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

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Outline

1. Motivation for CO_2 Utilization
2. State of CO_2 Utilization
3. Markets, State of Markets, and Potential
4. Conclusions and Potentials by 2030

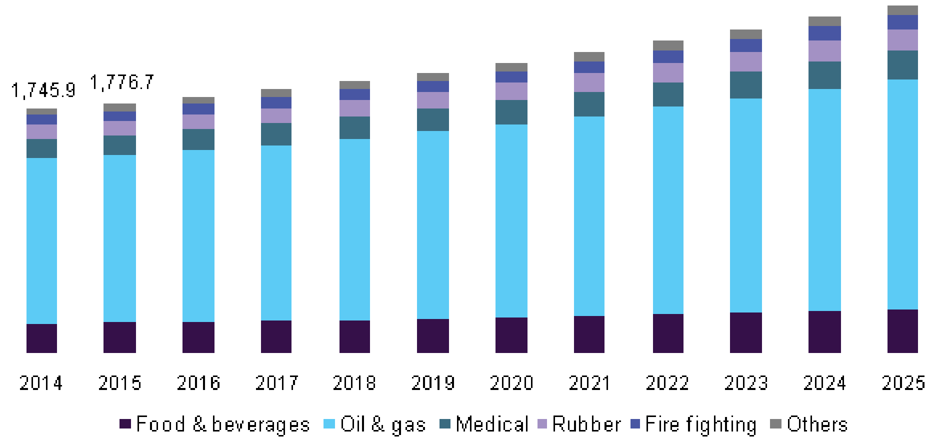
Why CO_2 Utilization

- 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 CO_2 Utilization

- Global consumption of CO_2 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 CO_2 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 CO_2 emissions = 37 billion metric tons
- Current usage rate ~0.5% of total emissions

CO_2 Sources: Quality, Cost, and Suppliers

Source	CO_2 Content (vol%)	CO_2 Emission Intensity	Primary Impurities	Capture Cost ($/tonne CO_2)
Corn Mill	Near 100%	3.1 kg/gal ethanol	n/a	$0–$5 – minor drying and purification
Natural	Near 100%	n/a	n/a	$0–$5 – minor cleanup
Biogas	35%–65 %	0.6–1.2 kg/m^3 biogas	CH_4, H_2S	$20–$75
Fossil Fuel-Fired Power Plants	3%–20%	499 kg CO_2/MWh (NG plant) 960 kg CO_2/MWh (Coal plant)	N_2, water, O_2, SO_X, Ar	$20–$90
Air Capture	0.04%	n/a	N_2, O_2, Ar	$100–$1,000

2018 U.S. CO_2 Suppliers and Market Share

Supplier	Production Capacity (MTD)	% of Total
Linde	9,172	24.9
Air Liquide	6,724	18.2
Praxair	5,874	15.9
Matheson	3,379	9.2
Reliant Holdings	2,617	7.1
POET Biorefining	1,043	7.1
CF Industries	880	2.4
Sandhill	635	1.7
Rentech Energy	590	1.6
AES Corp.	354	1.0
Abengoa Bioenergy	345	1.0
ADM	318	0.9

vol% = volume percent | $/tonne CO_2 = U.S. dollars per tonne of CO_2 | kg/gal = kilogram per gallon | kg/m^3 = kilograms per cubic meter | CH_4 = methane | H_2S = hydrogen sulfide | MWh = megawatt hour | N_2 = nitrogen | O_2 = oxygen | SO_X = sulfur oxide | Ar = argon | MTD = ???

Markets, State of Markets, and Potentials

Existing and Potential Uses of CO_2

- **Non-Reductive:** Use CO_2 in liquid or gaseous form
  - ~ 100% of current use
- **Reductive:** Use renewable or nuclear low cost, no carbon electricity to reduce CO_2 to a reactive intermediate for fuel, chemical, or material production:
  - Very limited commercial practice

Illustration by ???

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 CO_2U technologies used in this market are mineralization to carbonate aggregates and the use of CO_2 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 CO_2 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 CO_2U technology in reports on CO_2U

Photo from Stanislav Kondratiev, Unsplash

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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

6. Novel Materials – Reductive

- 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

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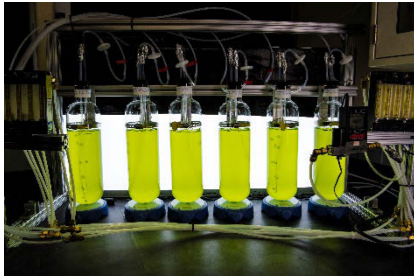

Photo by Dennis Schroeder, NREL 55029

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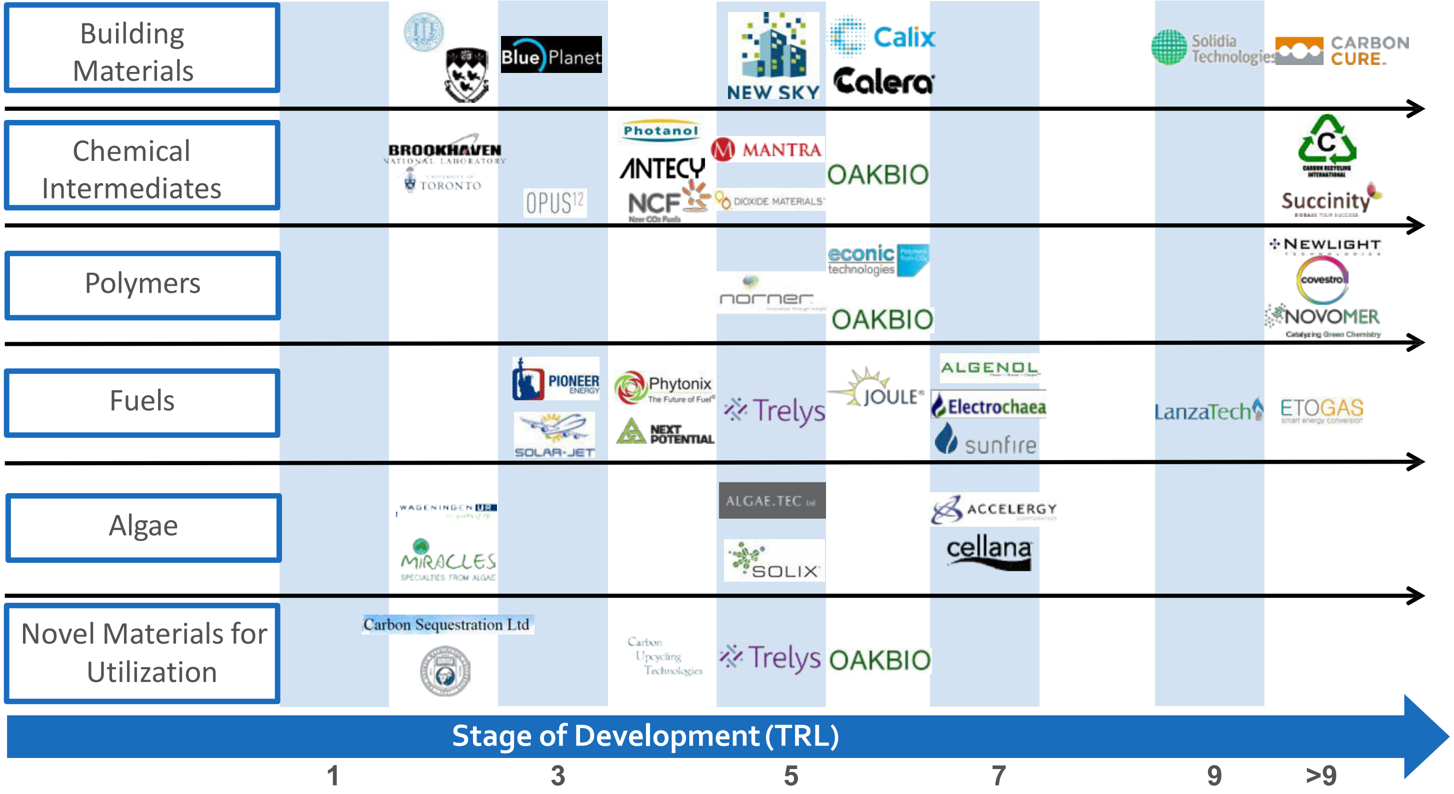
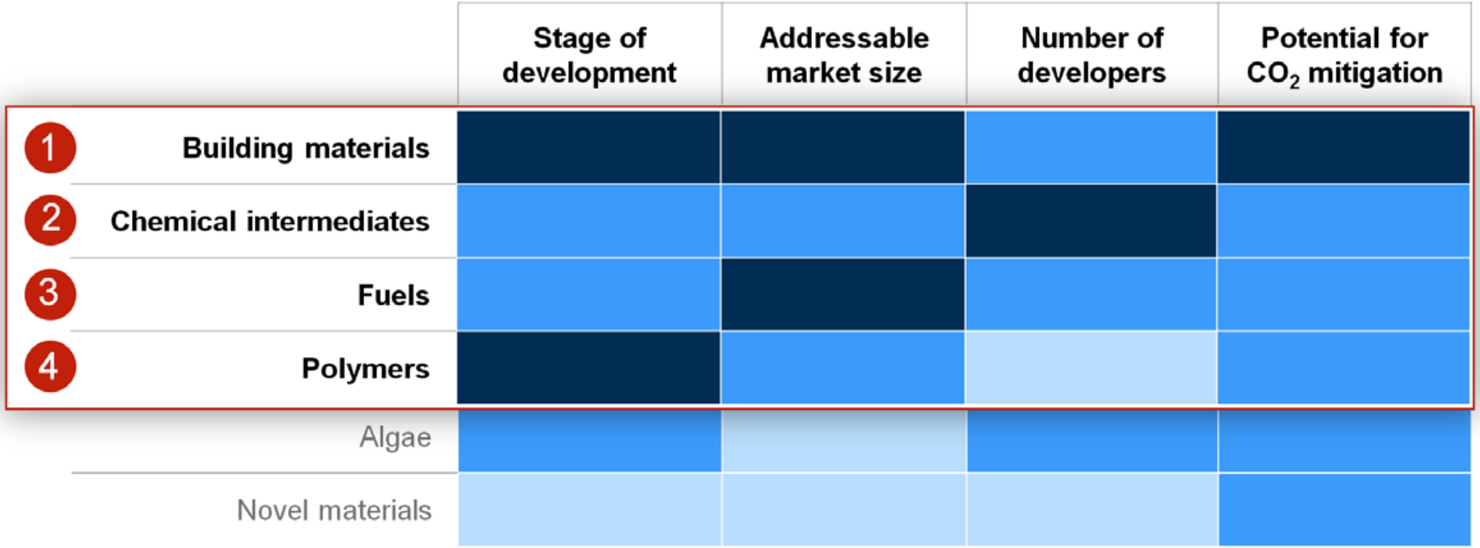
Ranking Developers by Technology Readiness Level (TRL) Reveals Maturity and Momentum in Specific Target Markets



Example companies from database to illustrate range of commercial readiness.

Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Which Markets Offer the Best Opportunities for Support and Investment



High (>25% of developers is near commercialization, the addressable market is a mature market, number of developers >50, prolonged abatement of CO_2)

Medium (<25% of developers is near commercialization, the addressable market is a developing market, number of developers between 10 and 50, mitigation of CO_2 by replacing conventional feedstock)

Low (no developers are near commercialization, the addressable market is unclear, number of developers below 10, CO_2 mitigation is minimal)

Source: Lux Research, University of Michigan

Developers of CO_2U Technology by Market

Building Materials

Carbon8, Blue Planet, Solidia Technologies, NEW SKY, Calix, CARBON CURE™, Calera

Chemical Intermediates

MANTRA, Carbon Recycling International, OAKBIO, DIOXIDE MATERIALS, OPUS12, Photanol, Succinity (Biobase your success), Mitsui Chemicals, ANTECY, NCF New CO2 Fuels

Fuels

SOLAR-JET, Phytonix (The Future of Fuel®), Electrochaea, Trelys, sunfire, JOULE®, PIONEER ENERGY, LanzaTech, ETOGAS (smart energy conversion), NEXT POTENTIAL, ALGENOL

Polymers

norner (Innovation through Insight), covestro, NOVOMER (Catalyzing Green Chemistry), econic technologies (Polymers from CO_2), NEWLIGHT TECHNOLOGIES, AsahiKASEI, OAKBIO

Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

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

Market	Number of Developers in EU	% TRL 5 or Lower	Number of Developers in North America	% TRL 5 or Lower
Building Materials	6	50%	10	60%
Chemical Intermediates	18	77%	25	92%
Fuels	7	86%	10	70%
Polymers	9	67%	4	25%
Total	**37**	**73%**	**48**	**75%**

- Most developments in CO_2U 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).

Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Progress that Companies Have Made in CO_2U from 2011 to 2016

Weighting for Visualization:

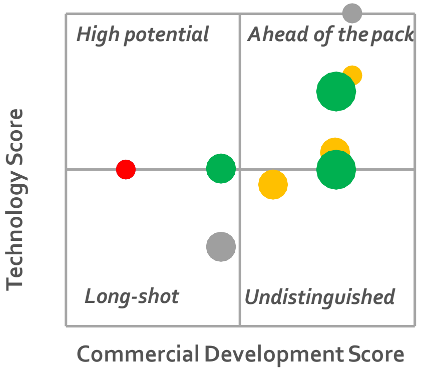
- **Y-axis – Technology Score:** 20% intellectual property (IP) strength, 10% regulatory factors, 30% competitive landscape score, 40% technology value
- **X-axis – Commercial Development Score:** 60% technology maturity, 25% developer maturity, 15% commercial maturity
- **Bubble size – CO_2 Mitigation Potential:** 30% ease of set-up, 50% market size, 20% extent that CO_2 is used as feedstock

Lux compared status of developers in 2011 and 2016:

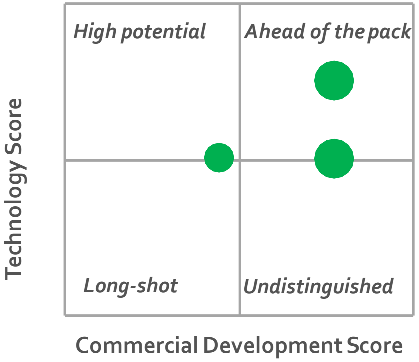
- Color coded the developers in the graph for 2011 based on situation in 2016
- Color in the 2016 graph notes the market segment

Active
Pivot
Discontinued
Idle or unknown

Example: Lux Innovation Grid 2011



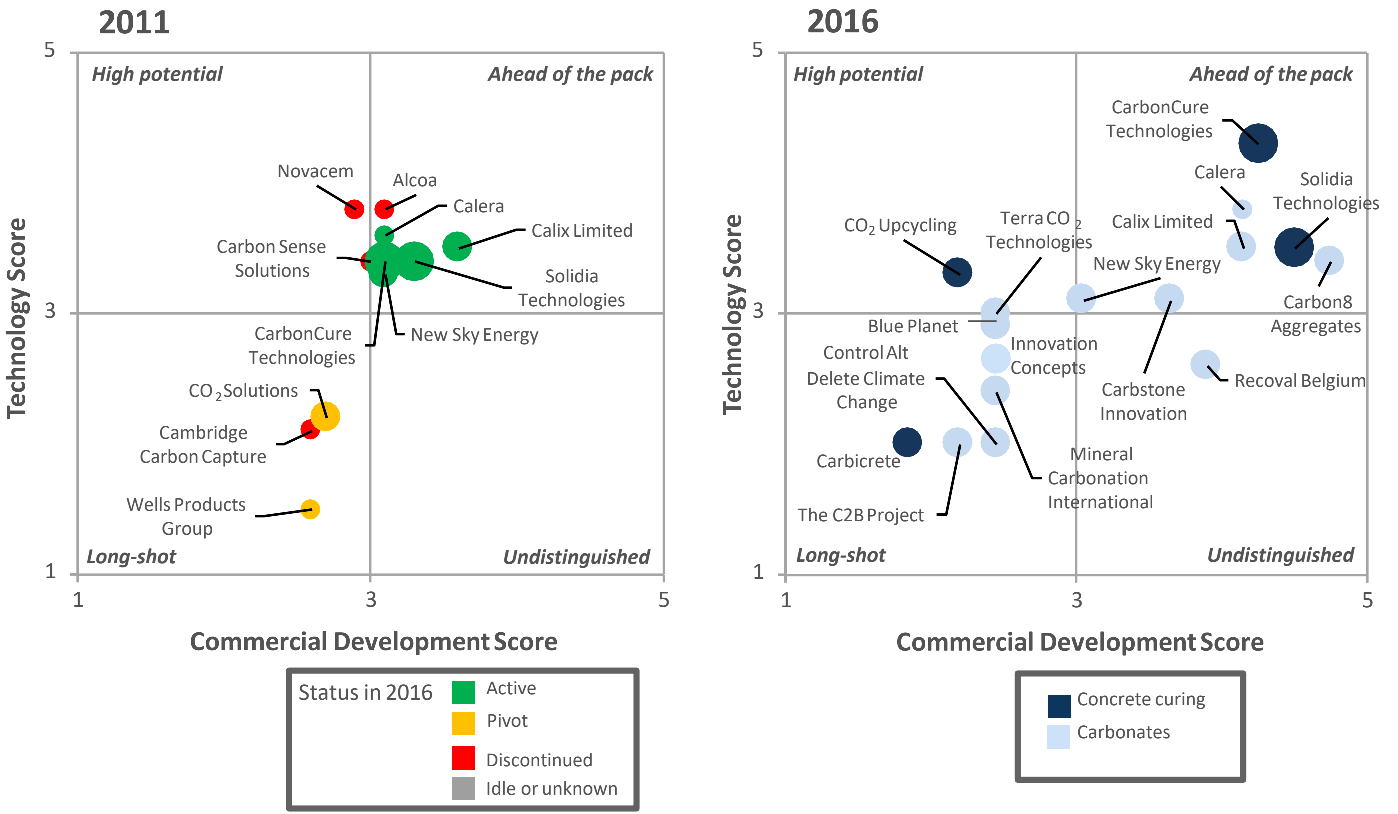
Example: Lux Innovation Grid 2016



Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Building Materials – Non-Reductive

Building Materials: Progress during the Last Five Years Has Been Significant, Immediate Opportunities



Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

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.

Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Case Study to Sequester CO_2 Using CO_2U Technology with No CAPEX for Users

Market

- 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_2U 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.

Company funding and development history

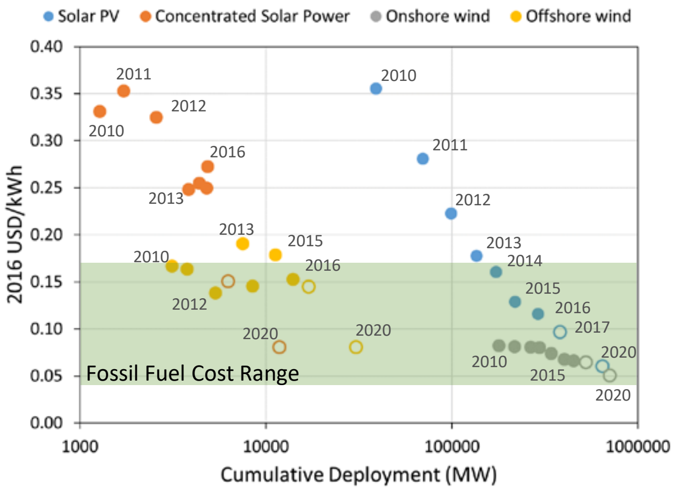
- 2007 Company founded in Canada
- 2007 Early prototype testing with Shaw Group
- 2012 Innovacorp leads an initial funding of $4M
- 2012 Completes first industrial scale production demonstration with Shaw Group
- 2012 Tweaked process to make amenable to ready-mix segment
- 2012 350 Capital leads Series A funding of an undisclosed amount
- 2013 Signs agreement with concrete block manufacturer Atlas Block
- 2013 Business Development Bank of Canada leads Series B funding of $3.3M
- 2015 Pangaea Ventures leads Series C funding of $2.5M
- 2016 Pangaea Ventures contributes another $1.4M in Series C funding
- 2016 Argos becomes first adopter of ready-mix technology

Source: Lux Research. “Global Roadmap Study of CO_2U Technologies.” Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Chemical Intermediates, Fuels, and Polymers – Reductive

Convergence of Trends Makes Reductive Paths to CO_2 Utilization Possible

Increasing Deployment and Decreasing Costs of Renewable Electricity



IRENA, Renewable Power Generation Costs in 2017

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

Growing Need and Opportunity for Utilizing Gaseous Carbon Waste Streams

Government, NGO, Industry, Academia, NAS

Ethanol Fermentation

$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + \mathbf{2CO_2}$

216 Existing U.S. Biorefineries Emit 45 million tons (Mt) of CO_2/year*

Opportunity: *Improve Biorefinery Carbon Utilization*

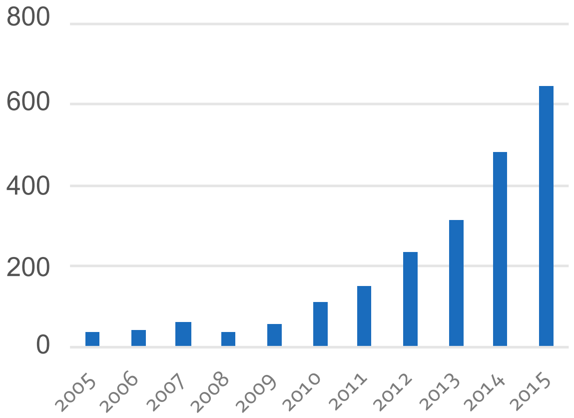
*D. Sanchez, et al., "Near-term deployment of carbon capture and sequestration from biorefineries in the United States." *PNAS* 115 (2018) 4875.

Publications on the Conversion of CO_2 by Catalytic Reduction Has Increased Significantly

Top 10 Institutes by Number of Publications

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

Number of Publications on Catalysis for CO_2 Reduction



Search on Web of Science using search string: TS=(((CO2 NEAR/2 reduct) OR ((carbon ADJ dioxide) NEAR/2 reduct*)) AND (*cataly*)) Time Span: 2005-2015*

Is this translating to increased commercialization?

Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

General Assumptions

Parameter	Assumption			Justification and Reference
	SOT	Target	Theoretical	
Electrolyzer Style	Polymer Electrolyte Membrane (PEM) Architecture			Scalable solution to reach high current density. Industrial validation/data (OPUS12, Dioxide Materials).
Current Density (mA/cm^2)	SOT*	1,500	2,000	SOT value depends on each product. Target values from hydrogen analysis (H2A)/PEM assumptions.
Cell Voltage (V)	SOT*	Theoretical + 0.6V	Theoretical	Both SOT and theoretical values depend on product. Target value +600mV cell overpotential on theoretical.
Faradaic Efficiency (%)	SOT*	95%	100%	SOT value depends on product. Target=SOT if SOT FE>95%.
Installed Capital Cost ($\$/m^2$)	22,000	10,000	5,000	H2A assumptions $900, $400, and $200/kW + SOT current density / cell voltage.
Single-Pass CO_2 Conversion (%)	20%	90%	100%	Rarely reported. 20% from 2018 Haas et al. (Siemens). 90% from 2018 Luc et al.
Electricity Price ($/kWh)	0.068	0.03	0.02	U.S. Energy Information Administration (EIA) electricity price (sensitivity: $0-$0.068 $/kWh).
CO_2 Capture Price ($/ton)	40	20	0	Carbon Capture and Storage (CCS)-CO_2 capture from power plants, first-of-a-kind (FOAK) bioethanol.
CO_2 Flowrate (kg/hr)	71,729			Estimated CO_2 from annual 200 million gallons of ethanol.
CO_2 Separations Cost	$50–$80 / tonne CO_2			IHS Process Economics Program (PEP).

SOT* is the actual SOT value for each product based on published literature.

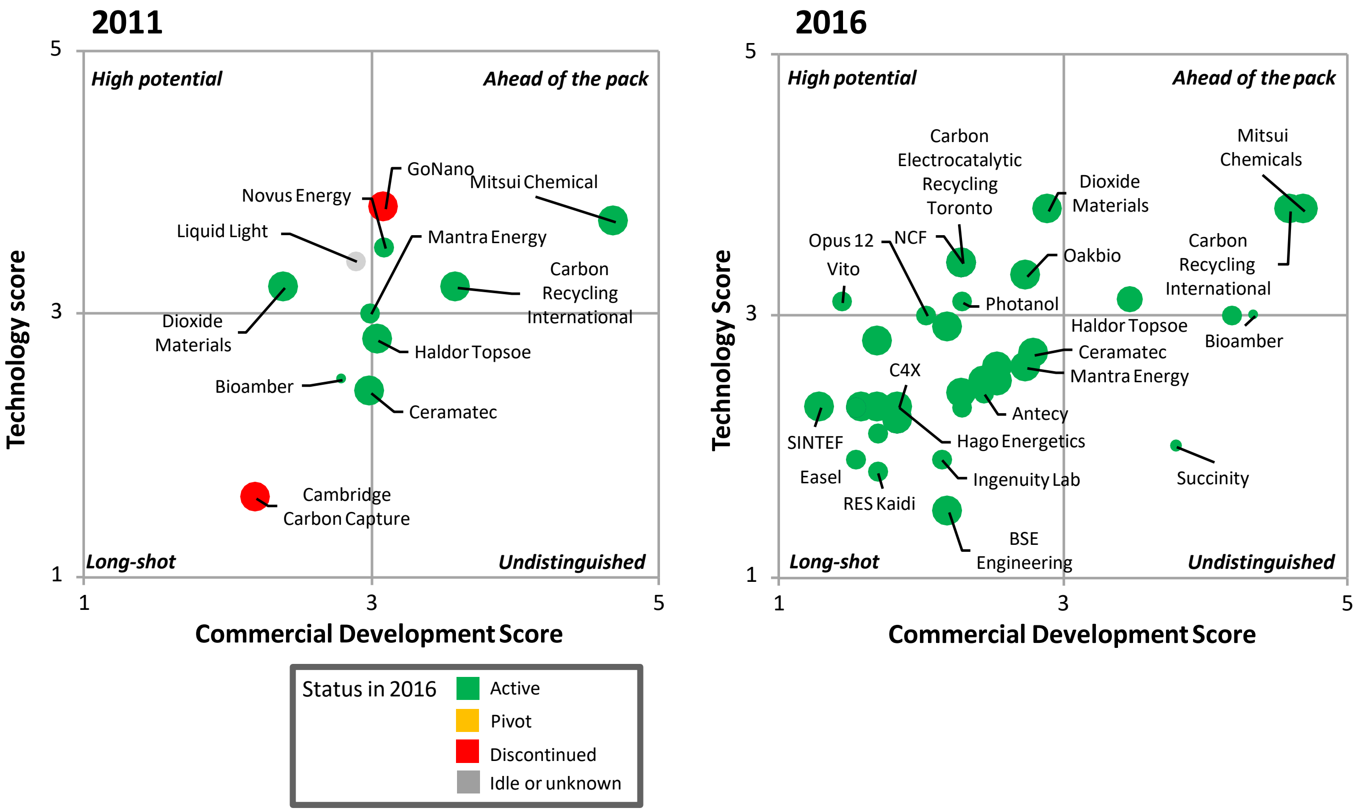
Target Subsidies for Products Greater than 2 Electrons

	Number of Electrons	Target FE (%)	Target Cell Voltage (V)	Target CD (mA/cm^2)	Target MSP ($/kg)	Market Price ($/kg)	Required CO_2 Subsidy to Reach Parity ($/MT)
CO	2	98	1.93	1,500	**0.22**	**0.23**	**$0**
Formic Acid	2	98	2.08	1,500	**0.25**	**0.63**	**$0**
Oxalic Acid	2	95	2.30	1,500	**0.44**	**1.73**	**$0**
Ethylene	12	95	1.82	1,500	**1.15**	**0.57**	**$150**
Ethanol	12	95	1.74	1,500	**0.70**	**0.51**	**$70**
Methane	8	95	1.66	1,500	**1.24**	**0.22**	**$340**
Methanol	6	95	1.80	1,500	**0.52**	**0.40**	**$65**

- 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 CO_2 depending on each product
- Currently, Low Carbon Fuel Standard (LCFS) credits in California are trading at ~$180 per MT CO_2, and the federal tax (45Q) credit provides $50/MT for CO_2 stored geologically, and $35/MT for CO_2 stored permanently via enhanced oil recovery. (Source: California Air Resources Board)

FE = ??? | CD = ??? | MSP = minimum selling price | MT = ???

Chemical Intermediates: Limited Progress Due to Lack of Incentives and Economic Feasibility



Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

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 CO_2 have been incentivized/funded by governments to lower carbon emissions, this has not been the case for chemicals

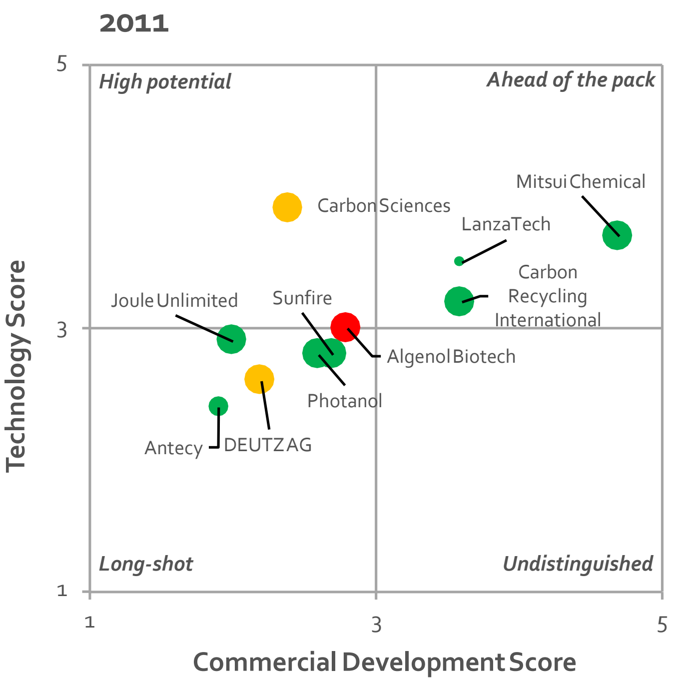
Dynamics:

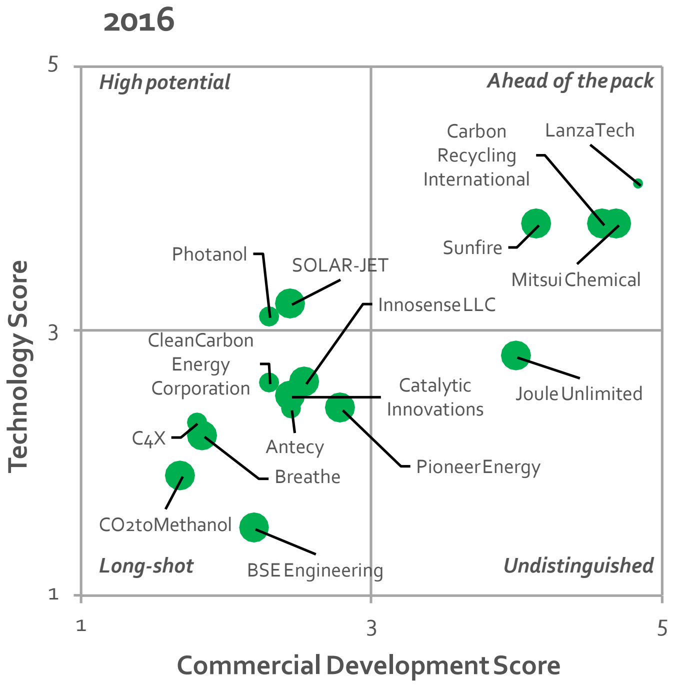
- Very few developers moved from pilot to commercialization stage for all market segments
- Number of start-ups has increased dramatically; investigating solutions for energy-efficient conversions of CO_2
  - Most start-ups tend to focus on catalysis and conversions by reduction as there is an unmet need for conversions that require low energy

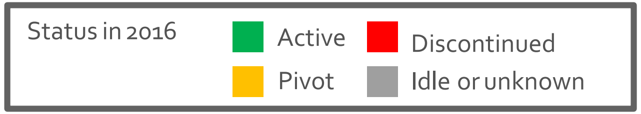
The methanol, syngas and formic acid market segments are shown separately in the following pages.

Source: Lux Research. “Global Roadmap Study of CO_2U Technologies.” Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Liquid Fuels: Several Developers Have Made Significant Steps Toward Commercialization







Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

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

Concentration of Developers:

- Four developers near commercialization or have commercialized CO_2U; LanzaTech is able to produce in scale
  - Note that LanzaTech converts carbon monoxide (CO) into ethanol, hence the low impact on CO_2 mitigation score
  - Methanol from CO_2 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 CO_2 capture, renewable energy supply, hydrogen generation, and CO_2 conversion in the case of methanol and on efficient (multi-step) conversion of CO_2 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.

Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Case Study on New Technology: From Concept to Full-Scale Production: LanzaTech

- 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 H_2 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

Market

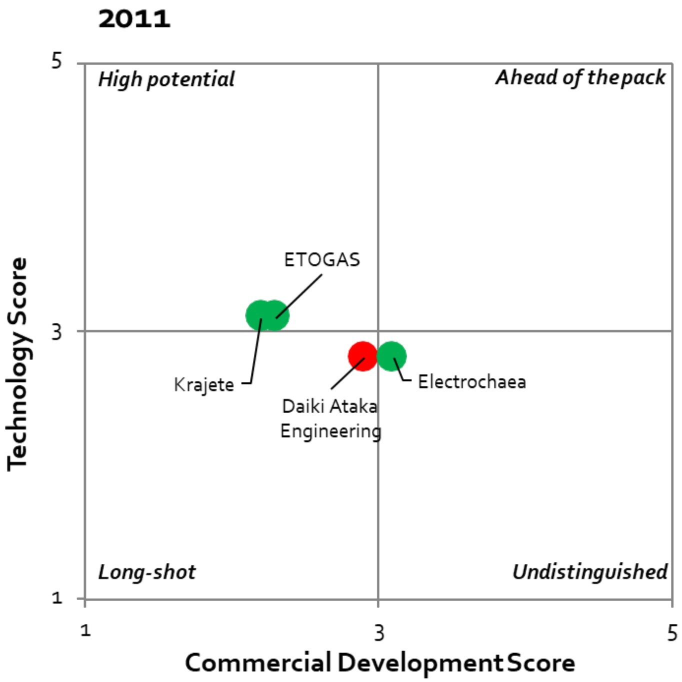
Company funding and development history

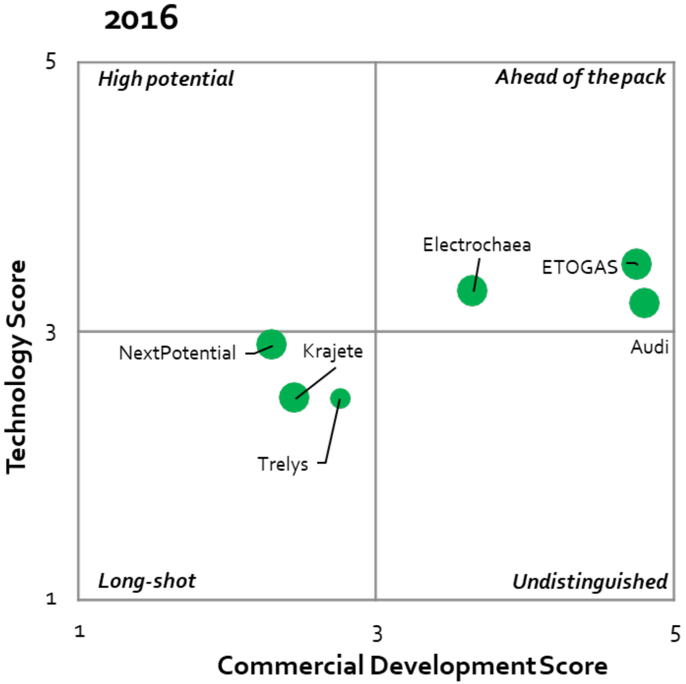
- 2005 — Company founded
- 2005-2007 — Lab research and first bioreactor design
- 2007 — $12 million in Series A funding from Khosla Ventures
- 2008 — 15,000 gallon/year pilot plant opened at a steel mill
- 2009 — NZ government grant of $9 million
- 2010 — Development partnerships including Baosteel, PNNL, Chinese Academy of Science
- 2010 — $18 million in Series B funding from Qiming Ventures
- 2011 — 100,000 gallon/year pre-commercial plant opened near Shanghai
- 2012 — Successfully operated pre-commercial plant, and opened another at the same size
- 2012 — $56 million in Series C funding from Burril Malaysian Life Sciences Fund, $15 million debt funding from Western Technologies Investments
- 2013 — Production of commercial units and aviation fuel for certification
- 2014 — First two commercial plants operating using steel gas to ethanol process. $112 million in Series D funding from Mitsui

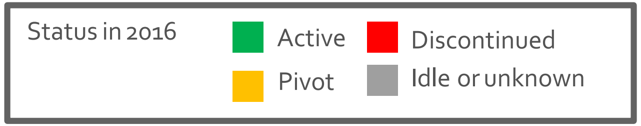
LanzaTech was able to commercialize their biofuel production from CO by fermentation in 9 years by (i) development of differentiated technology and (ii) multiple successful rounds of funding.

Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

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

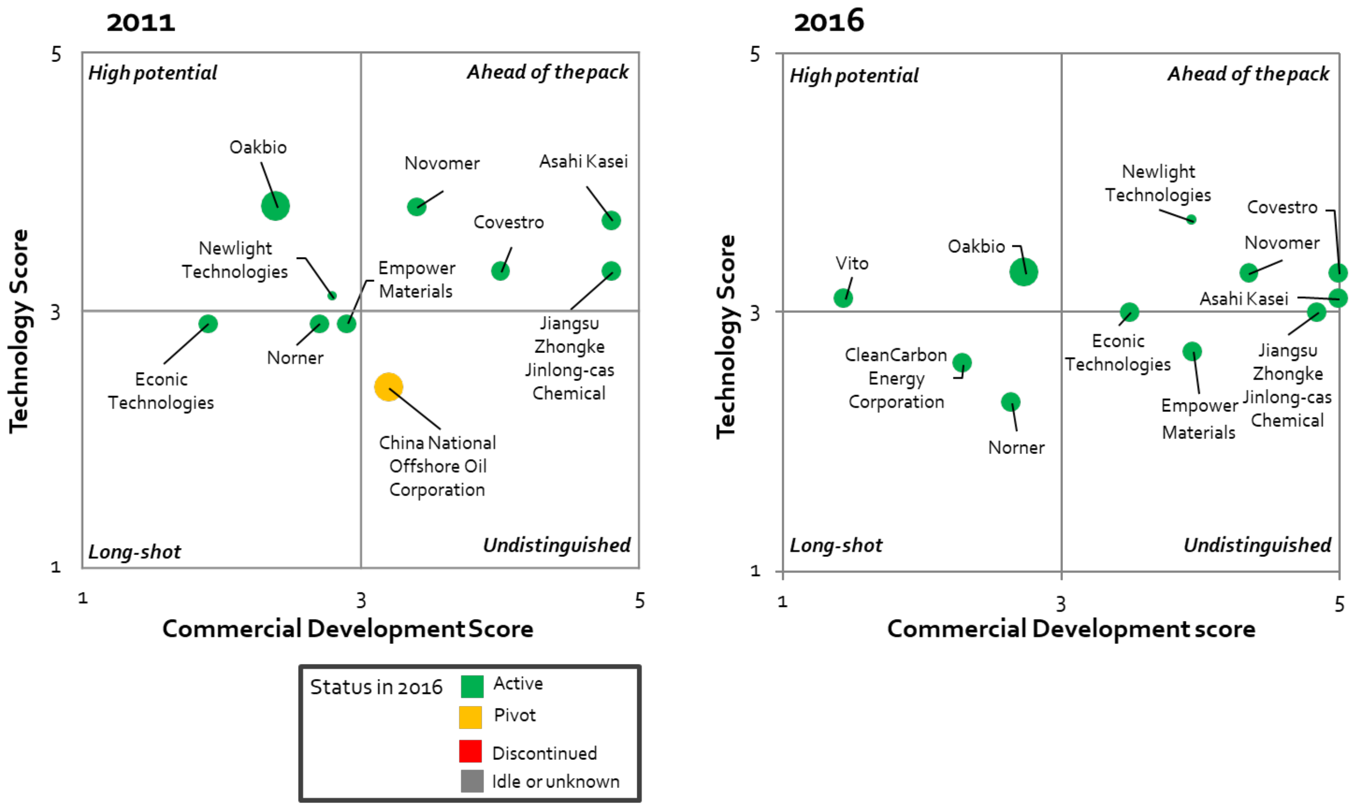






Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Polymers: Limited Number of Corporations Investing in CO_2 Mitigation Due to Lack of Incentives



Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Polymers from CO_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_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_2
    - Production capacity is a small fraction (<1%) compared to polymers from conventional feedstocks

Dynamics:

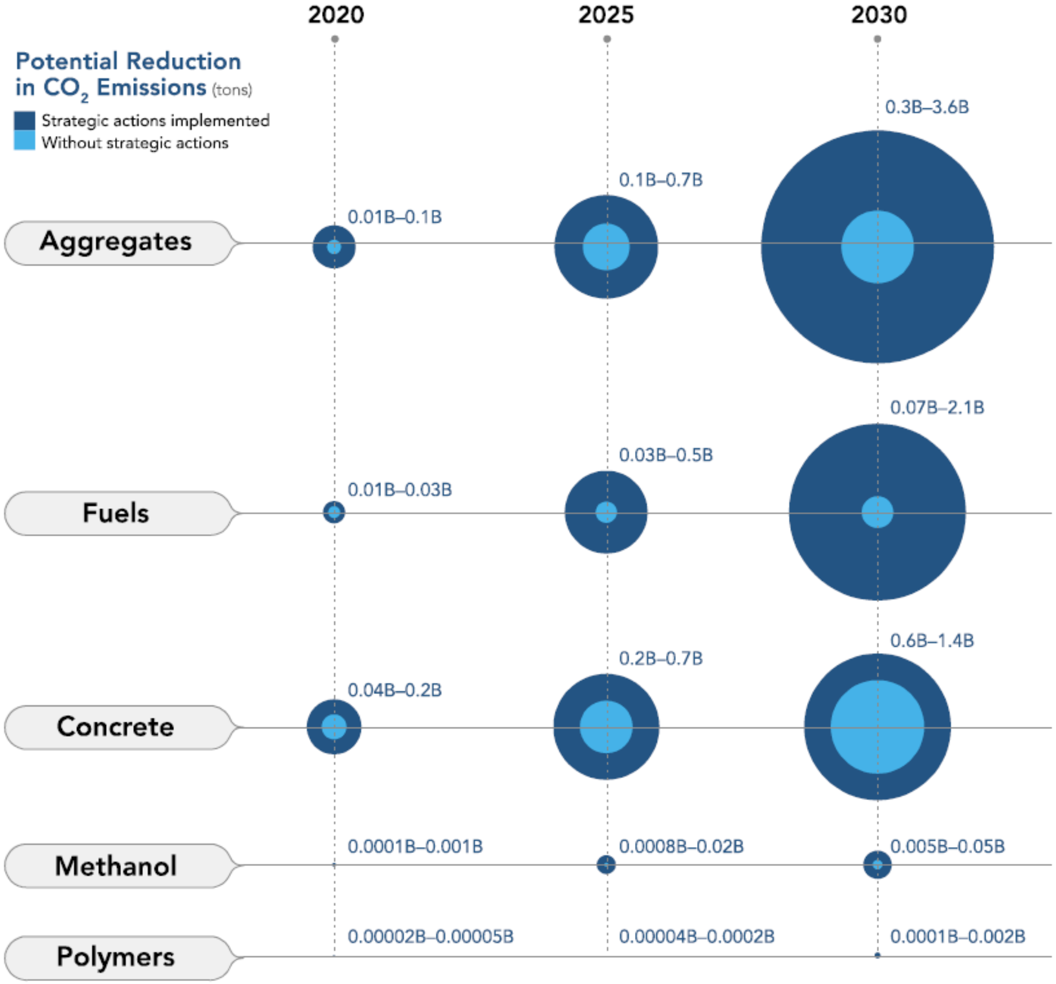
- Developers are successful to move from lab and pilot to commercialization stage:
  - However, very few new initiatives showing that follow-up projects from the developers and competing companies is relatively low
  - This is most likely due to the relatively high cost of polymers made from CO_2

The lack of new startups shows that it is unlikely that new routes using CO_2 to produce polymers will be commercialized without additional incentives.

Source: Lux Research. “Global Roadmap Study of CO_2U Technologies.” Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

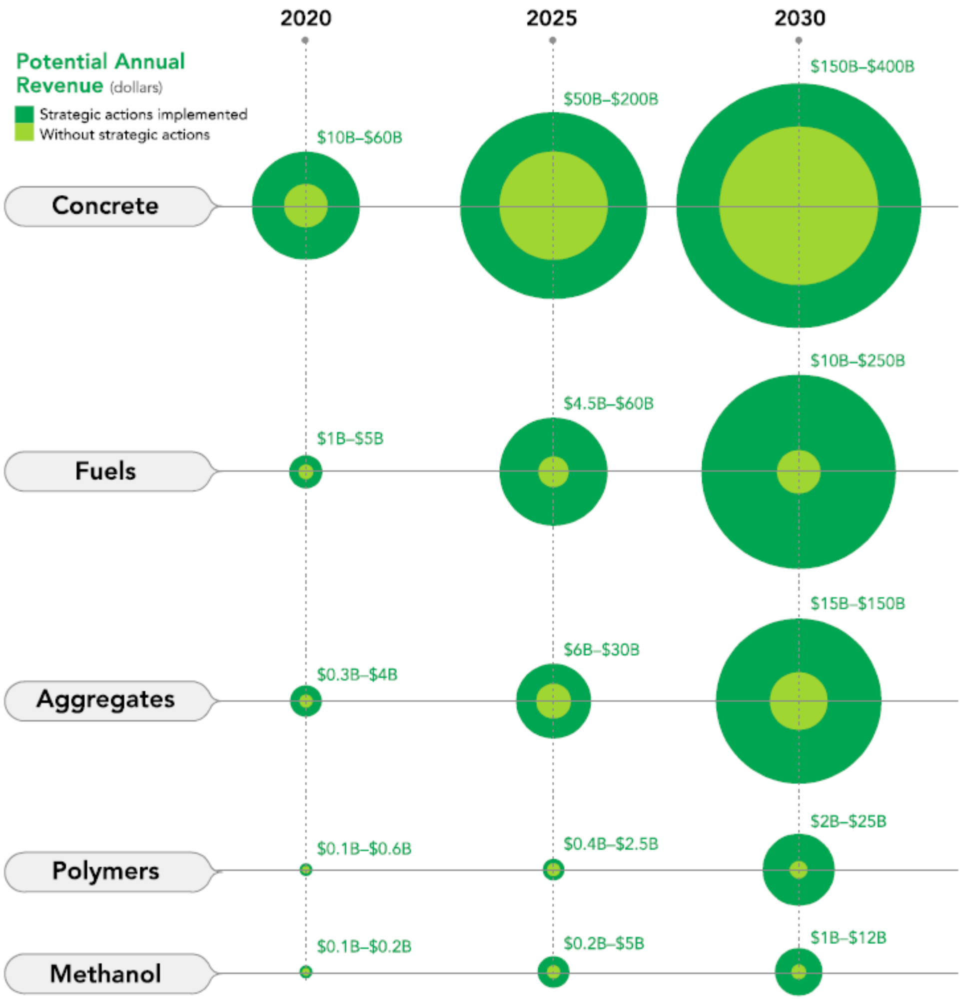
Conclusions and Potential by 2030

CO_2U Product's Mitigation Potential in Tonnes CO_2 Captured



Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

CO_2U Product's Market Potential



Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Conclusions: CO_2U 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_2U) can make an important impact on these efforts.
  - Carbon capture and storage (CCS) remains an added cost, whereas CO_2U utilizes CO_2 to produce materials, fuels, or chemicals
- Significant progress has been made in CO_2U 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_2U open up access to markets valued at $700 billion.
  - **CO_2U has the potential to utilize 7 billion tonnes of CO_2 (~ 30 fold increase from 2018 CO_2U levels) per year by 2030. This is equivalent to approximately 15% of current global CO_2 emissions.**

Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Q&A

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Back-Up Slides

Scenarios Allow for Estimation of Timelines for Significant Market Penetration

Market	Market introduction	Market penetration (Pessimistic)	Market penetration (Optimistic)	Market penetration (Best case)	Main assumption for barrier
Concrete	2014	pre-2020	pre-2020	pre-2020	No technology barriers
Aggregates	2012	pre-2030	pre-2030	pre-2025	Low-cost product that requires cost-competitive CO_2U
Methanol	2011	pre-2030	pre-2025	pre-2020	Integration of carbon capture, CO_2 conversion, and hydrogen supply at scale
Formic acid	post-2016	post-2030	pre-2030	pre-2025	Research in CO_2U technology to form formic acid is lagging
Syngas	post-2016	pre-2030	pre-2025	pre-2025	Integration of carbon capture, CO_2 conversion, and hydrogen supply at scale
Polymers	2002	pre-2030	pre-2025	pre-2025	Access to low-cost CO_2
Methane	2013	post-2030	post-2030	post-2030	Low-cost product that requires cost-competitive CO_2U
Liquid fuels	post-2016	post-2030	pre-2030	pre-2025	Integration of carbon capture, CO_2 conversion, and hydrogen supply at scale

- The markets are listed in order of initial market penetration of products made by CO_2U as estimated by Lux Research
- Market introduction is defined as the first time production in scale occurred by CO_2U. Note that introduction of polymers is early due to development of polycarbonates from CO_2 in 2002 by Asahi Kasei. Other developments for polymers from CO_2 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 CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Market Drivers: Curing of Concrete Using CO_2 Offers Increase in Performance and CO_2 Abatement

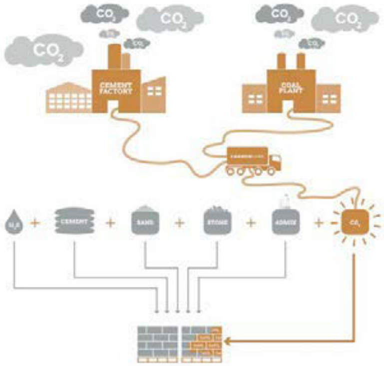
Market:

- 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

Concrete



Source: Carboncure

Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Market Drivers: Carbonate Aggregate Potential for High Impact on CO_2 Abatement

Carbonates Market:

- Carbonate aggregates produced from CO_2 can be used in concrete, asphalt, and construction fill
- Conversion of CO_2 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 CO_2 derived carbonates
  - Carbonate aggregates from CO_2 compete with the current process of mining carbonates from quarries.

Drivers:

- 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 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 CO_2 storage

Aggregates

Source: Calera

Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Market Drivers: Conversion of CO_2 to Methanol Driven by Desire for Fuels from Renewable Sources

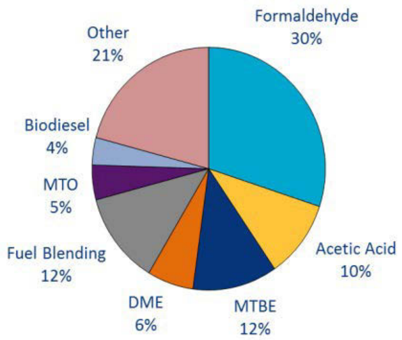
Largest demand for total methanol market is in chemicals:

- 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

Methanol



Source: Methanex

Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Market Drivers: Syngas Is Versatile as a Chemical Intermediate, Making It Suitable for Current Studies on CO_2 Conversion

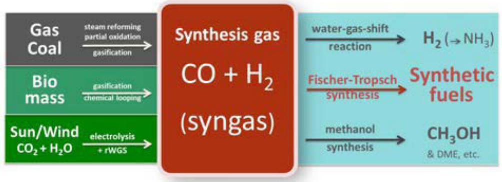
Syngas market:

- The syngas ($CO + H_2$) 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 CO_2 conversion as CO_2U will not be able to compete with other methods to generate power.

Developers of CO_2 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

Syngas



Source: SyngasChem

Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Market Drivers: Polymers from CO_2 Dominated by Polycarbonates and Polyols

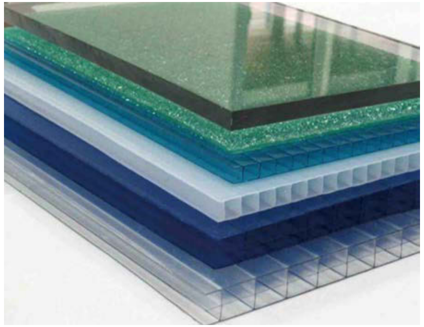
Market:

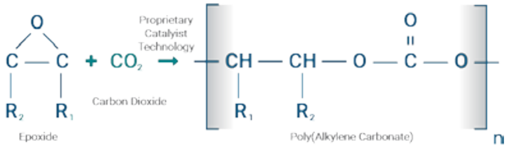
- Fewer developers as compared to the other three markets:
  - Focus on production of polycarbonates and polyols from CO_2
  - Research into other types of polymers is more fragmented
- Mainly large companies involved in the development of polymers:
  - Partially due to access to know-how and production facilities

Reduction of CO_2 emissions at chemical and material plants:

- Funding in place in Europe for companies to explore possibilities of using CO_2 as a feedstock
- Reduction of CO_2 emissions at the industrial plant:
  - Note that often CO_2 is not the only source of carbon, thereby limiting the impact of CO_2 mitigation
- Exploration of alternative feedstocks:
  - Use of CO_2 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 CO_2

Polymers





Source: Empower Materials

Source: Lux Research. "Global Roadmap Study of CO_2U Technologies." Distributed by the Global CO_2 Initiative, University of Michigan, Nov. 2018.

Market Drivers: Methane from CO_2 Competes with Low-Price Natural Gas

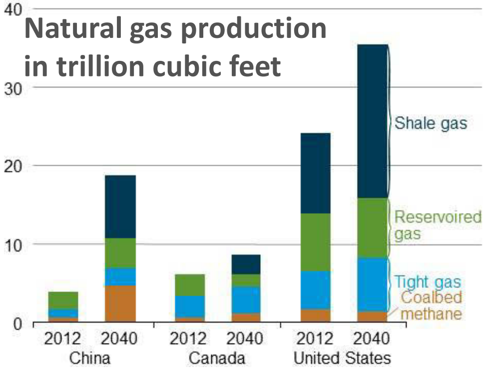
Market:

- 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.

Methane



Source: Audi-egas

Source: Lux Research. "Global Roadmap Study of CO_2U Technologies Distributed by the Global CO2 Initiative, University of Michigan, Nov. 2018

Market Drivers: Mandates for Renewable Fuels Offer Opportunities for Liquid Fuels from CO_2

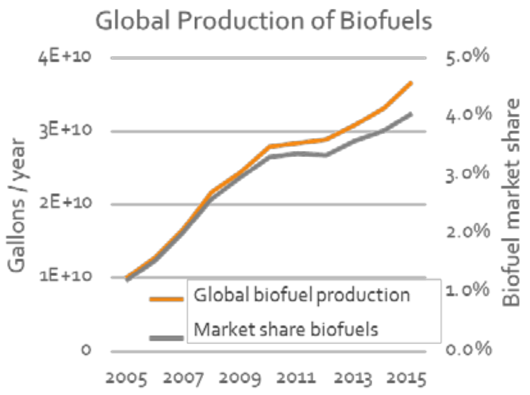
Liquid Fuels

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 CO_2 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, CO_2 supplier, converter and user)
- Note that fuels from CO_2 conversion target the same market as biofuels from bio-based feedstocks
  - Global market share of bio-fuels has increased to 4% in 2015



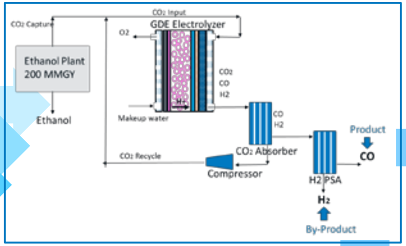
Source: Lux Research

Slide 80

Source: Lux Research. “Global Roadmap Study of CO_2U Technologies Distributed by the Global CO2 Initiative, University of Michigan, Nov. 2018

General Techno-Economic Analysis (TEA) Methodology

Process Model



Feedstock Composition

Operating Conditions

Conversion Yields

Flow Rates

Equipment Sizing/Costing and Raw Material Accounting

Cost

Minimum Selling Price (MSP)

$

Product Yield

kg or million Btu (Mbtu)

Approach:

- Design conceptual process include all major steps, core conversion, CO_2 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