Production of sustainable fuels and chemicals from waste gas streams

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Symposium on Bio-Fuels and Chemicals
La Jolla, CA
30th April 2015

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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)
What does this mean for fuels?

2014
1.4 trillion gallons
Transport fuel
50%
700 billion gallons
2030
210 billion gallons
15%
30% from non-fossil sources

Source: EIA short term energy outlook February 2015

Source: UNEP, 2011 Bridging the Emissions Gap

Based on 100M/G capacity plants

Biofuels today:
<30 billion gallons
24 billion gallons ethanol
by 2030 biodiesel
100 million gallons cellulosic

Additional 1000, 200 M gpy facilities

Only 14% of the 2 degree target
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

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

- 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**
- Steel, PVC, Ferroalloys
- ~1.4B MTA (Steel only) *

**Biogas**
- LFG, Methane
- ~184.2T M³ *

**Solid Waste**
- Industrial, MSW, DSW
- >2B MTA ′

**Biomass**
- >1.3B MTA (US Alone) ′

Convert waste carbon streams to:
- CO
- CO + H₂
- CO + H₂ + CO₂
- CO₂ + H₂
- CO₂ + H₂O + 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

The earth is formed

Jurassic Park!

We arrive

Hadean | Archean | Proterozoic | Phanerzoic

Billions of Years ago

Carbon Dioxide

• Hydrogen
• Carbon monoxide
• Carbon dioxide
• Methane

1. Reduced atmosphere
2. CO₂-rich atmosphere
3. O₂-rich atmosphere

Life begins on earth!
Gas fermentation

Gases were the only carbon and energy source used by the first life forms.
Unique Chemistry

- **Biological Water-Gas-Shift (WGS) reaction – Making Hydrogen on Demand**
  - Carbon Monoxide dehydrogenase (CODH) enzyme:
    \[ CO + H_2O \rightarrow CO_2 + H_2 \]
  - Allows any CO:H$_2$ concentration to be used

- **Electron-Bifurcating enzymes – Coupling of an Uphill with a 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

Wang et al., *J Bacteriol*: 195: 4373-86
The LanzaTech Process: Ready for Deployment Today

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

Gas Feed Stream → Proprietary Microbe → Gas Reception → Compression Fermentation → Recovery → Product Tank

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

Multiple plants at various scales demonstrating different key aspects of process
Successful Technology Demonstration

LanzaTech

• 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

• 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.
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

**CO Utilization for T600 Pilot Plant**

**CO Utilization in the pilot plant has been improved since the design of the Demo reactors**
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.
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

The LanzaTech Process

Gas Feed Stream

Gas reception
Compression
Fermentation
Recovery
Product tank

Per tonne of LanzaTech Ethanol

<table>
<thead>
<tr>
<th></th>
<th>CO₂ MT</th>
<th>kg PM</th>
<th>kg NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Averted from flare</td>
<td>2.1</td>
<td>0.6</td>
<td>4.1</td>
</tr>
<tr>
<td>Displaced gasoline</td>
<td>+0.5</td>
<td>+2.5</td>
<td>+7.4</td>
</tr>
<tr>
<td>Energy required for LanzaTech Process</td>
<td>-0.8</td>
<td>-0.2</td>
<td>-0.8</td>
</tr>
<tr>
<td>Avoided per tonne of ethanol</td>
<td>1.8</td>
<td>2.9</td>
<td>10.7</td>
</tr>
</tbody>
</table>
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)**

<table>
<thead>
<tr>
<th></th>
<th>Steel (BF)</th>
<th>Steel (BOF)</th>
<th>Calcium Carbide</th>
<th>FerroAlloy</th>
<th>Phosphorous</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO₂</strong> (M tonnes)</td>
<td>50,500,000</td>
<td>1,700,000</td>
<td>1,800,000</td>
<td>600,000</td>
<td>600,000</td>
</tr>
<tr>
<td><strong>PM</strong> (tonnes)</td>
<td>70,300</td>
<td>2,400</td>
<td>6,100</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td><strong>NOₓ</strong> (tonnes)</td>
<td>225,800</td>
<td>7,700</td>
<td>3,700</td>
<td>2,600</td>
<td>2,500</td>
</tr>
<tr>
<td><strong>Equivalent Cars</strong></td>
<td>10,600,000</td>
<td>350,000</td>
<td>375,000</td>
<td>125,000</td>
<td>125,000</td>
</tr>
</tbody>
</table>

Utilizing LanzaTech Technology is Equivalent to Removing 11,600,000 Cars from the Road Each Year!
The LanzaTech gas fermenting microbe can make both ethanol and 2,3-butandiol.
C₄ Chemicals from Gases: BDO/Butadiene

Two Step Route:
1. Butanediol production

Direct route: Developing a Butadiene producing organism

CO + H₂ → 2,3-Butanediol

1. Catalytic dehydration

2. Reductive elimination

1,3-Butadiene → Butanediol

Butanediol → Butenes

1. 1-Butylene (But-1-ene)
2. 2-Butylene (But-2-ene)
3. Isobutylene (2-Methylpropene)

Butenes → Butenes

2. Catalytic dehydration

Methyl Ethyl Ketone (MEK/Butanone)

New Route to C₄s Without Current Supply Challenges
1 Organism, over 25 Products...

- Acetyl-CoA

  - Pyruvate
    - Fatty Acids, Terpenoids, Aromatics
  - Succinate
  - Lactate

  - Butyrate
    - 3-Hydroxy
    - Butyrate (3-HB)
  - 1-Butanol
  - 1,3-Butanediol (1,3-BDO)
  - Acetone
  - Isopropanol

  - Ethanol
  - Acetate

- CO/H₂

- 2,3-Butanediol (2,3-BDO)

- Biodiesel (FAEE)
- 3-Hydroxypropionate (3-HP)
- Jet Fuel
- Isoprene

- Amino Acids
- Acetoin
- 2-Butanol
- 1-Propanol
- 1,2-Propanediol
- Methyl Ethyl Ketone (MEK)

- Partnerships
  - 1,3-Butadiene
  - Biopolymers
  - Butylene

- Lab Scale Process
- Scaled-Up Process

- Discovery

- LanzaTech
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. autoethanogenenum*

- 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

<table>
<thead>
<tr>
<th>Primary Adh</th>
<th>K&lt;sub&gt;cat&lt;/sub&gt; [sec&lt;sup&gt;-1&lt;/sup&gt;]</th>
<th>K&lt;sub&gt;m&lt;/sub&gt; [mM]</th>
<th>K&lt;sub&gt;cat&lt;/sub&gt;/K&lt;sub&gt;m&lt;/sub&gt; [sec&lt;sup&gt;-1&lt;/sup&gt; mM&lt;sup&gt;-1&lt;/sup&gt;]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetaldehyde to Ethanol</td>
<td>93 ± 6</td>
<td>5.5 ± 1.4</td>
<td>1.7 x 10&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Secondary Adh</th>
<th>K&lt;sub&gt;cat&lt;/sub&gt; [sec&lt;sup&gt;-1&lt;/sup&gt;]</th>
<th>K&lt;sub&gt;m&lt;/sub&gt; [mM]</th>
<th>K&lt;sub&gt;cat&lt;/sub&gt;/K&lt;sub&gt;m&lt;/sub&gt; [sec&lt;sup&gt;-1&lt;/sup&gt; mM&lt;sup&gt;-1&lt;/sup&gt;]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetone to Isopropanol</td>
<td>51.4 ± 0.8</td>
<td>0.60 ± 0.02</td>
<td>8.6 x 10&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
<tr>
<td>Acetoin to 2,3-Butanediol</td>
<td>145 ± 4</td>
<td>71 ± 5</td>
<td>2.0 x 10&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

**Directed evolution to modify selectivity and co-factor requirement**

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

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

In collaboration with Wayne Patrick lab @ University of Otago
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

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

![](image)

Product titer (g/L)

(~44% Isopropanol selectivity)
Global Recognition

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:
- Industrial Growth
- Energy Security
- Energy Efficiency

Allows:
- Land
- To Produce Food
- For People