint ventures with corporates.

## VCPE raised for sustainable products by technology




## Largest VCPE deals to create sustainable products




| | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 1Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total funding ($ million) | 17 | 144 | 323 | 689 | 377 | 721 | 922 | 1155 | 205 | 382 | 480 | 246 | 185 | 494 | 289 | 340 | 131 |
| Total deals | 10 | 25 | 24 | 21 | 20 | 32 | 37 | 36 | 19 | 24 | 20 | 25 | 22 | 24 | 25 | 44 | 12 |

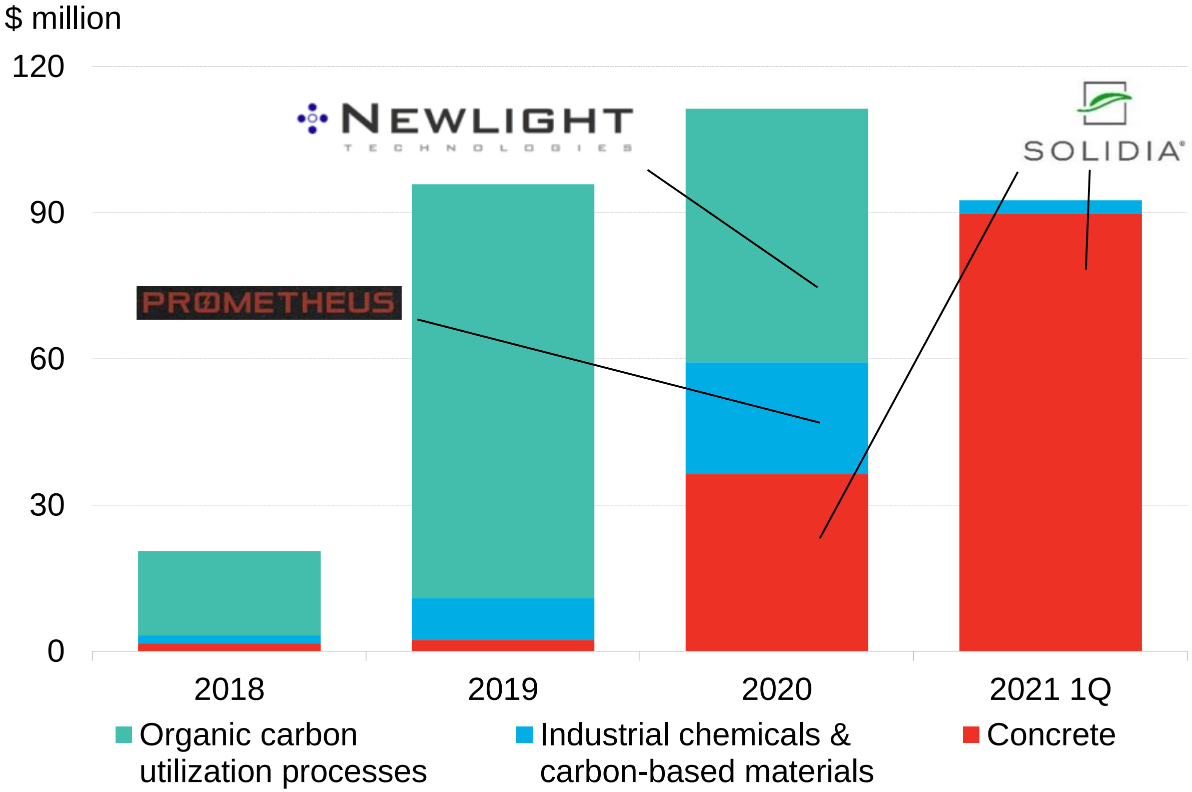
*Source: BloombergNEF, CB Insights. Note: Bubbles represent deals over $5 million in each year.*

# VC investment trends for using CO2 as a feedstock

VC funding for CO2-to-products has been relatively slow-growing until 2020, when the topic gained a lot of interest and many startups launched products. A few significant deals caused annual VC funding to surpass $100 million in 2020. This momentum, paired with the plethora of net-zero and carbon-negative goals set by corporations, should mean that interest (and funding) in the space will continue to grow.

These technologies do not usually attract traditional venture capital money. Where VC funding has occurred it is usually from corporate venture arms, most commonly from energy, chemical and transport companies. In 2020, BMW I Ventures led a round in Prometheus Fuels. In 2021, BP Ventures invested in Solidia Technologies, and Chevron Technology Ventures invested in Blue Planet.

## VCPE investments into carbon utilization technologies




*Source: BloombergNEF, CB Insights. Note: Logos indicate most funded companies each year.*

### Investor spotlight: NRG

As corporates look to act on climate change, many are looking for innovative ways to store or use carbon. NRG, a large U.S.- based power producer, has funded different innovations in this space.

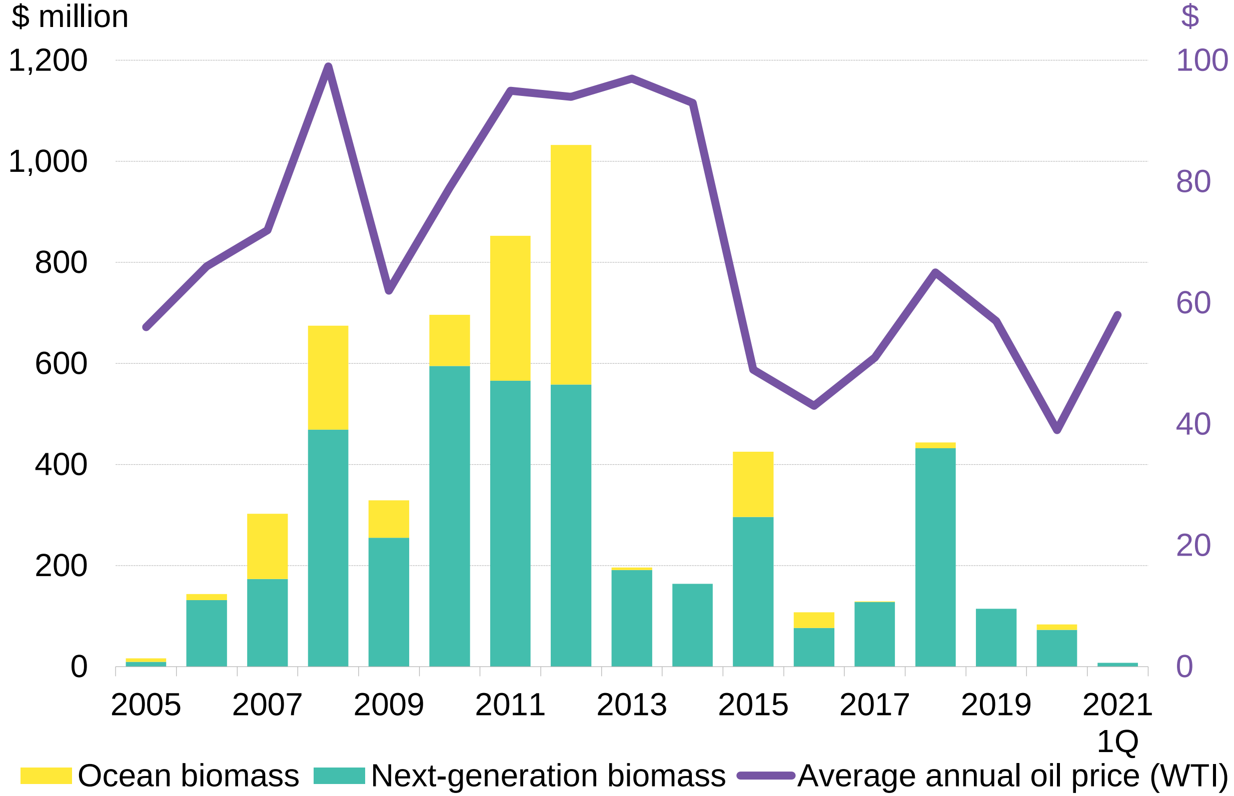
- NRG initially focused on direct investments. From 2009-2015, it invested in 10 climate-related startups. These ranged from DAC company Global Thermostat to fuels company Cool Planet.
- After 2015, NRG pulled back its direct investment and teamed up with the X-Prize competition to offer a 5-year $20m carbon capture innovation prize. The group recently awarded the prize to CarbonCure Technologies and CarbonBuilt.
- This indirect early-stage investing has gained popularity in recent years, with companies such as X-Prize, Techstars and Plug and Play organizing innovation competitions on behalf of large corporations like Equinor, Exxon Mobil or Shell.

# VC investment trends for using underutilized or waste biomass

In the late 2000s and early 2010s, high oil prices catalyzed investment into a set of technologies that could make carbon-based products from under-utilized biomass. Between 2005 and 2015, $4.8 billion flowed to startups. A subsequent drop in oil price saw many of these companies go bankrupt or lose value. Between 2017 and 1Q 2021, only $777 million has been invested (with algae startups raising virtually nothing). 65% of this was from two large follow-on deals for Enerkem in 2018 and 2019.

However, climate-focused investors continue to see the importance of supporting cellulosic bio-product startups, if with smaller sums of money. In the past five years, the most prominent investors have been firms like Breakthrough Energy Ventures, BP and Braemar Energy Ventures.

## VCPE investments into underutilized biomass




*Source: BloombergNEF, CB Insights*

**Investor spotlight: The Carbon to Value Initiative**

Initial costs to develop these technologies can be very high, and startups struggle to fund significant upfront capital costs through venture capital. The Carbon to Value Initiative combines the conventions of a typical venture accelerator program with added exposure to potential corporate partners.

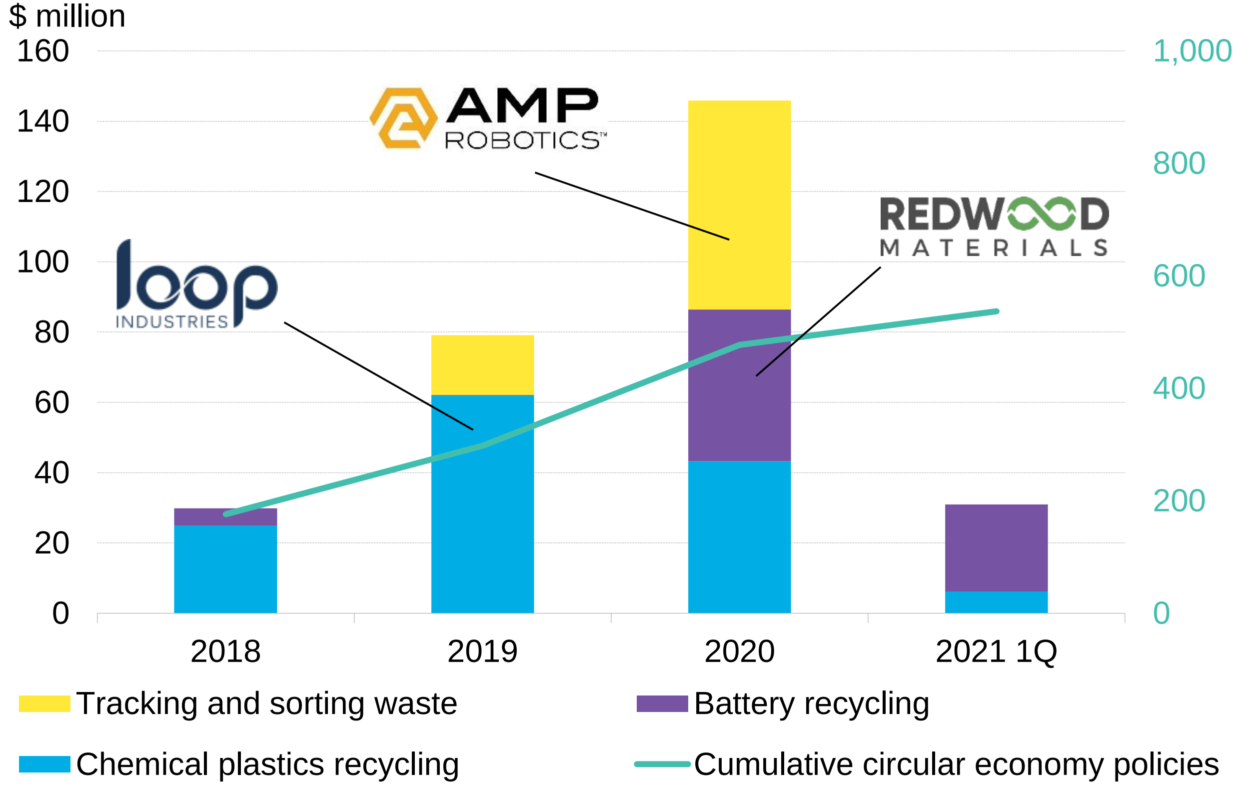
- The six-month program accelerates startups using various sources of carbon to make sustainable products. Cemvita Factory, one of twelve 2021 BNEF Pioneers, is in the first cohort.
- Along with a cohort of startups, the Carbon to Value Initiative brings together a group of leading corporate, academic and governmental stakeholders called the Carbontech Leadership Council. This council will help create opportunities for commercialization through partnerships and mentorship, which is key to scaling these types of technologies.

# VC investment trends in battery recycling and chemical recycling

Recycling materials and products is logistically complex and requires large upfront infrastructure investments. These characteristics usually lead to low investment from venture capital. However, increasing circular economy policy announcements have provided the incentive for investment.

While venture money has increased, it has not led to a meaningful uptick in recycling capacity. Loop Industries, the chemical recycler most funded by VCs in the past five years, has a small amount of capacity currently operating. What is more likely to help recycling companies scale capacity are joint ventures and asset funding from corporate partners. Loop Industries has partnered with Suez, a prominent environmental services company, to build its first large plant. When constructed, this shared facility will produce 84,000 metric tons/year. See BNEF tool here.

## VCPE investments into recycling technologies




*Source: BloombergNEF, CB Insights. Note: Logos indicate most funded companies each year.*

**Investor spotlight: Closed Loop Partners**

Recycling startups struggle to scale without licensing their tech or partnering with a large financier. Closed Loop Partners, a circular economy investment firm, is set up to try and tackle this problem with multiple stages of financing. The firm has invested $130 million in the past five years.

- Closed Loop Partners offers investment options from seed and series A rounds up to project finance. The firm has an early-stage investment group called Closed Loop Ventures Group.
- This Closed Loop Ventures Group will invest up to $500,000 in initial investment rounds, with the option for follow-on funding from Closed Loop Partners.
- Closed Loop Partners has limited partners like Walmart, Unilever, Johnson & Johnson and PepsiCo, which benefit directly from the circular economy innovations spun out of Closed Loop Partners.

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