Comparative Economics of Carbon Capture into Alternative Dispositions, Routes, and End Products

New Technologies & Economics for Carbon Capture/Sequestration Conference
Chapel Hill, North Carolina
March 29, 2019

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Why CO$_2$ Utilization

- Carbon capture and sequestration will always be added cost and not driven by market factors. Carbon capture and utilization could be driven by market factors and provide market opportunities for lowering carbon dioxide (CO$_2$) emissions.

- Technologies which use CO$_2$ (pure or as emitted) for revenue generation:
  - Using it unchanged like enhanced oil recovery (EOR), carbonated drinks, supercritical CO$_2$ solvent, etc.
  - Converting it into a value-added end product like a building material (concrete), fuel, or chemical
State of CO$_2$ Utilization
State of CO₂ Utilization

- Global consumption of CO₂ was 206 million metric tons in 2017 of which 29 million metric tons (14%) entered merchant market in liquid or solid form.
- Remaining 177 million metric tons consumed captively in gaseous form, mainly for production of urea (nitrogen fertilizer) or EOR.

The global CO₂ market size was valued at USD 6.0 billion in 2015 and is expected to grow at a compound annual growth rate (CAGR) of 3.7% over the next nine years. Development in EOR technology mostly in North America and the Middle East. African region is anticipated to drive growth.

- 2018 worldwide CO₂ emissions = 37 billion metric tons
- Current usage rate ~0.5% of total emissions
### CO₂ Sources: Quality, Cost, and Suppliers

<table>
<thead>
<tr>
<th>Source</th>
<th>CO₂ Content (vol%)</th>
<th>CO₂ Emission Intensity</th>
<th>Primary Impurities</th>
<th>Capture Cost ($/tonne CO₂)</th>
<th>2018 U.S. CO₂ Suppliers and Market Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn Mill</td>
<td>Near 100%</td>
<td>3.1 kg/gal ethanol</td>
<td>n/a</td>
<td>$0–$5 – minor drying and purification</td>
<td>Linde: 9,172 (24.9%)</td>
</tr>
<tr>
<td>Natural</td>
<td>Near 100%</td>
<td>n/a</td>
<td>n/a</td>
<td>$0–$5 – minor cleanup</td>
<td>Air Liquide: 6,724 (18.2%)</td>
</tr>
<tr>
<td>Biogas</td>
<td>35%–65%</td>
<td>0.6–1.2 kg/m³ biogas</td>
<td>CH₄, H₂S</td>
<td>$20–$75</td>
<td>Praxair: 5,874 (15.9%)</td>
</tr>
<tr>
<td>Fossil Fuel-Fired Power Plants</td>
<td>3%–20%</td>
<td>499 kg CO₂/MWh (NG plant)</td>
<td>N₂, water, O₂, SOₓ, Ar</td>
<td>$20–$90</td>
<td>Matheson: 3,379 (9.2%)</td>
</tr>
<tr>
<td>Air Capture</td>
<td>0.04%</td>
<td>n/a</td>
<td>N₂, O₂, Ar</td>
<td>$100–$1,000</td>
<td>Reliant Holdings: 2,617 (7.1%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>POET Biorefining: 1,043 (7.1%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CF Industries: 880 (2.4%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sandhill: 635 (1.7%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rentech Energy: 590 (1.6%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>AES Corp.: 354 (1.0%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Abengoa Bioenergy: 345 (1.0%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ADM: 318 (0.9%)</td>
</tr>
</tbody>
</table>

vol% = volume percent | $/tonne CO₂ = U.S. dollars per tonne of CO₂ | kg/gal = kilogram per gallon | kg/m³ = kilograms per cubic meter | CH₄ = methane | H₂S = hydrogen sulfide | MWh = megawatt hour | N₂ = nitrogen | O₂ = oxygen | SOₓ = sulfur oxide | Ar = argon | MTD = ???

### 2018 U.S. CO₂ Suppliers and Market Share

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Production Capacity (MTD)</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linde</td>
<td>9,172</td>
<td>24.9</td>
</tr>
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<td>Air Liquide</td>
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<td>Matheson</td>
<td>3,379</td>
<td>9.2</td>
</tr>
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<td>Reliant Holdings</td>
<td>2,617</td>
<td>7.1</td>
</tr>
<tr>
<td>POET Biorefining</td>
<td>1,043</td>
<td>7.1</td>
</tr>
<tr>
<td>CF Industries</td>
<td>880</td>
<td>2.4</td>
</tr>
<tr>
<td>Sandhill</td>
<td>635</td>
<td>1.7</td>
</tr>
<tr>
<td>Rentech Energy</td>
<td>590</td>
<td>1.6</td>
</tr>
<tr>
<td>AES Corp.</td>
<td>354</td>
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</tr>
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</tr>
<tr>
<td>ADM</td>
<td>318</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Markets, State of
Markets, and Potentials
Existing and Potential Uses of CO₂

- **Non-Reductive**: Use CO₂ in liquid or gaseous form
  - ~100% of current use
- **Reductive**: Use renewable or nuclear low cost, no carbon electricity to reduce CO₂ to a reactive intermediate for fuel, chemical, or material production:
  - Very limited commercial practice
Six Potential Markets

1. Building Materials – Non-Reductive
   - Thermodynamically easy to make carbonates, less energy necessary. Makes market attractive for developers as technology is more readily scalable.
   - Main two CO₂U technologies used in this market are mineralization to carbonate aggregates and the use of CO₂ to cure concrete

2. Chemical Intermediates – Reductive
   - Many research projects to make conversions more efficient, e.g., by developing more efficient catalysts
   - Niche markets have been commercialized, e.g., production of methanol using geothermal energy in Iceland
   - Methanol, syngas, and formic acid are widely being developed

3. Fuels – Reductive
   - Production of fuels from CO₂ fits within the large macro trend to produce low carbon fuels such as bio-based fuels
   - Fuels are often mentioned as the largest potential market for CO₂U technology in reports on CO₂U
Six Potential Markets

4. Polymers – Reductive
   • Several production routes have already been commercialized for high value products for niche markets, such as polyhydroxyalkanoates and polycarbonates

5. Algae – Non-Reductive
   • Enhance the growth rate and production rate of algae by adding gaseous CO$_2$ technology to grow algae for bio-fuels and chemicals

   • Very high value materials such as carbon fiber
   • Technology area is mostly at early research stage with some interesting results reported in the scientific literature
Ranking Developers by Technology Readiness Level (TRL) Reveals Maturity and Momentum in Specific Target Markets

Example companies from database to illustrate range of commercial readiness.

### Which Markets Offer the Best Opportunities for Support and Investment

<table>
<thead>
<tr>
<th></th>
<th>Stage of development</th>
<th>Addressable market size</th>
<th>Number of developers</th>
<th>Potential for CO₂ mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 Building materials</strong></td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td><strong>2 Chemical intermediates</strong></td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>3 Fuels</strong></td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>4 Polymers</strong></td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Algae</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Novel materials</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
</tr>
</tbody>
</table>

**Legend**

- **High** (>25% of developers is near commercialization, the addressable market is a mature market, number of developers >50, prolonged abatement of CO₂)
- **Medium** (<25% of developers is near commercialization, the addressable market is a developing market, number of developers between 10 and 50, mitigation of CO₂ by replacing conventional feedstock)
- **Low** (no developers are near commercialization, the addressable market is unclear, number of developers below 10, CO₂ mitigation is minimal)

**Source:** Lux Research, University of Michigan
Developers of CO₂U Technology by Market

Building Materials
- Carbon3B
- Blue Planet
- Solidia Technologies
- NEW SKY
- Calix
- CARBON CURE
- Calera

Chemical Intermediates
- MANTRA
- OAKBIO
- O2DIOXIDE MATERIALS
- OPUS12
- Photanol
- Succinity
- Mitsubishi Chemicals
- ANTEC
- NCF

Fuels
- Phytonix - The Future of Fuel
- Electrochaea
- Trelis
- Sunfire
- PIONEER ENERGY
- LanzaTech
- ETOGAS
- Next Potential
- ALGENOL

Polymers
- Econic Technologies
- Newlight Technologies
- AsahiKASEI

The Number of Developers between Europe and North America Is Comparable with Slight Differences in Market Focus

- Most developments in CO$_2$U technology are early stage (equal or lower than TRL 5) with approximately 85 key active developers in the Europe and North America
- For both continents, a key area of research is in chemical intermediates focusing on CO$_2$ conversion to methanol, CO, syngas, or formic acid
- Developers in building materials are especially strong in North America, whereas Europe is stronger in CO$_2$ conversion to polymers. The latter is partially caused by the culture of collaboration in the European Union (EU).

<table>
<thead>
<tr>
<th>Market</th>
<th>Number of Developers in EU</th>
<th>% TRL 5 or Lower</th>
<th>Number of Developers in North America</th>
<th>% TRL 5 or Lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Materials</td>
<td>6</td>
<td>50%</td>
<td>10</td>
<td>60%</td>
</tr>
<tr>
<td>Chemical Intermediates</td>
<td>18</td>
<td>77%</td>
<td>25</td>
<td>92%</td>
</tr>
<tr>
<td>Fuels</td>
<td>7</td>
<td>86%</td>
<td>10</td>
<td>70%</td>
</tr>
<tr>
<td>Polymers</td>
<td>9</td>
<td>67%</td>
<td>4</td>
<td>25%</td>
</tr>
<tr>
<td>Total</td>
<td>37</td>
<td>73%</td>
<td>48</td>
<td>75%</td>
</tr>
</tbody>
</table>

Progress that Companies Have Made in CO₂U from 2011 to 2016

Weighting for Visualization:

- **Y-axis – Technology Score:** 20% intellectual property (IP) strength, 10% regulatory factors, 30% competitive landscape score, 40% technology value
- **X-axis – Commercial Development Score:** 60% technology maturity, 25% developer maturity, 15% commercial maturity
- **Bubble size – CO₂ Mitigation Potential:** 30% ease of set-up, 50% market size, 20% extent that CO₂ is used as feedstock

Lux compared status of developers in 2011 and 2016:

- Color coded the developers in the graph for 2011 based on situation in 2016
- Color in the 2016 graph notes the market segment

Building Materials – Non-Reductive
Building Materials: Progress during the Last Five Years Has Been Significant, Immediate Opportunities

Curing of Concrete by CO$_2$ Is an Immediate Opportunity

Concentration of Developers:
- High number of developers are near commercialization; whereas we have observed a relatively low number of early stage developers
- The success of commercialization for building materials is linked to:
  - Relatively low amount of energy required for carbonation
  - *Concrete made by curing with CO$_2$ has better performance characteristics (20% improvement in compressive strength) than traditional curing methods*

Dynamics:
- Several developers have moved from pilot to commercialization stage from 2011–2016 for both market segments:
  - Note that several early-stage developers disappeared as they were not able to develop a product beyond pilot stage
  - We have found several new developers of mineralization to produce aggregates

Building materials can have a significant impact on CO$_2$ emissions with additional allocated resources.

CarbonCure Technologies in Canada is a developer of a CO$_2$ injection technology for concrete curing.

- Made technology available for both pre-cast and ready-mix concrete markets.
- CarbonCure uses an equipment leasing model:
  - Eliminates capital expenditure (CAPEX) for its customers.
  - Charges customer on a per cubic meter (m$^3$) of produced concrete.
- Improves compressive strength of Portland cement concrete by 10%–20%:
  - Can reduce cement demand by 5–10% and water demand by 30–60 liters per m$^3$ concrete.
- Technology was spun out of McGill University by Founder/CEO Robert Niven.
- Timeline from founding to revenue generation was 6 years.

CarbonCure Technologies commercialized CO$_2$U in six years by (i) utilizing a licensing and leasing model to eliminate CAPEX for its customers (ii) using CO$_2$ injection technology developed at a university.

Chemical Intermediates, Fuels, and Polymers – Reductive
Convergence of Trends Makes Reductive Paths to CO₂ Utilization Possible

Increasing Deployment and Decreasing Costs of Renewable Electricity

Growing Need and Opportunity for Utilizing Gaseous Carbon Waste Streams

Future Levelized Costs: $0.02–$0.07/ kilowatt (kWh)

216 Existing U.S. Biorefineries Emit 45 million tons (Mt) of CO₂/year*

Opportunity: Improve Biorefinery Carbon Utilization

Publications on the Conversion of CO₂ by Catalytic Reduction Has Increased Significantly

<table>
<thead>
<tr>
<th>Institute</th>
<th>Number of Publications</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S Department of Energy (DOE)</td>
<td>136</td>
</tr>
<tr>
<td>Chinese Academy of Sciences</td>
<td>79</td>
</tr>
<tr>
<td>Japan Science Technology Agency</td>
<td>63</td>
</tr>
<tr>
<td>Centre National de la Recherche Scientifique</td>
<td>63</td>
</tr>
<tr>
<td>University of California San Diego</td>
<td>55</td>
</tr>
<tr>
<td>Tokyo Institute of Technology</td>
<td>52</td>
</tr>
<tr>
<td>Princeton University</td>
<td>47</td>
</tr>
<tr>
<td>University of California Berkeley</td>
<td>38</td>
</tr>
<tr>
<td>California Institute of Technology</td>
<td>38</td>
</tr>
</tbody>
</table>

## General Assumptions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
<th>Justification and Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyzer Style</td>
<td>Polymer Electrolyte Membrane (PEM) Architecture</td>
<td>Scalable solution to reach high current density. Industrial validation/data (OPUS12, Dioxide Materials).</td>
</tr>
<tr>
<td>Current Density (mA/cm²)</td>
<td>SOT* 1,500 2,000</td>
<td>SOT value depends on each product. Target values from hydrogen analysis (H2A)/PEM assumptions.</td>
</tr>
<tr>
<td>Cell Voltage (V)</td>
<td>SOT* Theoretical + 0.6V Theoretical</td>
<td>Both SOT and theoretical values depend on product. Target value +600mV cell overpotential on theoretical.</td>
</tr>
<tr>
<td>Faradaic Efficiency (%)</td>
<td>SOT* 95% 100%</td>
<td>SOT value depends on product. Target=SOT if SOT FE&gt;95%.</td>
</tr>
<tr>
<td>Installed Capital Cost ($/m²)</td>
<td>22,000 10,000 5,000</td>
<td>H2A assumptions $900, $400, and $200/kW + SOT current density / cell voltage.</td>
</tr>
<tr>
<td>Single-Pass CO₂ Conversion (%)</td>
<td>20% 90% 100%</td>
<td>Rarely reported. 20% from 2018 Haas et al. (Siemens). 90% from 2018 Luc et al.</td>
</tr>
<tr>
<td>Electricity Price ($/kWh)</td>
<td>0.068 0.03 0.02</td>
<td>U.S. Energy Information Administration (EIA) electricity price (sensitivity: $0-$0.068 $/kWh).</td>
</tr>
<tr>
<td>CO₂ Capture Price ($/ton)</td>
<td>40 20 0</td>
<td>Carbon Capture and Storage (CCS)-CO₂ capture from power plants, first-of-a-kind (FOAK) bioethanol.</td>
</tr>
<tr>
<td>CO₂ Flowrate (kg/hr)</td>
<td>71,729</td>
<td>Estimated CO₂ from annual 200 million gallons of ethanol.</td>
</tr>
<tr>
<td>CO₂ Separations Cost</td>
<td>$50–$80 / tonne CO₂</td>
<td>IHS Process Economics Program (PEP).</td>
</tr>
</tbody>
</table>

SOT* is the actual SOT value for each product based on published literature.
### Target Subsidies for Products Greater than 2 Electrons

<table>
<thead>
<tr>
<th></th>
<th>Number of Electrons</th>
<th>Target FE (%)</th>
<th>Target Cell Voltage (V)</th>
<th>Target CD (mA/cm²)</th>
<th>Target MSP ($/kg)</th>
<th>Market Price ($/kg)</th>
<th>Required CO₂ Subsidy to Reach Parity ($/MT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>2</td>
<td>98</td>
<td>1.93</td>
<td>1,500</td>
<td>0.22</td>
<td>0.23</td>
<td>$0</td>
</tr>
<tr>
<td>Formic Acid</td>
<td>2</td>
<td>98</td>
<td>2.08</td>
<td>1,500</td>
<td>0.25</td>
<td>0.63</td>
<td>$0</td>
</tr>
<tr>
<td>Oxalic Acid</td>
<td>2</td>
<td>95</td>
<td>2.30</td>
<td>1,500</td>
<td>0.44</td>
<td>1.73</td>
<td>$0</td>
</tr>
<tr>
<td>Ethylene</td>
<td>12</td>
<td>95</td>
<td>1.82</td>
<td>1,500</td>
<td><strong>1.15</strong></td>
<td>0.57</td>
<td><strong>$150</strong></td>
</tr>
<tr>
<td>Ethanol</td>
<td>12</td>
<td>95</td>
<td>1.74</td>
<td>1,500</td>
<td><strong>0.70</strong></td>
<td>0.51</td>
<td><strong>$70</strong></td>
</tr>
<tr>
<td>Methane</td>
<td>8</td>
<td>95</td>
<td>1.66</td>
<td>1,500</td>
<td><strong>1.24</strong></td>
<td>0.22</td>
<td><strong>$340</strong></td>
</tr>
<tr>
<td>Methanol</td>
<td>6</td>
<td>95</td>
<td>1.80</td>
<td>1,500</td>
<td><strong>0.52</strong></td>
<td>0.40</td>
<td><strong>$65</strong></td>
</tr>
</tbody>
</table>

- Products requiring > 2 electrons not economically competitive even under best-case target conditions
- In absence of positive market forces and in addition to achieving target conditions, policy/subsidy drivers will be required in the range of $65–$340 per MT CO₂ depending on each product
- Currently, Low Carbon Fuel Standard (LCFS) credits in California are trading at ~$180 per MT CO₂, and the federal tax (45Q) credit provides $50/MT for CO₂ stored geologically, and $35/MT for CO₂ stored permanently via enhanced oil recovery. (Source: California Air Resources Board)
Chemical Intermediates: Limited Progress Due to Lack of Incentives and Economic Feasibility

Chemical Intermediates that Can Also Be Used as Fuels Offer the Best Opportunity

**Concentration of Developers:**
- Low number of developers near commercialization; high number of early stage developers
- Highest number of developers for three market segments: carbon monoxide (syngas), oxalic acid, and formic acid:
  - Reduction reactions involved for these three are less complicated than others
  - These chemicals can be used as intermediates, but also as fuels or precursors to fuels
  - Fuels from CO₂ have been incentivized/funded by governments to lower carbon emissions, this has not been the case for chemicals

**Dynamics:**
- Very few developers moved from pilot to commercialization stage for all market segments
- Number of start-ups has increased dramatically; investigating solutions for energy-efficient conversions of CO₂
  - Most start-ups tend to focus on catalysis and conversions by reduction as there is an unmet need for conversions that require low energy

The methanol, syngas and formic acid market segments are shown separately in the following pages.

**Source:** Lux Research. “Global Roadmap Study of CO₂U Technologies.” Distributed by the Global CO₂ Initiative, University of Michigan, Nov. 2018.
Liquid Fuels: Several Developers Have Made Significant Steps Toward Commercialization

Liquid Fuel Is Still at the Early Stages in Terms of Being Economical

Concentration of Developers:
- Four developers near commercialization or have commercialized CO₂U; LanzaTech is able to produce in scale
  - Note that LanzaTech converts carbon monoxide (CO) into ethanol, hence the low impact on CO₂ mitigation score
  - Methanol from CO₂ is closest to production in scale

Dynamics:
- Development has been relatively fast for this market due to available funding for projects and mandates set by government for renewable fuels:
  - Stage of development went from pilot testing in lab in 2011 to pilot testing at commercial scale in 2016
  - Focus of developments has been on integrating CO₂ capture, renewable energy supply, hydrogen generation, and CO₂ conversion in the case of methanol and on efficient (multi-step) conversion of CO₂ into fuels in the case of other liquid fuels.
  - Note that Europe is leading as it has set targets to create a low carbon-emission mobility economy
  - Diesel and jet fuels are better targets than gasoline

The significant progress made during the last 5 years shows that the technology is available to be developed to produce at scale.

LanzaTech: Developer of ethanol production from CO via anaerobic microbes

- Began research based off a microbe purchased in 2005, but it proved too environmentally sensitive
- Combined selective evolution and recombinant technology to produce a more suitable microbe, and their founder’s previous experience in bioprocesses allowed a successful bioreactor design in under 2 years
- LanzaTech develops proprietary microbe strains to convert waste gases containing CO and H₂ into chemical intermediates and fuels:
  - Ethanol production from steel mill gas
  - Alcohol to jet fuel process at pilot stage in a partnership with Virgin Atlantic, who started test flights in 2017
- Process requires minimal treatment of waste gas before feeding it to microbes, reducing cost
- Timeline from founding to commercial operation was 8 years with over $200 million in grants and funding

LanzaTech was able to commercialize their biofuel production from CO by fermentation in 9 years by (i) development of differentiated technology and (ii) multiple successful rounds of funding.

Methane: Significant Progress in Europe during Last 5 Years Due to Funding of Projects

Polymers: Limited Number of Corporations Investing in CO₂ Mitigation Due to Lack of Incentives

Polymers from CO\textsubscript{2} Shown to Be Possible, Currently Not Economical

### Concentration of Developers:

- Five developers are near commercialization; few early stage developers:
  - Several companies have shown that polymers from CO\textsubscript{2} can be produced in scale
    - Most companies have focused on polycarbonates and polyols (polyols are used to produce polyurethane). This allows for replacing technology that uses dangerous phosgene gas.
  - Some developers are corporations (Covestro and Asahi Kasei) that have used know-how in catalysis to develop commercial pilot plants for polymers from CO\textsubscript{2}
    - Production capacity is a small fraction (<1\%) compared to polymers from conventional feedstocks

### Dynamics:

- Developers are successful to move from lab and pilot to commercialization stage:
  - However, very few new initiatives showing that follow-up projects from the developers and competing companies is relatively low
  - This is most likely due to the relatively high cost of polymers made from CO\textsubscript{2}

The lack of new startups shows that it is unlikely that new routes using CO\textsubscript{2} to produce polymers will be commercialized without additional incentives.

Source: Lux Research. “Global Roadmap Study of CO\textsubscript{2}U Technologies.” Distributed by the Global CO\textsubscript{2} Initiative, University of Michigan, Nov. 2018.
Conclusions and Potential
by 2030
CO₂U Product’s Mitigation Potential in Tonnes CO₂ Captured

CO₂U Product’s Market Potential

Conclusions: CO$_2$U Offers Opportunities to Mitigate CO$_2$ Emissions Driven by Market Factors

- CO$_2$ mitigation is important to decrease the risks associated with carbon emissions. Carbon capture and utilization (CO$_2$U) can make an important impact on these efforts.
  - Carbon capture and storage (CCS) remains an added cost, whereas CO$_2$U utilizes CO$_2$ to produce materials, fuels, or chemicals
- Significant progress has been made in CO$_2$U during last 5 years, with many technologies shown to be scalable:
  - Momentum is in favor for four markets:
    1. Construction materials
    2. Fuels
    3. Chemical intermediates
    4. Polymers
  - Funding and incentives are necessary to move toward full-scale capabilities
- Aggressive technology development and favorable policies for CO$_2$U open up access to markets valued at $700 billion.
  - CO$_2$U has the potential to utilize 7 billion tonnes of CO$_2$ (~30 fold increase from 2018 CO$_2$U levels) per year by 2030. This is equivalent to approximately 15% of current global CO$_2$ emissions.

Back-Up Slides
### Scenarios Allow for Estimation of Timelines for Significant Market Penetration

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- The markets are listed in order of initial market penetration of products made by CO₂U as estimated by Lux Research.
- Market introduction is defined as the first time production in scale occurred by CO₂U. Note that introduction of polymers is early due to development of polycarbonates from CO₂ in 2002 by Asahi Kasei. Other developments for polymers from CO₂ are in the 2012–2016 time-frame.
- Threshold for time of penetration is achieving more than 2% market share; at this point we believe enough momentum has occurred to drive adoption of technology.

**Source:** Lux Research. “Global Roadmap Study of CO₂U Technologies.” Distributed by the Global CO₂ Initiative, University of Michigan, Nov. 2018.
Market Drivers: Curing of Concrete Using CO$_2$ Offers Increase in Performance and CO$_2$ Abatement

Market:
- Current concrete curing processes use heat and steam
  - Curing of concrete by CO$_2$ injection, add-on to current processes

Curing of concrete by CO$_2$ injection is driven by performance and cost:
- Curing of CO$_2$ is partially driven by increasing performance and reducing cost
- No changes in codes and standards necessary
- CO$_2$ emissions are high for production of concrete. It is a market that would also be a source of CO$_2$
  - However, incentives to reduce CO$_2$ emissions are low
- Funding was available for developers in the past; especially strong in the United States and Canada. Several companies are in the commercialization stage.
- Concrete offers a solution for permanent CO$_2$ storage. CO$_2$ curing would reduce water usage

Market Drivers: Carbonate Aggregate Potential for High Impact on CO₂ Abatement

Carbonates Market:

- Carbonate aggregates produced from CO₂ can be used in concrete, asphalt, and construction fill
- Conversion of CO₂ into carbonates offers the potential to convert low-value materials (such as solid wastes containing calcium oxide, slugs from steel plants, or ash from municipal incinerators) into useful products.
- A drawback is that these materials have to be transported to the site where carbonates are produced, thus increasing the price of CO₂ derived carbonates
  - Carbonate aggregates from CO₂ compete with the current process of mining carbonates from quarries.

Drivers:

- CO₂ emissions are high for production of concrete. It is a market that would also be a source of CO₂
  - However, incentives to reduce CO₂ emissions are low
- Funding in the past for developers; especially strong in the United States and Canada. Several companies are in the commercialization stage
- Concrete and others offer a solution for permanent CO₂ storage

Market Drivers: Conversion of CO$_2$ to Methanol Driven by Desire for Fuels from Renewable Sources

Largest demand for total methanol market is in chemicals:
- Formaldehyde (30%) followed by methyl tert-butyl ether, acetic acid and dimethyl ether
- Methanol to olefins is an emerging sector
- Use as a fuel blend is becoming more popular and will further drive up demand in the future

**Methanol from CO$_2$ is currently only cost competitive in special scenarios:**
- Funding for ‘renewable’ methanol is tied to production of energy from renewable sources
- Limited by the cost of hydrogen, usually produced by the electrolysis of water
  - To produce cheap hydrogen, electricity source must be inexpensive (e.g., hydrothermal source in Iceland, wind in Germany)
- Policies and regulations for CO$_2$ mitigation could help reduce costs
  - Driven by reduction of carbon emissions as set by COP21 in Paris
- Major hurdles for the renewable methanol market are the current high production costs and low production volumes

Source: Methanex

Market Drivers: Syngas Is Versatile as a Chemical Intermediate, Making It Suitable for Current Studies on CO₂ Conversion

Syngas market:

• The syngas (CO + H₂) market is growing with a CAGR at 8%, although relatively small in size currently:
  – Use of syngas is versatile, more reactive than e.g., methanol
• Syngas can be used to make liquid fuels (by Fischer-Tropsch reaction) as well as chemical intermediates (e.g., methanol)
• Syngas is also used for power generation. However, this is not applicable to CO₂ conversion as CO₂U will not be able to compete with other methods to generate power.

Developers of CO₂ conversion choose syngas as it can be used to produce a range of chemicals and fuels:

• More versatile as an add-on to a current industrial plant, production of syngas allows developers to produce fuels or chemical intermediates down stream:
  – For example, the technology can be used for an add-on to steel plants to decrease carbon emissions
• No direct incentives for companies to use renewable sources to produce syngas currently
• Renewable alternatives include generation of syngas from biomass

Market: Polymers from CO₂ Dominated by Polycarbonates and Polyols

Market:
- Fewer developers as compared to the other three markets:
  - Focus on production of polycarbonates and polyols from CO₂
  - Research into other types of polymers is more fragmented
- Mainly large companies involved in the development of polymers:
  - Partially due to access to know-how and production facilities

Reduction of CO₂ emissions at chemical and material plants:
- Funding in place in Europe for companies to explore possibilities of using CO₂ as a feedstock
- Reduction of CO₂ emissions at the industrial plant:
  - Note that often CO₂ is not the only source of carbon, thereby limiting the impact of CO₂ mitigation
- Exploration of alternative feedstocks:
  - Use of CO₂ as a feedstock made during production of other chemicals/polymers
- Currently, the thermo-catalytic process is not cost-competitive due to cost of process and cost of CO₂

Market: Methane is produced from resources such as shale gas, tight gas, and coalbeds:
- Most natural gas production is expected to come from shale gas
- Bio-methane from renewable sources is being investigated to reduce CO$_2$ emissions:
  - Methane from CO$_2$ conversion will compete with bio-methane, both can be introduced in the net as substituted natural gas

Drivers:
- Funding in Europe for co-electrolysis of CO$_2$ and water is ongoing as several countries have high alternative energy capacities such as hydro-electric or wind power
- Funding to lower carbon emissions, Europe is ahead of the pack
  - Consortiums set up in Europe involving members of the value chain (universities, energy supplier, CO$_2$ supplier, converter, and user)
- Shale gas is replacing coal burning plants in the United States; thereby reducing carbon emissions and reducing the drive for reduction of CO$_2$ emissions in countries such as the United States.

Source: Lux Research. “Global Roadmap Study of CO$_2$U Technologies Distributed by the Global CO2 Initiative, University of Michigan, Nov. 2018
Market:  
- Liquid fuel market consists of gasoline, diesel, and kerosene  
- This market also includes fuel additives such as methanol and ethanol  
- Biofuel segment from renewable sources such as sugar cane has been growing due to funding and incentives  
  - Fuels from CO₂ conversion has a negligible market share currently  

Drivers:  
- Funding is in place for renewable fuels to lower carbon emissions, Europe is ahead of the pack  
- Europe has a mandate to have 10% of fuels from renewable sources by 2021:  
  - Source of energy would have to be renewable  
- Consortiums set up in Europe involving members of the value chain (universities, energy supplier, CO₂ supplier, converter and user)  
- Note that fuels from CO₂ conversion target the same market as biofuels from bio-based feedstocks  
  - Global market share of bio-fuels has increased to 4% in 2015  

Source: Lux Research. "Global Roadmap Study of CO₂U Technologies Distributed by the Global CO2 Initiative, University of Michigan, Nov. 2018
General Techno-Economic Analysis (TEA) Methodology

Approach:
- Design conceptual process include all major steps, core conversion, CO₂ recycle, product purification, etc.
- Analyze and report three cost numbers: SOT, target, and theoretical conditions
  - SOT: Major assumptions and technical metrics based on published results in the open literature
  - Target: Technical metrics based on attainable process improvements (engineering judgement)
  - Theoretical: Technical metrics based on thermodynamic limitations
- Calculate minimum selling price (MSP) using discounted cash-flow rate of return on investment, equity payback, taxes, and 2016 U.S. dollars
- Perform comparative analysis for various conversion pathways and same product from different pathways
- Perform inclusive sensitivity analysis:
  - Identify key cost drivers
  - Research and development and policy needs to realize economic advantage of a product over existing market value