CARBON CAPTURE, UTILIZATION, AND STORAGE GAME CHANGERS IN ASIA AND THE PACIFIC

2022 COMPENDIUM OF TECHNOLOGIES AND ENABLERS

ASIAN DEVELOPMENT BANK

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ADB recognizes "Korea" as the Republic of Korea.

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Foreword

As the climate bank for Asia and the Pacific, the Asian Development Bank (ADB) strives to see a sustainable low-carbon region in the next half of this century. While the destination has been decided, the path of technologies is still uncertain. The winning low-carbon solution will emerge as technologies develop, experience is gained, and funding is determined. Hence, ADB has kept its near-term as well as long-term technological options open. This is the reason why hydrogen; carbon capture, utilization, and storage (CCUS); energy efficiency; renewable energy; energy storage; and so many other significant technologies have been pursued simultaneously by ADB.

CCUS has a special space among the many options for low-carbon development in Asia. It helps in ensuring energy security, decarbonization of hard-to-abate industries, and compliance with international commitments. At the same time, it guarantees a relatively low disruption in the existing arrangements. However, the utilization of captured carbon is still in a relatively nascent stage. Hence, there is a need to closely track the developments in carbon dioxide capture, utilization, and storage.

The maiden compendium of CCUS technologies in 2021 explained the salient features of cutting-edge developments. This year, ADB is bringing another set of interesting CCUS technologies. As was the case in the first publication, this year's compendium presents a set of technologies that are at different stages of development. They range from early-stage laboratory ideas to fully developed technology that just needs to be commercialized at a mass scale.

I would like to take this opportunity to thank the Department of Business, Energy and Industrial Strategy, Government of the United Kingdom for their support in this publication through their contribution to the carbon capture and storage fund of ADB. I would also like to acknowledge the technical advice provided by the Global CCS Institute, Australia while preparing this compendium.

ADB will be happy to take these ideas forward in its developing member countries once their commercial viability is proven. We look forward to hearing from the investment community to practicing industries.

Priyantha Wijayatunga
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Sectors Group
Asian Development Bank

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The main contributors to this compendium are Carbfix ohf. (Ólafur Einar Jóhannsson); Carbon Upcycling Technologies Inc. (Kristin Skelton); CEMEX Global Research and Development (Davide Zampini); Chalmers University of Technology (Maximilian Biermann); DyeCoo (Ernst Siewers); CO2Tech—a CO2CRC company; Global Algae Innovations, Inc. (David Hazlebeck and Mark Hazlebeck); Karbon Korea (Won Dong Cho and Jahye Kim); Southpole (Philip Moss); Sustainable Energy Solutions (Owen Hart); Verdox (Jonte Boysen); and WOIMA Finland Oy (Henri Kinnunen and Tapio Gylling). The Global CCS Institute (Matthew Loughrey and Nouman Mirza) provided guidance and support in gathering technology information considered for this compendium.

ADB's Climate Change and Disaster Risk Management Division, Climate Change and Sustainable Development Department (CCSD); East Asia Department; Pacific Department; Procurement, Portfolio, and Financial Management Department; South Asia Department; and the Southeast Asia Department reviewed and provided comments on the draft of this compendium.

Guidance in the preparation of this compendium was provided by Priyantha Wijayatunga, senior director and Kee-Yung Nam, principal energy economist, energy sector office (SG); supported by Charity Torregosa, senior energy officer, SG; Maria Dona Aliboso, operations analyst, SG; Marinette Glo, operations assistant, SG; and ADB consultants Darshak Mehta and Remife De Guzman. Maria Theresa Mercado, consultant (ADB); Mike Cortes cover design; Edith Creus, typesetter; Levi Rodolfo Lusterio, proofreader; and Lawrence Casiraya, page proof checker supported the editing and layout of this publication.

Abbreviations

ADB	Asian Development Bank
BEIS	Department of Business, Energy and Industrial Strategy (BEIS), Government of the United Kingdom
CAPEX	capital expenditure
CCC	cryogenic carbon capture
CCS	carbon capture and storage
CCUS	carbon capture, utilization, and storage
CDR	carbon dioxide removal
CO_2	carbon dioxide
CUT	carbon upcycling technologies technology
DACS	direct air capture and storage
DMC	developing member country
ESA	electro-swing adsorption
EU	European Union
GHG	greenhouse gas
HPC	hot potassium carbonate
LNG	liquefied natural gas
LSNG	liquid synthetic natural gas
MACE	mechanically assisted chemical exfoliation
MEA	monoethanol amine
MENA	Middle East and North Africa
NOx	nitrogen oxide
OPEX	operating expenditure
R&D	research and development
sc-CO_2	supercritical carbon dioxide
SCM	supplementary cementitious materials
SES	Sustainable Energy Solutions
SOx	sulfur oxide
US	United States
vol	volume
WtE	waste-to-energy

WEIGHTS AND MEASURES

€	euro
°C	degree Celsius
GJ	gigajoule
GT	gigaton
kg	kilogram
KWh	kilowatt-hour
L	liter
m^2	square meter
MJ	megajoule
MW	megawatt
MW_{th}	megawatt thermal
NM^3h	normal meter cube per hour
s	second
t	ton
tCO_2	ton of carbon dioxide

Note: "ton" refers to "metric ton" equivalent to 1,000 kilograms.

Overview

This compendium of game-changing carbon capture, utilization, and storage (CCUS) concepts deals with four interesting carbon dioxide (CO_2) capture technologies, five CO_2 utilization technologies, one CO_2 storage technology, and one enabler concept. The technologies presented are in various stages of development ranging from research and development to commercial deployment. The concepts included in this compendium were furnished by CCUS technology providers and enablers through their responses to an email questionnaire prepared by the consultant team of the Asian Development Bank (ADB) through regional Technical Assistance 9686: Integrated High Impact Innovation in Sustainable Energy Technology (Subproject 2)—Prefeasibility Analysis for Carbon Capture, Utilization, and Storage.

This compendium is not exhaustive. Other ideas are available and may also be added in the future. Similarly, there are likely to be more suppliers of the same technology. ADB looks forward to other opportunities to add to this collection of ideas on CCUS, which could help ADB developing member countries achieve low-carbon development.

The first step in the process of CCUS is the capture of CO_2. Over the years, technologies have been deployed and conceptualized. Just as the compendium of 2021, which described CO_2 capture technologies that have used membrane or have used novel centrifuge to dramatically reduce the size of the capture equipment, this year's compendium has another set of interesting technologies that could change the game. One technology is a novel non-amine CO_2 absorption technology, which claims to be less toxic and may cost about a third of what amine-based capture is expected. Another idea is capturing CO_2 through application of cryogenics. This technology will not involve chemicals and could be efficient. The third CO_2 capture technology featured in this compendium is based on electrochemical adsorption that requires no consumables and less energy than direct air CO_2 capture technologies. In addition to these, when full-scale capture is not feasible because of site conditions such as low availability of waste heat, partial CO_2 capture could be an option to consider in the near-term. This technique is likely to reduce capital and operating cost.

As Asia undergoes rapid urbanization, making cities livable becomes an important development criterion for the ADB developing member countries (DMCs). Proper solid waste management and sustainable energy generation are two necessities that are met through waste-to-energy plants. Hence, several such plants are expected to be set up in Asia in the coming years. While energy generation and waste elimination are already addressed by such projects, the greenhouse gas (GHG) emission issue due to waste-to-energy projects can be met through CO_2 capture. The paradigm shift in waste collection as well as processing suggests that the waste will primarily comprise of biomass. Thus, CO_2 capture from waste-to-energy projects will be essentially negative emission projects. ADB has included one such application in this compendium. Another interesting feature of the project is the production of low-carbon fuel from the captured CO_2.

Other CO_2 usage technology that the compendium explores includes a textile dyeing technology that utilizes supercritical CO_2. Conventional textile dyeing industry is a huge consumer and polluter of water. According to an estimate, textile dyeing accounts for 20% of industrial water pollution.[1] Dyeing of textiles using supercritical CO_2 will reduce the water usage by more than 90%, thus significantly reducing water pollution. This is a perfect example of CO_2 usage contributing to sustainable development. Application of this technology can lead to a huge benefit to the textile oriented DMCs in Asia like Bangladesh, India, Indonesia, Pakistan, the People's Republic of China, Thailand, and Viet Nam.

CO_2 in algae farming is another practical utilization of CO_2 included in this compendium. As illustrated in this compendium, advances in commercial algae cultivation using waste CO_2 can result in savings in energy and resources in the production of protein for feeds, and oil for fuel and polymer production.

Another early-stage CO_2 technology involves the use of captured CO_2 to make building materials that could substitute for steel, cement, and wood. Rapidly growing Asia will likely experience a huge construction boom. This material will help not only absorb CO_2 but also help reduce the production of materials that contribute to more than 10% of global GHG emissions.

Also introduced in this compendium is the upcycling of inorganic feedstocks into enhanced materials through mineralization with CO_2. The technology reduces the carbon footprint of concrete by permanently storing CO_2 and producing a price-competitive substitute for cement.

Mimicking and accelerating the natural process of CO_2 storage into basalt rock formations is another novel CO_2 storage technology showcased here. The technology's pilot project demonstrated that carbonating water with captured CO_2 and injecting it into basalt rock formations can mineralize CO_2 within 2 years which is way faster than the natural process. CO_2 storage in rock formations also has storage potential that is greater than the emissions of the burning of all fossil fuels on Earth.

While the 2021 compendium included CO_2 hubs as one of the enablers, this year's compendium included a platform where carbon credits are used to create a financial tool to incentivize GHG savings through the use of CO_2 removals. Considering the progress in the climate negotiations, financing the CCUS through the carbon markets is a reality that needs to be kept in mind.

[1] R. Kant. 2012. Textile dyeing industry: An environmental hazard. *Natural Science*. 4(1): p. 23.

Game-Changing Carbon Dioxide Capture Technologies

Carbon Dioxide Capture through Hot Potassium Carbonate Absorption

Technology provider

Karbon CCS Limited (Republic of Korea; Norway)

Technology description

Hot potassium carbonate (HPC) is a well-established process for extracting carbon dioxide (CO_2) from mixed gases such as town gas, ammonia, hydrogen, natural gas, and ethylene oxide. It is used in thousands of industrial facilities worldwide. However, conventional HPC processes are inefficient when the concentration of CO_2 in the mixed gas is low, at 5%–30%. Although efficiency can be increased by pressurizing exhaust gas to 10–15 bar, mechanical compressors are too bulky and expensive.

The key innovation of Karbon Technology eliminates the need for bulky and expensive mechanical compressors. Karbon Technology pressurizes industrial exhaust gas by combusting it together with natural gas and air in the combustion chamber of a gas turbine. The resulting secondary exhaust gas exits the gas turbine at 10–15 bar, a pressure at which the HPC process efficiently extracts CO_2. The key absorbent—potassium carbonate—is inert, nontoxic, inexpensive, environmentally benign, and has a small footprint. Figure 1 illustrates Karbon's HPC carbon capture process.

Box 1: Karbon Hot Potassium Carbonate Carbon Capture Key Features

Technology Highlights

- 90%–95% of carbon dioxide (CO_2) from exhaust gas
- Cost of capture could be as low as $30 per ton of CO_2 captured
- Uses as low as 2 gigajoules of energy per ton of CO_2 captured
- Uses inert, inexpensive and environmentally benign CO_2 absorbent
- Wide range of application

Development Stage

- Pilot demonstration

Sectors of Application

- Process industries
- Power plants
- Maritime

Technology advantages

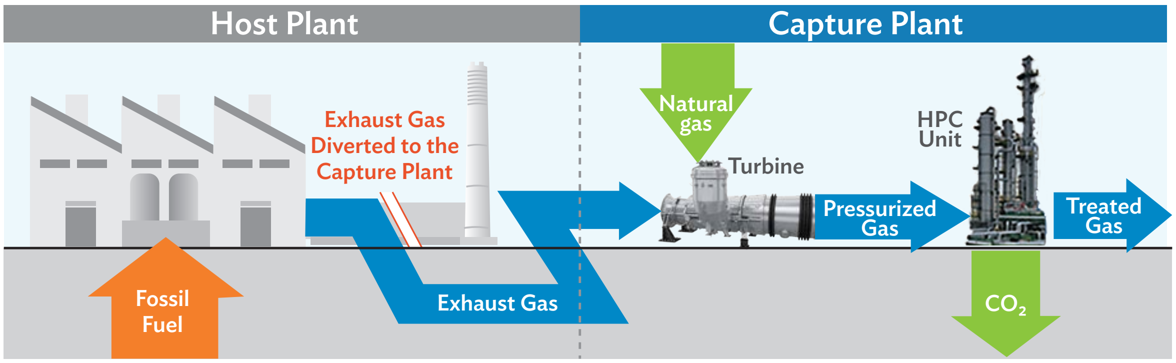
Key technology advantages of Karbon HPC carbon capture process includes the following:

(i) Karbon HPC process has an energy penalty of 2.5~3.5 gigajoules (GJ) per ton of CO_2 captured depending on the CO_2 concentration in flue gas.[2]

(ii) Cost of CO_2 capture with Karbon could be as low as $30 per ton of CO_2 captured.[3]

[2] Amine processes use 3–4 GJ per ton of CO_2 captured.
[3] Subject to cost of energy.

Figure 1: Karbon Technology Hot Potassium Carbonate Carbon Capture



CO_2 = carbon dioxide, HPC = hot potassium carbonate.

Source: Karbon.

(iii) Karbon can decarbonize flue gas from boilers, reciprocating engines and gas turbines ranging from 2 megawatts (MW) and upward to 1,000 MW on land and sea.

(iv) Karbon captures between 90%–95% of CO_2 from exhaust gas. The actual percentage captured is a design choice, which depends on the requirements and economics of the facility in question.

(v) All components of Karbon Technology are off-the-shelf and industrially mature. Construction could be simple and fast with use of standard components.

(vi) Karbon uses potassium carbonate as CO_2 absorbent, which is inert, nontoxic, and requires no replacement over time.

(vii) Karbon, operating under high-pressure atmosphere, requires about 1/3rd less land compared to other technologies operating at low pressure. Being retrofit technology, Karbon can also be installed adjacent to the host plant without any interruption to its operation.

(viii) Other pollutants such as sulfur oxides (SOx), particulate matter, nitrogen oxides (NOx), carbon monoxide, and mercury can be removed in series with the Karbon process.

Related costs

(i) Upfront investment for Karbon plants capturing CO_2 from coal-fired power plants:

  (a) $350 million – Capture 1 million tons of CO_2 per year

  (b) $1,000 million – Capture 95% of CO_2 from a 1,000 MW power plant

(ii) Operating costs—Less than $3 per ton of CO_2 captured, excluding the cost of natural gas, which varies by location and transport cost of CO_2 In the United States (US), for a 1,000 MW coal-fired power plant, the cost of natural gas is currently about $25 per ton of CO_2 captured.

(iii) Unit costs—All-in cost including capital cost is as low as $40 per ton of CO_2.

Potential application in Asia and the world

(i) **Addressable market.** By 2100, climate goals will require up to 100 gigatons (GT) of CO_2 to be sequestered per year. At a conservative carbon price of $20 per ton, this represents a market of $2 trillion.

(ii) **Industrial sector.** Karbon Technology captures CO_2 from exhaust gases emitted power plants, steel mills, cement factories, petrochemical plants.

(iii) **Shipping sector.** Karbon Marine captures CO_2, NOx and methane slip from piston-based ship engines and small power plants. It is a far less expensive decarbonization solution than switching fuels, which the shipping industry is actively considering.

Status and next steps

(i) **Siemens Energy.** Karbon is in close consultation with Siemens Energy regarding turbines for CO_2 capture. Siemens Energy performed full-scale tests, combusting natural gas with flue gas. Siemens Energy is now performing the final detailed engineering of Siemen's SGT turbines to the specifications of Karbon.

(ii) **Republic of Korea.** Karbon formed a consortium to bid to install a Karbon plant at a liquefied natural gas (LNG) power plant owned by KEPCO, to capture CO_2 for storage from a nearby depleted gas field.

Challenges in scale-up and deployment

The main challenge is to bring together the various parties necessary for commercial viability, particularly the off-taker of CO_2, for industrial uses, or for government-subsidized sequestration, as well as a willing engineering, procurement, and construction contractor. Karbon's focus is on commercialization, which will accelerate once some key engineering, procurement, and construction consortium member has completed its detailed engineering.

Technology provider background

Karbon specializes in extraction, transport, infrastructure, and trading of CO_2. Its Karbon Technology is a low-cost method of extracting high-quality CO_2 from flue gases on an industrial scale, removing substantially all CO_2 and other pollutants, including SOx, methane, and particulate matter. It was invented and developed by Karbon's principals. Although Karbon CCS Ltd was established in 2016, the technology has been in development for over 20 years.

Karbon is commercializing globally, notably with capture plants under development at coal-fired power plants in the US. Karbon has also developed a shipborne version of the Karbon Technology for the shipping industry, which is under heavy pressure to reduce GHG emission. As CO_2 will become a globally traded commodity transported by ship, Karbon have designed a dual-cargo long-distance LNG-CO^2 carrier to deliver LNG on one leg of a voyage and CO_2 on the other.

Further reading

F. Levihn, L. Linde, K. Gustafsson, and E. Dahlen. 2019. Introducing BECCS through HPC to the research agenda: The case of combined heat and power in Stockholm. *Energy Reports* 5: pp. 1381–1389. https://www.sciencedirect.com/science/article/pii/S2352484719301829.

Carbon Dioxide Capture through Cryogenic Cooling

Technology provider

Sustainable Energy Solutions, a Chart Industries Company, United States

Technology description

Cryogenic Carbon Capture involves the following steps, as illustrated in Figure 2.

(i) The exhaust gas (stream 1) cools to near 0°C in direct contact heat exchangers, which condenses most of the water.

(ii) A blower provides pressure for process pressure drop.

(iii) A mole-sieve dryer removes the remaining moisture.

(iv) The exhaust gas proceeds through a multi-stream heat exchanger where it cools to near the frost point, the point at which the CO_2 begins to desublimate.

(v) This cold exhaust gas (stream 2) enters the patented desublimating heat exchanger, where CO_2 desublimates onto counter-flowing liquid droplets formed from stream 3, separating the

Box 2: Cryogenic Carbon Capture Key Features

Technology Highlights

- High purity (>99.9%) liquid carbon dioxide product
- 30%–60% lower energy consumption

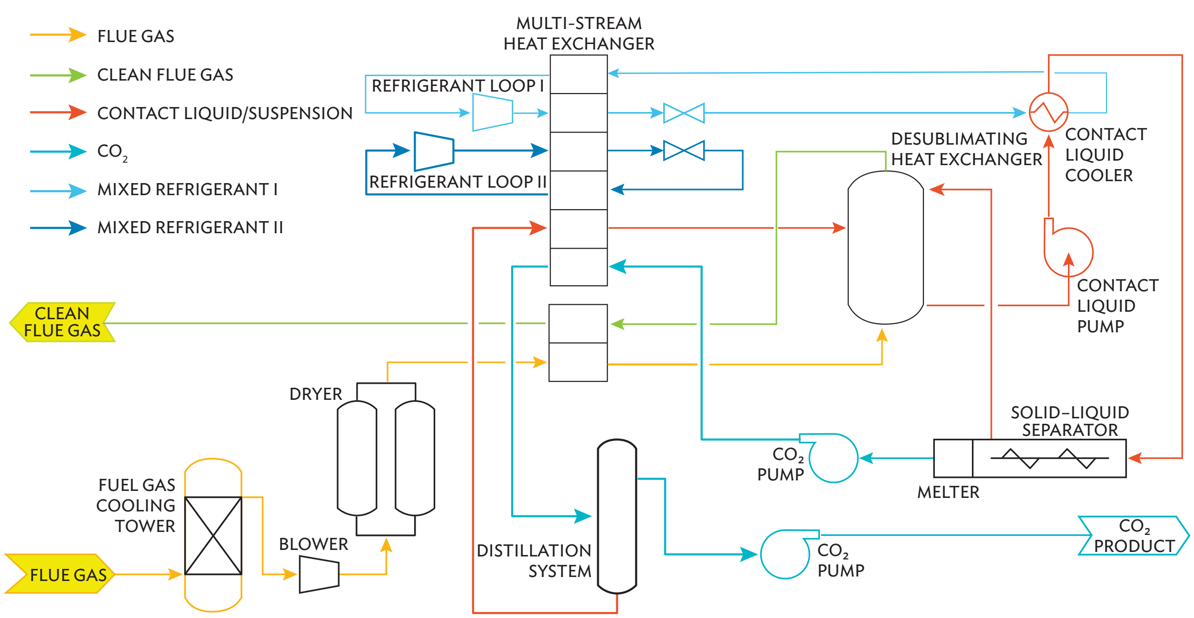
Development Stage

- Pilot demonstration

Sectors of Application

- Power production—coal, natural gas, and biofuels
- Cement and similar kilns
- Steel
- Industrial boilers
- Refineries

Figure 2: Sustainable Energy Solutions Cryogenic Carbon Capture Process Flow Diagram



CO_2 = carbon dioxide.
Source: Sustainable Energy Solutions.

CO_2 as a condensed phase from the remaining light gas.

(vi) The remaining cold light gases warm back to ambient temperature through the multi-stream heat exchanger, where they help cool the incoming gas, and the light gases leave the system (stream 6).

(vii) The suspended CO_2 solids separate from the cold liquid across a barrier filter and drop into a separate chamber where they melt under pressure to form a CO_2 liquid.

(viii) This liquid CO_2 (stream 4) enters a distillation system that separates remaining impurities to produce a high-pressure liquid CO_2 product (stream 5) at ambient temperature and very high purity (>99.9%).

(ix) The cooling for the process is provided by two refrigeration loops that exchange heat with the cold contact liquid that is used in the desublimating heat exchanger.

Sustainable Energy Solutions (SES) is currently testing improvements to the cryogenic carbon capture (CCC) process. These advanced methods and unit operations improve energy efficiency, decrease capital costs, simplify the process, and increase process reliability.

Technology advantages

The advantages of CCC compared to leading alternative carbon capture technologies (e.g., amine-based capture technologies) include:

(i) Achieves high capture rates, up to capturing all of the process-generated CO_2 and some of the CO_2 entering the process with the air, with electricity requirements that are half of published alternatives, depending on scale, gas composition, and other plant specifics;

(ii) Consumes 30%–60% lower energy;

(iii) Has lower capital and operating costs;

(iv) Generates smaller footprint;

(v) Robustly handles NO_X, SO_X, mercury, and other pollutants;

(vi) Enables efficient and cost-effective grid scale energy storage addressing the largest challenges with some renewables and load leveling;

(vii) Recovers a significant amount of usable water from gas streams, requiring minimal water for operation;

(viii) Retrofits any stationary source of CO_2 (power plants, industrial plants, chemical plants, etc.) without new steam generators or upstream process modification; and

(ix) Built around equipment familiar to power and industrial customers (e.g., refrigeration systems, heat exchangers, processing vessels) with no toxic chemical emissions.

Potential application in Asia and the world

CCC can be applied in CO_2-emitting sources including power production (coal, natural gas, biofuels, waste incineration, etc.), kilns (cement, refractory, glass, etc.), industrial boilers, and refineries. The CCC process can capture CO_2 from small commercial (capturing ~100–500 tons CO_2/day) to very large plants (e.g., power plants with >10,000 tons CO_2/day).

Status and next steps

SES completed field testing in a variety of industrial settings, including power plants, heat plants, cement kilns, and industrial CO_2 sources, that were fired with biomass, municipal waste, coal, natural gas, shredded tires, and combinations of these. With over 3600 hours of operation, the CCC process has repeatedly demonstrated robust, high CO_2 capture. For example, when SES operated the CCC skid at a commercial cement plant, the average capture level was 97% from a flue gas stream with high levels of CO_2 (averaging 20 mol percentage).

Together with CarbonCure Technologies Inc., SES participated in the world's first integrated demonstration of CO_2 capture and utilization from cement for concrete production. SES captured CO_2 from the Argos Roberta cement plant near Calera, Alabama. This 99.5% pure captured CO_2 was shipped to a construction project where CarbonCure used the CO_2 for curing ready-mix concrete.

Sustainable Energy Solutions' Cryogenic Carbon Capture Demonstration. Demonstration plant at Argos Roberta cement plant (photo by Sustainable Energy Solutions).

Carbon Dioxide Utilization. Captured CO_2 utilization in concrete (photo by Sustainable Energy Solutions).

SES also demonstrated at a coal-fired power plant. After the field testing, the CCC process was operated for >600 continuous hours in the SES lab. SES is currently building a CCC pilot plant that will capture 30+ tons of CO_2/day from a cement kiln.

Challenges in scale-up and deployment

The next stage of SES development is building a small commercial pilot system (~30–45 tons of CO_2/day). Funding and key technology and project partners have been secured. The pilot is set to begin operation in early 2024.

Technology provider background

SES was founded in 2008 to develop and commercialize the CCC process. SES has been awarded nationally competitive contracts in the last 15 years. In December of 2022, Chart Industries acquired SES and provides the manufacturing and commercialization expertise needed to field large-scale systems.

Further reading

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Carbon Dioxide Capture through Electro-Swing Adsorption

Technology provider

Verdox (United States)

Technology description

Verdox's core electro-swing adsorption (ESA) technology relies on the electrochemical toggling of the affinity of electrodes to CO_2 (Figure 3). Upon charging the cell, the electrodes are activated and capture CO_2 from a feed stream at any concentration. When the cell is discharged, a stream of pure gas is released.

Box 3: Verdox Electro-Swing Adsorption Key Features

Technology Highlights

- Uses 70% less energy than existing direct air capture technologies
- Plug-in device
- Requires no consumables
- No by-products

Development Stage

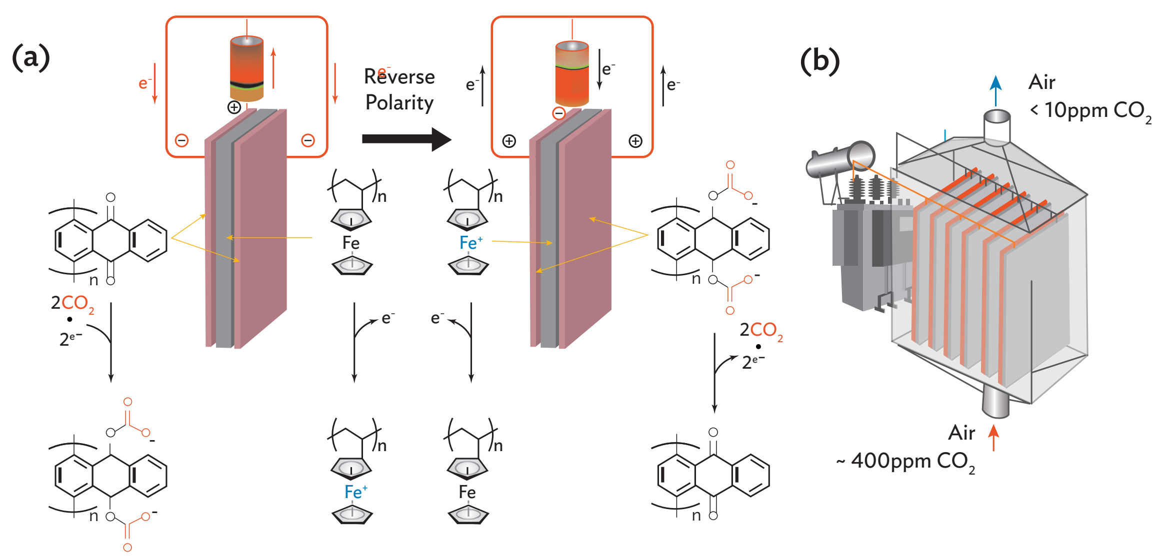
- Research and development

Sectors of Application

- Direct air capture, point source carbon capture

Figure 5 shows a schematic of a single ESA electrochemical cell with porous electrodes and electrolyte separators. The outer electrodes, coated with poly-1,4-anthraquinone composite, can capture CO_2 on application of a reducing potential via carboxylation of quinone, and release the CO_2 on reversal of the polarity. The inner polyvinylferrocene-containing electrode serves as an electron source and sink for the quinone reduction and oxidation. An illustration of a direct air capture device with a stack of the electrochemical cells is in Figure 5b. The materials listed in Figure 3 are only examples of types of materials that Verdox uses in its systems.

Figure 3: Schematic Diagram of Electro-Swing Adsorption



CO_2 = carbon dioxide.

Source: S. Voskian and T.A. Hatton. 2019. *Energy Environ. Sci.* 12: 3530 DOI: 10.1039/C9EE02412C.

Technology advantages

The Verdox system is an electrochemical plug-in device that can be connected to any feed CO_2 concentration, including ambient air, to produce 95% pure CO_2. The only input required for operation is electricity, and no consumables are required. Existing direct air capture technologies rely on heating and cooling large contactors, which creates significant energy losses, requires heat integration, and is prone to operational outages. These temperature swing or pressure swing adsorptions systems also have significantly lower capture efficiency at lower CO_2 concentrations, like direct air capture, which is not the case for Verdox's solution. The Verdox process produces no by-products.

Verdox's ESA system uses up to 70% less energy per ton of CO_2 than existing solutions in low-concentration and direct air CO_2 capture. Verdox's energy requirements for fully commercial solutions are below 3 gigajoules/ton (GJ/t).[4] This, together with lower capital costs, results in significantly lower costs per ton captured at scale. Verdox's system does not rely on heat for regenerating the material, thus removing location constraints, which are challenging for an industry that is already location-constrained by sequestration sites.

Potential application in Asia and the world

Verdox's platform technology can be used to capture CO_2 directly from the atmosphere anywhere in the world and can also address point-source emissions. Within point-source capture, the company is focusing on applications where the CO_2 concentration is around or below 5%, such as in aluminum smelting.

Related costs

Verdox anticipates the costs of its fully developed capture technology to be $40–$80 per ton of CO_2. The company expects capital and operating expenses to both account for roughly half of total cost each at scale.

Status and next steps

Verdox was scheduled to perform its first field tests in the second half of 2022 and is gearing up for deploying its first pilot units in 2023 and 2024.

Verdox has secured $80 million in committed capital to date from a syndicate including Breakthrough Energy Ventures, Prelude Ventures, and Lowercarbon Capital.

Challenges in scale-up and deployment

The main barriers for adoption of Verdox's ESA system are costs of production at small scale, lacking sequestration infrastructure, and inefficient pricing of externalities. Funding the deployment of early first-of-a-kind plants is necessary in moving down the cost curve by scaling up production. Widespread deployment of CO_2 sequestration infrastructure would also speed up deployment of carbon capture technology.[5] Last, if governments were to force emitters to internalize the costs of CO_2 pollution, adoption of carbon capture technology would significantly increase.

Technology provider background

Verdox is solving the affordability challenge of capturing CO_2 directly from the air and other dilute sources with its patented electro-swing adsorption process that saves >70% on energy and cost versus traditional approaches. The ESA system, developed from cutting-edge research at Massachusetts Institute of Technology, uses only electricity as an input and requires no waste heat or water. This eliminates the limitations of existing solutions and allows Verdox devices to run entirely on renewable energy. Verdox's ESA process thereby enables hard-to-decarbonize industries to reach net zero and provides a path for low-cost, permanent CO_2 removal. The company was founded in late 2019 by Brian Baynes, T. Alan Hatton, and Sahag Voskian.

4 According to Verdox, at large scales, they expect plant costs to have energy costs of around $20 per ton (t), using $0.05/kilowatt-hour (kWh). If energy costs for competitors are similar, users of competing technologies would pay $67/t (i.e., $47/t more for energy).

5 Sequestrati on infrastructure refers to the equipment, permitting, and verification required for storing CO_2 in geologic formations under the earth's surface.

Verdox's customers typically have one of two motivations for capturing CO_2: storing CO_2 underground or using CO_2 in their process. Companies that work with Verdox to capture CO_2 at emission sites or directly from the air for sequestration aim to lower their environmental footprint and reach net zero. Companies that want to use the captured CO_2 in their processes or products see Verdox's ESA units as infinite sources of CO_2 that have the added benefit of recycling CO_2 that was previously emitted into the atmosphere.

Further reading

Verdox.com

- Rathi. 2022. Bill Gates Invests in Carbon Capture Startup After Tech Breakthrough. *Bloomberg*. 2 February.
- D. Chandler. 2019. MIT engineers develop a new way to remove carbon dioxide from air. *MIT News*. 24 October.
- N. Stauffer. 2020. A new approach to carbon capture. *MIT News*. 9 July.

Partial Capture of Carbon Dioxide

Technology provider

Chalmers University of Technology (Sweden)

Technology description

Partial CO_2 capture is a CCS concept that targets to capture only a share of available CO_2 at an industrial site given certain limitations such as energy prices, regulations, and CO_2 concentration in the flue gas. Design and cost simulations, and pilot validation studies indicate that partial capture could lead to lower capital requirements and lower specific costs (capital and operating costs) per ton CO_2. These cost savings aim to help facilitate a near-term implementation of CCS. Eventually, partial CO_2 capture must lead to either full capture, co-mitigation with renewable feedstock and/or energy resources, or the transition to carbon-free production technology in line with the Paris Agreement. A possible timeline of deployment is shown in Figure 4.

Box 4: Chalmers University of Technology Partial Carbon Capture

Technology Highlights

- Lower absolute cost and specific cost of capture per ton of carbon dioxide

Development Stage

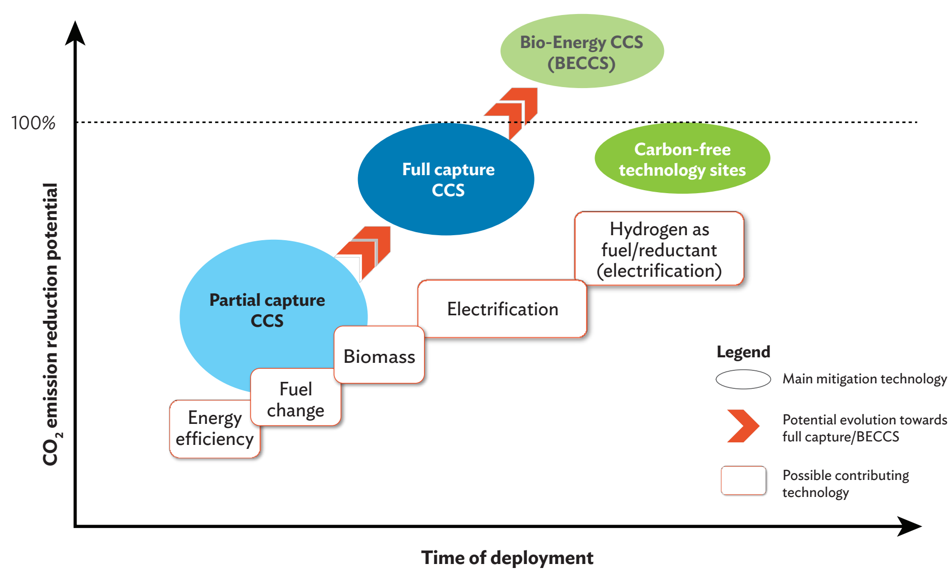
- Research and development

Sectors of Application

- Process industries such as cement, iron and steel, oil refineries, pulp and paper
- Waste incineration
- Power generation

The concept of partial CO_2 capture is based on common solvent-based capture processes, e.g., using aqueous amines, that follow a standard post-combustion flowsheet (minor process modifications, such as absorber cooling and rich solvent splitting

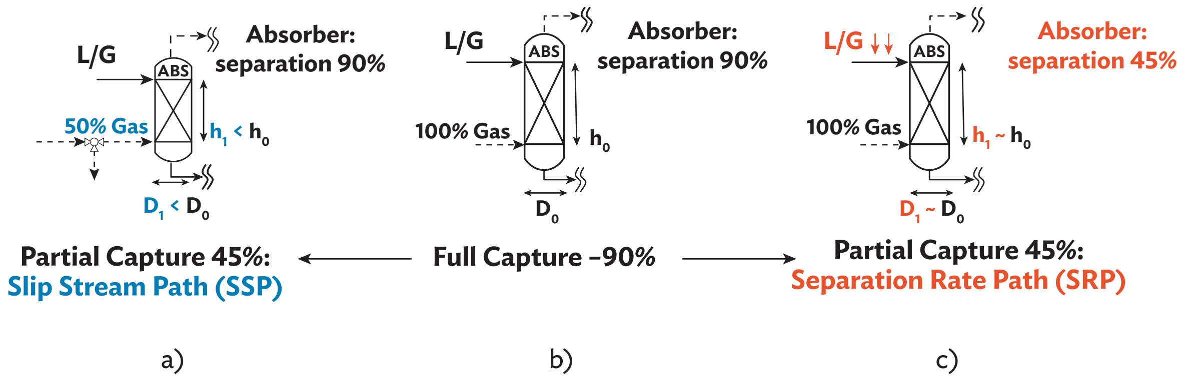
Figure 4: Timeline for the Deployment of Partial Carbon Dioxide Capture



CCS = carbon capture and storage.

Source: M. Biermann. 2022. Partial CO_2 Capture to Facilitate Cost-Efficient Deployment of Carbon Capture and Storage in Process Industries. PhD thesis. Gothenburg: Department of Space, Earth and Environment; Chalmers University of Technology. https://research.chalmers.se/publication/531680.

Figure 5: Design Paths for Partial Capture



Note: a) and c) from a designated CO_2 source compared to full capture b); simplified process scheme (only absorber shown; dimensions of remaining equipment are adapted as well). Indices "0" refer to full-capture reference dimensions, indices "1" refer to partial-capture design dimensions.

Source: M. Biermann, F. Normann, F. Johnsson, and R. Skagestad. 2018. Partial Carbon Capture by Absorption Cycle for Reduced Specific Capture Cost. *Ind. Eng. Chem. Res.* 57:(45). DOI: acs.iecr.8b02074. http://pubs.acs.org/doi/10.1021/acs.iecr.8b02074.

have been assessed). Partial capture is therefore quite broadly applicable. However, the achievable cost savings are highly site-specific and thus, require a techno-economic assessment with sufficient detail (for example on heat recovery potential and CO_2 sources, temporal variations of heat and CO_2 availability, space constraints, power transmission, modes of CO_2 transport).

Figure 5 illustrates examples of plant configuration for full capture and partial-capture cases. Full capture where 100% gas passes through the process and 90% CO_2 is captured is explained by Figure 7b. In this case the capture vessel has a height of h_0 and diameter of d_0.

Figure 7a represents partial capture of the plant. In this case the CO_2 is captured only to the extent where there is enough waste heat or requirement by legal or any of the cases described in cases 1 to 6 earlier. In this example, since the partial-capture requirements are low, the height of vessel h1, is lower than the full capture (Figure 7b) dimension, h_0, while diameter D_1 is also lower than the full-capture diameter D_0. The gas entering the vessel is just 50% (or equal to the requirement). The CO_2 captured is 90% of the entered amount and hence, it is almost 45% of the total CO_2 available in the plant. Based on the dimensions of the plant, the capital cost required for installation of this partial-capture plant is lower.

Figure 7c represents another partial-capture design of the plant. In this case, the plant size is big enough to capture 90% CO_2 of the total gas available. However, the amount of capture fluid is less than the amount available for full capture, resulting in partial capture of the CO_2. In this case, the dimensions of the plant are similar to that of the full-capture dimensions. Hence, the capital cost of the plant is same as the full capture plant. However, the operating costs are lower compared to base case.

There are several industrial site conditions wherein partial capture could be implemented and favored over full capture. Examples of these site conditions include:

(i) High CO_2 concentration (lowers heat demand per ton of CO_2 for partial capture, see Figure 6).
(ii) Availability of low-cost energy including waste heat that is insufficient for full capture but is enough to capture a portion of the emitted CO_2.
(iii) Flexibility of industrial plant to vary their product portfolio to meet market conditions. For example, the capture rate of CO_2 can be

adapted to meet the markets for heat/power co-generated next to the industrial main product.

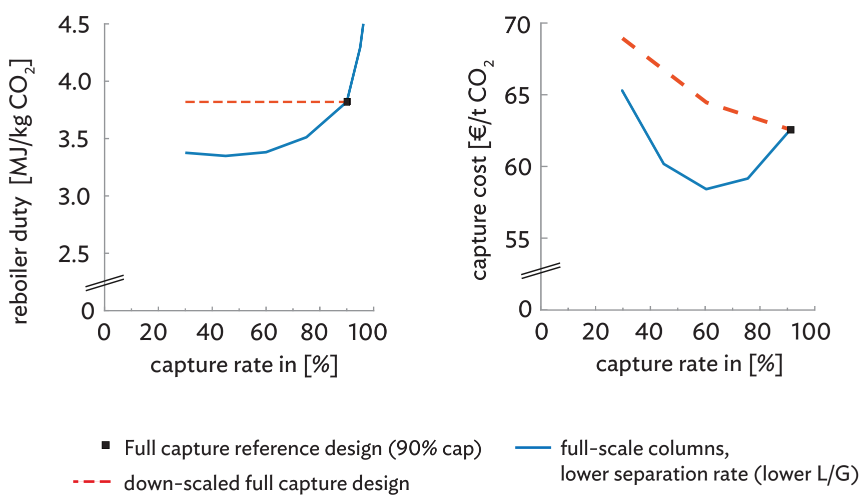
(iv) The presence of multiple stacks emitting flue gases of different CO^2 qualities. In such case, only the most feasible stack(s) can be targeted for capture.

Technology advantages

For CO_2 capture from a single or combined stack (e.g., waste incineration, cement dry kiln), a typical solvent-based process can be devised for partial CO_2 capture by designing the process with full-sized columns but initially operating it at lower liquid-to-gas ratios and at full gas flow. Thereby, the CO_2 separation rate in the absorber is lowered and the CO_2 loading in the solvent leaving the column is augmented. The release of CO_2 in the desorber, thus, requires a lower the specific reboiler duty (megajoule [MJ]/kilogram of carbon dioxide [$kgCO_2$]) by 8%–12 % for gases of ~20 volume (vol) % CO_2, which was confirmed in pilot-scale field test.[6] For gases >17 vol.% CO_2, this could lead to savings in capture cost of 6%–10% per ton of CO_2 compared to full capture (despite working against economy of scale). This rather modest cost saving per ton CO_2 would, however, correspond to a yearly saving of >30% (Table 1) in combined operating expenses (OPEX) and capital expenses (CAPEX) since less CO_2 is captured. Such a design allows for flexible operation (varying load, e.g., adapting the capture rate to the seasonal load of district heating from waste incineration) and is inherently full-capture-ready so that full capture can be eventually achieved by increasing the liquid-to-gas ratio (extending the piping and heat exchanger surfaces between the columns), providing additional energy, and adding equipment downstream of the capture unit. Figure 6 illustrates a comparison between full- and down-scaled capture design.

For multistack sites (e.g., refineries, steel mills), initially capturing from the most cost-effective stacks (large flows and high CO_2 concentration) and utilizing low-temperature excess heat can save up to ~25% of the cost for CO_2 capture, transport, and storage as

Figure 6: Full-Scale vs. Down-Scaled Capture Design



CO_2 = carbon dioxide, kg = kilogram, MJ = megajoule.

Source: M. Biermann, F. Normann, F. Johnsson, and R. Skagestad. 2018. Partial Carbon Capture by Absorption Cycle for Reduced Specific Capture Cost. *Ind. Eng. Chem. Res.* 57:(45). DOI: acs.iecr.8b02074. http://pubs.acs.org/doi/10.1021/acs.iecr.8b02074.

6 M. Biermann, F. Normann, F. Johnsson, R. Hoballah, and K. Onarheim. 2022. Capture of CO_2 from Steam Reformer Flue Gases Using Monoethanolamine: Pilot Plant Validation and Process Design for Partial Capture. *Ind. Eng. Chem. Res.* https://pubs.acs.org/doi/10.1021/acs.iecr.2c02205.

compared to full capture. The pie charts in Figure 7 illustrate this for a Swedish refinery, where scenario (a) is 90% CO_2 capture from the steam methane reformer flue gas (20 vol% CO_2) powered entirely by excess heat (excess steam, increased load of recovery boilers, installation of heat exchanger network to raise low-pressure steam) and scenario (b) is 90% CO_2 capture from all four major stacks (8–20 vol% CO_2) requiring the importation of external energy (electric boilers, heat pumps) in addition to excess heat.

Potential application in Asia and the world

The concept of partial CO_2 capture can be applied anywhere. However, it is important to stress that it can only be part of a comprehensive mitigation strategy that eventually leads to full mitigation. It is the near-term (5–10 years), where partial CO_2 capture is possible.

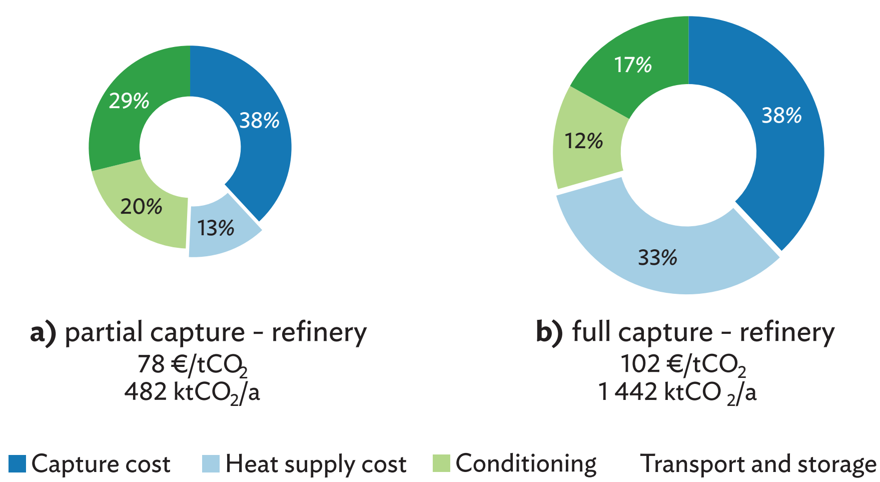
Especially suitable is process industry with large flows of CO_2, high-CO_2 concentration, and available excess heat, where alternative full mitigation is not feasible or available for the foreseeable future. An example is the cement industry or the steel industry (for sites that just have or are about to reinvest into coal-based blast furnaces and therefore will not invest into direct reduction technology with natural gas or hydrogen for the next ~15–20 years).

Other applications include waste incineration or pulp and paper mills, where biogenic and fossil carbon is co-processed, and the capture of the fossil CO_2 can bring fossil CO_2 emissions to zero. The development to full capture can then provide negative emissions (CO_2 removal from the atmosphere).

Related costs

Table 1 presents a generic comparison of a 90% full-capture design with a 60% partial-capture design via lower separation rates (same gas flow; same column size). Based on a gas flow of 200 kilograms/second (kg/s) with 20 vol% CO_2 and CO_2 capture with 30 weight (wt) % aqueous monoethanolamine (MEA). Cost comparison for a steam cost of €17/t steam (for comparison: steam from NG boiler ~€25/t steam), 7,000 hours operation/year; 25 years lifetime; discount rate of 7.5%. The example is taken from Biermann, Normann, Johnsson, and Skagestad (2018), in which absolute and specific cost savings for partial capture via lower separation rates are 26%

Figure 7: Carbon Dioxide Capture Cost Savings from Partial Capture and Full Capture



a = annum; k = kilo, tCO_2 = tons of carbon dioxide, € = Euro.

Sources: M. Biermann. 2022. Partial CO_2 Capture to Facilitate Cost-Efficient Deployment of Carbon Capture and Storage in Process Industries. PhD thesis. Gothenburg: Department of Space, Earth and Environment; Chalmers University of Technology. https://research.chalmers.se/publication/531680; M. Biermann, C. Langner, S. Roussanaly, F. Normann, and S. Harvey. 2022. The Role of Energy Supply in Abatement Cost Curves for CO_2 Capture from Process Industry – A Case Study of a Swedish Refinery. *Appl. Energy*. 319. pp. 119273. https://doi.org/10.1016/j.apenergy.2022.119273.

Table 1: Comparison between 90% Full-Capture vs. 60% Partial-Capture Design

		Full capture	Partial capture	Relative Change
Separation in absorber	%	90	60	–33%
Specific reboiler duty	MJ/kg CO_2	3.82	3.38	–12%
Annual CO_2 captured	Mt CO_2/yr	1.310	0.873	–33%
Investment cost	M€2015	125.6	93.4	–26%
Annualized CAPEX + OPEX	M€2015/yr	82.0	51.0	–38%
CAPEX	€2015/t CO_2	9.5	10.6	+11%
OPEX	€2015/t CO_2	53.0	47.8	–10%
specific cost	€2015/t CO_2	62.6	58.4	–7%

€ = Euro, CAPEX = capital expenditure, CO_2 = carbon dioxide, M = million, MJ = megajoule, Mt = million ton, OPEX = operating expenditure, t = ton, yr = year.

Source: M. Biermann, F. Normann, F. Johnsson, and R. Skagestad. 2018. Partial Carbon Capture by Absorption Cycle for Reduced Specific Capture Cost. *Ind. Eng. Chem. Res.* 57 (45). DOI: acs.iecr.8b02074. http://pubs.acs.org/doi/10.1021/acs.iecr.8b02074.

and 7%, respectively, compared to full capture. These moderate savings can add to the ones likely present if site-specific conditions (see refinery example above) are considered as well.

Status and next steps

- Research. Partial CO_2 capture for process industry has been studied in ~20 academic journal and conference contributions by the group around professors Normann and Johnsson.
- Pilot tests. The most recent study includes the pilot-scale field test of CO_2 capture from steam methane reformer flue gases conducted by Aker Carbon Capture AS and validates previous modeling work on the energy savings when operating columns at lower separation rates.
- Commercial relevance. The Norcem cement plant in Brevik, part of the Norwegian CCS project "Longship," plans to apply partial CO_2 capture (no involvement of Chalmers University of Technology), i.e., by targeting a capture rate ~50% of the site CO_2 due to restrictions in available heat.
- Next steps. A thorough academic techno-economic assessment is required on the inherent full-capture-ready design as a two-step CCS deployment comparing it to other designs and an immediate, single step full-capture implementation.

Challenges in scale-up and deployment

- **Support**. Interest of engineering, procurement, and construction companies to check the validity of the concept with their own cost data and technology.
- **Support**. In Europe, the price for emission allowances has reached a level which may be sufficient for partial (or full) capture. Policy measures that trigger investments and guarantee carbon prices at sufficient levels may still be needed, for instance, carbon contracts for difference.
- **Challenge**. The necessity for eventual full capture bears the question whether industrial stakeholders can timewise afford to deploy CCS stepwise or are required to deploy full capture immediately once they can justify the investments (25–30 years left until net zero is needed when aiming at 2050s).

Technology provider background

The Chalmers University of Technology is one of the leading engineering universities in Sweden. At the Division of Energy Technology (~60 staff), the core research activities focus on (i) thermal conversion processes (chemical looping combustion, fluidized bed technologies for combustion/gasification, thermochemical recycling of plastics, gas cleaning); (ii) diagnostic measurements and modeling (on-site industrial research in support of compliance with stringent emissions regulations); (iii) modeling and analysis of energy systems (model-based energy systems analysis for supply, distribution and demand of grid-based energy carriers); and (iv) process integration and process systems engineering (analysis and conceptual design of carbon-neutral and resource efficient industrial processes).

The application of solvent-based CO_2 capture has been researched by the group led by Filip Johnsson and Fredrik Normann since 2011, and the concept of partial CO_2 capture since 2015.

Further reading

F. Normann, R. Skagestad, M. Biermann, J. Wolf, and A. Mathisen. 2019. *CO2stCap -Reducing the Cost of Carbon Capture in Process Industry Final report.* https://research.chalmers.se/publication/512527.

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Game-Changing Carbon Dioxide Utilization Technologies

Utilization of Carbon Dioxide Captured from Waste-to-Energy Plants in Synthetic Natural Gas Production

Technology provider

WOIMA Finland Oy

Technology description

The ccWOIMA® carbon capture unit is stand-alone that unit can be retrofitted to existing power plants or combined with the wasteWOIMA® waste-to-energy (WtE) plant to generate carbon-neutral energy.

The ccWOIMA® carbon capture plant is based on CO_2 Capsol's patented end-of-pipe carbon capture technology. It utilizes hot potassium carbonate (HPC) as a solvent to capture CO_2 of the flue gas flow. The plant as shown in Figure 8 is designed to use only electricity as its energy source to simplify retrofitting existing power plants, but steam can also be utilized if available.

The captured CO_2 is then available for storage or utilization (e.g., synthetic methane production) in gaseous or liquid form. The purity of captured carbon is more than 95%.

WOIMA is a member of the EnergySampo CCU consortium that is building a next generation synthetic methane liquid synthetic natural gas (LSNG) production plant in Vaasa, Finland. The innovative modular plant complex producing the LSNG consists of four main processes (Figure 9): (i) the capture of CO_2 from the flue gases of the Westenergy plant, (ii) the production of green hydrogen through an electrolysis process, (iii) the combination of hydrogen and CO_2 into synthetic methane in the chemical methanation process, (iv) and the liquefaction of synthetic methane into transport fuel.

The carbon capture solution in the EnergySampo plant complex is the ccWOIMA® 20,000 tons per

Box 5: ccWOIMA Carbon Capture Plant Key Features

Technology Highlights

- Can be retrofitted to existing power plants to generate carbon-neutral energy
- More than 90% carbon dioxide (CO_2) capture rate
- Captured CO_2 purity of more than 95%
- Energy consumption of 200–300 kilowatt-hour/ton CO_2 captured
- Lifecycle cost of \$27/ton–\$43/ton of captured CO_2
- Uses safe and environment friendly potassium carbonate as CO_2 absorbent

Development Stage

- Pilot demonstration

Sectors of Application

- Energy sector—waste-to-energy, biomass, and fossil fuel power plants annum (tpa) module, which is the first part of the complex to enter into production. The carbon capture process, as shown in Figure 8, happens in the absorber where the CO_2 in the flue gas is chemically absorbed through a reaction with potassium carbonate (K_2CO_3) forming potassium bicarbonate ($KHCO_3$). The CO_2 content of the flue gas is thereby gradually reduced across the length of the absorber, leaving the absorber as CO_2-lean flue gas. The CO_2-rich solvent leaving the absorber is pumped to the stripper section of the desorber. The low partial CO_2 pressure in the desorber forces the solvent to release its high CO_2 content into the steam flow. Steam is then condensed back to water and the CO_2 is collected for further utilization or storage.

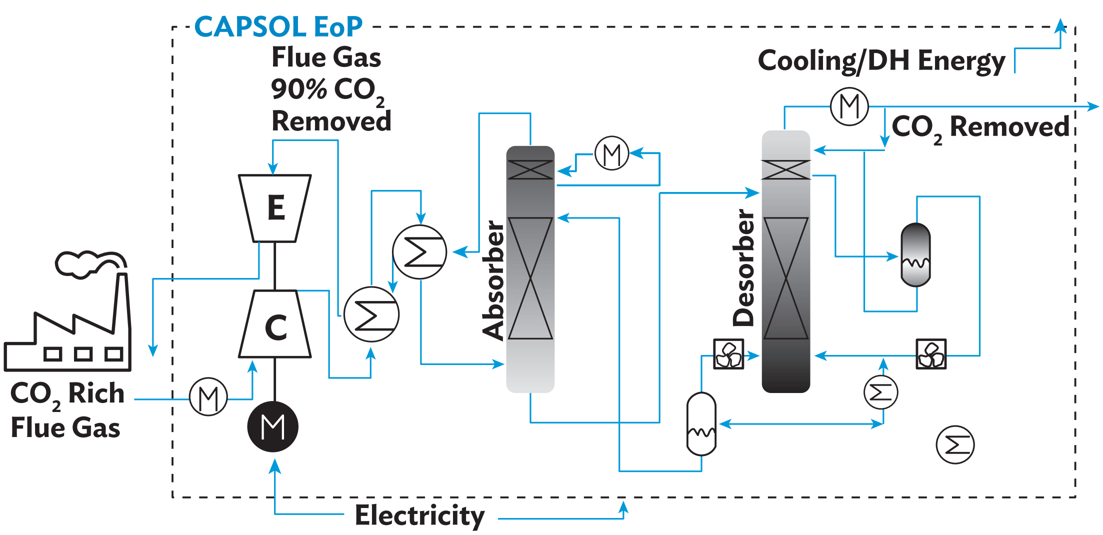
Green hydrogen production is a process by which hydrogen is produced from water through electrolysis using green electricity. The electrolysis process requires an electrolytic cell, which is a container that holds water and an electrolyte. An electrolyte is a medium that conducts electricity between two electrodes. Inside the cell, electricity is passed through the electrolyte, which separates the oxygen and hydrogen atoms in the water. The hydrogen atoms then migrate to the cathode, where they are collected.

The electricity used to power the electrolysis process can come from a variety of renewable sources, such as wind, solar, or hydroelectric power. The process produces pure hydrogen gas for a variety of applications, in this case methanation.

Methanation is a chemical process used to convert CO_2 and hydrogen into methane, a valuable fuel source and the main component of natural gas. The methanation process typically takes place at high temperatures and pressures in a reactor filled with a catalyst such as nickel, cobalt, or iron. This catalyst helps the reaction to occur by providing an active site where the hydrogen and CO_2 molecules can react. The methanation process is a critical part of the synthetic natural gas production process and is used to produce a variety of fuels and chemicals.

LSNG liquefaction is a process used to convert natural gas into liquid fuels. In this process, natural gas is cooled to subzero temperatures and then compressed until it reaches its liquid state. The process includes a series of steps including pre-treatment, cooling, compressing, and condensing. This liquefaction of the gas reduces its volume by up to 600 times, making it easier to store and transport. The liquefied gas is

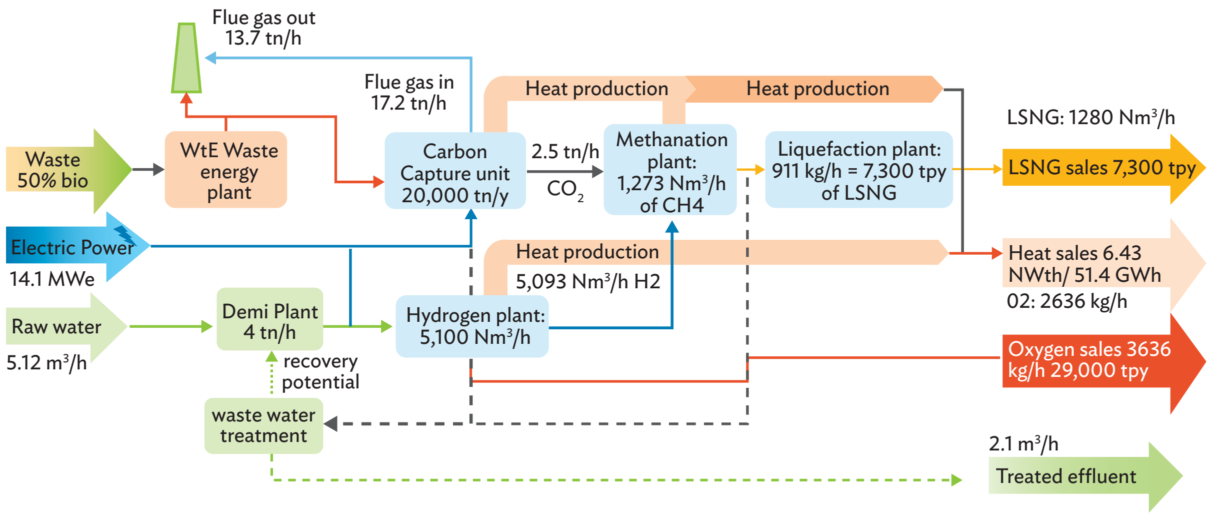
Figure 8: The ccWOIMA Carbon Capture Plant Process



CO_2 = carbon dioxide, DH = district heating.

Source: CO_2 Capsol AS Company Presentation. 2021. Oslo, Norway.

Figure 9: EnergySampo CCU Liquid Synthetic Natural Gas Production



CO_2 = carbon dioxide, GWh = gigawatt-hour, kg/h = kilogram per hour, LSNG = liquid synthetic natural gas, m3/h = cubic meter per hour, MWe = megawatt (electric), MWth = megawatt (thermal), Nm3/h = normal cubic meter per hour, tn/h = tons per hour, tn/y = tons per year, tpy = tons per year.

Source: EnergySampo CCU Pilot Project Presentation. 2023. Mustasaari, Finland.

then used as a transportation fuel, or transported to a regasification facility, where it is converted back into gaseous form and delivered to customers.

All four processes are equally important in the production of LSNG. They also all rely on technologies that have been around for decades and have hundreds of references in the field each. However, it is only recently that, through innovation and development, these technologies have become cost-competitive and can offer a true alternative to fossil natural gas. It is forecasted that the natural gas price will climb above $10/million British thermal unit by 2025, which is also roughly the levelized production cost of LSNG making it the preferred environmentally friendly option for gas consumers.

The processes generate excess heat, which is utilized in the local district heating network. It also reduces the fossil CO_2 emissions of the local WtE power plant by 25%. The LSNG supply will utilize the existing natural gas and biogas distribution networks, thus enabling and ensuring the efficient utilization of the methane-bound green hydrogen.

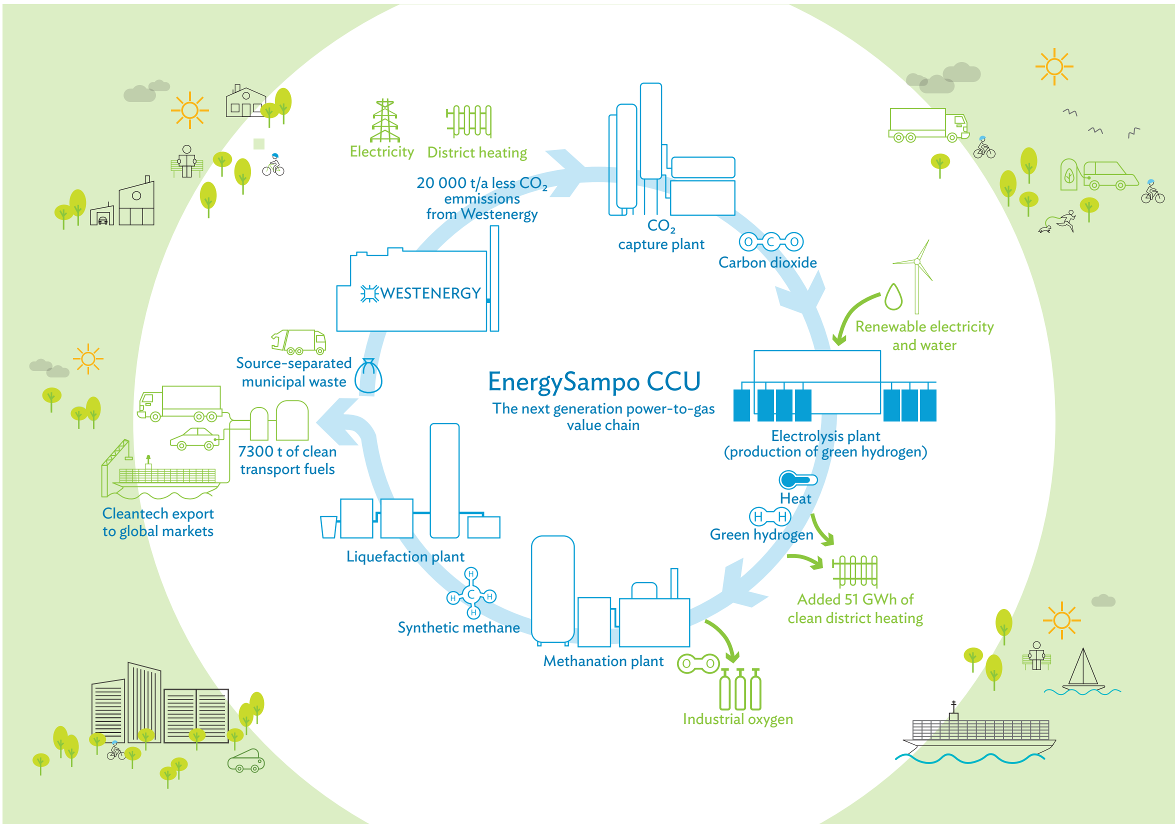
The construction starts by the end of 2023 and enters production in 2025. The production process is powered by 100% renewable wind energy. The value chain of EnergySampo CCU consortium is illustrated in Figure 10.

Technology advantages

HPC offers a commercially available alternative to proprietary amines in carbon capture. Because of ccWOIMA's patented energy recuperation process, the energy consumption of the ccWOIMA® capture process is 200–300 kilowatt-hour (kWh)/ton of CO_2 captured (i.e., 0.7–1.1 GJ/ton of CO_2 captured). The plant has been designed to work on electricity alone, in case no thermal energy is available. But a combination of steam and electricity is also possible to power the process. The above energy consumption figures apply to both cases. Typically, the cost of thermal energy is cheaper than that of electricity, making it the preferred option is most cases.

The ccWOIMA® is available in three modular pre-engineered and prefabricated size classes: 20,000; 75,000; and 200,000 tons of CO_2 captured per

Figure 10: EnergySampo Carbon Capture Utilization Value Chain



CCU = carbon capture utilization.

Source: EnergySampo CCU Pilot Project Presentation. 2023. Mustasaari, Finland.

annum. The ccWOIMA® is a completely stand-alone easy-to-install unit and the delivery project does not interfere with the existing facility. The carbon capture delivery time is less than 15 months. This modularity of ccWOIMA® could allow fast-track projects for small-to-medium-scale power plants. The footprint for the 20,000-tpa plant is less than 1,000 square meters (m^2). The required utility connections are electricity, potable water lines, and evacuation of thermal energy, if that is utilized. See page 23, for the model of a ccWOIMA® plant.

One of the ccWOIMA® plant design bases is a 30-year life span , i.e., the plant material and equipment selection supports operating the plant for 30 years without any major overhaul. Naturally, standard annual corrective, preventive and predictive maintenance is required. Thus, the plant offers 600,000; 2,250,000; and 6,000,000 tons of CO_2 savings over its life cycle for the 20,000-; 75,000-; and 200,000-tpa plant versions. And if the produced LSNG is used in power generation for example, it is possible to recapture and recycle the same CO_2 in perpetuity.

The key advantages of the EnergySampo CCU include

- diversifying the Finnish energy infrastructure;
- reducing reliance on imported energy;
- extending the life span of the existing natural gas storages and distribution networks;
- utilizing the excess, mostly night-time, wind energy in green hydrogen production;
- creating new export potential for Finnish companies; and
- decarbonizing the power generation in the Vaasa (Finland) region.

The key advantages of ccWOIMA®:

- its ability to run on flexible power source (electricity and/or steam);
- it uses solvent that has been proven in thousands of plants globally in multiple industries;
- it uses cheap globally available solvent commonly used as an additive in food;
- it is completely safe—no hazard to environment or people;
- it produces noncarcinogenic solution—captured CO_2 is totally free of degraded (potentially carcinogenic) amines; and
- is available in three different-size carbon capture plants for immediate delivery.

The stand-alone ccWOIMA® unit can be retrofitted to existing power plants or combined with the wasteWOIMA® WtE plant to generate carbon-neutral or even carbon-negative energy, depending on the fuel. One of the key drivers behind carbon capture in the WtE segment is the upcoming inclusion of WtE in the European Union (EU) Emissions Trading System around 2028. This forces WtE plant owners and/or operators to either invest in carbon capture solutions or purchase carbon credits to offset their CO_2 emissions. It will lead to accelerated product development and eventually reduced costs in the carbon capture field where Europe acts as a role model for the rest of the world.

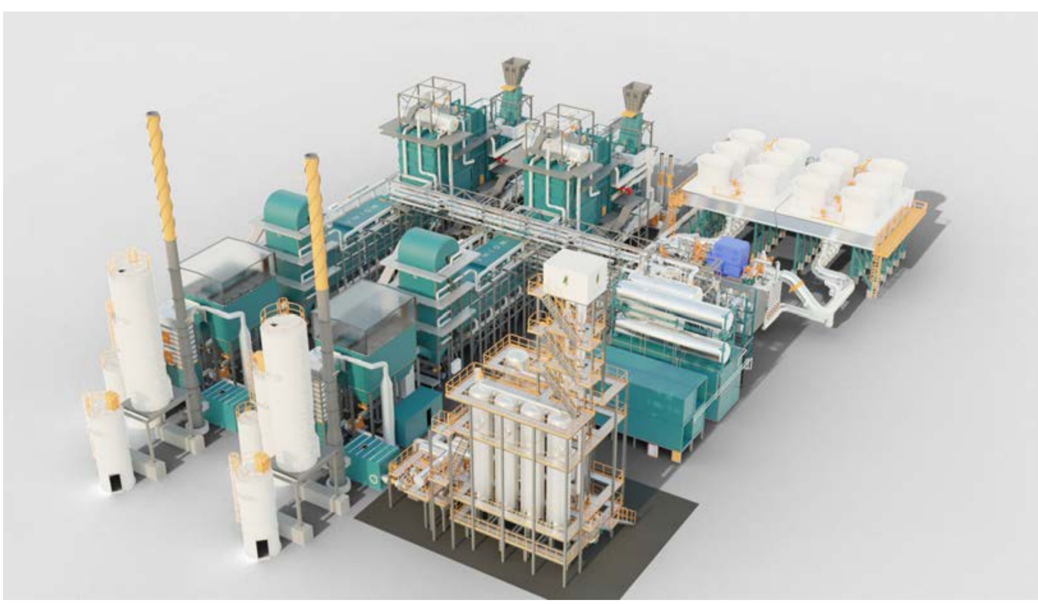
Related costs

The carbon capture project cost is not linear, and economies of scale apply to it even more than to other technical solutions, i.e., larger unit have a significantly lower unit capture cost. Typical capital investment range for the modular ccWOIMA® plant is \$213/ton–\$532/ton of CO_2 capture capacity, or \$11/ton–\$27/ton of captured CO_2 over the life span of the plant. Operating expense for the plant typically ranges between \$16/ton and \$32/ton of captured CO_2. These lead to a life cycle cost of \$27/ton–\$43/ton of captured CO_2.

Potential application in Asia and the world

The likely first adaptors for the CCUS technology are the more developed countries lacking their own oil and gas production, such as Japan, the Republic of Korea, and Singapore in Asia, as well as the EU countries, the United Kingdom, Australia, and New Zealand.

The LSNG produced from captured CO_2 is one route to reducing natural gas dependency. The LSNG utilizes the already existing LNG infrastructure, thus, offering



Rendering of a ccWOIMA Carbon Capture Plant. Replacing One-off Design Approach with Modular Concept - Woima Corporation (WOIMA Finland Oy Company Presentation. 2022. Vaasa, Finland) an easy transition to a sustainable fuel source. Other potential CO_2 off-take applications are chemical and food industries, as well as greenhouses. All these opportunities are universal, although greenhouses are likely to be used more in colder climates.

Challenges in scale-up and deployment

The two key challenges in expanding the CCUS market are project financing and lack (or cost) of CO_2 off-take. In project financing more innovative financing approaches, such as using the future carbon credits as part of the financing package. On the off-take side, storage solutions logistics are costly, and utilization solutions are still in their infancy. Clearly, public funding plays a key role in the commercialization of both carbon capture and CO_2 utilization solutions.

Technology provider background

WOIMA was established in 2017 with a vision of revolutionizing the WtE market segment. WOIMA's small-to-medium-scale wasteWOIMA® power plant is a modular pre-engineered and prefabricated solution that enables fast delivery time, minimized on-site presence, workshop-level quality control, and the lowest capital and OPEX in the market. WOIMA's business model practically de-risks the project delivery completely. This localized solution decentralizes waste management and WtE power generation using local fuel (waste), employs local people, and delivers energy to local people and businesses.

WOIMA has global delivery capability through the cooperation with minority shareholder Sumitomo SHI FW Energia Oy, a subsidiary of the Sumitomo Heavy Industries Group. They provide sustainable energy solutions with more than 500 global references.

Further reading

CO2CAPSOL
Sustainable Bus. 2018. Vaasa, Finland, towards carbon neutrality with biogas fuelled Scania buses. 29 October.

WOIMA Corporation
WOIMA. 2022. Climate Positive Synthetic Methane Production Starts in the Vaasa Region in 2025. Press Release. 8 March.

Carbon Dioxide Utilization in Textile Dyeing

Technology provider

DyeCoo Textile Systems B.V. (The Netherlands)

Technology description

Dyeing polyester fabrics is done by bringing dyestuff into the polymer structure. Polyester polymer when heated above 110°C swells creating cavities where dye molecules fit in. After cooling down the polyester, the dye molecules are trapped in the polymer cavities. By this principle the dye molecules are fixed into the polyester matrix and the fabric gets its wash fastness properties.

In conventional dyeing process, which happens between 120°C and 135°C and a pressure of 5 bar, polyester is dyed using water and dispersing agents to transport the dye molecules to the polyester. Coming in close contact with the polyester during the process, dispersed dye molecules having high affinity for the polyester, migrate into the polyester cavities from the water. The dispersing agent remains in the water. At the end of the process, however, not all the dye is transferred into the polyester leaving the water polluted with dye, dispersing agent, and chemicals used to promote and control the dyeing. After dyeing, the fabric is washed to remove surface dye and give the fabric the right properties.

Dyecoo's textile dyeing technology uses supercritical carbon dioxide (sc-CO_2) as process solvent instead of using water to bring the dyestuff into the textile. Polyester has a good affinity for sc-CO_2. Supercritical CO_2 dissolves a little in the polyester promoting the swelling and opening of the cavities. The dye molecules can, by nature, dissolve in the sc-CO_2 like sugar in water. So, no chemicals are needed to make sc-CO_2 a transport medium to bring the dye into the polyester. The dye molecules for water and sc-CO_2 dyeing are the same.

Box 6: DyeCoo Textile Systems Key Features

Technology Highlights

- Uses reclaimed carbon dioxide
- Saves water
- Saves energy used for water treatment
- Allows chemical-free dyeing
- Prevents water pollution

Development Stage

- Commercial

Sector of Application

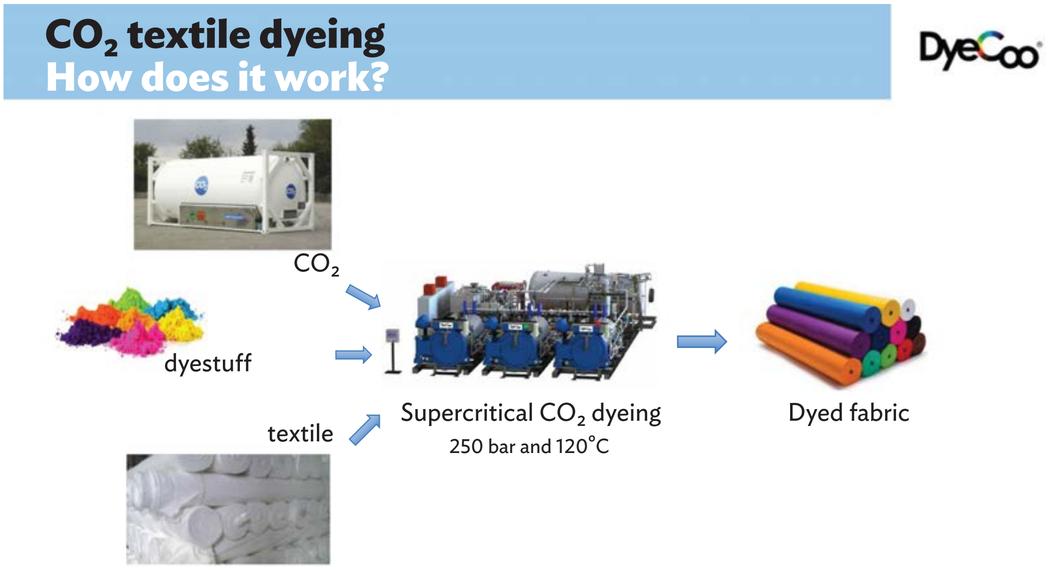
- Textile industry

For the process shown in Figure 11, the fabric or yarn is placed on a roll or bobbin into the pressure vessel. The pure dyestuff (a dry powder) is in a cartridge placed in the pressure vessel. The vessel is closed and filled with CO_2 until it reaches the right dyeing conditions. These conditions are a temperature between 110°C and 120°C and a pressure of 250 bar.

Circulating through the machine, as shown in Figure 12, sc-CO_2 picks up dye molecules from the dye cartridge and brings this to the fabric. The dye is captured by the polyester because of high affinity of dye for polyester. After a fixed time for dyeing and leveling the vessel is depressurized by releasing the CO_2 through a separator where the CO_2 is cleaned into the CO_2 work tank in the machine, ready to be reused for the next batch. Up to 95% of the CO_2 is recycled in the process. The last bit of CO_2 is released to the atmosphere (as recompression takes more energy than it saves as CO_2). The vessel is opened, and the fabric is dyed, still dry and ready for use.

Technical grade CO_2 collected as waste product from industrial processes and from biological processes like fermentation, and sourced from gas companies can be used for the process. As the quality of the CO_2 is the same everywhere in the world, sc-CO_2 dyeing always gives the same result.

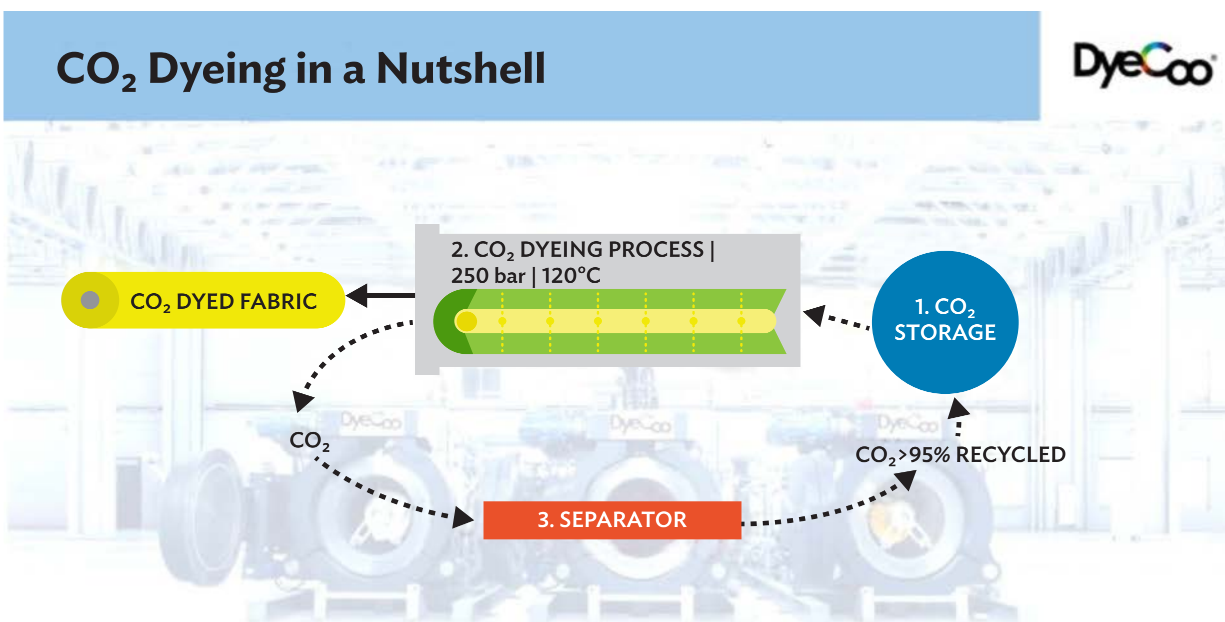
Figure 11: Carbon Textile Dyeing Process



°C = degree Celsius, CO_2 = carbon dioxide.

Source: DyeCoo corporate presentation. 2022.

Figure 12: Carbon Dioxide Dyeing in a Nutshell



°C = degree Celsius, CO_2 = carbon dioxide.

Source: DyeCoo corporate presentation. 2022.

Technology highlights and advantages

Unlike conventional methods of dyeing polyester, DyeCoo's technology uses reclaimed sc-CO_2 instead of water and avoids the use of process chemicals, like dispersing and leveling agents. DyeCoo's technology results in a clean and zero liquid waste textile dyeing process. Today's installed capacity for sc-CO_2 textile dyeing is roughly over 50 million meters per year and equates to over 475 million liters (l) of water and waste water being saved, by sc-CO_2 textile dyeing alone.

The most advanced sc-CO_2 textile dyeing facility at the moment is Cleandye in Viet Nam, which serves as a benchmark factory for Adidas and Decathlon. Cleandye consumes less than 25 liters of water per kg fabric from greige to finished fabric and the only water usage is only for pre- and post-treatment steps. A total water footprint of 25 l/kg fabric (greige in—finished fabric out) is roughly a factor 3 to 4 better than the industry average (70 l/kg to 120 l/kg).

The true sustainable impact of sc-CO_2 textile dyeing lies in the elimination of the use of water and chemicals in the dyeing phase and the absence of wastewater from the dyeing phase. Based on a 2022 least-cost analysis executed in Viet Nam, it is shown that a CO_2 dyeing routing versus a traditional water dyeing routing can significantly reduce the overall carbon footprint, primary energy usage and water footprint. In some cases, the reduction potential is far >50%.

Related costs

Capital expense for a DyeCoo dyeing unit (excluding auxiliary equipment) is approximately $2.93 million for a 3–3.5 ton/day CO_2 dyeing capacity. The operational cost for a fourth-generation CO_2 dyeing machine is on average around $1/kg and competitive with traditional water dyeing for fabrics in the supply chains of international brands and retailers.

Potential application in Asia and the world

The textile industry is worldwide and present at large scale in many Asian countries.[7] Industry reports indicate that global textile market valued at $994 billion in 2021 could grow at a compounded annual growth rate of 4% from 2022 to 2030, while polyester fiber market value was estimated at $88.29 billion with a compound annual growth rate of 8.93% from 2021 to 2026.[8, 9]

Information from DyeCoo indicates that, in terms of quantity, polyester fibers represent more than 50% of the total fiber types (like polyester, polyamide, cotton, and wool) for textiles. More than 70% of the polyester supply chain for international brands and retailers lies in Asia, hence the largest impact of sc-CO_2 dyeing technology could be expected in Asia. This is also driven by the typical high volume PET dyeing operations that could justify investment in large capacity CO_2 dyeing operations.

DyeCoo sc-CO_2 dyeing machines are in use in Taipei,China; Thailand; and Viet Nam. Next machines will be installed in the Republic of Korea. Advanced contacts for machine deployment are in India and Bangladesh. In Europe, the first machines will be installed in the Netherlands by early 2023. Türkiye is another country for potential deployment of the DyeCoo machines.

Status and next steps

DyeCoo developed and industrialized the technology over the past 10 years and is currently selling its fourth-generation CO_2 dyeing machines, which are capable to dye both yarn and fabric in the same machine. Future steps will include increasing the application range beyond polyester materials and focusing on further steps to reduce energy usage and

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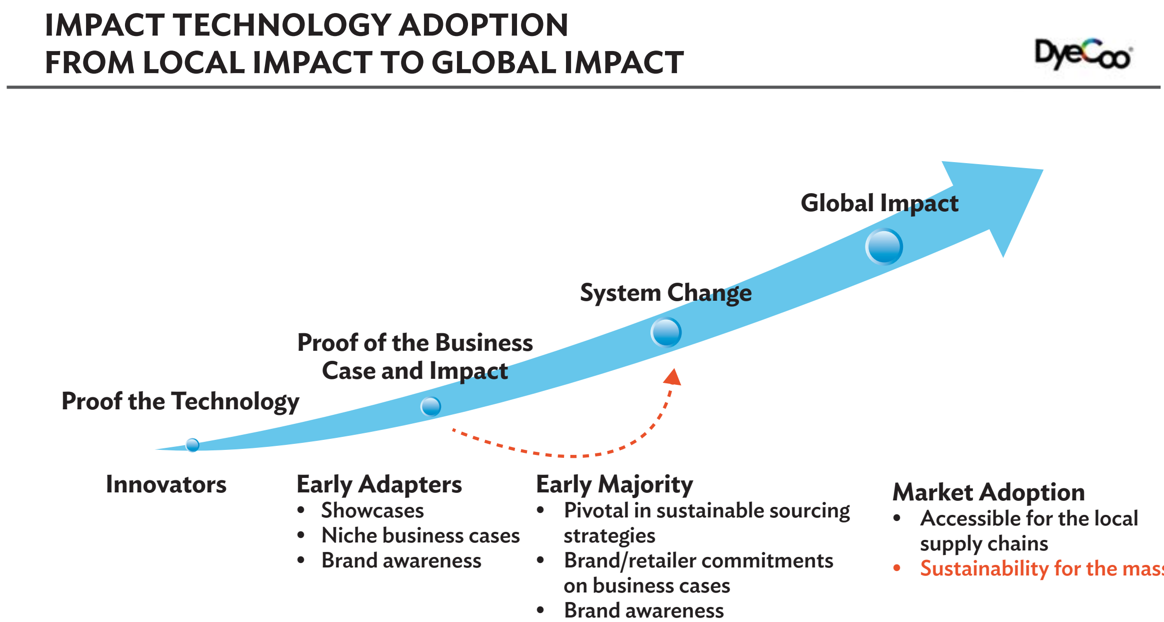
7 Five of the top 10 economies exporting textiles are in Asia. These are the People's Republic of China; Viet Nam; Bangladesh; India; and Hong Kong, China. (*Top 10 Exporting Countries of Textile and Apparel Industry*. Fibre2Fashion. Top 10 Exporting Countries of Textile and Apparel Industry - Fibre2Fashion.)

8 Grand View Research. *Textile Market Size, Share and Trends Analysis Report By Raw Material (Cotton, Wool, Silk, Chemical), By Product (Natural Fibers, Nylon), By Application (Technical, Fashion)*, By Region, And Segment Forecasts, 2022–2030. Global Textile Market Size and Share Report, 2022–2030 (grandviewresearch.com).

9 Polyester Fiber Market. 2022. *Polyester Fiber Market Segmentation By the Product Type (Polyester Staple Fiber, PSF and Polyester Filament Yarn, PFY), By Application (Apparel, Industrial and Consumer Textiles, Household and Institutional Textiles, and Carpets and Rugs), By Grade (PET and PCDT), and By Product (Solid and Hollow) Industry Forecast to 2027*. Market Data Forecast. Polyester Fiber Market Size, Share and Trends | 2022 to 2027 (marketdataforecast.com).

Figure 13: Impact Technology Adoption from Local to Global



Source: DyeCoo corporate presentation. 2022.

to customize solutions to fit with industrial business cases for fabric and yarn dyeing.

Challenges in scale-up and deployment

As CO_2 dyeing is technologically and commercially proven, DyeCoo is moving away from the early adopters and innovators and is entering the stage for larger scale adoption, driven by investment business cases supported by brands and retailers. Figure 13 illustrates how the adoption of impact technologies transitions from local to global impact.

Impact technologies such as DyeCoo's dyeing technology are inherently linked with higher capital expenditure investments, but often provide competitive operational cost versus conventional technologies. For impact technologies to be successful, DyeCoo sees the need for technological confidence in the market and solid business cases that are driven by a top-line demand from the market. Commitment of brands and retailers to investments based on impact technologies to drive systematic change in their supply chains based are also crucial. A big help would be the introduction of stricter legislation and policy frameworks that provide incentives for the use of impact technologies over conventional technologies.

Technology provider background

DyeCoo Textile Systems B.V., established in 2008, designs, develops, builds, and sells commercial production machines for dyeing textile fabric and yarn using sc-CO_2. Eight clients in Asia and Europe are using DyeCoo's technology and machines for coloring textiles for leading textile brands and retailers worldwide.

Further reading

DYECOO.com
CLEANDYE.com

Carbon Dioxide Utilization in Algae Protein and Oil Production

Technology provider

Global Algae Innovations, Inc. (United States)

Technology description

Global Algae Innovations, Inc. (Global Algae) has leveraged radical advances in large-scale algae production along with a systems approach and a detailed techno-economic model to develop breakthroughs throughout the entire process. Global Algae is demonstrating these advances in an 8-acre algae farm that includes one of the world's largest open pond raceways. It is the world's only large-scale open raceway facility that relies on either direct air capture or power plant flue gas as the CO_2 source.

Technology advantages

Algae farming sequesters CO_2 in two ways. First, the algae cultivation directly captures CO_2 from the atmosphere, and a portion of the algal oil is converted into polymer products for long-term sequestration of the carbon. Second, the growth of algae allows for natural habitat restoration including rainforest regrowth, which will capture CO_2 and store it in both above ground and below ground biomass.

Further to sequestration of carbon dioxide, cultivation of algae for simultaneous production of edible protein and oil could also be a solution to deforestation. Algae farming is 25 times more productive than soy and palm oil, allowing communities to help restore the environment, prosper economically, and help meet the world's growing protein and oil demand. Each acre of algae will produce protein equivalent to 17 acres of soy and vegetable oil equivalent to 8 acres of palm, so 25 times less land is required for production of these important commodities.

Box 7: Global Algae Innovations' Advanced Algae Farming Key Features

Technology Highlights

- Captures carbon dioxide while growing algae that can be used to make food and agricultural products
- Helps solve deforestation
- Saves energy compared to other algae farming methods

Development Stage

- Pilot demonstration

Sectors of Application

- Food
- Agriculture

Related costs

Capital costs for the eight-acre pilot farm will be approximately $65 million. Operating costs will be approximately $5 million per year. Once at commercial scale, the capital investment will be approximately $500 million and operating costs will be approximately $60 million. The farm will capture nearly 8,000 tons of CO_2 per year from the atmosphere.

Potential application in Asia and the world

The technology is applicable in any country that has enough land, sunlight, and water.

Status and next steps

Global Algae is currently fully funded for research and development (R&D) through 2025. It has two contracts that will allow Global Algae to break ground in Fall 2022 on a scale-up demonstration. They have 19 other active contracts from the Government of the US to continue our research and continue to lower the cost of production. They are also breaking ground on their XPRIZE Carbon Capture competition facility in the fourth quarter of 2022.[10]

[10] Xprize Carbon Competition is a $100 million competition aimed at tackling climate change and rebalancing Earth's carbon cycle. Xprize Carbon Competition is funded by the Musk Foundation.

Challenges in scale-up and deployment

Global Algae is working toward a two-step scale-up to become competitive with commodity pricing at commercial scale. Global Algae have secured the funding needed to break ground and operate the partially built first step of the scale-up. Global Algae is seeking funding to build the remainder of the pilot farm. At this point, funding is the single largest barrier to commercialization of algae farming.

Technology provider background

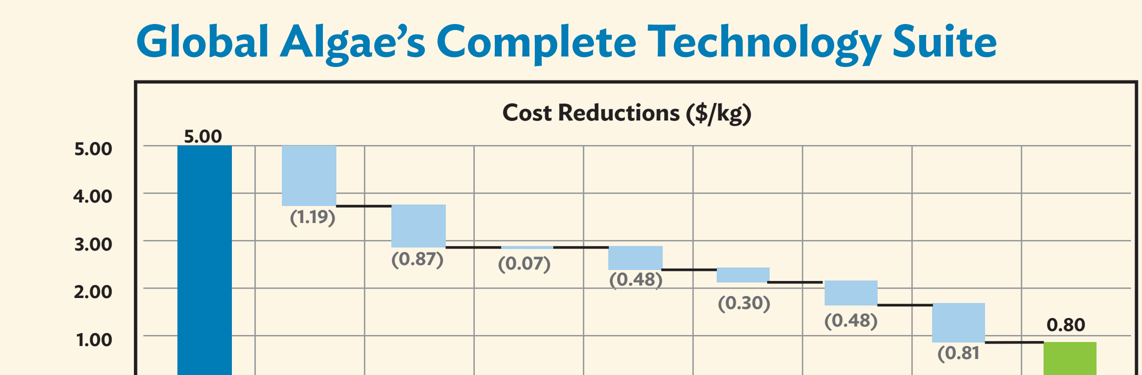
Global Algae Innovations was founded in 2013 to harness the unparalleled productivity of algae to provide food and fuel for the world, dramatically improving the environment, economy, and quality of life for all people. Algae farming achieves 25 times more productivity per water or land input than any other crop, so commercialization of algae farming for commodities will radically transform the world for the better. Global Algae has developed 65 innovations in algae cultivation and processing such that algae oil and protein are now projected to be economically competitive for commodities.

Global Algae has implemented 65 innovations at large scale including 11 major breakthroughs and have R&D in progress on over 85 additional innovations in algae farming. As shown in Figure 14, these advances achieve an order of magnitude improvement over conventional technologies.

Further reading

Global Algae.

Figure 14: Global Algae's Key Innovations and Energy Cost Reductions



	Conventional	Cultivation	Harvesting	Nutrient Supply	Stability and Inoculation	CO_2 Supply	Extraction	Extraction	Global Algae
Major Breakthroughs	-	3	2	0	1	2	1	2	11
Other Key Innovations	-	19	7	1	14	4	4	5	54
R&D in progress		37	7	8	13	9	9	2	85

CO_2 = carbon dioxide, kg = kilogram, R&D = research and development.

Source: Global Algae Innovations.

Carbon Dioxide Utilization in Biogenic Construction Materials

Technology provider

CO2Tech (Australia)

Technology description

Lignik Technology is based on the Lignik process, which was developed as a part of Australian CO_2 utilization research work. Its objective was on the production of low-cost and disaster-resistant houses for developing countries and enabling large-scale manufacture of prefabricated house construction materials to address the housing shortage crisis in the developing countries.

In the Lignik process (Figure 15), naturally occurring capnophilic microbes feed on CO_2 and biowaste to produce product/s that can be used as construction materials, thereby sequestering CO_2 into the construction product. Microbes obtain their hydrogen and energy for the capnophilic process from the biowaste. In this process, biowastes are fractionated into three basic components that are then upgraded into the final three products via capnophilic (Figure 15a), carbonization (Figure 15b) and closed-cell structurization processes (Figure 15c) that consume CO_2.

Box 8: Lignik Technology Key Features

Technology Highlights

- Utilizes carbon dioxide (CO_2) to produce disaster-resistant building materials.
- Captures 58% more CO_2 than other capnophilic processes.
- Sequesters 1 ton of CO_2 per 10 square meters of Lignik building material.

Development Stage

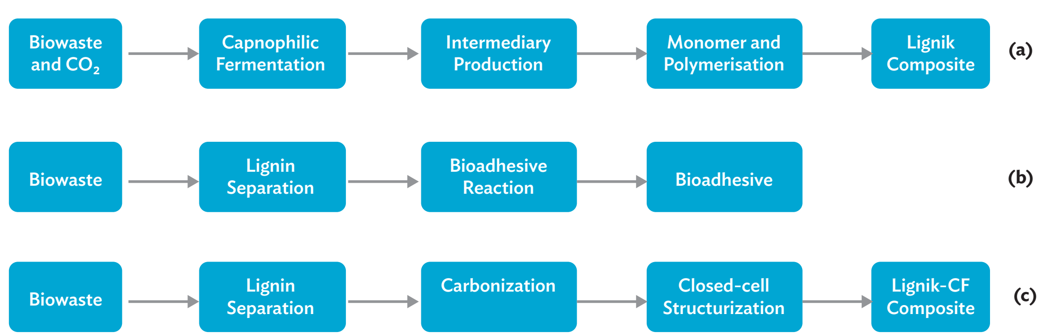
- Pilot demonstration

Sector of Application

- Construction

Fractionation of biomass thermochemically separates out cellulose, hemicellulose, and lignin. During the capnophilic process, the microbes consume CO_2 and the renewable carbon from the sugars to produce an intermediary chemical in a fermenter, which operates at approximately room temperature and pressure. A set quantity of the intermediary chemical is polymerized, with the rest used to convert some of the lignin into a bioadhesive. A major portion of the lignin is, however, treated to produce the Lignik composite. The leftover lignin is treated and undergoes carbonization for the production of the carbon fibers, which are then sent to the closed-cell structurization

Figure 15: Lignik Composite Production Process



CO_2 = carbon dioxide, CF = carbon fiber.

Source: A. Ghayur. 2019. Latrobe Valley circular industrial ecosystem. Federation University Australia. PhD dissertation: pp. 108.

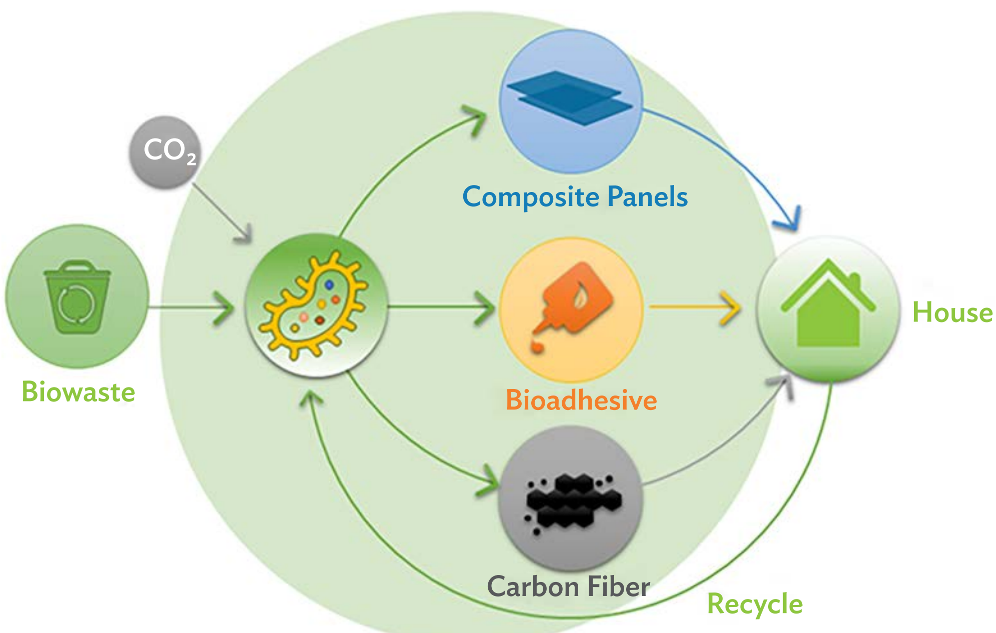
process where the polymer and further gaseous CO_2 are consumed to produce the carbon fiber composite. CO_2 needs to be pure for all the processes.

The processes themselves can tolerate significant impurities, although purity ensures that the final product itself contains no contaminants harmful to humans (any impurities could be incorporated into the building structure). Overall, for 10 tons of biomass consumed, 1 ton of CO_2 is needed. This CO_2 can come from any point source, provided that the source does not contain any harmful contaminants. If gaseous CO_2 is not available, the capnophilic microbes can easily consume carbonate salts (e.g., sodium carbonate) as a substitute, without compromising the production quality or yield.

The Lignik process is based on commercial technologies and has been specifically designed and optimized to consume 58% more CO_2 than any competing capnophilic process. These commercial technologies are the bioreactors for the capnophilic process, carbonization equipment for the carbon fibers, and the closed-cell structurization reactor. The Lignik process produces nearly zero waste and requires no external energy source.

As shown in Figure 16, the process yields three sustainable products—composite, bioadhesive, and carbon fiber—that could replace brick, concrete, and steel for the construction sector. Chemically identical to other forms of composite, adhesive, and carbon fiber, these products have properties superior to brick and concrete construction but use less material and result in lower overall construction costs. Houses based upon Lignik materials can be designed to offer superior disaster resistance to earthquakes, water damage, etc., although this would require structural engineering-related requirements for disaster-prone areas to be incorporated in the building design. The materials are also better insulated against heat and cold than traditional components, thereby reducing energy requirements and further decreasing carbon emissions.

Figure 16: Products of the Lignik Process



CO_2 = carbon dioxide.

Source: A. Ghayur. 2022. Lignik: A step-change for CO_2 utilization in the construction industry. *Carbon Capture Journal*. 90: pp. 2–4

As Lignik products can be designed to be 3D-printed as a single unit or be utilized in wall panel-based constructions, they can potentially lower construction costs further and enable prefabricated construction. The low material composition and density of the products also lead to lower overall weight, which facilitates relatively easier container transportation of the buildings to the final destination. Finally, the Lignik process results in the 100% recycling of its products, which promotes the establishment of a circular economy with no waste.

Technology advantages

- All Lignik materials are made from CO_2, and so each building sequesters approximately 1 ton of CO_2 per 10 m^2 of construction. Thus, a 70 m^2 house can potentially sequester around 7 tons.
- Each commercial production facility has the potential to sequester annually up to 1.5 million tons using current commercially available machinery. Research, development, and demonstration has the potential to further increase this capacity.
- There is global potential to sequester billions of tons of CO_2 annually using 100% renewable housing.

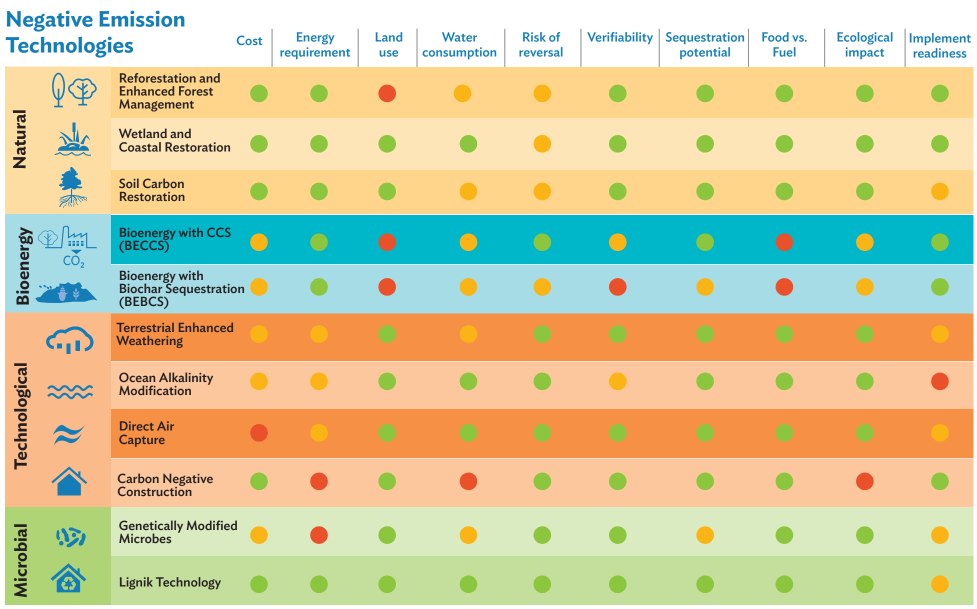
Lignik Composite Sample. Lignik products can be designed to be 3D-printed as a single unit or be utilized in wall panel-based constructions (Photo by A. Ghayur. 2019. Latrobe Valley circular industrial ecosystem. Federation University Australia. PhD dissertation: pp. 108)

- In contrast to the bioethanol production process, the Lignik process does not consume food (see Food vs. Fuel in Figure 17). It consumes nonfood and biowastes that are produced as a waste component of food crops. This also eliminates the issue of land use, as no food-growing land is utilized for the process.
- The Lignik process does not emit CO_2 as a waste product, unlike bioethanol and biogas processes.
- Microbes consume hydrogen from biowaste, thus eliminating the need of an energy-intensive hydrogen supply.
- Widely available, naturally occurring microbes were specifically selected over genetically engineered ones to reduce potential future risks.
- The Lignik process is a negative emission technology that can sequester more CO_2—at least 58% more CO_2 than other any other capnophilic process.
- Buildings constructed from the process can potentially be 100% recyclable. Figure 18 provides the applications and strengths of houses constructed using Lignik materials.
- A Lignik-based building construction process has minimum impacts to natural ecosystems as there is no requirement of topsoil extraction for bricks and sand mining.
- The feedstock is renewable and thus the supply is constant. In contrast, developing countries are running out of minable clay and sand for brick- and concrete-based carbonation technologies. The supply issue associated with mined clay and sand in developing countries is also leading to multifaceted social issues, such as continuously increasing costs and perhaps illegal activities and processes within the industry.

Related costs

Detailed techno-economic simulations for the production of the Lignik materials (platform chemicals) have shown that the upfront capital cost for a commercial-scale facility in Australia is approximately $150 million. Such a facility could produce enough platform chemicals for the construction of 10,000 houses annually, which equates to the sequestering of 100,000 tons of CO_2 per year. This capital cost does not include the cost

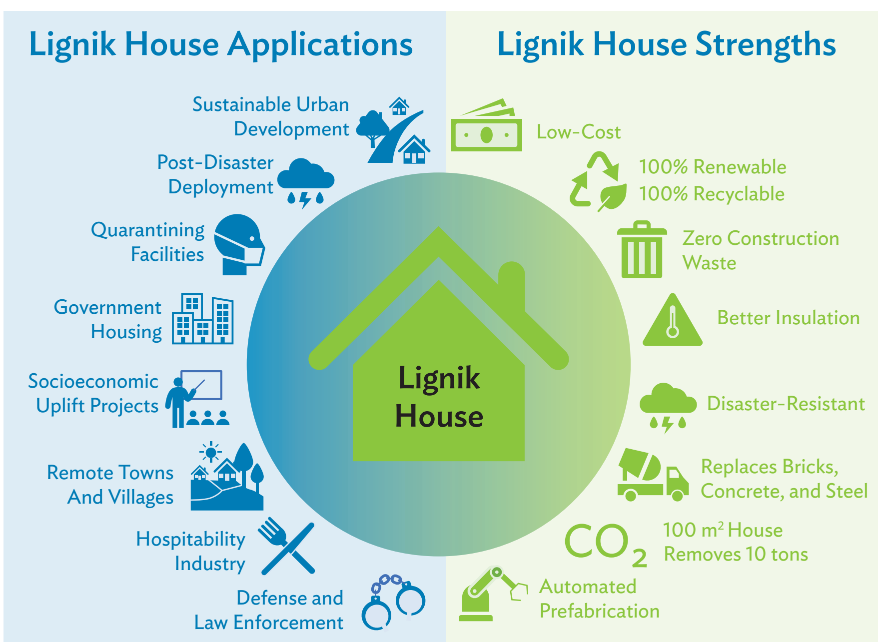
Figure 17: Lignik Technology Comparison with Negative Emission Technologies (Traffic Light Rating System)



Note: Red circle—High resource requirements/high cost, risk; Yellow circle—Moderate resource requirements/moderate cost, risk; Green—Low resource requirements/low cost, risk.

Source: A. Ghayur. 2022. Lignik: A step-change for CO2 utilisation in the construction industry. *Carbon Capture Journal*. 90: pp. 2–4.

Figure 18: Lignik House Strengths and Applications



CO_2 = carbon dioxide, m^2 = square meters.

Source: CO2Tech. 2022. “Development of renewable composites for a circular bioeconomy.” Melbourne, Australia.

for the construction of the houses; it is only for the production of the intermediary platform chemical materials. The techno-economic simulations also show the annual operating costs were approximately $30 million for the modeled Australian site. These costs would vary depending upon the location and size of the facility.

Potential application in Asia and the world

The low-cost Lignik Technology was specifically developed for application in developing countries, albeit with the potential for global application. As indicated in Figure 18, low-cost houses made of Lignik materials are also suitable for

- fast deployment of post-disaster housing facilities;
- fast deployment of quarantining facilities;
- sustainable urban development;
- government housing projects;
- donor agency-supported projects;
- socioeconomic uplift projects (e.g., schools, clinics);
- remote location towns and villages; and
- the hospitality industry.

Additionally, this technology is also applicable in countries where stubble-burning practices lead to environmental issues. This stubble is ideal as a biowaste feedstock for the capnophilic microbes. Thus, by producing 100% renewable housing, developing countries could tackle the twin challenges of pollution and a housing shortfall.

Status and next steps

CO2Tech, the commercial arm of CO_2CRC (see below), has completed the following R&D activities:

- the development of the Lignik process,
- sourcing of microbes, and
- the preparation and analysis of sample Lignik wall panels.

Currently, wall panels made from these materials are being prepared for accelerated weathering tests to assess the potential life span of constructed houses. The long-duration weathering test results and the associated wall panel samples should be available in the second half of 2023.

A concept study for a demo-scale facility and detailed techno-economic simulations for a commercial-scale facility was completed in 2021. The techno-economic study indicates that the project is commercially viable and CO_2Tech is currently engaged in a multiyear project to further develop these novel materials for commercial applications and to explore further cost-reduction avenues for prefabricated houses.

Challenges in scale-up and deployment

The steps and challenges toward the scale-up and deployment of the Lignik process and products are as follows:

Step I: Next-Stage Support for Demonstration House

The immediate, next stage is the construction of a demonstration-scale house in Australia. CO2Tech has started engagement with potential funders and industrial partners and welcomes any interested parties to contact CO2Tech to support this project.

Step II: Pilot Housing Project

The subsequent step is the first pilot housing project in a developing country, which could potentially be aligned with a socioeconomic project to help uplift the standards, including, but not limited to buildings for schooling, remote clinics, and other facilities. CO2Tech welcomes expressions of interest and any monetary and in-kind support for this project.

Step III: Commercialization Support

As the Lignik process was engineered explicitly for a developing country, a cost lower than typical brick and concrete construction was a priority. During the techno-economic simulations, it was found that achieving lower costs required large-scale production. Thus, a commercially viable facility needs to manufacture over 10,000 houses each year, with production at this scale only viable in countries with large housing markets.

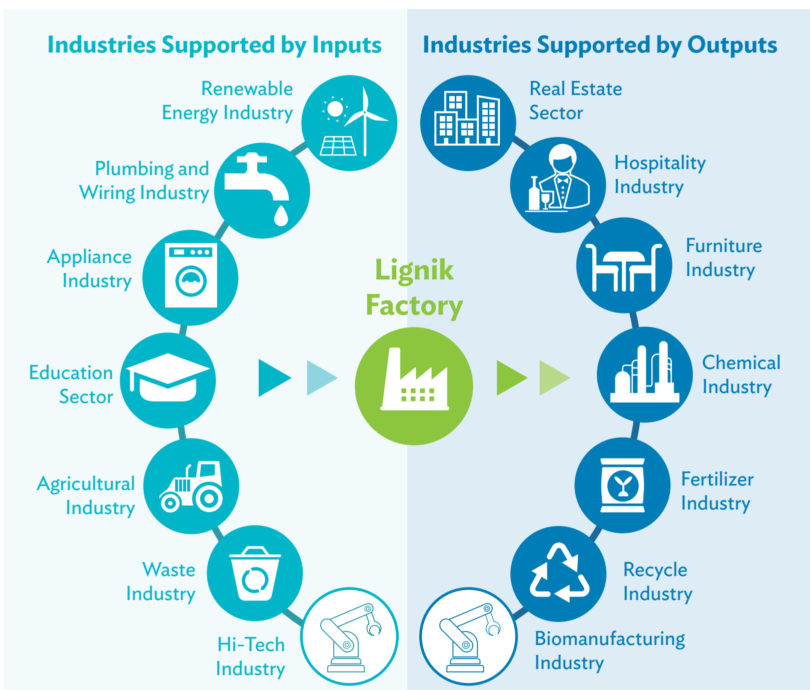
Support from local government, including donor agency facilitation, is needed to showcase the display house, the pilot housing project, and the potential for developing countries. The project is expected to create sustainable manufacturing jobs, provide low-cost housing, and help in socioeconomic upliftment of developing countries (Figure 19).

Technology provider background

CO2Tech was established in 2020 in Australia as a wholly owned subsidiary of CO_2CRC. CO_2CRC is Australia's leading not-for-profit company researching CCUS research and has been undertaking commercially relevant demonstrations of carbon storage, capture, and utilization for more than 15 years.

CO_2Tech has been working on bringing the knowledge gained within CO_2CRC to market, across an innovative portfolio of carbon to products, direct air capture, carbon capture, and hydrogen technologies. Lignik Technology is one such product, suitable for the housing industry. Two other novel technologies are HyCaps, a cost-effective hybrid process for CO_2 capture and CO_2Sorb, novel adsorbents for capturing CO_2 from high-pressure natural gas. In addition, CO2Tech is also involved in the R&D of direct air carbon capture and hydrogen storage technologies, as well as renewable dimethyl ether as a drop-in replacement for liquefied petroleum gas and diesel.

Figure 19: Economic Activity Spurred by a Lignik Factory



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Carbon Dioxide Storage in Cementitious Materials

Technology provider

Carbon Upcycling Technologies Inc. (Canada)

Technology description

Carbon Upcycling Technologies (CUT) has developed a patented, novel mechanically assisted chemical exfoliation (MACE) process to mineralize CO_2 emissions into enhanced materials. The MACE process reduces the carbon footprint of concrete with a twofold approach—(i) permanently capturing CO_2 in solid feedstock materials, and (ii) replacing cement.

The technology (Figure 20) facilitates the chemical adsorption of gaseous CO_2 emissions into exfoliated inorganic feedstocks, allowing CUT to "upcycle" a variety of feedstocks including quarry fines, steel slag, fly ash, natural pozzolans, crushed glass, and other industrial by-products. By utilizing low-grade or waste material feedstocks, as well as waste CO_2 emissions, as process inputs, CUT can produce a price-competitive substitution for cement.

Through extensive testing and validation with third-party laboratories, CUT has proven that CO_2-enhanced supplementary cementitious materials (SCM) outperform raw material feedstocks by 20%–60% across key performance metrics. Traditionally, cement, which is a highly carbon-intensive material, is used as the main binder for concrete, whereas CUT's CO_2-enhanced SCMs improve the strength of concrete by 30%–40% allowing for cement reductions and resulting in less carbon-intensive cement and more durable concrete mix designs that have improved chloride permeability and sulfate expansion resistance.

CUT has commercially demonstrated the highest cement reductions in concrete mix designs for any technology in the ready-mix and precast concrete mix spaces to date. This has been demonstrated with

Box 9: Carbon-Upcycled Cementitious Materials

Technology Highlights

- Can sequester around 30–100 kilograms of carbon dioxide per ton of feedstock
- Can reduce clinker use by 20%–40% in cement mixes
- Can increase strength of concrete by 30%–40% allowing for cement reduction

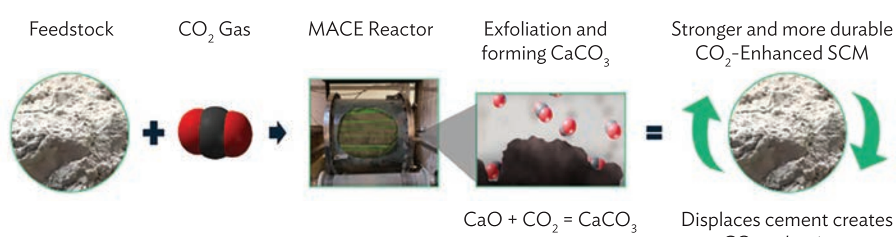
Development Stage

- Commercial

Sectors of Application

- Cement, Ready-mix Concrete, Precast concrete, Plastics, Steel Slags

Figure 20: Carbon Upcycling's Mechanically Assisted Chemical Exfoliation Process



CaO = calcium oxide, $CaCO_3$ = calcium carbonate, CO_2 = carbon dioxide, MACE = mechanically assisted chemical exfoliation, SCM = supplementary cementitious material.

Source: Carbon Upcycling Technologies, Inc. (Canada).

consistent uptime from the Calgary demonstration site which currently produces 20 tons per day for low-carbon concrete applications. Feasibility for future scale-ups is already underway with cement partners in North America and Europe to facilitate integrated projects at cement plants at 200 tons per day and greater.

Technology advantages

CUT's technology offers several advantages over other carbon utilization pathways. CUT's process

(i) utilizes a versatile range of feedstocks—natural pozzolans, iron or steel slags, fly ash, or low-reactivity clays;

(ii) has tested over 30+ materials, natural and industrial by-products in its process, enabling the use of local feedstocks;

(iii) can utilize flue gas with low CO_2 concentration directly from a cement kiln without the need for CO_2 capture;

(iv) can be energy efficient, with less than 60 kWh/ton of CO_2-enhanced SCM;

(v) can sequester around 30–100 kg of CO_2 per ton of feedstock through direct CO_2 sequestration;

(vi) can reduce clinker use by 20%–40% in cement mixes through displacement with highly reactive feedstocks; and

(vii) can be scaled readily. CUT has already scaled its technology by 10,000,000 times since its conception in 2014. The original reactor was about the size of a cookie jar which produced <250 grams/year.

Related costs

CAPEX for a full-scale commercial deployment of 60,000–80,000 tpa of CO_2-upcycled cementitious materials costs about $14 million. Operating expense per ton of processed materials costs about $34. Cost per ton of CO_2 abated (direct and indirect) is about $35.

CUT can compare its technology to the traditional approach of building cement kilns for clinker production. Traditional kilns will typically have a CAPEX of $300/ton of annual production and have a challenging permitting process that can be difficult to overcome for new builds. Conservatively, CUT has a CAPEX of $175/ton–$230/ton of annual production, along with a more attractive permitting proposition than traditional cement kilns due to the positive environmental, social, and governance impact. The cost of upcycling a low-grade material into a CO_2-enhanced SCM is less than the market price of cement, allowing the cement partner to extend the existing production capacity profitably.

Potential application in Asia and the world

Asia is the world's largest building materials market and is consistently growing faster than any other region in the world. With its growing need for energy and steel, the continent also produces the largest amounts of low-grade industrial by-products in the world, namely fly ash and iron and steel slags. Opportunities for CUT's technology are currently being explored with partners in Japan and Singapore to introduce more SCM to the respective markets and to the Philippines, India, and Thailand to produce low-cost cement alternatives from fly ash and rice husk ash. CUT is actively looking for more partnership opportunities in the region to build upon the market investigation to date.

CUT's technology can provide three critical benefits in Asia:

(i) directly and indirectly reduce emissions associated with cement and concrete production;

(ii) beneficiate and upcycle local industrial wastes from critical industries such as steel, glass, and mining; and

(iii) improve the circularity of local economies through waste upcycling while reducing transportation distances.

Status and next steps

CUT's technology has progressed rapidly over the last 4–5 years. Since 2018, it has:

- Deployed over 12,000 m^2 of low-carbon concrete in the Canadian construction market.
- Demonstrated over 12% cement reductions in commercial mixes in Western Canada, which is the highest reductions achieved by a carbon utilization company in the world.

- Signed memorandums of understanding with four of the world's largest cement companies, including CEMEX, CRH, and Holcim.
- Collaborated with over 12 research and industrial partners, including National Renewable Energy Laboratory the Universities of Toronto, Waterloo, Calgary, and Virgin Hyperloop.
- Demonstrated technology and product compliance with relevant standards of the American Society for Testing and Materials and Canadian Standards Association.
- Scaled its commercial pilots to a continuous reactor design and is working on installing full-scale reactors at cement plants to reduce emissions at the source with its largest partners in the cement industry.

Challenges in scale-up and deployment

The building materials industry is a challenging sector to decarbonize and has been recognized as one of the hard-to-abate sectors globally. The high volume, low margin nature of the business requires new technologies to be extremely cost-competitive even at early stages of development, while the globally ubiquitous footprint requires the technology to be versatile and fit for purpose. Additionally, the regulations associated with building materials require the technology providers to offer solutions that are compliant with local safety and regulatory standards.

CUT's technology has demonstrated its versatility using a range of feedstocks, ranging from steel slags and crushed glass to low-reactivity clays. Importantly, it has also demonstrated, through its Canadian pilot, that it can drastically reduce cement content in ready-mix concrete mix designs while adhering to stringent building and construction standards. The technology creates SCMs that are compliant with current regulatory standards set by the US and Canada's material regulators, ASTM and SCA. CUT has gone through stringent approval processes and is well-equipped with the knowledge and expertise to ensure its SCMs meet the approval and safety standards in new markets. It further demonstrates its versatility in that the technology is modular so it can be de-skidded and reconfigured to fit multiple different types of spaces, it can also be scaled up or down to meet a client's production capacity. A smaller unit would use a space of approximately 11 meters by 3 meters and a larger unit would use a space of approximately 20 meters by 60 meters.

To develop further and scale rapidly, CUT's technology requires commercial-scale deployment across the globe to test its commercial competitiveness at scale and demonstrate the emission reductions in a variety of contexts that have already been validated in Canada.

CUT has already demonstrated that its technology can be deployed in Asia cost-effectively through technical results and requisite financial modeling and is seeking cement and concrete partners to commercially deploy the technology in the region. CUT's utilization of waste materials from the aggregate, steel, and glass industries is an important contributor to CUT's ability to deliver a cost-competitive solution even in the challenging Asian market.

Technology provider background

Striving to be the world's most impactful carbon technology company, CUT was founded in 2014 in Calgary, Alberta, Canada with a vision of converting CO_2 emissions into valuable products for the building materials industry. CUT has won numerous awards, including the Carbon XPrize X-Factor award, 76West competition prize in New York (2019), and received a Solar Impulse Efficient Solution Label.

Email: info@carbonupcycling.com

Further reading

https://carbonupcycling.com/.

Game-Changing Carbon Dioxide Storage Technology

Turning Carbon Dioxide into Stone

Technology provider

Carbfix ohf. (Iceland)

Technology description

Carbfix turns captured CO_2 into stone underground in less than 2 years through a proprietary technology that imitates and accelerates natural processes. With Carbfix technology, captured CO_2 is mixed with water and becomes carbonated. The process of carbonating the water can either be done at the surface or downhole, depending on which would be more favorable and more economical. The carbonated water is injected into basalt rock formations. Carbonated water is acidic. The more carbon you can pack into the water, the more acidic the fluid will become. Carbfix's carbonated water reacts with rocks underground and releases available cations such as calcium, magnesium, and iron into the water stream. Over time, these elements combine with the dissolved CO_2 and form carbonates filling up the empty spaces (pores) within the rocks. The carbonates are stable for thousands of years and can thus be considered permanently stored. The timescale of this process initially surprised scientists. In the Carbfix pilot project, it was determined that at least 95% of the injected CO_2 mineralizes within 2 years, much faster than previously thought. Figure 21 illustrates the natural process imitated by the Carbfix process. The photo shows Carbfix's flagship project in Iceland.

Box 10: Carbfix Key Features

Technology Highlights

- Permanent storage. Imitates and accelerates natural stone formation (mineralization)
- Low operational risk
- Safe, no risk of carbon dioxide (CO_2) leakage
- Agnostic in terms of industry and capturing technology.

Development Stage

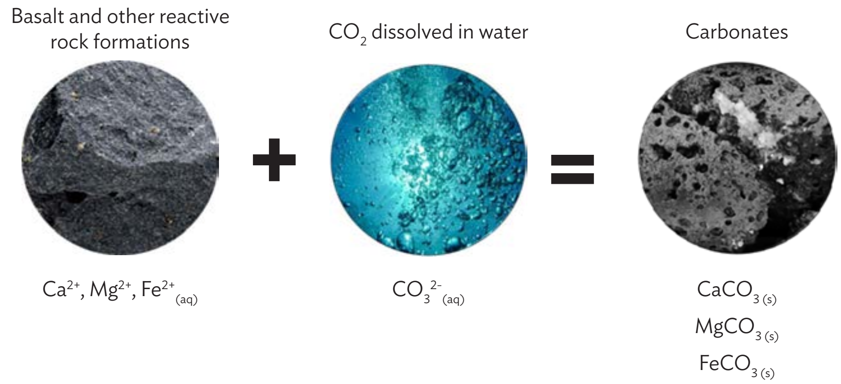
- Commercial

Sectors of Application

- Geothermal
- CO_2-emitting heavy industries
- Direct air capture
- On-site injection or hub development

The injected carbonated water is denser than the surrounding water in the geological formation and therefore tends to sink after it has been injected. This differs from the more conventional methods of carbon capture and storage, which depend on cap rock to prevent possible leakage of gaseous CO_2 injected into deep formations. Young basaltic rocks are highly fractured and porous such that water seeps easily through the interconnected cracks and empty spaces underground.

Figure 21: Carbfix Process



aq = aqueous, Ca^{2+} = calcium ion, $CaCO_3$ = calcium carbonate, CO_2 = carbon dioxide, CO_3^{2-} = carbonate ion, Fe^{2+} = ferrous ion, $FeCO_3$ = ferrous carbonate, Mg^{2+} = magnesium ion, $MgCO_3$ = magnesium carbonate, s = solid.

Source: Carbfix.

Carbfix flagship project. Carbon dioxide capture and mineral storage at the Hellisheidi Geothermal power plant in Iceland (photo by Carbfix).

Technology advantages

The main energy requirement associated with the Carbfix technology is the energy to pressurize CO_2-charged water to 25 bars at 25°C. The energy demand at 25°C as a function of CO_2 partial pressure for the pressurization of 1 ton of CO_2-charged pure water is approximately 75 kWh.

Compared to the traditional carbon storage of injecting CO_2 in gaseous form, the concept of Carbfix presents key different advantages:

- the risk of leakages are eliminated;
- CO_2 is permanently removed;
- high public acceptance, natural process, no additives;
- drilling operations and well material less expensive;
- low financial risk;
- low operational risk;
- network can be gradually expanded over time;
- on-site storage for a single source emitter;
- long-term monitoring not needed;
- no defined storage limits;
- can be developed to cater for onshore emitters of different-size category, different global locations, at emitters site or via hubs or terminals and for the increasing segment of direct air capture (DAC) companies; and is
- currently developing offshore applications and utilizing other geological formations and seawater.

Related costs

Carbfix will focus on providing permanent storage through mineralization technology, which is agnostic to both the industry and in terms of capture technology. The choice of capture technology and thus the cost of capture is much related to the industry in question and the quality and density of the CO_2 streams. Whether the captured CO_2 needs to be transported or can be injected on-site next to emitting facilities, affects the cost of transport. The dissolution of CO_2 in water and injection in the subsurface is a site-specific process but in general the least energy intensive as part of the whole value chain. Indication for investment cost is both site- and size-specific and will depend on different factors that need to be considered. These evaluations are being carried out in the consultancy process that Carbfix offers and where designing and building a pilot project becomes part of the process when positive indications from feasibility studies prove favorable to continue the project. The size of an operational unit may be an on-site unit for a small and/or medium size emitter, to a building of a storage terminal where million tons of CO_2 can be injected and permanently stored.

Potential application in Asia and the world

As a sign of ever-increasing interest in CO_2 mineral storage, Carbfix has compiled a mapping tool (www.carbfix.com/atlas) that shows the feasibility of applying the Carbfix technology as part of the climate strategies of industries and countries.

The global storage potential is greater than the emissions of the burning of all fossil fuels on Earth. While the International Energy Agency has estimated that approximately 1,000 billion tons of CO_2 emission should be avoided by 2060 to meet the goals of the Paris Agreement, it is estimated that with Carbfix technology, Europe can theoretically store at least 4,000 billion tons of CO_2 in rocks, while the US can theoretically store at least 7,500 billion tons.

Status and next steps

Carbfix has ongoing research on using seawater and on other rock formations for injection.

The Carbfix process requires substantial amounts of water to carry out the CO_2 in dissolution and to promote reactions underground. However, the water is sourced from the same reservoir in which the injection takes place and is therefore circulated and reused to a certain extent. But even dry regions that lack fresh water may still be good geological candidates. Carbfix has developed the scientific basis for using seawater to dissolve CO_2 instead before injection, significantly expanding the applicability of the technology. Laboratory testing showed positive results, and a field site demonstration of mineral storage using seawater is scheduled in 2022.

When evaluating suitable rock types for the Carbfix method, the following parameters must be considered: host-rock chemistry, reactivity, porosity, and permeability, as well as reservoir pressure and temperature conditions during CO_2 injection. The most favorable rock types for carbon mineralization are mafic and ultramafic rocks (magnesium- and iron-rich) due to their high reactivity and abundant pore space, as in the case of young basalts. Basaltic rocks, peridotites, and other rocks with more intermediate compositions, such as andesite, dacite, and rhyolite have been demonstrated to show potential for carbon mineralization. There have been experimental studies on andesitic, dacitic, and rhyolitic rocks with successful mineralization. Thus, indicating that the application of Carbfix extends beyond just basaltic rock.

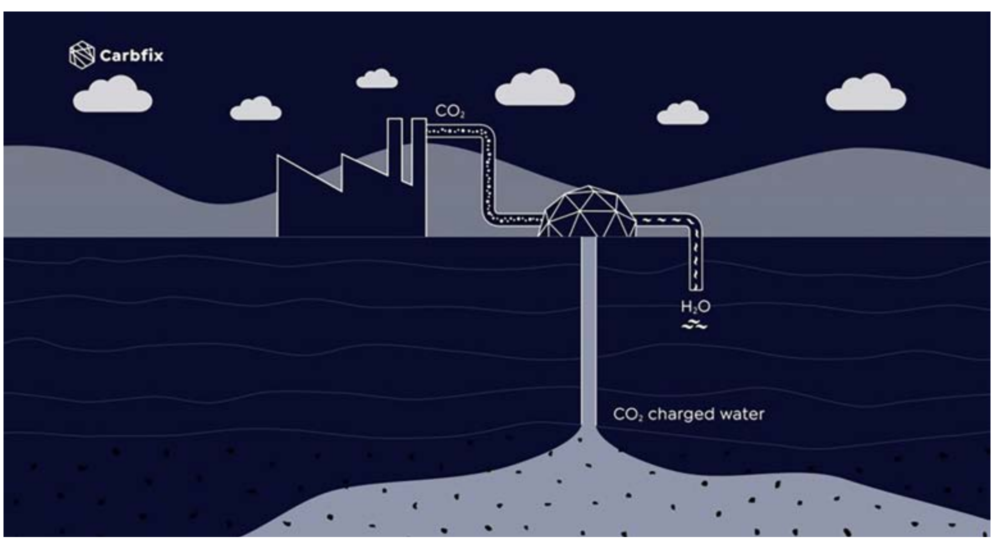
As for commercial activities, Carbfix has defined three paths for commercialization:

(i) On-site capture and storage (Figure 22)—This is the most economical path fitting for emitters in favorable locations with water and favorable rock type.

(ii) Mineral storage hubs—designed in areas with favorable conditions, assisting emitters located in not favorable areas. CO_2 would then be transported in pipes, tank containers, tank carriers (trucks), tank rail wagons or with vessels, as is the case with Coda terminal in Iceland. The idea with this option, as with the on-site capture and storage and direct air capture and storage, is to establish similar operations in other parts of the world. Coda will be operational from the first quarter 2026, and would be able to receive and inject 500,000 tons yearly. Scale up to 3 million ton yearly is planned for 2030/2031. Figure 23 gives an image of the Coda terminal.

(iii) Direct air capture and storage (Figure 24)—Here Carbfix works with direct air capture (DAC) companies, offering injection of captured CO_2 in favorable locations for injection. This method is more for the voluntary market, where CO_2 credits are being traded voluntarily. Carbfix has been working with the first DAC company in the world, Climeworks, since 2016, and is in the process of building up and providing DAC facilities in the US, in addition to enlarged operation for DAC start-up companies in Iceland.

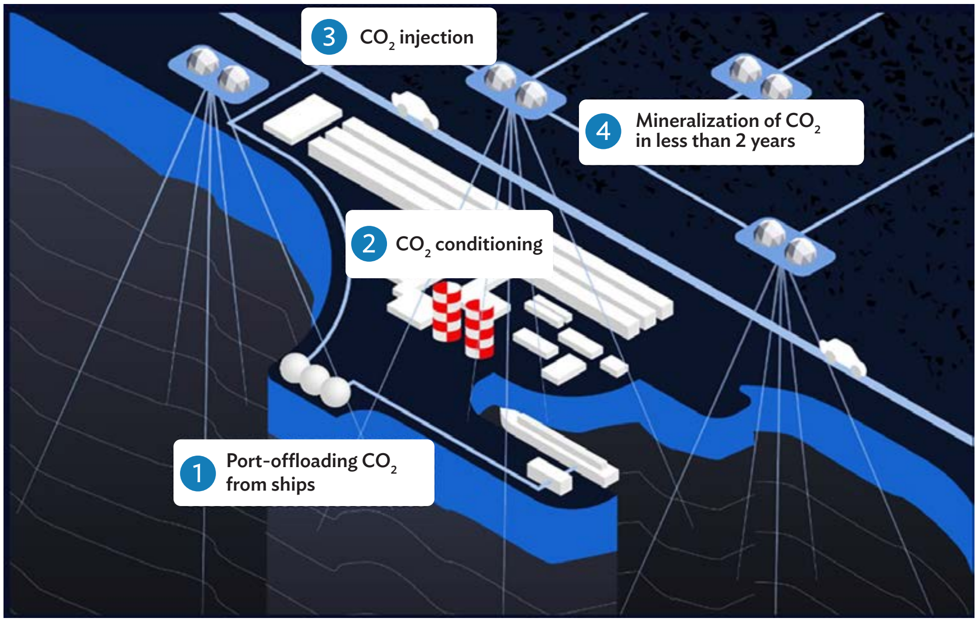
Figure 22: On-Site Capture and Storage Diagram



CO_2 = carbon dioxide, H_2O = water.

Source: Carbfix.

Figure 23: Coda Terminal and Storage Site



CO_2 = carbon dioxide.

Source: Carbfix.

Figure 24: Direct Air Capture and Storage

CO_2 = carbon dioxide, H_2O = water.

Source: Carbfix.

Challenges in scale-up and deployment

The legal framework for the capture and injection of CO_2 underground in Icelandic ground, including the Carbfix technology, is in accordance with EU directive 2009/31/EC on the geological storage of carbon dioxide, that has been implemented into Icelandic law (Act No 7/1998, with later amendments). Looking globally, it is of portentous importance for utilization of Carbfix technology that the methodology is considered as part of national CCS legislation around the globe.

Technology provider background

Carbfix is a start-up company established in 2020, building on R&D dating back from 2007 when it was established as a research project. It was essentially Reykjavik Energy, Carbfix's parent company, the University of Iceland, Columbia University, and CNRS out of Toulouse that joined forces intending to develop a technology that would speed up nature´s way of storing CO_2 permanently as minerals within specific rock formations.

The first injections of CO_2 were carried out in Iceland in 2011 and continued ever since, bringing total injected CO_2 above 100,000 tons injected. The number could be higher, but lack of CO_2 in Iceland has been the limiting factor. Carbfix is addressing this by expanding the application to be used in relation to the increased attention DAC is gaining and by establishing a scalable onshore CO_2 mineral storage hub in Iceland.

After the R&D phase in 2007, successful and scientifically peer-reviewed results from injections since 2011, with verified full-chain certification methodology in 2022, Carbfix has reached a development phase where the focus is on scale-up globally. With approximately 70% of the seabed and 5% of land globally representing basalt bedrock, the success from Iceland is ready to be scaled up to contribute to the permanent removal of CO_2 globally.

Further reading

Carbfix.com
Twitter | LinkedIn | Instagram | Facebook

Carbon Dioxide Capture, Utilization, and Storage Technology Enabler

Enabling Carbon Dioxide Removals through Collective Purchasing Vehicle

Enablers

South Pole (Switzerland) **and Mitsubishi Corporation** (Japan)

Description of facility

NextGen Carbon Dioxide Removal (CDR) Facility is a collaboration between South Pole and Mitsubishi Corporation to help scale-up carbon dioxide removal as it

- aggregates demand from buyers for high-quality technical carbon removals;
- curates project pipeline that issues certificates from technical carbon removal solutions;
- executes off-take agreements and financial transactions, certificate delivery to buyers from a diverse portfolio;
- develops partnerships with investors, think tanks, and market regulators; and
- enables transformative carbon removal projects and scaling of removal technologies by making them bankable.

The facility purchases carbon dioxide removals (CDRs), that have been certified under an endorsed standard of the International Carbon Reduction and Offset Alliance, from five different technology sectors—high-temperature biochar production and storage, biomass carbon removal and storage (BiCRS), direct air capture and storage (DACS), enhanced rock weathering, and product mineralization. Figure 25 illustrates how NextGen CDR Facility works.

Advantages and highlights of the facility

NextGen CDR Facility helps organizations achieve their last mile of net zero commitments with high-quality removals by

- reducing transaction costs and prices for technical removals by joining forces with other buyers;
- providing access to limited supplies of technical removals available through 2030;
- diversifying carbon removal portfolio beyond nature-based solutions to manage permanence risks and supply bottlenecks in; and
- de-risking procurement of technical removals through a diversified, managed portfolio run by experienced professionals.

Box 11: NextGen Carbon Dioxide Removal Facility Key Features

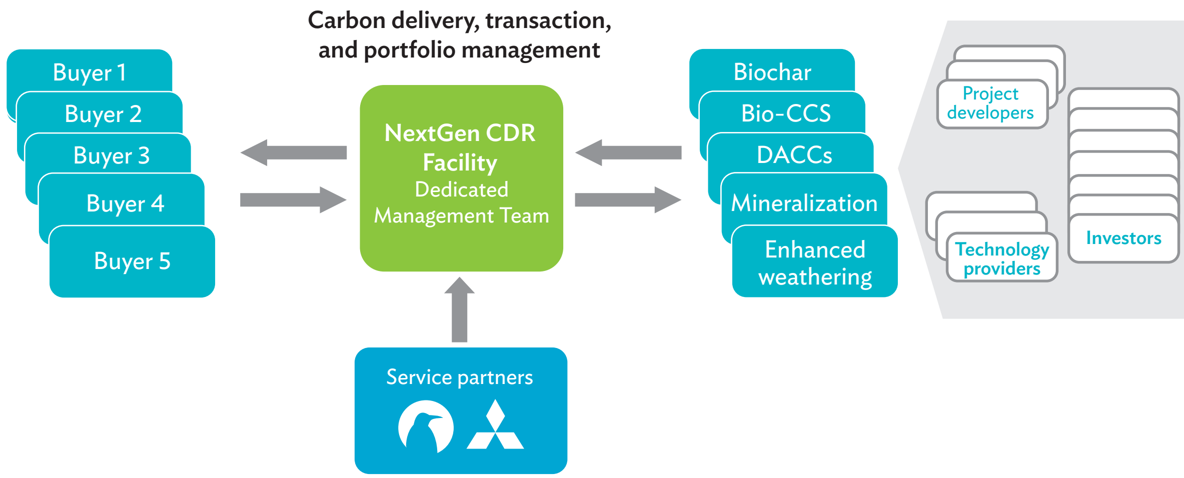
Facility Highlights

- Diversified technical carbon removal portfolio
- De-risks procurement of technical carbon removals

Sectors of Application

- All carbon dioxide-emitting sectors (except enhanced oil recovery)

Figure 25: NextGen Carbon Dioxide Removal Facility Structure



CCS = carbon capture and storage, CDR = carbon dioxide removal, DACCS = direct air capture and storage.

Source: South Pole.

Potential application in Asia and the world

NextGen could help facilitate the transfer of new and emerging climate technologies to Asia while generating new carbon revenues in countries looking to act as carbon storage hubs. Projects identified for NextGen include biomass-related projects in Southeast Asia with significant potential for growth given the renewable energy resource in the region. Production of biochar for agricultural use, use of minerals for enhanced sequestration, and BiCRS projects are particularly relevant, although there may be potential for DACS for geological storage.

Status and next steps

Sourcing through South Pole and Mitsubishi channels has created a pipeline of 66 carbon removal projects to date. A breakdown of these pipeline projects is shown in Table 2.

NextGen CDR has started working on several projects in Asia, Europe, Middle East, and North Africa region

Table 2: NextGen Carbon Dioxide Removal Project Pipeline

Project Type	Number of Projects Identified
BiCRS	15
Biochar	18
DACS	11
Enhanced weathering	8
Mineralization	14

BiCRS = biomass carbon removal and storage, DACS = direct air capture and storage.

Source: South Pole.

(MENA), and Latin America. These projects include the following:

(i) **Project Medusa—Product mineralization in concrete aggregate, Europe:** Using a proprietary process, water is used as a solvent to bond calcite ions and CO_2 into manufactured-limestone concrete aggregate for creating carbon-negative products.
Durability: 100+ years
Year Operational: 2018
Volume: 10 ktCO_2e/year

(ii) **Project Torch—Biochar, Europe:** Straw and wood waste is converted to biochar via high-temperature pyrolysis, locking in carbon for agricultural applications when mixed with soil and compost in the ground per European Biochar Certificate Carbon Sink guidelines.
Durability: 100+ years
Year Operational: 2018
Volume: 10 ktCO_2e/year

(iii) **Project Ivy—Enhanced weathering, MENA and Latin America:** Silicate rocks are ground into fine particles and spread across large areas of land to significantly accelerating the natural process of weathering, increasing the geological CO_2 capture properties.
Durability: 1,000+ years
Year Operational: 2023
Volume: 100 ktCO_2e/year

(iv) **Project Flash—Product mineralization in concrete products, Asia:** CO_2 is converted into solid mineral carbonates using additives and carbonation curing technology to produce carbon-negative concrete products.
Durability: 100+ years
Year Operational: 2023
Volume: 25 ktCO_2e/year

(v) **Project Cyclone—Direct air capture and storage, North America:** CO_2 is captured through a chemical filtration process, with further chemical processing purifying the CO_2 into a gas that is injected into depleted Class VI wells for geologic sequestration and storage.
Durability: 1000+ years
Year Operational: 2024
Volume: 500 ktCO_2e/year

(vi) **Project Siren—BiCRS, Europe:** CO_2 from emissions and waste resulting from biomass combustion used to generate heat and energy are captured and transported by ship to various locations for geological storage.
Durability: 1,000+ years
Year Operational: 2025
Volume: 200 ktCO_2e/year

The NextGen CDR Facility has engaged a diverse range of partners from across the CDR ecosystem to ensure the credibility of the technical removals market, and the investor networks that can support exponential growth in the industry.

Key challenges in scale-up

(i) **Supply.** The removals ecosystem is still nascent and there are few sizable and available projects from which to source high-quality removals.

(ii) **Cost.** Prices for technical removals currently range between ~$100/ton to more than $2,000/ton, although costs are expected to decrease significantly at scale.

(iii) **Bankability.** The novel nature of projects and lack of current regulatory and commercial incentives to reward technical removals means project struggle in securing financing.

(iv) **Certification.** Standard methodologies for removals are yet to be developed.

Enabler Background

- South Pole is a global carbon market specialist with over 1,400 staff in 27 offices across six continents, and one of the few climate unicorns with a market valuation of $1 billion. South Pole is widely recognized for its leadership and expertise in carbon markets, with a track record of over 700 projects and the largest market share in voluntary carbon markets.
- Mitsubishi Corporation is a leader in carbon removal technology and project development and Japan's largest trading company. Mitsubishi Corporation brings expertise, global corporate relationships through its network of 1,700 group companies, and the stability of a multibillion-dollar company to the facility.

Further reading

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Other studies under Technical Assistance 9690 may be accessed through the following link: https://www.adb.org/projects/52041-003/main#tabs-0-2.

Please visit www.adb.org to see the publications and studies of ADB on CCUS under other technical assistance projects of ADB.

Carbon Capture, Utilization, and Storage Game Changers in Asia and the Pacific

2022 Compendium of Technologies and Enablers

The Asian Development Bank (ADB) strives to facilitate a sustainable low-carbon future for Asia and the Pacific within the next half of this century. Analyzing the potential of carbon capture, utilization, and storage (CCUS) to secure that low-carbon environment, this compendium highlights 11 CCUS technologies and enablers—most of which are ready for mass deployment. It explores how CCUS can enhance sustainable energy security and compliance with international commitments, as well as decarbonizing industries—with relatively low disruptions to existing operations. Featuring technical, economic, and financial insights, the publication encourages collaborations between ADB members and stakeholders to develop such technologies.

About the Asian Development Bank

ADB is committed to achieving a prosperous, inclusive, resilient, and sustainable Asia and the Pacific, while sustaining its efforts to eradicate extreme poverty. Established in 1966, it is owned by 68 members —49 from the region. Its main instruments for helping its developing member countries are policy dialogue, loans, equity investments, guarantees, grants, and technical assistance.

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