Production of sustainable fuels and chemicals from waste gas streams

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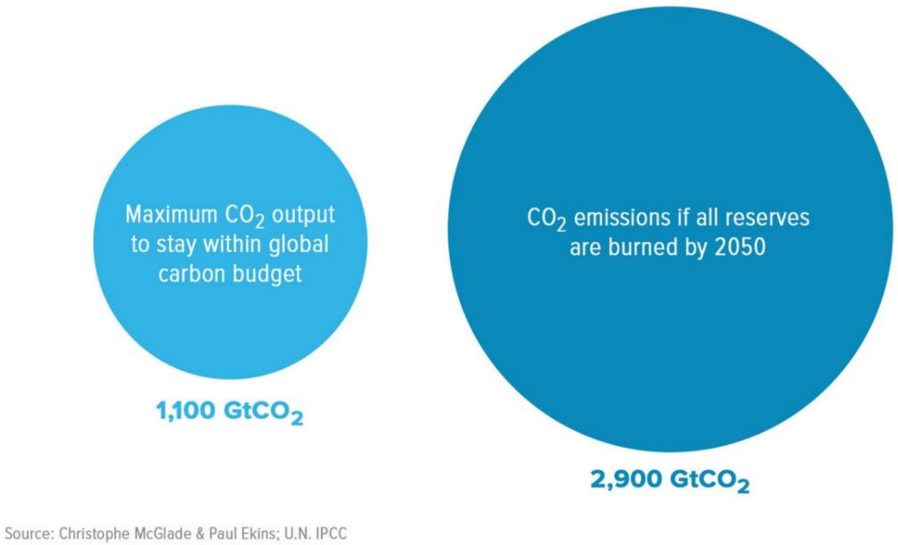
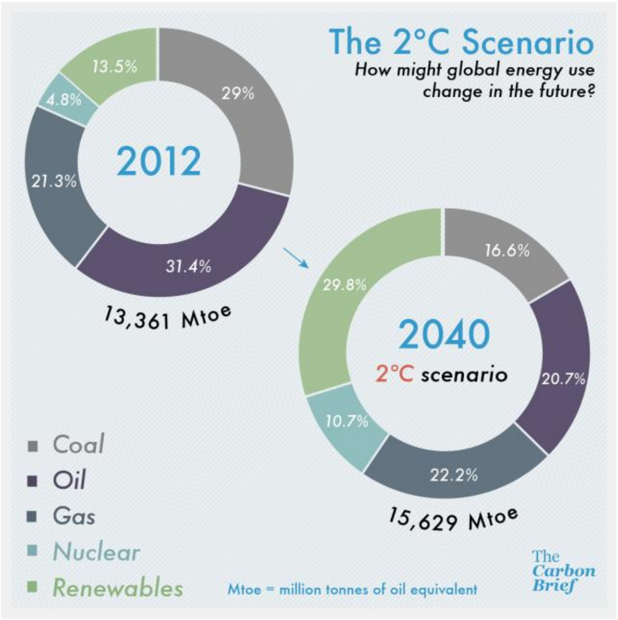
Staying within 2 degrees





80% Coal Reserves
Untouched until 2050

50% Gas Reserves
Untouched until 2050

33% Oil Reserves
Untouched until 2050

Sources:
Nature Geoscience 7, 709–715 (2014)
U.N. IPCC Climate Change 2014 Synthesis Report: http://www.ipcc.ch/report/ar5/syr/

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What does this mean for fuels?

2014

50%

Transport fuel

1.4 trillion gallons

700 billion gallons

2030

15%

30% from non-fossil sources

210 billion gallons

Biofuels today:

Additional 1000, 200 M gpy facilities by 2030

Only 14% of the 2 degree target

Source: EIA short term energy outlook February 2015

Source: UNEP, 2011 Bridging the Emissions Gap

Based on 100M/G capacity plants

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The remaining 86%

TODAYS TECHNOLOGIES ARE NOT ENOUGH
NEW FEEDSTOCKS, NEW APPROACHES ARE NEEDED

SPEED TO SCALE AND MARKET ARE KEY

How we treat carbon will define our generation

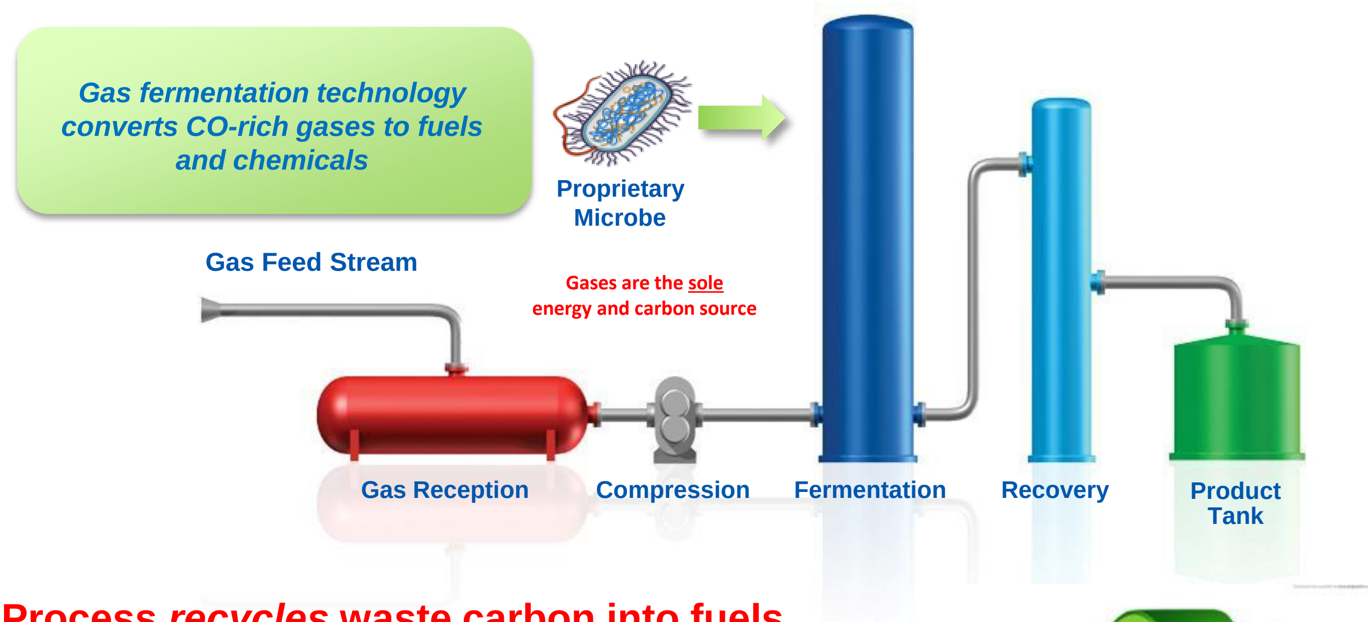
Recycle to Reduce Pressure on Reserves

Carbon Reduction through Re-use and Recycling

A 2-degree carbon budget will require countries to leave 80 % of coal, 50 % of gas and 33 % of global oil untouched.

Organization for Economic Growth and Development, Nature

The LanzaTech Process



- **Process *recycles* waste carbon into fuels and chemicals**
- **Process brings underutilized carbon into the fuel pool via *industrial symbiosis***
- **Potential to make material impact on the future energy pool (>100s of billions of gallons per year)**

Waste carbon streams as a Resource

Industrial Waste Gas	Biogas	Solid Waste	Biomass	CO_2
Steel, PVC, Ferroalloys	LFG, Methane	Industrial, MSW, DSW		
~ 1.4B MTA (Steel only) *	~184.2T M^3 *	>2B MTA *	>1.3B MTA (US Alone) *	

Reforming — Gasification — Renewable H_2 — Renewable Electricity

CO	$CO + H_2$	$CO + H_2 + CO_2$	$CO_2 + H_2$	$CO_2 + H_2O + e^-$

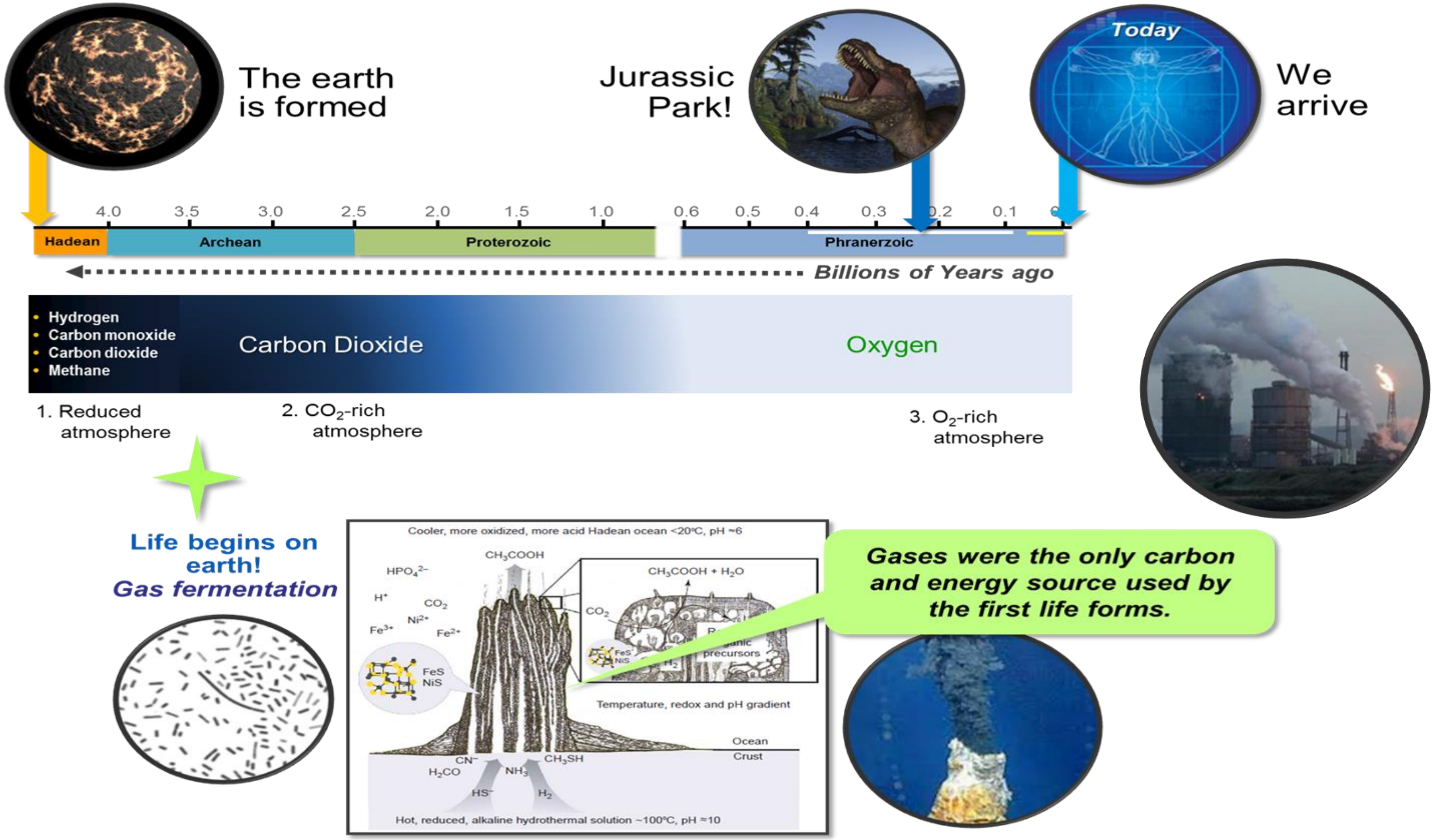
Gas Fermentation

✓ ***Available*** ✓ ***High Volume/Low Intrinsic Value*** ✓ ***Most Point Sourced***

✓ ***Non-Food***

*2010 global production; 2012 proven gas reserves data (IEA, UNEP, IndexMundi, US DOE *Billion Ton Update*)

Ancient Biology for a Modern Need



Unique Chemistry

- **Biological Water-Gas-Shift (WGS) reaction – Making Hydrogen on Demand**
  - Carbon Monoxide dehydrogenase (CODH) enzyme:

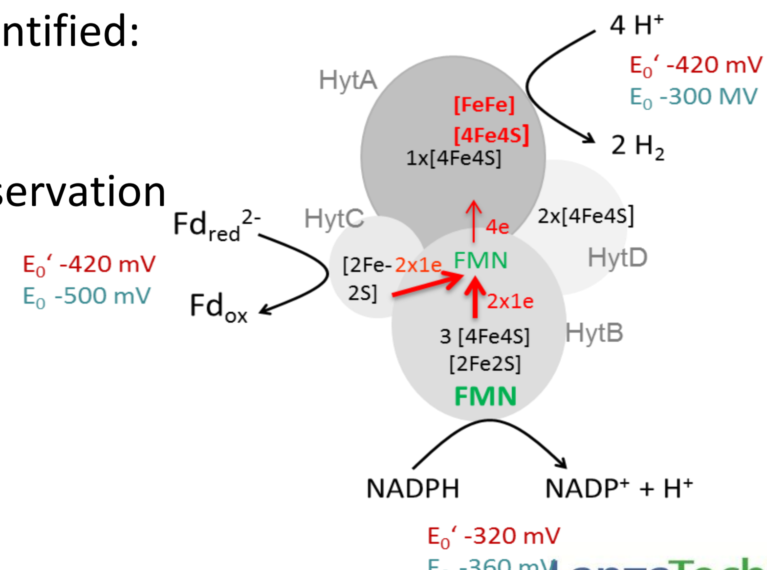
$$CO + \mathbf{H_2}O \longrightarrow CO_2 + \mathbf{H_2}$$

$[H_2]$

Ambient temperature
Ambient pressure

  - Allows any $CO{:}H_2$ concentration to be used

- **Electron-Bifurcating enzymes – Coupling of an Uphill with an Downhill Reaction**
  - Two novel Electron-Bifurcating enzymes identified:
    - Nfn Complex and Hyt hydrogenase
  - Allows organism to couple with energy conservation
  - Allows efficient and reversible reduction of CO_2 with H_2 to formate



Collaboration with
Thauer lab
@ MPI Marburg

Max-Planck-Institut

Wang et al., *J Bacteriol*: 195: 4373-86

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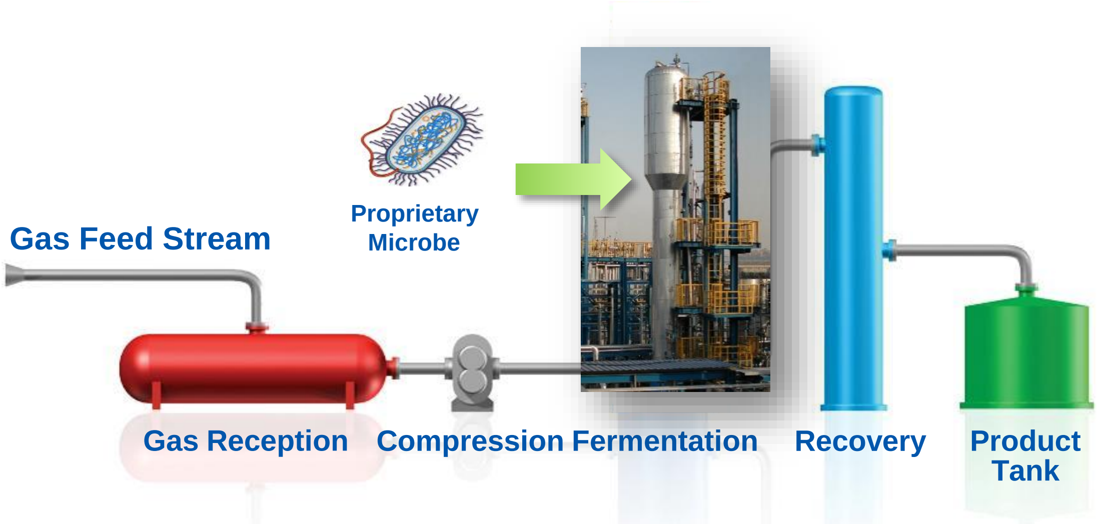
The LanzaTech Process: Ready for Deployment Today

Gas fermentation technology converts C-rich gases to fuels and chemicals



40,000 combined hours on stream
Multiple runs exceeding 2000 hours

Multiple plants at various scales demonstrating <u>different</u> key aspects of process

Successful Technology Demonstration

LanzaTech BAOSTEEL

- Pre-commercial facility in operation in Shanghai for >8 months meeting and exceeding all its performance targets and milestones
- Capacity 400,000 litres/year ethanol
- Technology has been approved in China for commercial deployment, by the NDRC

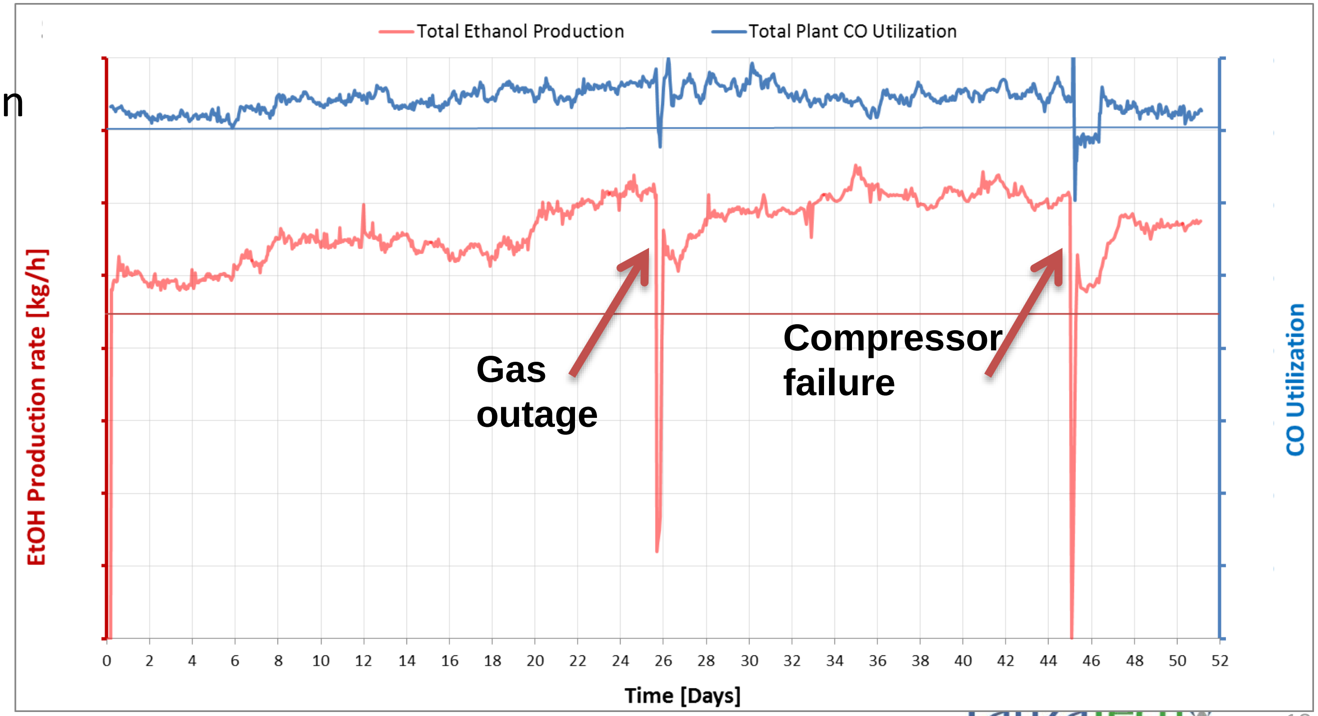
LanzaTech 首钢集团 SHOUGANG GROUP

- Operation of additional 400,000 litres/year plant with second Chinese Partner, Shougang Group, in Beijing
- Sustainability Assessment of Beijing plant currently underway with RSB.

Co-locating LanzaTech's Technology Steel Mill brownfield sites reduces land footprint, improves economics and reduces construction time

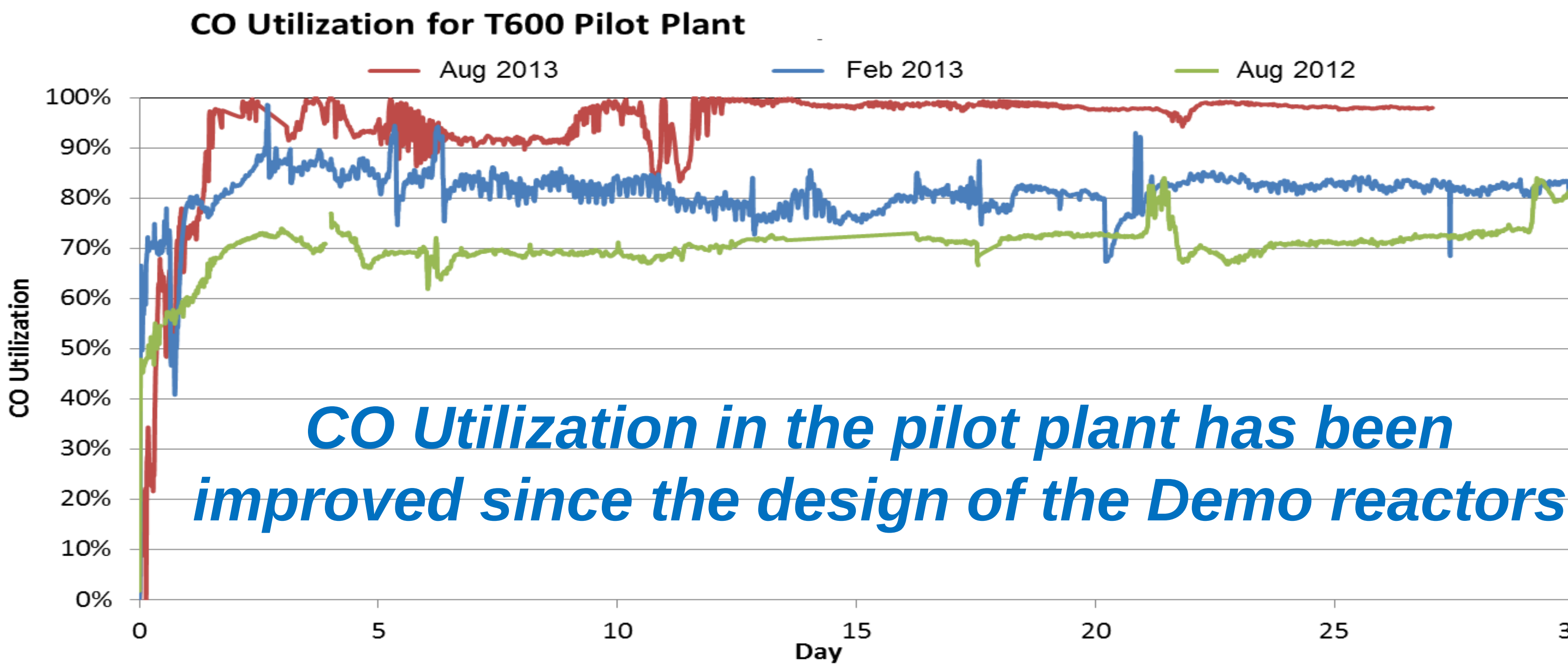
Successful Technology Demonstration

- Successful demonstrations at six industrial sites to date: New Zealand, Asia, United States
- Technology proven using industrial gas, chemicals, utilities, and water
- Over 40,000 total hours on stream
- Continuous runs > 2000 hours



Improvement in Reactor Design & Operation

- **CO utilization has improved with advances in reactor design**
- **LanzaTech Pilot plant operations have shown > 95% CO utilization**



MSW to fuel

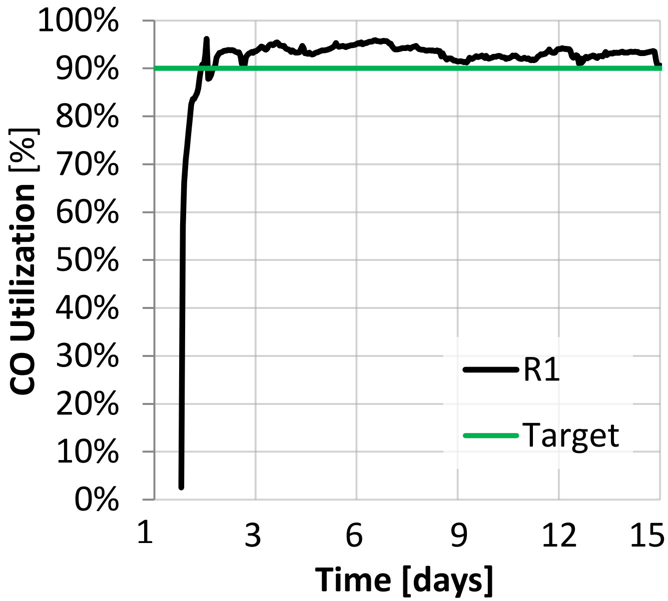
Pilot plant at gasification site

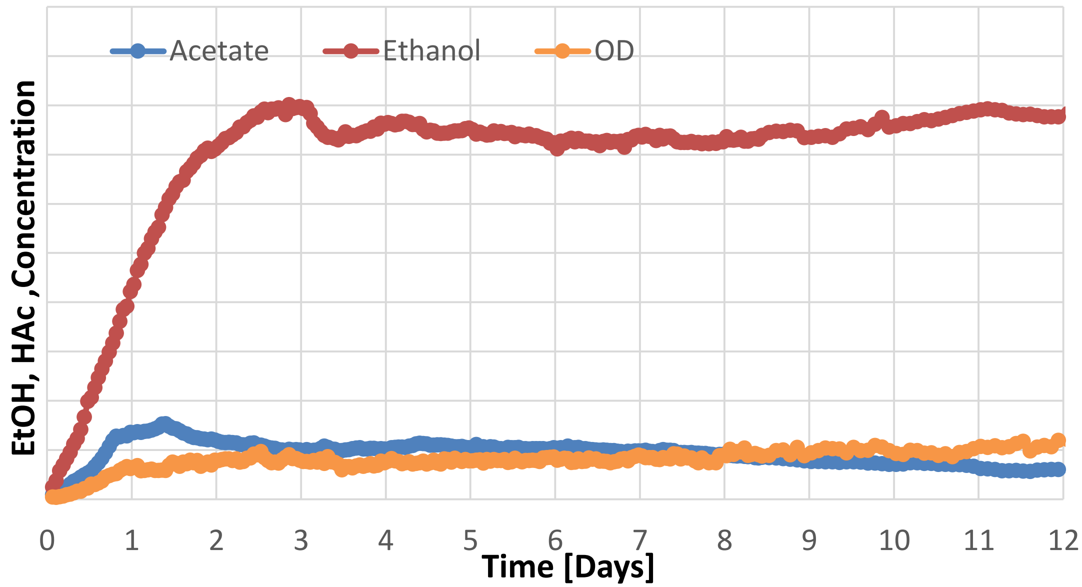
Project overview

LanzaTech has a two year partnership with a major Asian chemical company to convert live-feeds of syngas produced from municipal solid waste (MSW) into ethanol.

LanzaTech has designed, installed, and operates a pilot plant producing ethanol at a MSW processing facility.

Continuous stable ethanol production from MSW





- Continuous with live feeds of MSW Syngas proven
- Operation at commercial ethanol production rates and yields
- Gas utilization efficiency exceeds 90%
- All gas contaminant and variability issues understood and overcome.

LanzaTech are the only company to demonstrate continuous fuel production from MSW syngas.

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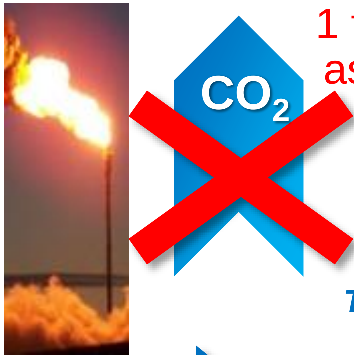
Why does it matter?



1 tonne ethanol produced as CO averted from flare

5.2 barrels of gasoline are displaced by every tonne of ethanol produced

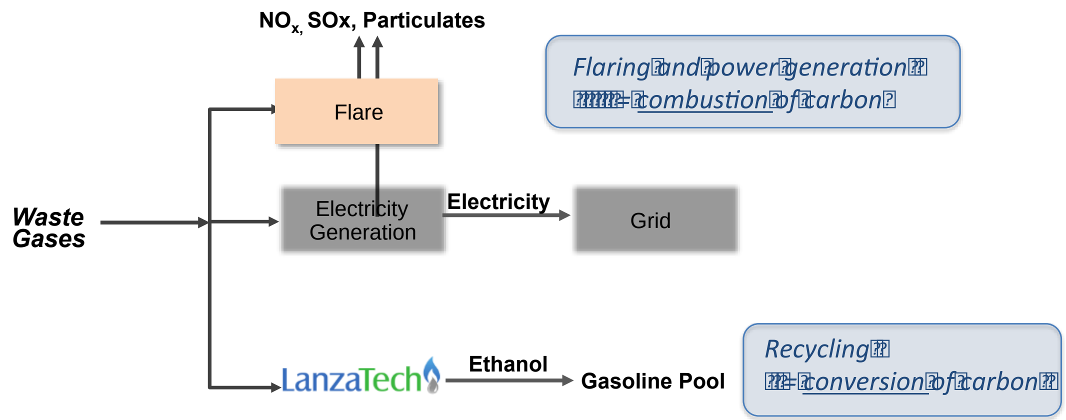
Per tonne of LanzaTech Ethanol

	CO_2 MT	kg PM	kg NOx
Averted from flare	2.1	0.6	4.1
Displaced gasoline	+0.5	+2.5	+7.4
Energy required for LanzaTech Process	-0.8	-0.2	-0.8
Avoided per tonne of ethanol	**1.8**	**2.9**	**10.7**

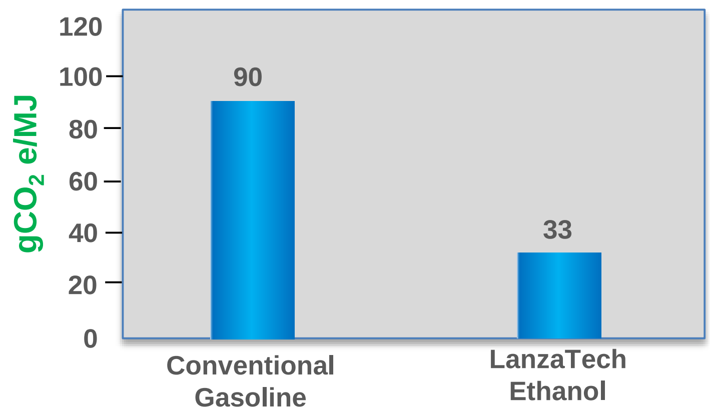
Recycling Waste Gases Produces Low Carbon Fuels

Reduce GHG Emissions

50-70% GHG Reduction over Petroleum Gasoline



Life Cycle GHG Emission



Life Cycle Analyses (LCA) performed in cooperation with , Michigan Tech University,, Roundtable on Sustainable Biomaterials (RSB), E4Tech, and Tsinghua University

Reduce Air Pollutants

>85% reduction in NOx and Particulate Matter compared to combustion at a typical US steel mill

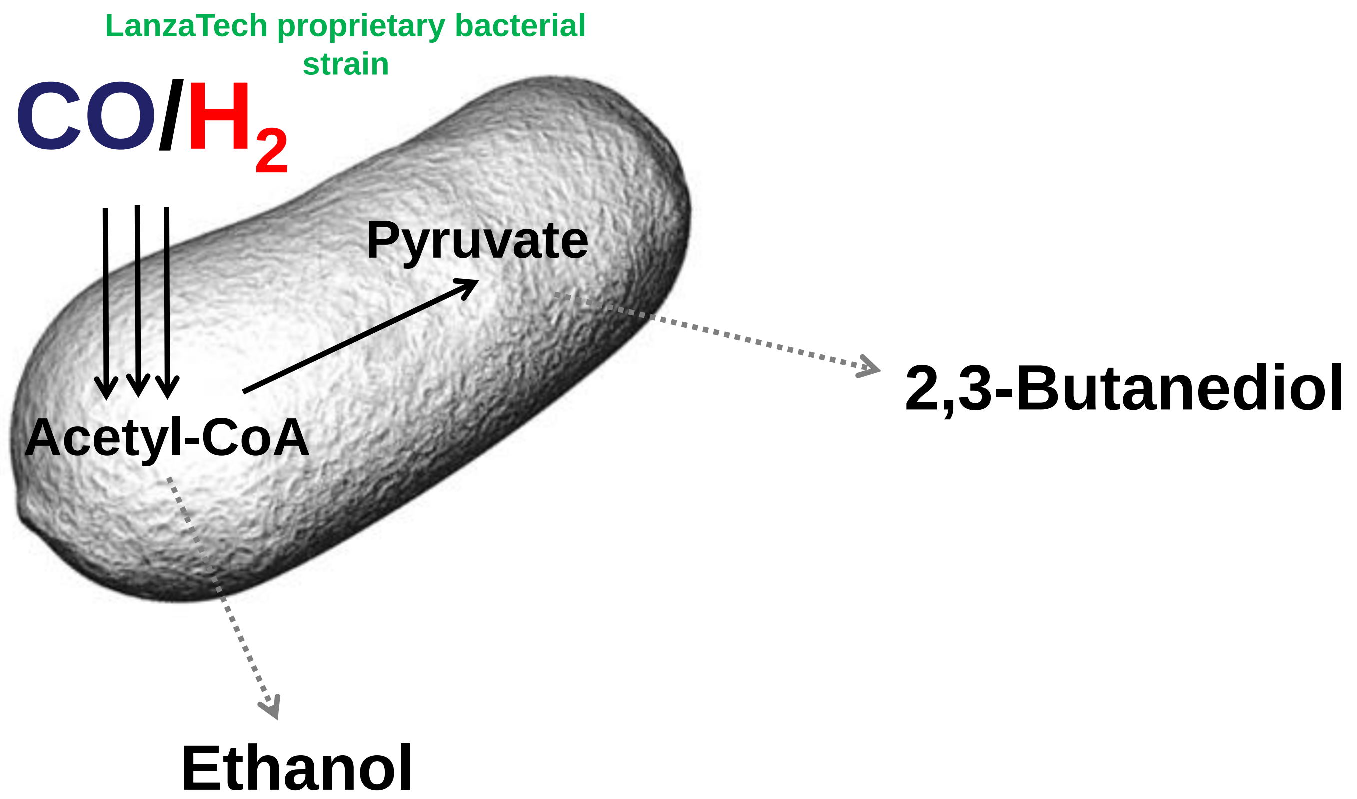
Recycling Waste Gases Impacts GHG *and* Air Pollution

Total Annual Emissions Reduction Potential (China)

	Steel (BF)	Steel (BOF)	Calcium Carbide	FerroAlloy	Phosphorous
CO_2 (M tonnes)	50,500,000	1,700,000	1,800,000	600,000	600,000
PM (tonnes)	70,300	2,400	6,100	800	800
NOx (tonnes)	225,800	7,700	3,700	2,600	2,500
Equivalent Cars	*10,600,000*	*350,000*	*375,000*	*125,000*	*125,000*

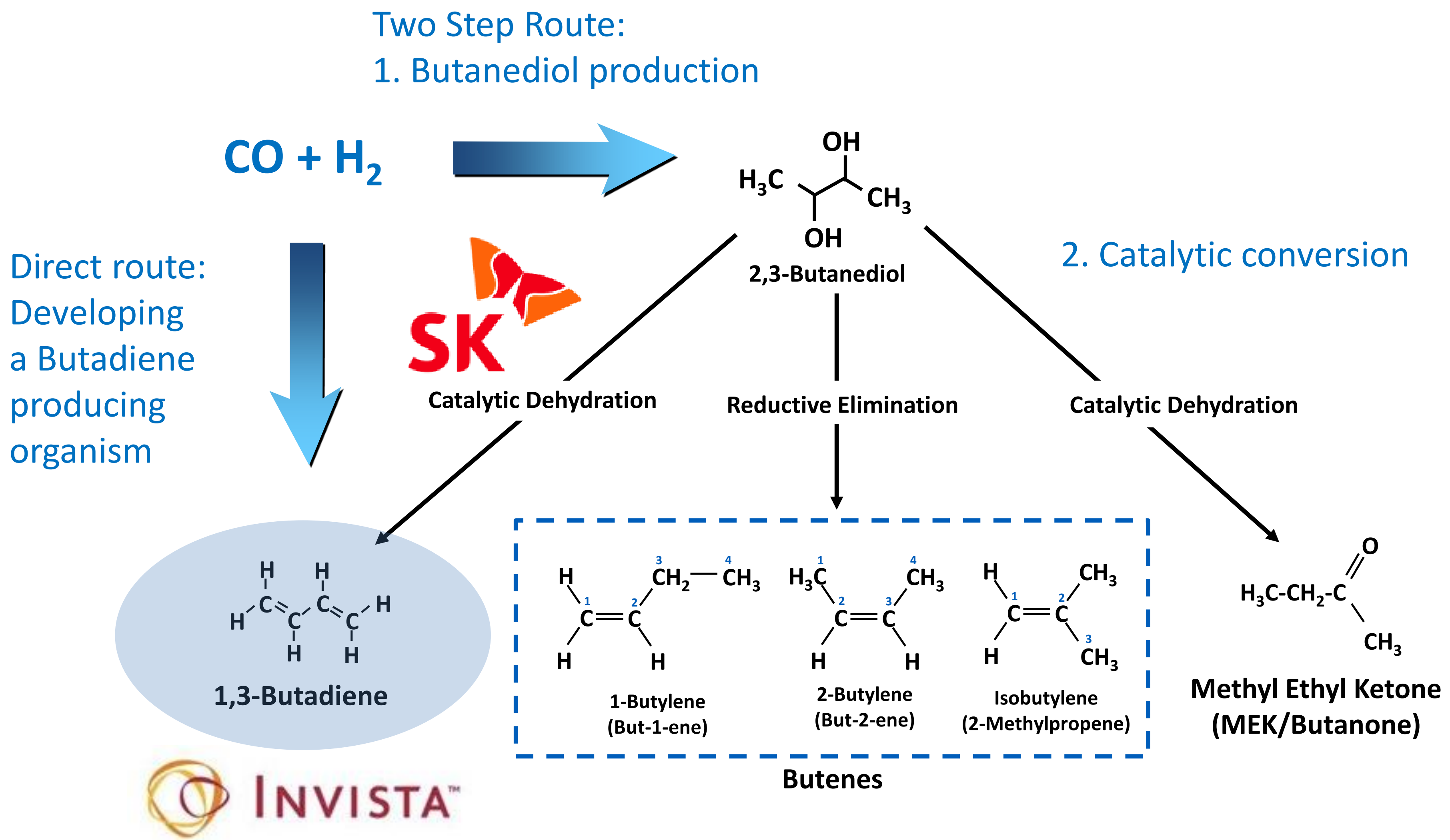
Utilizing LanzaTech Technology is Equivalent to Removing 11,600,000 Cars from the Road Each Year!

Fuel ***and*** Chemicals from Gas



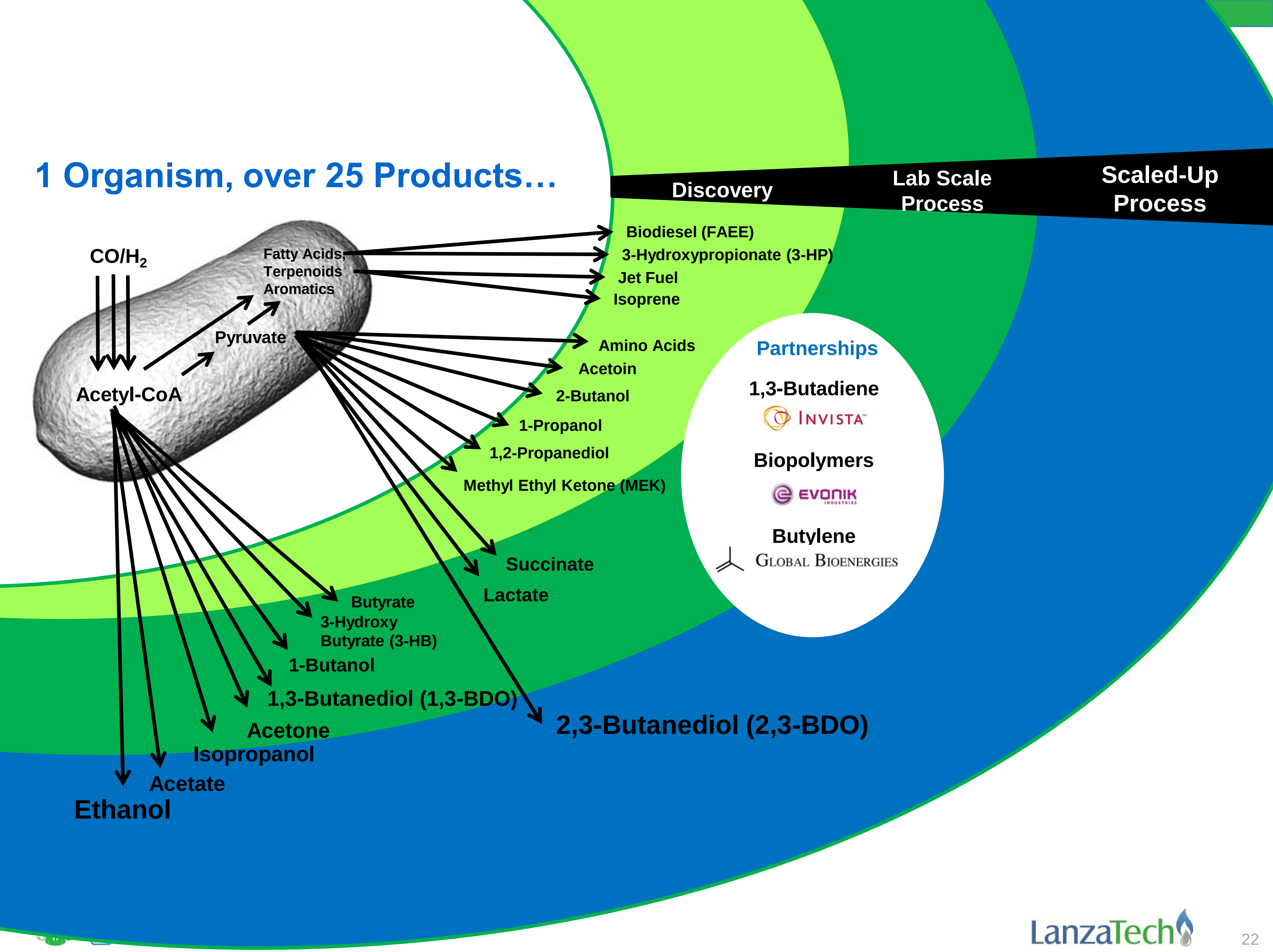
The LanzaTech gas fermenting microbe can make ***both*** *ethanol and 2,3-butanediol*

C_4 Chemicals from Gases: BDO/Butadiene



New Route to C_4s Without Current Supply Challenges

1 Organism, over 25 Products…



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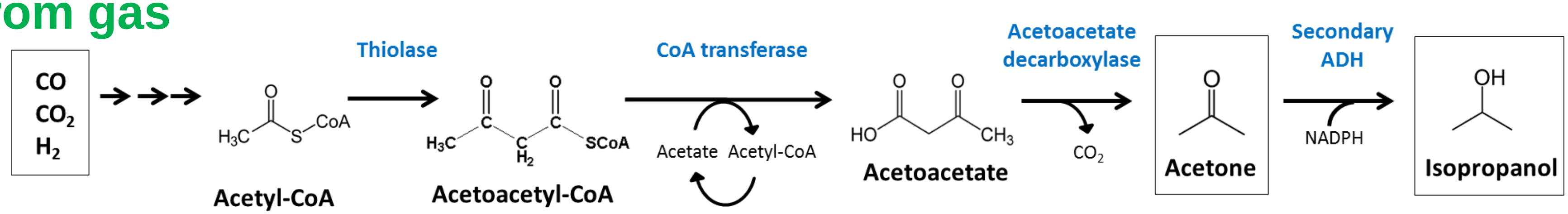
Example: Acetone and Isopropanol

1) Demonstrated selective production of either acetone and isopropanol from gas



- Integration of ABE fermentation enzymes responsible for conversion of acetyl-CoA to acetone (thiolase, CoA transferase, acetoacetate decarboxylase) into gas fermenting *C. autoethanogenum*

- Identified a novel native primary:secondary alcohol dehydrogenase in *C. auto* for reduction of acetone to isopropanol
  - Highly efficient conversion of acetone to isopropanol
  - KO of enzyme to stop production at acetone

C. autoethanogenum Primary:secondary ADH

Characterized native primary:secondary ADH enzyme of *C. autoethanogenum*

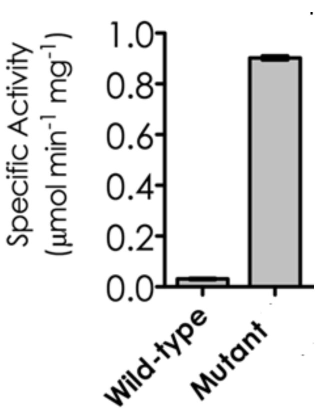
- Strictly NADPH dependent
- Plays role in conversion of acetaldehyde to ethanol and acetoin to 2,3-butanediol in metabolism of *C. auto*, but highest activity of non-native substrate acetone

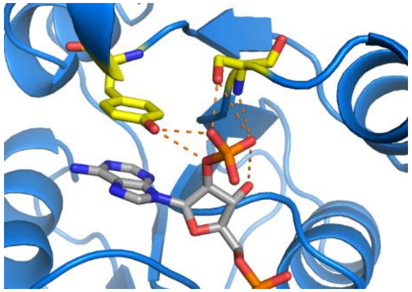
	K_{cat} [sec^{-1}]	K_m [mM]	K_{cat}/K_m [sec^{-1} mM^{-1}]
Primary Adh			
Acetaldehyde to Ethanol	93 ± 6	5.5 ± 1.4	**1.7 x 10^4**
Secondary Adh			
Acetone to Isopropanol	51.4 ± 0.8	0.60 ± 0.02	**8.6 x 10^4**
Acetoin to 2,3-Butanediol	145 ± 4	71 ± 5	**2.0x 10^3**

Directed evolution to modify selectivity and co-factor requirement

- Switched co-factor from NADPH to NADH
- Changed selectivity

In collaboration with Wayne Patrick lab @ University of Otago



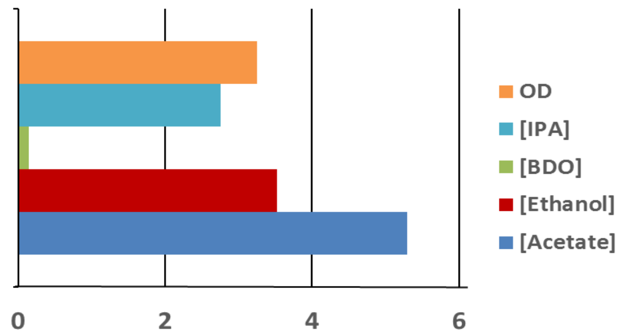


Köpke et al., 2014,. *AEM* 80: 3394-403

Example: Acetone and Isopropanol

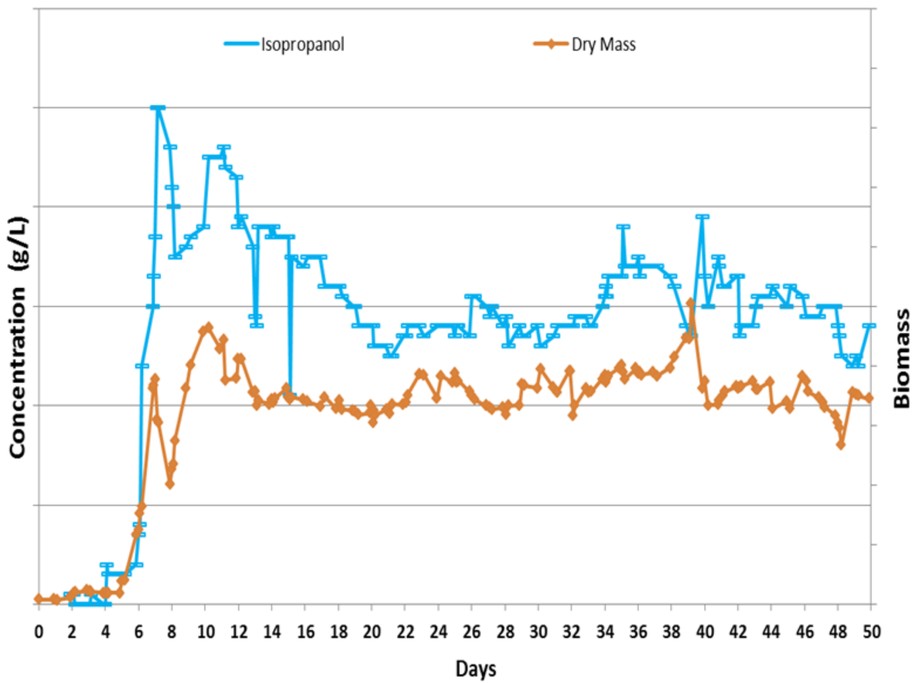
2) Optimizing acetone and isopropanol production in continuous fermentation and elimination of ethanol as byproduct

- Small scale assay developed to screen pathway variants



(~44% Isopropanol selectivity)

- Continuous fermentation for 50+ days established and optimized process conditions to improve titer and eliminated ethanol as byproduct



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LanzaTech Global Partnerships

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Global Recognition

2015

WBM Bio Business Award Winner 2015

Feedstock of the Year Award and CEO Jennifer Holmgren won Business Person of the Year

Finalist in the Entrepreneurship Category of the Circular Economy Awards.

#1 Hottest Company in Biofuels and #5 in Biochemicals

2014

Global Cleantech 100 North American Company of the Year Award

The Guardian Sustainable Business Innovation Award for Carbon and Energy Management.

Technical Development Award from World Petroleum Council

Breakthrough Innovation Award at the Platts Global Metals Award.

2013

One of 23 companies globally with promise of "significantly impacting the way business and society operate."

Listed in Sustainia guide to innovative solutions at the forefront of sustainable transformation.

Global Cleantech 100 Continued Excellence winner.

Sustainable Innovation Award at Platts Global Energy Awards

LanzaTech and Virgin Atlantic named 2013 Observer Ethical Award Winners

Ancient Biology for Modern Needs

Aligns:

Allows: