LanzaTech

Nasdaq: LNZA

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TOM DOWER

VP, PUBLIC POLICY

SEPTEMBER 13, 2023

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Certain statements in this presentation (the "Presentation") may be considered forward-looking statements. Forward-looking statements generally relate to future events or LanzaTech Global, Inc.'s (the "Company") future financial or operating performance. For example, statements concerning the following include forward-looking statements: the potential success, cost and timing of the Company's technology platform development activities; the potential attributes and benefits of the Company's technology platform; the Company's ability to compete with other companies currently marketing or engaged in the development of similar technologies; the size and growth potential of the markets for the Company's technology and the Company's ability to serve those markets; the rate and degree of market acceptance of the Company's technology; and the Company's ability to expand its business. In some cases, you can identify forward-looking statements by terminology such as "may", "should", "expect", "intend", "will", "estimate", "anticipate", "believe", "predict", "potential" or "continue", or the negatives of these terms or variations of them, or similar terminology. Such forward-looking statements are subject to risks, uncertainties, and other factors which could cause actual results to differ materially from those expressed or implied by such forward-looking statements. These forward-looking statements are based upon estimates and assumptions that, while considered reasonable by the Company and its management, as the case may be, are inherently uncertain. New risks and uncertainties may emerge from time to time, and it is not possible to predict all risks and uncertainties. Factors that may cause actual results to differ materially from current expectations include, but are not limited to, various factors beyond management's control, including general economic conditions and other risks, uncertainties and factors associated with companies, such as the Company, that are engaged in developing proprietary carbon capture technology; changes to environmental laws and regulations; changes to ethanol regulation; and overall business and economic conditions affecting the global carbon capture, utilization and storage industry. Nothing in this Presentation should be regarded as a representation by any person that the forward-looking statements set forth herein will be achieved or that any of the contemplated results of such forward-looking statements will be achieved. You should not place undue reliance on forward-looking statements in this Presentation, which speak only as of the date they are made and are qualified in their entirety by reference to the cautionary statements herein. Except as required by law, the Company undertakes no duty to update these forward-looking statements.


OUR "CLIMATE TIME BOMB IS TICKING"
– Antonio Guterres, U.N. Secretary-General
The processes that underlie human civilization are making our planet **uninhabitable**
[1]National Centre for Atmospheric Science
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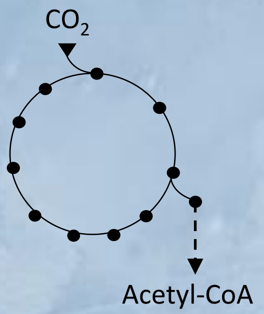
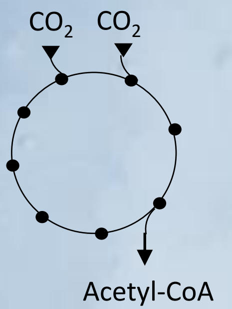
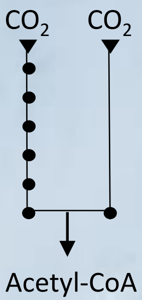
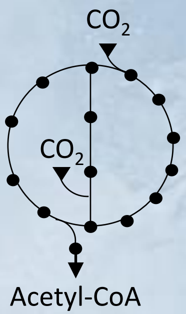
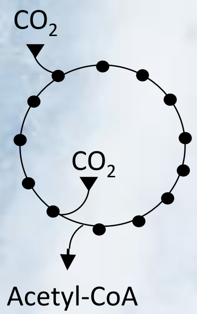
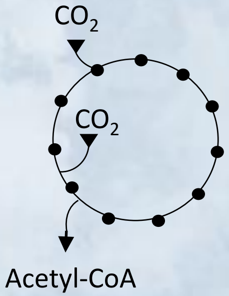
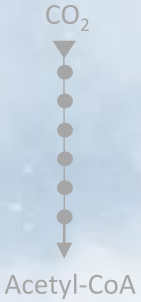
At LanzaTech, we have turned to one of the **Earth's oldest type of organisms** to learn how it adapted to **an inhospitable environment** to repair our planet

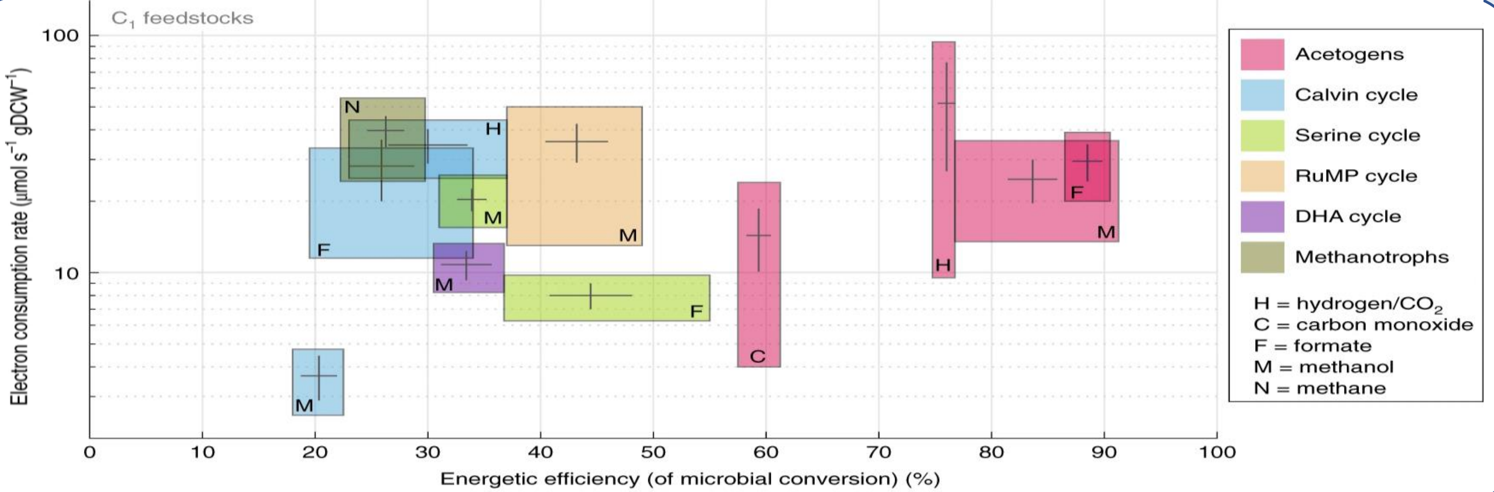
Image credit: Pacific Ring of Fire 2004 Expedition. NOAA Office of Ocean Exploration;, Dr. Bob Embley, NOAA PMEL, Chief Scientist.

BIOLOGICAL CO_2 FIXATION

Image credit: Pacific Ring of Fire 2004 Expedition. NOAA Office of Ocean Exploration;, Dr. Bob Embley, NOAA PMEL, Chief Scientist.

BIOLOGICAL CO_2 FIXATION PATHWAYS

CBB CYCLE	rTCA CYCLE	WL PATHWAY	3-HP CYCLE	4-HP/4-HB CYCLE	4-HB CYCLE	rGLY PATHWAY
						
7 ATP	2 ATP	<1 ATP	7 ATP	6 ATP	4 ATP	1 ATP
7.5 H_2	5 H_2	4 H_2	7 H_2	7 H_2	7 H_2	4 H_2



[2]

[1]Köpke (2022) *Nature Synth* 1: 584; Pavan et al. (2022) *Met Eng* 71: 117; Fast & Papoutsakis (2012) *Curr Opin Chem Eng* 1: 380

[2]Claassens et al. (2019) *Nature Cat* 2: 437

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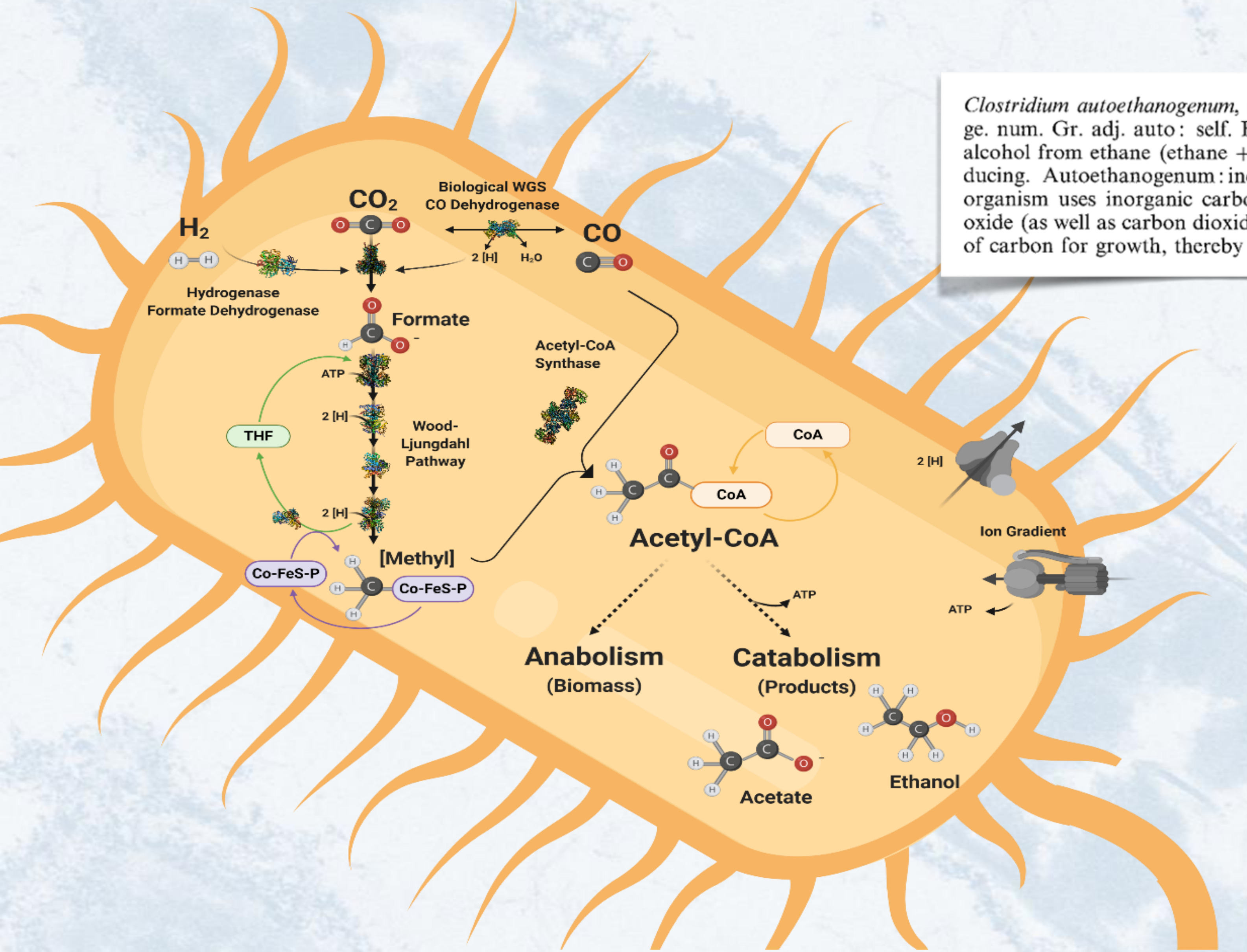
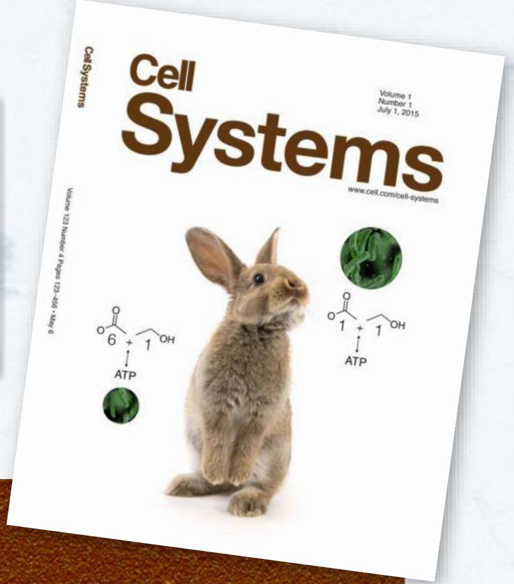
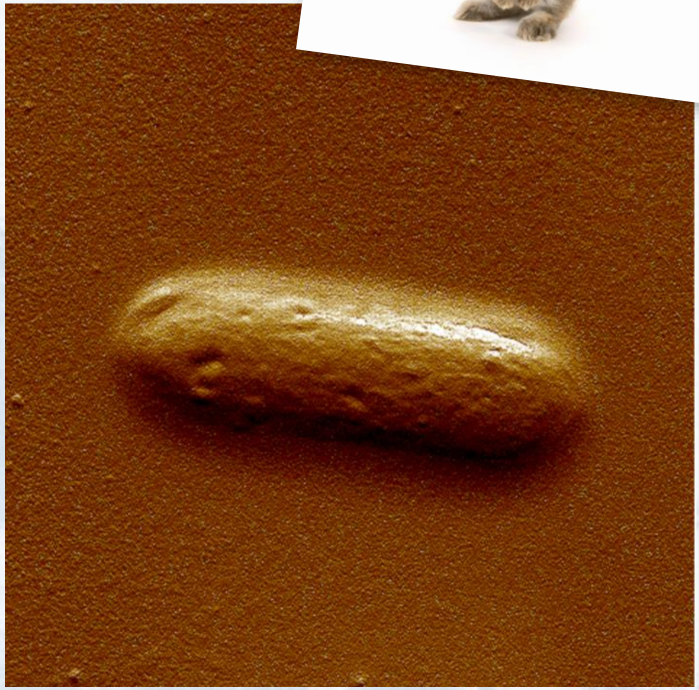
ANAEROBIC ACETOGENS — *CLOSTRIDIUM AUTOETHANOGENUM*



Clostridium autoethanogenum, sp. nov. au. to. etha. no. ge. num. Gr. adj. auto: self. Ethano: corresponding to alcohol from ethane (ethane + ol.). Gr. v. genum: producing. Autoethanogenum: indicating that the microorganism uses inorganic carbon, namely carbon monoxide (as well as carbon dioxide) as possible sole source of carbon for growth, thereby producing ethanol.





[1]Abrini et al. (1993) *Arch Microbiol* 161: 345; Valgepea et al. (2018) *Cell Systems* 4: 505

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BIOLOGY CAN USE A WIDE RANGE OF INPUT COMPOSITIONS

Steel and Ferroalloy Gas

Biomass

MSW

Refinery Gas

CO_2 + H_2

		H_2:CO Ratio	Carbon Efficiency	Energy Efficiency
CO	$6\ CO + 3\ H_2O \rightarrow C_2H_5OH + 4\ CO_2$	**0:1**	**33.3%**	**72.8%**
CO + H_2	$3\ H_2 + 3\ CO \rightarrow C_2H_5OH + CO_2$	**1:1**	**66.7%**	**78.5%**
CO + H_2	$4\ H_2 + 2\ CO \rightarrow C_2H_5OH + H_2O$	**2:1**	**100%**	**80.6%**
CO + H_2 + CO_2	$5\ H_2 + 1\ CO + 1\ CO_2 \rightarrow C_2H_5OH + 2\ H_2O$	**5:1**	**100%**	**82.1%**
H_2 + CO_2	$6\ H_2 + 2\ CO_2 \rightarrow C_2H_5OH + 3\ H_2O$	**1:0**	**100%**	**85.2%**

Multiple avenues to reach 100% carbon capture

Gas fermentation can flexibly add green H_2 to tailor carbon capture

[1]Köpke & Simpson (2020) *Curr Opin Biotechnol* 65: 180

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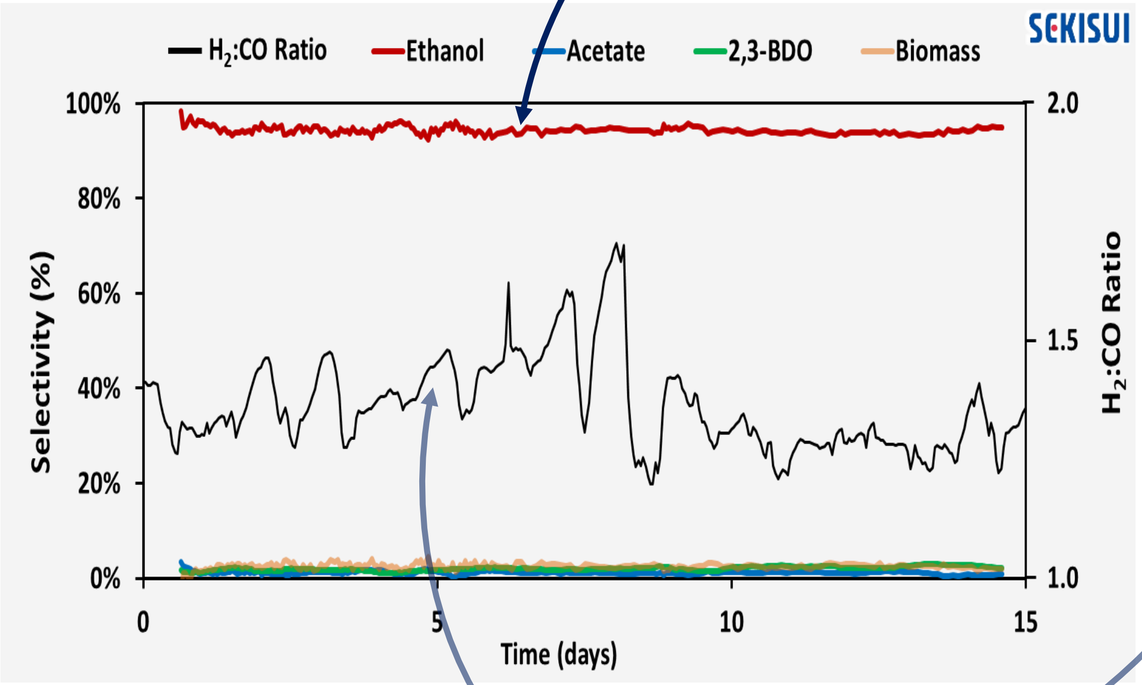
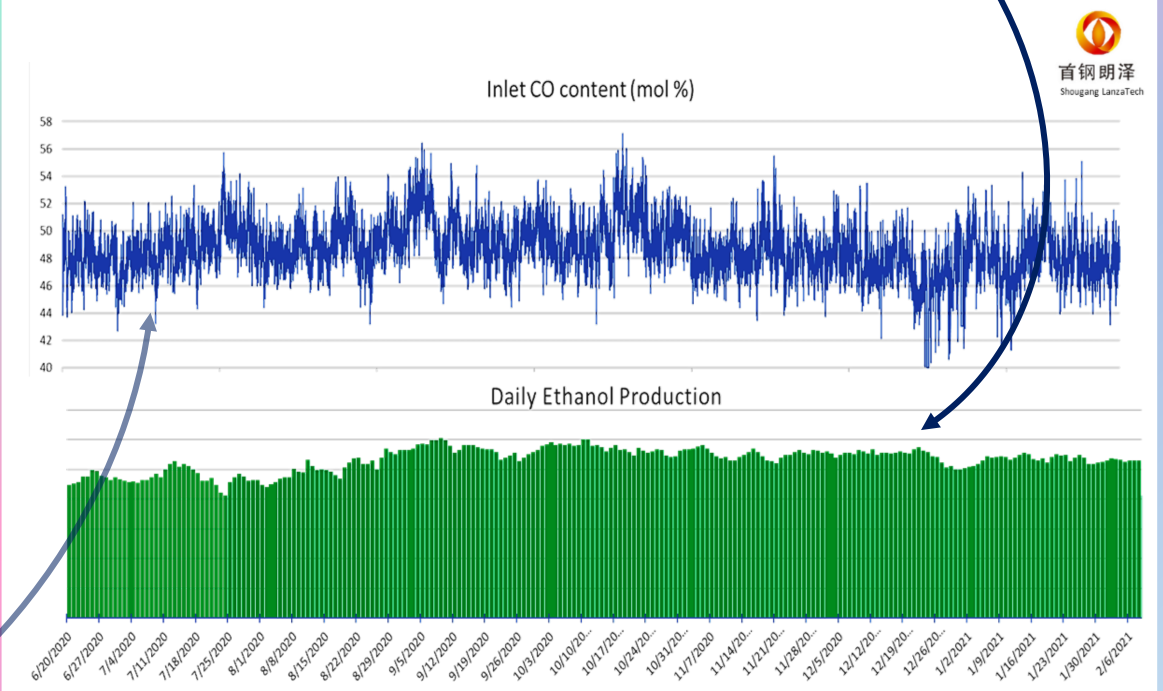
BIOLOGY CAN TRANSFORM CHAOTIC INPUTS INTO SELECTIVE OUTPUTS

SPECIFIC, NEAR-CONSISTENT ETHANOL PRODUCTION

INPUT: MUNICIPAL SOLID WASTE[1]



INPUT: STEEL MILL GAS[2]



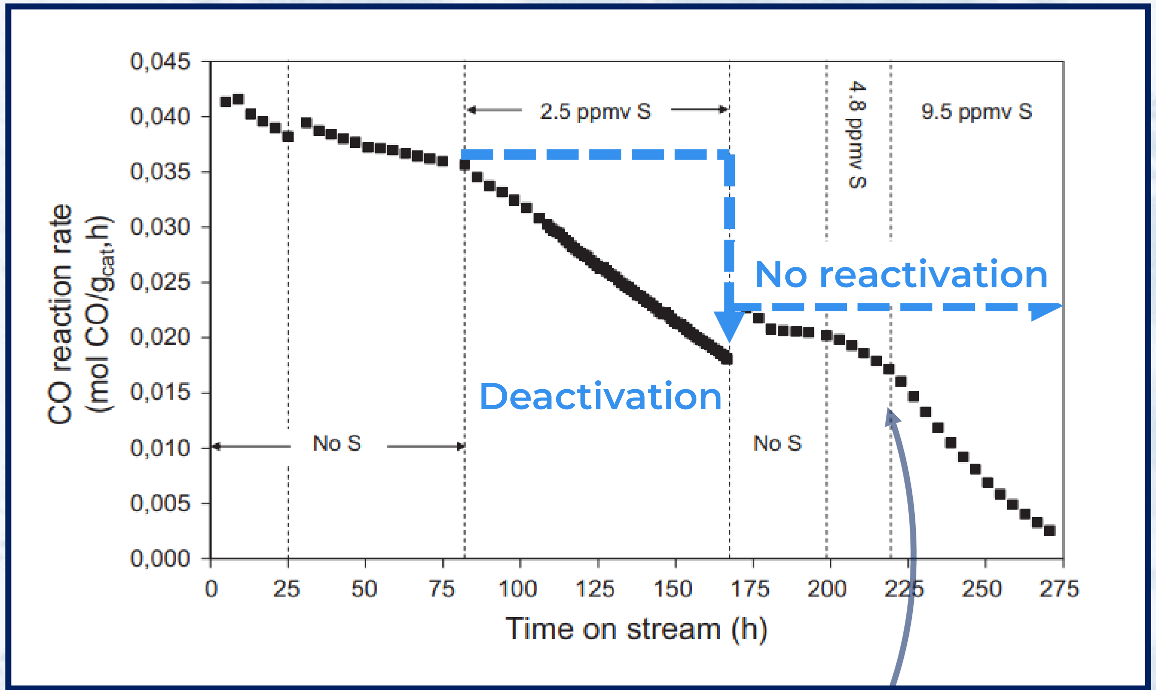
INCONSISTENT WASTE CARBON INPUT

[1]Köpke & Simpson (2020) *Curr Opin Biotechnol* 65: 180; [2]Fackler et al. (2021) *Ann Rev Chem Biomol Eng* 12: 439

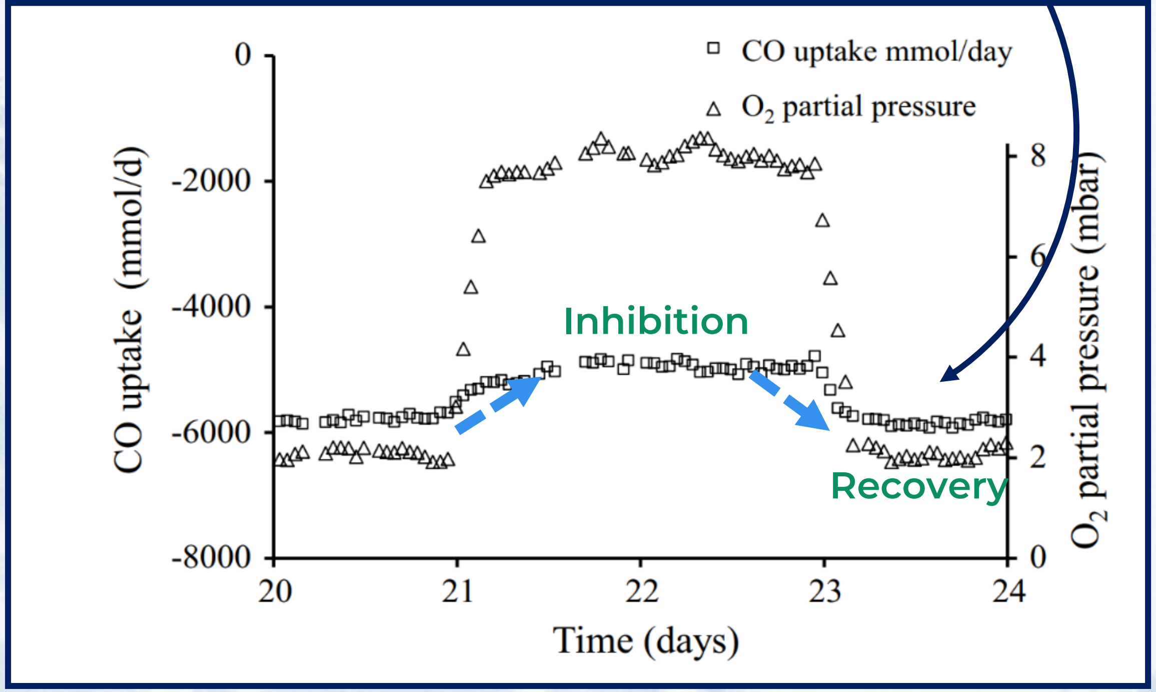
BIOLOGY CAN SELF-REGENERATE

BIOCATALYST REGROWS WHEN INHIBITOR IS REMOVED

FISCHER-TROPSCH CATALYST – S POISONING[1]



BIOCATALYST – O_2 INHIBITION[2]



THERMO-CATALYST POISONS ARE CUMULATIVE

[1]Borg et al. (2011) *J Catal* [2]Heijstra et al. (2017) *Microb Cell Fact*

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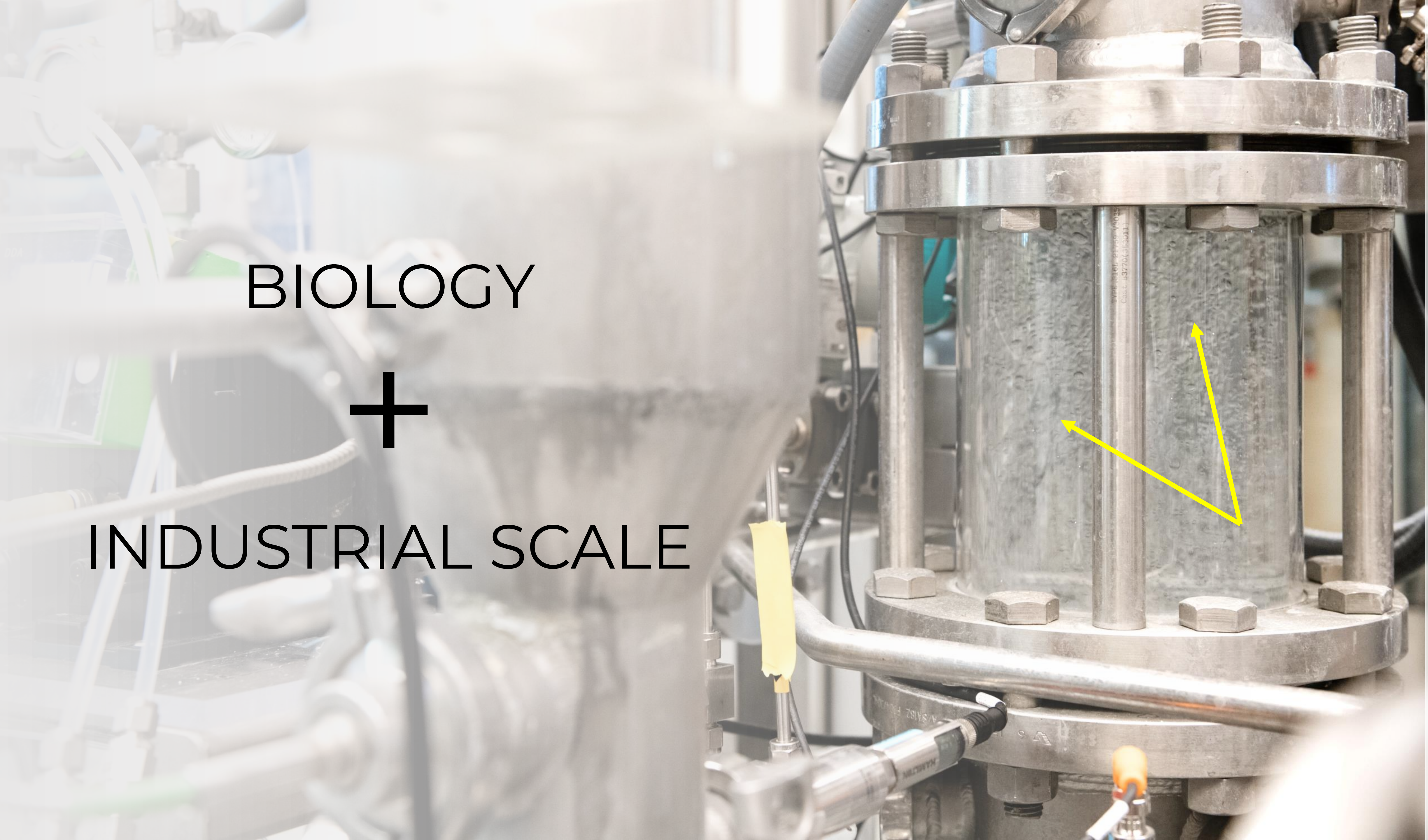
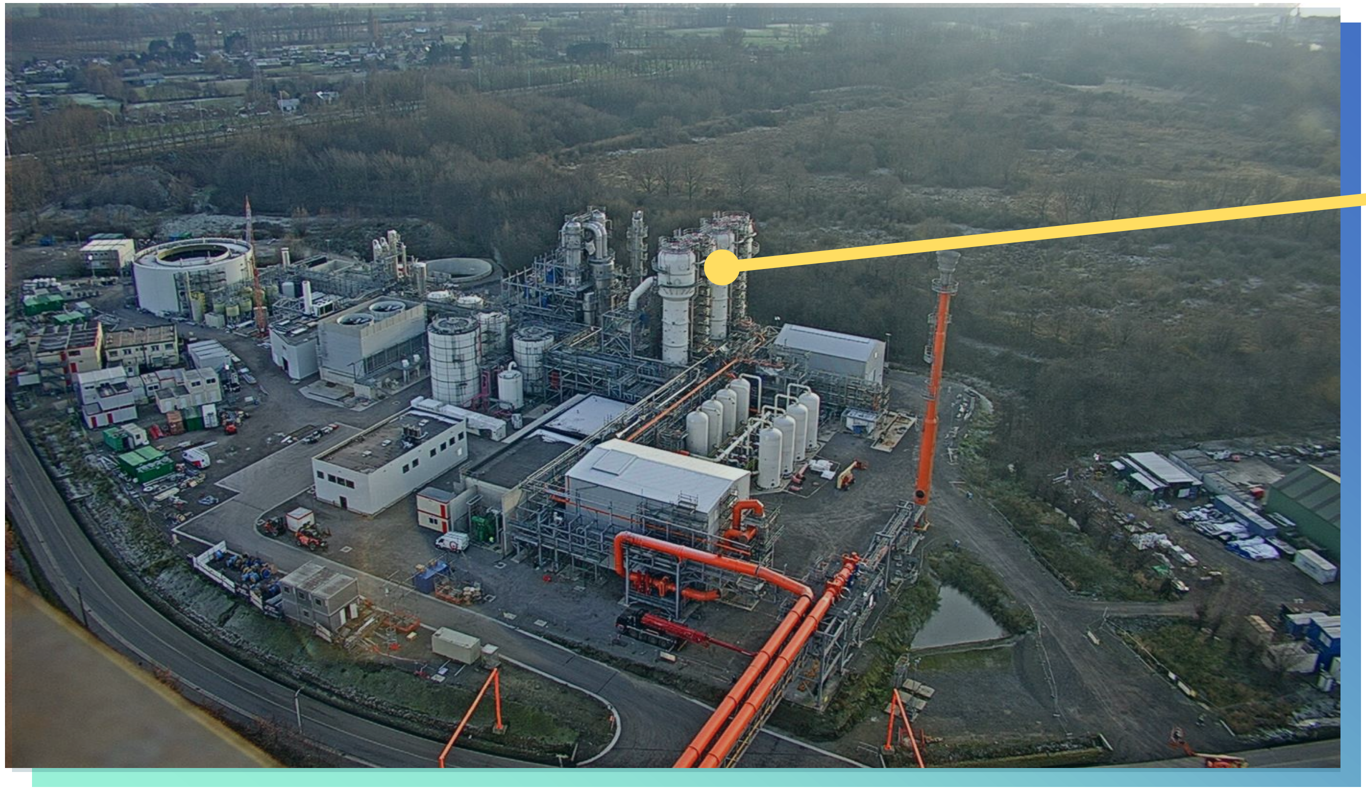
BIOLOGY

+

INDUSTRIAL SCALE



A BREWERY THAT PLUGS INTO AN INDUSTRIAL PLANT



GAS FERMENTATION

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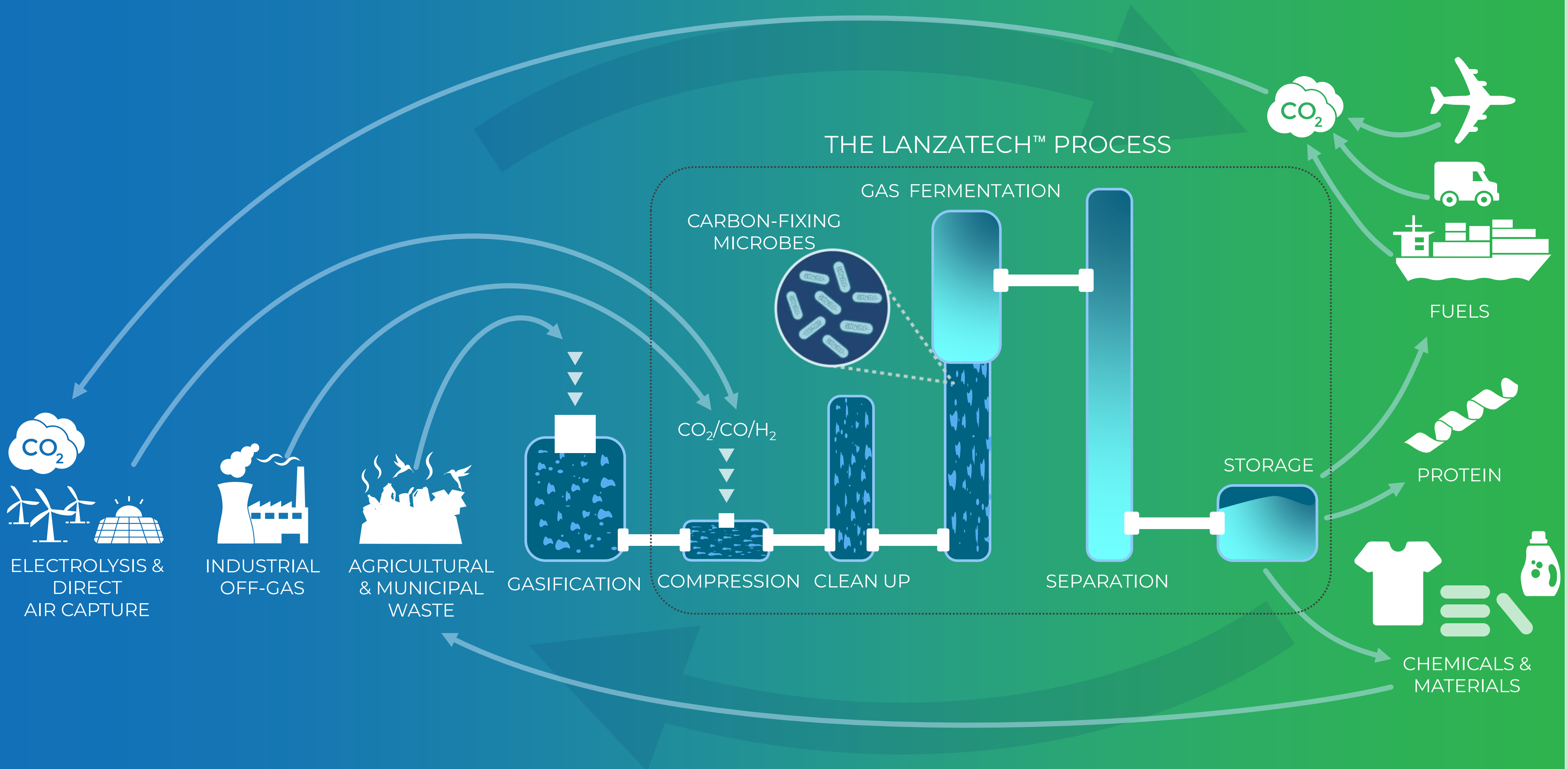
LANZATECH'S UNIQUE TRANSFORMATION PROCESS



Köpke & Simpson (2020) *Curr Opin Biotechnol* 65: 180; Fackler et al. (2021) *Ann Rev Chem Biomol Eng* 12: 439; Pavan et al. (2022) *Met Eng* 71: 117

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18+ YEAR JOURNEY OF SCALE UP

2005

Laboratory Scale

2008

Pilot Scale

30x

2012

Demonstration Scale

130x

2018+

Commercial Scale

Köpke & Simpson (2020) *Curr Opin Biotechnol* 65: 180-189; Fackler et al. (2021) *Ann Rev Chem Biomol Eng* 12: 439-470

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- ✓ OPERATING COMMERCIALLY ON INDUSTRIAL OFF GASES SINCE 2018
- ✓ TECHNOLOGY DE-RISKED, MULTIPLE PLANTS, GLOBALLY LICENSED

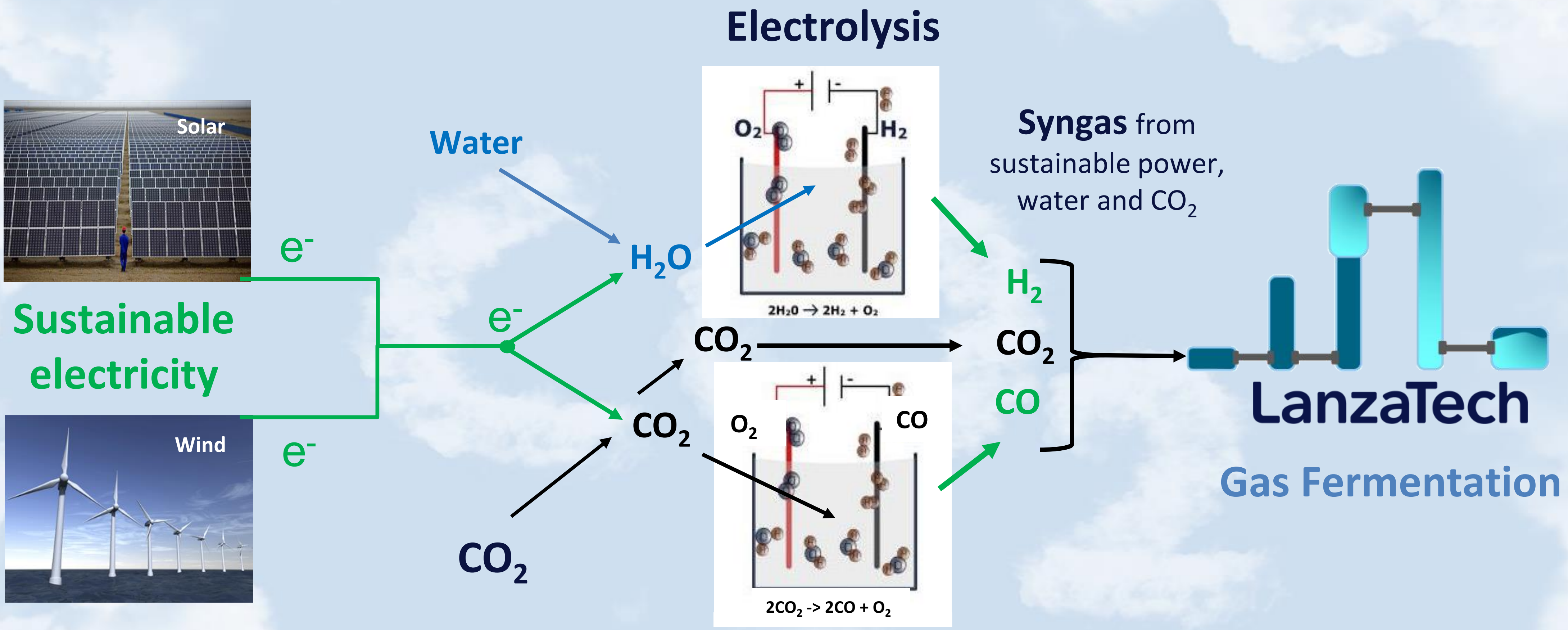
ArcelorMittal

LanzaTech

1st

- ✓ REFINERY GAS-TO-ETHANOL PROJECT IN THE WORLD
- ✓ PROJECT TO USE CO_2 AS A FEEDSTOCK

ELECTROLYSIS AS A PATH TO USE CO_2



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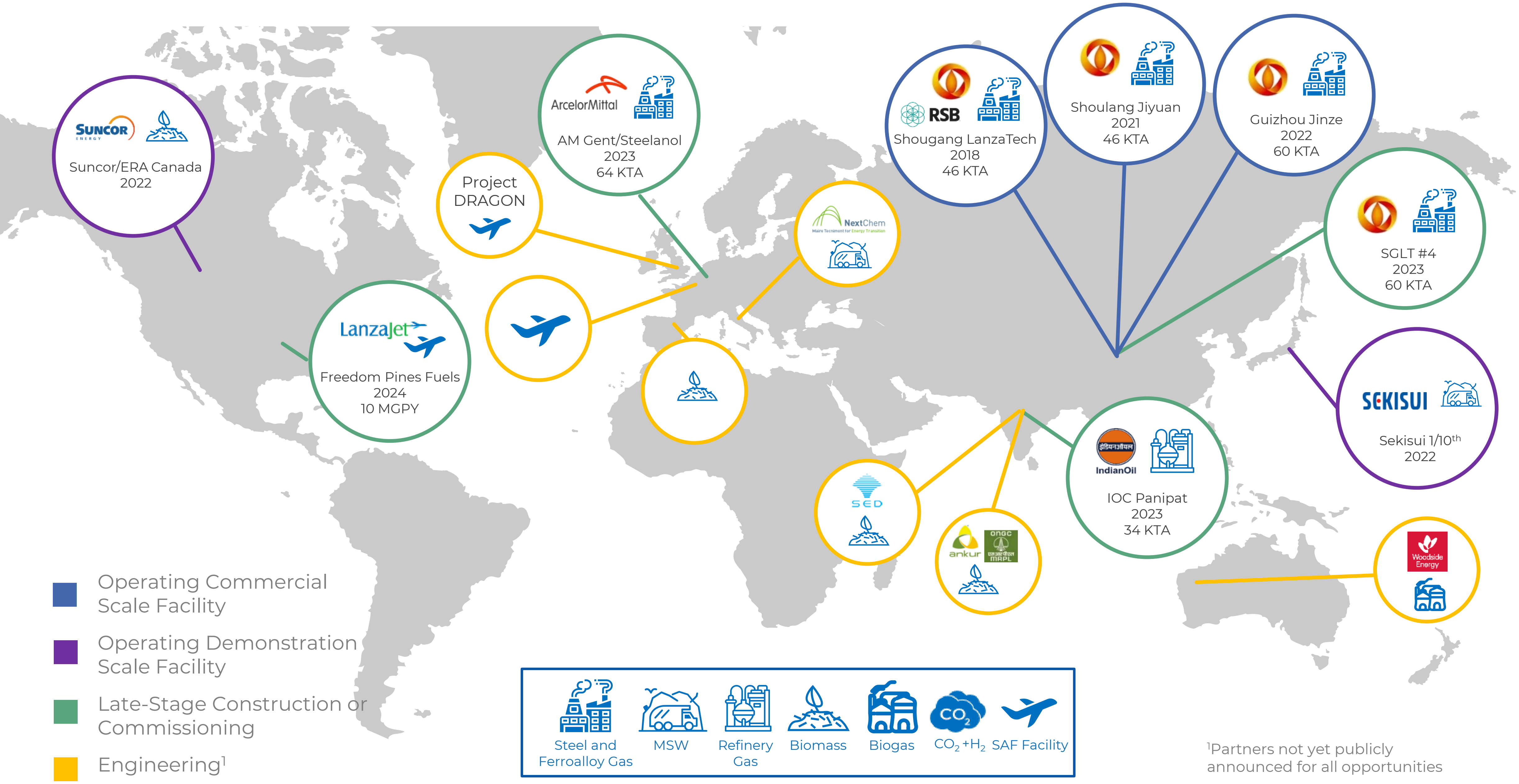
PROJECTS IN OPERATION, CONSTRUCTION & ENGINEERING GLOBALLY



[1]Partners not yet publicly announced for all opportunities

ON THE ROAD TO GIGATONS OF CARBON

500,000 tons CO_2

ANTICIPATED ANNUAL ABATEMENT ONCE THREE ADDITIONAL FACILITIES ARE OPERATIONAL

300,000 tons Product

ANTICIPATED ANNUAL PRODUCTION ONCE THREE ADDITIONAL FACILITIES ARE OPERATIONAL

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CARBON SMART™ PRODUCTS

POWER

CAN BE CARBON FREE

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FUELS
NEED CARBON

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CHEMICALS

FOR EVERYDAY PRODUCTS NEED CARBON

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10% GLOBAL EMISSIONS

DEMAND FOR SUSTAINABLE PRODUCTS CREATES DEMAND PULL FOR ADDITIONAL LICENSED BIOREFINING CCT PLANTS

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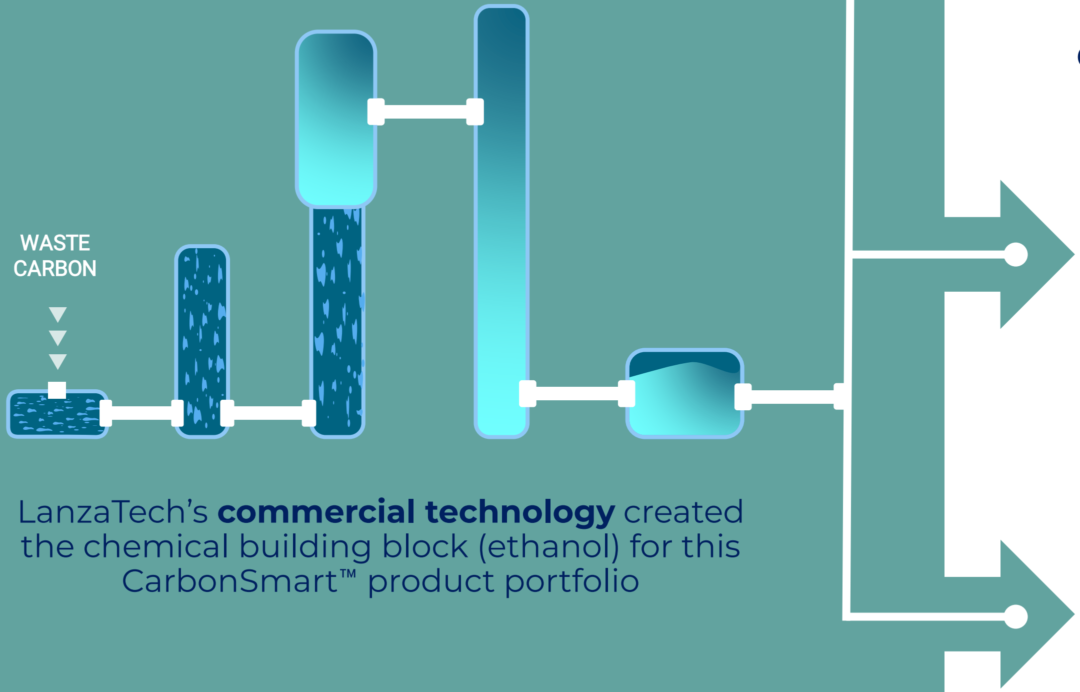
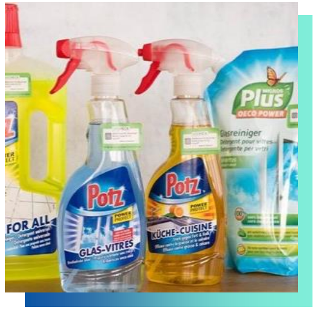
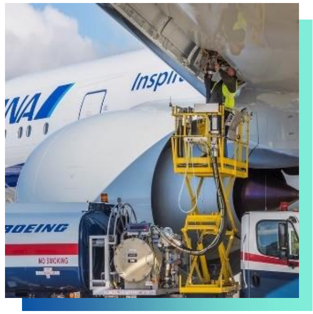


LanzaTech's **commercial technology** created the chemical building block (ethanol) for this CarbonSmart™ product portfolio

PRODUCTS MADE FROM CARBON EMISSIONS

TEXTILES	SHOE SOLES	PACKAGING
		
CLEANING PRODUCTS	**FRAGRANCES**	**SAF**
		
DETERGENTS	**CONTAINERS**	**SURFACTANTS**
		

COTY SINCE 1904 · ZARA · MIGROS · mibelle GROUP · CRAGHOPPERS · Unilever · L'ORÉAL · On · virgin atlantic · H&M MOVE · lululemon

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ETHANOL: A STARTING POINT FOR MULTIPLE PATHWAYS

BUILDING BLOCK OF THE FUTURE

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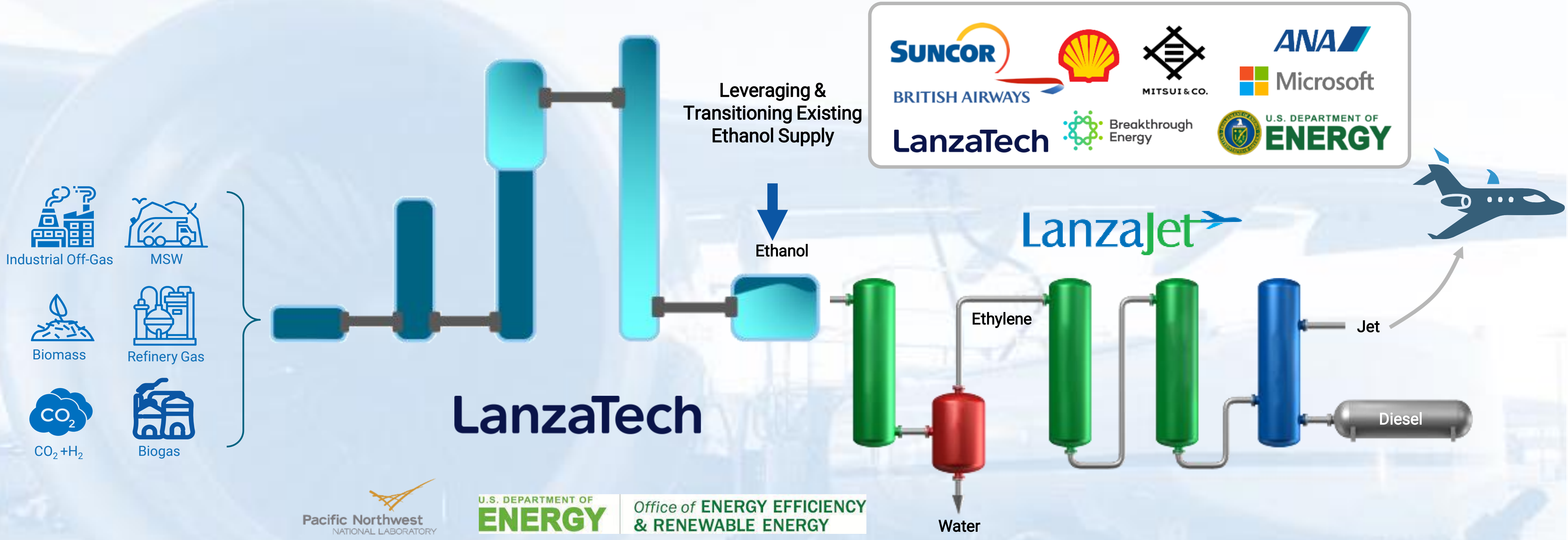
LANZAJET TURNS WASTE CARBON INTO SUSTAINABLE AVAITION FUELS



Drop-In Ready – ASTM Approved

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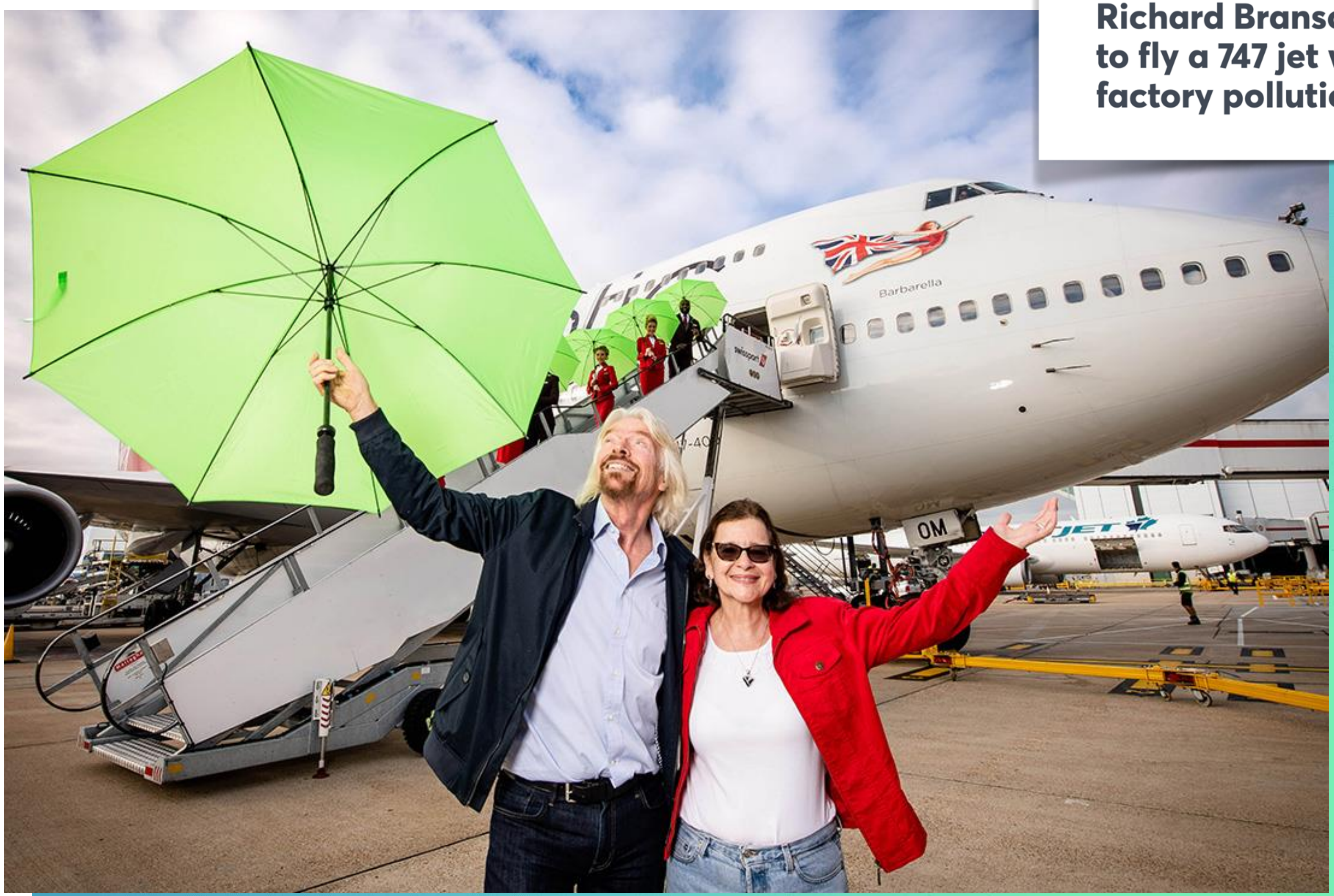

make it

Richard Branson's Virgin Atlantic set to fly a 747 jet with fuel made from factory pollution

LanzaJet

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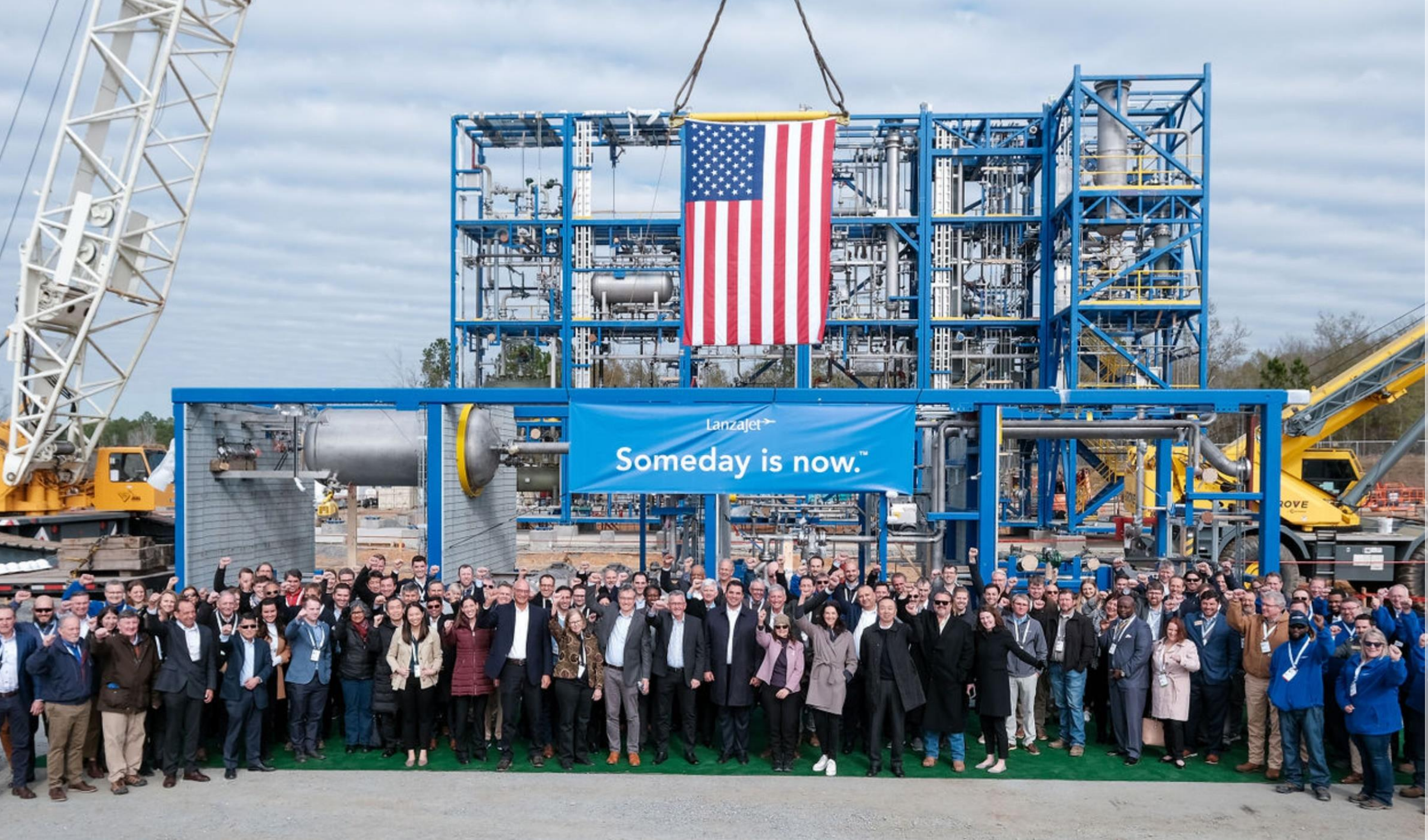

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FAST COMPANY

These gorgeous Zara party dresses are made from carbon emissions

Carbon created by a Chinese steel factory is fermented with bacteria and then ends up in this capsule collection.

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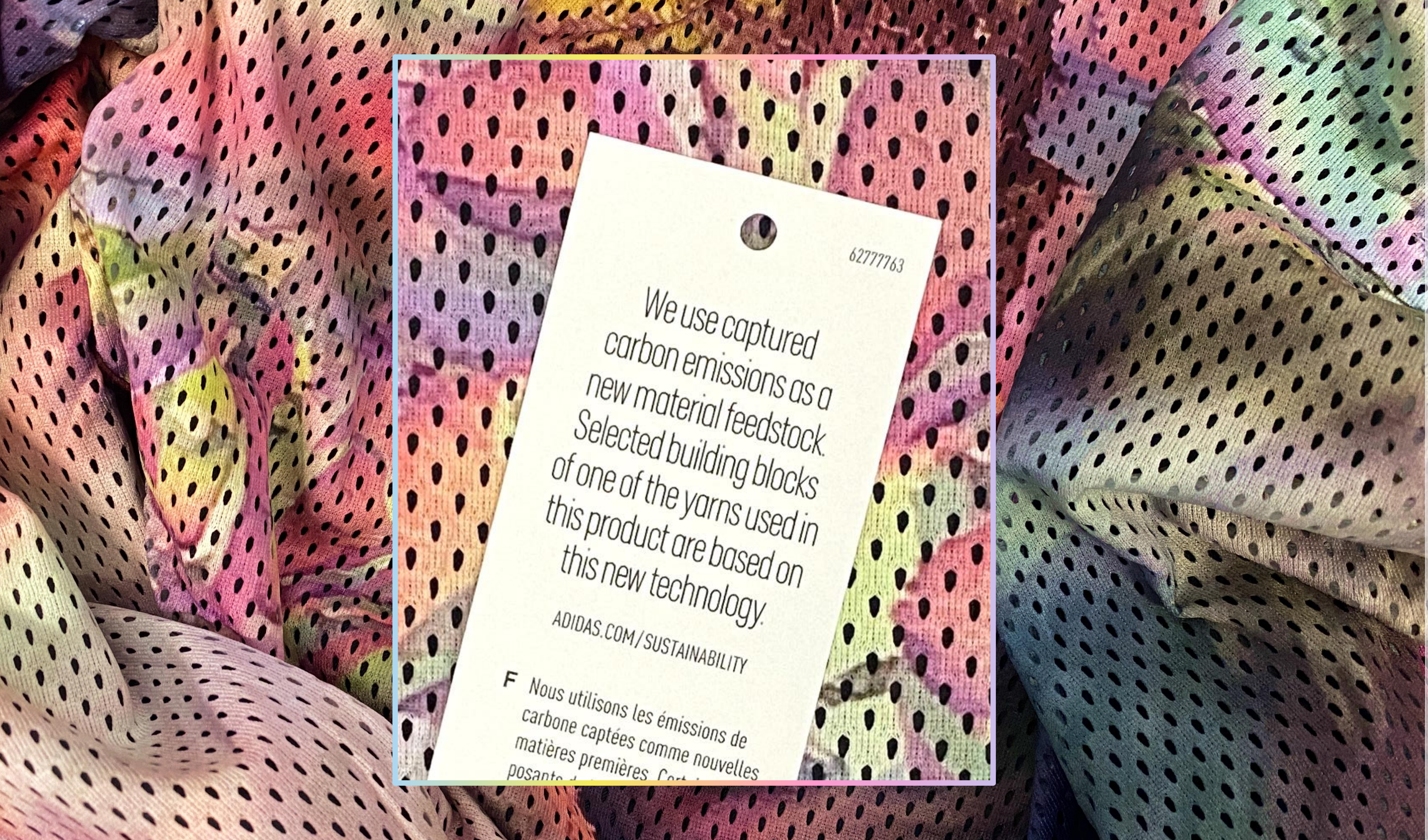
62777763
We use captured carbon emissions as a new material feedstock. Selected building blocks of one of the yarns used in this product are based on this new technology.
ADIDAS.COM/SUSTAINABILITY
F
Nous utilisons les émissions de
carbone captées comme nouvelles
matières premières.

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Forbes

Swiss Footwear Brand Develops A Running Shoe Made From Carbon Emissions

Run on clouds.

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Migros launches recycled carbon derived consumer cleaning products

MIGROS

mibelle GROUP

BSB Innovation Award® Environment 2021

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VOGUE BUSINESS

BEAUTY

Why Gucci's latest fragrance is made from recycled carbon

The Italian luxury house's new perfume, Where My Heart Beats, is Coty's first globally distributed fragrance manufactured using 100 per cent carbon-captured alcohol. *Vogue Business* has the exclusive.

BY KATI CHITRAKORN

April 3, 2023

"As carbon recycling becomes a bigger focus in beauty, **LanzaTech has emerged as the partner of choice.**"

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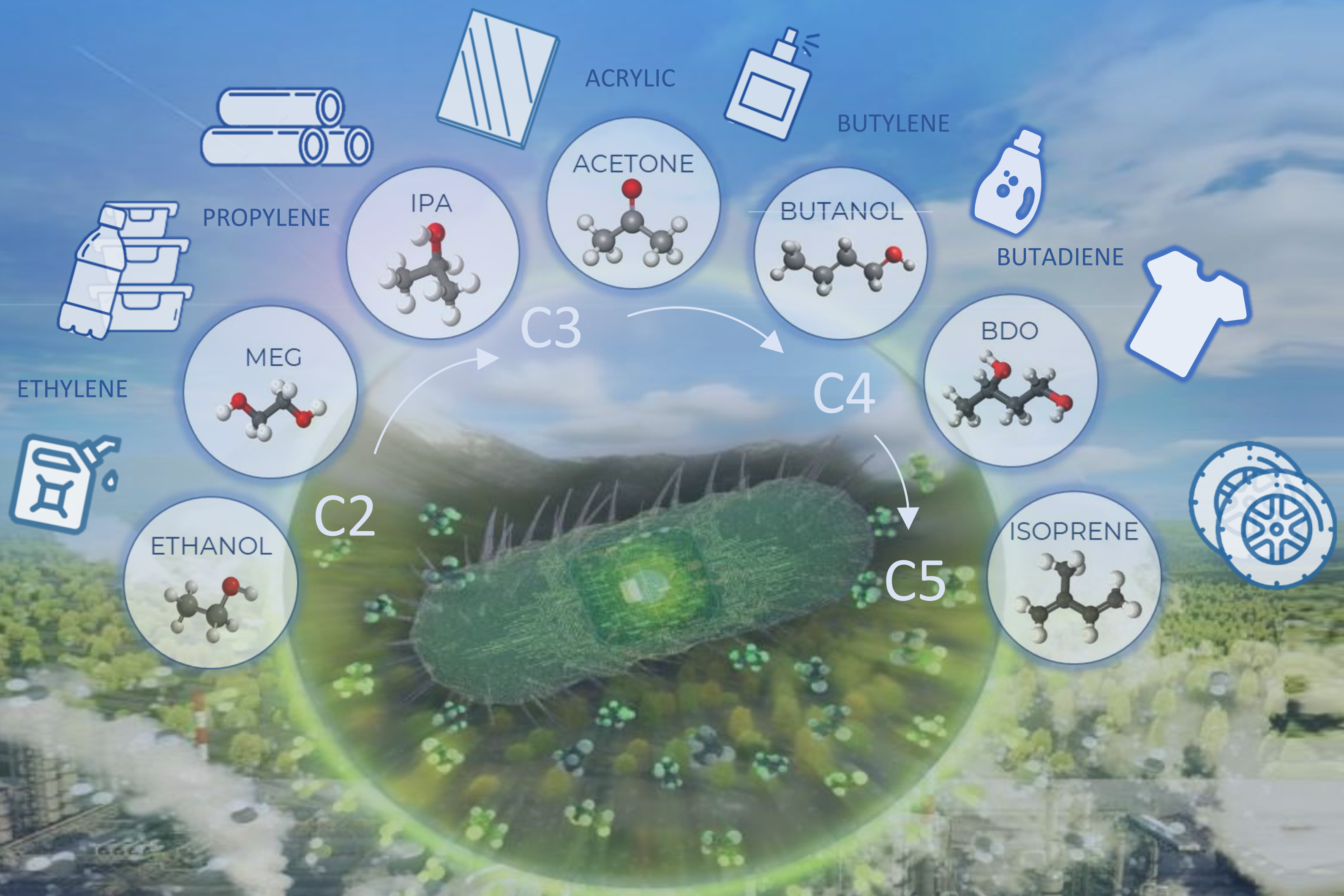
SYNTHETIC BIOLOGY

DIRECT PRODUCTION OF OTHER KEY BUILDING BLOCKS



Liew et al. (2022) *Nature Biotechnology* 40: 335; Karim et al. (2020) *Nature Chemical Biology* 16: 912

Image credit: Justin Muir

>100 PRODUCTS DEMONSTRATRATED VIA SYNTHETIC BIOLOGY

	Acids						Alcohols		Diols			Aromatics	Dienes	Esters	Ketones	Terpenes
	Carboxylic	Dicarboxylic	Hydroxy	Dihydroxy	Keto	Amino	Linear	Branched	1,2-	1,3-	2,3-					
C2	Acetic	Glyoxylic	Glycolic				Ethanol		MEG				Ethylene			
C3	Propionic		Lactic, 3-hydroxypropionic			Alanine	n-propanol	Isopropanol	1,2-PDO (R,S,mix)	1,3-PDO (R,S,mix)					Acetone	
C4	Butyric	Succinic	2-HB, 3-HB (R,S,mix), 4-HB	2-HIBA, 2-Ethylmalate	Ketovaleric		n-butanol	2-butanol		1,3-BDO (R,S,mix)	2,3-BDO (RR,meso,mix)		Butylene		Acetoin, MEK	
C5	Valeric		Citramalic		Ketoglutaric	Valine, Methionine	n-pentanol	isoamylalcohol					Isoprene			
C6+	C6-C14 Carboxylic acids		C6-C14 Hydroxyacids, PHB	Mevalonic	C6-C14 Alkylmalates	Leucine, Isoleucine	linear	branched				2-Phenyl ethanol, Salicylic, PHAB	FAEE, FABE			Monoterpenes, Diterpenes, Sesquiterpenes, Farnesene

C6-C14 Alcohols

LANZATECH'S ADVANCED SYNTHETIC BIOLOGY PLATFORM

FULLY-AUTOMATED GENERATION & SCREENING OF 1000S ANAEROBIC, GAS-FERMENTING STRAINS

RESULT OF A DECADE OF TOOL & WORKFLOW DEVELOPMENT, AS WELL AS SYSTEM CHARACTERIZATION

Köpke & Simpson (2020) *Curr Opin Biotechnol* 65: 180; Fackler et al. (2021) *Ann Rev Chem Biomol Eng* 12: 439

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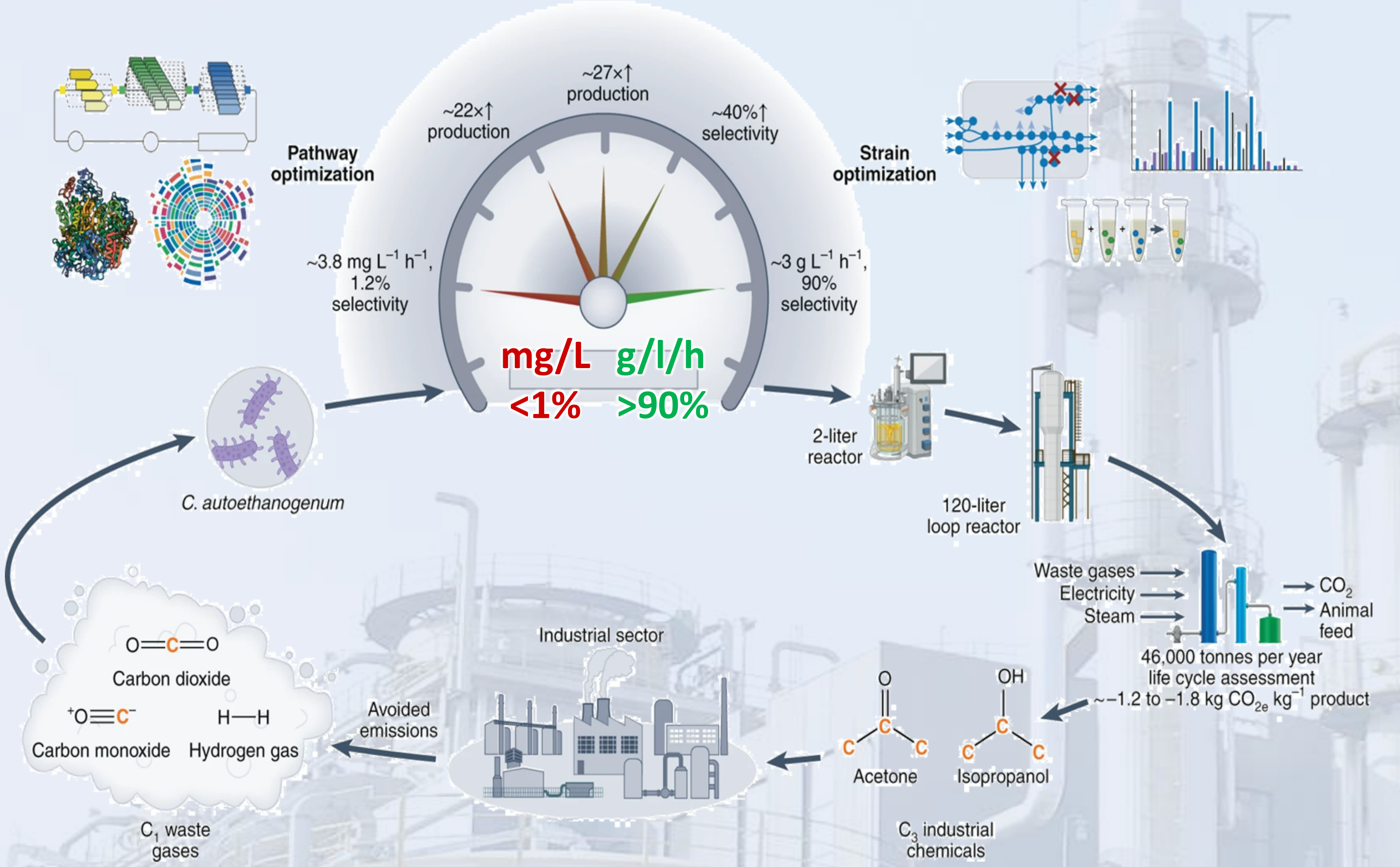
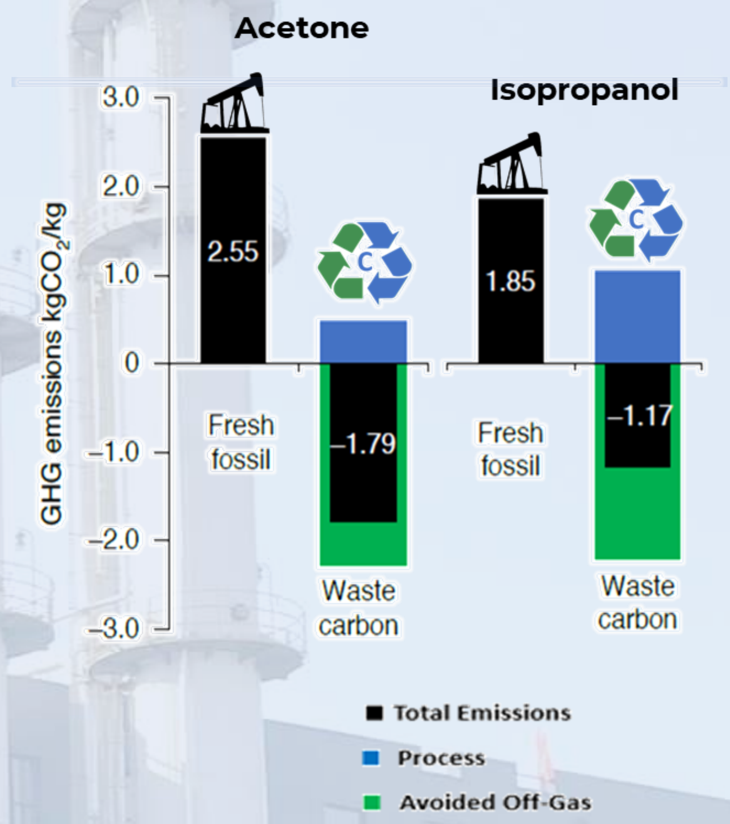
CARBON-NEGATIVE BIOMANUFACTURING OF ACETONE & IPA

Northwestern SYNTHETIC BIOLOGY
OAK RIDGE National Laboratory





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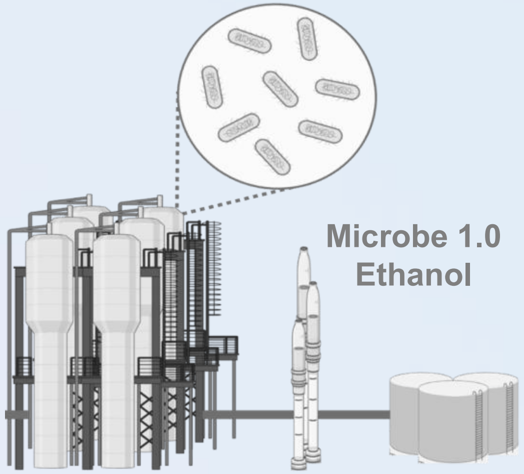
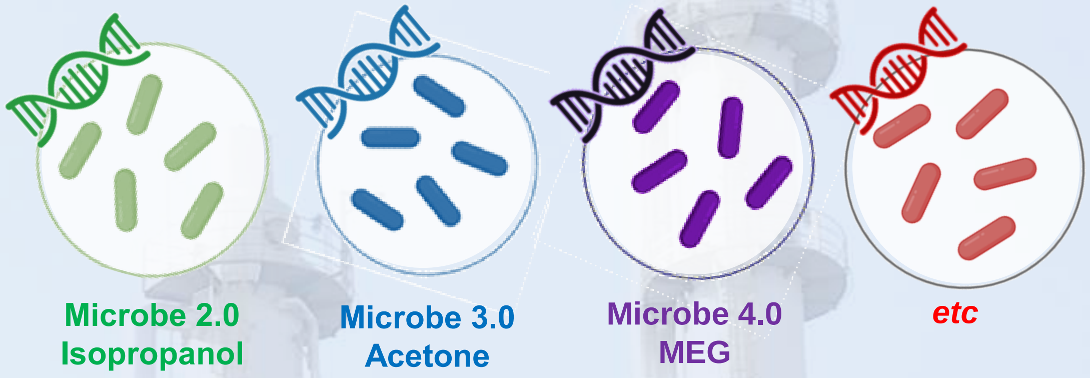
Liew, Nogle, Abdalla, … Leang, Jewett & Köpke (2022) Nature Biotechnology 40: 335–344;
Scown & Keasling (2022) Nature Biotechnology 40: 304-307; Karim, … Köpke & Jewett (2020) Nature Chemical Biology 16: 912–919

WHAT DO YOU WANT TO MAKE TODAY?



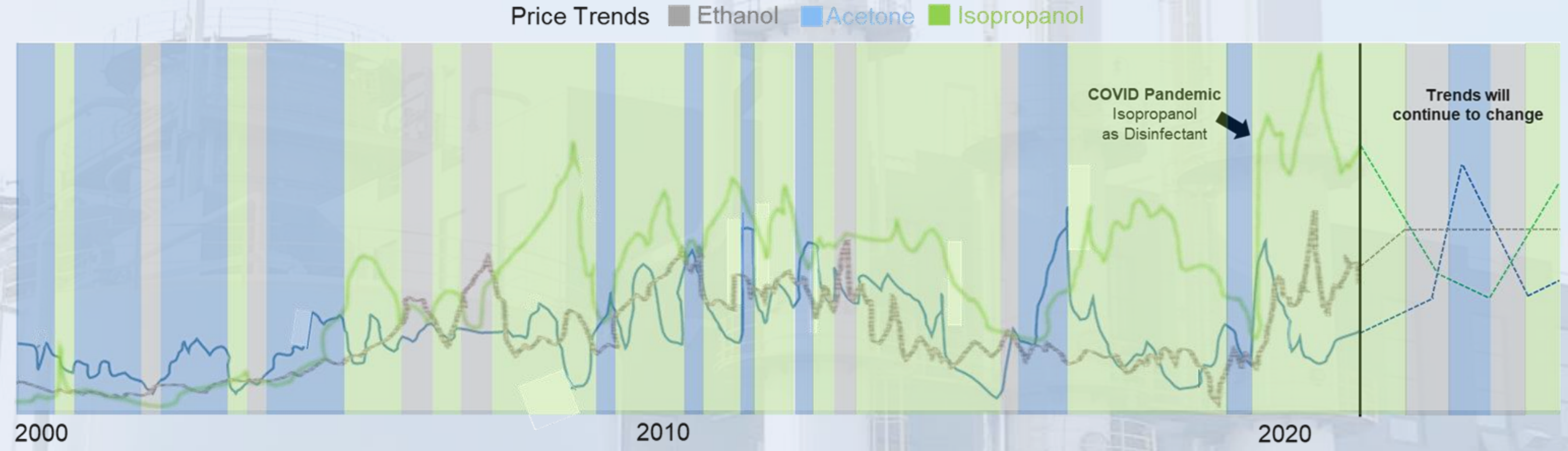
"HARDWARE"



"SOFTWARE"

✓ Same reactor ✓ Same feedstock ✓ Same process

DISRUPTION =
1) Rapid Reaction to Market Fluctuations 2) Feedstock ≠ Commodity



Source: ICIS

Images generated with Biorender.com.

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PROVIDING SOLUTIONS TO INDUSTRY LEADERS ACROSS SECTORS

✓ Same reactor ✓ Same feedstock ✓ Same process

Images generated with Biorender.com.

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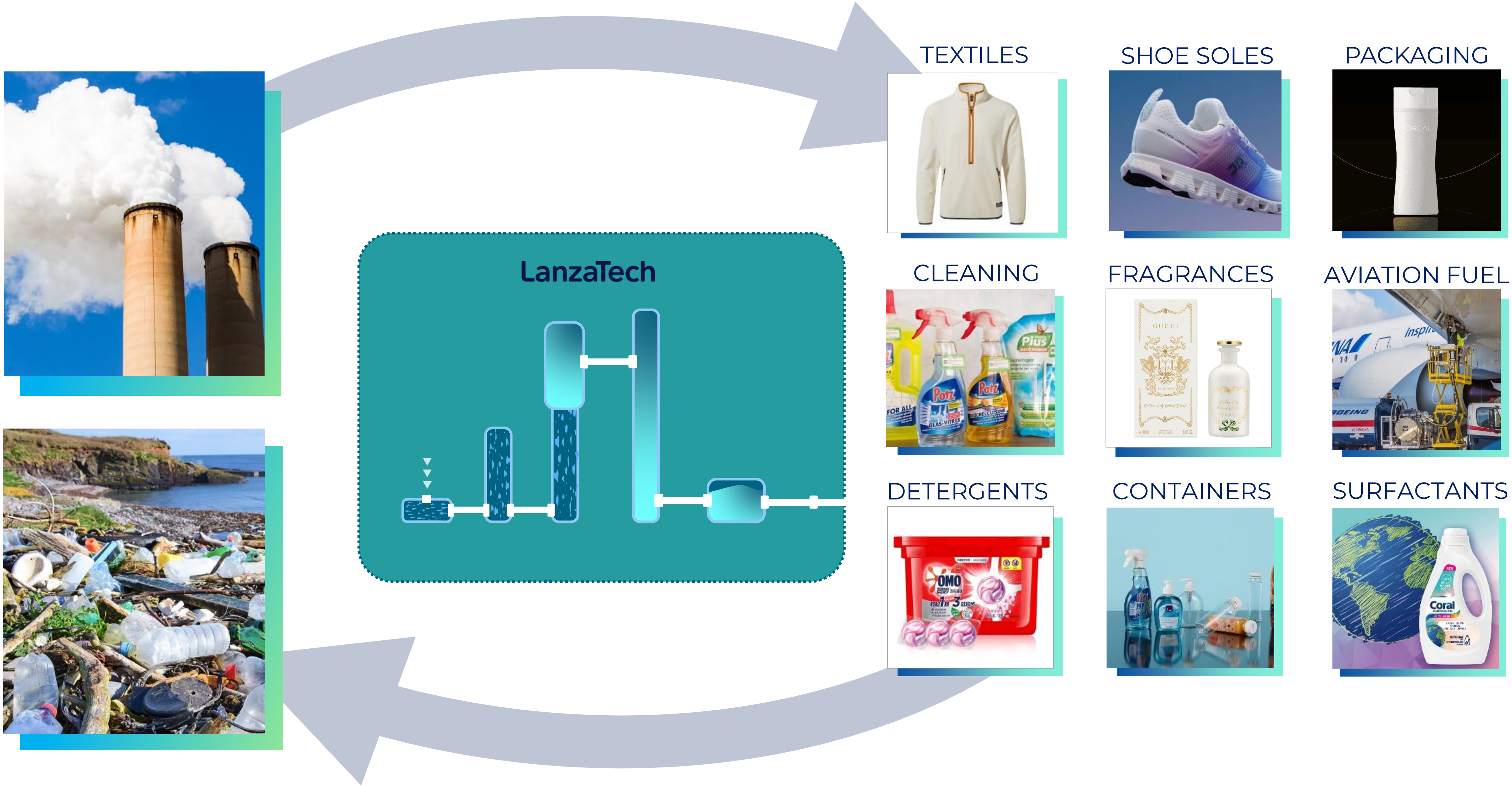
THE NEW CARBON ECONOMY IS DISTRIBUTED AND CIRCULAR



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THE WORLD HAS
ENOUGH CARBON ABOVE
GROUND TO MAKE
EVERYTHING WE NEED

WE CREATE VALUE
WHERE OTHERS
SEE WASTE

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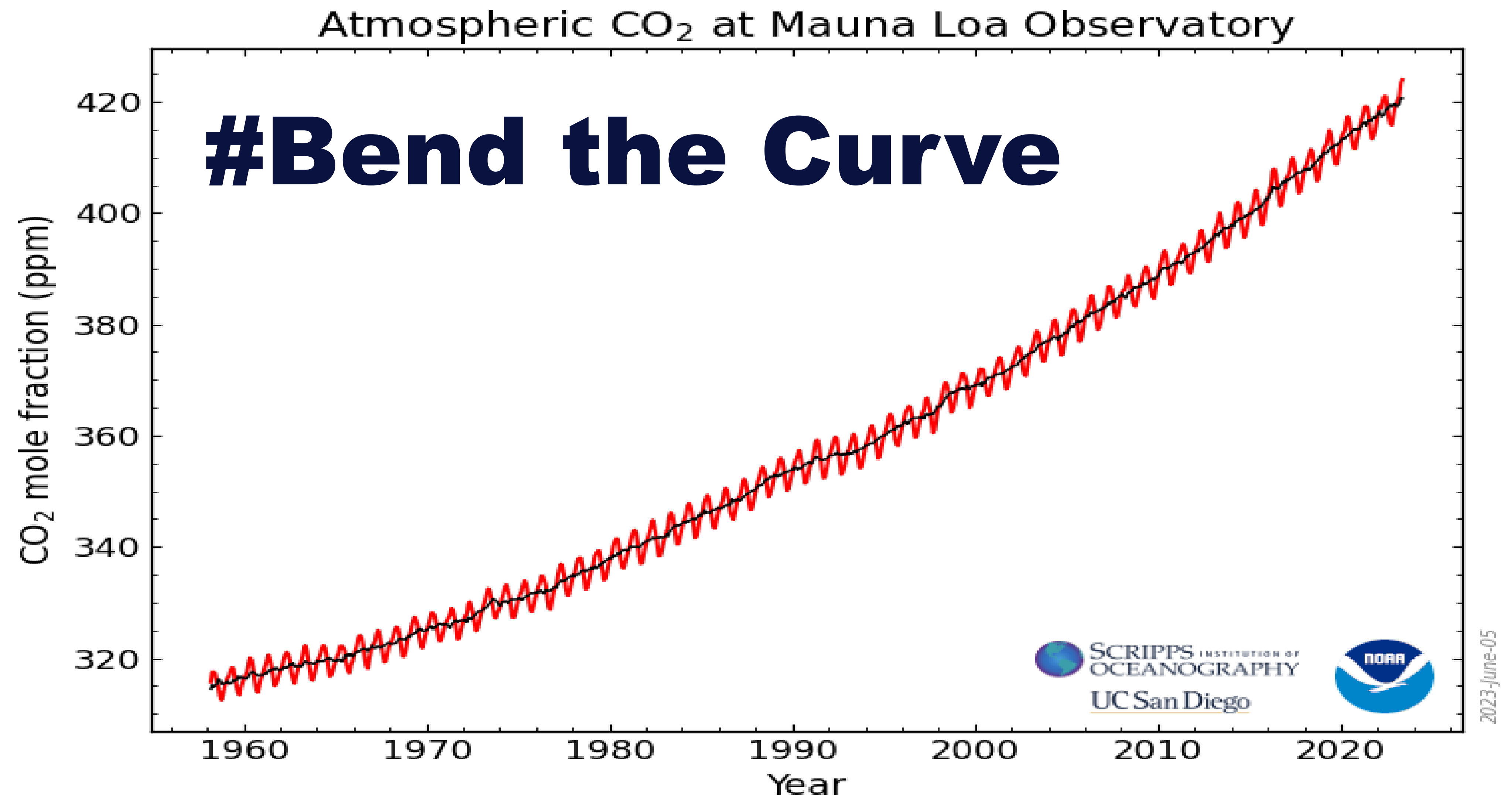

Atmospheric CO_2 at Mauna Loa Observatory
#Bend the Curve
420
400
380
360
340
320
CO_2 mole fraction (ppm)
1960
1970
1980
1990
2000
2010
2020
Year
SCRIPPS INSTITUTION OF OCEANOGRAPHY
UC San Diego
NOAA
2023-June-05

Engineering Biology for Climate & Sustainability

A Research Roadmap for a Cleaner Future.

1.5 Year Effort By Over 90 Global Contributors from Academia, Industry, Government & NGOs

Roadmap Leadership:

Emily Aurand, EBRC Director of Roadmapping
Sifang Chen, EBRC Postdoctoral Fellow | Senior Advisor, Carbon 180
Michael Köpke, EBRC Roadmapping WG Chair | VP Synthetic Biology, LanzaTech

- **Khalid Alam** – Stemloop, Inc.
- **Thomas Alexander** – North Carolina State University
- **Matt Amrofell** – Washington University in St. Louis
- **Peter Andeer** – Lawrence Berkeley National Laboratory
- **Adam Arkin** – University of California, Berkeley
- **Emily R. Aurand** – EBRC
- **Amin Espah Borujeni** – Massachusetts Institute of Technology
- **Sam Weiss Evans** – Harvard University
- **Trent Evans** – Washington University
- **Mike Fero** – TeselaGen Biotechnology, Inc.
- **Paul Freemont** – Imperial College London
- **Emily (Emm) Fulk** – Rice University
- **Kanya Long** – University of California, San Diego
- **Julius Lucks** – Northwestern University
- **Rebecca Mackelprang** – EBRC
- **Krishna Mahadevan** – University of Toronto
- **Cecilia Martinez-Gomez** – University of California, Berkeley
- **Caroline Masiello** – Rice University
- **Amy Stoddard** – Boston University
- **Emily Stoler** – Zymergen
- **Tyler Stukenbroeker** – Massachusetts Institute of Technology
- **Sean Sullivan** – Tufts University
- **Yinjie Tang** – Washington University in St. Louis
- **Bishal Thapa** – University of Idaho
- **Ania-Ariadna Baetica** – University of California, San Francisco
- **Debjyoti Banerjee** – Texas A&M University
- **Robert Beniach** – University of Michigan
- **Roel Bovenberg** – DSM
- **Nicole Buan** – University of Nebraska, Lincoln
- **James Carothers** – University of Washington
- **Ute Galm** – Curie Co.
- **Annelise Goldman** – Rice University
- **Daniel Goodwin** – Homeworld Collective
- **Jeffrey Gralnick** – University of Minnesota
- **Maneesh Gupta** – Air Force Research Laboratory
- **Karmella Haynes** – Emory University
- **Carolyn Mills** – Northwestern University
- **Tae Seok Moon** – Washington University in St. Louis
- **Steven Moss** – National Academies of Sciences, Engineering, and Medicine
- **Nik Nair** – Tufts University
- **Cynthia Ni** – Massachusetts Institute of Technology
- **Trent Northen** – Lawrence Berkeley Lab
- **Kersh Thevasundaram** – University of California, Berkeley
- **Esteban Toro** – Twist Bioscience
- **Tyler Toth** – Massachusetts Institute of Technology
- **Cara Tracewell** – Arzeda
- **Danielle Tullman-Ercek** – Northwestern University
- **Julia Turnšek** – University of California, Berkeley
- **Yonatan Chemla** – Massachusetts Institute of Technology
- **Sifang Chen** – EBRC
- **Kung-Hui (Bella) Chu** – Texas A&M University
- **Patrick Cirino** – University of Houston
- **Carrie Cizauskas** – Independent
- **Leah Davis** – Rowan University
- **Albert Hinman** – EBRC
- **India Hook-Barnard** – EBRC
- **Michael Jewett** – Northwestern University
- **Lauren Junker** – BASF
- **Cholpisit (Ice) Kiattisewee** – University of Washington
- **Michael Köepke** – LanzaTech
- **Javin Oza** – California Polytechnic State University
- **Megan Palmer** – Stanford University
- **Marilene Pavan** – LanzaTech
- **Paul Reginato** – Massachusetts Institute of Technology
- **Marianela Rodriguez-Carres** – BASF
- **Howard Salis** – Pennsylvania State University
- **Matthew Tuttle** – University of Tennessee, Knoxville
- **Ginni Ursin** – Independent
- **Natanya Villegas** – University of Oregon
- **Camille Wolf** – University of California, Davis
- **Quanhui Ye** – University of Illinois, Urbana-Champaign
- **Yasuo Yoshikuni** – Lawrence Berkeley National Laboratory
- **John J. Desmarais** – University of California, Berkeley
- **James Diggans** – Twist Bioscience Corporation
- **David Ding** – Univ. of California, Berkeley/DOE Joint Genome Institute
- **Kaitlyn Duvall** – EBRC
- **Robert Egbert** – Pacific Northwest National Laboratory
- **Emiley Eloe-Fadrosh** – Joint Genome Institute, Lawrence Berkeley National Lab
- **Brandon Lam** – Ginkgo Bioworks
- **Isaac Larkin** – FreeGenes Project
- **Allen (Seung Hwan) Lee** – Rice University
- **Kok Zhi Lee** – Purdue University
- **Angela Lee** – EBRC
- **Chien-Yuan Lin** – Lawrence Berkeley National Laboratory
- **Dan Siegal** – Ginkgo Bioworks
- **Pamela Silver** – Harvard Medical School
- **Blake Simmons** – Lawrence Berkeley National Laboratory
- **Chuck Smallwood** – Sandia National Laboratories
- **Kevin Solomon** – Purdue University; current affiliation University of Delaware
- **Liz Specht** – The Good Food Institute
- **Jesse Zalatan** – University of Washington
- **Yan Zhang** – Georgia Institute of Technology
- **Laurie Zoloth** – University of Chicago

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Engineering Biology for Climate & Sustainability

A Research Roadmap for a Cleaner Future.

Critical Assessment of Opportunities for Engineering Biology to Contribute to Tackling the Climate Crisis & Long-term Sustainability and Well-being of Earth and its Inhabitants

- Part I: Developing Novel Capabilities for Climate Change Mitigation & Ecosystem Resilience
- Part 2: Enabling Climate-friendly and Sustainable Production in Application Sectors
- Part 3: Social Dimensions and Policy Considerations

Novel Capabilities

Biosequestration of Greenhouse Gases

Mitigating Environmental Pollution

Conservation of Ecosystems & Biodiversity

Application Sectors

Food & Agriculture

Transportation & Energy

Materials Production & Industrial Processes

Roadmap Elements

Roadmap Goals	Objective, end-point, what we hope to accomplish/obtain.
Current State-of-the-Art	What we can accomplish today (generally attainable/achievable, and replicable, in most research laboratories).
Engineering Biology Breakthrough Capabilities	What breakthrough capability would make a big difference? How can we achieve the Goal with engineering biology.
Technical Milestones	Over time, what tool and technology developments do we need to achieve the Breakthrough Capability?
Bottlenecks and Potential Solutions	What are the bottlenecks to achieving the milestone? And what potential solutions might overcome the bottleneck?

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Engineering Biology for Climate & Sustainability

What can engineering biology do for climate and sustainability?

Carbon Capture and Transformation/Storage

Engineered organisms capture and convert CO_2 into useful products/solid carbon-containing compounds

Pollution Reduction

Engineered enzymes enable the breakdown of pollutants in the environment

Ecosystem Resilience

Engineered organisms help forest restoration and recovery from environmental stress

Industrial Processes

Biobased materials, such as bioplastics, to replace fossil-fuel derived products

Agriculture

Sustainable production of alternative meats and proteins with lower land use and carbon emissions

Transportation

New generation of sustainable biofuels lowers emissions from aviation and shipping

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Biosequestration of Greenhouse Gases

At-scale capture, storage, and utilization of GHGs by engineered organisms

Short-term	Medium-term	Long-term
Improve CO_2 uptake by engineering more efficient photosynthetic organisms (plants, algae, cyanobacteria).		
Engineer plants for optimized light collection and more efficient use of captured light for photosynthesis.	Engineer pathways and enzymes in photosynthetic organisms to increase the rate and efficiency of carbon fixation. Develop scalable carbon capturing platforms enabled by engineered green algae and cyanobacteria.	Combine and rewire native CO_2 fixation pathways (e.g., C3 and C4 pathways) and engineer organisms capable of utilizing multiple carbon fixation pathways.
Enable efficient carbon capture by engineered chemoautotrophs.		
Map and identify parts in CO_2 fixation pathways to increase the efficiency of carbon fixation in chemoautotrophic organisms.	Engineer complexes and metabolic pathways in chemoautotrophs to improve carbon fixation.	Demonstrate use of engineered chemoautotrophs to capture more CO_2 in the context of environmental or industrial processes.
Enable organisms to utilize captured carbon to produce value-added chemicals and materials.		
Engineer organisms to convert CO2, methane, or other C1 sources and intermediates (incuding methanol, formate, acetate) into value-added compounds.	Optimize the bio-utilization of CO_2 and methane emitted from point sources. Improve gas fermentation technologies.	Combine and rewire native carbon utilization pathways and engineer organisms capable of using multiple carbon metabolism pathways.
Enable carbon capture and utilization by enzymes or cell-free systems.		
Develop efficient enzymes for concentrating carbon from the atmosphere. Develop scalable cell-free systems as platforms for carbon capture and bioconversion.	Develop efficient and scalable cell-free systems capable of utilizing methane, formate, or CO_2 to produce commodity fuels and chemicals.	Develop self-contained and/or standalone cell-free CO_2 fixation systems for bio-enabled artificial photosynthesis. Develop new platform tools for multienzyme immobilization in cell-free systems.

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Biosequestration of Greenhouse Gases

Enable efficient carbon capture by engineered chemoautotrophs

Short-term: Map and identify parts in CO_2 fixation pathways to increase the efficiency of carbon fixation in chemoautotrophic organisms.

Bottleneck/Challenge: Identity and understanding of the most rate-limiting step to CO_2 sequestration in chemoautotrophic model organisms and the missing energy-coupling sites and interaction in native carbon fixation pathways (e.g., Wood-Ljungdahl pathway).

Potential Solution: Understand the role of all genes involved in carbon fixation in chemoautotrophic organisms through omics approaches, enzyme studies, mutagenesis or knockout experiments to identify the rate-limiting step and missing links.

Potential Solution: Map and understand the flux and bioenergetic links between carbon, nitrogen, phosphorus, sulfur metabolism in chemoautotrophs.

Bottleneck/Challenge: Knowledge of how changes in enzyme expression levels affect function in C1 pathways.

Potential Solution: Map protein-protein interactions, characterize transcription factors and multienzyme complexes and their dynamics, and identify metabolic substrate channeling between relevant enzymes.

Biosequestration of Greenhouse Gases
Enable efficient carbon capture by engineered chemoautotrophs

Medium-term: Engineer complexes and metabolic pathways in chemoautotrophs to improve carbon fixation.

Bottleneck/Challenge: Enzymes and cofactors optimized for recycling and energetics.

Potential Solution: Improve the efficiency of major CO_2 fixation or methane oxidizing enzymes.

Potential Solution: Discover or design new enzymes that are more efficient at capturing CO_2 or converting methane.

Potential Solution: Develop orthologous co-factors.

Bottleneck/Challenge: Limited molecular and genetic toolkits for domesticated chemoautotrophs.

Potential Solution: Develop broader toolsets (e.g., genome engineering, enzyme engineering, and cell-free systems) and high-throughput workflows for engineering chemoautotrophs, such as *Thermotoga neapolitana*, *Cupriavidus necator*, *Clostridia* species, and methanoarchaea.

Potential Solution: Develop high-throughput screening capabilities to reduce strain development cycle times.

Bottleneck/Challenge: High-throughput cultivation and product screening in context flammable and/or toxic gaseous substrates such as carbon oxides and methane.

Potential Solution: Develop new plate based or microfluidics based screening workflows that facilitate growth on gaseous substrates, while retaining or direct measuring of product concentrations.

Potential Solution: Develop analytics and sensor tools for dissolved concentrations of carbon oxide and methane gasses in screening assays.

Biosequestration of Greenhouse Gases

Enable efficient carbon capture by engineered chemoautotrophs

Long-term: Demonstrate use of engineered chemoautotrophs to capture more CO_2 in the context of environmental or industrial processes.

Bottleneck/Challenge: Air and many other potential industrial streams (e.g., cement plants, landfills) have low CO_2 or methane concentrations requiring expensive steps for gas concentration or compression.

Potential Solution: Engineer organisms for effective conversion at low or atmospheric CO_2 or methane concentrations.

Bottleneck/Challenge: Effective biocontainment strategies for deployed organisms.

Potential Solution: Develop low-cost methods to employ bio-orthogonal biochemistry.

Potential Solution: Develop risk analysis frameworks to define risk benchmarks.

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Biosequestration of Greenhouse Gases

Enable organisms to utilize captured carbon to produce value-added chemicals/materials

Short-term: Engineer organisms to convert CO_2, methane, or other C1 sources and intermediates (incuding methanol, formate, acetate) into value-added compounds.

Bottleneck/Challenge: Optimal electro-biochemical routes for carbon conversion into value added compounds are not known.

Potential Solution: Design electro-biochemical routes for minimizing the loss of carbon through metabolism or to directly sequestering carbon for bioconversion into value-added compounds. [58]

Potential Solution: Develop approaches to evolve promising chemolithoautotrophic organisms to increase yield of desired products.

Bottleneck/Challenge: Lack of platforms for genome-wide engineering of non-model chemoautotrophs with metabolic and physiological capabilities needed for optimized carbon conversion.

Potential Solution: Develop new genome scale modeling and engineering tools for rapidly generating and implementing carbon-optimized designs.

Potential Solution: Develop machine learning algorithms, artificial intelligence tools, cell-free systems, and multi-omics workflows to enable faster data-driven DBTL cycles in non-model microbes.

Bottleneck/Challenge: While acetate is a universal carbon source for many microbes (including model organisms such as yeast or E. coli) that have been engineered to produce value-added chemicals, the current process releases CO_2. [59]

Potential Solution: Chemoautotrophs are capable of producing acetate from CO_2 at high rates;[60] adapt efficient production strains for using acetate instead of sugars as substrate for value-added products and develop co-culture or coupled processes.

Biosequestration of Greenhouse Gases

Enable organisms to utilize captured carbon to produce value-added chemicals/materials

Medium-term: Optimize the bio-utilization of CO_2 and methane emitted from point sources.

Bottleneck/Challenge: High gas mass transfer is required; gases like methane, carbon monoxide or hydrogen are poorly soluble.

Potential Solution: Develop energy-efficient systems for harvesting products made by microbes grown in large-scale bioreactors.

Bottleneck/Challenge: Waste gas streams contain compounds that inhibit the activities of microbes and enzymes.

Potential Solution: Engineer and select microbes to tolerate different sources of greenhouse gas and metabolic byproducts.

Potential Solution: Improve enzymatic activity, stability, and reusability for converting CO_2 into chemicals.

Medium-term: Improve gas fermentation technologies.

Bottleneck/Challenge: Heterogeneity due to continuous gas feeding and gradients in bioreactor environments.

Potential Solution: Develop real-time, biobased monitoring tools (e.g., biosensors to detect and report dissolved gases such as carbon monoxide).

Potential Solution: Engineer microbes with focus on efficient utilization of variable, fluctuating gas ratios.

Biosequestration of Greenhouse Gases

Enable organisms to utilize captured carbon to produce value-added chemicals/materials

Long-term: Combine and rewire native carbon utilization pathways and engineer organisms capable of using multiple carbon metabolism pathways.

Bottleneck/Challenge: Flexible chassis organisms suitable for industrial scale cultivation.

Potential Solution: Engineer reversible flux-based CO_2 fixation, H2 production and methanogenesis/methanotrophy in, for example, Methanosarcinales.[61]

Potential Solution: Engineer consortia that can capture and utilize the full carbon life-cycle in a circular manner.

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Engineering Biology for Climate & Sustainability
Social and Nontechnical Dimensions Case Studies

- Case study 1: Release of engineered algae with increased carbon capture capability in U.S. coastal waters off California;
- Case study 2: Application of biofertilizers based on engineered rhizobia to corn fields in the American Midwest;
- Case study 3: High efficiency lithium biomining in Nevada with engineered microbes;
- Case study 4: Engineering cattle microbiomes to reduce methane emissions in American agriculture.

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LanzaTech

Nasdaq: LNZA

WELCOME TO THE POST POLLUTION FUTURE

Safety First

Science is real (and awesome)

Immigrants are welcome

The Climate is changing

Black Lives Matter

Feminism is for everyone

Love is love

LanzaTech