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Implementing CO_2 capture and utilization at scale and speed

GLOBAL CO_2 INITIATIVE
UNIVERSITY OF MICHIGAN

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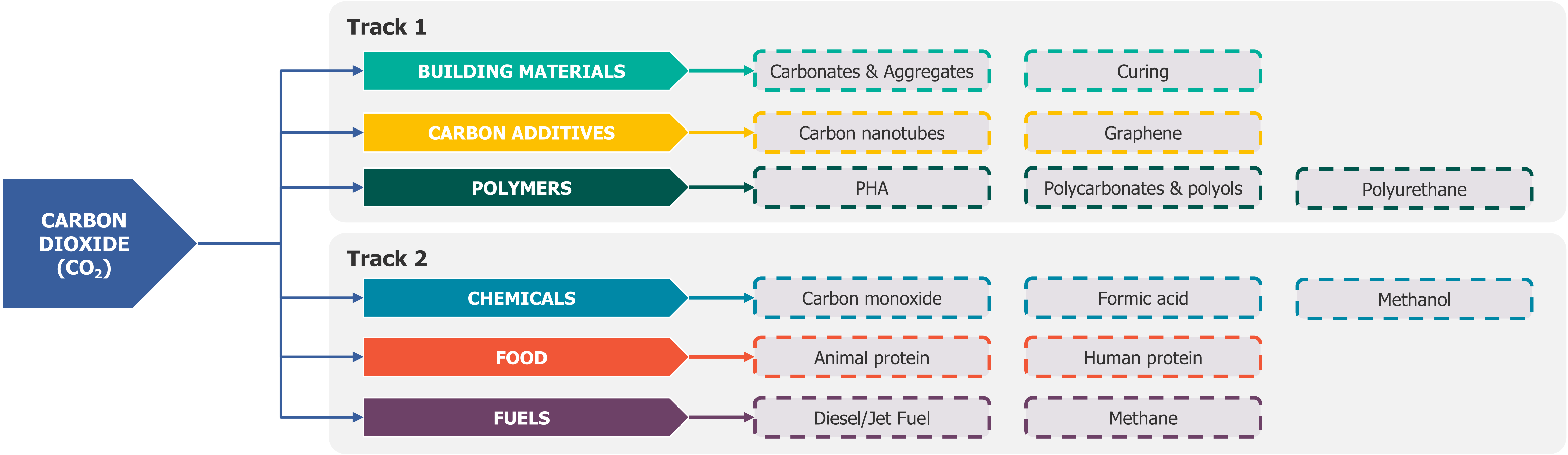
Table of Contents

Lux Research developed a taxonomy to segment the CCU landscape into Track 1 and Track 2 end products

Lux Research developed a taxonomy to capture the activity of the current CCU landscape based on six key target end products. Specific sub-products were identified within each end product based on a combination of primary research and desk research for priority target molecules. While numerous target molecules are possible from CCU technologies, the below taxonomy is assumed to represent the critical mass of the CCU landscape and with the highest potential to impact incumbent technologies, CO_2 abatement, and market adoption.

In addition, the CCU landscape is segmented into Track 1 and Track 2, as defined by the Global CO2 Initiative[1]. **Track 1 includes end products with the potential to remove CO_2 for more than 100 years** and are end products that have traditionally not used CO_2 as an input molecule. **Track 2 includes end products with the potential to remove CO_2 for less than 100 years** and are end products that require carbon content and typically have a shorter timeline before releasing CO_2 back into the atmosphere after use. Throughout this report, end products are grouped by Track 1 and Track 2.



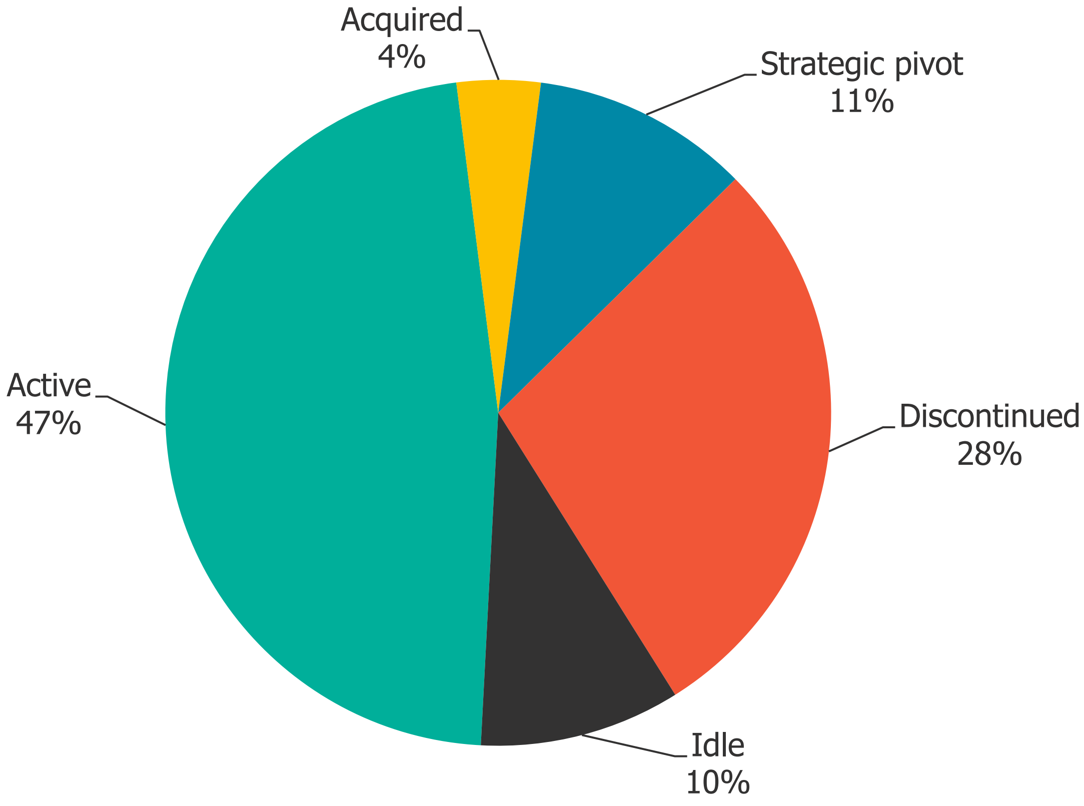
[1] Sick, Stokes, Mason, Frontiers in Climate – Negative Emissions Technologies, 2022 https://doi.org/10.3389/fclim.2022.878756

Only 47% of developers remain active in CCU technologies and development of CCU end products since 2016

In 2016 Lux Research identified 123 global developers who are actively engaged at the time in CCU technologies and development of CO_2-derived end products. These organizations include corporations, startups, and research institutes. In a review of the original developers, Lux Research found that:

- **Active (47%):** Leading startups identified in 2016 continue to make progress over the past five years and research institutes remain firmly committed to conducting early-stage R&D.
- **Acquired (4%):** Five startups were acquired during this time, including Liquid Light, Antecy, Skyonic Corporation, Novomer, and ETOGAS by fellow startups and corporations.
- **Strategic pivot (11%):** Developers either shifted away entirely from CCU, towards areas such as hydrogen, or have changed focuses on downstream products.
- **Discontinued (28%):** Several startups failed to make progress and founders have moved on to other ventures. Consortiums active at the time also concluded, though many individual members remain active in CCU.
- **Idle (10%):** Startups and research institutes make up the group of idle developers, with no public activity or recent research developments.

2021 Status of Developers Identified in 2016



New startups emerge despite major setbacks and failures since 2016 and academic activity reach all-time highs

As of 2021, Lux Research identified 160 developers active in CCU, with 94 new developers emerging since 2016. Of the new developers there are 11 corporations, 39 startups, and 44 research institutes.

- **Corporate R&D in CCU technologies remains modest despite growing interest.** Internal technology development remains minimal – or proprietary – as corporations have largely opted to partner, pilot, or license technologies developed by startups and research institutes.

- **Lower number of startups in 2021 should not be viewed as a sign of lost of momentum.** Despite a lower number of total startups in 2021, less than half of the startups in 2016 remain active today. The CCU startup ecosystem is becoming more mature with a higher rate of quality over quantity compared to the past.

- **Academic research in CCU continues to reach all-time highs.** Research groups focusing on CCU have doubled in the past five years highlighting both the early-stage technical developments still required and growing financial support for the space. Notably, several research institutes are targeting a wider range of CCU technologies than before.

Growing Interest in CCU Highlighted by Robust Ecosystem of CCU Developers in 2021

Number of developers

Figure for 2016 figures are reflective of all 123 developers identified in the 2016 study, including developers that have since been acquired, had a strategic pivot, discontinued, or gone idle.

The Americas and EMEA remain regional leaders as APAC ramped up activity in CCU over the past five years

The Americas and EMEA lead the global CCU ecosystem with 69 and 56 identified developers, respectively. APAC witnessed substantial growth in activity, more than tripling to 35 developers in 2021.

- **Nearly equal number of new developers emerging across the three regions.** Despite having the lowest number of total developers, the APAC region had 24 new developers emerge since 2016, matching the 34 of The Americas and 36 of EMEA.

- **Growing interest in APAC a key sign of global interest in CCU technologies.** The rising number of APAC developers is a key indicator of the potential opportunity of CCU on the global scale. Despite the overall lower activity compared to its regional peers, growing activity is expected to catch up in the coming years.

- **Despite half the developers in 2016 going inactive The Americas and EMEA continue to produce new developers.** In The Americas, 28 of its 60 developers were acquired, made a strategic pivot, discontinued, or went idle; similarly, 32 EMEA developers are no longer active in the CCU space. Yet, both regions continue to boast a robust ecosystem of developers the past five years.

CCU is a Global Interest as New Developers Emerge Across All Three Regions

Number of developers

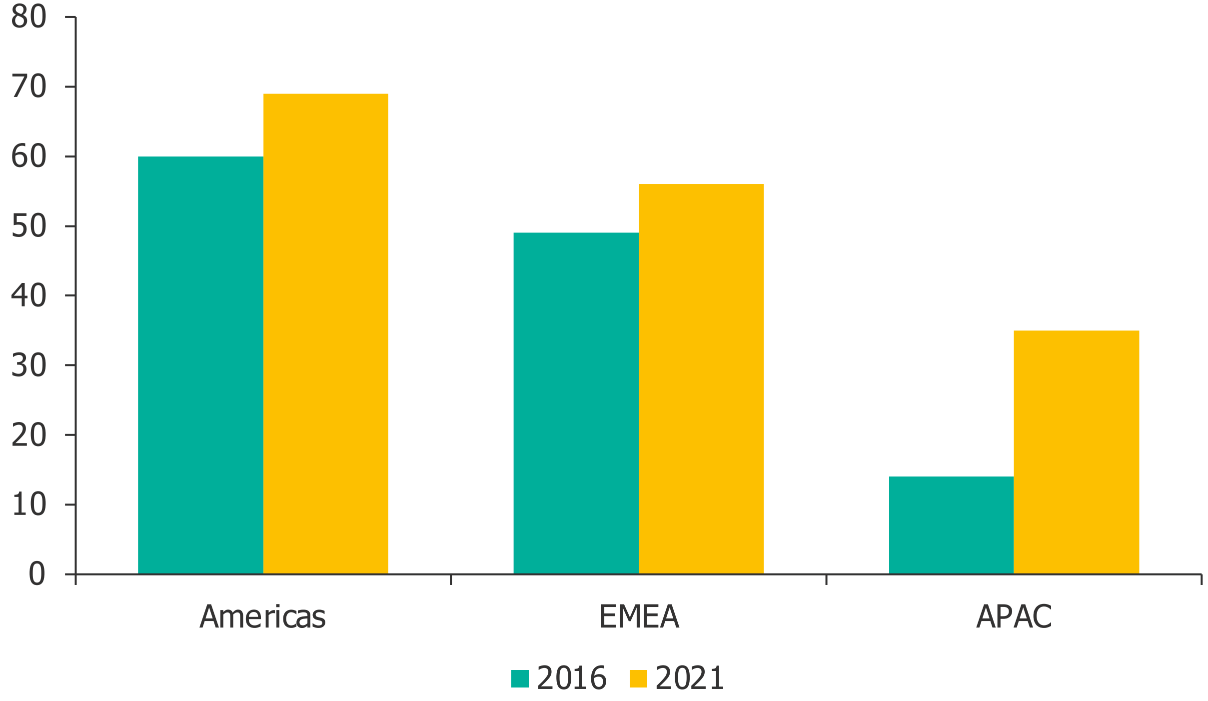


Figure for 2016 figures are reflective of all 123 developers identified in the 2016 study, including developers that have since been acquired, had a strategic pivot, discontinued, or gone idle.

Electrochemical conversion surpasses catalytic conversion and more than doubles in developers over the past five years

Technology pathways remained surprisingly flat over the past five years with only electrochemical witnessing significant changes.

- **Catalytic remains prominent across the CCU developer landscape.** 22 new developers emerged since 2016, offsetting an equal number that are now inactive.
- **Electrochemical becomes the leading technology of choice for CCU developers.** 42 new developers emerged since 2016, largely due to CCU developers looking to tap renewable electricity as its energy source.
- **Microbial developers remain minimal as past developers suffered major setbacks.** 9 new developers emerged since 2016, as scale-up challenges of biological processes forced developers into insolvency.
- **Mineralization remains steady as developers eye commercialization.** 14 new developers emerged since 2016, as both the technology matures, and commercial prospects begin to materialize.
- **Photocatalytic loses traction over the past five years.** Unlike other technology pathways, photocatalytic developers were unable to capitalize on the growing interest in CCU with only 4 new developers since 2016.

Electrochemical Pathways Emerge as the Clear Favorite of CCU Developers

Number of developers

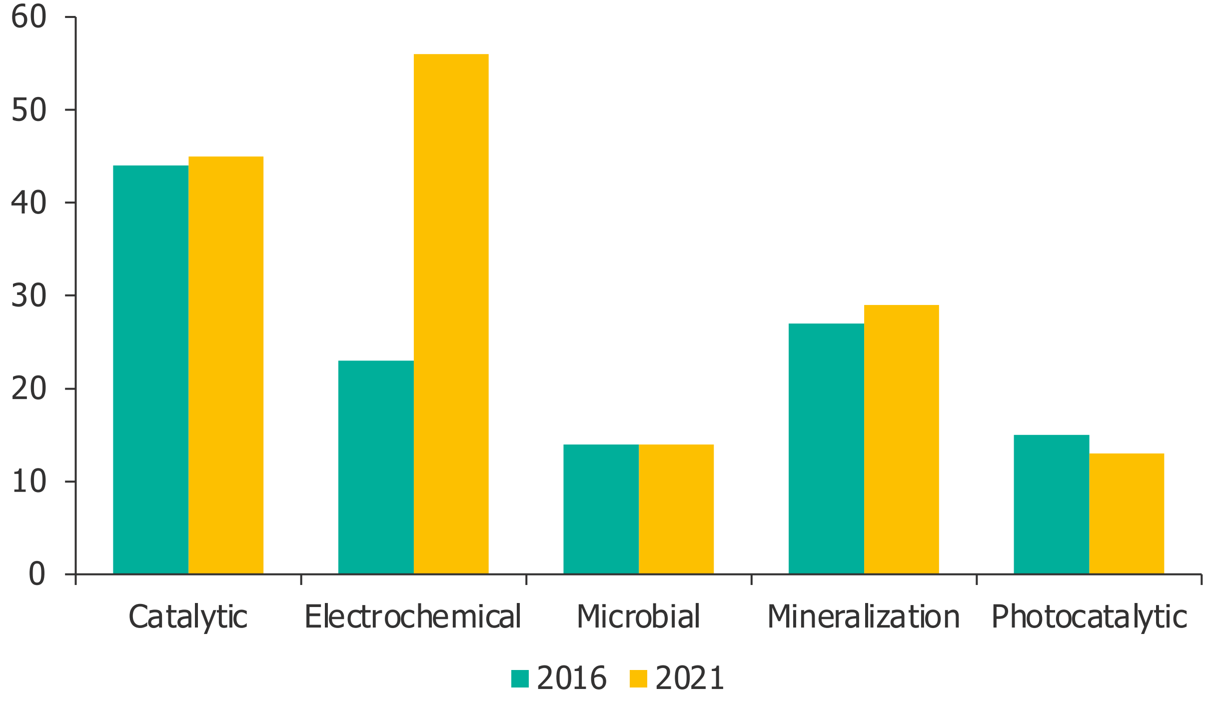


Figure for 2016 figures are reflective of all 123 developers identified in the 2016 study, including developers that have since been acquired, had a strategic pivot, discontinued, or gone idle.

Chemicals remains dominant as carbon additives, fuels, and food witness growing number of developers

Nearly all end products have more developers in 2021 compared to 2016, with chemicals leading the way with a total of 80 developers in 2021. Followed by buildings materials (30), fuels (26), polymers (11), food (8), and carbon additives (5).

- **Total number of building materials developers remains flat despite a flurry of new developers entering the space.** Since 2016, 14 new developers targeting building materials emerged making up for nine discontinued and idle developers, two that pivoted towards emissions removal, and one acquisition.
- **Despite being commercially deployed today, momentum has stalled for polymers.** Polymers remains the lone end-product with a lower number of developers in 2021 compared to 2016. The lack of new developers is likely due to the maturity of technology.
- **Developers targeting food end products witness major boom in developer activity.** While significantly lower in total number, 7 developers emerged since 2016 with the lone developer from 2016 pivoting away from chemicals and polymers to focus on proteins.

Chemicals Remains Dominant End Product for CCU Technology Developers

Number of developers

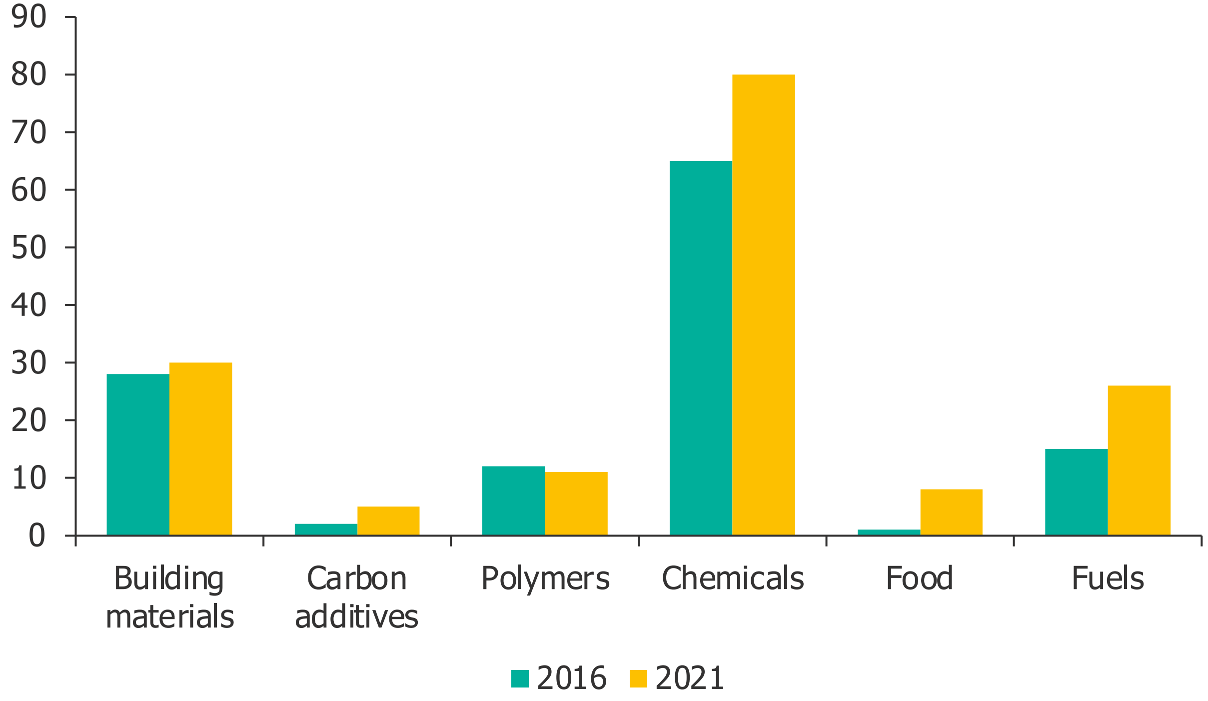


Figure for 2016 figures are reflective of all 123 developers identified in the 2016 study, including developers that have since been acquired, had a strategic pivot, discontinued, or gone idle.

Technology maturity does not guarantee commercial success as number of TRL 7 or higher developers fall since 2016

Developers working on early-stage technologies highlight the growth in the CCU landscape the past five years with 80 developers with TRL 3 or less technologies and 60 developers with TRL 4-6 technologies. The number of developers for both TRL 7 or higher decreased during the same period.

- **Boom in early-stage developers a strong sign for the CCU landscape.** 47 new developers with TRL 3 or less technologies and 39 new developers with TRL 4-6 technologies emerged since 2016. Given the developer landscape for higher TRL technologies, the significant increase for early-stage technologies in the past five years is a strong indicator of innovation interest and prospects for technology scale-up in the mid- to long-term.
- **The industry did not witness a significant transition of early-stage technologies into demonstration and commercial-scale projects.** With 8 and 14 TRL 7-8 and TRL 9 developers in 2016, respectively, the number of active developers in 2021 decreased. While several projects were announced during this time period, many have yet to begin operations. Since 2016, three TRL 9 developers were acquired with their technology rolled into corporate portfolios, three have discontinued operations, and one remains idle – highlighting that technology readiness does not guarantee market readiness.

Rising Number of Early-Stage Developers Will Likely Feed the Commercialization Pipeline

Number of developers

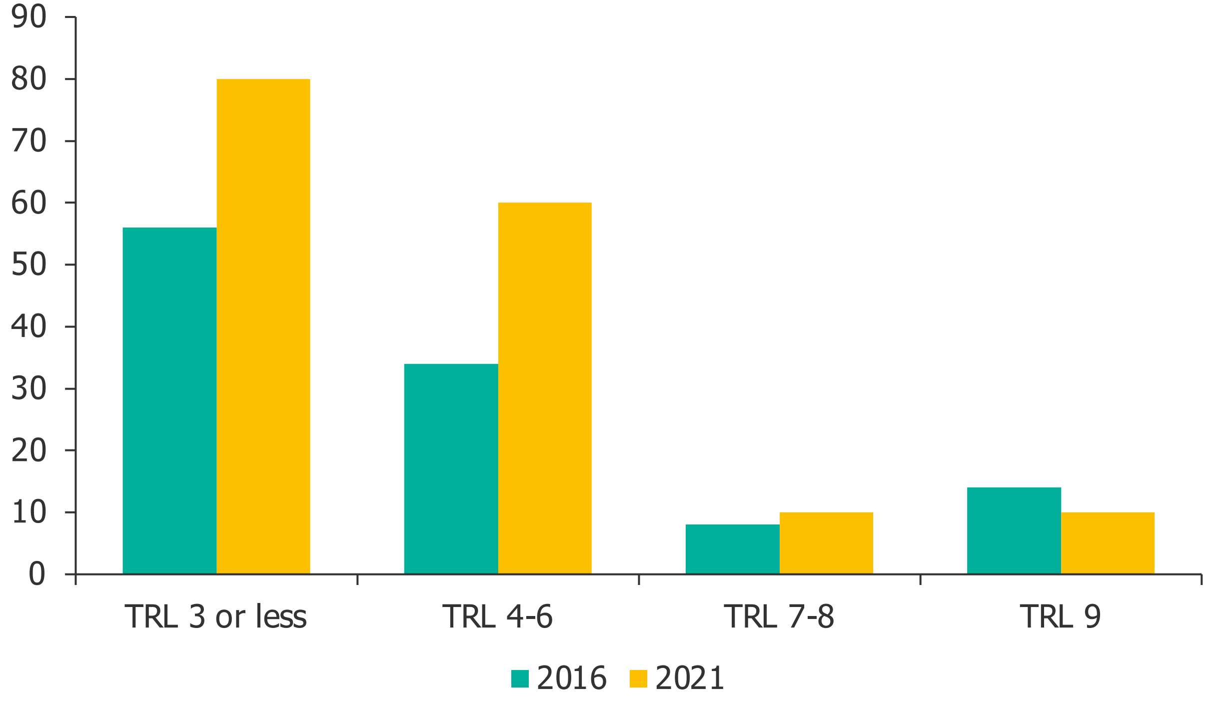


Figure for 2016 figures are reflective of all 123 developers identified in the 2016 study, including developers that have since been acquired, had a strategic pivot, discontinued, or gone idle.

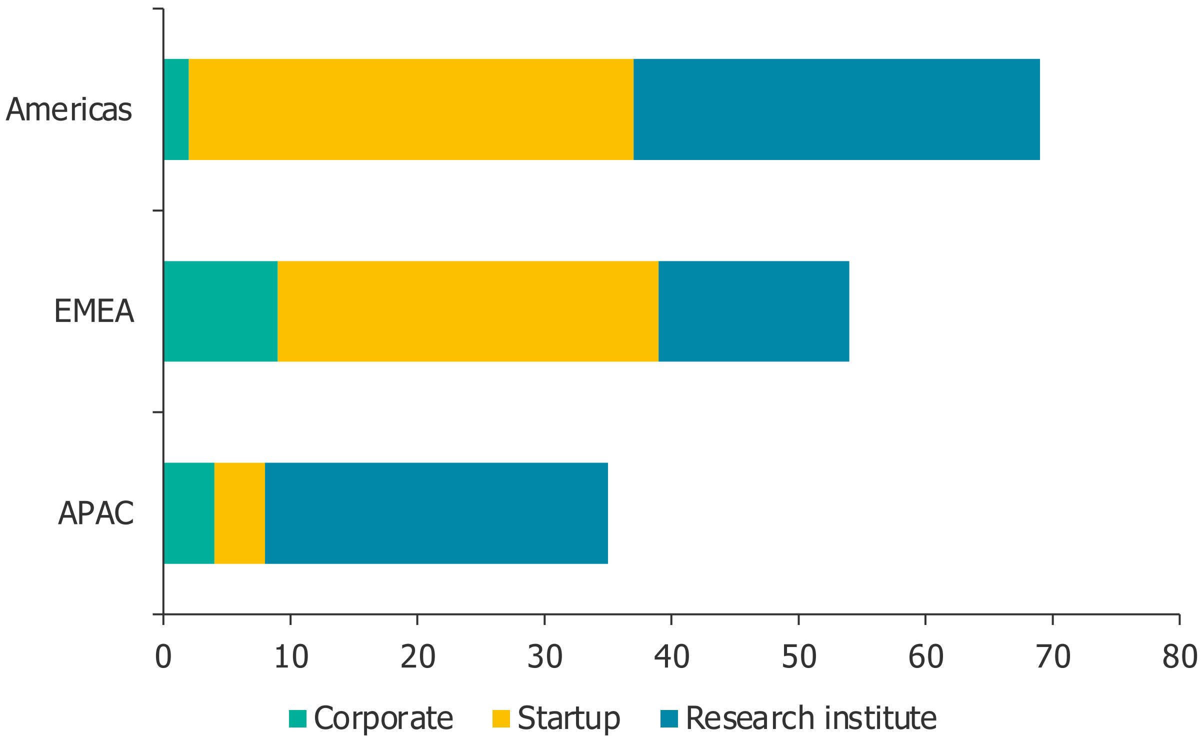
Agenda

Startups are heavily concentrated within The Americas and EMEA as APAC activity relies on research institutes

Of the 160 developers actively engaged in CCU technologies and developing CO_2-derived end products, 69 are based in The Americas, 56 in EMEA, and 35 in APAC.

- **The Americas continues to be the global epicenter for startup activity.** Specifically, the U.S. is home to 35 startups and hosts an equal amount of research institutes (32). Corporate technology development remains minimal, with corporations opting to directly partner with startups and research institutes instead.
- **Corporate activity heavily concentrated in EMEA.** Of the 15 total corporations, 9 are based in EMEA. This distribution is representative of EMEA's leadership role in corporate-led CCU technology development and is also highlighted by the two active consortiums identified based in The Netherlands and Germany. Germany leads all countries in EMEA with 12 total developers.
- **The APAC startup ecosystem remains in its infancy.** 27 of developers in the APAC region are research institutes, reflective of the overall innovation ecosystem of the region. While direct translation of academic research into corporate R&D portfolios remains the conventional route of technology commercialization in the region, an emergence of a CCU startup ecosystem is worth monitoring.

Distinct Innovation Strategies Highlighted by Distribution of Developer Types in Each Region

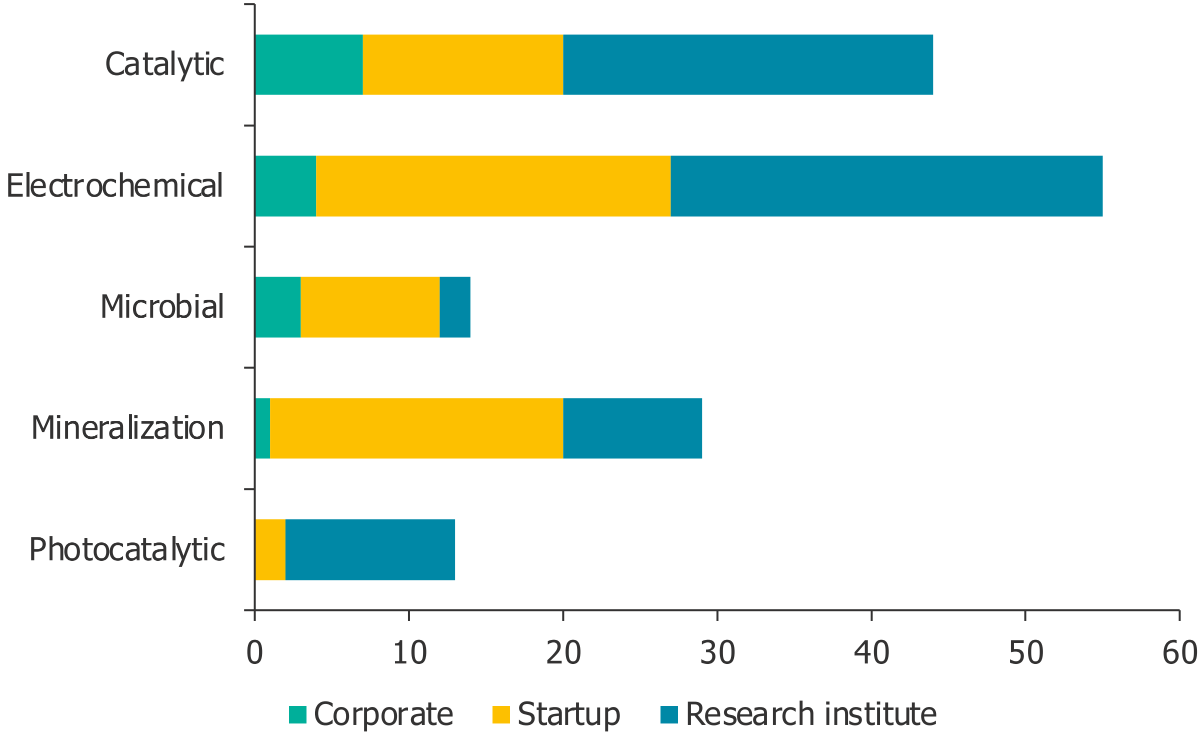


Electrochemical developers surpassed catalytic with the highest number of research institutes and startups

Electrochemical (56) and catalytic (45) pathways dominate the CCU landscape with mineralization (29), microbial (14), and photocatalytic (13) making up the balance.

- **Corporate developers are concentrated in catalytic technologies.** 50% (7) of all corporations are developing catalytic technologies.
- **Electrochemical surpassed catalytic as the technology of choice for the CCU landscape.** Ballooned by 42 new developers, electrochemical became the leading technology with the highest number of research institutes (28) and startups (23).
- **Emergence of developers targeting food end products provided boost to microbial technologies.** Despite having less than one-third of the developers of catalytic technologies, there is nearly an equal number (9) of startups pursuing microbial technologies.
- **Mineralization is heavily pursued by startups compared to other technologies.** Mineralization has the highest concentration of startups (19, 66%) with 6 new developers. Research institutes also witnessed growing activity with 7 new developers.
- **Photocatalytic remains an area solely pursued by research institutes.** While there are 2 startups continuing to develop photocatalytic solutions, new developers emerged in research institutes as the technology still requires significant fundamental R&D.

Electrochemical Leads Technology Pathway for All Developer Types

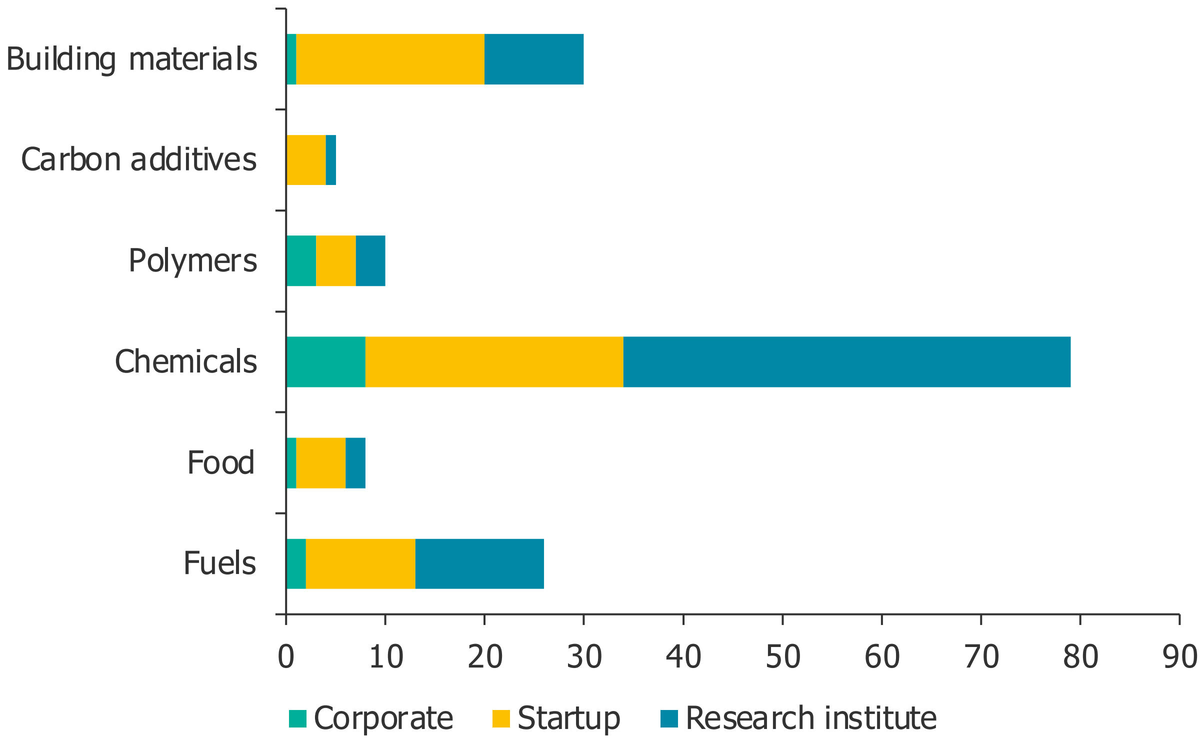


Developers favor chemicals with both high overall activity and distribution across the innovation spectrum

Chemicals makes up over half of the current CCU landscape with 80 developers. Followed by building materials (30), fuels (26), polymers (11), food (8), and carbon additives (5).

- **Prominent startup ecosystem for building materials as developers strive to scale-up technology.** 19 startups, second-highest, signal maturing technology space as research institute activity remains modest with 10 developers.
- **Carbon additives remain niche focus area for CCU developers.** Minimal activity with 4 startups and 1 research institute.
- **Landscape of chemicals represented by all developer types highlights growing interest.** With the largest number of developers, high activity is consistent across all organization types.
- **Fuels development gaining traction due to large addressable market.** 2 corporates, 11 startups, 13 research institutes make up a growing landscape targeting fuels.
- **Equal representation of developer types for polymers may be sign of stalled momentum.** Polymers are the only end product without a distinct trend towards a developer type as activity remains stagnant.
- **Emerging interest in food production leading to growing startup ecosystem.** A surge of 5 new startups entered the landscape despite only emerging in recent years.

Developers Targeting Chemicals Dwarf Other End Products in the CCU Landscape

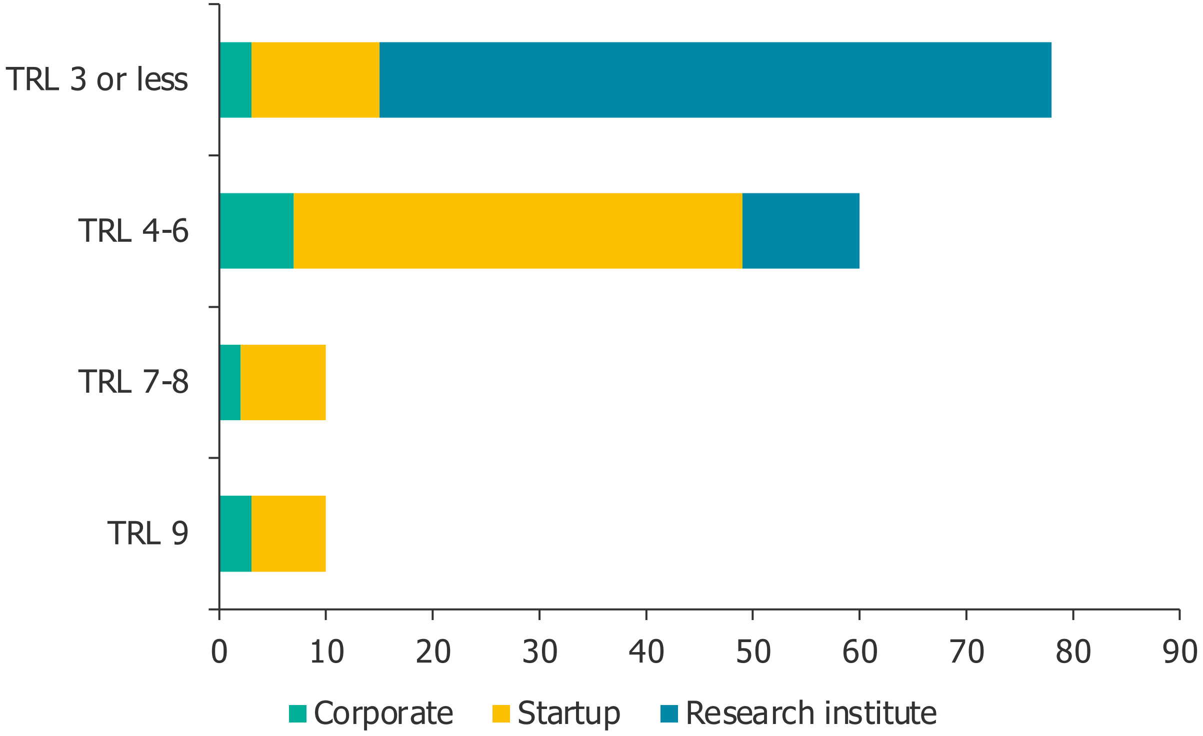


Robust pipeline of startups in the CCU landscape must overcome the innovation valley of death

Early-stage developers establishing a foundation for CCU technology with 80 developers with TRL 3 or less technologies. 60 are currently at lab-scale and pilot-scale (TRL 4-6), 10 at demonstration-scale (TRL 7-8), and 10 at commercial-scale (TRL 9).

- **Strong foundation of early-stage technology developers bodes well as the technology and market for CCU technologies evolve.** 63 research institutes, 85% of all research institutes, are active in TRL 3 or less technologies. The growing base of novel technologies will be instrumental in the evolution of the CCU landscape.
- **Robust pipeline of startups in lab-scale and pilot-scale face upcoming challenges.** TRL 4-6 is aptly named the innovation valley of death as developers fail to break beyond pilot-scale. Startups with TRL 4-6 make up 61% (42) of all startups highlighting both the rate of spinouts from research institutes and the challenges of overcoming the technical challenges of scale-up.
- **Startups that overcame the innovation valley of death are set to reach commercial-scale in coming years.** Upon reaching TRL 7-8, the transition to commercial-scale production for the 8 startups are still daunting, but not insurmountable.
- **Commercial-scale developers must validate their value proposition in the market.** Both corporations (3) and startups (7 at TRL 9 have overcame technical challenges and must focus on commercial success.

Pipeline of Research Institutes Well-Positioned to Feed the CCU Innovation Funnel



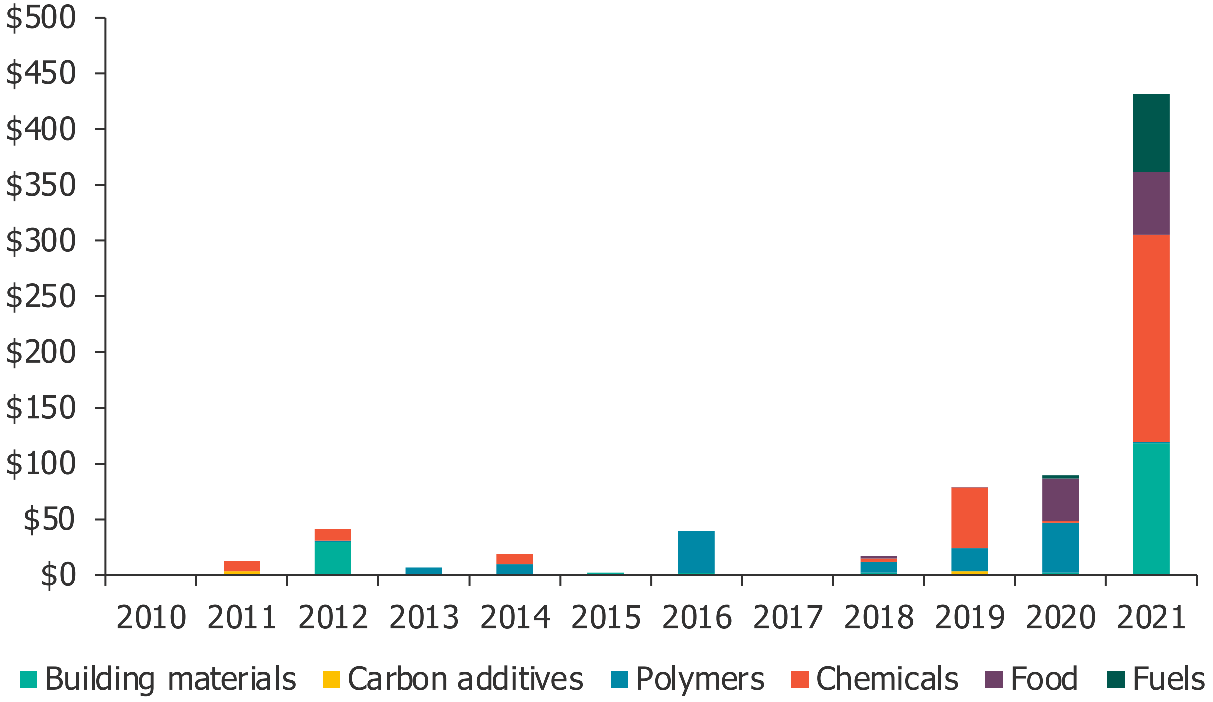
Venture Capital funding for CCU is getting increasingly diversified by end product as investments surpass US$430 million in 2021

Venture capital (VC) funding has emerged as a key metric to measure momentum in the CCU landscape. Outside of funding rounds by Solidia Technologies and CarbonCure in 2012, VC activity was strongly lacking pre-2016. Investments are keeping pace with the rising number of CCU startups, having increased nine-times by dollar-value since then.

- **Diversification of VC funding bodes well for the CCU landscape.** Since 2018, funding is being directed towards a variety of end products with all end products raising funding. The diversification is also an indication of the growing maturity of various technologies that were likely considered too nascent pre-2016.
- **Chemicals and building materials startups combine to raise US$367 million in funding since 2016.** The total funding makes up 67% of all VC investments during the time period. However, most notably is the emergence of food startups that were largely non-existent prior to 2018. Startups such as NovoNutrients, Air Protein, and Solar Foods have combined to raise US$48 million in 2021 alone.
- **VC funding will determine leaders and laggards in the CCU landscape.** As more startups enter the CCU landscape over the next decade, VC funding will be a key metric in identifying startups with the potential to provide cost-effect solutions at scale and weed out startups unable to keep up with the growing competition. Though, it is important to note that not all startups receiving funding, such as Air Co, are automatically deemed noteworthy.

Venture Capital Emerges as a Key Metric to Measure CCU Momentum

US$ million



VC funding rounds continue to grow as single deals in past two years dwarf the annual VC activity pre-2016

sunfire

Sunfire (Chemicals): CO_2 to syngas
Latest funding round: Oct. 2021 Series D; US$ 126M
Investor(s): Planet First Partners, HydrogenOne Capital

INFINIUM

Infinium (Fuels): CO_2 to jet fuel
Latest funding round: Oct. 2021 Series F; US$ 69M
Investor(s): Amazon, Mitsubishi Heavy Industries, NextEra Energy

NEWLIGHT

Newlight Technologies (Polymers): CO_2 to PHA
Latest funding round: Mar. 2020 Series F; US$ 45.1M
Investor(s): Valedor Partners

SOLIDIA

Solidia Technologies (Building materials): CO_2 to concrete
Latest funding round: Apr. 2021; US$78 M
Investor(s): Prelude Ventures, OGCI, BP, Piva

twelve

Twelve (Chemicals): CO_2 to CO and other chemicals
Latest funding round: Jul. 2021 Series A; US$ 57M
Investor(s): Munich Re Ventures, Microsoft, Evok Innovations, Breakout Ventures

Note: Above are the top five largest single VC funding rounds since 2016

Startup	Founded	Total VC funding raised (US$ million)
Sunfire	2010	171
Newlight Technologies	2003	106.6
Solidia Technologies	2008	105
Infinium	2020*	69
Twelve	2015	68
Solar Foods	2017	40.8
Air Protein	2019	32
Fortera	2019**	30
Econic Technologies	2011	23.7
Recarbon	2011	12
CarbonCure Technologies	2007	11.24
Deep Branch Biotechnology	2018	11
CarbonBuilt	2020	10
NewCO2Fuels	2011	9
Air Company	2017	8.5

*Likely using technology developed by GreyRock founded in 2006
**Formerly Calera Corporation founded in 2009

Growing academic activity is indicative of efforts underway to develop different CCU pathways

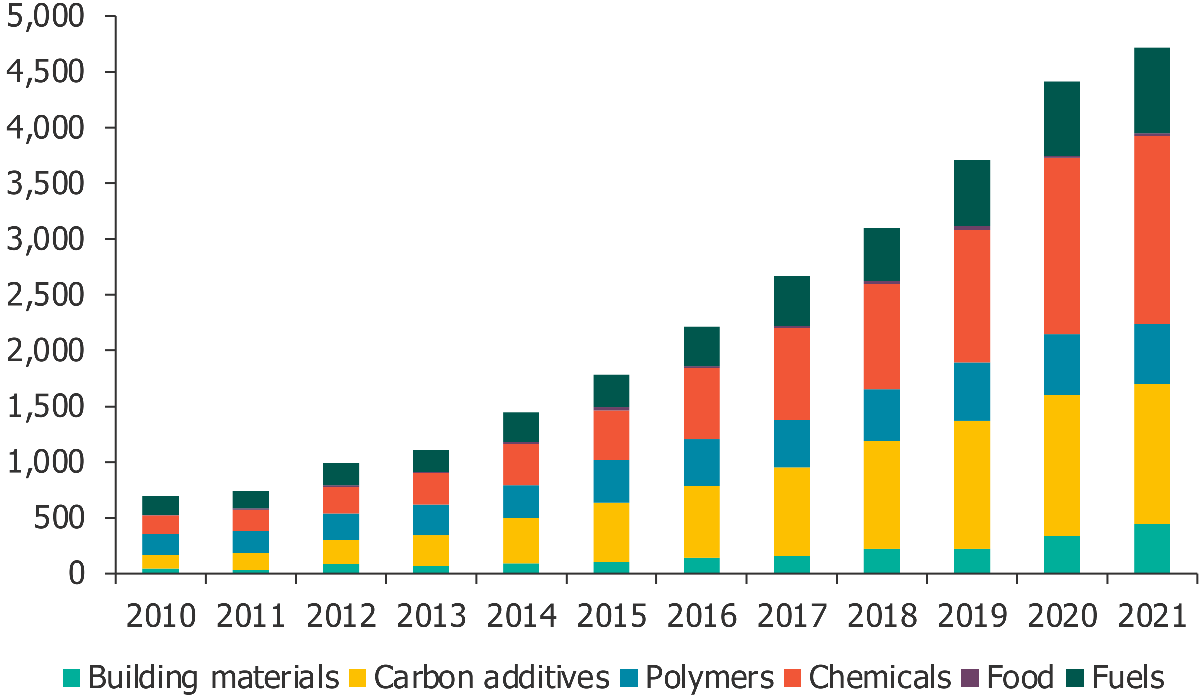
Academic activity in CO_2 utilization shows expediting growth over the last decade, with 2021 doubling the number of publications compared to 2016.

- **Chinese research institutes lead CCU academic publications by volume.** Chinese Academy of Sciences, Tianjin University, and Tsinghua University published approximately 2,500 publications since 2017 spanning multiple end products. The high number of publications are reflected in carbon additives, indicating China's sustained interest in carbon nanomaterials.
- **Building materials and chemicals show strongest momentum.** Between 2016 and 2020, the number of publications pertinent to the two end products have increased 2.3-times and 2.5-times, respectively.
- **Collaborations between national laboratories and universities are growing.** Federal funding for CCU is reflected in national laboratories, such as Lawrence Berkeley National Laboratory, collaborating on projects with various university groups, such as California Institute of Technology and University of California, Berkeley, to advance maturity of early-stage technologies.

Building materials and polymers are currently the only two commercially produced CCU end products, but growing activity in chemicals and fuels could represent the next wave of opportunity.

Expediting Growth in Academic Publications Highlight Growing Ecosystem for CCU

Number of academic publications



Three out of five most cited academic publications investigate novel electrochemical processes

Chinese Academy of Sciences; Buxing Han et. al 2020. Boosting CO_2 electroreduction on N,P-Co-doped carbon aerogels

Tianjin University; Jun Luo et. al 2017. Efficient and stable electroreduction of CO_2 to CH_4 on CuS nanosheet arrays

UCLA; Gaurav Sant et. al 2020. The role of gas flow distributions on CO_2 mineralization within monolithic cemented composites

Nanyang Technological University; Xin Wang et. al 2021. Enlarging the pi-conjugation of cobalt porphyrin for selective CO_2 electroreduction

Lawrence Berkeley National Laboratory; Daniel Miller et. al 2019. Preparation and characterization of crosslinked anion exchange membranes for artificial photosynthesis

Research Institute	Number of publications (2017-2021)
Chinese Academy of Sciences	1,951
Tianjin University	305
University of Science & Technology China	295
University of California system	235
Tsinghua University	216
Beijing University of Chemical Technology	183
Dalian University	351
Nanyang Technological University	322
University of Toronto	156
Korea Advanced Institute of Science & Technology	130
Lawrence Berkeley National Laboratory	127
Stanford University	116
Fudan University	115
Brookhaven National Laboratory	107
Wuhan University of Technology	102

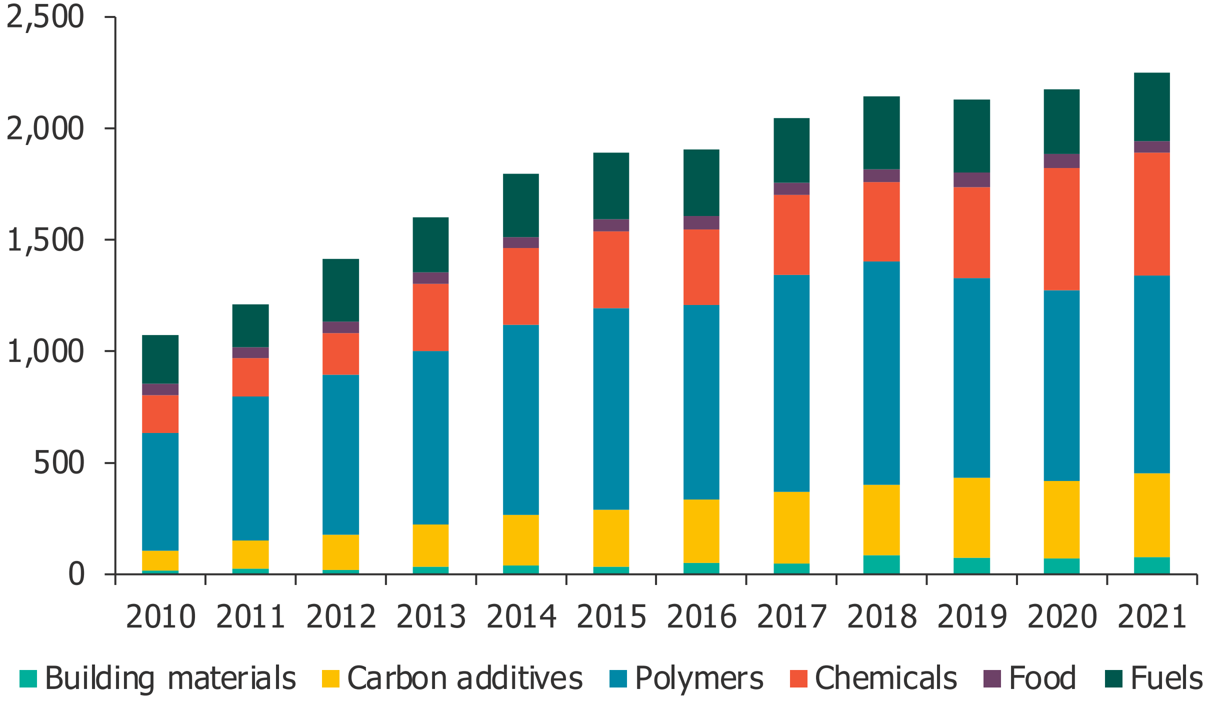
Note: Above are the top five most cited academic publications published since 2016

Patent activity shows a modest growth, with a large number of applications coming in for chemicals and polymers

Since 2016, patent publications continue to grow at a rate of 3% to 5% per year, with 2021 marking peak activity with 2,251 patents (71% applications and 29% grants).

- **Patent applications come from both corporations and academia.** Corporations involved with polymers, such as Covestro, and those actively engaged in multiple parts of the CCU value chain, such as SINOPEC and Linde, are key patent filers. Though they are challenged by Chinese research institutes in terms of total number of filings.
- **Solidia Technologies is a pioneering startup for patent activity.** The United States based startup currently holds 38 patents for its CO_2-to-concrete technology, the most of any single organization developing a CCU technology for building materials.
- **Building materials and chemicals companies have the fastest growing patent activity.** The two segments report growths of 35% and 59%, respectively, between 2016 and 2020 likely due to the end products having the highest number of developers compared to other end products. In terms of patent applications, both are witnessing an approximately two to three times higher number compared to grants, indicating strong innovation and commercialization activity. It is important to note that while building materials patent activity grew the fast during this time period, it has the second lowest total number of patent publications.

Patent Activity a Potential Leading Indicator of Upcoming Commercialization Activity
Number of patent publications



Chemicals and polymers dominate the patent portfolio of the most active patent filers since 2016

Covestro (189 patents): Synthetic or electrochemical pathways to produce polyols, polyurethanes, and other chemicals

SINOPEC (96 patents): Carbon dioxide methanation and electrochemical reduction of carbon dioxide

Siemens (76 patents): Electrolyzer and adsorbent technology for reduction of CO_2; catalytic methanation of CO_2

Haldor Topsoe (72 patents): Solid oxide electrolysis cells to produce carbon monoxide and syngas

BASF (63 patents): Catalysts for the methanation of CO_2 and other polymerization reactions

Organization	Number of patents (2017-2021)
Covestro	189
China Petroleum & Chemical (SINOPEC)	96
Siemens	76
Haldor Topsoe	72
BASF	63
Invista	60
Saudi Arabian Oil Company (Saudi Aramco)	50
Solidia Technologies	38
Dow Global	36
Toshiba	36
Saudi Basic Industries (SABIC)	33
Arkema	29
Avantium International	24
LG	28
Linde	23

Research institutes excluded in the above list

Note: Above are the top five patent filers since 2016

Agenda

CCU End Product Assessment
Track 1: Building materials, carbon additives, and polymers

Building Materials

Aggregates and curing are a strong near-term opportunity for CCU with low technical hurdles

TECHNOLOGY OVERVIEW

- CO_2 for building materials has two main applications: using CO_2 as a curing agent or chemically reacting CO_2 with minerals – mostly calcium and magnesium salts – to form aggregates required for concrete and asphalt production.
- Curing cement with CO_2 instead of water reportedly reduces emissions by 40% and brings down cement strengthening time from 28 days to < 24 hours.
- While conversion of CO_2 to most end products require high energy inputs, building material pathways do not pose thermodynamic constraints, allowing energy savings
- The process also results in lower overall emissions from cement production, with CO_2 permanently consumed and not re-emitted.

CHALLENGES AND PROSPECTS

- Building materials is currently the most mature market for non-EOR CCU and has the potential to utilize up to 7.3 Gt of CO_2 annually in the best-case scenario in 2050.
- Regulatory standards and prescriptions governing concrete are a challenge for widespread adoption of CO_2-based concrete, but both curing and aggregates remain near-term opportunities for CCU.
- In addition to adequate regulatory incentives, higher cost of CO_2-based aggregates – on average US$50/tonne compared to as low as US$10/tonne for incumbents – also hinder commercialization.

Number of Developers, Building Materials

Technology	Aggregates	Precast concrete
Technology maturity	Scale	Scale
Average developer TRL	5	5
CO_2 consumption (tCO_2/tonne product)	0.087 to 0.44	0.001 to 0.05
Market size, best case (2050)	US$337 billion	US$666 billion
CO_2 utilization potential, best case (annual Gt)	7.3	1.3
Cost tipping point, best case (year)	2031	2027

Note: The market size for aggregates and precast concrete are not mutually exclusive with anywhere between 18% to 24% of total aggregates used in precast concrete production.

Startups and research institutes lead activity in building materials as corporates largely play commercial deployment role

COMMERCIAL INTEREST

- Leading non-academic patent filers include Solidia Technologies (38), CarbonCure Technologies (9), Denka (7), and Holcim (4).
- In September 2021, Saudi Aramco published a patent describing a diffusion process to form a CO_2-adsorbed aggregate material for carbonated concrete mixtures.
- Cement manufacturing, being a mature and relatively linear technology, is responsible for limited growth in patents in recent years, but leading startups in the space are aggressively publishing patents relative to corporates.

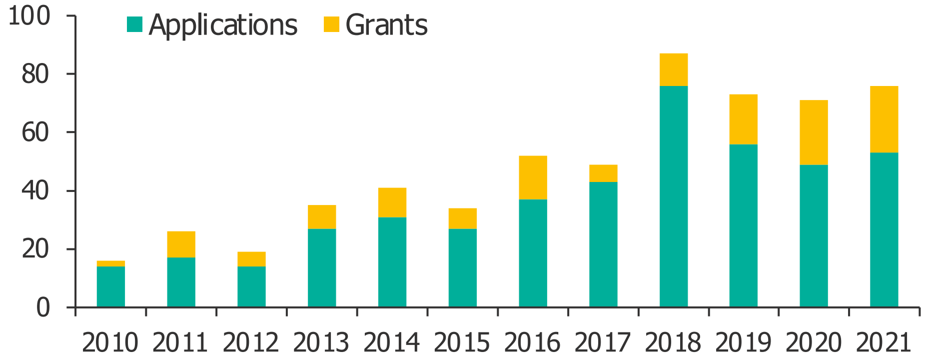
R&D INITIATIVES

- Leading academic institutes include Hunan University, Nanyang Technological University, McGill University, Hong Kong Polytechnic University, and University of Michigan.
- Earlier this year, researchers from McGill university published a paper on using carbonation curing to improve concrete resistance to low temperature sulfate attacks.
- Academic spin-offs are making a mark in building materials. Most recently, CarbonBuilt, a 2020 spin-off from UCLA, began work to develop a concrete mixture with lower cement content, thereby reducing raw material costs by 10% to 30%.

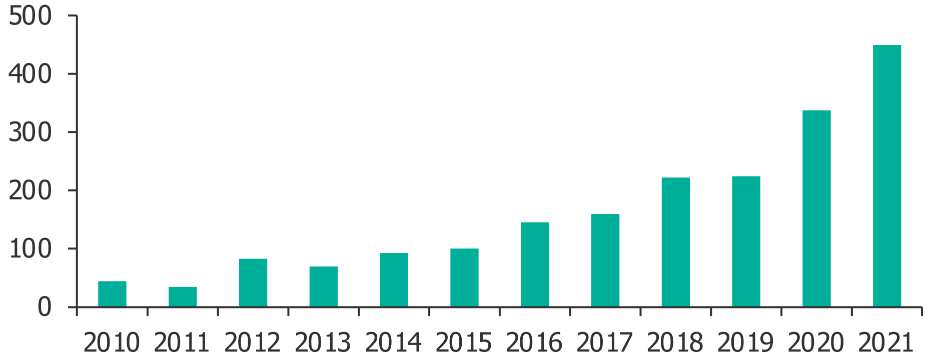
LUX TAKE

Novel processes are rapidly transitioning from research-level efforts to pilots and commercialization. The industry should expect continued growth as entities work on reducing the cost gap with incumbents and deploying technologies at scale.

Building Materials Patent Activity
Number of patent publications



Building Materials Academic Publications
Number of academic publications



Leading startups are raising funds to establish a stronger commercial presence and bring online additional projects

NOTABLE INVESTMENTS

- VC funding for building materials has been sporadic but present since 2011, given that the segment is the most mature CCU end product.
- 2021 witnessed a tremendous spike in funding, with just three companies securing US$118M – Solidia (US$78M), Fortera (US$30M), and CarbonBuilt (US$10M).
- Less than 30% of startups active in building materials raised VC funding in the last five years. The emerging trend of a few startups raising large capital hints at the market being able to deliver optimized technology over the next decade.

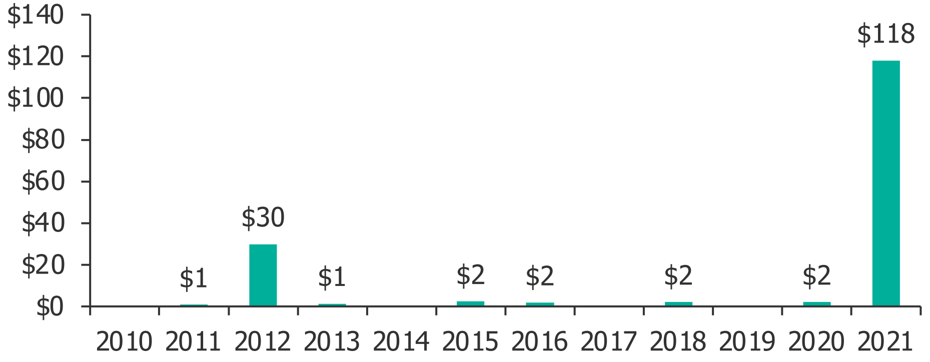
KEY DEVELOPMENTS

- VC funding is mostly directed towards commercialization plans.
- In early 2021, CarbonBuilt completed a demonstration that used CO_2 from coal and natural gas power plants to produce 5,000 concrete blocks. The company plans to use its recent Series A funding to develop its first commercial project.
- Fortera plans to use funds raised from its recent Series B to build its first commercial plant in California. The company expects to sell its CO_2-based cement in Q2 2022.

LUX TAKE

The notable funding in 2021 shows that building materials are an attractive end product for CCU. However, trends also point out that not all start-ups will meet success because of industry interest – VC funding will continue to be selective.

Building Materials VC Funding
US$ million



SOLIDIA
Total disclosed funding: US$105M
Investors: Imperative Ventures, Prelude Ventures, BASF, BP Ventures, OGCI

FORTERA
Total disclosed funding: US$30M
Investors: Temasek Holdings, Khosla Ventures

CARBON CURE
Total disclosed funding: US$11.2M
Investors: Breakthrough Energy Ventures, BDC Venture Capital

Lux Research

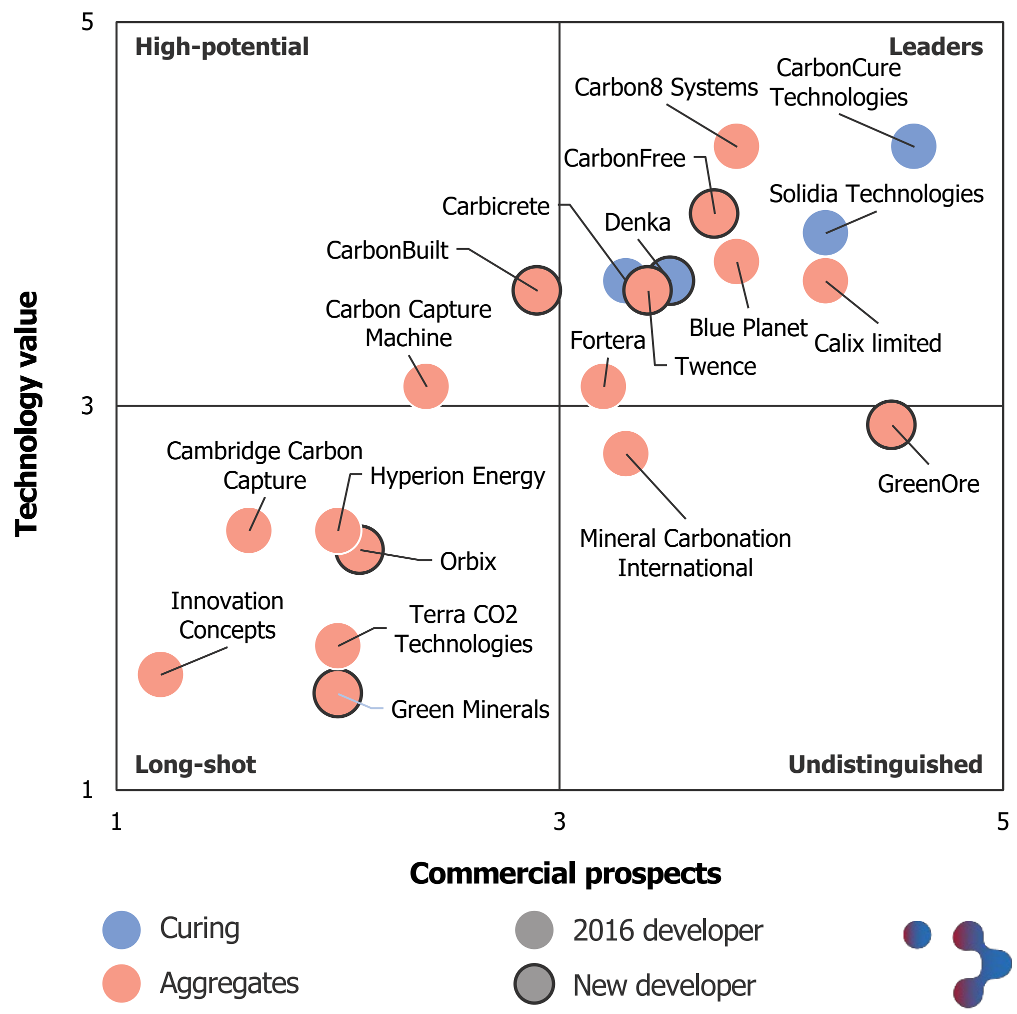
The landscape for building materials is maturing with leaders separating themselves from the pack

DEVELOPER LANDSCAPE

- Notably the developer landscape for building materials is beginning to segregate with leaders separating themselves from the pack with growing commercial momentum, while laggards have failed to gain traction in recent years.
- In total seven new developers emerged since 2016, with five immediately falling within or near the "Leaders" quadrant, a strong sign of near commercialization for building materials and low technical barrier-to-entry for both curing and aggregates processes.

MARKET DYNAMICS

- All developers targeting curing technologies are firmly positioned in the "Leaders" quadrant highlighting the value proposition of the performance benefits of shorter curing times and, in some cases, stronger final concrete products.
- With existing and upcoming demonstration and commercial-scale projects, differentiation amongst leading developers may rely entirely forming strong strategic corporate partnerships and potentially introducing novel business models to enhance relatively comparable technological offerings.



CarbonCure and Carbon8 have established themselves as leaders in the building materials space

CARBON CURE™

- The company was founded in 2007 and develops a proprietary concrete curing process by injecting CO_2 into the wet concrete mix to form nanoscale $CaCO_3$ minerals.
- To date the company has raised about US$12 million in venture capital funding, but future success will rely more on commercial partnerships.
- Key claims of the organization include enhancing compressive strength of Portland cement concrete (PCC) by 10% to 20% and a reduction of up to 10% in cement content and up to 60 liters of water per square meter of concrete.
- In terms of maturity, the company is at scale with its technology deployed at nearly 300 cement plants for 165 customers.
- Global CO_2 Initiative should consider CarbonCure a global leader in CO_2 curing with a drop-in technology for the cement industry; the progression of CO_2 curing will be dictated by CarbonCure's success

Carbon8®

- The company was founded in 2006 and develops its Accelerated Carbonation Technology (ACT) for producing aggregates under ambient temperatures.
- To date the company has raised about US$3.5 million from a private investor and is currently raising a US$7 million Series A round.
- Key claims of the organization include differentiation from incumbent processes with a 15-minute treatment time and lack of need for high temperature or pressure.
- In terms of maturity, the company is at scale and operates four commercial-scale facilities in the United Kingdom, Canada, and France.
- Global CO_2 Initiative should view Carbon8's licensing and leasing business model as a differentiator in the aggregate market; removing upfront capital costs by leasing equipment on a ten-year period directly to customers.

LUX TAKE

The building materials developer landscape is now about identifying winners and losers. With comparable technologies, growth potential for leading developers will rely on forming strategic partnerships, offering novel business models, and establishing a sufficient supply chain to meet the needs for widespread deployment.

Challenges for the industry center more around market and policy than technology-centric factors

Key Barriers and Risks	Means to Mitigate*
Technology barriers Low technology barriers, but addressing the trade-off between premium pricing of "green" CO_2-based building materials and lack of sufficient performance benefits relative to incumbents poses hurdles for adoption	• Optimizing the processing and production of CO_2-based concrete to **imbibe material performance enhancement** characteristics • Identifying novel CO_2-to-concrete conversion pathways
Policy and regulation barriers Currently, most standards for cement and concrete are tied a 28-day strength test compliance. Cement replacements, which include CO_2-based building materials, extend the set timeline. This delay plays unfavorably with conservative governing bodies that are resistant to adopting new protocols that take 2-3X longer. This challenge stands in addition to age-old lack of regulatory incentives	• **Accelerating testing processes** and establishing proof of performance for CO_2-to-concrete end products at early stages of the production process • Innovative business models and partnerships that allow CO2-to-concrete developers to leverage credits offered by the **U.S. 45Q incentive**
Supply chain and logistics barriers Accounting for CO_2 supply shortages increases dependence on carbon capture infrastructure	• Adopting technologies that **provide ownership of CO_2 feedstocks** • Deploying **modular technologies** that can be scaled up by increments based on production

* Examples of key developments pertinent to mitigation are listed on the next slide

Technology development and adoption will have to cope with increasingly stringent policies in cement industry

KEY TECHNOLOGY ACTIVITY

- **University of Alabama (United States):** Exploratory efforts on using a novel pre-carbonation technique – using gaseous CO_2 directly into concrete (OPC) slurries instead of diffusing CO_2 into precast concrete – to improve compression strength.
- **University of Toronto (Canada):** By increasing the concrete temperature, the group aims to allow the material to exhibit properties by day 28, that would normally be expressed only on day 90 – thereby passing regulatory standards.
- **A*STAR Institute of Chemical and Engineering Services (Singapore):** Has a patented integrated system for CO_2 capture and immediate subsequent conversion to aggregates. Integrated capture and utilization technologies create scope for CCU companies to benefit from 45Q credits.
- **Calix (Australia):** Novel high-CAPEX, high impact technology for cement decarbonization. Company's technology collects CO_2 from the cement calcination process, thereby addressing significant sources of CO_2.

KEY MARKET ACTIVITY

- **Global Cement and Concrete Association (United Kingdom):** The GCCA, which represents approx. 80% of the cement industry outside China, committed to carbon neutrality without relying on carbon offsets. The first step of the plan is reducing emissions by 50% by 2030.
- **California Air and Resource Board (United States):** In September 2021, California passed the nation's first Cement Decarbonization legislation, requiring the CARB to develop a strategy for cement manufacturing to reach net-zero emissions by 2045. The legislation takes effect from January 2022 and interim targets include a 40% emission reduction compared to 2019 levels by 2035.
- **Taisei (Japan):** In support of monetization of CO_2 feedstocks, the contracting company has developed a technology to convert CO_2 from manufacturing plants into building materials. The development comes in parallel with the Japanese government promoting decarbonization of the cement industry to reach carbon neutrality by 2050. The company aims to sell concrete with CO_2-infused calcium by 2030.

LUX TAKE

Technology developments in building materials are motivated by a need to create a stronger business case and to comply with standards set by a slow-moving industry. However, the highly conservative industry will likely be pressured by regulatory chokeholds to increase its flexibility and make way for faster commercialization of CCU technologies.

Aggregates hit cost tipping point in 2031 and grow to US$337 billion market as global demand continues to increase

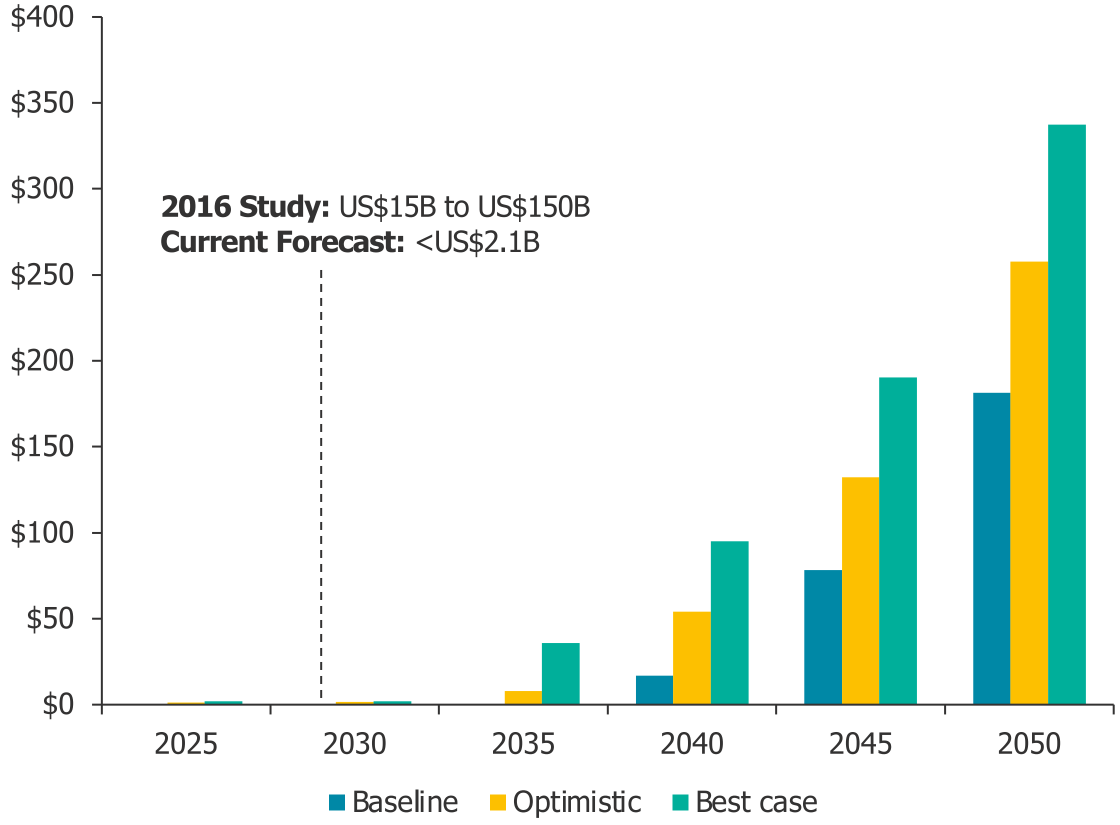
MARKET POTENTIAL

- The global aggregates market is expected to grow to US$1.8 trillion by 2050 with a CAGR of 3.3% as demand rises with rapid urbanization and global development.
- **Baseline.** Cost tipping point occurs in 2039 with a CAGR of 32% through 2050 to reach a market size of US$182 billion.
- **Optimistic.** Cost tipping point occurs in 2035 with a CAGR of 26% through 2050 to reach a market size of US$258 billion.
- **Best case.** Cost tipping occurs in 2031 with a CAGR of 22% through 2050 to reach a market size of US$337 billion.

MARKET DRIVERS

- Competition with low-cost aggregates remains the primary hurdle for widespread commercial adoption as developers must bring down the average US$50/tonne cost of CO_2-derived aggregates today.
- While further commercial advancements will continue to reduce costs, the aggressive roll out of carbon pricing by 2040 towards the high end (US$100/tonne) of the Carbon Pricing Leadership Coalition's analysis is the lone driver behind market adoption.
- Cost-parity without carbon pricing will only be achieved by 2044 in the best case scenario and by 2049 in the optimistic scenario.

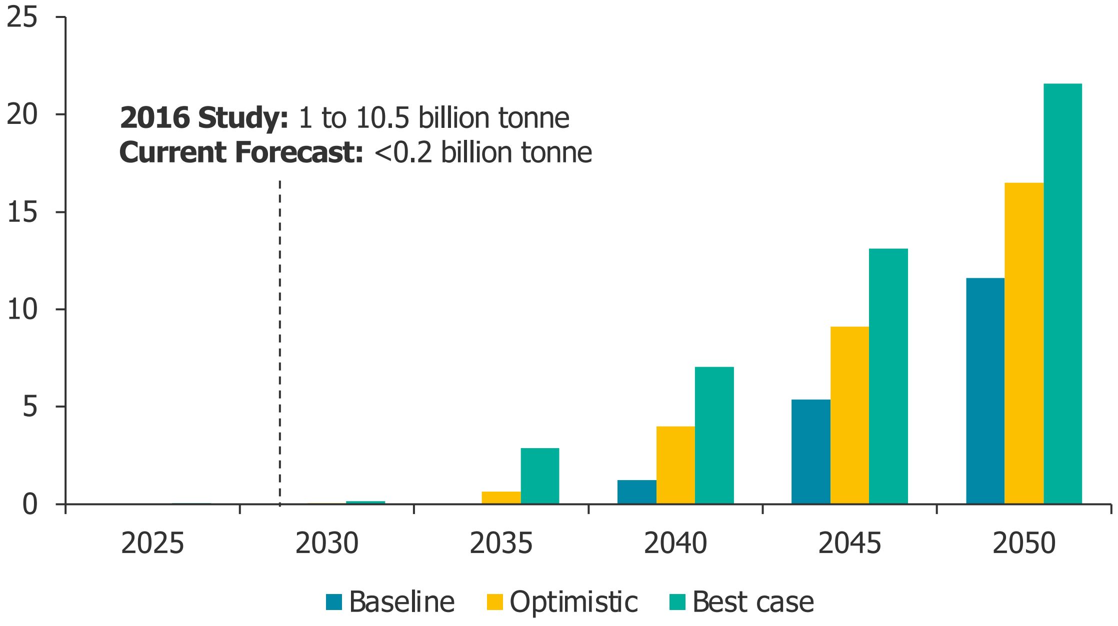
Global Aggregates Market Value
US$ billion



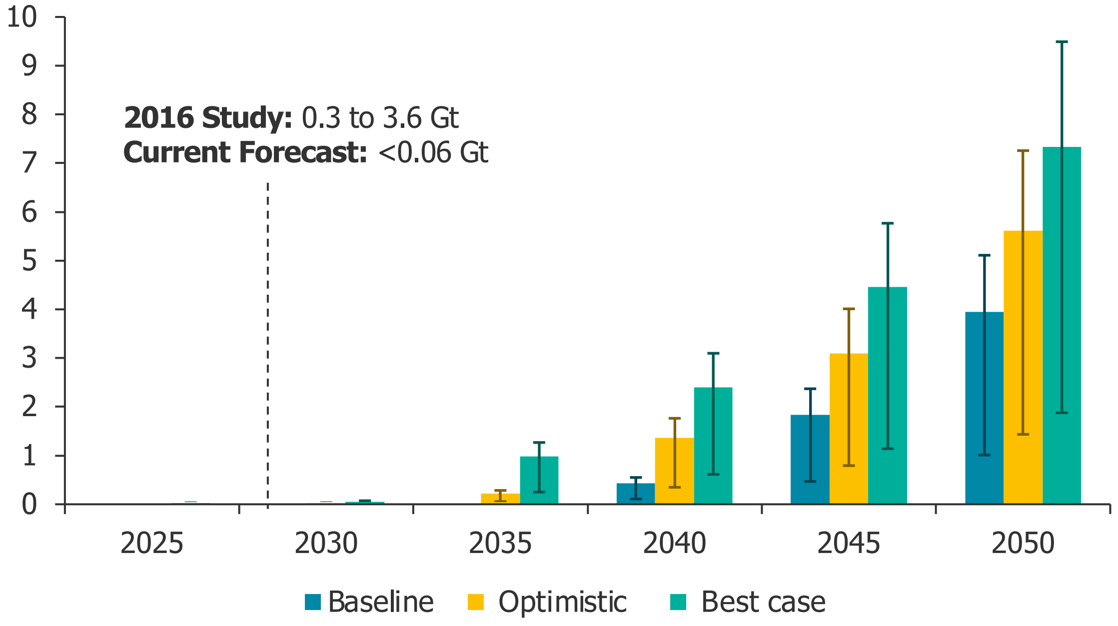
Note: The market size for aggregates and precast concrete are not mutually exclusive with anywhere between 18% to 24% of total aggregates used in precast concrete production.

Over 7.3 Gt of CO_2 can be potentially utilized annually as CO_2-derived aggregates take up 18% market share

Global Aggregates Market Volume
Annual billion tonne



Global Aggregates CO_2 Utilization Potential
Annual Gt of CO_2



Error bars reflect the range of CO_2 utilization in the low CO_2 uptake scenario of 0.087 tCO_2/tonne of aggregates and high CO_2 uptake scenario of 0.44 tCO_2/tonne of aggregates.

LUX TAKE

While commercial activity remains low today, rapid commercialization and entrants of new developers makes aggregates a near-term opportunity. Recent industry commitment to carbon neutrality will accelerate standardization, adoption, and the build out of a robust value chain to support the technology.

CO_2 curing reaches cost tipping point within the decade and sees widespread adoption as market size reaches US$666 billion

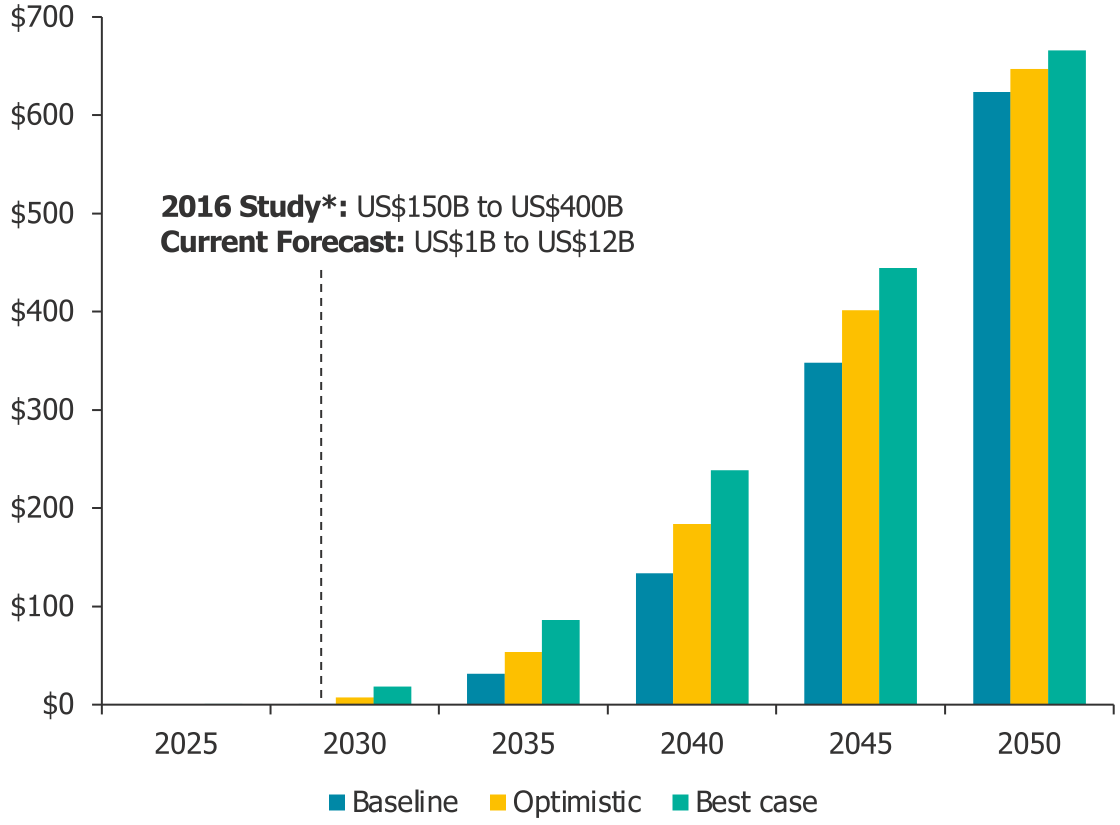
MARKET POTENTIAL

- The global precast concrete market is expected to grow to US$830 billion by 2050 with a CAGR of 5.2%.
- **Baseline.** Cost tipping point occurs in 2031 with a CAGR of 59% through 2050 to reach a market size of US$623 billion.
- **Optimistic.** Cost tipping point occurs in 2029 with a CAGR of 41% through 2050 to reach a market size of US$647 billion.
- **Best case.** Cost tipping point occurs in 2027 with a CAGR of 231% through 2050 to reach a market size of US$666 billion.

MARKET DRIVERS

- With both cost and performance benefits, curing is an immediate opportunity that offers improvements to existing precast concrete production processes and CO_2 utilization potential, albeit low.
- Implementation of carbon pricing will accelerate the timeline for cost parity but remains only a minor factor. In the baseline scenario, cost parity without carbon pricing is achieved by 2036, only five years later than with carbon pricing.
- Cost will be a minor factor and further acceleration of adoption will come as the industry sees the benefits of less water and cement usage.

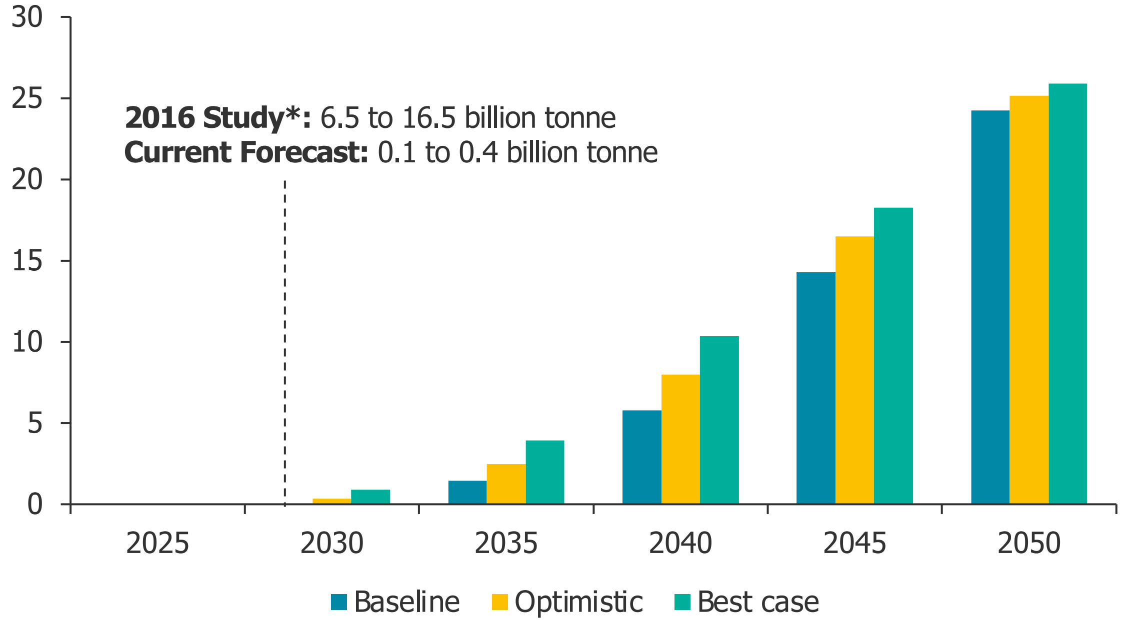
Global Precast Concrete Market Value
US$ billion (*2016 study includes all concrete)



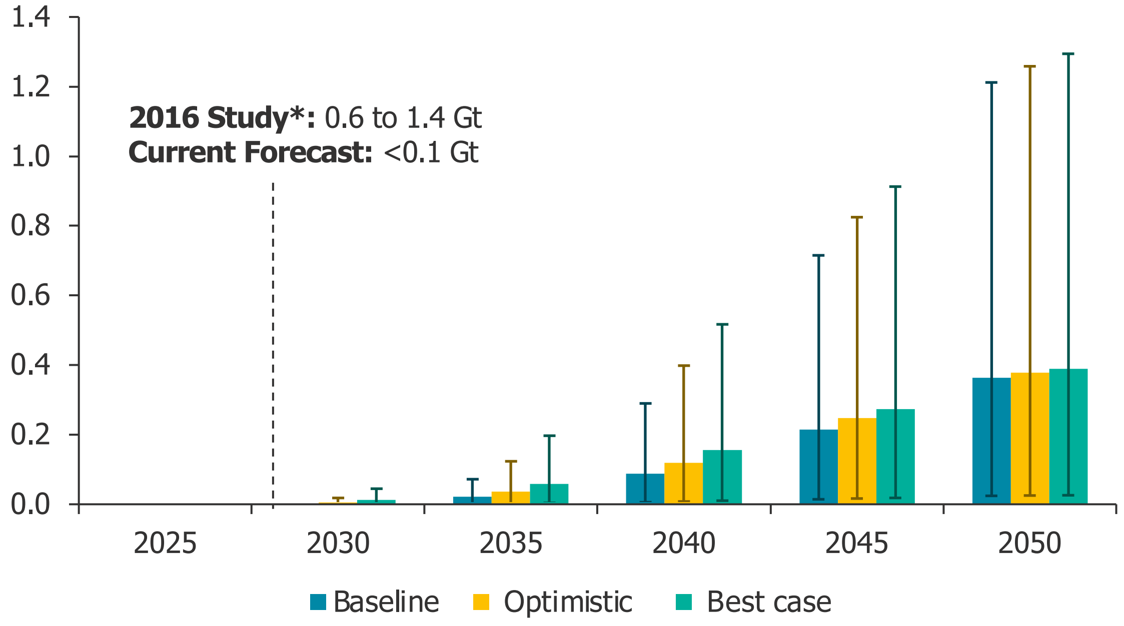
Note: The market size for aggregates and precast concrete are not mutually exclusive with anywhere between 18% to 24% of total aggregates used in precast concrete production.

Despite rapid adoption leading to 80% market share, curing's low utilization potential only utilizes 1.3 Gt of CO_2 in 2050

Global Concrete Market Volume
Annual billion tonne (*2016 study includes all concrete)



Global Curing CO_2 Utilization Potential
Annual Gt of CO_2 (*2016 study includes all concrete)



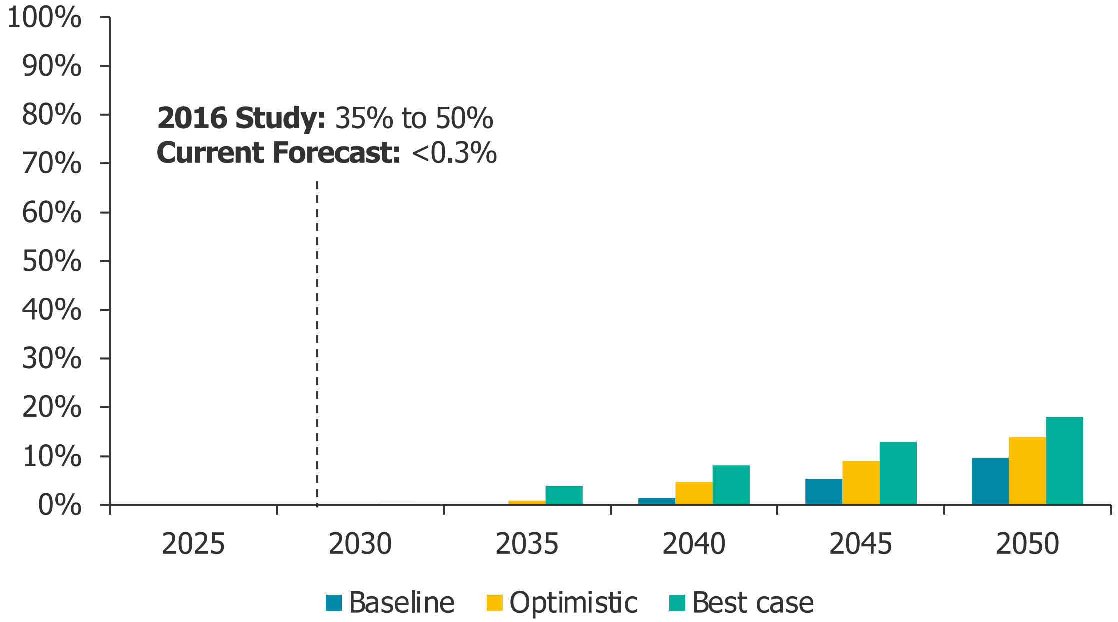
Error bars reflect the range of CO_2 utilization in the low CO_2 uptake scenario of 0.001 tCO_2/ tonne of precast concrete and high CO_2 uptake scenario of 0.05 tCO_2/ tonne of precast concrete.

LUX TAKE

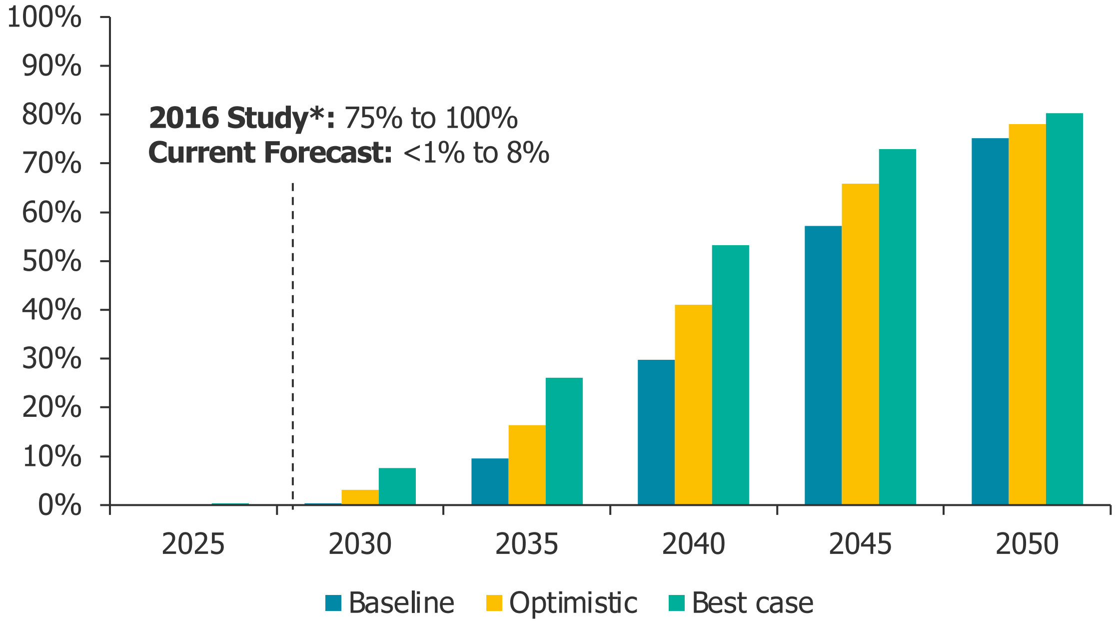
Curing presents an immediate commercial opportunity with a cost-competitive and performance enhancing solution. While direct CO_2 utilization potential is significantly lower than other end products, the reduction of cement usage will have an indirect impact on the industry's overall CO_2 footprint that should not be overlooked.

Projected market penetration of CO_2 aggregates and precast concrete curing for three adoption scenarios

Global Aggregates Market Penetration
% penetration rate



Global Precast Concrete Market Penetration
% penetration rate (*2016 study includes all concrete)



The overall market is the native incumbent market, and the penetration rate is defined as the potential replacement of incumbent product with CO_2-derived products based on the baseline, optimistic, and best case scenario. Projected market volume of aggregates is 119 billion MT by 2050 based on a 45 billion MT market volume in 2020 and an estimated CAGR of 3.3%. Projected market volume of precast concrete is 32 billion MT by 2050 based on a 7 billion MT market volume in 2020 and an estimated CAGR of 5.2%.

Carbon Additives

Carbon additives have a wide range of potential application but face significant commercialization challenges

TECHNOLOGY OVERVIEW

- Carbon additives includes carbon nanotubes (CNTs), carbon nanofibers (CNFs), carbon black, or graphene, where companies use two main pathways for CNT and other carbon nanomaterial production and one main pathway for graphene production.
- CO_2 can be catalytically converted to CNTs or other carbon nanomaterials using an iron-based catalyst along with other gases like H_2, CO, or CH_4; they can also be produced via CO_2 electrolysis using a carbonate-based electrolyte. Graphene can be produced using mechanochemical exfoliation in the presence of an oxidizing gas, catalyst, and acid.
- These materials are attractive for the amount of CO_2 they consume and for the novel mechanical, thermal, or electronic properties they imbue into end products.

CHALLENGES AND PROSPECTS

- While performance claims are comparable to incumbent materials, there is a severe lack of players and no production process has yet been validated at scale. Beyond the technical challenge and high capital costs required to scale, startups in this space will also need to seek strategic partnership in order to co-locate operations to capture CO_2.
- Cost, supply chain security, product quality, and developing end applications with strong value propositions are critical challenges to overcome for these materials.
- Given the lack of regulations benefiting CO_2-based technologies, CO_2-based carbon additives need to exhibit similar or improved performance benefits at comparable cost to incumbent additives, elsewise, adoption will remain limited.

Number of Developers, Carbon Additives

Technology	Carbon black
Technology maturity	Development
Average developer TRL	6
CO_2 consumption (tCO_2/tonne product)	3.7 to 4.2
Market size, best case (2050)	US$66 billion
CO_2 utilization potential, best case (annual Gt)	0.2
Cost tipping point, best case (year)	2041

Note: Some developers target carbon nanotubes and carbon nanofibers, but the market is expected to become saturated by 2030 and dominated by non-CO_2-based products. These two markets are unlikely to be potential opportunities and are not included.

Research institutes lead the way in activity while corporates are relatively inactive in this space

COMMERCIAL INTEREST

- Leading non-academic patent filers include Seerstone (18), Zeon Corporation (11), C2CNT (now known as Carbon Corp; 10), and Solid Carbon Products (7). Seerstone and Solid Carbon Products were formed by the same founder and share similar technologies.
- In 2021, Zeon Corporation was granted this patent to use a fluidized bed process and produce CNTs via catalyst and CO_2, but it has not yet commercialized the technology.
- Despite the overall increasing activity, the conversion of patent quantity to commercialization has been poor. Note that most patent filers are academic institutions.

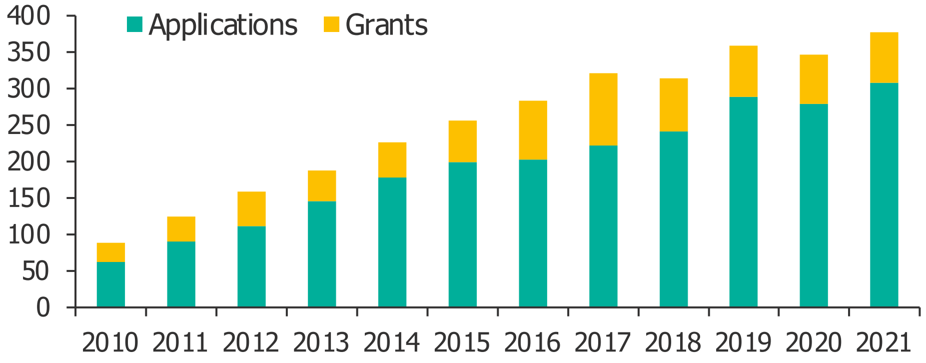
R&D INITIATIVES

- Leading academic institutes include the George Washington University, the Chinese Academy of Sciences, Beijing University of Chemical Technology, and Tianjin University.
- In 2017, researchers from Vanderbilt University outlined a method to isolate catalytic species from scrap metal and react it with CO_2 to form CNTs in this paper.
- Although there is a flurry of publications, especially from Chinese universities, there has been little translation to corporate entities. Key spinoffs include Carb Corp (from George Washington University) and SkyNano Technologies (from Vanderbilt University).

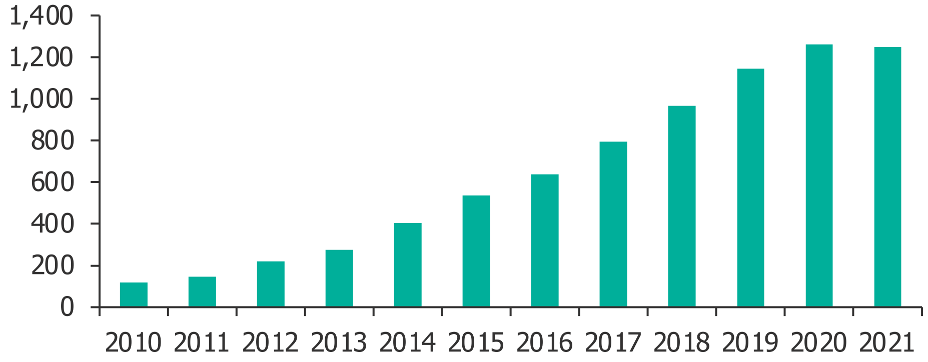
LUX TAKE

While activity is anticipated to continue increasing, the industry should expect that there will be little commercialization without introduction of strong external drivers or incentives. Instead, view this rise as a reflection of academic interest.

Carbon Additive Patent Activity
Number of patent publications



Carbon Additive Academic Publications
Number of academic publications



Venture investments have been low due to limited number of startups and high risk of capital-intensive manufacturing facilities

NOTABLE INVESTMENTS

- VC funding for carbon additives has been extremely scant due to the low number of startups in the space and the risky and long timelines for return on investment. VC activity is expected to remain stagnant as the space will be slow to see new startups.
- Key rounds have included Solid Carbon Products ($2.5 million) and Carbon Corp ($3.5 million). However, this funding does not capture capital pledged from strategic investment ($25 million for Carbon Corp) or subscription agreement ($15 million for Solid Carbon Products; see Developer Spotlight for more details).

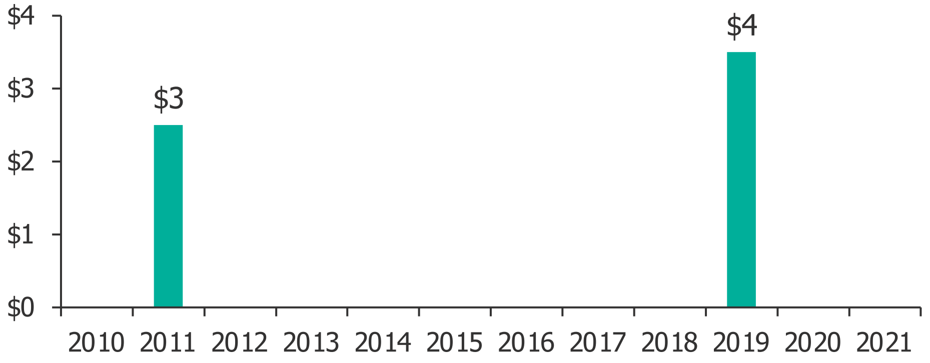
KEY DEVELOPMENTS

- Initial funding rounds supported process validation and prototyping; further funding has been intended for scaling, though no group has yet successfully scaled.
- Finding strategic partners to help scale or accelerate targeted market development will be key for startup growth, as seen by Capital Power's strategic investment into Carbon Corp, which will simultaneously help Carbon Corp scale and reduce Capital Power's emissions. Alternatively, Bergen Carbon Solutions went public in 2021 to maintain its momentum and gain leeway in terms of available cash on hand.

LUX TAKE

The low level of VC funding is indicative of the poor commercial potential of CO_2-based carbon additives. A severe lack of viable players also demonstrates this point. Future investment will trickle in slowly over time, but overall remain low.

Carbon Additives VC Funding
US$ million



Solid Carbon Products

Total disclosed funding: $2.5 million
Investors: RenewableTech Ventures

Carbon Corp

Total disclosed funding: $3.5 million
Investors: Sustainable Development Technology Canada

BERGEN CARBON SOLUTIONS

IPO date: April 2021
Shareholders: Saga Pure, Finn Blydt-Svendsen (COO), Jan Børge Sagmos (CEO)

Lux Research

CARBON ADDITIVES: DEVELOPER ASSESSMENT

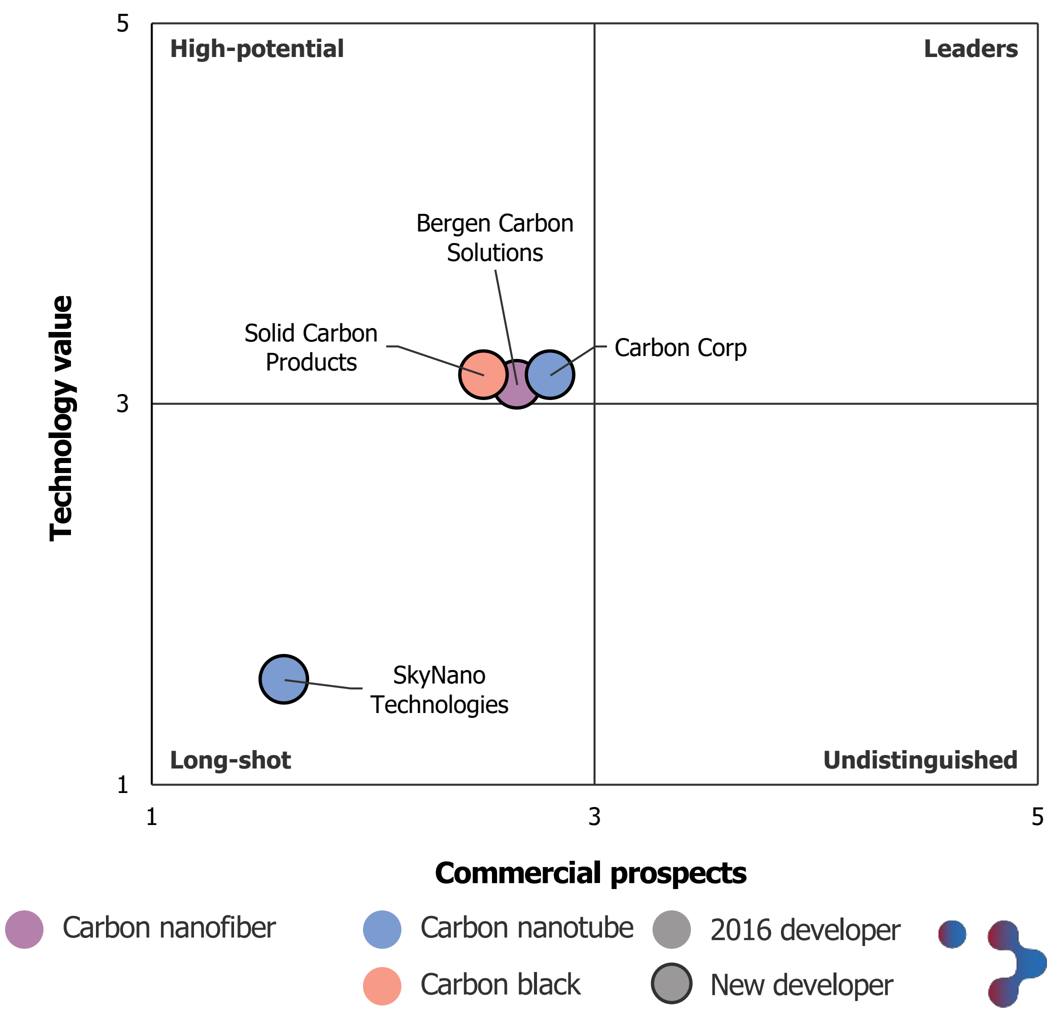
The landscape for carbon nanomaterials is sparse as startups face low commercial prospects

DEVELOPER LANDSCAPE

- There is a dearth of developers for carbon additives and none of the involved startups have progressed beyond the pilot stage, though Carbon Corp does have the funding and partnership to scale commercially.
- Although all players produce CNTs, Solid Carbon Products will likely first target carbon black based on market pull, whereas Bergen Carbon Solutions aims to push CNFs into the market. The ability to produce a variety of carbon materials potentially opens more entry points to market.
- The number of developers is not expected to proliferate over time and competition will remain low.

MARKET DYNAMICS

- Incumbent carbon additives have struggled with commercialization, but initial successes had been predicated on targeted product development; Carbon Corp and Solid Carbon Products are differentiated for burgeoning partnerships in cement and tires, respectively, but commercial maturity overall is low and no one developer is a leader in the space.
- This market will continue to struggle with long development times, challenges with scaling, and nebulous value propositions for materials that don't necessarily offer advantages beyond consuming CO_2.



Carbon Corp and Solid Carbon Products have begun to target specific end use applications

Carbon Corp

- The company was founded in 2017 based on research by Stuart Licht at George Washington University; it develops CNTs from CO_2 using an electrolyzer with a molten lithium carbonate ($LiCO_3$) electrolyte
- To date the company has raised about US$28.5 million from investors, including a power generation company and government funding; in 2019 the company announced strategic investment from Capital Power, which will support costs of up to US$25 million for scaled production
- Key claims of the organization include its ability to consume approximately 4 tCO_2 per tonne of CNT produced; also claims its process is low cost and has a high production rate
- In terms of maturity, the company is at the pilot stage, but plans to build a 2,500 tpa commercial-scale facility with Capital Power
- Global CO_2 Initiative should consider Carbon Corp as having the highest commercialization potential for CO_2–based CNTs and monitor for scaling as well as purchase orders for use in concrete from Lehigh Hanson

Solid Carbon Products

- The company was founded in 2009 and developed a carbon-negative platform technology to convert CO_2 into solid carbon products (CNT, carbon black, carbon nanofibers) using Bosch and Boudouard reactions
- To date the company has raised about US$17.5 million from venture capital; it planned to raise a Series C of US$35 million where RenewableTech Ventures pledged a US$15 million subscription agreement, but has not publicly closed the round
- Key claims of the organization include its ability to produce high-aspect-ratio products with conductivity of 10 S/cm to 60 S/cm; the process consumes 3.7 tCO_2 per tonne of product produced
- In terms of maturity, the company has a 2 tonne/month pilot plant and plans to scale to 50 tonne/month
- Solid Carbon Products has a flexible platform using seemingly simple reactions; Global CO_2 Initiative should monitor for announcements of a strategic investor that can help it scale and see if its early discussions with Goodyear translates to commercial transaction for tires

LUX TAKE

The carbon additives landscape is sparse with only a handful of players. Growth potential for leading developers will require strong end application development with clear value propositions and strategic partnerships that can drive commercialization – key factors for materials that have historically struggled to be commercially relevant.

Finding the right end applications to showcase CO_2-based carbon additives' value proposition remains key for commercial success

Key Barriers and Risks	Means to Mitigate*
Technology barriers Medium technology barriers; common challenges for incumbent additives include high price, inconsistent quality, and a lack of valuable end application — CO_2-based additives should expect similar issues Paradoxical problem wherein carbon additives require high capital costs to establish production facilities, but economies of scale are required to drive down production cost	• Optimizing the processing and production of CO_2-based carbon additives to **ensure consistency in material performance and decrease cost** • Identifying novel CO_2-to-carbon additive conversion pathways or additions to existing processes that increase efficiency • Development of **modular production units that can decrease capital costs barriers and allow for easier integration into a variety of existing facilities**
Policy and regulation barriers Carbon additives are applicable to a myriad of different end products and may require market-specific proof of performance or certification Beyond policy, the public has historically been wary of perceived dangers of nanotechnology, at times engendering protest and forcing companies to alter their use of nanomaterials in order to appease consumer opinion	• **Establishing standardized testing and proof of performance for CO_2-based carbon additives** at early stages of the production process • Focusing on applications that interface indirectly with the consumer
Supply chain and logistics barriers Accounting for CO_2 supply shortages increases dependence on carbon capture infrastructure	• **Co-location of production facilities** in sites with access to readily available CO_2 feedstock

* Examples of key developments pertinent to mitigation are listed on the next slide

Developments in CO_2-based carbon additives have been predicated on technology push rather than market pull

KEY TECHNOLOGY ACTIVITY

- **George Washington University (United States):** Research from Stuart Licht's lab covers a variety of technologies, including the use of high-performance alloys and cost-effective electrolytes, boron doping for increased CNT conductivity, development of magnetic CNTs, production of carbon nano onions as an additional allotrope, and others. While Carbon Corp is commercializing Licht's CNT technology, ongoing research aims to improve synthesis and performance of CO_2-based carbon nanomaterials.
- **Northeastern University and Nano-C (United States):** Researchers assessed the use of introducing CO_2 directly into a CVD chamber – the incumbent method of manufacture – and its effect on carbon nanomaterial formation. This work helps illustrate if CO_2 can simply be injected into incumbent processes, allowing users to capitalize on existing equipment.
- **Wuhan University (China) and Massachusetts Institute of Technology (United States):** Exploratory efforts on using affordable anodes and designing a highly scalable electrochemical cell. While this work is not highly differentiated, it does underscore the potential of building scalable electrolysis units.

KEY MARKET ACTIVITY

- **Carbon Trifecta (United States)**: This nonprofit organization explores a comprehensive solution of carbon capture, conversion to carbon additives, and integration of advanced manufacturing like 3D printing for end products. It aims to establish a scientific, corporate, and political community, creating an industrial ecosystem to mitigate CO_2 and create value-add end products.
- **Carbon Corp (Canada)**: Building off Licht's work at George Washington University, Capital Power announced strategic investment into Carbon Corp to build the largest commercial-scale CO_2-to-CNT facility with initial capacity of 2,500 tpa and ability to scale to 7,500 tpa. The facility will use emissions from an existing power plant; it will validate the scalability of CO_2-to-CNT and the ability to integrate into existing infrastructure.
- **National Nanotechnology Initiative (United States):** The NNI requested over US$1.7 billion for its 2021 budget, contributing to a US$31 billion year to date total since its formation in 2001. Nanotechnology is broadly supported by government funding despite public health concerns, but CO_2-to carbon additive projects remain elusive.

LUX TAKE

Activity in the carbon additive space is motivated by technology push rather than market pull or policy change. Overall momentum is low. Despite fringe support for nanotechnology broadly, there is a lack of a compelling business case for CO_2-based carbon additives; improvements in performance or cost alone will not be insufficient.

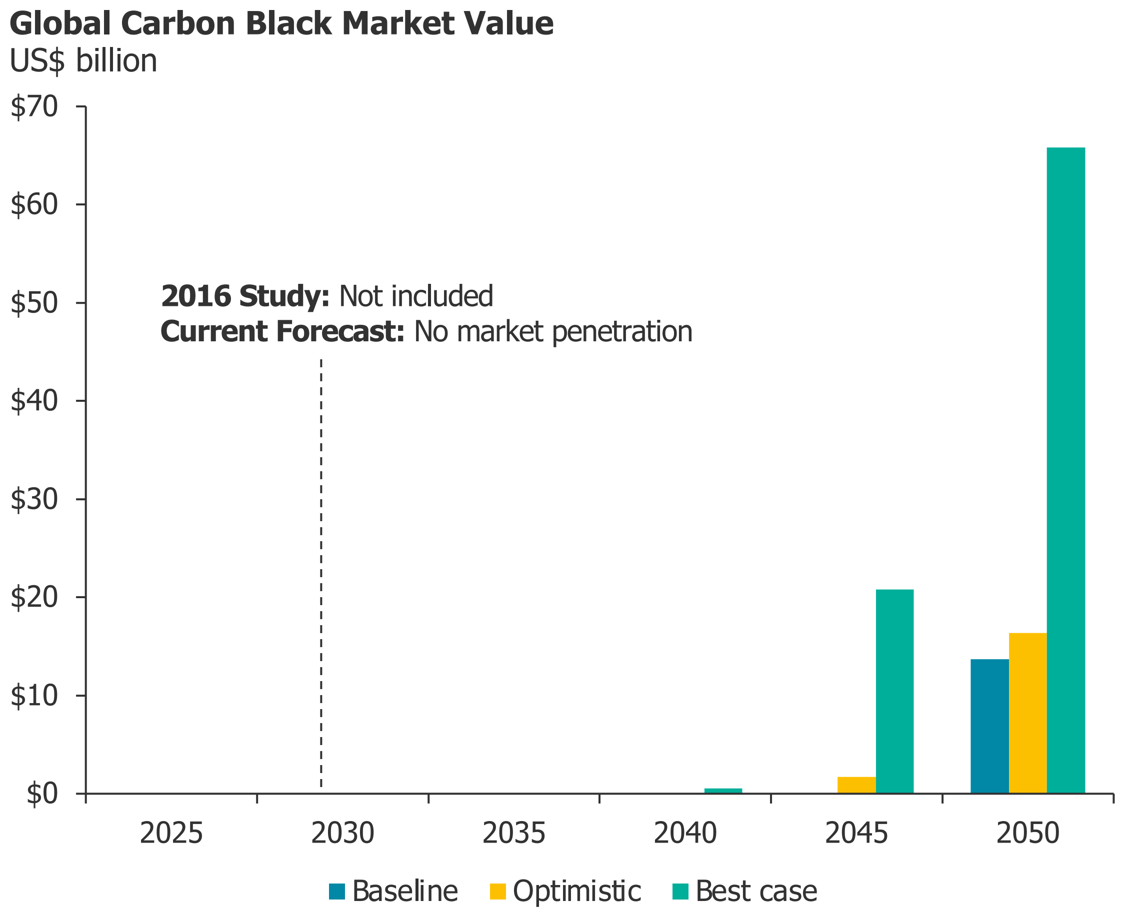
Cost tipping point is not reached until 2041, but rapid market penetration grows to US$66 billion market

MARKET POTENTIAL

- The global carbon black market is expected to grow to US$97 billion by 2050 with a CAGR of 5.5% buoyed by strong growth prospects of the automotive industry, resulting in increasing demand for tires.
- **Baseline.** Cost tipping point occurs in 2047 with a CAGR of 35% through 2050 to reach a market size of US$13.7 billion.
- **Optimistic.** Cost tipping point occurs in 2045 with a CAGR of 58% through 2050 to reach a market size of US$16.4 billion.
- **Best case.** Cost tipping occurs in 2041 with a CAGR of 43% through 2050 to reach a market size of US$66 billion.

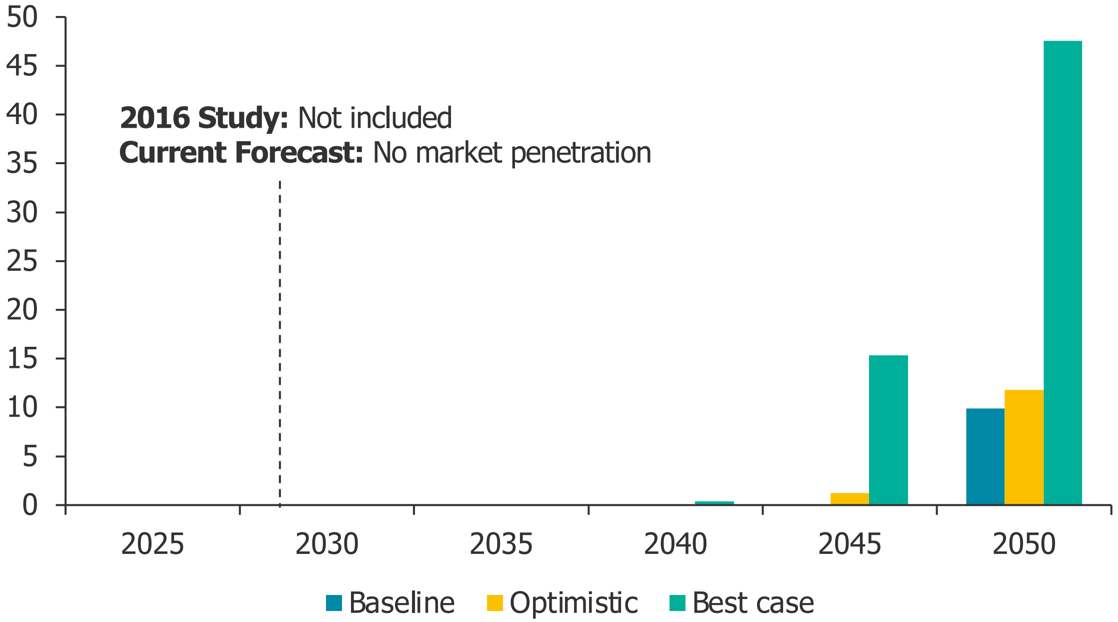
MARKET DRIVERS

- Stiff competition from virgin carbon black producers as well as waste tire recyclers that are already integrated in the tire manufacturing supply chain prevents market traction before 2040.
- Today's high estimated costs of US$4,800/tonne for CO_2-based carbon black can only be reduced with significant manufacturing capacity scale-up; despite modest CO_2 utilization potential per product carbon pricing plays a negligible factor in offsetting high costs
- Cost-parity without carbon pricing will be achieved in the same year (2041) in the best case scenario

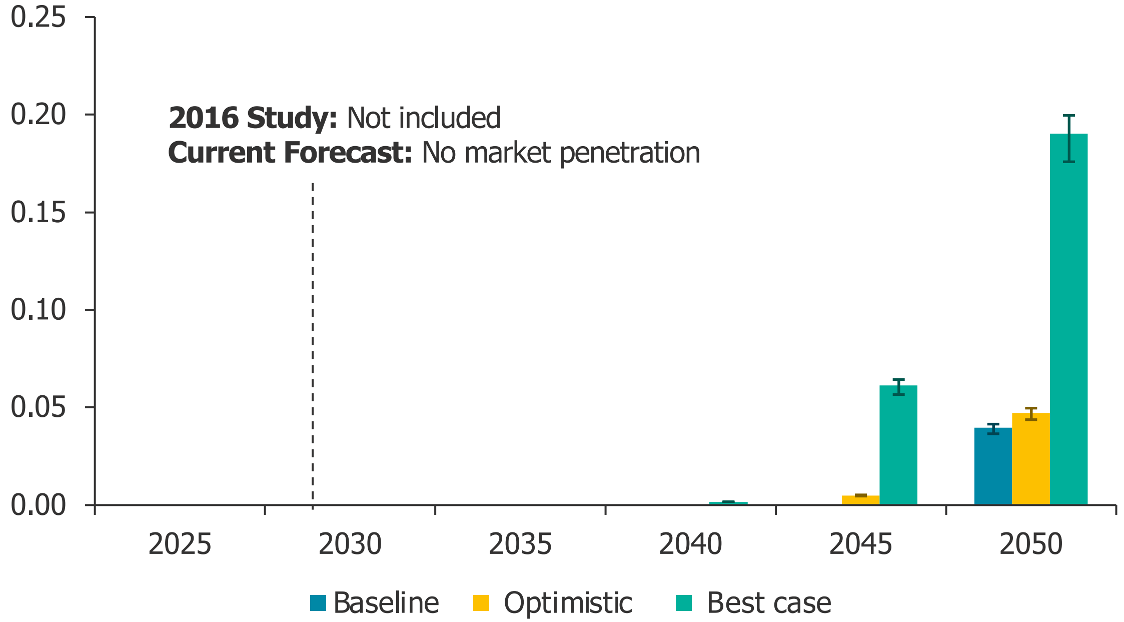


Market penetration witnesses a late surge in 2050 to reach 68% with the potential to utilize 0.2 Gt of CO_2

Global Carbon Black Market Volume
Annual million tonne



Global Carbon Black CO_2 Utilization Potential
Annual Gt of CO_2



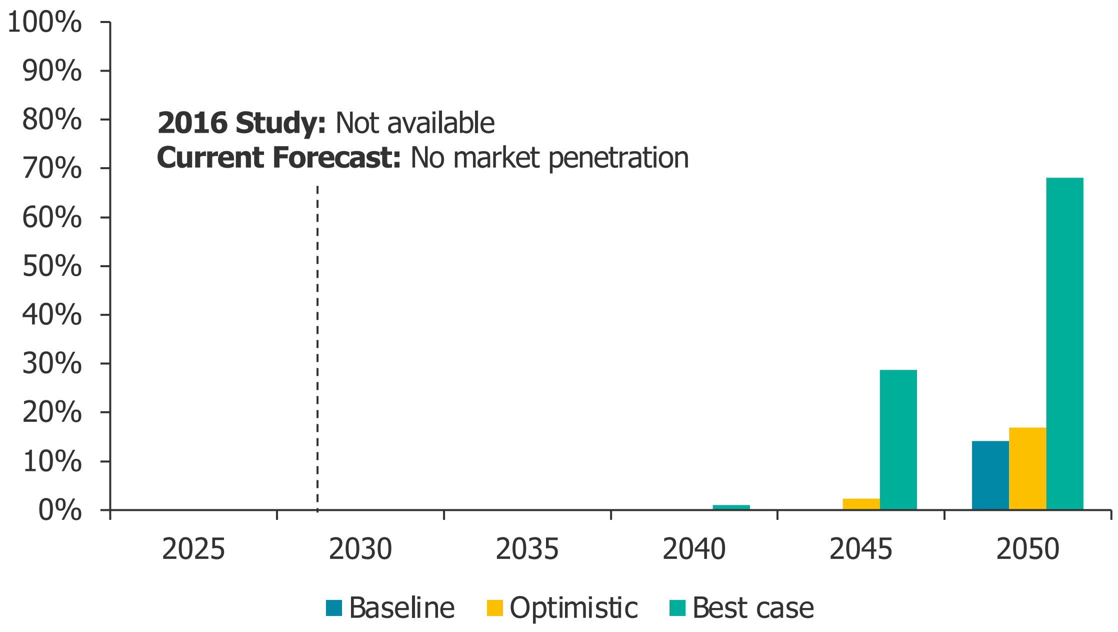
Error bars reflect the range of CO_2 utilization in the low CO_2 uptake scenario of 3.7 tCO_2/ tonne of carbon black and high CO_2 uptake scenario of 4.2 tCO_2/ tonne of carbon black.

LUX TAKE

Despite an initial commercial focus on the carbon black market, the dearth of developers and lack of commercial manufacturing capacity leaves the prospects of CO_2-based carbon black highly speculative. Stiff competition from alternative carbon black technologies (i.e. biomass) will also inhibit market adoption for CO_2-based products.

Projected market penetration of CO_2-based carbon black for three adoption scenarios

Global Carbon Black Market Penetration
% penetration rate



The overall market is the native incumbent market, and the penetration rate is defined as the potential replacement of incumbent product with CO_2-derived products based on the baseline, optimistic, and best case scenario. Projected market volume of carbon black is 70 million MT by 2050 based on a 14 million MT market volume in 2020 and an estimated CAGR of 5.5%.

Polymers

CO_2 utilization for polymers focuses largely on polyol production using catalytic technologies

TECHNOLOGY OVERVIEW

- Polymer production from CO_2 mainly targets polycarbonate (PC) polyols, polycarbonates, and polyhydroxyalkanoates (PHAs).
- CO_2 can be catalytically converted to aromatic or aliphatic polycarbonate polyols. Aromatic PCs result from the reaction of CO_2 with an alcohol, phenol, and bisphenol. Aliphatic PCs are produced via the copolymerization of CO_2 with an epoxide in the presence of a catalyst. Polyols are then used as precursors to produce polyurethanes (PU) via a reaction with an isocyanate.
- Similarly, biological pathways relying on CO_2-consuming microorganisms can be used for the production of biodegradable PHAs.

CHALLENGES AND PROSPECTS

- Currently, the polyols have a CO_2 content ranging between 20% and 40% by weight and exhibit similar performance as fossil-based counterparts. Production of PU using CO_2-based polyols can also result in low flammability of the PU.
- Given the lack of regulations benefiting CO_2-based technologies, CO_2-derived polyols need to exhibit similar or improved performance benefits to their fossil-based counterparts to justify a premium cost.
- As an existing commercial process, it presents a near-term opportunity for the chemicals industry to adopt CO_2-based technologies. However, reliance on costly CO_2 capture, and uncertainty about performance benefits represent key challenges for this application.

Number of Developers, Polymers

Technology	Polyurethane
Technology maturity	Scale
Average developer TRL	6
CO_2 consumption (tCO_2/tonne product)	0.05 to 0.25
Market size, best case (2050)	US$191 billion
CO_2 utilization potential, best case (annual Gt)	0.01
Cost tipping point, best case (year)	2028

Note: Some developers target polyhydroxyalkanoates (PHA), but the market is still in its infancy and has historically struggled to gain commercial adoption despite its end-of-life attributes. This market is unlikely to be potential opportunities and is not included.

Large chemical conglomerates drive the development of CO_2-based polymers, with polyurethane attracting the most interest

COMMERCIAL INTEREST

- Leading non-academic patent filers include Covestro (171), Invista (40), BASF (37), and Dow (36). Covestro's position as the main patentor is in line with its expertise and ambition to create sustainable polyurethanes, either from CO_2 or recycled products.
- Production pathways for CO_2-based polyurethanes dominate the patent landscape of CO_2-based products. Increased consumer demand for sustainable alternatives to foams, adhesives and other rigid products drives the development in this space.
- A plateau in patent output aligns with commercial products already reaching the market.

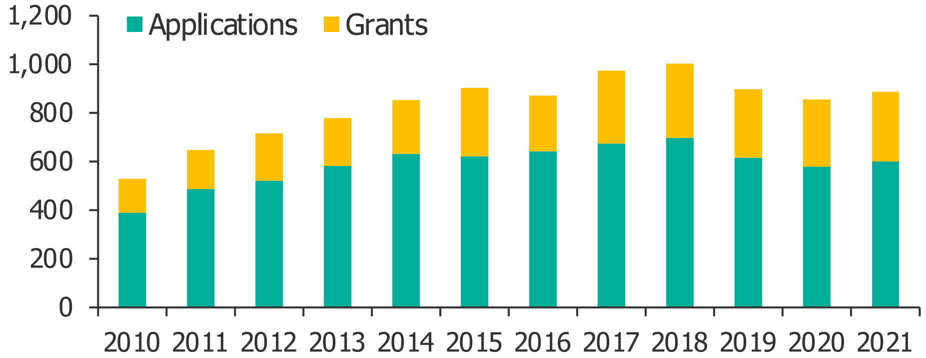
R&D INITIATIVES

- Leading academics such as the Chinese Academy of Sciences, Texas A&M, University of Texas, University of Toronto, and Oxford University focus on novel catalyst development.
- Texas A&M, for instance, targets the direct copolymerization of CO_2 without dehydrating agents; Oxford University, in turn, focus on yield improvements while tuning the process to enhance the mechanical and thermal properties of the resulting products.
- As corporates already use the process commercially, no relevant technology transfer initiatives resulting in commercial spin-outs have been observed.

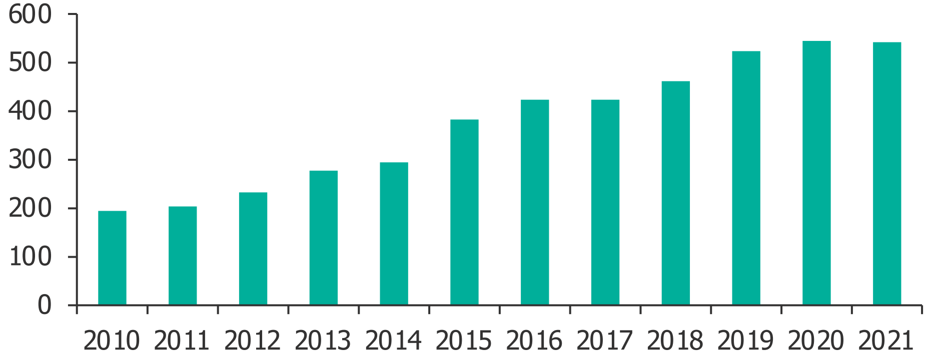
LUX TAKE

While academic activity has been increasing, corporate innovation has dominated the space. This is likely to continue in the near-term as companies continue to scale-up the production of CO_2-based polymers with improved performance.

Polymers Patent Activity
Number of patent publications



Polymers Academic activity
Number of academic publications



Venture investments have been modest in this space, as the development of new materials involves high risks

NOTABLE INVESTMENTS

- VC funding for CO_2-based polymers has been limited, seeing US$131 million being invested over the past decade. VC funding is mostly directed towards PHA development.
- Newlight Technologies, which focuses on the development of PHAs from CO_2 and methane is the largest funding recipient, with a total of US$107 million. The company received US$45 million in 2020 and approximately US$21 million in 2019.
- The limited investment in startups producing polycarbonate polyols reflects the in-house development activities that corporates carry out.

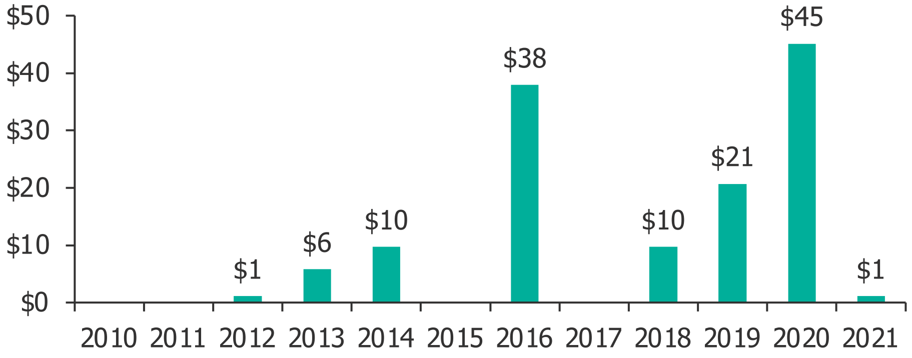
KEY DEVELOPMENTS

- The latest funding round by Newlight (2020) coincided with the commissioning of a new commercial-scale production facility in California for its biodegradable PHB – a form of PHA – product, and the launch of cutlery and drinking straw consumer products.
- More recently, Empower Materials received US$1.1 million in funding in 2021 to continue developing its line of CO_2-based binders, including polyethylene carbonate and propylene carbonate.

LUX TAKE

The limited funding showcases the industry's acknowledgement of the difficulty of introducing new polymers to the market, in the case of PHA. While PUs will continue to garner interest, corporates are set to spearhead development activity.

Polymers VC Funding
US$ million



NEWLIGHT
Total disclosed funding: $107M
Investors: Third Seven Capital, Valedor Partners

ECONIC
Total disclosed funding: $23M
Investors: OGCI, Woodford Investment Management, IP Group

EMPOWER MATERIALS
Total disclosed funding: $1.1M
Investors: Breakthrough Energy Ventures, BDC Venture Capital

Lux Research

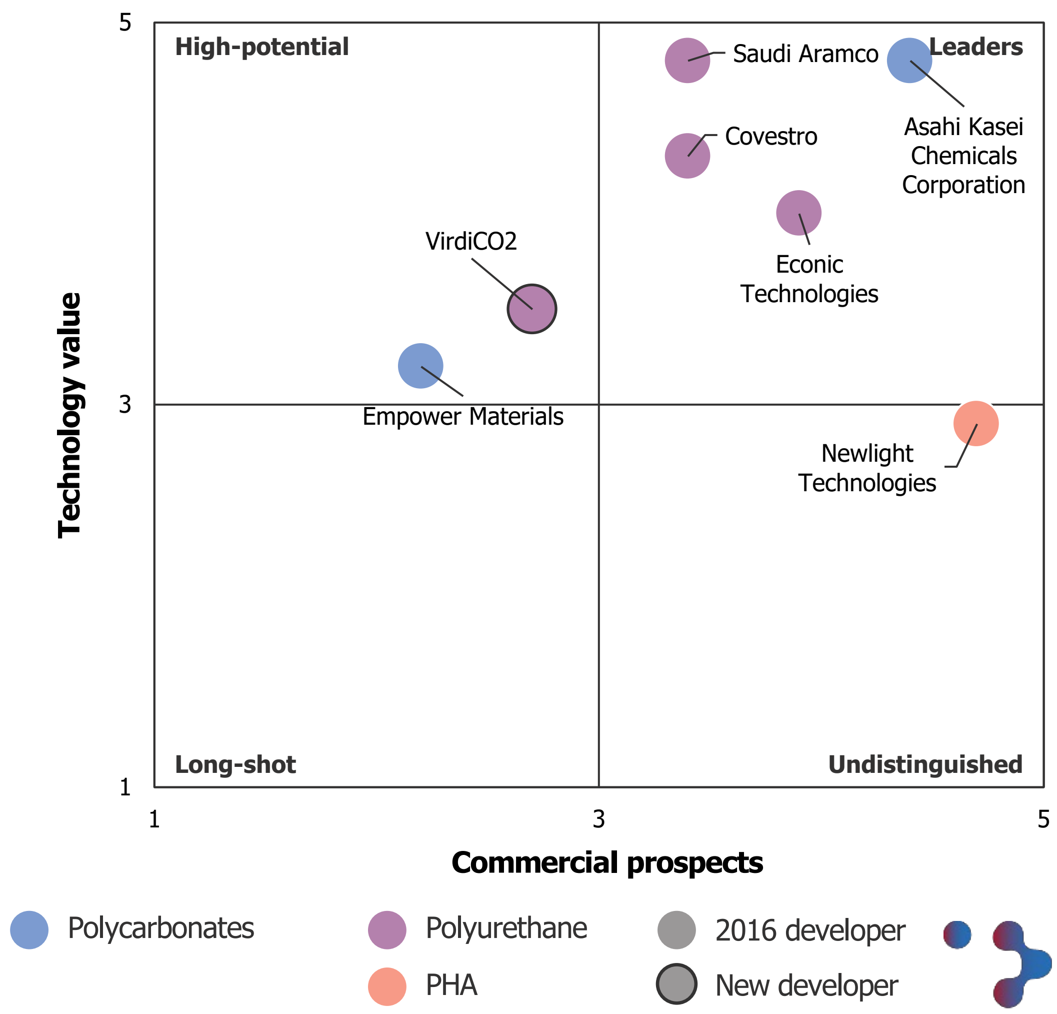
Corporates dominate the landscape of CO_2-based polymers largely due to their resources and expertise

DEVELOPER LANDSCAPE

- The developer landscape is relatively sparse and slow moving. Most players have been active for over 10 years, with corporate developers dominating the landscape.
- These companies are already offering their CO_2-based polymers commercially, while showcasing new applications for such materials.
- Only one developer has entered the space in the last 5 years – ViridiCO2 – and it remains in early development stage, with no specific application in sight. This is in line with the long development time and significant resources required to develop new polymers and applications.

MARKET DYNAMICS

- The positioning of developers in the "Leaders" quadrant responds largely to their ability to modify their catalyst systems to adjust the properties of CO_2-based polymers to match the needs of specific applications.
- The progress of these CO_2-based polymers will be largely contingent on developers improving catalyst efficiencies and process costs and the availability of low-cost CO_2-capture.
- Similarly, the formation of partnerships that demonstrate the potential of the produced materials in well-known products (e.g. foams, adhesives, rigid boards, packaging) will be crucial and will see the "Leaders" further cementing their position in the market.



Covestro and Econic have both demonstrated the performance of their CO_2-based polyols in polyurethanes

ECONIC

- Econic develops catalysts that reacts CO_2 with a range of epoxides to form polyols, which can be used to produce polyurethanes with a lower environmental footprint.
- To date the company has raised ~US$23 million in venture capital funding from investors including OGCI and Third Seven Capital.
- Key claims of the organization include a tunable catalyst that allows it to determine the percentage of CO_2 incorporated in polyols – allowing up to 50% CO_2 incorporation by weight. Varying CO_2 levels can lead to increased flame and chemical resistance, or rigidity strength.
- In terms of maturity, the company began operating a demonstration facility in 2018. Econic plans to sell its catalysts to chemical companies with existing polyol and PU production capabilities.
- Global CO_2 Initiative should regard Econic's technology as promising due to its high degree of carbon uptake and performance. It should monitor Econic's collaborations to verify cost and performance.

covestro

- In cooperation with RWTH Aachen, the company developed a catalyst technology to produce polyether carbonate polyols using CO_2 as feedstock, which it then uses in the production of polyurethanes.
- Key claims of the organization include the ability to incorporate up to 20% of CO_2. Also, the mechanical properties of the resulting PUs are at least at the level of conventional thermoplastic PUs of similar hardness, or even exceed them (e.g. tensile strength, moldability).
- Since 2016, Covestro has been operating a 5,000MT per annum plant in Germany. It uses CO_2 as a by-product of a neighboring chemicals plant.
- The company has partnered with downstream application developers to showcase its material in walkways, shoes, wind turbine components, and automotive parts.
- Global CO_2 Initiative should view Covestro's strategy of application development as key to the success of the overall CO2-based polymers space, even when CO_2 content is not the highest in the industry.

LUX TAKE

The production of polycarbonate polyols as a feedstock for the production of polyurethanes is the most mature application of CO_2-based polymers. However, growth will be strongly dependent on developers focusing on applications that demonstrate similar or improved performance to incumbent materials.

Key barriers and risks include finding the right applications for CO_2-based polymers and development of end-of-life infrastructure

Key Barriers and Risks	Means to Mitigate*
Technology barriers Medium technology barriers, but cost reductions are necessary to scale-up production. Delivering products with clear performance characteristics compared to incumbents remains key	• Optimizing catalytic process technologies to improve product yields • Focusing on application development to **determine optimum CO_2 content that leads to desirable performance characteristics**
Policy and regulation barriers No regulatory barriers have been identified for the adoption of CO_2-based polymers. Regulatory incentives for more sustainable polymer development is starting to focus more on recyclability and biodegradability attributes and not so much on CO_2 content.	• **Creation of certification standards for polymers with captured-CO_2 content** • Accelerating development of technologies with biodegradability attributes (e.g. PPC, PHA) on par with the deployment of waste collection and separation infrastructure capable of **separating novel materials from conventional recycling streams**
Supply chain and logistics barriers Accounting for CO_2 supply shortages increases dependence on carbon capture infrastructure Infrastructure for end-of-life recovery of materials is lacking	• **Co-location of production facilities in sites with access to low-cost CO_2 feedstock** • Collaboration with different value chain stakeholders to develop recycling technologies in parallel with collection and composting infrastructure

* Examples of key developments pertinent to mitigation are listed on the next slide

Key developments center on lower cost and high-performance materials able to take up CO_2 from waste gases

KEY TECHNOLOGY ACTIVITY

- **University of Oxford (United Kingdom):** Development of catalyst technologies for copolymerization of CO_2 and epoxides for the production of novel high-molar mass polycarbonates with attractive thermal and mechanical properties (i.e. elongation, toughness, thermal stability).
- **Texas A&M (United States):** Develops polycarbonates using novel catalysts that react epoxides, CO_2 and carbonyl sulfide. The process can tune the polycarbonate to obtain PCs with attractive optical properties.
- **University of Zürich (Switzerland):** The university is developing methods for the production of PHB using photoautotrophic cyanobacteria relying on CO_2 and light as feedstocks. The group focuses on medium design, the genetic engineering to accumulate PHB, and the continuous operation of photobioreactors.
- **University of Heidelberg (Germany):** Together with BASF, the group is developing a process that employs butynediol, expoxides, and CO_2 to produce polycarbonates and polyurethanes. The process for PU production does not rely on isocyanates.

KEY MARKET ACTIVITY

- **Argonne National Laboratory (United States):** A team from government and academia partnered to execute a comprehensive assessment of material flows of polyurethane in the U.S. The team is focused on understanding new opportunities for recycling and replacing the chemicals used in its production for low-carbon alternatives.
- **Danimer Scientific (United States):** The company, in partnership with Mars Wrigley, has developed a PHA packaging with certification for home composting. Though the PHA is not based on CO_2, this certification addresses the lack of composting infrastructure and differing standards to deal with biodegradable materials such as PHA.
- **Carbon4PUR (EU):** In an effort to secure low-cost CO_2 feedstock and support the decarbonization efforts of the steel industry, the consortium led by Covestro is developing a technology to recover CO and CO_2 from blast furnace gas to produce polyols. The consortium also focuses on the use of such polyols for insulation boards and coatings.

LUX TAKE

Technology developments in polymers are motivated by the need to reduce costs and to demonstrate the high-performance of the resulting products. While no regulatory barriers exist to adopt CO_2-based materials, incentives are still lacking. Improving the end-of-life of polymers will benefit the deployment of CO_2-based alternatives.

Polyurethane hits cost tipping point by the end of the decade and steadily gains market traction towards US$191 billion market size

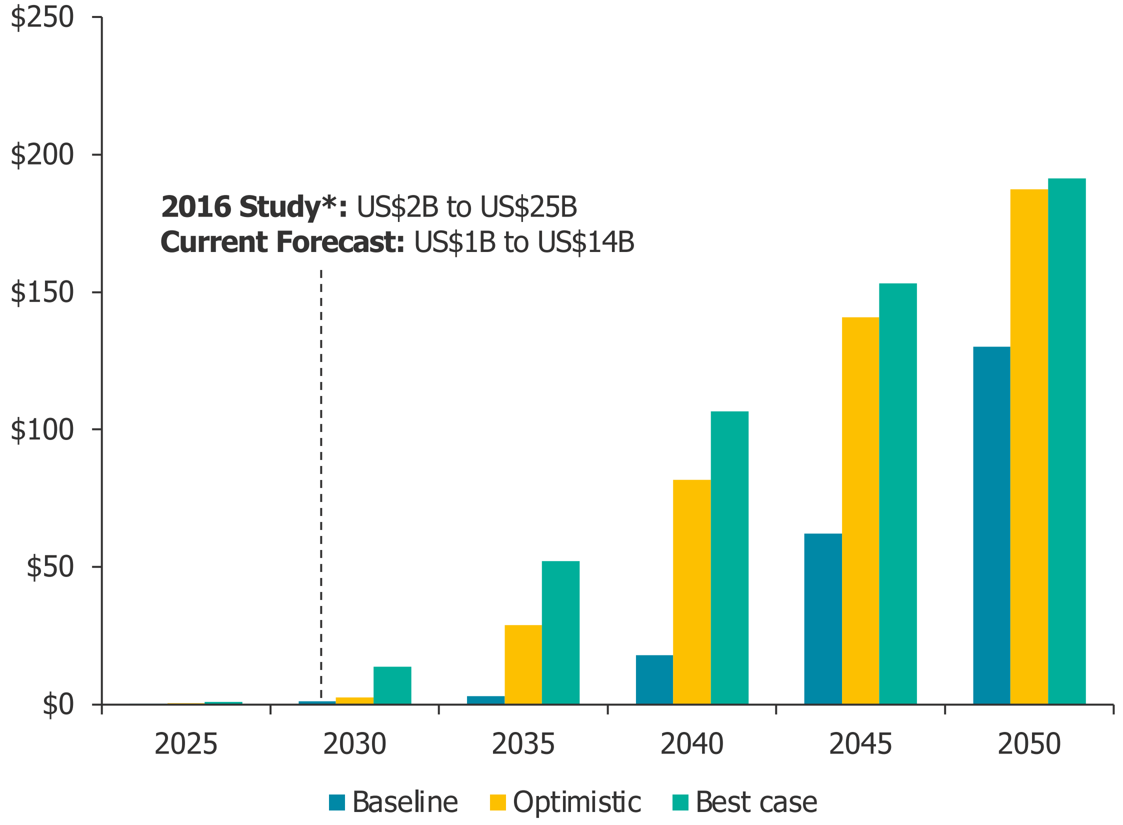
MARKET POTENTIAL

- The global polyurethane market is expected to grow to US$217 billion by 2050 with a CAGR of 3%
- **Baseline.** Cost tipping point occurs in 2038 with a CAGR of 26% through 2050 to reach a market size of US$130 billion.
- **Optimistic.** Cost tipping point occurs in 2031 with a CAGR of 20% through 2050 to reach a market size of US$187 billion.
- **Best case.** Cost tipping occurs in 2028 with a CAGR of 18% through 2050 to reach a market size of US$191 billion.

MARKET DRIVERS

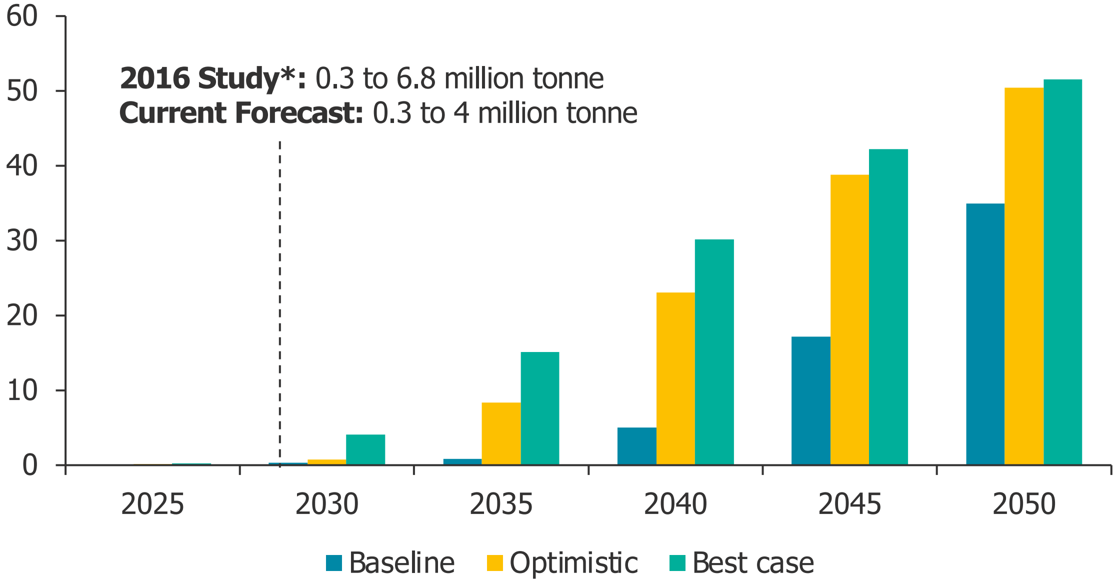
- While cost competitiveness would typically result in a shift towards CO_2-derived products, performance characteristics of polyurethanes for specific applications may prompt the industry to seek alternatives
- Advancements in catalyst technology will be the main driver in cost reduction with carbon pricing having a minimal impact
- Cost-parity without carbon pricing will be achieved in 2028 in the best case scenario and by 2031 in the optimistic scenario, both of which are the cost topping point with carbon pricing

Global Polyurethane Market Value
US$ billion (*2016 study on polycarbonates and polyols)

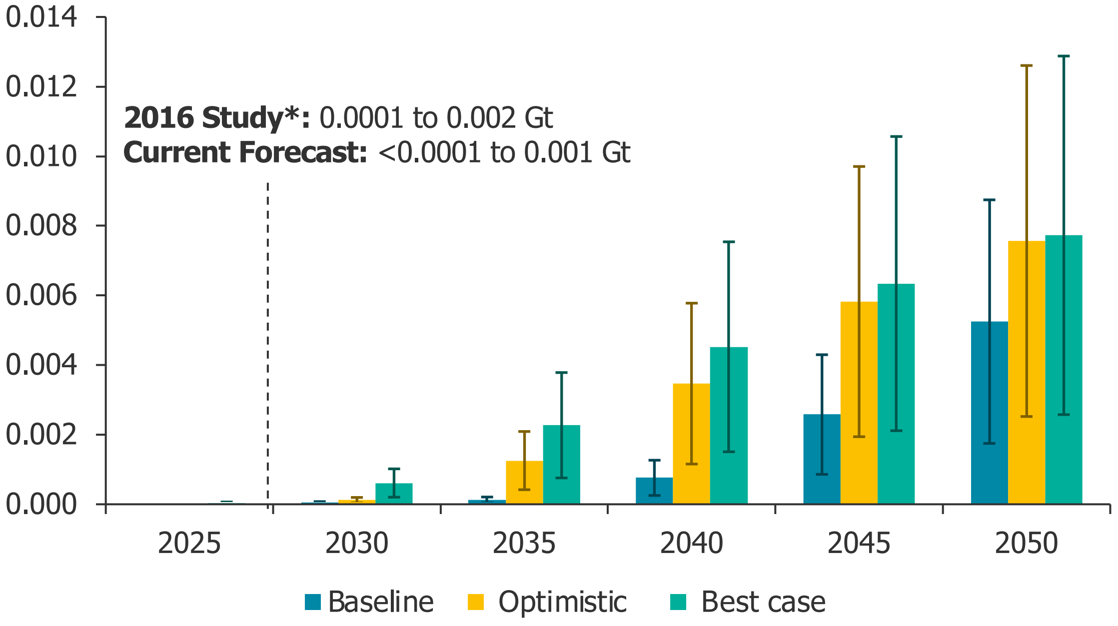


Less than 0.02 Gt of CO_2 can be potentially utilized annually as CO_2-derived polyurethane take up 88% market share

Global Polyurethane Market Volume
Annual million tonne (*2016 study on polycarbonates and polyols)



Global Polyurethane CO_2 Utilization Potential
Annual Gt of CO_2 (*2016 study on polycarbonates and polyols)

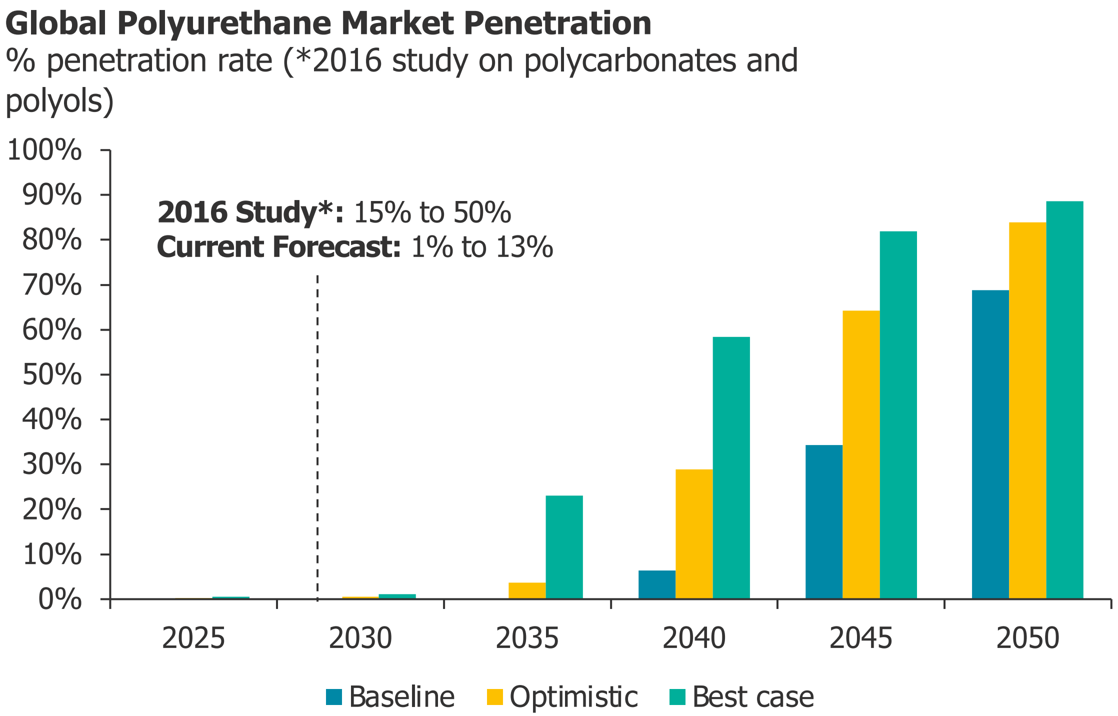


Error bars reflect the range of CO_2 utilization in the low CO_2 uptake scenario of 0.05 MT of CO_2/MT of polyurethane and high CO_2 uptake scenario of 0.25 MT of CO_2/MT of polyurethane.

LUX TAKE

Despite the low CO_2 utilization potential CO_2-derived polyurethane are expected to quickly gain market traction given its common use in consumer-facing products and signals in the industry indicate companies are willing to accept a premium assuming there is public recognition of their sustainability efforts.

Projected market penetration of CO_2-derived polyurethane for three adoption scenarios



The overall market is the native incumbent market, and the penetration rate is defined as the potential replacement of incumbent product with CO_2-derived products based on the baseline, optimistic, and best case scenario. Projected market volume of polyurethane is 58 million MT by 2050 based on a 24 million MT market volume in 2020 and an estimated CAGR of 3%.

CCU End Product Assessment
Track 2: Chemicals, food, and fuels

Chemicals

CO_2 utilization for chemicals focuses on C1 chemicals using thermochemical, electrochemical, or biochemical technologies

TECHNOLOGY OVERVIEW

- CO_2 utilization technology for chemicals usually target C1 chemicals such as carbon monoxide (or syngas), formic acid, and methanol; more complex molecules such as ethylene, mono-ethylene glycol (MEG), or ethanol can also be produced.
- Technologies are either thermochemical via heterogeneous catalysis, electrochemical with the use of CO_2 electrolyzers, or biological via microbial conversion.
- CO_2 utilization present the chemical sector with a decarbonization pathway while retaining the use of the carbon atom, assuming the CO_2 feedstock is non-fossil in nature.

CHALLENGES AND PROSPECTS

- CO_2 utilization for chemicals is an energy-intensive process that also requires an external source of hydrogen, preferably green hydrogen for zero-carbon chemicals, result in production costs often magnitudes more expensive than their fossil counterpart.
- There are currently no regulatory incentives for the adoption of low-carbon chemicals in the industry, which is needed to offset the higher cost of CO_2-based chemicals.
- Target molecules are globally-traded commodities with highly optimized supply chains and low profit margins, limiting the willingness of the industry to pay a premium and further exacerbating the challenges for widespread adoption.

Number of Developers, Chemicals

Technology	Methanol	Formic acid
Technology maturity	Introduction	Development
Average developer TRL	6	4
CO_2 consumption (tCO_2/tonne product)	1.28 to 1.5	0.49 to 0.96
Market size, best case (2050)	US$183 billion	US$0.8 billion
CO_2 utilization potential, best case (annual Gt)	0.53	0.001
Cost tipping point, best case (year)	2036	Cost parity today

Note: Many technology developers target syngas which itself is not a product but an intermediate that is consumed within the operation itself. As such, there is no market for syngas.

Large corporations lead the IP landscape for CO_2-based chemicals but growing academic activity suggests potential for breakthroughs

COMMERCIAL INTEREST

- Leading patent filers include Liquid Light (acquired by Saudi Aramco in 2017), Siemens, and Haldor Topsoe – start-ups that also have sizeable IP portfolio include Dioxide Materials and FuelCell Energy.
- CO_2 electrolysis technology dominates the IP landscape – the aforementioned companies all develop electrochemical platforms for CO_2 conversion.
- As the space develops, technology differentiation will become key, and we expect IP activity to ramp up as companies will seek to protect their competitive advantage.

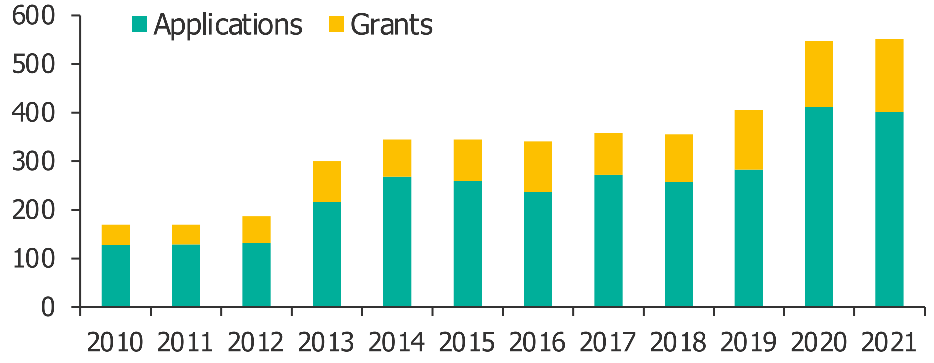
R&D INITIATIVES

- Leading academic institutes include the Chinese Academy of Sciences, Centre National de la Recherche Scientifique (CNRS), and the Korea Advanced Institute of Science Technology (KAIST).
- The institutes typically focus on novel catalyst development, whether for thermochemical or electrochemical platforms. For example, KAIST focuses on the development of Ni-based electrocatalysts for reduction of CO_2.

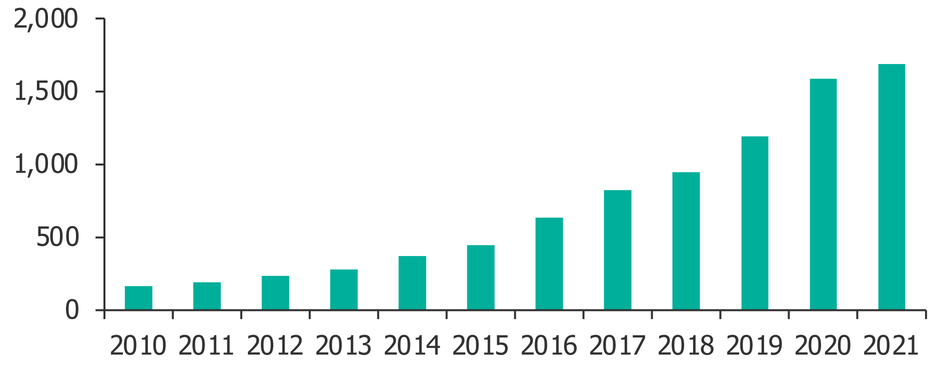
LUX TAKE

The ramp up in patent activity shows that companies are gearing up for scale but an even faster growth in academic activity indicates that there are still opportunities for disruptive technologies in the space.

Chemicals Patent activity
Number of patent publications



Chemicals Academic activity
Number of academic publications



Venture capital activity picks up in recent years with growing pool of technology developers

NOTABLE INVESTMENTS

- VC funding in CO_2-based chemicals has ramped up with a total of US$273 million in disclosed funding, of which US$186 million came in 2021 alone.
- The largest funding recipient is Sunfire with a US$126 million Series D in October 2021, followed by Twelve who raised a total of US$68 million since inception, including US$57 million in 2021
- The growing pool of startups in CO_2-based chemicals provides more opportunities for VC funds to play into the market and funding will likely ramp up over the years.

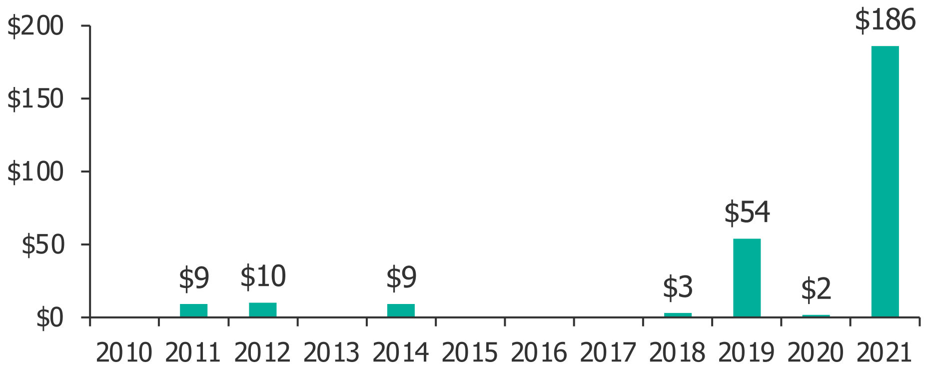
KEY DEVELOPMENTS

- VC funding targets early-stage opportunities as the CO_2-based chemicals space is not yet commercial – technology-scale up in chemicals is capital intensive and startups needs significant cash injections to progress to higher TRLs.
- The recent funding raise of Twelve and Cemvita Factory will enable both companies to advance towards commercialization – Twelve is currently pursuing commercial opportunities with its CO_2 electrolyzer while Cemvita is building its first pilot unit to demonstrate its synthetic biology platform for CO_2 utilization.

LUX TAKE

The initially-low funding is likely due to the VC industry's lack of recognition for CO_2 utilization combined with sparse opportunities earlier in the decade. Given that development today is mostly driven by startups, VC funding will likely grow.

Chemicals VC funding
US$ million



twelve

Total disclosed funding: $68M
Investors: Capricorn Technology Impact Fund, Carbon Direct Capital Management

CEMVITA FACTORY

Total disclosed funding: $10M
Investors: Energy Capital Ventures, Mitsubishi Heavy Industries

Dioxide Materials – The CO_2 Recycling Company

Total disclosed funding: $4M
Investors: ARPA-E

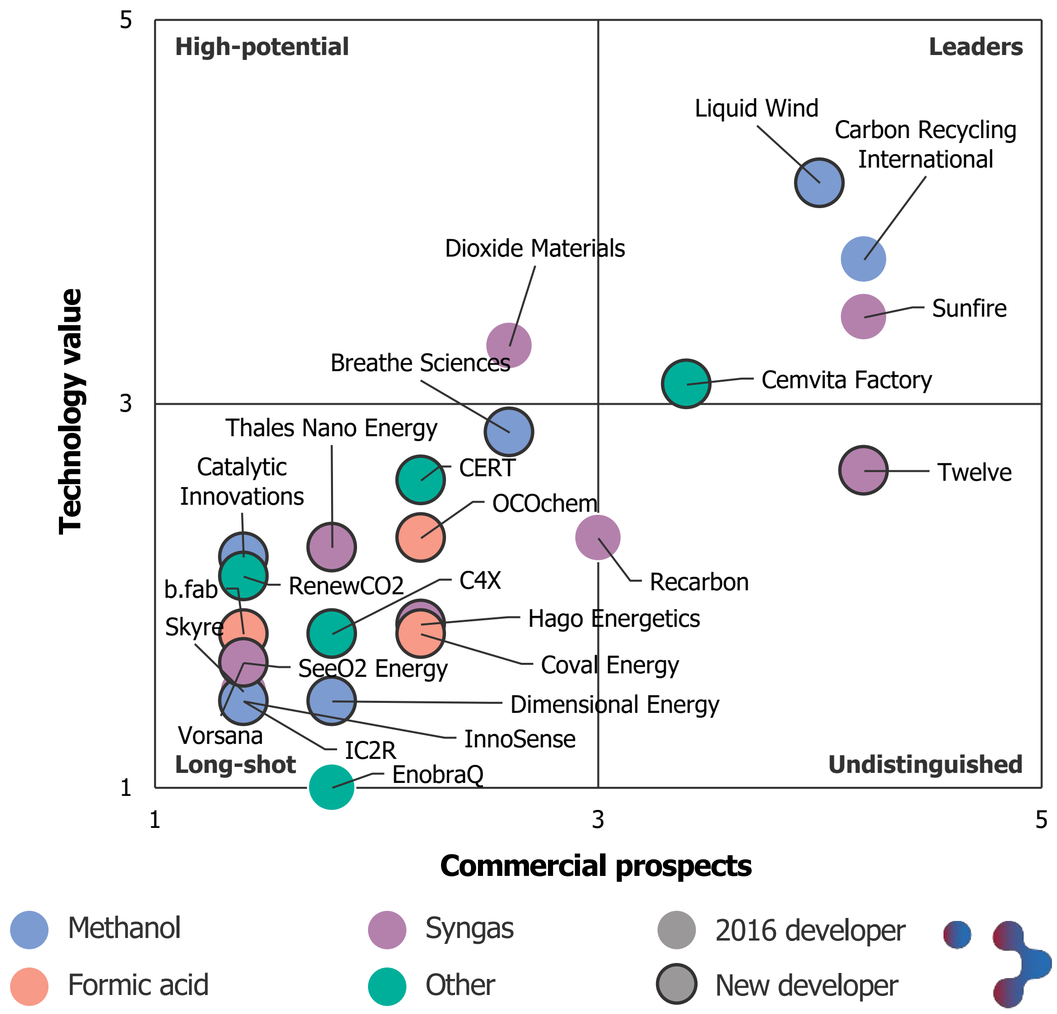
Startups crowd the developer landscape but still lack differentiation and struggle to commercialize

DEVELOPER LANDSCAPE

- The developer landscape for CO_2-based chemicals is highly crowded, dominated by startups, and immature; many of the companies are less than five years old.
- The majority of startups focus on CO_2 electrolysis technology for producing either syngas, methanol, or formic acid.
- Given the relatively early stage of development, technology developers today are largely undifferentiated; however, some startups such as Sunfire and Carbon Recycling International are ahead of the pack due to higher performance or more advanced stage of development.

MARKET DYNAMICS

- Methanol is a clear near-term winner in CO_2-based chemicals, with both Liquid Wind and Carbon Recycling among the leaders in the space; the catalytic technology for converting CO_2 to methanol is validated at demo-scale and ready for commercialization.
- Startups that are breaking away from the competition (Sunfire, Cemvita, Twelve) are doing so by attracting external partners either for funding or for project development.
- Given the capital-intensive nature of scaling up novel chemical platforms, partnerships will be the key driver for commercial success in the space.



Sunfire and Cemvita Factory are developing novel technology approaches to CO_2 utilization for chemicals

sunfire®

- The company was founded in 2010 and is based in Germany. Its core product is a stack of high-temperature solid oxide cells that can be used for both water and CO_2 electrolysis; for the latter, the stack operates in co-electrolysis mode to produce syngas from water and CO_2
- To date the company has raised about US$200 million; most recently the company close a US$126 million Series D funding round led by Lightrock and Planet First Partners
- With regards to its CO_2 electrolyzer, key claims of the organization include a system efficiency of 84% and a stack lifetime of 50,000 hours
- In terms of maturity, the company is at demo scale and offers a 3.0 MW CO_2 electrolyzer; it expects commercial systems above 10 MW by 2025
- Global CO_2 Initiative should regard Sunfire as a leader in CO_2 electrolysis technology and monitor the company's scale-up as it gears up for commercialization

CEMVITA FACTORY

- The company was founded in 2017 and develops a synthetic biology platform; its focus is on engineering cyanobacteria for CO_2 utilization
- To date the company has raised about US$10 million of disclosed funding; most recently the company closed its Series A funding round of undisclosed amount led by Energy Capital Ventures, Mitsubishi Heavy Industries, and Oxy Low Carbon Ventures
- Key claims include a scale-up timeline of 5 years from initial strain optimization to 10,000-liter demo capacity for engineering cyanobacteria; additionally, the company has a product portfolio of 35 chemicals
- In terms of maturity, the company is at laboratory-scale; it completed strain optimization at the 1-liter capacity for CO_2-to-ethylene and plans to build a pilot unit by 2022.
- Global CO_2 Initiative should monitor Cemvita as it the first application of synthetic biology for CO_2 utilization technology, however, Cemvita will likely face challenges as it scales from lab to production.

LUX TAKE

The production of chemicals from CO_2 is still at the development stage. While more mature applications such as CO_2 hydrogenation for methanol have been scaled to the demo stage, new technological approaches such as high-temperature electrolysis or synthetic biology offer interesting commercialization opportunities.

Key barriers and risks includes the lack of regulatory support to drive adoption and the need for a cheap source of renewable energy

Key Barriers and Risks	Means to Mitigate*
Technology barriers Medium technology barriers; technologies for converting CO_2 into chemicals are still at the development stage and require improvements in energy efficiency and selectivity, given that energy costs are often the largest contributor to costs of production.	• Improve economics via development of **high-performance catalysts with longer lifetimes** • Enhancing single-pass syngas conversion efficiency to **minimize energy consumption as well as recycling streams within the system** for CO_2-to-methanol conversion • **Optimizing catalyst and system performance** to breakthrough the current 60% energy efficiency ceiling for CO_2-to-CO
Policy and regulation barriers Despite the broader decarbonization movement sweeping through the chemical industry, there is still a lack of concrete policies to incentivize the adoption of low-carbon feedstock in the sector.	• Incentivize adoption with **policies that take into account the carbon footprint of the chemical**, which would penalize the use of fossil carbon in the supply chain and make alternative sources of carbon feedstock (such as CO_2) more economically viable.
Supply chain and logistics barriers Due to the high energy demand for conversion, the production of CO_2-based chemicals requires cheap renewable energy in order to approach price-parity with fossil chemicals. These resources are only limited to certain geographies in the world, for the Middle East, Australia, Africa, and South America.	• Mitigate lack of local capacity for renewable energy production with the **establishment of a global renewable energy trading network** with hydrogen (either in pure form or as ammonia) as an energy carrier • **Success in CO_2-based chemicals invariably depends on successful development of a hydrogen economy.**

* Examples of key developments pertinent to mitigation are listed on the next slide

Companies focusing on technologies with improved performance or collaborating to accelerate development and deployment

KEY TECHNOLOGY ACTIVITY

- **Dioxide Materials (United States):** Unlike competing CO_2 electrolysis developers, the company use a novel anionic exchange membrane (AEM) in its system, claiming an energy efficiency of 80% and catalyst selectivity of up to 98% for carbon monoxide.
- **Cemvita (United States):** Technology developers need a renewable source of hydrogen to combine with CO_2 which leads to high costs; Cemvita's microbial platform obtains hydrogen directly from water which will likely result in lower costs of production and allow the company to operate independently of local renewable energy availability.
- **Siemens and Evonik (Germany):** The companies formed the Rheticus project in 2018 to produce butanol and hexanol from CO_2; Siemens' CO_2 electrolyzer will produce carbon monoxide which feeds into Evonik's microbial platform to produce alcohols. Higher-value specialty chemicals made from butanol and hexanol can stomach the higher costs of CO_2 utilization better than a commodity market such as methanol.

KEY MARKET ACTIVITY

- **BASF (Germany):** In July 2020, BASF made available the carbon footprint of its portfolio of 45,000 products to customers. The move will lead to a better understanding of the role of using fossil carbon in the supply chain and highlights the potential of alternative sources of carbon, including CO_2 gas for CO_2 utilization applications.
- **Voltachem (Netherlands):** The Voltachem initiative was launched in 2014 and is a collaborative of large corporations and research institutions to accelerate the electrification of industry. Key projects including the development of electrolysis platforms for CO_2 utilization in industry.
- **Air Products, ACWA Power (Saudi Arabia).** Air Products and ACWA Power announced an agreement to build a US$5 billion, 1 GW electrolzyer and a 1.2 million tpa green ammonia facility in the planned city of NEOM in Saudi Arabia. The green ammonia will be shipped around the world for renewable hydrogen supply, developing a renewable energy export supply chain with the potential to feed energy and feedstock needs for CO_2 utilization projects in regions with lack of access to a cheap source of renewable energy.

LUX TAKE

Market adoption of CO_2-based chemicals relies on low costs coupled with strong regulatory incentives. Momentum in technology innovation is growing but implementation of regulatory measures lags – successful validation of the technology at demo-scale is therefore crucial to de-risk the technology and attract support of policymakers.

Lux Research

Methanol hits cost tipping point in 2036 and grows to US$183 billion market with consistent global demand for commodity chemicals

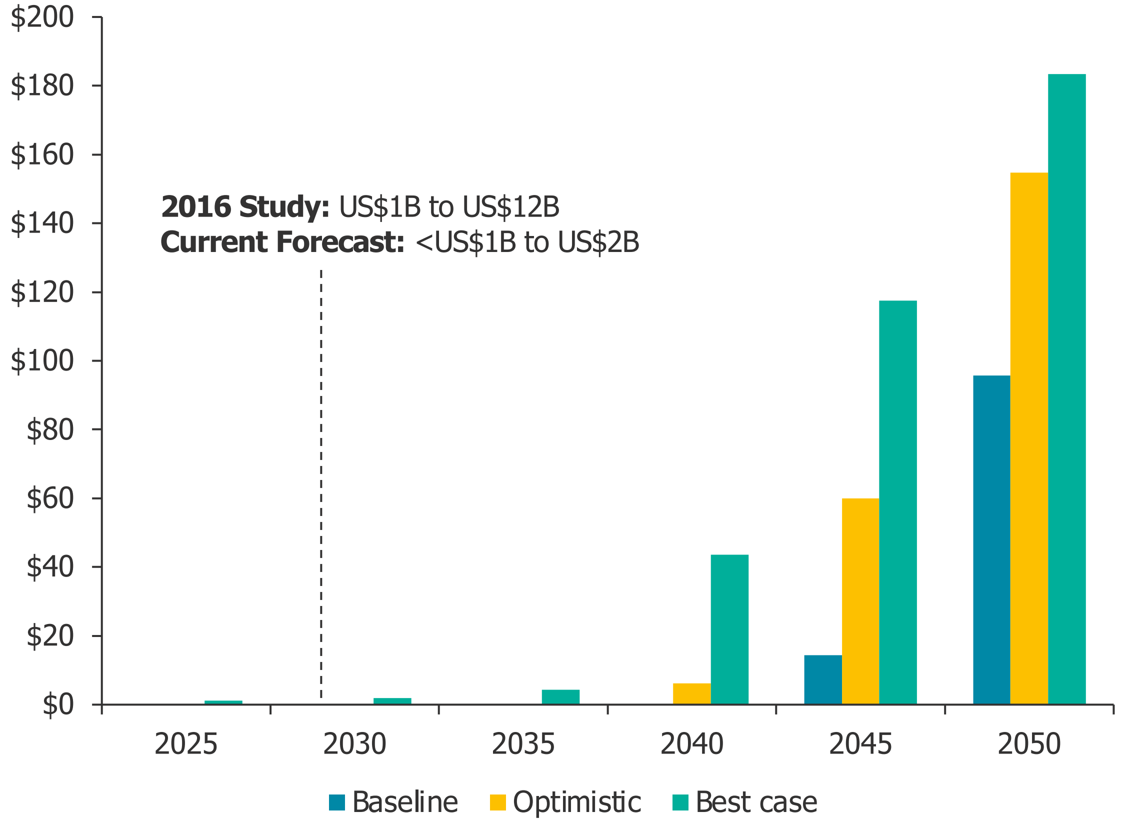
MARKET POTENTIAL

- The global methanol market is expected to grow to US$204 billion by 2050 with a CAGR of 5% as demand for commodity chemicals continues to rise.
- **Baseline.** Cost tipping point occurs in 2044 with a CAGR of 55% through 2050 to reach a market size of US$96 billion.
- **Optimistic.** Cost tipping point occurs in 2040 with a CAGR of 38% through 2050 to reach a market size of US$255 billion.
- **Best case.** Cost tipping occurs in 2036 with a CAGR of 25% through 2050 to reach a market size of US$183 billion.

MARKET DRIVERS

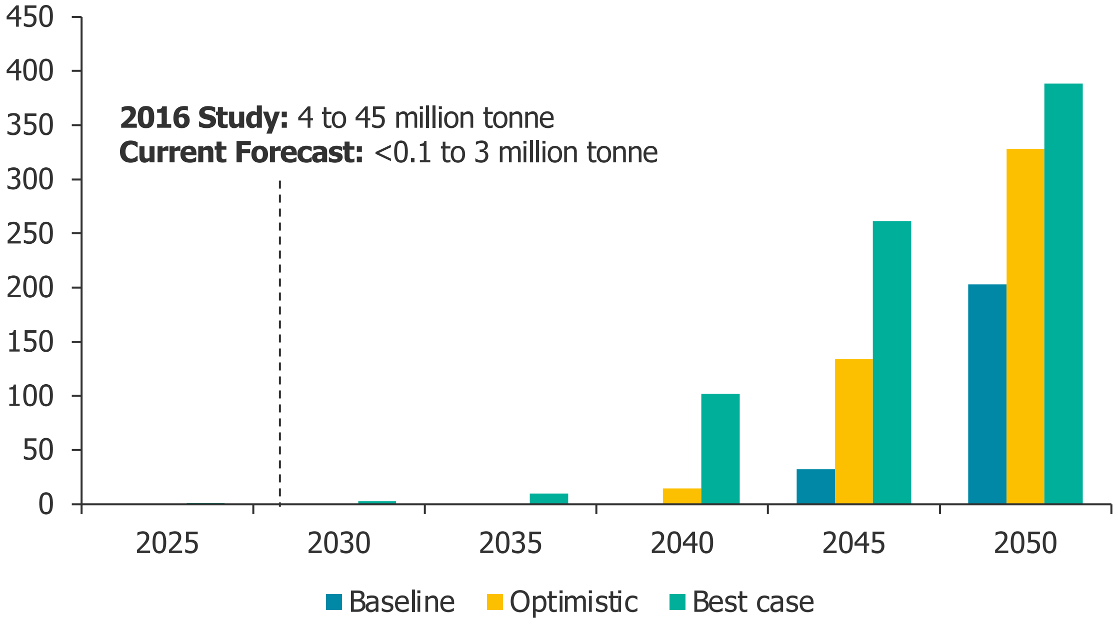
- As a commodity chemical, significantly reducing cost of production from the current US$1,381/tonne remains the key commercialization hurdle.
- While carbon pricing will play a role, advancements in electrolysis technology, CO_2 hydrogenation catalysts, and access to low-cost renewable electricity will have the most impact on CO_2-derived methanol economics; specifically renewable electricity prices of US$10/MWh
- Cost-parity without carbon pricing will still be achieved by 2039 in the best case scenario and by 2043 in the optimistic scenario, highlighting policy's lesser role in CO_2-derived methanol adoption

Global Methanol Market Value
US$ billion

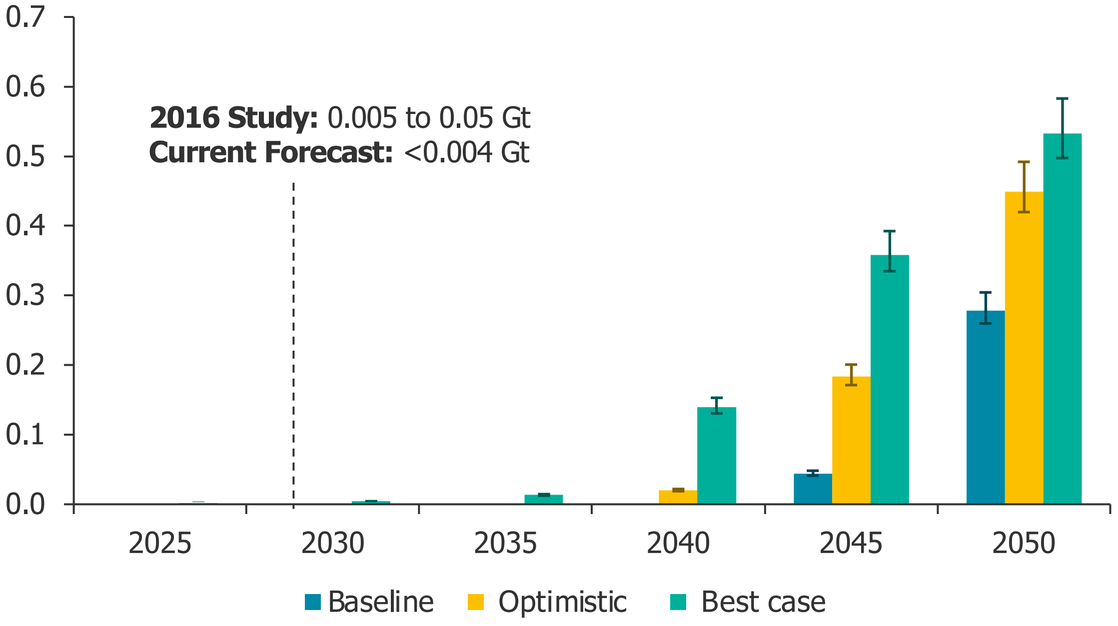


Nearly 0.6 Gt of CO_2 can be potentially utilized annually as CO_2-derived methanol take up 90% market share

Global Methanol Market Volume
Annual million tonne



Global Methanol CO_2 Utilization Potential
Annual Gt of CO_2



Error bars reflect the range of CO_2 utilization in the low CO_2 uptake scenario of 1.28 tCO_2/ tonne of methanol and high CO_2 uptake scenario of 1.5 tCO_2/ tonne of methanol.

LUX TAKE

Continued technology advancements and growing capacity of low-cost renewable electricity will play a key role in accelerating the commercialization of CO_2-based methanol. However, despite rapid adoption, CO_2 utilization potential is inherently limited by the size of the global methanol market itself.

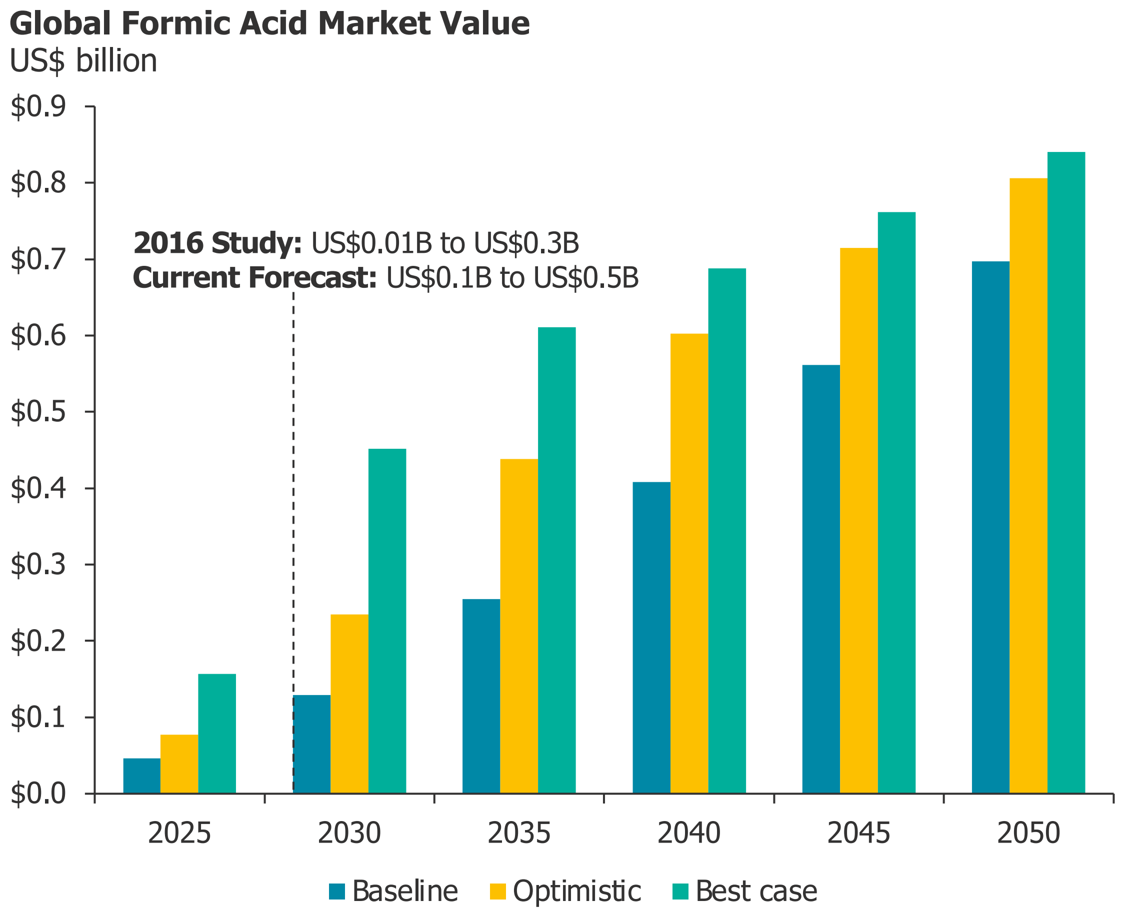
CO_2–based formic acid already cost competitive and witnesses widespread adoption to reach market size of US$841 million

MARKET POTENTIAL

- The global formic market is expected to grow to US$883 million by 2050 with a CAGR of 2%.
- **Baseline.** Cost parity is already achieved with a CAGR of 14% through 2050 to reach a market size of US$697 million.
- **Optimistic.** Cost parity is already achieved with a CAGR of 16% through 2050 to reach a market size of US$806 million.
- **Best case.** Cost parity is already achieved with a CAGR of 17% through 2050 to reach a market size of US$841 million.

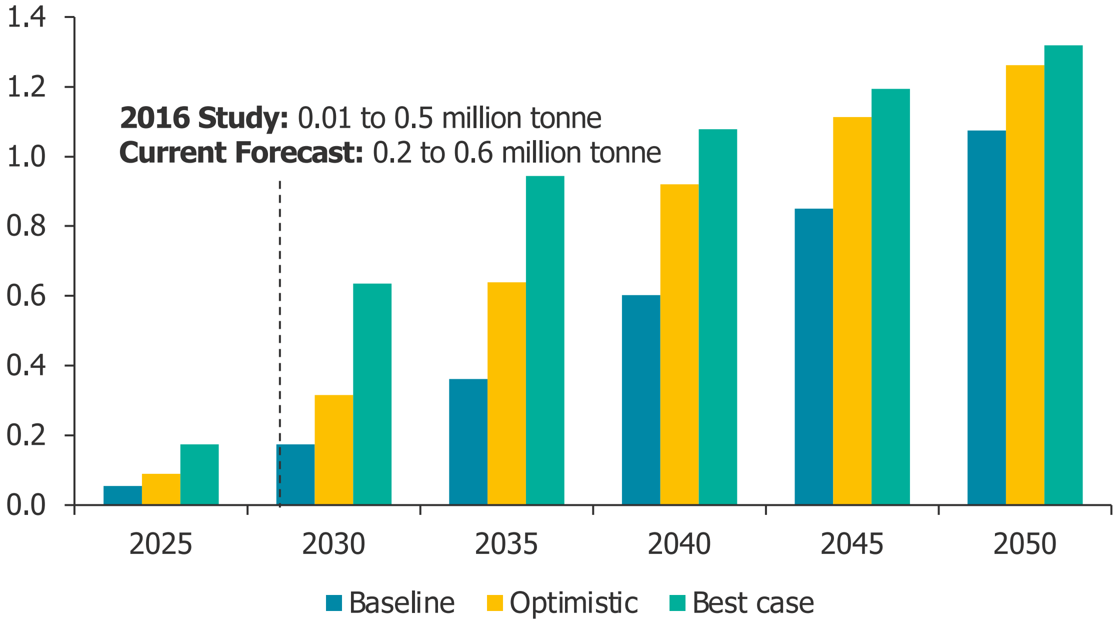
MARKET DRIVERS

- With CO_2-based formic acid already at cost parity with the incumbent, widespread adoption will be slowed by market dynamics – not technological advancements – with a highly consolidated formic acid industry likely to maximize their existing assets before shifting to an electrochemical platform for formic acid production
- Cost will be a non-factor and the acceleration of adoption will only come as the industry sees the benefits of supply chain security and sustainability benefits

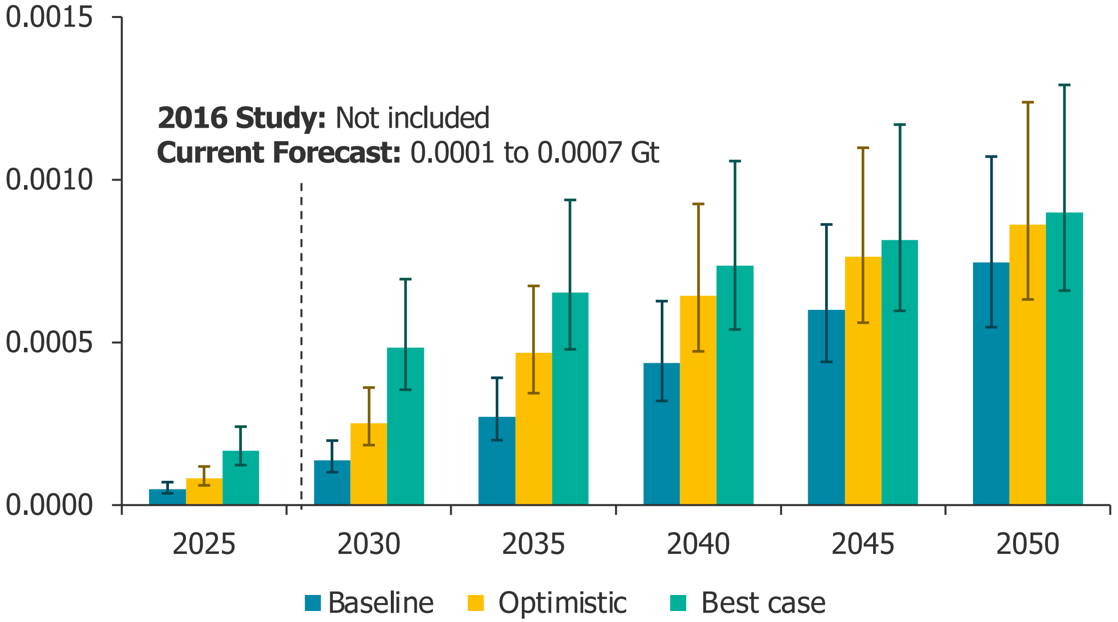


Despite a 95% market penetration, formic acid's inherently small market size leads to a negligible CO_2 utilization potential

Global Formic Acid Market Volume
Annual million tonne



Global Formic Acid CO_2 Utilization Potential
Annual Gt of CO_2



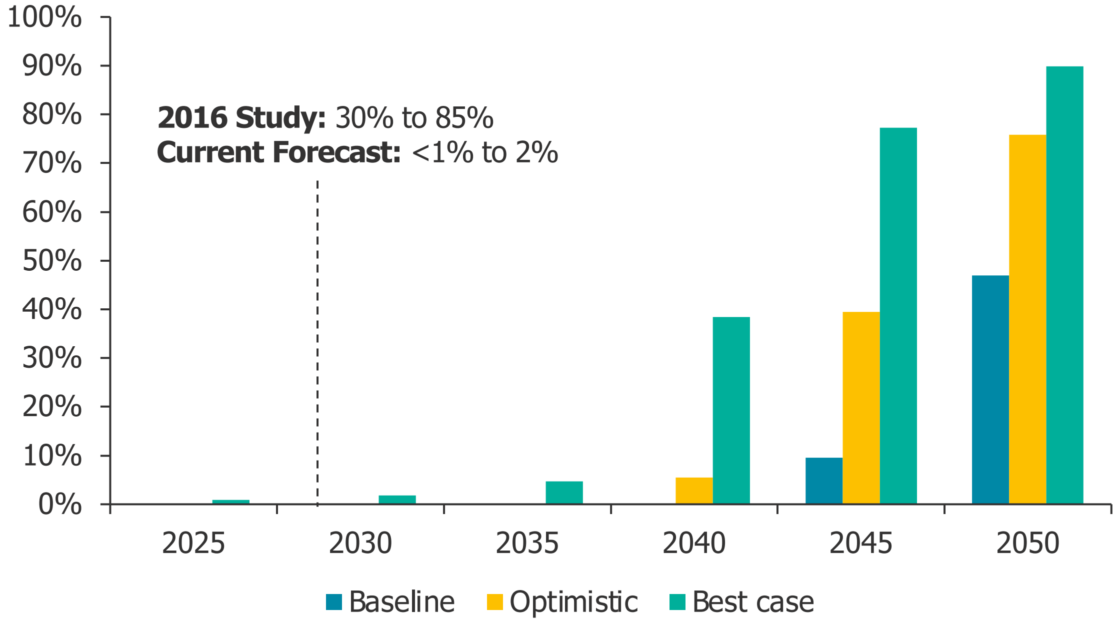
Error bars reflect the range of CO_2 utilization in the low CO_2 uptake scenario of 0.49 MT of CO_2/MT of formic acid and high CO_2 uptake scenario of 0.96 MT of CO_2/MT of formic acid.

LUX TAKE

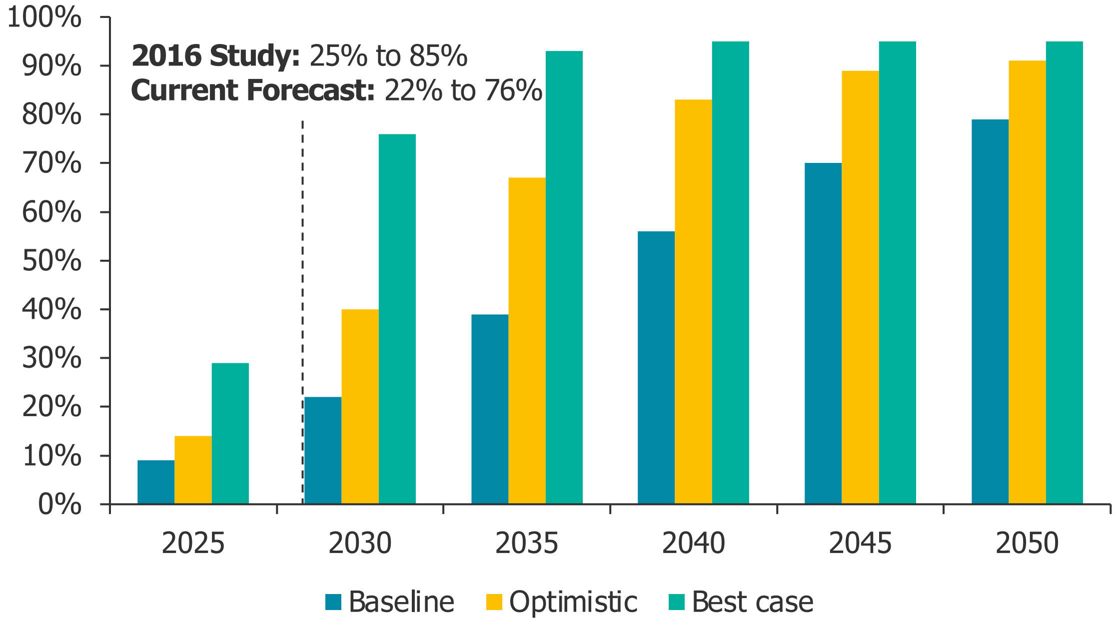
With no emerging applications or competitive technologies, CO_2-based formic acid will displace conventional formic acid in the long-term. The overhaul of the existing formic acid supply chain remains key barrier, with the timeline only potentially accelerated with swift regulatory policies.

Projected market penetration of CO_2-based methanol and CO_2-based formic acid for three adoption scenarios

Global Methanol Market Penetration
% penetration rate



Global Formic Acid Market Penetration
% penetration rate



The overall market is the native incumbent market, and the penetration rate is defined as the potential replacement of incumbent product with CO_2-derived products based on the baseline, optimistic, and best case scenario. Projected market volume of methanol is 432 million MT by 2050 based on a 100 million MT market volume in 2020 and an estimated CAGR of 5%. Projected market volume of formic acid is 1.4 million MT by 2050 based on a 780,000 MT market volume in 2020 and an estimated CAGR of 2%.

Food

Protein production for animal and human consumption is a nascent opportunity gaining significant industry interest

TECHNOLOGY OVERVIEW

- Single cell protein is produced through microbial fermentation where the CO_2 is consumed along with hydrogen and nitrogen to produce high protein content (50% to 85%) cellular biomass
- Both genetically modified and wild-type microbes are currently used; advancements in synthetic biology to increase protein content and optimize energy and fuel conversion are a vital key towards commercial scale up
- Majority of CO_2-to-protein developers are in the lab scale with activity concentrated in research institutes and speculations of increasing corporate R&D to build up technical know-how and proprietary processes

CHALLENGES AND PROSPECTS

- Given the early-stage nature of developments, technical challenges of the microbial conversion process is the primary focus; scale-up in production will introduce an entirely new set of challenges with regards to hydrogen and nutrient sourcing
- While single cell protein can serve both the animal feed and human food markets, stringent food safety regulations for human consumption and established fish and livestock agriculture industry will present challenging barriers for widespread adoption
- Conversely, an emerging supply gap between animal feed demand and production capacity is driving industry interest in alternative protein sources to meet the needs of the growing fish and livestock industry

Number of Developers, Food

Technology	Animal feed
Technology maturity	Lab
Average developer TRL	3
CO_2 consumption (tCO_2/tonne product)	0.5 to 0.7
Market size, best case (2050)	US$921 billion
CO_2 utilization potential, best case (annual Gt)	0.34
Cost tipping point, best case (year)	2042

Note: Some technology developers target human protein but the regulatory and certification for human consumption remains challenging to predict. Until further visibility, this market is a niche market opportunity and is not included.

Interest is only beginning to pick up as an expected rise in academic activity will undoubtedly transition to more commercial activity

COMMERCIAL INTEREST

- Leading non-academic patent filers include Invista (11), Genomatica (3), and The Coca Cola Company (3), highlighting the wide range of R&D interest from various companies
- Kiverdi (parent company of Calysta) published a patent encompassing the microbial ecosystem for the production of protein and food via a suite of wild-type and genetically modified microbes
- While there is growing industry interest in CO_2-derived proteins, this has yet to be reflected in tangible commercialization and productization efforts

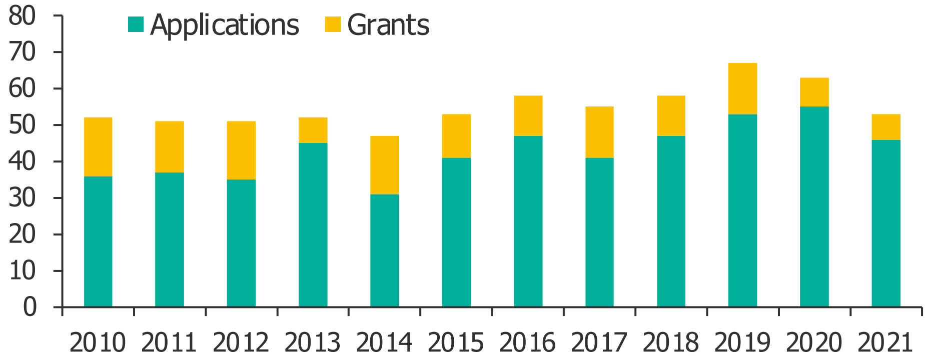
R&D INITIATIVES

- Leading academic institutes include the U.S. Department of Agriculture, Chinese Academy of Sciences, and the University of California System
- In 2020, VTT Technical Research Centre and Aalto University published a comparative techno-economic analysis highlighting the raw materials and energy needs for large-scale CO_2-derived protein production
- Growing academic activity will undoubtedly serve as the foundation of an emerging innovation landscape through numerous startup spinoffs

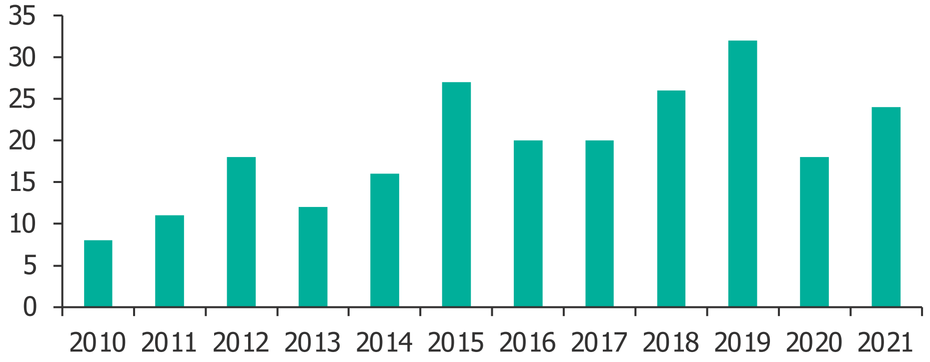
LUX TAKE

Outside of a select few developers, core technology development for CO_2-to-protein remains concentrated in research institutes or with proprietary in-house corporate R&D; developments are still at the earliest of stages.

Food Patent Activity
Number of patent publications



Food Academic Activity
Number of academic publications



Lux Research

CO_2-to-food startups add a new dynamic to the CCU landscape as VC funding is funneled towards startups for production scale up

NOTABLE INVESTMENTS

- VC funding in CO_2-to-food startups is a recent phenomenon, with $94 million in funds raised in the last two years.
- Developers targeting human food protein dominated the VC funding landscape with US$42 million for Solar Foods and US$32 million for Air Protein
- The emergence of CO_2-to-food startups in recent years adds another dynamic to the CCU developer landscape; despite long-term development timelines it can be expected to attract higher rates of funding going forward due to its consumer-facing aspect

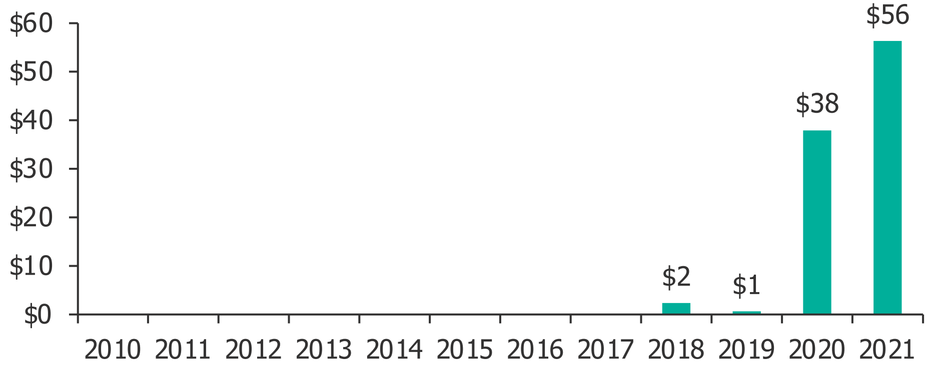
KEY DEVELOPMENTS

- Majority of VC funding is focused on building first-of-its-kind production facilities, with both Solar Foods and Novonutrients utilizing the recent injection of capital to scale up production beyond lab-scale
- Novonutrients is also building out its value chain downstream, engaging with fish feed companies in preparation for the production of its aquaculture feed alternative by 2023
- Clear signs point to VC funding being funneled towards startups with already proven lab-scale production capabilities

LUX TAKE

This is likely only the beginning of robust ecosystem for CO_2-to-protein startups as industry, investor, and consumer interest in alternative proteins will accelerate startup and VC activity in the years to come.

Food VC funding
US$ million



SOLAR FOODS
Total disclosed funding: $42M
Investors: Fazer, Finish Climate Fund, Lifeline Ventures

AIR PROTEIN™
Total disclosed funding: $32M
Investors: Barclay, ADM Venture, GV

Deep Branch BIOTECHNOLOGY
Total disclosed funding: $10.9 M
Investors: Novo holdings, DCM Venturing, European Innovation Council

Lux Research

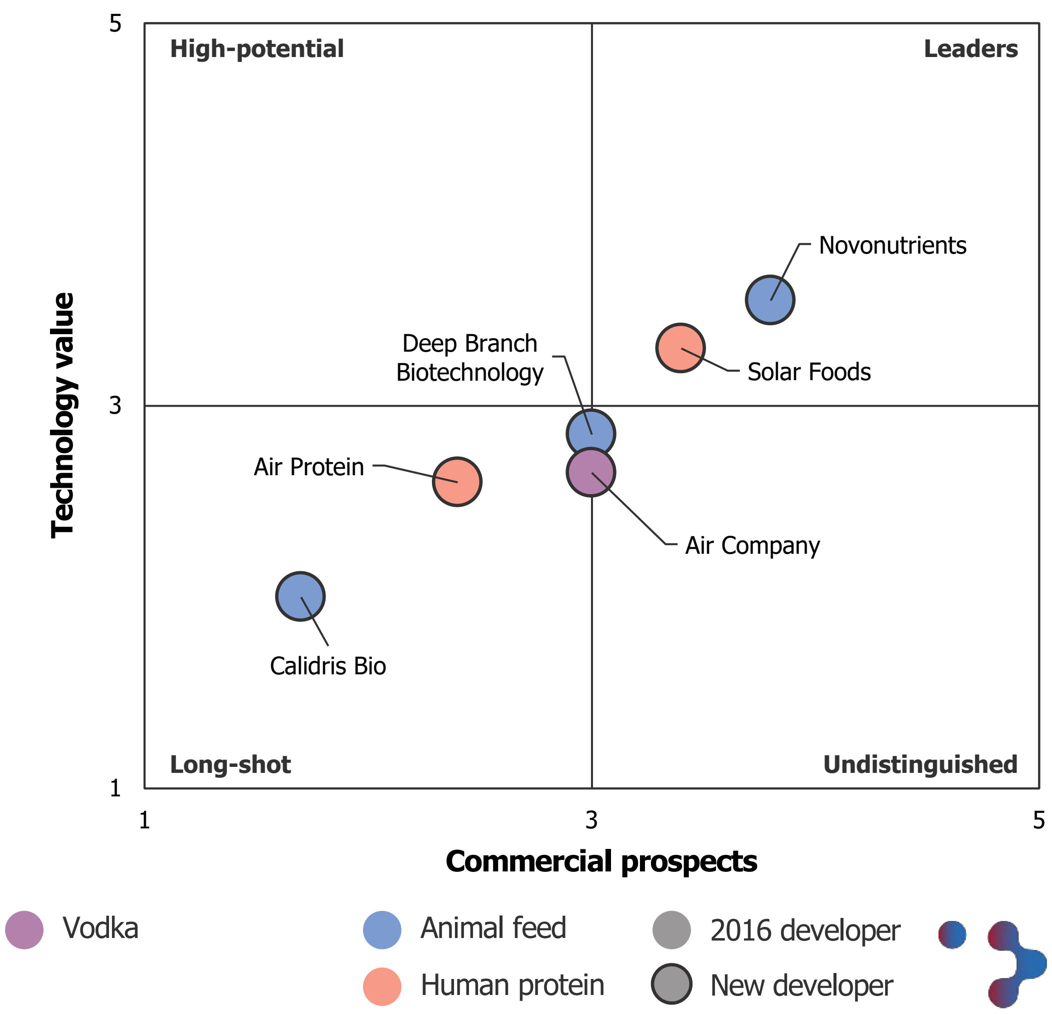
CO_2-to-food landscape remains sparse, but likely to see an uptick in activity in coming years with growing corporate interest

DEVELOPER LANDSCAPE

- The CO_2-to-food landscape remains in its nascent stages with no developer older than four years old with both Air Protein and Calidris Bio founded in 2019
- All developers remain in early-stages of development, either still in lab-scale production or small-scale pilots. Only Air Company is currently selling a commercial product, producing ethanol for vodka.
- Growing interest from the agriculture and food industry and influx of recent capital into the ecosystem will likely result in newly formed startups in the coming years

MARKET DYNAMICS

- Decreasing arable land, increasing food demand, and global decarbonization efforts is driving market interest in CO_2-to-food with key players such as ADM, Sainsbury's, and Fazer Group each with active collaborations with developers
- The market is segmented by animal feed and human protein developers. While human protein faces a stringent regulatory approval process, animal feed competes directly with an emerging portfolio of alternative solutions, such as insect- and algae-based products



Animal and human protein remain promising long-term opportunities but face challenging market dynamics

novonutrients food from CO_2

- The company was founded in 2017 and specializes in converting industrial CO_2 to single cell protein, utilizing hydrogen as a fuel source and harnessing microbial fermentation
- To date the company has raised about US$9.7 million in funding; most recently the company closed a US$4.7 million seed round led by Happiness Capital
- Key claims include over 90% CO_2 utilization at scale with its looping gas bioreactor that converts approximately 5 CO_2 for ever tonne of hydrogen
- In terms of maturity, the company operates a pilot system producing between 1,000 tonnes to 2,000 tonnes of protein flour; the company plans to build its systems on site of industrial facilities to source CO_2
- Global CO_2 Initiative should view the company's use of hydrogen as a fuel source and strategy to install systems directly at the CO_2 source key in improving energy efficiencies and keeping final product costs low

SOLAR FOODS

- The company was founded in 2017 and specializes in synthesizing proprietary protein powder – Solein – with its proprietary protein-producing fermentation platform using CO_2 and hydrogen
- To date the company has raised about US$42 millions; most recently the company closed a US$22 million Series A funding round led by Finnish food company Fazer Group
- Key claims include producing a 50% to 60% protein content product; the company is also targeting the use of green hydrogen and CO_2 derived from biogenic sources or direct air capture
- In terms of maturity, the company operates a 1 kg/day protein pilot-scale unit with plans to build a 3.5 tonne/day demonstration-scale facility by 2021
- Global CO_2 Initiative should be cautiously optimistic of Solar Foods prospects; the human food market faces significant regulatory hurdles that remain as major roadblocks for mass adoption

LUX TAKE

The production of food from CO_2 is at an early stage of development. With growing environmental regulations around land and water use for conventional protein, technical and financial support for the scale-up of production are a key signs of momentum of the technology as a major form of alternative proteins in the long-term.

Nascent technology leads to highly speculative barriers and risks across technology, regulation, and supply chain

Key Barriers and Risks	Means to Mitigate*
Technology barriers Desired use of green hydrogen as a fuel source for many developers will lead to challenges in procuring the necessary supply and adding to overall production costs	• **Optimizing the source of green hydrogen** close to the production plant is a key strategy currently being implemented
Policy and regulation barriers Immature technology remains difficult for policymakers and regulators to approve CO_2-derived protein due to lack of existing data, production capacity, and studies on the safety of the product	• **Establishing public awareness on benefits of CO_2-derived protein** and establishing proof of performance at early stages of the production process • **Reduce or eliminate the use of heavy metals** to mitigate the risk of toxic byproducts from fermentation
Supply chain and logistics barriers Sourcing of green hydrogen and CO_2 source remains challenging as CO_2-derived protein competes with a broad range of industries seeking the same feedstocks	• Co-location to gain access to both green hydrogen and CO2 with a focus on **small-scale distributed production strategy**

* Examples of key developments pertinent to mitigation are listed on the next slide

Lux Research

Key technology and market activity remains heavily concentrated within the leading developers and institutes

KEY TECHNOLOGY ACTIVITY

- **Solar Foods (Finland).** Solar Foods announce intentions to integrate electrolyzers into its production system, generating green hydrogen from renewable energy on-site for consumption instead of transporting hydrogen to the facility. In addition, focusing on high purity biogenic CO_2 sources such as ethanol facilities to reduce cost of CO_2 compared to point source captured or direct air captured CO_2.
- **Novonutrients (United States).** Novonutrients' gas fermentation system are capable of remediating large amounts of contaminants from industrial production, but the system explicitly avoids heavy metals that cannot be altered to a nontoxic form to avoid toxic byproduct production.
- **National Renewable Energy Laboratory (United States).** National Renewable Energy Laboratory is applying computational fluid dynamics simulation in order to identify more efficient bioreactor design and operating parameters for single cell protein production via gas fermentation.

KEY MARKET ACTIVITY

- **REACT-FIRST (United Kingdom).** The Nottingham-based consortium will be led by Deep Branch Biotechnology for the production of CO_2-derived protein from Drax Power's Selby power station. Notably, the consortium will focus on nutrition optimization, feed production, and downstream stakeholder engagement.
- **Singapore Food Agency (Singapore).** In December 2020 Singapore Food Agency granted the world's first regulatory approval of cell-based meat for Eat Just's cell-based chicken. While cell-based protein is technically different from CO_2-based protein, the approval is a key signal of the potential openness of regulators to protein sources for human consumption beyond the current plant-based and insect-based alternatives.
- **Unilever (United Kingdom).** Unilever is actively diversifying its protein portfolio with an expansion into plant-based proteins and exploring opportunities in algae to mycoproteins. Unilever is one of many consumer goods companies looking to balance its portfolio with CO_2-derived and cell-based proteins and is a key market development to watch.

LUX TAKE

CO_2-derived protein for both animal and human consumption is still at an early stage, with a sparse landscape of developers. Competition from plant-derived and insect-derived protein will slow down near- and mid-term prospects. Global CO_2 Initiative should monitor the space and only expect further advancements when more players enter the space.

Cost tipping point not expected until 2042, but companies seeking sustainable alternatives drive growth to reach US$921 billion market

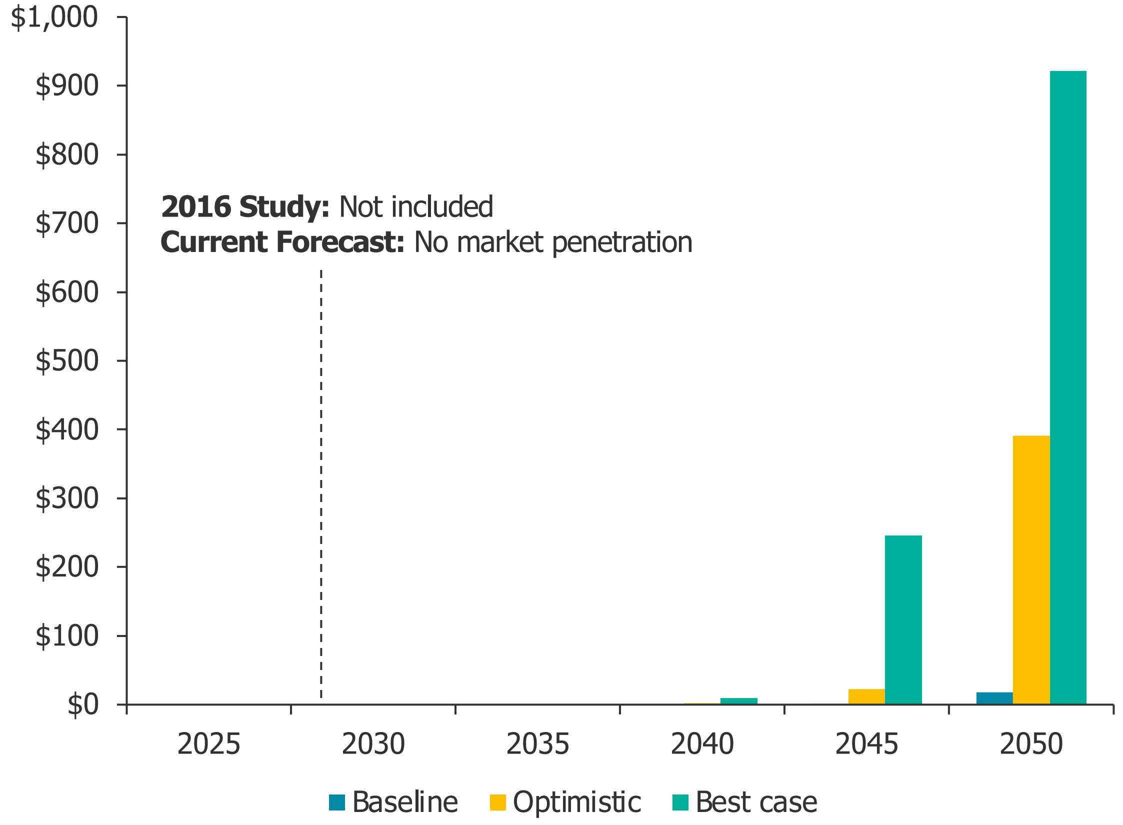
MARKET POTENTIAL

- The global animal feed market is expected to grow to US$3.1 trillion by 2050 with a CAGR of 6% due to population and economic growth.
- **Baseline.** Cost tipping point is never achieved, but introduction of product into the market begins in 2045 with a CAGR of 54% through 2050 to reach a market size of US$18 billion.
- **Optimistic.** Cost tipping point occurs in 2047 with a CAGR of 34% through 2050 to reach a market size of US$391 billion.
- **Best case.** Cost tipping occurs in 2042 with a CAGR of 36% through 2050 to reach a market size of US$921 billion.

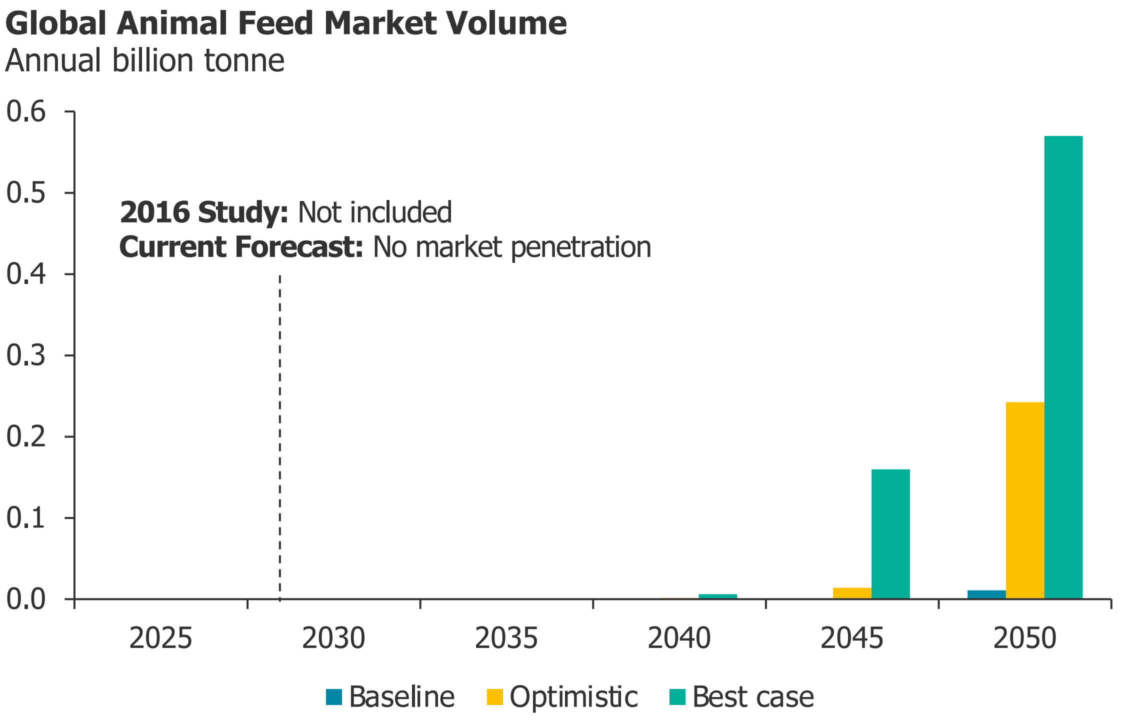
MARKET DRIVERS

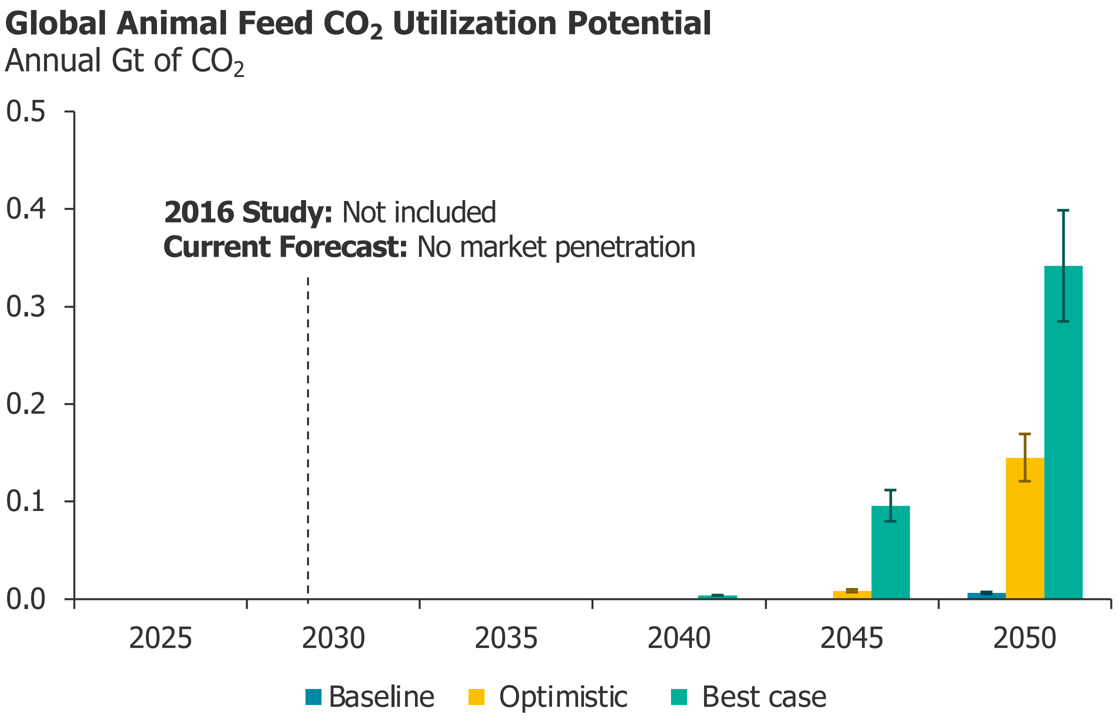
- Due to the early-stage of the technology, cost competitiveness is likely two decades away; in addition, faces stiff competition from alternative proteins currently entering the market, such as plant- and insect-derived proteins.
- Carbon pricing is negligible in accelerating adoption, instead growing demand from consumer-facing brands seeking sustainable alternatives will accelerate market traction
- Cost-parity without carbon pricing will be achieved in 2043 in the best case scenario and 2048 in the optimistic scenario, both only one year later compared to with carbon pricing

Global Animal Feed Market Value
US$ billion



Approximately 0.4 Gt of CO_2 utilization potential with CO_2-derived proteins reaching 29% market penetration by 2050



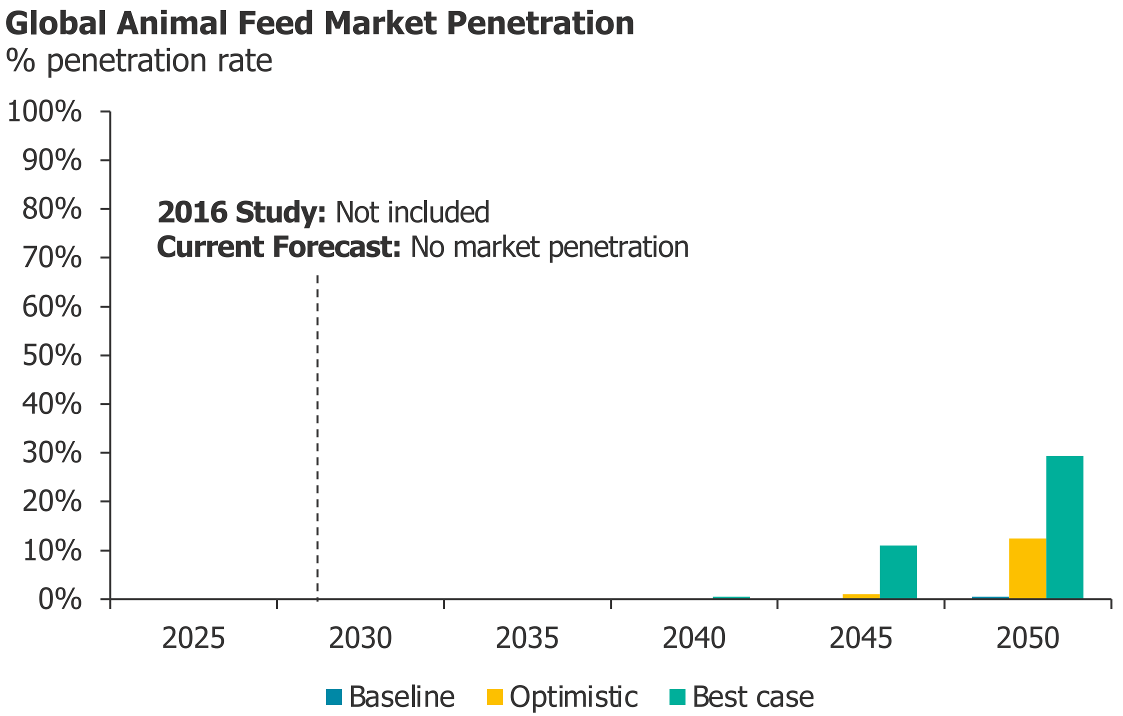


Error bars reflect the range of CO_2 utilization in the low CO_2 uptake scenario of 0.5 tCO_2/ tonne of animal feed and high CO_2 uptake scenario of 0.7 tCO_2/ tonne of animal feed.

LUX TAKE

Large addressable market of animal feed due to growing demand plays a key role in the emergence of CO_2-derived proteins by 2050. While direct utilization of CO_2 remains low, the adjacent emission benefits from the reduction in the use of arable land, fertilizer, and other resources should not be overlooked.

Projected market penetration of CO_2-derived proteins for animal feed consumption for three adoption scenarios



The overall market is the native incumbent market, and the penetration rate is defined as the potential replacement of incumbent product with CO_2-derived products based on the baseline, optimistic, and best case scenario. Projected market volume of animal feed is 1.9 billion MT by 2050 based on a 337 million MT market volume in 2020 and an estimated CAGR of 6%.

Fuels

CO_2 conversion to methane or jet fuel represents a high revenue opportunity but remains a long-term solution for decarbonization

TECHNOLOGY OVERVIEW

- Conversion of CO_2 to either liquid hydrocarbons such as diesel or aviation fuel through reverse water gas shift (RWGS) reaction followed by Fischer-Tropsch, or to gaseous fuels like methane via solid catalysts or microbes.
- Fuel production has a high CO_2 uptake potential upwards to 6 tCO_2 per tonne of fuel and with downstream fuel processing capable of being integrating into existing fuel infrastructure for production, storage, and transport
- Converting CO_2 to fuels is a capital-intensive process that requires a considerable amount of energy to break up the CO_2 molecule. Scaling up the technology with rely on new regulations that favor low-carbon fuels.

CHALLENGES AND PROSPECTS

- Fuels do not store CO_2 for extended time periods. The technology is an open-loop carbon cycle, where fuels re-release CO_2 back into the atmosphere when burned.
- The overall carbon intensity of the fuel is hinged to the carbon footprint of hydrogen used in the process, creating a need for on-site electrolyzers to produce green hydrogen, as well as the source of CO_2 (point source vs. direct air capture).
- The aviation industry can heavily impact the commercialization of CO_2-based fuels. The technology is the only scalable option to decarbonize the sector with a liquid-based fuel, and cost reduction can be achieved by sourcing low-cost CO_2, potentially from biogas instead of direct air capture.

Number of Developers, Fuels

Technology	Jet fuel	Methane
Technology maturity	Introduction	Introduction
Average developer TRL	6	4
CO_2 consumption (tCO_2/tonne product)	3 to 6	0.8 to 1
Market size, best case (2050)	US$1.8 trillion	US$214 billion
CO_2 utilization potential, best case (annual Gt)	7.6	4.0
Cost tipping point, best case (year)	2042	2038

Both academic and patent activity are mainly focused on new catalyst developments, with academics reporting higher activity

COMMERCIAL INTEREST

- Several large corporations such as Siemens, Toshiba, BASF, SABIC, Haldor Topsoe, and Air Liquide are among the top patent filers, even if they are not directly pursing fuels
- Air Liquide filed a patent in 2017 describing the synthesis and application of a hydrotalcite catalyst that reportedly operates at a lower temperature, thereby reducing energy costs
- IP trajectory will depend on ongoing R&D and commercialization of new materials that facilitate cheaper and faster conversion of CO_2.

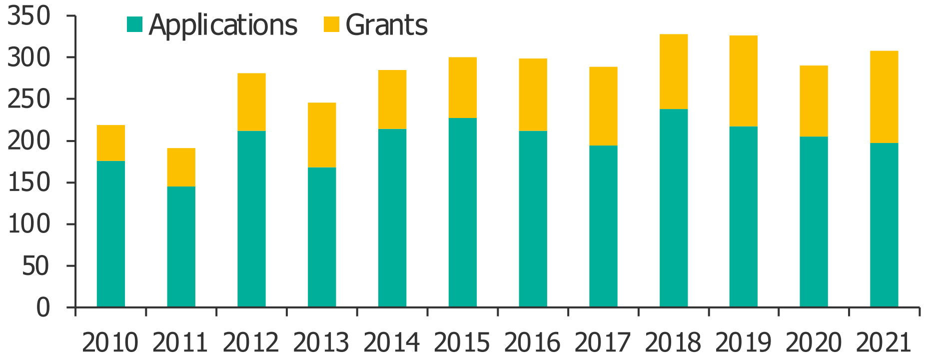
R&D INITIATIVES

- Leading academic institutes include the Chinese Academy of Sciences, Tianjin University, and the University of California System.
- Government funded agencies such as the U.S. Department of Energy and the Scientific Research National Center (CNRS) in France are highly active.
- Research activity predominantly explores reaction kinetics and development of catalysts for CO_2 methanation. Type of catalysts include transition metals as a cheaper alternative to noble metals, hydrotalcites, ruthenium-based, and photocatalysts.

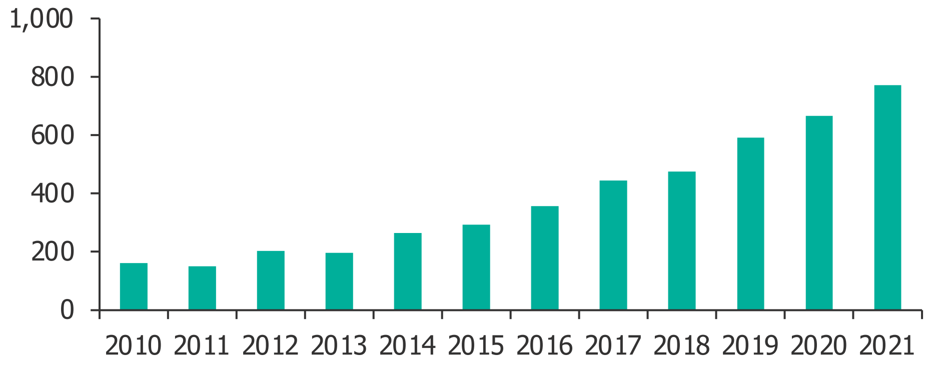
LUX TAKE

Academic activity shows significantly higher activity that patent applications, confirming that CO_2-to-fuels is still an emerging technology pathway. This trend is likely to continue until the technology breaks past the existing cost-barrier.

Fuels Patent Activity
Number of patent publications



Fuels Academic activity
Number of academic publications



Venture capital activity for fuels over the last decade shows few companies raising high capital

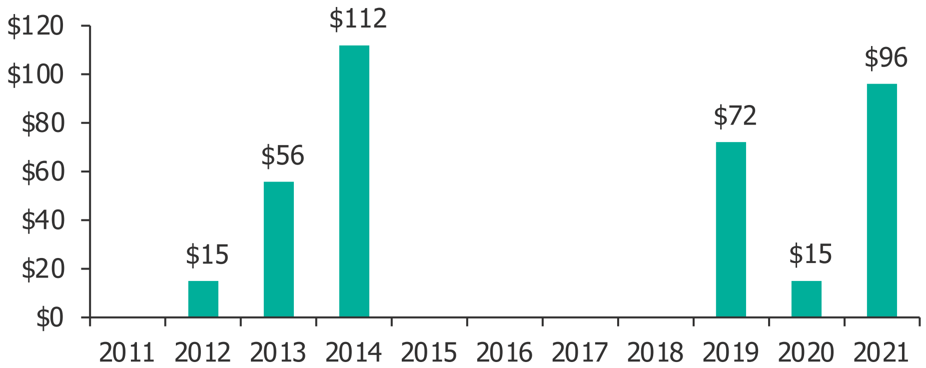
NOTABLE INVESTMENTS

- After a notable gap of almost five years, VC activity for fuel is beginning to rise again, but is limited to a few companies raising larger average round sizes.
- VC funding for fuels was dominated by LanzaTech between 2012 and the 2014. The company raised a total of US$180 million for its microbial conversion of flue gas to fuels.
- More recently, startups that have raised funding use pure CO_2 as a feedstock instead of a gaseous mixtures. 2021, in particular, witnessed a sharp increase in funding; Infinium raised $69 million and Synhelion raised $21.7 million.

KEY DEVELOPMENTS

- Companies raising funding have two main commonalities – they rely on renewable electricity and target the commercial transportation sector, specifically aviation.
- Infinium plans to use its funding to compete the development of its commercial plant with a reported annual capacity of 40 MGY. The company has gained the attention of e-commerce giants like Amazon who are seeking to decarbonize their operations.
- LanzaTech, although still active in fuels, plans to use its recent 2019 funding to explore end-products such as PE/PET, hinting challenges in CO_2-based fuel production.

Fuels VC funding
US$ million



INFINIUM
Total disclosed funding: US$69 M
Investors: Amazon, NextEra Energy, AP Ventures, Mitsubishi Heavy Industries

Synhelion
Total disclosed funding: US$21.7 M
Investors: AMAG Automobil, SMS Contrast, CEMEX Ventures

PROMETHEUS
Total disclosed funding: US$12.7 M
Investors: BMW, Maersk, Metaplanet Holdings

LUX TAKE

Industries were not ready to adopt pure CO_2 streams for fuel production in the first half of the decade, preferring flue gas technologies such as LanzaTech. However, increased pressure to decarbonize is diversifying CO_2-to-fuel production pathways.

Lux Research

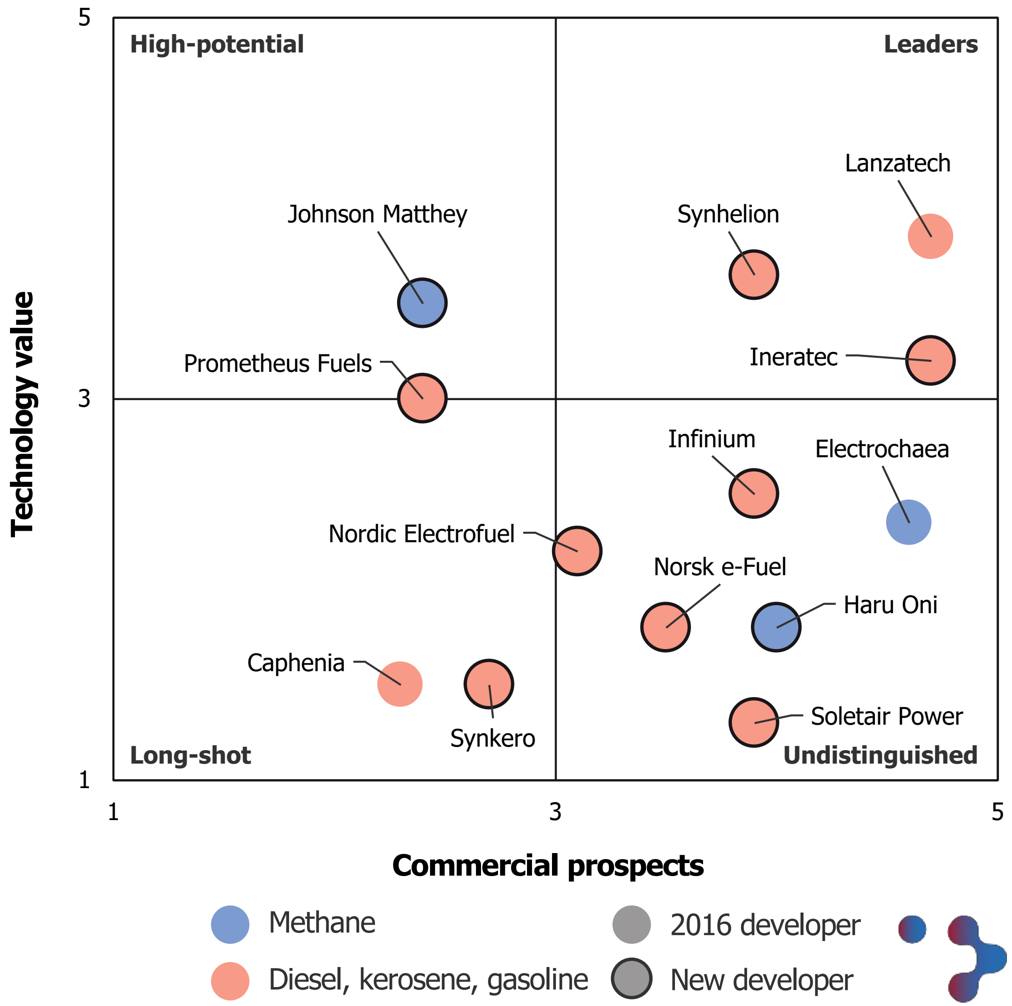
Several startups and corporate consortia focusing on long-chain hydrocarbon fuels have emerged

DEVELOPER LANDSCAPE

- Most entities developing CO_2-based fuels are startups. Six entities were founded in the last five years, indicating growing demand for low-carbon fuels. Haru Oni is a notable consortium comprising Siemens, Porsche, and others that aims to produce 130,000-liters of eFuel by 2022 in Chile.
- Majority of companies use thermochemical pathways to combine hydrogen, mostly green hydrogen produced with renewable electricity, with CO_2, from industrial effluents, biomass, or direct air capture, to produce long-chain hydrocarbon fuels.
- Almost 70% of the companies are focused on producing jet fuels either as the sole product or as one of their offerings.

MARKET DYNAMICS

- Companies are able to form partnerships across the transportation value chain, spanning automotive giants, logistics firms, and airlines, but are challenged from a technological perspective. To cope, startups are deploying novel catalysts developed at national laboratories in their pilots.
- Several startups have announced plans to establish commercial scale CO_2-based fuel facilities. Norsk's first commercial plant is expected to have a capacity of 10 MLY by 2023. Synkero is developing a 50,000 tpa SAF plant at the Port of Amsterdam, expected to be operational by 2027.
- The availability of ample renewable electricity will become the prime consideration for where new companies and future projects will emerge.



Ineratec and Synhelion gaining strong commercial traction with plans for first demonstration-scale commercial facilities

INERATEC

- Develops a portfolio of compact reactors to convert CO_2 or methane into liquid hydrocarbon fuels; also offers an integrated system of reforming and Fischer-Tropsch reactors.
- The company's first synthetic fuel plant, with an annual capacity of 3,500 tons is expected to launch in 2022 in Germany.
- Unlike several competitors, Interatec sources CO_2 from biogas instead of direct air capture (DAC), which will result in a significantly cheaper synthetic fuel.
- The company uses commercial catalysts in its reactors and has partnered with companies like Clariant and Sasol. Since the reactors are limited by the effectiveness of the catalyst, such partnerships are important.
- Global CO_2 Initiative should view Interatac as a high potential startup given its operational experience. Its partnerships with companies like Clariant and Sasol, that have significant footprint in gas-to-liquid technologies adds differentiation in a fast-growing landscape.

Synhelion

- Develops a solar-powered thermochemical reactor to convert water and CO_2 to syngas. The syngas is subsequently converted into liquid fuels by Fischer-Tropsch.
- The company raised a total of $22 million in 2021 across three funding rounds. Notable investors are AMAG Automobil, SMS Contrast, CEMEX Ventures, and the German Ministry for Economic Affairs and Energy.
- Currently at pilot scale with a production capacity of 10-liters per day but plans to establish its first commercial facility by 2025 with a capacity of 40,000-liters per year; expects a production cost of US$1/liter by 2040.
- In September 2021, Synhelion acquired Helioken, a concentrated solar power (CSP) developer that uses concentrating mirrors to raise the temperature of heat transfer fluids to 1,500 ^{o}C, thereby increasing efficiency.
- Global CO_2 Initiative should monitor Synhelion's aggressive scale up strategy and commercial momentum over the next few years and assess whether the company is on the trajectory to validate its cost claims.

LUX TAKE

Leading companies in CO_2-based fuels are targeting liquid hydrocarbons over methane, predominantly because of the diversity of end products and wider applications in the transportation sector. There is a significant production capacity in the pipeline through 2030, and companies that show operational efficiency at scale will emerge as strong leaders.

Key barriers and risks stem from the lack of sufficient economic incentive to offset the high cost of production

Key Barriers and Risks	Means to Mitigate*
Technology barriers Costs for CO_2-based fuels are several times higher than its fossil-based counterpart, predominantly due to the high costs of producing hydrogen. Bio-based fuels is a less expensive alternative. Additionally, cost-driven technology barriers usher the aviation industry to pursue emission offsetting instead of adopting CO_2-based fuels	• Cheaper production pathways through development of **catalysts**; desired properties include low noble metal content, higher conversion efficiency, and minimal depletion • Developments in producing lower cost renewable hydrogen • Development of new CO_2-to-fuel conversion pathways
Policy and regulation barriers CO_2-to-fuel developers will need to have a thorough understanding of the ASTM regulations that govern both aviation fuels and sustainable aviation fuels (SAFs). ASTM D7566 currently limits SAF blends to 50% and has a higher focus on bio-based fuels instead of CO_2-based fuels. Current regulations account for Fischer-Tropsch reaction to produce fuels for commercial transportation CO_2-based fuels are not mentioned.	• Establishing cemented requirements for the **thermodynamic properties and requirements** for CO_2-based fuels • Better accounting of **Scope 2 and Scope 3** emissions associated with CO_2-based fuels • Commercial production of CO_2-based fuels to increase credibility of the technology as a **scalable alternative** to fossil-based and bio-based fuels
Supply chain and logistics barriers Access to cheap and renewable energy is essential for CO_2-based fuels to claim a significantly lower carbon intensity than its fossil-fuel counterpart. Additionally, the development of CO_2 capture facilities are needed to provide enough feedstock to allow CO_2-to-fuel plants to reduce costs through economies of scale.	• Addressing **intermittency** of renewable sources like wind and solar • Promoting **hydrogen as an energy carrier** to power CO_2 capture units and CO_2 conversion to fuels • Technologies that allow ownership of CO_2 feedstock instead of relying on a third-party, and development of **modular CO_2 capture systems**

* Examples of key developments pertinent to mitigation are listed on the next slide

Lux Research

Corporate R&D, partnerships, and investments target commercial deployments of CO_2-based fuels

KEY TECHNOLOGY ACTIVITY

- **National University of Singapore (NUS) and Shell (Singapore):** Jointly developing a $4.6 million research project, spanning three years, to develop a novel electrochemical process to produce ethanol and n-propanol from CO_2. The molecules can be blended with gasoline to deliver low-carbon fuel. Although the process will rely on high performing catalysts, the electrochemical approach differs from traditional catalytic or methanation pathways used to produce fuels.
- **Joint Center for Artificial Photosynthesis (United States):** U.S. DOE program based in Caltech. Self-healing catalysts that absorb light and trigger CO_2 reduction to methane. The system absorbs sunlight, CO_2, and water, while allowing oxygen molecules to escape. Researchers also target the technology for low-cost solar hydrogen generation applications.
- **FReSMe project (Sweden):** Five-year Horizon 2020 funded research program to establish a TRL 6 CO_2-to-fuel plant, showing scope for retrofits. CO_2 was captured from effluents from steel making and combined with green hydrogen. Methanol produced was used for maritime transportation.

KEY MARKET ACTIVITY

- **Maersk (United States):** In September 2021, the world's largest shipping vessel operator invested in two California-based waste-to-fuel startups (WasteFuel and Prometheus Fuels), signifying the growing relevance of CO_2-based fuels in transportation. Maersk, having previously shown interest in green methanol, adds CO_2-based fuel to its existing bio-methanol supply; updates on the initiative will be important to monitor.
- **Electrochaea (Germany/United States):** German Power-to-X startup, developing biocatalysts to convert CO_2 and renewable hydrogen into methane, established a California subsidiary to expand operations in North America. The company recently sold a 15% stake to Baker Hughes and plans to integrate its technology with Baker Hughes' CO_2 capture units. Industrial emitters in the U.S. can follow a similar strategy to Baker Hughes and use CO_2 utilization to claim 45Q rebates.
- **Siemens and Porsche (Chile):** 'Haru Oni' pilot to produce 130,000-liters of fuel by 2022 with CO_2 from direct air capture (DAC) and green hydrogen using wind energy and proton exchange membranes (PEM). DAC is an expensive source of CO_2, and commercial viability will need to be assessed.

LUX TAKE

Growing number of pilots and commercial plants in the U.S. and Europe are indicators for fuel as viable CO_2 utilization market, especially given limited competing technologies. Developments are either focused on developing new catalysts or reducing the cost of hydrogen production. Electrochemical pathways are gaining traction but remain concentrated in laboratory studies.

Rapid adoption occurs following cost tipping point in 2042 to grow to US$1.8 trillion market with increased demand for aviation

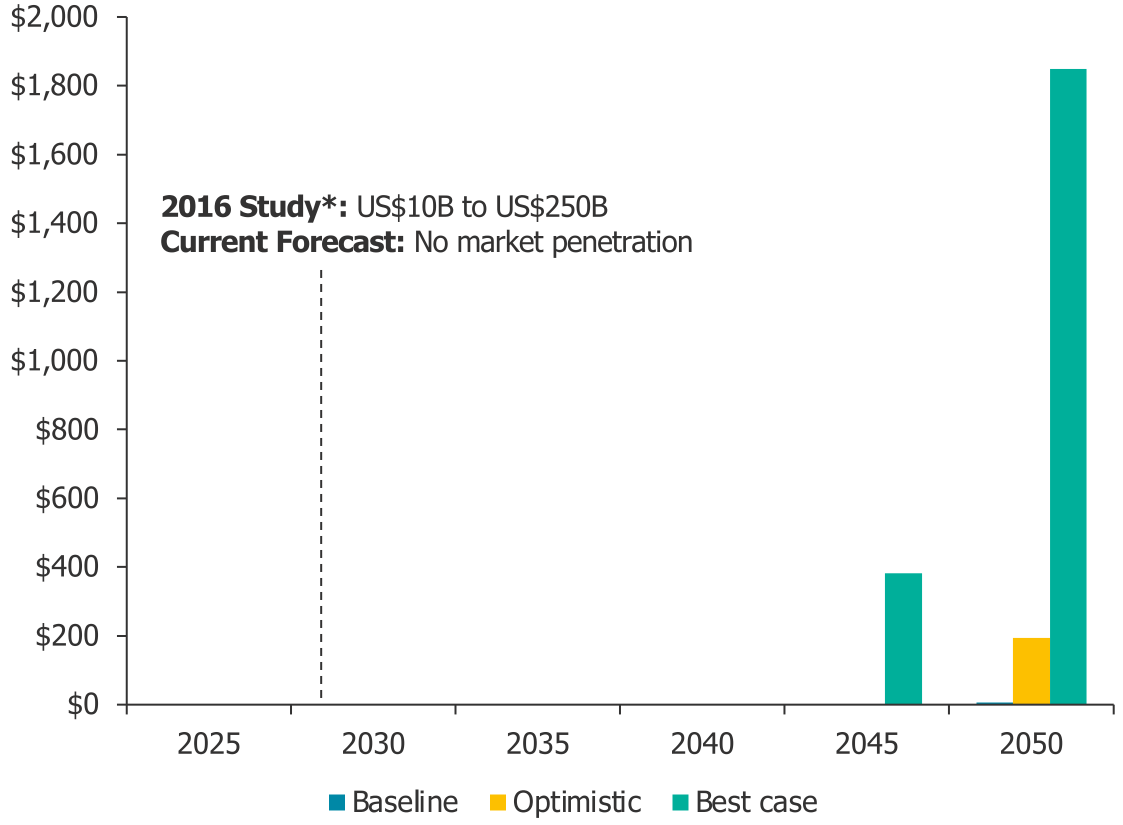
MARKET POTENTIAL

- The global jet fuel market is expected to grow to US$3.4 trillion by 2050 with a CAGR of 8% as demand rises from increased tourism, regional carriers in emerging economies, and economic growth.
- **Baseline.** Cost tipping point is never achieved, but product enters the market in 2049 and reaches a market size of US$5 billion.
- **Optimistic.** Cost tipping point occurs in 2047 with a CAGR of 75% through 2050 to reach a market size of US$194 billion.
- **Best case.** Cost tipping occurs in 2042 with a CAGR of 53% through 2050 to reach a market size of US$1.8 trillion.

MARKET DRIVERS

- Fuel costs range between 70% to 85% of airline operational costs, making CO_2-derived jet fuel economically unfavorable. However, a niche group of airlines will likely spearhead adoption at less than 10% price premium
- Technology advancements will continue to reduce costs, but the potential rising prices of kerosene along with carbon pricing will be the foundational driver for cost competitiveness for CO_2-derive jet fuel
- Cost-parity without carbon pricing will only be achieved by 2050 in the best case scenario with the optimistic and baseline scenarios failing to reach the market by mid-century

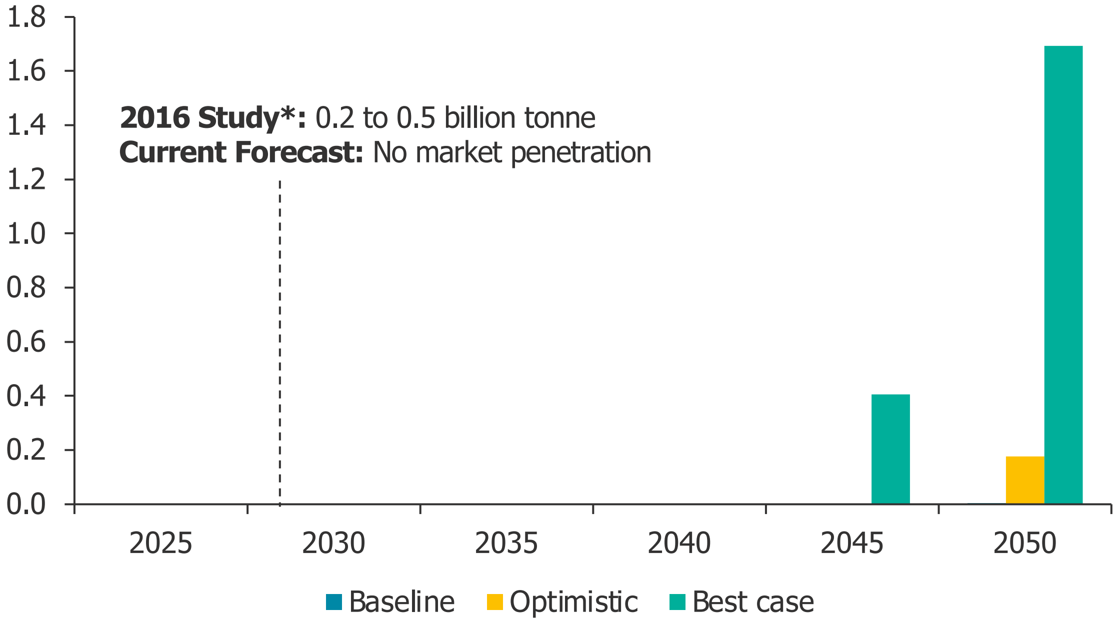
Global Jet Fuel Market Value
US$ billion (*2016 study includes all liquid fuels)



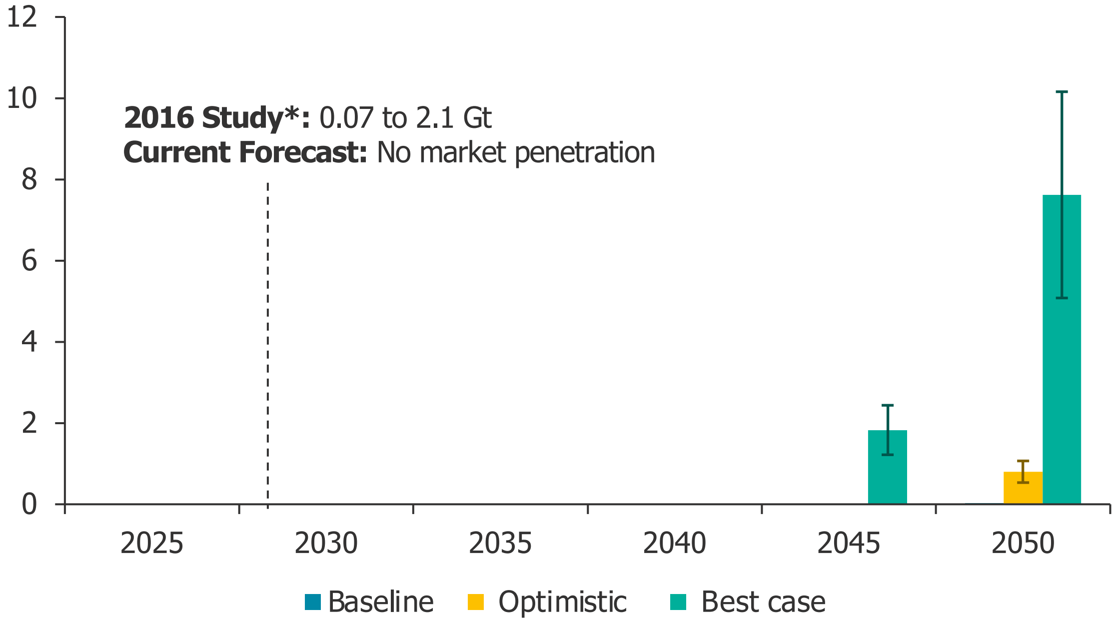
Note: The market size for jet fuel was projected during the global COVID-19 pandemic. Near-term projections for demand will likely be significantly impacted but expected to recover 2030 and beyond.

Over 10 Gt of CO_2 can be potentially utilized annually as CO_2-derived jet fuel take up 55% market share

Global Jet Fuel Market Volume
Annual billion tonne (*2016 study includes all liquid fuels)



Global Jet Fuel CO_2 Utilization Potential
Annual Gt of CO_2 (*2016 study includes all liquid fuels)



Error bars reflect the range of CO_2 utilization in the low CO_2 uptake scenario 3 tCO_2/tonne of jet fuel and high CO_2 uptake scenario of 6 tCO_2/tonne of jet fuel.

LUX TAKE

CO_2-derived jet fuel is a long-term, but promising, opportunity. The aviation sector is largely committed to liquid-based fuels and will need to introduce a new alternative fuel into the mix as bio-based fuels face feedstock limitations and production capacity struggles to keep pace with strong demand prospects.

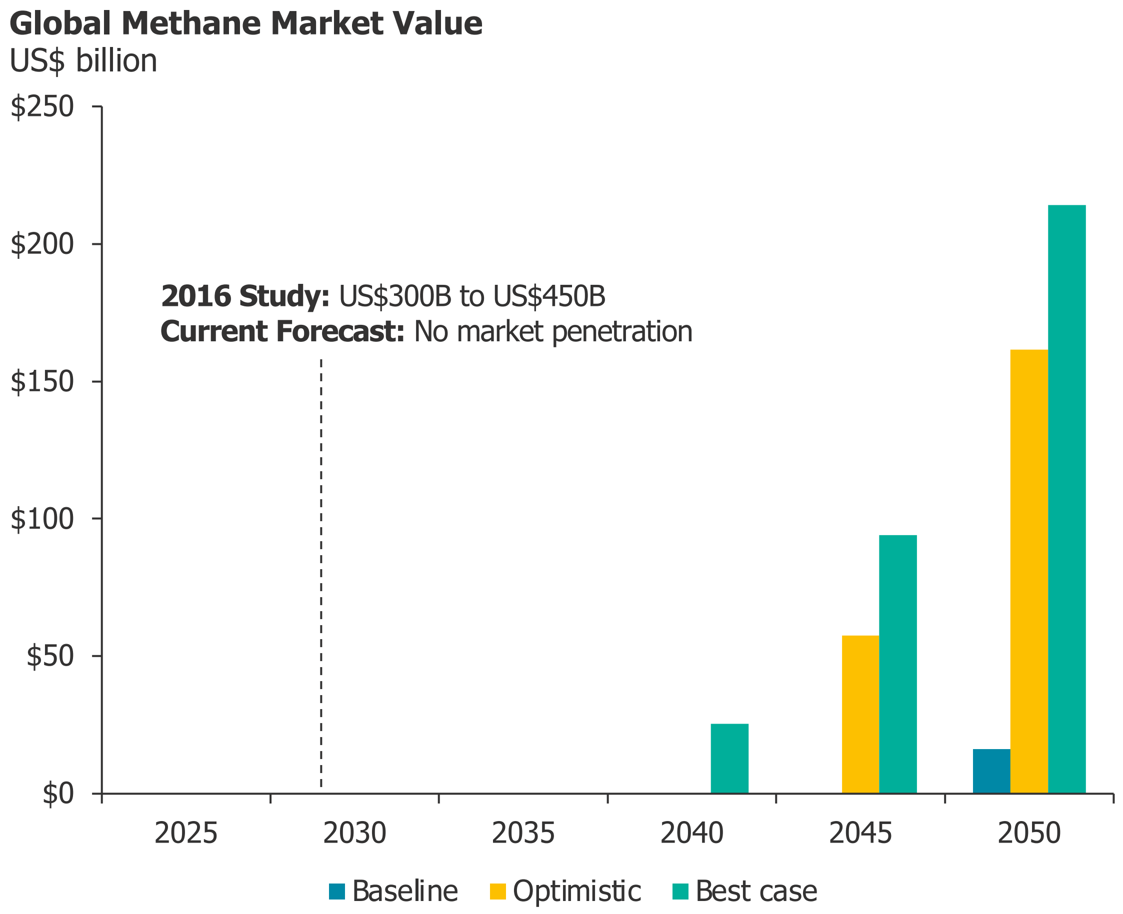
CO_2-derived methane reaches cost tipping point by 2038 but witnesses limited adoption as market size reaches US$214 billion

MARKET POTENTIAL

- The global methane market is expected to grow to US$3.8 trillion by 2050 with a CAGR of 3% driven by large shift away from coal in emerging economies.
- **Baseline.** Cost tipping point occurs in 2050 with an immediate uptake of CO_2-derived methane to reach a market size of US$16 billion.
- **Optimistic.** Cost tipping point occurs in 2041 with a CAGR of 38% through 2050 to reach a market size of US$162 billion.
- **Best case.** Cost tipping point occurs in 2038 with a CAGR of 32% through 2050 to reach a market size of US$214 billion.

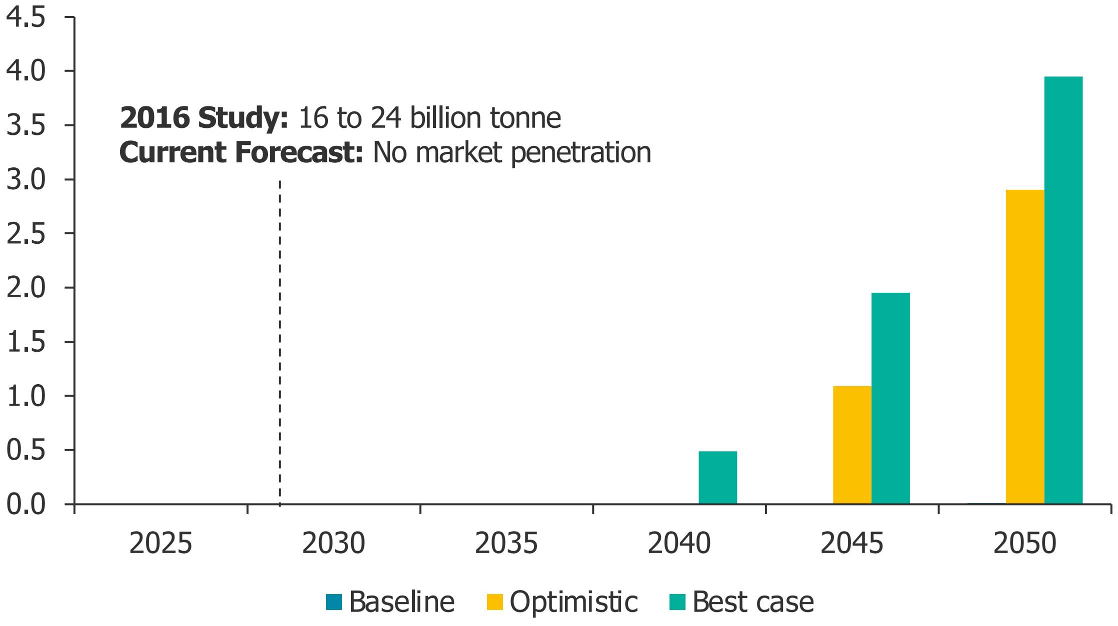
MARKET DRIVERS

- Cost reduction via technology advancements and access to low-cost green hydrogen and renewable electricity remains key to improving CO_2-derived methane's economics
- Carbon pricing plays an instrumental role in the acceleration of the timeline for cost parity. In the best case scenario, cost parity is never achieved without the introduction of carbon pricing
- Faces stiff competition from alternative technologies, such as renewable natural gas, which is already commercially available and gaining market traction in markets such as the U.S. and Europe

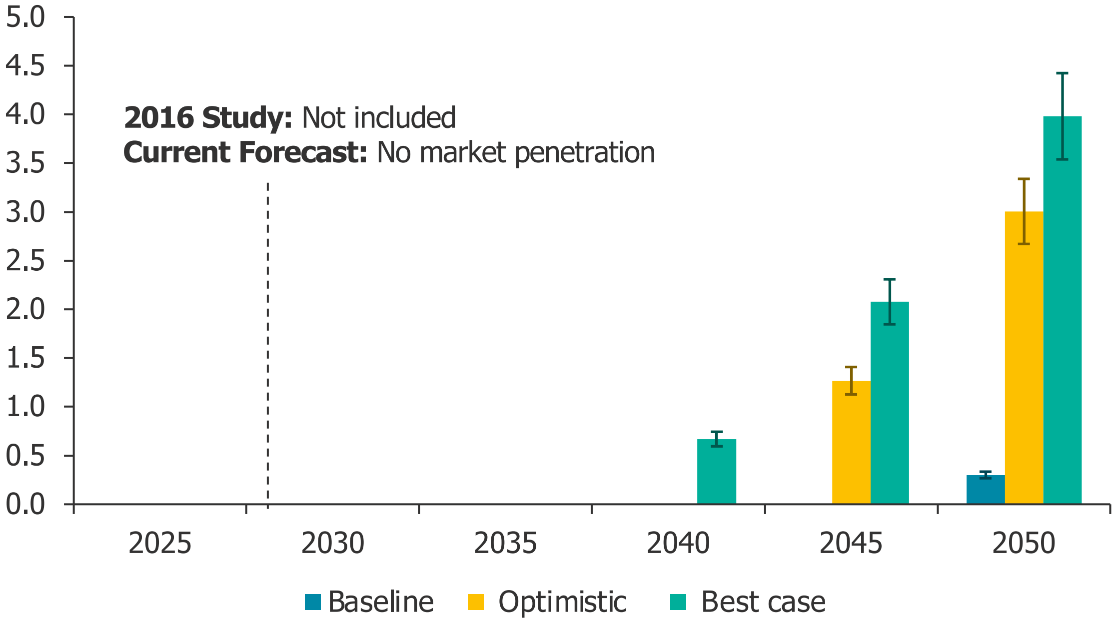


Large global methane market results in 4.4 Gt of CO_2 utilization potential despite only 6% market penetration by 2050

Global Methane Market Volume
Annual billion tonne



Global Methane CO_2 Utilization Potential
Annual Gt of CO_2

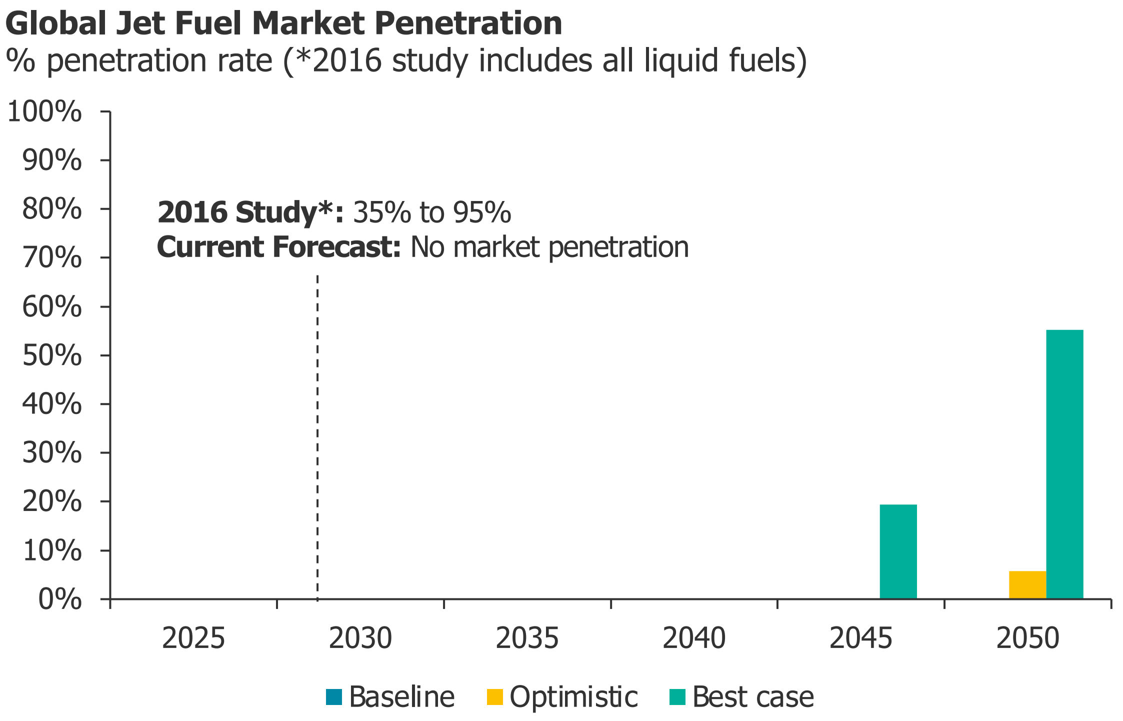


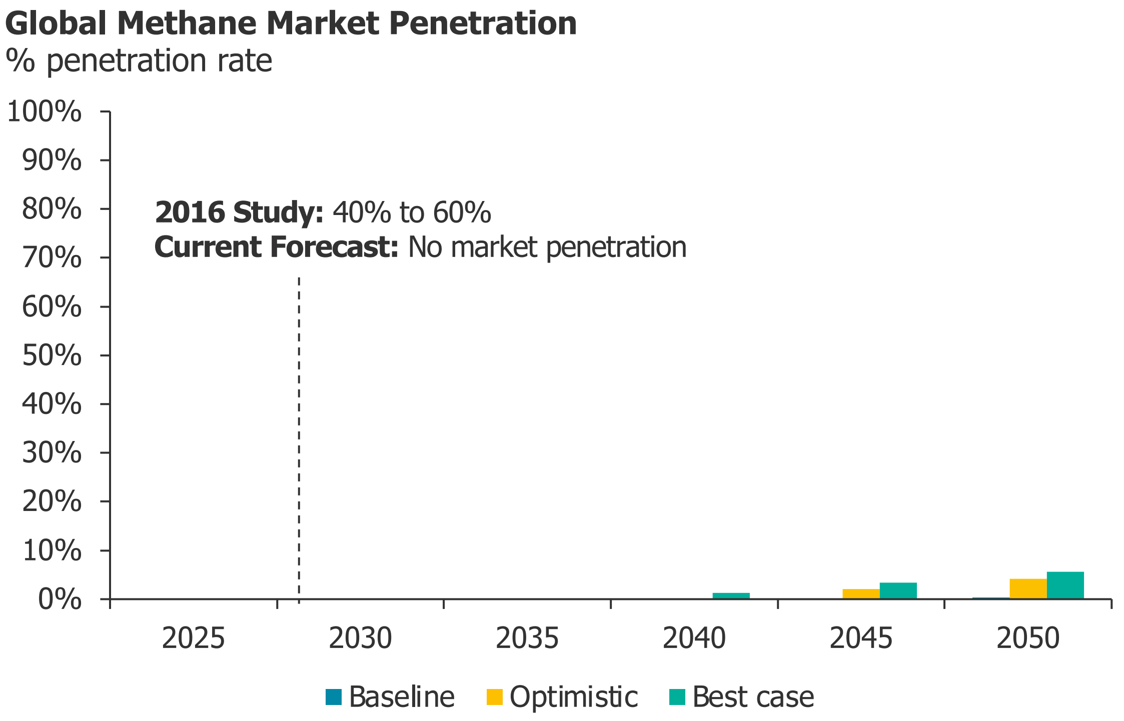
Error bars reflect the range of CO_2 utilization in the low CO_2 uptake scenario of 0.8 tCO_2/tonne of methane and high CO_2 uptake scenario of 1 tCO_2/tonne of methane.

LUX TAKE

Despite low market penetration rates of CO_2-derived methane, the outlook remains promising in the long-term. While economics and competing technologies will deter widespread adoption, the large addressable market for natural gas results in both promising economic and CO_2 utilization potential.

Projected market penetration of CO_2-based jet fuel and CO_2-based methane for three adoption scenarios





The overall market is the native incumbent market, and the penetration rate is defined as the potential replacement of incumbent product with CO_2-derived products based on the baseline, optimistic, and best case scenario. Projected market volume of jet fuel is 3.1 billion MT by 2050 based on a 305 million MT market volume in 2020 and an estimated CAGR of 8%. Projected market volume of methane is 79 billion MT by 2050 based on a 32 billion MT market volume in 2020 and an estimated CAGR of 3%.

Agenda

1 Progression of the CCU landscape

2 State of the CCU landscape

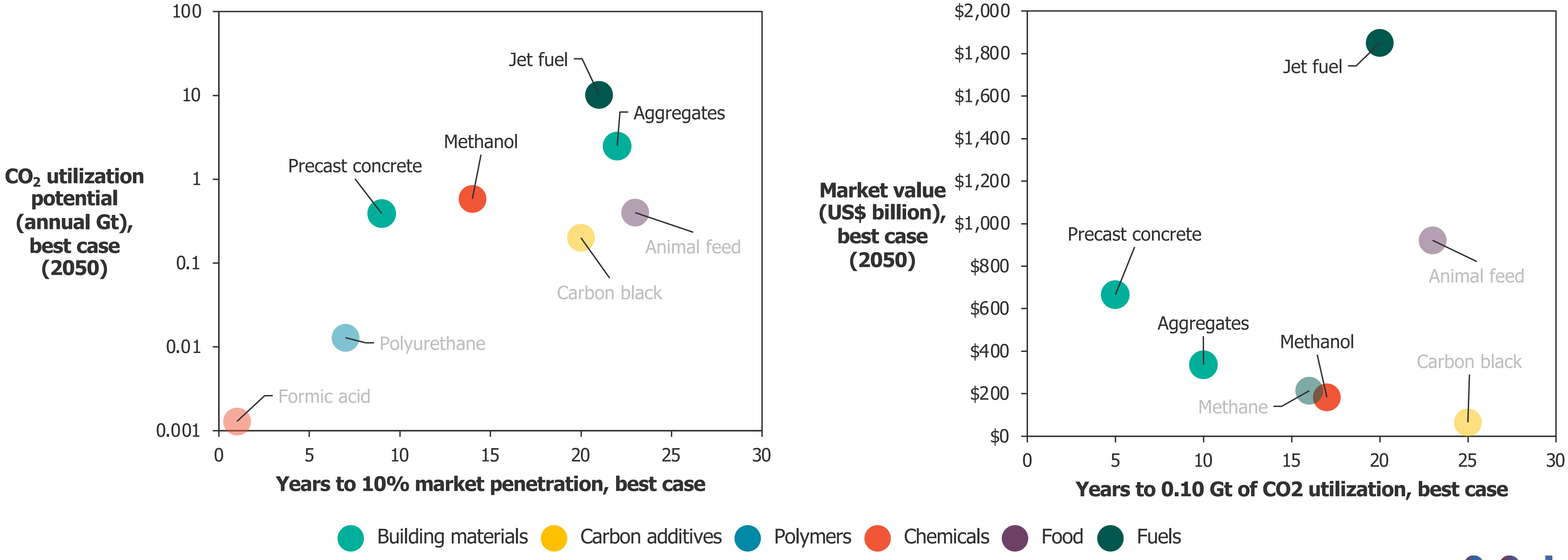
3 CCU end product assessment

4 Opportunity assessment and scenario analysis

5 Strategic recommendations

Lux Research analyzed best case scenario key metrics to identify high potential CCU end product opportunities in Track 1 and Track 2

Based on the findings from the CCU end product assessment, Lux Research analyzed key metrics including potential market value (US$ billion), annual CO_2 utilization potential (Gt CO2), technology maturity, and years until market penetration to identify priority opportunities for assessment in Track 1 and Track end products. **Lux Research and Global CO_2 Initiative identified aggregates and precast concrete (Track 1) and jet fuel and methanol (Track 2) that offer the best opportunities for immediate government and private sector support.**



Note: CCU end products not present in the above figures failed to reach 10% market penetration or utilize 0.1 Gt of CO2 in the best case scenario.

Opportunity Assessment
Track 1: Precast concrete and aggregates

Precast concrete

CO_2-cured precast concrete's key value propositions are its improved performance and faster curing times

CO_2-cured precast concrete is defined by the following features:

Carbon sequestration: Unlike non-durable CCU end products, CO_2-cured precast concrete presents a unique opportunity for long-term CO_2 storage with no potential CO_2 leakage. However, due to the low CO_2 utilization rate per unit of precast concrete produced (between 0.001 to 0.05 tCO2/tonne precast concrete), overall utilization potential remains low to alternative solutions for the building materials industry, such as CO_2-derived aggregates.

Process improvements: CO_2 curing significantly improves hardening time with reports of carbonation reaching the industry standard 28 days strength between 4 hours to 24 hours. In addition, CO_2 curing is a bolt-on solution to existing concrete mixing facilities, facilitating the injection of CO2 along with other common concrete admixtures and additives.

Materials cost reduction: While CO2 curing introduces an additional input, the process reduces water consumption between 17% to 20% and reduces cement requirements by between 3% to 6%.

Improved performance: CO_2 curing is cited in literature to enhance the compressive strength of concrete by 10% to 25% depending on the length of curing. Within 24 hours, CO_2-cured precast concrete can reportedly reach 45.8 MPa compressive strength compared to that of moisture-cured concrete at 37.3 MPa.

Each of these features have the potential advantage to address the following key market needs of the construction companies – **increased productivity, materials security, improved safety,** and **decarbonization.**

Market Needs	Carbon sequestration	Process improvements	Materials cost reduction	Improved performance
Increased productivity	No advantage	Major advantage	Limited advantage	No advantage
Materials security	No advantage	No advantage	Limited advantage	No advantage
Improved safety	No advantage	Limited advantage	No advantage	Major advantage
Decarbonization	Major advantage	Limited advantage	Limited advantage	No advantage

Major advantage | Limited advantage | No advantage

Despite the relatively small CO_2 utilization potential for CO_2 curing, low barrier of entry may address immediate market needs

- CO_2 curing presents both operational and decarbonization benefits along the entire value chain for construction companies
- Widespread adoption of the technology will largely depend on a shift of industry standard practices when the process and performance improvement benefits are clearly defined

The CO_2-cured precast concrete value remains fragmented with technology developers seeking buy-in from construction companies

Raw Materials		Technology Conversion				End Users	
THE LINDE GROUP / PRAXAIR	Strategic partner supplying liquefied CO_2 to Carbonclave	CARBON CURE	Over 500 customers globally using its CO_2 curing technology	Denka	Uses coal ash and novel additive for cement-free CO_2 curing	CORESLAB STRUCTURES	Construction company offering CarbonCure's solution for projects
Air Liquide	Supplies "emission-sourced" CO_2 to CarbonCure customers	Solidia Technologies	CO_2 injection in wet concrete to form calcium carbonate nanoparticles	CarbiCrete	Cement-free concrete from steel slag binder and cured with CO_2	HOLCIM	Supplies Solidia Technologies' precast concrete in the U.S.

Value Chain

The value chain for CO_2-cured precast concrete is largely fragmented with minimal activity in the raw materials and end user segments. In terms of raw materials suppliers, the current CO_2 supply for concrete curing is provided by industrial gas players that capture, liquefy, and transport the required CO_2 volumes directly to construction sites. Due to the small-scale nature of CO_2 curing and locations of construction sites, the co-location with an industrial CO_2 source may not be possible and the construction of direct air capture units may be restricted. The eventual need for the distribution of emissions-sourced CO_2 to the end use location will be a key component in the logistics of CO_2 curing. In terms of end users, there is still a limited number of players offering CO_2-cured concrete. Despite CarbonCure's impressive customer base of over 500 plants globally, CO_2-cured concrete remains a niche segment of the overall industry (<0.1%), with few technology developers entering the space.

Regulations

Novel building materials face numerous testing, validation, and certification processes before becoming commercially available. While CO_2 curing is considered an admixture and is curtained under ASTM C494 (Standard Specification for Chemical Admixtures for Concrete), other ASTM standards such as ASTM C150 (curing times) and ASTM C595, C845, and C1157 (cement variables) present regulatory barriers for wider adoption of CO_2-cured concrete.

In the U.S., the Buy Clean Task Force will likely be a boon for CO_2-cured concrete. The task force will accelerate demand for low-carbon building materials, including steel, concrete, and asphalt, by giving preference in the procurement process for low-carbon construction materials. While there will unlikely be an industry wide willingness to pay a green premium, policies such as this can have an indirect incentive for construction companies to provide CO_2-cure concrete in its offerings.

CO_2-cured precast concrete continues to be positioned as a sustainability solution despite potential operational benefits

CO_2-cured precast concrete is positioned as a sustainability solution, but potentially offers operational benefits as well

Increased productivity: The construction industry continues to streamline operations for improving profitability. Adoption of building information management (BIM) software, prefabrication, and modular construction approaches continue to rise as tools for increasing productivity and accelerating project timelines.

Materials security: The global pandemic and supply chain disruptions highlights the susceptibility of construction materials costs, including lumber, concrete, and steel, with an approximate 20% year-over-year price increase in 2021. While CO_2-curing does not eliminate the use of key input materials, it provides some form of insulation from price volatility by reducing input needs.

Improved safety: Building codes and standards will continue to influence the quality of construction materials and an increasing need for resilient buildings to withstand extreme weather events.

Decarbonization: The Global Cement and Concrete Association (GCCA) set out a roadmap for a 25% reduction in emissions associated with concrete production by 2030. Downstream, green building initiatives driven by consumer demand will increase scrutiny on a building's carbon footprint beyond energy consumption.

CONCRETE SUPPLY CO. / LAUREN CONCRETE

Market need: Decarbonization, increased productivity
Details: Concrete Supply Co. and Lauren Concrete both partner with CarbonCure to offer ready-mix and precast concrete utilizing the CO_2 curing process. Both organizations tout seamless integration with operations and sustainability of the product.

CORESLAB STRUCTURES

Market need: Decarbonization, material security
Details: Positions precast concrete as a waste reduction and materials efficiency strategy for construction projects. Highlights the use of recycled materials and waste feedstocks as aggregates for a complete sustainability solution.

COMPASS datacenters

Market need: Decarbonization
Details: Compass Datacenters announced in 2020 all its data centers will utilize CarbonCure's CO_2-cured concrete with an estimated 1,800 tCO_2 reduction per campus. Other tech firms LinkedIn, Amazon, and Infosys will also do the same for new builds.

CO_2-cured concrete can potentially address growing market needs in the construction, but has yet to have a breakthrough in the conservative industry

- Despite potential operational benefits such as reduced materials use, fasting curing times, and drop-in integration with existing operations, CO_2-cured precast concrete continues to be positioned in the market as a premium and sustainability offering.
- Client driven demand for CO_2-cured concrete may stimulate wider availability from the construction industry, but current market readiness remains limited to high-margin, sustainability focused industries. A stark shift in the construction industry is required for CO_2-cured concrete to be considered the standard offering.

Over 2.5 million CO_2 curing systems requiring over US$7.8 billion in investments needed to meet CO_2-cured precast concrete demand

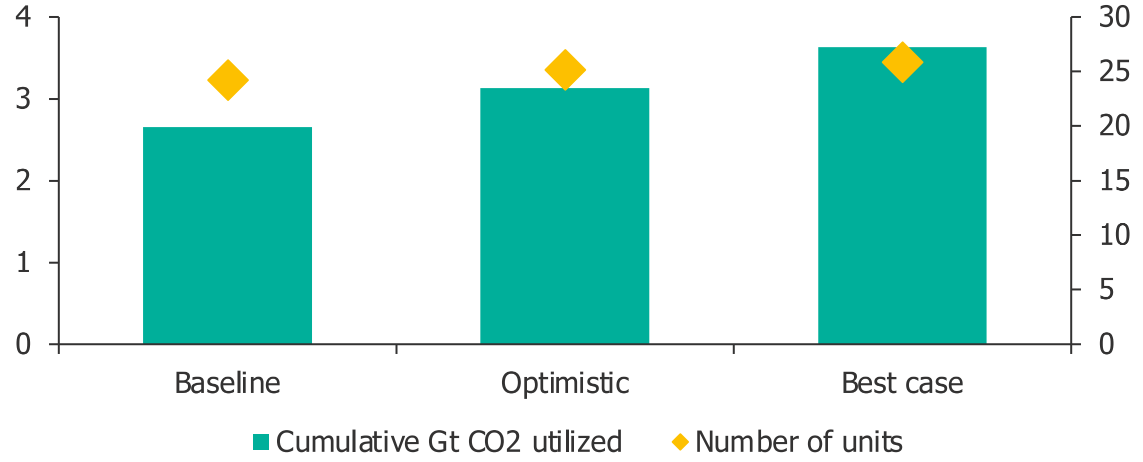
Current production of CO_2-cured precast concrete is minimal with CarbonCure an industry leader in terms of production volumes.

CarbonCure is the leading producer of CO_2-cured concrete with over 500 units installed across its network of 388 producers. There is an estimated annual production capacity of 5 million tonnes of CO_2-cure concrete combined. One of CarbonCure's CO_2 curing system has an estimated production capacity 10,000 tpa of CO_2-cured precast concrete and serves as the operable unit.

Over 2.5 million CO_2 curing systems will need to be deployed in order to meet the potential market demand for CO-cured precast concrete.

- **Baseline:** US$8.5 billion in capital costs and over 2.4 million CO_2 curing systems deployed. A total of 2.7 Gt of CO_2 is cumulatively utilized through 2050, resulting in a US$3.2 billion investment per Gt CO_2 utilized.
- **Optimistic:** US$6.9 billion in capital costs and over 2.5 million CO_2 curing systems deployed. A total of 3.1 Gt of CO_2 is cumulatively utilized through 2050, resulting in a US$2.2 billion investment per Gt CO_2 utilized.
- **Best case:** US$7.8 billion in capital costs and nearly 2.6 million CO_2 curing systems deployed. A total of 3.6 Gt of CO_2 is cumulatively utilized through 2050, resulting in a US$2.1 billion investment per Gt CO_2 utilized.

Precast Concrete: Production Units Required
Cumulative Gt CO_2 (left axis); Units (100,000s; right axis)



Low capital costs and simple operations present a low barrier to entry for rapid rollout of CO_2 curing units.

- Both technological and commercially mature, CO_2 curing will rely on new entrants into the market to achieve the scale required.
- The need for over 2.5 million systems highlights the decentralized nature of the construction industry. Shift towards prefabrication of precast concrete slabs may accelerate scaleup, but market potential ultimately relies on steady supply of containerized CO_2 and operational changes in the construction industry.

PRECAST CONCRETE: OPPORTUNITY ASSESSMENT

Assessing the uncertainty of large-scale deployment based on maturity levels of factors impacting CO_2-cured precast concrete

Factors	Level of Maturity	Precast concrete
Product		While leading developers such as CarbonCure are approved under ASTM C494, other entrants into the space will require to go through numerous testing, validation, and certification processes before becoming commercially available. Despite CO_2 curing being a bolt-on process to existing operations, the introduction of CO2 inherently creates a "new" product that will likely take time for the industry to willingly adopt.
Technology		CO_2 curing is a commercially mature technology and currently deployed in the market. The capture, liquefaction, storage, and transport of CO_2 leverages existing industry processes and equipment. The curing process itself also presents a bolt-on opportunity with existing operations for concrete admixtures mixing and CO_2 is a drop-in to the incumbent curing process.
Market organization		The value chain for CO_2-cured precast concrete remains fragmented, largely due to the nature of the technology itself. CO_2 curing typically requires small-scale, on-site CO_2 supply which is unlikely to be achieved via a vertically integrated system equipped with direct air capture. Instead, CO_2 supply remains dictated by large industrial gas players distributing CO_2 from a centralized location, unlikely to always be closely located to the construction location.
Market readiness		Market demand continues to be driven by end users specifically requesting the use of CO_2-cured precast. The bottleneck remains at the construction company level, where CO_2 curing has yet to be adopted as a standard offering and remains a niche, premium offering.
Manufacturing		CO_2-cured precast concrete is commercially available in the market today by select concrete producers. CO_2 curing installations utilize off-the-shelf industry equipment and are a bolt-on to existing concrete mixing units. However, CO_2-cure concrete reportedly makes up <0.1% of the concrete market today.

High maturity   Medium maturity   Low maturity

Industry and market openness remains the key to unlocking the potential for CO_2-cured concrete

Level of Impact	Scenario
Low to negative impact	**Widespread eligibility for carbon credits for sequestered CO_2 in cured concrete.** Carbon credits and taxes continue to be positioned as linchpin of the widespread deployment of CCU technologies. However, the expansion of existing carbon credit schemes, such as the U.S. 45Q, to include CO_2-cured concrete will have **low impact** on the **market readiness** and does not alleviate concerns for adopting a novel **product** by the industry. In addition, due to inherently low CO_2 utilization potential (potentially <1% by weight), carbon credits will have a negligible impact on the economics. With CO_2 curing a **mature technology**, the industry is unlikely to develop a process with higher CO_2 utilization potential to reap the benefits of a carbon credit scheme.
High impact	**Customer-driven demand of carbon neutral buildings.** The growing focus on sustainability will accelerate deployment of CO_2-cured concrete in the construction of new campuses and buildings, especially for image conscious companies and universities. This will have a **high impact** on **manufacturing** with an increase in production capacity to fulfill new projects. In parallel, initiatives such as the U.S. Buy Clean Task Force and the inclusion of CO_2-cured concrete along with recycled steel and waste materials under the LEEDS certification will positively impact both **market readiness** and **market organization** as construction companies seek to add CO_2-cured concrete to their standard offerings to meet growing demand.
Medium impact	**Industry-led consortiums for large-scale deployment.** While consortiums promoting the decarbonization of the concrete and cement industry currently exist, an industry led consortium focused on the integration of the value chain will have a **medium impact** on the currently fragmented **market organization.** Mitsubishi Corporation's Green Concrete Consortium is a prime example and the expansion of similar arrangements in key geographical regions with growing concrete demand and formal supply agreements with upstream CO_2 suppliers has the potential to lower the barriers of **market readiness** with a turnkey CO_2 curing offering in the market.
High impact	**Non-sustainability benefits of CO_2 curing realized.** CO_2-cured concrete is consistently positioned in the market for its sustainability attributes, though it possesses performance advantages such as faster curing times, higher strength, and reduction in consumables. Given CO_2-cured concrete makes up < 0.1% of the market today, there is a lack of analysis on the impact of integrating CO_2 curing into existing operations. However, the non-sustainability benefits related to improved productivity and faster project timelines has a potential **high impact** on **market readiness** and lead to scale up in **manufacturing** with increased deployments.

High impact   Medium impact   Low to negative impact

 Source: LinkedIn

Consumer-driven demand for carbon neutral buildings

Big technology firms are under intense public scrutiny for the way they handle data, the way they influence public opinion, and impact local services – as a result they are facing increasing societal resistance and political pressure. In addition to the socio-political pressure, **growing concerns around the carbon footprint of their operations**, such as data centers, are also drawing criticisms.

Combined with ambitious carbon-neutrality goals, companies such as Amazon, Apple, Facebook, Google, and Microsoft, take a diversified approach in their decarbonization efforts with a combination of procuring renewable electricity, installing on-site energy storage systems, and ensuring expansion of their existing and new campuses are fully carbon neutral. Beyond achieving LEED Certification Platinum ratings, the **industry requests CO_2-cured concrete for all its development projects**. Consequentially, others climate-forward organizations such as universities, research institutes, and business parks follow suit and demand project developers to utilize CO_2-cured concrete as well. While government agencies do not mandate the use of CO_2-cured concrete, low-carbon, and recycling materials for federally funded projects, it establishes preferential procurement for these materials as part of all public tenders.

While new construction projects for this set of clientele makes up only 1% of global concrete use, it results in a **rapid scale-up** of CO_2 curing units. However, the inclusion of CO_2-cured concrete as a preferential construction material for government-funded projects, concrete producers install CO_2 curing units as a standard offering in their product portfolio with the fear of missing out on future high-profile private projects and a robust pipeline of government-backed infrastructure projects.

Lux Research

 Source: Compass Datacenters

Non-sustainability benefits of CO_2 curing realized

CO_2-cured concrete is positioned today almost entirely as a sustainability solution, despite the reports of significant faster curing times and higher strength compared to incumbent curing processes. Thorough lifecycle assessments have been conducted on the benefits of CO_2-cured concrete related to lower carbon footprint, reduced water consumption, and reduced materials input, but none on the operational benefits of its use.

A new study conducted by leading construction companies analyzed the benefits of utilizing CO_2-cured concrete across the entire project lifecycle identifies non-sustainability benefits, highlighted by **faster project completion timelines, lower labor costs, and increased productivity.** The industry is enamored by theses attributes and begin leveraging CO_2-cured concrete as part of its standard offering. First-movers in this space report an increase in total projects, garnering strong attention from the rest of the industry.

In result, the industry witnesses a **rapid scale-up** of CO_2 curing units with an **appetite for the price premium** of the CO_2-cured concrete due to the costs being offset by savings from elsewhere in the project budget, especially lower labor costs. However, the technology still faces some challenges for universal adoption. While CO_2 curing itself is a bolt-on solution with existing concrete admixtures mixing, the accelerated curing time disrupts the traditional project planning schedule with site managers needing to adjust workflows and tasks around a 24-hour curing time compared to the previous 28 days. As more project data is reported, the industry eventually establishes a new standard operating procedure optimized for CO_2-cured concrete projects.

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Aggregates

CO_2-derived aggregates' long-term carbon storage potential, drop-in capability, and feedstock flexibility are their most defining features

CO_2-based aggregates are defined by the following features:

Long-term CO_2 storage: A key value proposition of CO_2-based aggregates is their stability, which allows them to store CO_2 indefinitely, without the risk of CO_2 leakage over time. Coupled with the high CO_2 utilization potential of aggregates (up to 0.45 tCO_2/tonne aggregate), aggregates offer an attractive carbon sink with ample application potential in the construction industry given that they make up for between 70% to 85% of the weight concrete.

Direct replacement of natural aggregates: CO_2-based aggregates exhibit similar mechanical properties than quarried aggregates in concrete and can thus reduce the need to mine more natural aggregates.

Feedstock flexibility: The production of CO_2-derived aggregates can be realized by using quarried minerals as well as waste streams such as steel slag, coal fly ash, air pollution control residues, or bauxite residues, among others. Hence, CO_2 aggregates provide an upcycling pathway for waste that would otherwise be landfilled. This results in additional cost benefits for producers of CO_2-derived aggregates due to the avoidance of waste disposal costs.

Each of these features have the potential advantage to address the following key market needs of the building materials industry: **Decarbonization** and **circularity.** Other key needs of the construction industry include **high mechanical performance of materials** and **low-cost.**

Market Needs	Long-term CO_2 storage	Drop-in capability	Feedstock flexibility
Decarbonization	Major advantage	Limited advantage	Major advantage
Circularity	Major advantage	No advantage	Major advantage
High mechanical performance	No advantage	No advantage	No advantage
Workability	No advantage	No advantage	No advantage

Major advantage | Limited advantage | No advantage

CO_2-based aggregates address limited market needs; high costs and competition with low-cost commodities will hamper adoption

- While the technology enjoys of feedstock flexibility, using quarried feedstocks will increase the cost of the technology. Procuring waste feedstocks also incurs logistical costs. Feedstock availability could limit the scale of the technology, as well as cost reductions.
- The technology will largely depend on incentives to be profitable in the near term: likely a mix of carbon credits, procurement preferences, landfill fee avoidance.

Despite limited demonstrations today, the value chain for CO_2-derived aggregates is emerging

Raw Materials		Technology Conversion				End Users	
Petronor, Repsol	Partnered with OCO Technology to process refinery waste	Blue Planet	Developer of CO_2 mineralization technology	Carbon8	Developer of CO_2 mineralization technology	Mitsubishi Corporation	Provides a market outlet to Blue Planet's product through real estate subsidiaries
VICAT	Will feed CO_2 from flue gas and bypass dust to Carbon8's technology	O·C·O Technology	Licensee of Carbon8's technology for aggregates production	MCi	Developer of CO_2 mineralization technology	SFO	SFO Airport used Blue Planet's aggregates in a demo project

Value Chain

The concrete industry is already used to sourcing both virgin and waste mineral feedstocks; the industry already uses the latter to substitute clinker in cement. In Europe, 5% of materials used in the production of clinker come from industry waste or byproducts. Developers of CO_2-based aggregates are able to use CO_2 directly from flue gas emissions. In line with this, cement manufacturers are partnering with mineralization developers to explore the use of their own emissions and mineral byproducts for the production of aggregates and supplementary cementitious materials (SCMs). However, the number of such initiatives remains limited, even as some developers start demonstrating the technology at a commercial scale. The use of mineralization technologies to produce SCMs, which directly replace cement, remains behind aggregates in terms of maturity. Conglomerates with activities both in building materials production and real estate development have the opportunity to drive the market forward.

Regulations

Novel building materials face numerous testing, validation, and certification processes before becoming commercially available. Aggregates must be tested to ensure the quality of the aggregate under standards such as ASTM C33, C136, and C289. Similarly, concretes using CO_2-based aggregates would need to meet standards such as ASTM C140 (concrete density), C150 (curing times) and ASTM C595 (concrete variables). Meeting such standards presents barriers for wider adoption of concrete using CO_2-based aggregates.

The EU's Carbon Border Adjustment Mechanism already offers a pathway to make CO_2-based aggregates and SCMs more competitive, but the adoption of CO_2 aggregates is going to be contingent upon the introduction of a combination of instruments such as carbon taxes and tipping fees that prevent the landfilling of valuable industrial waste. These mechanisms are required for CO_2 aggregates and SCMs to become a viable alternative to ultra-low cost commodities.

Lack of performance benefits continue to hamper market adoption and the construction industry remains cost-sensitive

The primary market needs met by CO_2 aggregates relate to decarbonization and the circular economy.

Decarbonization: More than 130 countries have announced net zero carbon dioxide emissions targets. With the cement industry being responsible for about 8% of the global CO_2 emissions, decarbonization solutions for the industry become paramount. In line with this, the Global Cement and Concrete Association (GCCA) – whose members account for 80% of total cement production outside of China – has set out a roadmap for a 25% reduction in emissions associated with concrete production by 2030.

Circularity: No specific targets exist regarding recycled content of waste materials within concrete. Yet, industry associations such as the European Cement Association (Cembureau) are in favor of the use of waste materials for cement and concrete production. Similarly, top cement producers such as Holcim are raising their targets for recycled content in their materials to 30% by 2030, while CEMEX aims to raise to 50% the amount of waste that they use as alternative fuels and raw materials.

Improved performance: Development of concrete with improved mechanical performance, including the ability to withstand longer lifetimes without the need for maintenance is an ongoing endeavor. However, the construction industry has little tolerance for high-cost solutions.

eni / HOLCIM	Holcim is collaborating with Eni on the carbonation of olivine for low-carbon aggregates production	HEIDELBERG CEMENT	LEILAC will develop a pilot for its low-carbon cement technology at HeidelbergCement's plant in Hanover, Germany.
bp / CEMEX	Cemex partnered with BP to decarbonize cement; focus is on low-carbon power, transport, and CCUS.	FORTERA	Fortera and Lehigh Hanson announced a pilot at a cement facility in California to reduce emissions from cement production
Carbon8 / CEMEX	Cemex partnered with Carbon8 Systems to evaluate the company's mineralization technology to produce low-carbon construction products	Mitsubishi Corporation / Blue Planet	Mitsubishi Corporation partnered with Blue Planet to help it commercialize its aggregates technology to help it meet its decarbonization targets

High costs of CO_2 aggregates and their lack of performance improvements over incumbents will hamper adoption

A number of R&D efforts are ongoing in the industry to develop technologies that aid cement producers in their decarbonization targets. However, most companies are at an exploratory stage, with CO_2 mineralization being only an option within a portfolio of decarbonization and circularity options within the cement industry. This reflects the high-costs that CO_2 aggregates currently face, as well as the lack of performance advantages it offers to concrete.

Nearly 54,000 facilities and US$47 billion in investments needed for CO_2-based aggregates to meet their full market potential

While commercial plants for CO2-derived aggregates are available, current market penetration remains minimal

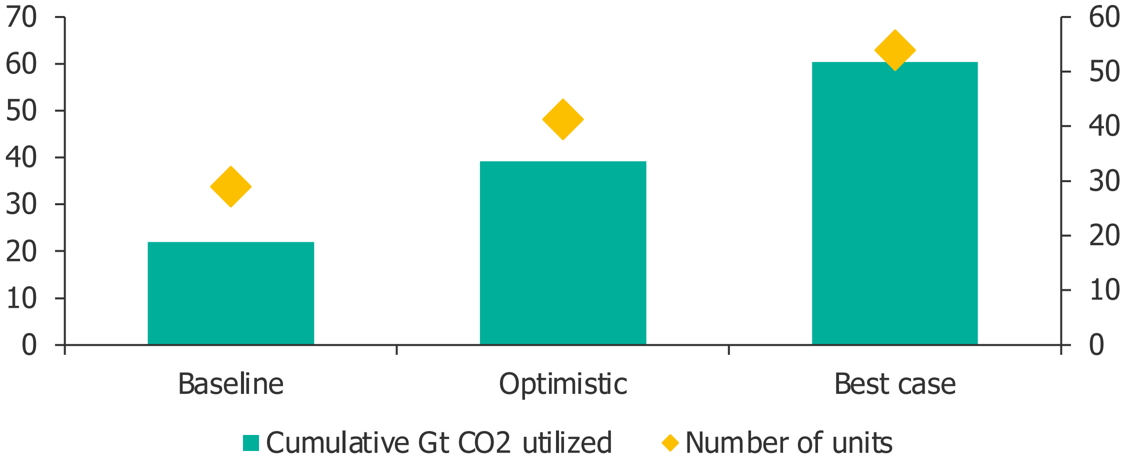
Carbon8 Systems and OCO Technology, which licenses the former's technology, are the main producers of CO_2 aggregate at a commercial scale. OCO Technology operates three plants. One of OCO Technology's facilities has a nameplate capacity of 100,000 tpa and plans to expand capacity to 400,000 tpa by 2024; the latter serves as the operable unit.

Nearly 54,000 facilities will need to be deployed in order to meet the potential market demand for CO_2-based aggregates.

- **Baseline:** US$56 billion in capital costs and over 29,000 facilities constructed. A total of 22 Gt of CO_2 is cumulatively utilized through 2050, resulting in a US$2.6 billion investment per Gt CO_2 utilized.
- **Optimistic:** US$38 billion in capital costs and over 41,000 facilities constructed. A total of 39 Gt of CO_2 is cumulatively utilized through 2050, resulting in a US$0.9 billion investment per Gt CO_2 utilized.
- **Best case:** US$47 billion in capital costs and nearly 54,000 facilities constructed. A total of 60 Gt of CO_2 is cumulatively utilized through 2050, resulting in a US$0.8 billion investment per Gt CO_2 utilized.

Aggregates: Production Units Required

Cumulative Gt CO_2 (left axis); Units (1,000s; right axis)



Manufacturing facilities could struggle to source sufficient feedstock economically

- Few developers are scaling up their CO_2-based aggregate technologies, leading to substantial rollout in order achieve the best-case scenario.
- While the capacity of a single plant can be increased to reduce the number of plants needed, such raise in capacity will be limited by the volume of industrial waste feedstock available in the vicinity of a facility.

Assessing the uncertainty of large-scale deployment based on maturity levels of factors impacting CO_2-derived aggregates

Factors	Level of Maturity	Aggregates
Product		Functional properties of CO_2-based aggregates are similar to those of natural aggregates. Producers such as OCO technology boast certifications according to standards BS EN 13055-1 and BS EN 13242, but such standards are only valid for application in the U.K.. Application at a wider scale will require compliance with e.g. ASTM standards. Novel aggregate systems that also boast reactive properties, as in the case of SCMs can replace a fraction of aggregates as well as cement; however, product development is needed.
Technology		The CO_2 mineralization technology is mature and has been deployed in the market. The largest CO_2-aggregates plants have a capacity of 100,000 tonnes of aggregate per year. While such plants rely on pure CO_2 gas, developers have started bringing online more plants using CO_2 from flue gas, a trend that is expected to become dominant in the next 1-2 years.
Market organization		While the technology is fairly developed, limited projects using the products in an end-application in the market are available; similarly, providers of mineral feedstocks are likely to vary by region, and thus haven't been fully mapped. Hence, costs of CO_2-based aggregates are expected to vary significantly depending on the logistics of materials and the potential introduction of a carbon tax.
Market readiness		Aggregates are widely used as a significant fraction of concrete; CO_2-based aggregates would serve as direct replacements. However, there is currently limited demand for concrete with captured CO_2 given the cost premium that CO_2-derived aggregates add.
Manufacturing		The three OCO Technology facilities in the UK, as well as a Carbon8 facility in Frrance are the only ones producing CO_2-based aggregates at scale. More capacity is expected from these companies as well as others such as Fortera. Lifetime of the plants has a high level of uncertainty at 10 years.

High maturity Medium maturity Low maturity

Regulatory factors are critical in accelerating the adoption of CO_2-derived aggregates utilizing waste feedstocks

Level of Impact	Scenario
Low to negative impact	**Eligibility for carbon credits for sequestered CO_2 in aggregates.** Given the relatively larger CO_2 utilization rate for aggregates (as high as 44% by weight) compared to CO_2-curing, CO_2-derived aggregates present a sizable carbon sink to be leveraged by industry. Due to the high concentration of CO_2, a carbon credit or tax can have a substantial financial impact on the final product cost, depending on the CO_2 price. Despite this, carbon credits applied to aggregates have a **low impact** on **market readiness** as the product remains more costly than incumbent aggregates in a price-sensitive industry.
Low to negative impact	**Circular economy initiatives boost waste feedstock utilization.** The industry is incentivized to transition away from virgin minerals and positioned as a circular economy solution for industrial waste management. Buoyed by tipping fees serving as a direct financial incentive for utilizing waste feedstocks, the shift still only has a **low impact** on **market organization.** While a niche ground of new players, such as Repsol which is seeking a pathway to process refinery waste, the industry's existing sourcing strategy for waste mineral feedstocks may be stymied by a lack of players in the upstream portion of the value chain willing to participate.
Medium impact	**Market standardization catalyzing technology deployment and product adoption.** While leading cement producers such as Cemex and Holcim actively engaged in the development of CO_2-derived aggregates today, an industry-accepted testing and verifications standards leads to a **medium impact** on both **market organization**, **market readiness**, and **product**, resulting in a rapid scale up of initial large-scale aggregate **manufacturing** facilities in key geographies. In parallel, standardization also occurs at the **technology** level with bolt-on systems becoming prevalent as an add-on feature for existing and adjacent industries with readily available waste feedstock streams, such as steel slag and fly ash.
High impact	**Regulators increase scrutiny on the minerals industry.** Concerns around the environmental impact of quarrying continue to increase as it relates to loss of land, ecosystem damage, and water quality in the local area. While there is unlikely to be a blanket ban on quarrying activities, regulators may limit the expansion of quarrying capacity, forcing the industry to seek alternative sources. This regulatory push will have a **high impact** on **manufacturing** as the industry scales up production to meet aggregate demands and consequentially improve **market readiness** as industry adopts novel solutions to supplement its portfolio needs.

High impact | Medium impact | Low to negative impact

 Source: CEMEX

Market standardization catalyzing technology and product adoption

With the world exiting the COVID pandemic, many countries across the globe resume their aggressive infrastructure development plans supported by trillions-of-dollars of government funding provided by post-COVID recovery plans. From rapid urbanization projects to the construction of transportation infrastructure, aggregate demand witnesses an initial shock. **Short-term demand for aggregates far exceed existing manufacturing capacity as both aggregate producers and project developers scramble to secure the limited supply available in the market.**

In order to insulate itself from increasing prices, supply shortages, and delayed construction projects, the world's leading aggregate producers accelerate the industry's **acceptance of CO_2-derived aggregates through a coordinated and aggressive establishment of industry-accepted testing and verification standards** for the inherently "new" material in the market. More importantly, the industry leverages its existing sourcing strategy for waste mineral feedstocks and forming collaborations to tap a steady stream of waste feedstocks using **bolt-on systems in a capital-light approach** compared to constructing greenfield facilities to accelerate capacity expansion.

In result, the industry witnesses a **rapid scale-up** of facilities, laying the foundation for future commercial expansion. The short-term stressor results in a new era of the aggregates industry with **CO_2-derived aggregates establishing itself as a standard offering** and the initial surge of facilities serving as blueprints for others to replicate. New entrants from adjacent industries also scale up activity as the CO_2-derived aggregates market formally materializes alongside virgin materials.

 Source: Con-Agg Companies

AGGREGATES: SCENARIO

Regulators increase scrutiny on the minerals industry

Similar to the growing public sentiment around fossil fuel's impact on the environment and demand for sustainability-driven initiatives, the minerals industry is next in line in terms of receiving public backlash. While the impacts of quarrying are long-documented, public outcry over insufferable noise, dust, and smoke are renewed as quarrying operations expand to keep up with aggregate demand. Beyond the public-facing complaints, renewed studies on the **impact of land loss, damage to the ecosystem, and water quality bring quarrying back into the spotlight.**

Governments react swiftly in imposing further restrictions on the minerals industry, enacting several regulations to address the immediate impacts related to noise and dust to appease the public outcry. While governments largely allow the minerals industry to continue operating existing production sites, it **imposes a limit on new extraction**, putting much of the leading aggregate producers' mineral reserves in jeopardy. In response, the industry is supported by government to seek alternative sources for aggregates, **leading to leaders in the industry commercializing CO_2-derived aggregates technologies already within their portfolio.**

Due to the government-imposed restrictions, governments offer a combination of direct funding, public loans and guarantees, and tax breaks to jumpstart the industry. In result, first-movers benefited from **reduced upfront capital costs** through government support, leading to a **rapid scale-up** of facilities. In addition, with the limitation of new aggregate production capacity, increase in incumbent aggregate price leads to a **reduction in the price gap** with CO_2-derived aggregates, further accelerating market adoption.

Lux Research

Opportunity Assessment
Track 2: Methanol and jet fuel

Methanol

CO_2-based methanol's carbon footprint, drop-in capability, and scalability are its most defining features for the chemical industry

CO_2-derived methanol is defined by the following features:

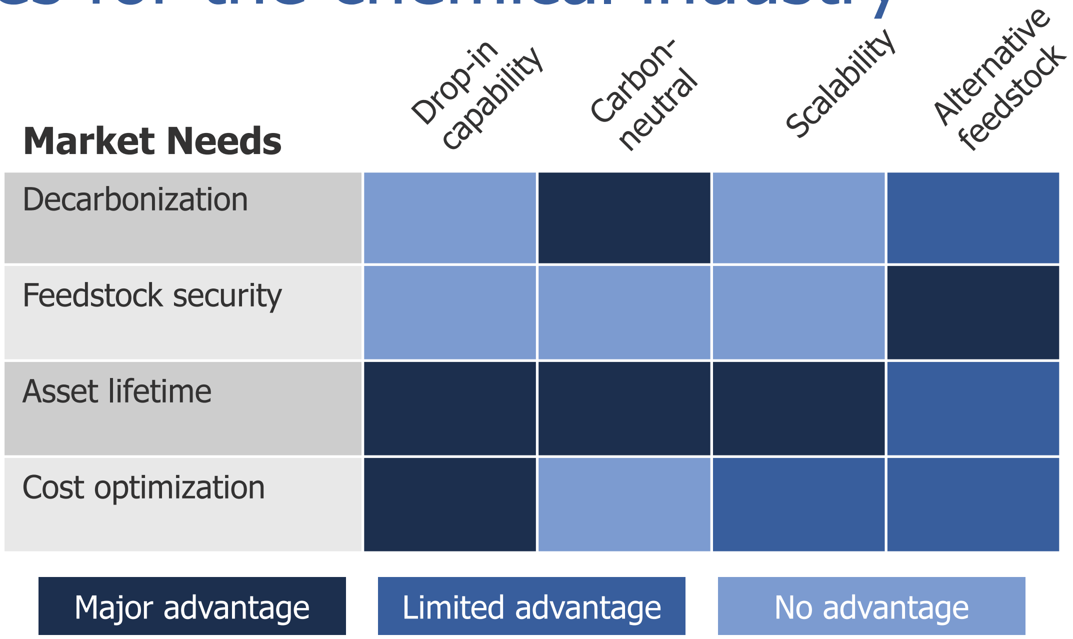
Drop-in replacement: Methanol produced from CO_2 and hydrogen is physically and chemically identical to fossil methanol and is thus fully compatible with existing infrastructure in the chemical sector.

Carbon-footprint: CO_2-based methanol can be carbon-neutral if produced from captured CO_2 and green hydrogen. Given that methanol is essential to the production of formaldehyde and subsequently polymers, swapping fossil methanol with its CO_2-based counterpart upstream is an important solution for decarbonizing the chemical sector.

Scalability: The chemical industry is thermochemical in nature and a fossil methanol plant typically operates at the million-ton capacity. As a thermochemical platform, a CO_2 hydrogenation facility for methanol can match the scale of conventional methanol plants and will not require significant reconfiguration of the downstream supply chain.

Alternative feedstock: Methanol producers are tied to the oil and gas sector for feedstock procurement. Given that CO_2 supply is not geographically constrained, CO_2-based methanol offers the chemical industry the opportunity to take greater ownership of their supply chain and insulate themselves from supply disruptions.

The defining features of CO_2-derived methanol have the potential to address the following key market needs of the chemical sector: **decarbonization**, **feedstock security**, **asset lifetime,** and **cost optimization.**



CO_2-based methanol addresses key market needs, but high costs and lack of regulatory support will severely limit adoption.

- With the main cost contributor being the electricity used to produced methanol, sourcing a cheap source of renewable electricity is imperative for CO_2-based methanol to compete with fossil methanol.
- Regulatory support can bridge the price gap between fossil and CO_2-based methanol; the current lack of regulatory promoters in the chemical sector will need to change in order to incentivize adoption.

The technologies for CO_2-based methanol are ready to scale but there is a glaring lack of off-takers in the chemical sector

Raw Materials		Technology Conversion				End Users	
Global Thermostat	Direct air capture for CO_2-to-methanol Haru Oni project	TOPSOE	ReShift technology for syngas production via CO_2	Carbon Recycling International	Developer of CO_2-to methanol technology; operates 4,000 tpa unit	Cargill	Offtakes green methanol for biodiesel production
carbon clean	Industrial CO_2 capture technology provider for Liquid Wind project	JM	CO_2-to-methanol catalyst and engineering services provider for Haru Oni	BASF We create chemistry	Develops catalysts for CO_2-to-methanol conversion	ExxonMobil	Converts CO_2-based methanol to gasoline in Haru Oni project

Value Chain

The value chain for CO_2-to-methanol involves the integration of distinct technologies – carbon capture for CO_2, water electrolysis for hydrogen, and catalysts for CO_2 hydrogenation to methanol. All of these technologies are currently ready for deployment at the commercial scale with multiple technology developers across the value chain. However, there is a lack of chemical players with publicly disclosed initiatives to offtake CO_2-based methanol and incorporate it in their operations. This is why planned commercial-scale projects are all targeting the fuels sector to leverage existing regulatory incentives for low-carbon fuels – however, CO_2-based methanol competes with an array of options in the low-carbon fuels sector and is unlikely to make an impact due to poorer performance compared to hydrotreated vegetable oil, for example. It is likely that the chemical sector will consider CO_2-based methanol once the cost of production decreases, which should occur as the technology scales to the commercial stage.

Regulations

The lack of market interest from the chemical sector is largely due to the high cost of CO_2-based methanol, but the lack of regulatory promoters remains a key barrier for wider adoption. As a globally traded commodity, a single regulatory mechanism incentivizing the use of CO_2-based methanol or imposing penalties on fossil methanol is challenging to implement. However, regional policy measures on the import of fossil-based products, such as the EU's proposed Carbon Border Adjustment Mechanism (CBAM) may promote commercial activity. Mechanisms such as CBAM offer a blueprint on how to incentivize a regional market by imposing penalties of imported fossil-based products, including methanol, by leveling the marketing for locally-produced CO_2-based methanol.

CO_2-based methanol needs to overcome the cost barrier in order to attract interest from the chemical sector

CO_2-based methanol addresses the decarbonization and feedstock security needs of the chemical sector, but costs remain a key barrier.

Decarbonization: Industrial nations such as Japan, the EU, and China have announced carbon-neutrality pledges. Chemical corporations such as BASF have also unveiled carbon-neutrality roadmaps. These pledges drive the demand for low-carbon solutions such as CO_2-based methanol.

Feedstock security: Global geopolitical tensions are increasing volatility in the oil & gas market, which has a negative impact on the chemical sector as it relies on the oil & gas industry for feedstock. The industry is looking for novel solutions that reduces their reliance on the fossil industry and mitigate their exposure to the highly volatile oil & gas market.

Asset lifetime: The chemical sector is under pressure to adopt low-carbon solutions to decarbonize but it is also locked-in into their fossil industrial assets for the next few decades. Solutions that allows continued utilization of such assets while producing a low-carbon product are therefore desirable.

Cost optimization: Methanol is a commodity and operates in a highly competitive market. The industry cannot handle solutions that lead to significant cost increase in methanol production.

BASF We create chemistry

Market need: Decarbonization
Details: Launched Carbon Management strategy to address the carbon footprint of its products and accelerate the development of CO_2-free processes for chemical production

TotalEnergies

Market need: Asset lifetime
Details: TotalEnergies partnered with Sunfire to produce CO_2-derived methanol at one of its refineries in Germany; Sunfire to supply green hydrogen via its SOEC technology

OCI

Market need: Feedstock security
Details: OCI acquired BioMCN, a renewable methanol producer, in 2015 to expand the feedstock supply to biogas and other renewable sources

CO_2-based methanol addresses several market needs but it is not yet ready for the market due to its high cost

- As a globally-traded commodity, competitiveness trumps all other market needs. CO_2-based methanol today is several magnitudes more expensive than its fossil counterpart due to high electricity prices and this will remain the key barrier to widespread commercialization.
- Regulatory measures such as the EU's proposed Carbon Border Adjustment Mechanism (CBAM) can level the playing field, but implementation is several years away.

Nearly 7,800 facilities and over US$17 billion in investments needed for CO_2-derived methanol to achieve best case scenario

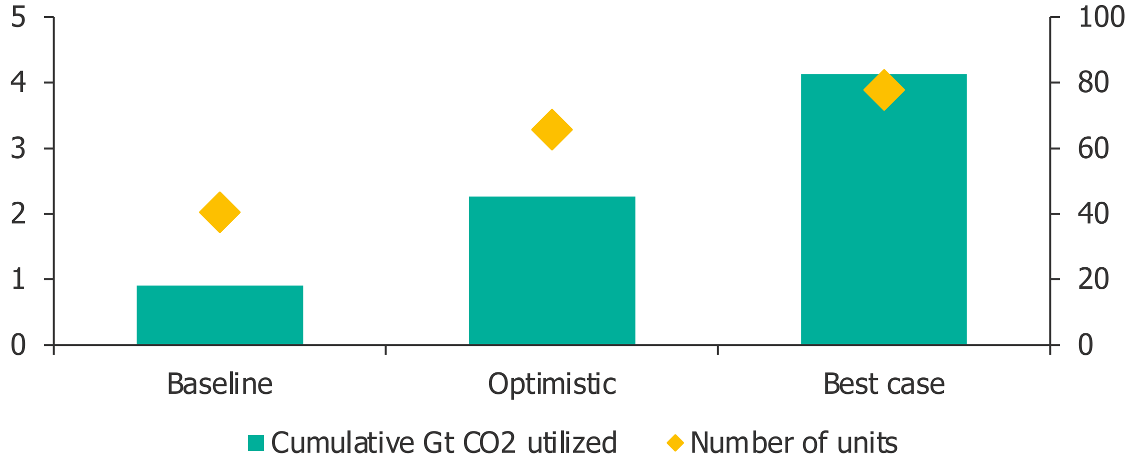
The current production of CO_2-based methanol is very low, with only one demonstration-scale facility in operation.

Carbon Recycling International is the only company operating at the demo-scale with a 4,000 tpa plant in Iceland. The company plans to launch 50,000 tpa facilities at the commercial scale and serves as the operable unit.

Nearly 7,800 CO_2-to-methanol facilities will need to be deployed in order to meet the potential market demand for CO_2-based methanol.

- **Baseline:** US$38 billion in capital costs and over 4,000 facilities constructed. A total of 0.9 Gt of CO_2 is cumulatively utilized through 2050, resulting in a US$42 billion investment per Gt CO_2 utilized.
- **Optimistic:** US$18 billion in capital costs and over 6,500 facilities constructed. A total of 2.3 Gt of CO_2 is cumulatively utilized through 2050, resulting in a US$8 billion investment per Gt CO_2 utilized.
- **Best case:** US$17 billion in capital costs and nearly 7,800 facilities constructed. A total of 4.1 Gt of CO_2 is cumulatively utilized through 2050, resulting in a US$4.2 billion investment per Gt CO_2 utilized.

Methanol: Production Units Required
Cumulative Gt CO_2 (left axis); Units (100s; right axis)



Slow penetration rates and scale-up may significantly impact learning experience curves and subsequent cost reductions.

- CO_2-based methanol production is currently at the demo scale and will require significant market scale-up of over 7,800-times in order to meet the projection of the best-case scenario.
- To reduce the scale-up magnitude, the capacity of a single commercial facility can be increased – a conventional fossil methanol plant has a capacity of 1 million tpa which is 20-times larger than CRI's commercial facility

Assessing the uncertainty of large-scale deployment based on maturity levels of factors impacting CO_2-derived methanol

Factors	Level of Maturity	Methanol
Product		CO_2-derived methanol is a drop-in replacement for their fossil fuel counterparts and integrate directly into existing infrastructure and chemical processes. This enables quick product introduction into the industry when CO_2-derived methanol is available at scale.
Technology		CO_2 hydrogenation is a well-established technology with continued advancements occurring at the academic and industry level with focus on novel catalysts, efficiency improvements, and higher selectivity for methanol. The supply of CO_2 and green hydrogen is also expected to increase to meet the needs of production through 2050.
Market organization		All the main actors for a CO_2-derived methanol supply chain have been identified but have yet to be fully integrated – with many of organizations acting individually or only connecting segments of the value chain. Only with the first series of commercial projects will result in the full integration, with the Haru Oni and Liquid Wind projects expected to come online within the next five years.
Market readiness		While methanol is a globally traded commodity with existing use in the chemical industry as a precursor for several downstream products, high production costs relative to fossil fuel counterparts and a lack of regulatory incentives remain major hurdles to widespread adoption. Aside from one-off developments, demand for CO_2-derived methanol is limited in the market.
Manufacturing		Carbon Recycling International began operating its 4,000 tpa demonstration facility in Iceland in 2013 and the facility continues to produce today. While significant capacity expansion is required through 2050, the operational success of Carbon Recycling International lays the foundation for future plants.

High maturity | Medium maturity | Low maturity

The emergence of the hydrogen economy can unlock the commercial potential for CO_2-derived methanol

Level of Impact	Scenario
Low to negative impact	**Green chemistry takes significant commercial stride.** As the chemical industry faces both consumer and regulatory pressures to decarbonize, the industry taps CO_2-derived methanol as a key platform chemical, unlocking various downstream conversions, such as olefins production, for synthetic materials, plastics, and other durable goods. The world's largest chemical companies, such as BASF, Sinopec, INEOS, commit to carbon neutrality by 2050 and must expand its portfolio beyond bio-based methanol as it comes under scrutiny for land use change, further accelerating CO_2-derived methanol. However, these two scenarios will have a **low impact** on the global-scale related to **manufacturing** and **market readiness**.
High impact	**Growth of hydrogen economy enables cost-competitive CO_2-derived methanol.** The success of all CO_2-derived chemicals hinges on the successful development of a hydrogen economy. With announced green hydrogen capacity expected to exceed 100 GW within the decade, electrolyzer manufacturing capacity and large-scale projects will result in low-cost green hydrogen through a combination of improved efficiency and integrated of low-cost renewable electricity. This tipping point in the hydrogen economy will have a **high impact** on **technology** and **market readiness** as CO_2-derived methanol competes directly on the commodity market.
Medium impact	**Large-scale facilities led by consortiums tackle the learning curve.** Chemical industry consortiums are prevalent today, with the likes of Voltachem dedicated to the development of electrochemical platforms for CO_2 conversion in industry. Coordination between stakeholders via the consortiums address the lack of integration in **market organization** today, bringing together CO_2 and hydrogen suppliers, technology developers, and short-term offtake agreements. Consortium-led large-scale projects will have a **medium impact** on **technology**, **manufacturing**, and **market organization**, setting the precedent on the value chain alignment necessary for successful commercial-scale deployment for CO_2-derived methanol.
Medium impact	**Green methanol economy analogous to the current bio-based fuel industry.** In a push for commodity and feedstock independence, governments support the build out of manufacturing capacity and establish the necessary market mechanism, such as blending mandates and credits, for the use of non-fossil methanol, including CO2-derived methanol. This scenario is reminiscent of the U.S.'s regulatory push for bio-based fuels over the past 15 years and will have **medium impact** on **manufacturing** and **market readiness**, as the industry is obligated to incorporate a percentage of green methanol into its portfolio.

High impact | Medium impact | Low to negative impact

METHANOL: SCENARIO

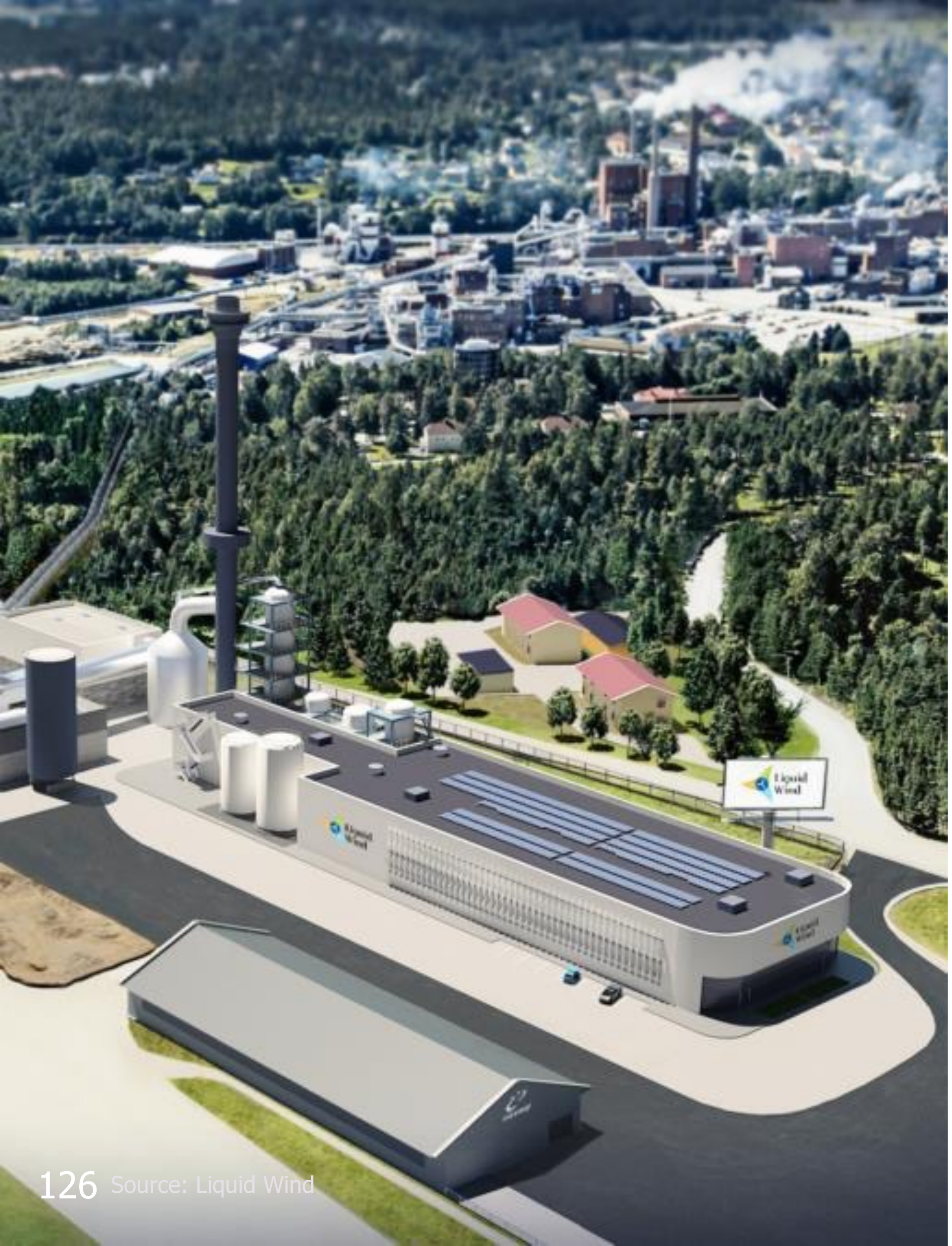
Hydrogen economy enables cost-competitive, CO_2-derived methanol

The hydrogen economy is a key driver for decarbonizing the global energy system. The International Energy Agency's (IEA) Net Zero Emission scenario projects a 480% demand for hydrogen by 2050, exceeding 500 million tonnes. This will be a five-fold increase from today's hydrogen demand, with 300 million tonnes composing of green hydrogen. The realization of this **capacity expansion for green hydrogen will result low-cost green hydrogen, with cost-parity achieved with renewable electricity prices falling below $20/MWh.**

With the influx of green hydrogen capacity, several installations will be co-located next to chemical production sites, including advanced technologies including CO_2 catalytic hydrogenation facilities to produce CO_2-derived methanol. Leading technology developers active in both hydrogen and methanol, such as HaldorTopsoe, Johnson Matthey, and BASF, will **parlay the success of the hydrogen economy into successful widespread commercial deployments.**

In result, the proliferation of the hydrogen economy will have significant impacts on the economic viability of CO_2-derived methanol, specifically in **reduction of operational costs** for both hydrogen input and electricity requirements. Co-location with electrolyzers will also result in the **rapid scale-up** of facilities. However, the industry will need to address the stark change in business model as production shifts from centralized, large-scale units to distributed, small-scale operations. Given the geographical advantages of certain regions with low-cost renewable electricity, this may result in a shift in the supply chain for methanol without the parallel emergence of hydrogen energy carriers, such as liquid hydrogen energy carriers (LOHC), metal hydrides, and metal organic frameworks (MOF) capable of supply large quantities of hydrogen to a central location.

 Source: Adobe



Source: Liquid Wind

METHANOL: SCENARIO

Large-scale facilities led by consortiums tackle the learning curve

Consortiums bringing together corporations across the entire value chain for CO_2-derived methanol are critical in understanding the logistical and technical challenges that large-scale facilities will face. Today, three key consortiums are underway in constructing large-scale facilities across the globe.

Maersk, Orsted, and several other Danish companies formed a unique partnership in 2020 to develop a 250,000 tpa synthetic fuel facility in three phases. This project will have a total electrolyzer capacity of 1.3 GW coupled with CO_2 capture for the production of both CO_2-derived methanol and synthetic jet fuel by 2030. In Chile, the **Haru Oni project includes Siemens Energy, Enel Green Power, and ExxonMobil plans to scale up to a total production capacity of 550 million liters of gasoline** via Methanol-to-Gasoline (MTG) by 2026. The facility targets the production of 350 tpa of CO_2-derived methanol by the end of 2022 via green hydrogen and direct air capture CO_2. **The Liquid Wind consortium also brings together Haldor Topsoe, Siemens Energy, amongst others for a 50,000 tpa methanol facility by 2024.**

These consortiums gain advantages from potential government support **to reduce upfront capital costs**, **reduction in operational costs** due to streamlined feedstock and electricity supply, and a **potential price premium** for the downstream product. The most critical aspect, however, is how these large-scale facilities serve as blueprints for future facilities. With leading companies involved along the entire value chain, the project development and operational learnings will play a key role in the success of future facilities.

Lux Research

Jet fuel

CO_2-derived jet fuel's drop-in capability and carbon neutrality are its most defining features for aviation industry adoption

CO_2-derived jet fuel is defined by the following features:

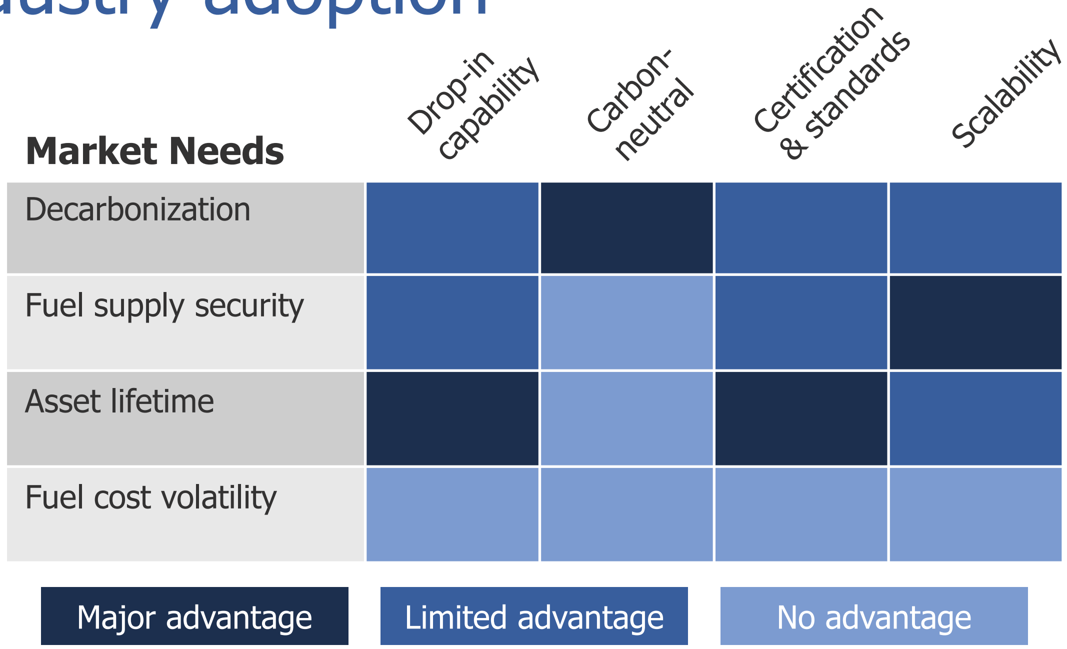
Drop-in replacement to kerosene: As a chemically identical product to incumbent Jet A1 fuel, CO_2-derived jet fuel boats major advantages as it relates to incumbent aviation infrastructure, including the aircraft, airport, and fueling, require little to no modifications from the status quo. In addition, drop-in capability enables apples-to-apples comparisons related to pricing and performance.

Potentially carbon-neutral: While the source of CO_2 utilized for jet fuel production will determine the well-to-wing carbon intensity, CO_2-derived jet fuel can be potentially carbon-neutral with the use of direct air captured CO_2. However, further lifecycle assessments will be required and likely on a project-by-project basis to ensure CO_2 circularity.

Existing certification and standards: Jet fuel has existing and extensive certification processes under ASTM D7566 and ASTM 1655. Due to the historical approval of alternative pathways under these two standard, CO_2-derived jet fuel will unlikely face additional challenges in gaining approval for commercial use.

Production scalability with existing processes: Downstream processing following the production of synthetic crude into jet fuel fractions can potentially occur within existing refinery assets with technologically and commercially feasible processes well understood by industry.

The defining features of CO_2-derived jet fuel have the potential to address the following key market needs of the aviation sector: **decarbonization**, **fuel supply security**, **asset lifetime, mitigating fuel cost volatility.**



CO_2-derived jet fuel addresses several market needs, but cost concerns remain the primary hurdle for industry adoption

- Drop-in capability and existing certifications and standards present unique value propositions for CO_2-derived jet fuel as the aviation industry looks to prolong its existing fleet and operations
- However, with fuel costs making up most of airline operational costs, CO_2-derived jet fuel offers no advantage, and likely will be disadvantage, without external intervention

Upstream activity is more active than downstream: technology development is rampant, but off-takers are limited

Raw Materials		Technology Conversion				End Users	
Carbon Engineering	Partnered with LanzaTech for feasibility study on DAC conversion to jet fuel	JM	Johnson Matthey unveils HyCOgen, end-to-end synthetic fuel platform	Shell	Shell produced 500 L of jet fuel from green H_2 and flue gas CO_2	KLM	KLM demonstrated first commercial flight with synthetic fuel in 2021
CLIMEWORKS	Direct air capture for Synhelion and Eni's solar splitting process	SIEMENS energy	Haru Oni project to scale production to 500 million L by 2026	LanzaJet	120M gallons of jet fuel and synthetic diesel by 2023 using alcohol-to-fuel tech	MABANAFT	Mabanaft to buy 500 million L of synthetic fuels from Haru Oni

Value Chain

Upstream activity in the value chain, comprising DAC and power-to-liquid developers, has higher momentum than downstream activity, which comprises of off-take customers of jet fuel. CO_2-derived jet fuels are fast moving from technology validation to scaling commercial production capacity but face significant challenges because of **green hydrogen being an expensive feedstock**. Airlines thus show limited adoption, although early-stage projects signal growth by 2050. The development of **CO_2 transportation infrastructure** is also crucial to adoption of jet fuels, and jet fuels being able to leverage existing infrastructure (pipelines, storage tanks, refueling stations) is a major benefit. **Newer projects are being developed close to airports** to minimize transportation costs – LanzaJet's upcoming facility in Illinois allows fuel transportation by ship and pipeline to two major airports, and Ineratec's upcoming facility is located close to the Frankfurt airport.

Regulations

Costs for CO_2-derived jet fuels will not fall at a rate fast enough to match the uptake capacity needed for the aviation industry to meet its decarbonization goals, creating a vacuum and need for regulatory support. While the EU supports adoption of SAF in intra-EU flights through its **ETS system**, similar mechanisms for long distance carriers are lacking. The EU has proposed a mandate to grow the market penetration for synthetic aviation fuel from 0.7% in 2030 to 28% in 2050. Additionally, **current ASTM specifications limit SAF blends** to 50% for aviation and will need to be re-visited as SAF production increases and airlines begin to test pilots. In the near term, **regulatory support to reduce feedstock costs**, for both CO_2 and green hydrogen, and **subsidize power purchase agreements** for renewable energy will have the largest impact; companies will be incentivized to increase on-site electrolyzer capacity and heavy reliance on biogenic CO_2 can shift to CO_2 capture and DAC.

CO_2-derived jet fuels is attractive for decarbonization but will have to overcome major cost barriers to attain market readiness

CO_2-derived jet fuel supports sustainability and operational needs of aviation, but its role in decarbonization is paramount

- **Decarbonization:** The International Air Transport Association (IATA) in Oct. 2021 pledged for the global aviation industry to reach net-zero by 2050, and since then, several countries and airlines have announced near term goals for SAF substitution goals
- **Fuel supply security:** Allows airlines to establish a tighter control on fuel supply as reliance on fossil fuels reduce and upstream activity is limited
- **Asset lifetime:** Repurpose and continue operations of existing pipeline networks, blending and storage tanks, and airport refueling stations
- **Fuel cost volatility:** Airlines need to discount risks associated with fossil fuel prices and be able to scale fuel production by demand, which can be done with DAC and green hydrogen

Despite its high decarbonization potential, market readiness for CO_2-based jet fuel will be limited by feedstock costs

- Decarbonization is currently the only driving force for adoption of jet fuels. Airlines will only consider other market needs like fuel cost volatility and asset lifetime when CO_2-based jet fuels become more economical
- Most companies use biogenic CO_2 because it is cheaper, but using CO_2 derived from DAC can eliminate geographic limitations of biomass and move production closer to airports

AIR FORCE OPERATIONAL ENERGY	**Market need:** Fuel supply security **Details:** DAC to produce jet fuel for the Air Force to have access to fuel at any location and allow more efficient regional refueling; have backup when transportation infrastructure is damaged
LJ	**Market need:** Decarbonization, fuel supply security **Details:** 120M gallons by 2023; plant is near the Illinois river for ship transport as well as pipelines connected to two major Chicago airports
atmosfair	**Market need:** Decarbonization **Details:** Small-scale plant (8 barrels or 336 gallons) in Germany to show technology viability and boost adoption; aims for a cost of 5 EUR/liter by 2030

Nearly 21,000 facilities and US$4.8 trillion in investments needed to meet CO_2-derived jet fuel's potential market demand

Current production of synthetic jet fuel is low, specifically for jet fuel relying on carbon capture and direct air capture

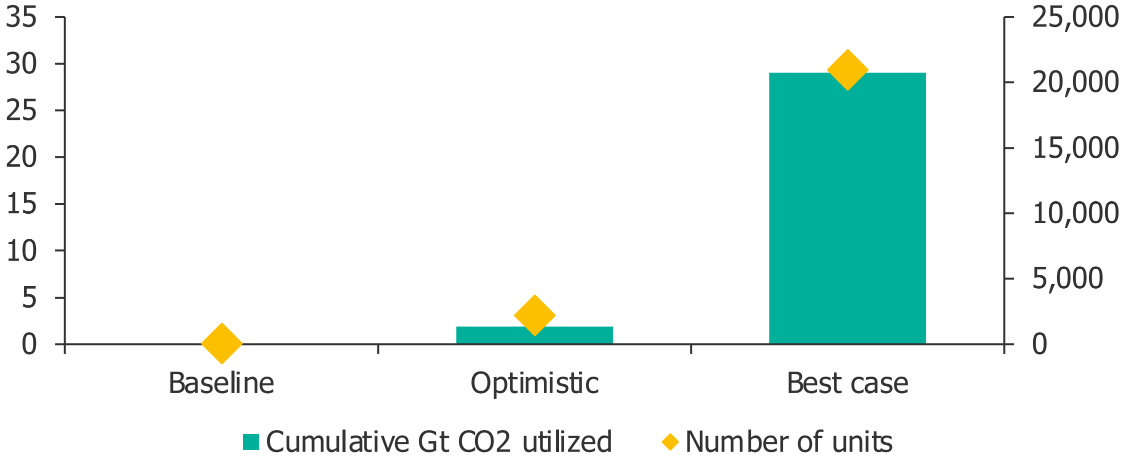
Most jet fuel production today uses alcohol-to-jet pathways and a combination of biomass gasification and Fischer-Tropsch. Jet fuels are a significant market for CCU but is yet to gain strong commercial traction. Norsk E-Fuels plans to bring online a 10 million liter per year demonstration facility by 2023 and a 100 million liter per year commercial facility by 2029; the latter serves as the operable unit.

Nearly 21,000 facilities will need to come online in order to meet the potential market demand for synthetic jet fuel.

- **Baseline**: US$33 billion in capital costs and nearly 60 facilities constructed. A total of 0.02 Gt of CO_2 is cumulatively utilized through 2050, resulting in a US$1,354 billion investment per Gt CO_2 utilized.
- **Optimistic**: US$414 billion in capital costs and more than 2,200 facilities constructed. A total of 1.9 Gt of CO_2 is cumulatively utilized through 2050, resulting in a US$221 billion investment per Gt CO_2 utilized.
- **Best case**: US$4,814 billion in capital costs and nearly 21,000 facilities constructed. A total of 29 Gt of CO_2 is cumulatively utilized through 2050, resulting in a US$166 billion investment per Gt CO_2 utilized.

Jet Fuel: Production Units Required

Cumulative Gt CO_2 (left axis); Units (right axis)



There is insufficient production capacity for CO_2-derived jet fuels today, both online and announced

- CO_2-derived jet fuel production is mostly under demonstration today. Projects are slowly being announced but will take approximately five years before the first commercial scale operations come online.
- The need for 21,000 facilities with a capacity of 100 million liters per year highlights the scale and centralized nature of conventional refineries today – CO_2-derived jet fuel may signal a shift towards more distributed, small-scale operations in the future.

Assessing the uncertainty of large-scale deployment based on maturity levels of factors impacting CO_2-derived jet fuel

Factors	Level of Maturity	Jet fuel
Product		Synthetic jet fuels are a drop-in replacement for their fossil derived counterpart and integrate easily into existing operations and infrastructure. The product offers a major advantage in being able to leverage existing pipelines, storage tanks, and refueling stations.
Technology		The capacity of CO_2 capture as well as green hydrogen production as poised to increase through 2050, providing sufficient feedstock availability for synthetic jet fuel production. Cost reduction is a major need of the hour, not unsimilar to most CO_2-derived products.
Market organization		Upstream value chain has more activity than downstream. Production facilities are slowly being established, but the current lack of production is limiting airlines from testing and flying with synthetic jet fuels. However, regulations are starting to favor synthetic jet fuels and will spur downstream activity.
Market readiness		Significantly higher costs relative to fossil fuel derived counterpart is a major hurdle since fuels contribute to the bulk of airline operating costs. Decarbonization is the main driver at the moment, and other market needs, while important, are supplementary and will only gain prominence when significant cost reduction is achieved.
Manufacturing		Current production capacity is low, specifically for synthetic jet fuel relying on carbon capture and direct air capture. Capacity will have to grow significantly through 2050 and will require several trillions in capital expenditure (CAPEX).

High maturity   Medium maturity   Low maturity

Early adopters willing to pay a premium play an integral role in kickstarting synthetic jet fuel's commercialization

Level of Impact	Scenario
	Inclusion of synthetic fuels in existing low-carbon fuel initiatives. Given the mature market mechanism and regulatory frameworks governing the bio-based fuels industry, governments across the world opt to follow the likes of Germany, Norway, and the United Kingdom by introducing blending mandates for synthetic fuels in the aviation industry. Despite the historical progress of bio-based fuels, mandates will have a **low impact** on **manufacturing** and **market readiness** as the high costs of synthetic fuels outweighs any likely incentives or subsidies to stimulate adoption.
	Large-scale access to low-cost, renewable electricity. With electricity cost consistently making up 50% to 60% of synthetic fuel's cost stack, new synthetic fuel facilities are strategically located in regions showcasing the lowest LCOE for solar and wind. In parallel with growing momentum in the hydrogen economy, access to low-cost, renewable electricity and green hydrogen supply will have a **high impact** on **manufacturing** and **technology**, although questions remain on the necessary steps to establish an integrated **market organization** connecting points-of-production to high-demand locations.
	ICAO launches commercial-scale consortium for synthetic fuels. With numerous major airlines committing to carbon neutrality, such as United Airlines, Cathay Pacific, and Delta, the aviation governing body ICAO proceeds to embark on its Sustainable Aviation Fuel Vision 2050 roadmap with the early implementation of synthetic fuel facilities across major airports with an established consortium of players across the value chain to serve as a commercial study on the technical and operational feasibility of the technology. The consortium will have a **medium impact** on **manufacturing**, **market organization**, and **market readiness**, launching a network of synthetic jet fuel production, but will be demonstration in nature given the small volumes compared to the fuel demand of the airports.
	The U.S. miliary prioritizes energy security for its operations. Self-sufficiency remains a core strategy for the U.S. military, and it has a historical precedence in adopting emerging technologies far from economic viability. Of the 752 total U.S. bases globally, the U.S. military opts to deploy synthetic jet fuel facilities with direct air capture at bases it deems isolated or in high conflict zones to insulate itself from fuel supply chain threats and ensure fuel supply. Given the U.S. military's appetite to pay significant premiums, this will have a **high impact** on **manufacturing** and **technology** with others able to gain insights and learnings from these early facilities.

High impact   Medium impact   Low to negative impact

ICAO launches commercial-scale consortium for synthetic fuels

The International Civil Aviation Organization (ICAO) unveiled its 2050 ICAO Vision for Sustainable Aviation Fuels roadmap in 2017. The original roadmap starts off with the industry blending up to 2% sustainable aviation fuel in 2025 and eventually ramping up to 50% by 2050, almost entirely fulfilled by bio-based fuels. However, **feedstock constrains leads to a stagnation in capacity expansion** of Hydroprocessed Esters and Fatty Acid (HEFA) and Alcohol-to-Jet (ATJ) did not live up to its potential as the supply of fuel ethanol remain tied to road transportation. **An urgent revision of ICAO's roadmap is made to introduce synthetic fuels into the mix well before the 2050 to fill the supply gap.**

ICAO taps some of the leading major airlines who have committed to carbon neutrality, the world's largest airports, government agencies, and aviation fuel logistics companies in forming a consortium to conduct a large-scale study on the operational and technical feasibility of synthetic fuels. The **consortium focuses on key logistical challenges of providing sufficient CO_2 and hydrogen, exploring both on-site generation and imported supplies, and accelerates the ASTM certification of synthetic fuels for commercial use.**

The consortium supported long-term strategic partnerships and combined funding to build out the value chain. In result, **lower upfront capital costs**, **feedstock price reductions**, and **long-term offtake agreements** were established as part of the **rapid scale-up** of facilities globally. This large-scale study serves as the industry's blueprint for further advancements, identifying key bottlenecks in feedstock and fuel logistics, areas of operational efficiency improvements, and key requirements for seamless integration of characteristically different industrial processes.

 Source: ICAO

 Source: U.S. Navy

JET FUEL: SCENARIO

The U.S. military prioritizes energy security for its operations

Recent military conflicts around the world raise the concern level of the U.S. Department of Defense as it continues to revise its strategy. In order to bolster its strategic global positions and insulate itself from potentially avoidable external threats, the U.S. military doubles down on its self-sufficiency strategy through the **adoption of numerous energy technologies, including small modular reactors and synthetic fuels,** to provide its global bases with the necessary energy supply.

With over 750 U.S. bases globally and 11 aircraft carriers in operations, the U.S. military conducts a threat level assessment and identifies that one-tenth of its operations are in either isolated or high conflict zones where the security of a readily available fuel supply is not a guarantee, either due to lack of local resources or challenging logistics. In order to mitigate risk and enable self-sufficiency, **the U.S. military opts to construct direct air capture and synthetic fuel facilities at these locations to supply its vehicles and jets.** The adoption of alternative fuels is not foreign to the U.S. military, with a historical track record of supporting the initial production of a wide-range of emerging fuel technologies, including the now defunct algae-based fuels, and **paying significant price premiums** in the process.

Due to this history of supporting the development and commercialization of emerging technologies, the U.S. military will be unfazed by current capital and production costs will the **rapid scale-up** of synthetic fuel facilities. These deployments will enable developers to go to market with the benefits of the operational excellence and learning curve gained through this initial set of facilities for supplying synthetic fuels for passenger airlines, though the cost of synthetic fuels will need to be further reduced via low-cost renewable electricity and cost-competitive green hydrogen.

Agenda

Lux Research

The CCU landscape has witnessed significant growth, elevated by the strategic recommendations laid out in the 2016 study

The CCU landscape has evolved and is currently thriving with a myriad of emerging technology developers targeting a wider range of end products. Coupled with increasing attention around climate change, decarbonization, and carbon neutrality, CCU is witnessing a convergence of critical supporting factors that previously existed in isolation or were not present at all. Since 2016, several key strategic recommendations in technology, market, and policy have been put into action and have played key roles in the evolution of the CCU landscape.

Funding alternative and novel processes. Following the strategic recommendation of funding alternative processes to catalytic conversion, such as electrochemical, the CCU industry witnessed a doubling of developers developing electrochemical pathways since 2016. In the process, electrochemical is now the leading technology of choice as CCU developers look to tap the rise of renewable electricity as a key energy input source.

Support the development of long shot technologies. While CCU developers continue to focus on the production of chemicals as the target CCU end product, end products such as carbon additives and food witnessed a growing number of developers emerge since 2016. In parallel, these two end products also witnessed significant growth in academic publications highlighting both the strong support for long-term technologies and continued advancements underway.

Support technology scaleup and value chain development. Though the industry did not witness a significant transition of early-stage technologies into demonstration and commercial-scale projects, many of the promising developers of 2016 still operating today are set to reach commercial-scale in coming years with projects either announced, under construction, or currently operational. Those that are operational today have overcame technical challenges and shifting focus towards commercial operations.

Increase access to capital to CCU technology developers. Venture capital funding was strongly lacking leading up to 2016, but has now evolved into a key metric to measure the momentum in the CCU landscape. Funding is being directed towards a variety of end products, highlighting both he diversification of the CCU landscape and the growing maturity of various technologies that were likely considered too nascent pre-2016. Venture capital funding in 2021 along in the CCU space surpassed the combined funding of the past decade.

Government support for early-stage research and development. Academic research in CCU has reached all-time highs with research groups focusing on CCU more than doubling in the past five years. This has led to a boom in early-stage R&D (TRL 3 or less), providing a strong indictor of innovation interest and prospects of novel technologies entering the space in the mid- to long-term. Notably, several research institutes are also targeting a wider range of CCU technologies and consistently adding to the growing repository of academic publications in the space.

Continued financial and technical support for R&D remains paramount for the future of the CCU landscape

While certain CCU technologies and developers have matured since 2016, it does not obviate the need for the development of novel technologies and processes for existing CCU end products or new potential end products. Continued financial and technical support for R&D is critical for the long-term success of CCU, especially with the growing number of developers with TRL 6 or less technologies. The pipeline of research institutes and startups in the lab-scale are well-positioned to feed the CCU innovation funnel and will undoubtedly play a critical role in the later phases of the CCU industry. The following strategic recommendations target early-stage technology development and capitalize on the momentum of the previous five years.

Continued funding of R&D for long-term technologies. Despite the maturation of developers in the CCU landscape since 2016, the average TRL across all developers is TRL 5, highlighting the potential opportunities for continued support for research and development (R&D). While conventional research grants and funding for academia remain important, it is critical to establish funding focused on the eventual participation in pilot and demonstration activities. Research institutes should launch various programs designed to encourage entrepreneurship based on in-house R&D, by providing the support system to spinout a commercial entity, such as a startup, or promote IP transfer to a corporate via the institute's commercial liaison office. In parallel, governments should take an active role in fostering collaboration between corporations and academia by promoting translational research. While academic research in the CCU space often generates novel findings, many times the research lacks realistic commercial applications. The public-private partnership allow corporations to guide early-stage technology development from inception with a clear focus on industrial applications, addressing commercial benchmarks and technical bottlenecks that are imperative for large-scale production and market adoption.

Establish programs to promote first-of-its-kind production facilities. With the maturation of the CCU landscape since 2016, many of the developers that still remain active have moved up in TRL and are on the cusp of first-of-its-kind commercial facilities. However, this stage of innovation remains a critical point in successful technology commercialization, where technology developers often face significant challenges in raising capital to support its commercialization efforts. At this point of the roadmap, it becomes less of a technical hurdle and instead is a commercial hurdle as tradition investors are turned off by high risks and uncertainties. Government support is critical at this stage and should be focused on funding opportunities and programs target high potential technologies in order to avoid stagnation.

In the following section, Lux Research draws on the learnings of the four priority end products – precast concrete, aggregates, methanol, jet fuel – and outlines the strategic recommendations for the next phase of growth for CCU that offer the best opportunities for immediate government and private sector support and action now.

Identifying key levers for accelerating large-scale deployment of production facilities for priority CCU end products

Lux Research drew correlations between the key factors of each opportunity assessment – product, technology, market organization, market readiness, manufacturing – to identify potential levers – capital cost, operational cost, product price, number of units – that can improve the outlook for large-scale deployment. The below table summarizes the key factors derived from the scenario analysis relevant to each each lever of the four priority CCU end products. Note, in some instances, the key factors may be applicable across multiple end products.

	End product	Capital cost	Operational cost	Product price	Number of units
Track 1	Precast concrete	A turnkey, standardized CO_2 curing **technology** can potentially reduce capital cost	Vertically integrated **market organization** with supply agreements for CO_2 can potentially reduce operational cost	Implementation of carbon credits for sequestered CO_2 can potentially incentivize **product** adoption	Both customer-driven demand for low-carbon buildings and performance benefits can potentially accelerate deployment of **manufacturing**
Track 1	Aggregates	Standardization of **technology** with bolt-on systems can potentially reduce capital cost	Circular economy initiatives aligning **market organization** with waste feedstock suppliers can potentially reduce operational cost	Implementation of carbon credits for sequestered CO2 can potentially incentivize **product** adoption	Regulations capping quarrying activity can potentially lead to rapid deployment of **manufacturing** and improve **market readiness**
Track 2	Methanol	Improved **market organization** can potentially improve capital costs with better **technology** integration	Large-scale renewable electricity and hydrogen integrated into the **market organization** can potentially reduce operational costs	Green chemistry initiatives from the chemical industry can potentially improve **market readiness** for higher **product** costs	Consortium-led large-scale projects can potentially tackle the learning curve for **manufacturing** and **technology**
Track 2	Jet fuel	Consortium-driven initiatives improve **market organization** and **manufacturing**, potentially reducing capital costs through financial support	Large-scale renewable electricity and hydrogen integrated into the **market organization** can potentially reduce operational costs	Airline offtake agreements can potentially improve **market readiness** for higher **product** costs	Large-scale deployment of production facilities can improve **manufacturing** and **technology** learning curves

The maturation of CCU technologies since 2016 have moved segments of the industry into the critical deployment phase

Based on each scenario, Lux Research qualitatively assessed the impact – high, medium, low – to identify which levers present the best opportunity for each specific end product. The following section is a synthesis of key strategic actions required to propel priority CCU end products into the market for three key actors – government, private sector, and technology developers.

	End product	Capital cost	Operational cost	Product price	Number of units
Track 1	Precast concrete	Low impact	Medium impact	Low impact	High impact
Track 1	Aggregates	High impact	Medium impact	Low impact	High impact
Track 2	Methanol	Medium impact	High impact	Medium impact	Medium impact
Track 2	Jet fuel	Medium impact	High impact	Medium impact	High impact

High impact | Medium impact | Low impact

LUX TAKE

With the evolution of the CCU landscape since 2016, the maturation of key enabling technologies are now in the deployment phase, either pilot or commercial. With first-of-kind commercial facilities online today or expected in coming years, the continued expansion of production facilities remains critical for CCU technologies to move down the experience curve to improve the economics of future facilities. Strong government support will play a critical role, but the parallel emergence of a hydrogen economy may play an even larger role in unlocking the full potential for CCU by providing access to low-cost green hydrogen and renewable electricity.

Direct government participation is a key lever for jumpstarting the large-scale adoption of CCU end products

The growing innovation activity in CCU will undoubtedly continue, driven by academia, startups, and corporations. However, the pace in which the implementation of these technologies in the market will largely be dictated by government through both direct and indirect policies. Government possibly plays the most important role in the future of CCU and can jumpstart the deployment of production capacity with direct market participation.

Preferential procurement for CCU end products. The initial market penetration for CCU end products is critical for large-scale deployment of production capacity, by providing real-world examples of the advantages of utilizing CCU end products. However, with many CCU end products replacing market-driven, cost sensitive commodities, a price premium will largely hinder adoption outside of niche consumers. But instead of an industry-wide mandate requiring the use of CCU end products, government and military can indirectly stimulate production through preferential procurement programs. In addition, governments can also provide direct funding, loans, or tax breaks for in support of bringing production capacity online.

Implementing mandates to industry. The direct participation of government is essential in creating and shaping markets for emerging technologies. Historically, such measures have been put in place for renewable energies, electric vehicles, and bio-based fuels throughout the U.S. and Europe. While the eventual fall in prices of these technologies and eventual widespread commercial adoption was due to significant manufacturing capacity scale up and maturation of a supply chain, the initial phases were heavily government supported. Similar market mechanism will be required to jumpstart the CCU industry. Governments should establish industry-level mandates for integrating CCU end products into their portfolio, providing financial support for first-movers until both the value chain and market readiness of the CCU end product materializes and matures.

Setting limitations or prohibitions on incumbent products. While blanket bans on certain technologies has not had historic success, the approach is gaining traction in recent years. Several countries have laid out target dates for banning the sale of new internal combustion engine vehicles and ceasing construction of thermal generation assets, such as coal-fired power plants. However, it is yet to be seen if governments will be able to follow through with these types of initiatives and phase out certain technologies. Rather than an outright ban, governments instead can limit the expansion of incumbent products instead, requiring the industry to seek alternatives, including CCU end products, to meet growing demand beyond existing production capacities. This may lower the barrier to entry for CCU end products, but in many cases also faces stiff competition from other alternatives. Additionally, the political discourse of these types of policies will vary country to country, as many emerging economies will likely prioritize economic growth and national security over decarbonization.

Supporting CCU deployment through the inclusion of the technology in infrastructure development plans

The implementation of carbon credits, taxes, and other pricing mechanisms will undoubtedly be rolled out globally and offer some form of benefits to CCU end products. But now the CCU landscape is in the critical deployment phase with key CCU technologies ready for large-scale deployment. Continued support for pilot-scale and demonstration facilities is still important for emerging processes and technologies, but government must take immediate action in bringing online the first wave of CCU production facilities.

Developing an infrastructure enabling the CCU economy. Beyond the scale-up of the CCU technology, commercial success hinges on the combination of a series of key inputs, including CO_2, green hydrogen, renewable electricity, and in some cases other additional feedstocks. These key components are all currently fragmented in various industries and the establishment of the appropriate infrastructure will be required to bring all inputs to a single location. While the build-out of renewable electricity and green hydrogen capacity is likely to occur via the hydrogen economy, CO_2 supply remains distributed amongst point source emission sites, such as power plants and industrial facilities. Governments currently planning out infrastructure development for the hydrogen economy should also take into consideration the transport network for CO_2 as well. However, a key strategic decision must be made on if CCU will be better served via a centralized, large-scale production model, reminiscent of the current industrial mode of operation, or if the introduction of a distributed, small-scale production model is more ideal. While the latter offers benefits in terms of co-locating CCU facilities at the point of emissions or point of product consumption, it will drastically alter the fabric of industrial processes.

Loans, direct funding, and other tax breaks for project developers. One of the major stumbling blocks of emerging technologies is the upfront capital requirements for large-scale facilities that carry a high level of uncertainty and risk due to its novel nature. Financial programs in the past have been paramount in stimulating new industries by providing loans, guarantees, and direct funding for pioneer facilities and subsequent expansions. Governments must play a continued active role in this regard as it relates to CCU technologies to lower the potential risks and attract eventual investments from the private sector into the space.

Introduce policies and insurance for engineering firms. Leading engineering companies are critical in the deployment of CCU technologies, providing the engineering, procurement, and construction (EPC) services to bring online commercial-scale facilities. However, novel process technologies, especially those not developed in-house, are very unlikely to be adopted by major EPC firms. Governments must put in place a mechanism providing a form of insurance and liability coverage for the EPC firms embarking on deploying first-of-its-kind CCU technologies.

Adjacent decarbonization and sustainability trends play an integral role in the private sector's impact on CCU technologies

Sustainability is growing in prominence and the objectives of the United Nation's Sustainable Development Goals (SGDs) have become key business drivers, dictating the development of technology and business models to address these challenges. In parallel, decarbonization is witnessing an equal amount of attention with global cooperation and policies accelerating a shift towards net-zero. The falling prices for renewable energies have emerged as cost-competitive alternatives to fossil fuels and growing capacity is enabling the ambitions of a green hydrogen economy. With both of these trends, the private sector must play a key role in coupling CCU technologies to unlock the full potential of CCU.

Coupling the CCU economy with the hydrogen economy. Access to both low-cost renewable electricity and an ample supply of green hydrogen is critical for many high potential CCU end products, such as jet fuel and methanol. However, the development of large-scale renewable electricity and electrolyzer capacity often falls outside of the realms of CCU developers. While hydrogen can eventually be applied to the power and road transportation sector as a means of decarbonization, it has alternative options through electrification. On the other hand, hard-to-abate sectors such as industry, do not have such luxuries and will remain locked into its carbon-dependent pathways. In order to shift away from fossil fuel-based carbon, the private sector must utilize CO_2 as a new feedstock. The growing availability of renewable electricity and green hydrogen are also the keys to unlocking the economic competitiveness of many process. The actors in the private sector currently making aggressive plans for the development of hydrogen hubs across the world must take into consideration the implementation of CCU technologies in parallel and integrate the CCU value chain along side it.

Coupling the CCU economy with the circular economy. There is clear momentum in the circular economy as governments investigate regulatory mechanism to shift away from the existing linear model of consumption towards a restorative and regenerative design. Currently, CCU technologies are not explicitly highlighted in the circular economy, with a greater focus on consumer-facing products such as plastic waste. While there is growing incentive around plastic recycling to reduce the production of virgin plastic materials, demand for plastics will far exceed the capacity of recycled plastics, leaving a gap in supply that can be fittingly filled through CO_2-derived products. In order to meet growing demands, the private sector should position CCU technologies as a critical component in the circular economy and aids in closing the full loop of circularity. Similar to the integration of the value chain around the hydrogen economy, the private sector should implement a CCU value chain as a complement to the circular economy value chain as a secondary source of carbon feedstock.

The private sector plays a critical role in the growth and development of a CCU ecosystem and value chain

The CCU landscape has undergone significant transformation since 2016 with a rise in innovation activity, venture capital funding, and several technology developers making strides in scaling up their technologies. The catalyst of early-stage research has built a foundation of innovation solutions for the long-term prospects of CCU. Both government and private funding have spearheaded transformational technology developments, but the last step toward market applications must be executed by the private sector. The private sector must mobilize the necessary stakeholders and funding in building out the CCU ecosystem and initiative the critical step in bringing CCU technologies to market.

Support the development and quality of the ecosystem. Currently the value chain for CCU remains largely fragmented, with raw material suppliers, technology developers, and end users working together in various silos. The disconnect between critical stakeholders remains large and the establishment of a value chain will require the orchestration from leading organizations in the private sector who have the existing supply chains and partners to bring together a robust CCU ecosystem. The private sector should play an active role in coordinating the required stakeholders for the various CCU end products to ensure there is a synchronization between each part of the value chain, just as any incumbent product today. The establishment of a consortium by a single or group of private sector organizations is valuable. But with the maturation of priority CCU technologies, alignment of the technical and market expertise is equally important as well with the private sector taking a leading role in this regard. The key objective of each consortium should be on the intention of establishing a commercial facility, providing an opportunity for additional stakeholders to gain insights on the technical and operational experiences for future facilities.

Providing technical support through shared pilot facility. While large-scale, commercial facilities are critical and being announced with the CCU ecosystem, many of the leading technology developers are only just embarking on pilot-scale production with several more emerging players entering the space each year. Rather than financially supporting one-off pilot-scale facilities, either through direct investments or partnerships, the private sector should establish industrial clusters for testing and piloting early-stage CCU technologies that can eventually be integrating into existing or new business units. This not only provides a capital light approach, with numerous developers being able to used shared facilities and equipment, but it also gives the private sector a first-hand look at emerging processes and provide ongoing technical and market support from cluster members. The use of an industrial cluster concept also enables the private sector to couple CCU technologies with the previously mentioned hydrogen economy and circular economy initiatives.

Establishing clear value propositions for CCU end products should be the top priority for technology developers

The maturity level for the four priority CCU end products are medium (precast concrete and aggregates) and high (methanol and jet fuel) but has yet to be adopted at a large-scale by its respective industries. Despite drop-in or nearly drop-in replacements to its incumbent counterparts, the value proposition of both the technologies and the end products are not clearly defined by technology developers with nuanced differences in production processes and final products. In order to gain market traction and industry adoption, technology developers must make strides in establishing clear standardization and lifecycle assessments to prominently highlight the inherent value of CCU end products.

Technology and product standardization. In the case of jet fuel and methanol, the CCU end product and its characteristics, are well-defined and understood by the industry. As a chemically, identical, drop-in replacement to its incumbent counterparts, these two products offer advantages in leveraging existing infrastructure as well as seamlessly integrating into downstream industrial processes. However, this is not the case for precast concrete and aggregates. While certain technology developers of these inherently novel materials boast various product certifications, such standards may be limited in terms of geography or application. Technology developers must take an active role in spearheading the creation of international certification standards, such as ASTM and ISO, specific to their respective CCU end products. This will be critical in lowering the hesitancy of industry to incorporate CCU end products into their existing processes and products. While a unique set of standards governing CCU end products remains interesting, technology developers should focus their attention on integrating CCU end products as annexes within incumbent standards and certifications.

Project lifecycle assessments. While there is increasing activity and support for the lifecycle assessment for various CCU end products related to carbon footprint and resource requirements, there is a growing value proposition for CCU end products beyond the utilization of CO_2. Technology developers with existing and upcoming customers, must coordinate in establishing lifecycle assessments with a scope beyond sustainability attributes and take into account operational and strategic advancements that the CCU technology may offer. From an operational standpoint, technology developers should assess the impact of labor productivity, project efficiency, and profitability, amongst other key performance indicators common within each respective sector. In terms of strategic advantages, technology developers must assess its projects beyond the core operations and take into considerations impact on supply chain dynamics, insulation from volatility of commodity goods, and other externalities that have knock-on effect to the industry but seldom included in the project itself. The quantitative understanding of these benefits and the sensitivity analysis associated with each of these factors can potentially enhance the value proposition of the CCU end products the technology developers offer.

Appendix:
Methods and Data Sources

GLOBAL CO_2 INITIATIVE
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Methodology
May 2022

Lux Research forecasted the addressable market for CCU end products and estimated market penetration for three scenarios

Lux Research developed a market forecast model for the global production capacity and global market size for CCU end products to 2050. Using in-house knowledge and secondary information from annual reports, market reports, and technical publications, Lux Research forecasted the addressable market for CCU end products and estimated market penetration based on technological advancements for cost reductions, financial policies and incentives, and willingness to adopt decarbonization technologies by the industry. The various factors provide a cost tipping point for industry adoption when CCU end products become the preferred technology choice for the industry. The following diagram shows the methodology used in assessing addressable markets.

Addressable Market
Estimate market size in 2020

Triangulation and vetting of 2020 market size numbers based on secondary information from annual reports, market reports, and technical publications to establish a baseline market size in 2020.

Addressable Market
Projected growth of total market to 2050

Triangulation and vetting of projected compound annual growth rate (CAGR) based on secondary information from annual reports, market reports, and technical publications to establish addressable market to 2050.

Market Penetration
Market penetration of CCU end products

Estimation of market penetration based on three scenarios – baseline, optimistic, best case. Each scenario has different levels of factors driving market adoption related to cost, incentives, and willingness to adopt.

Market Size
Market volume, value, and CO_2 utilization

Estimation of the market size in terms of volume (tonne), value (US$), and CO_2 utilization (Gt) in 2050 based on total addressable market and market penetration of the three scenarios.

Market forecast estimates are based on a triangulation of reputable sources. The estimates are used to establish a starting point and magnitude of the market size for the analysis. Lux Research acknowledges the wide range of available market size estimates in the public domain and does not intend to replicate or replace the numbers reported. Sources and assumptions related to market size metrics are included in tables on the following slides.

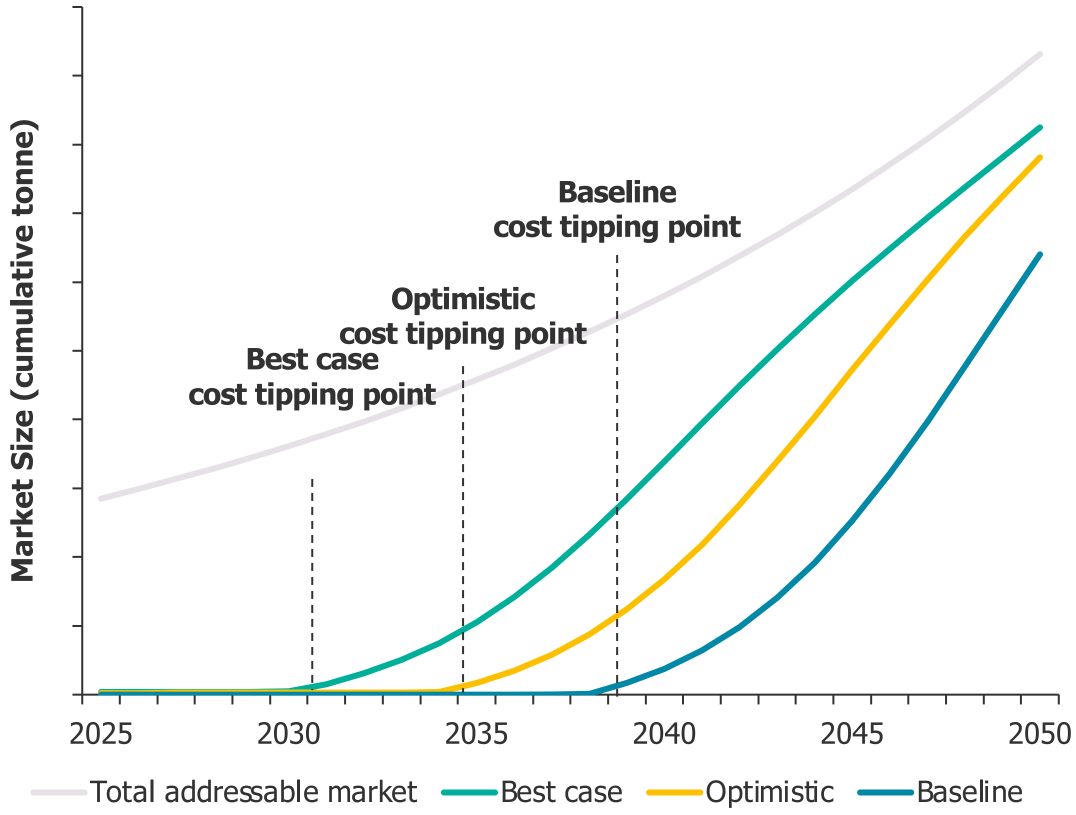
Lux Research forecasted three market penetration scenarios based on cost reductions, financial incentives, and willingness to adopt

Lux Research forecasted three market penetration scenarios to identify a cost tipping point when CCU end products become the preferred technology choice for the industry. The inflection point is based on the following inputs:

- **Cost variables.** A baseline incumbent product cost (US$/tonne) is established in 2020 from on secondary market information and is projected through 2050 based on historical price changes. The CCU end product cost ($US/tonne) for 2020 is estimated and an annual cost improvement is assumed based on Lux's in-house expertise and models for the three scenarios.
- **Financial incentives.** A US$10/tonne carbon price is assumed to be introduced in 2020 based on World Bank's Carbon Pricing Dashboard. Annual increase in carbon price is based on the range Carbon Disclosure Project deems necessary by 2040 (US$50/tonne to US$100/tonne) for the three scenarios.
- **Adoption variables.** Two key adoption variables were assessed qualitatively – competing technologies and industry willingness to adopt. Competing technologies include the development of non-CCU, but low-carbon or zero-carbon technologies addressing the same end product. Willingness to adopt is based on the priorities of sustainability, performance advantages, and non-quantifiable benefits that can counterbalance a higher end product cost. These factors are assessed based on Lux's in-house expertise and ongoing primary research with technology developers and industry executives.

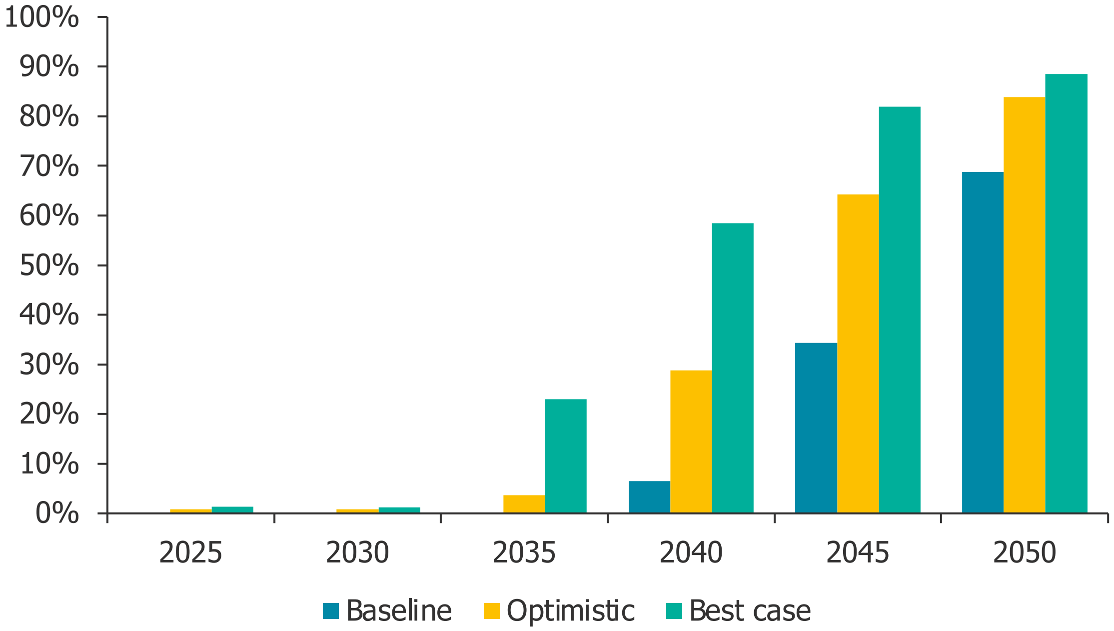
Lux Research aims to provide a global view of CCU adoption in its market forecast, but acknowledges the regional variations related to the above three variables that can accelerate or impede adoption timelines.

Lux Research Forecasts Market Penetration of CCU End Products for Three Scenarios



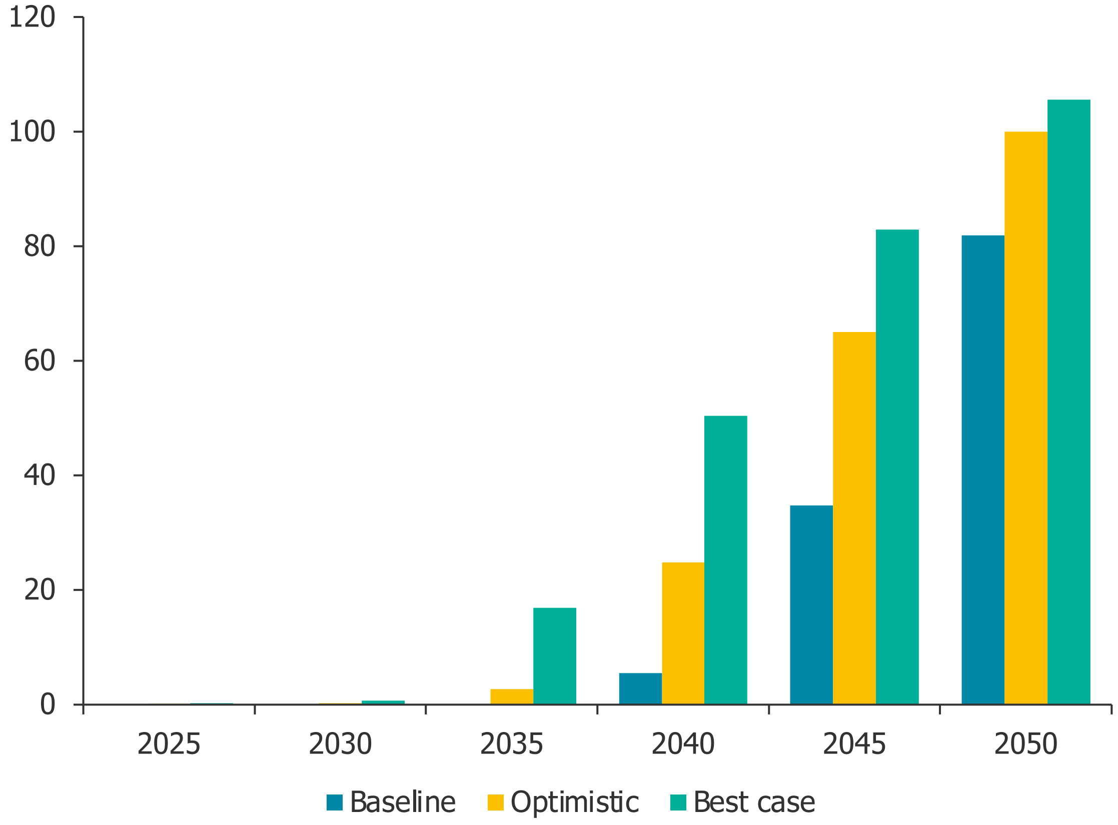
Lux Research projected the market penetration (%) and market volume (tonne) for three different scenarios

Example: Market Penetration
Market penetration (%)



Lux Research uses the projected market penetration (%) of the total addressable market as the foundation of its market forecast. Market penetration (%) is converted to volume (tonne) based on the total addressable market and further converted to market value (US$) and CO_2 emissions utilization potential (Gt) through its respective conversions.

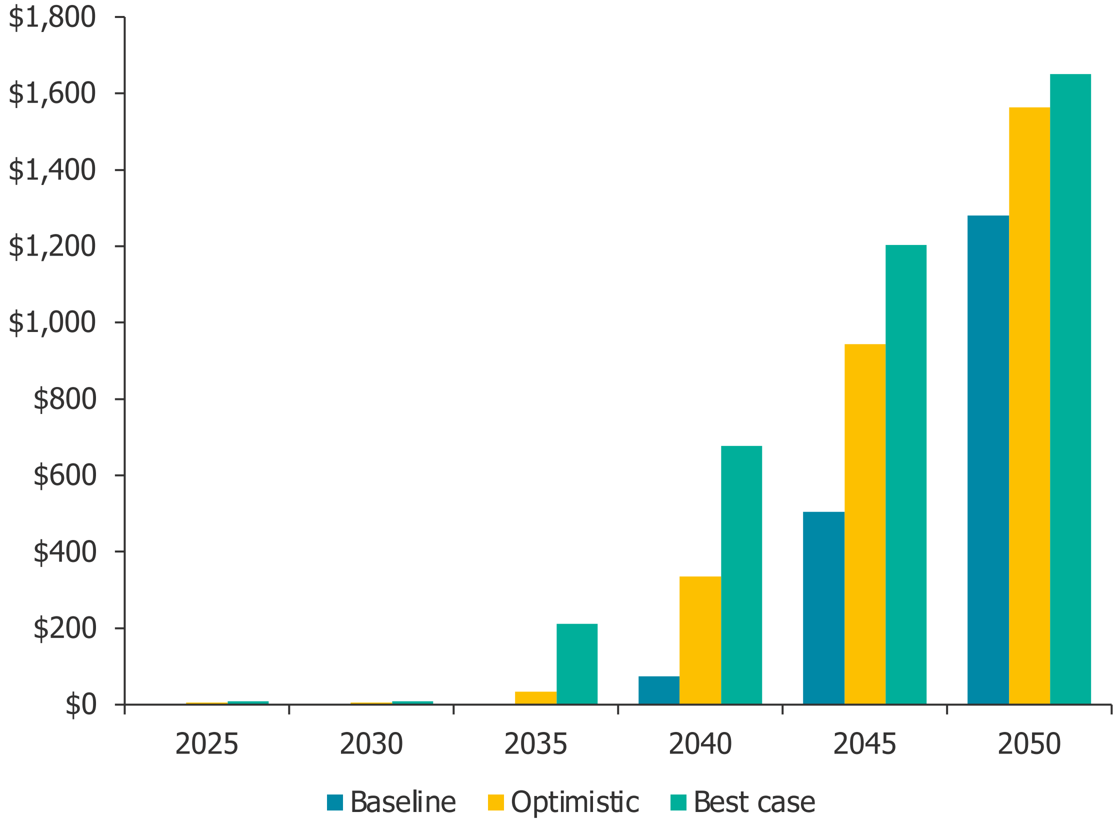
Example: Market Volume
Annual billion tonne



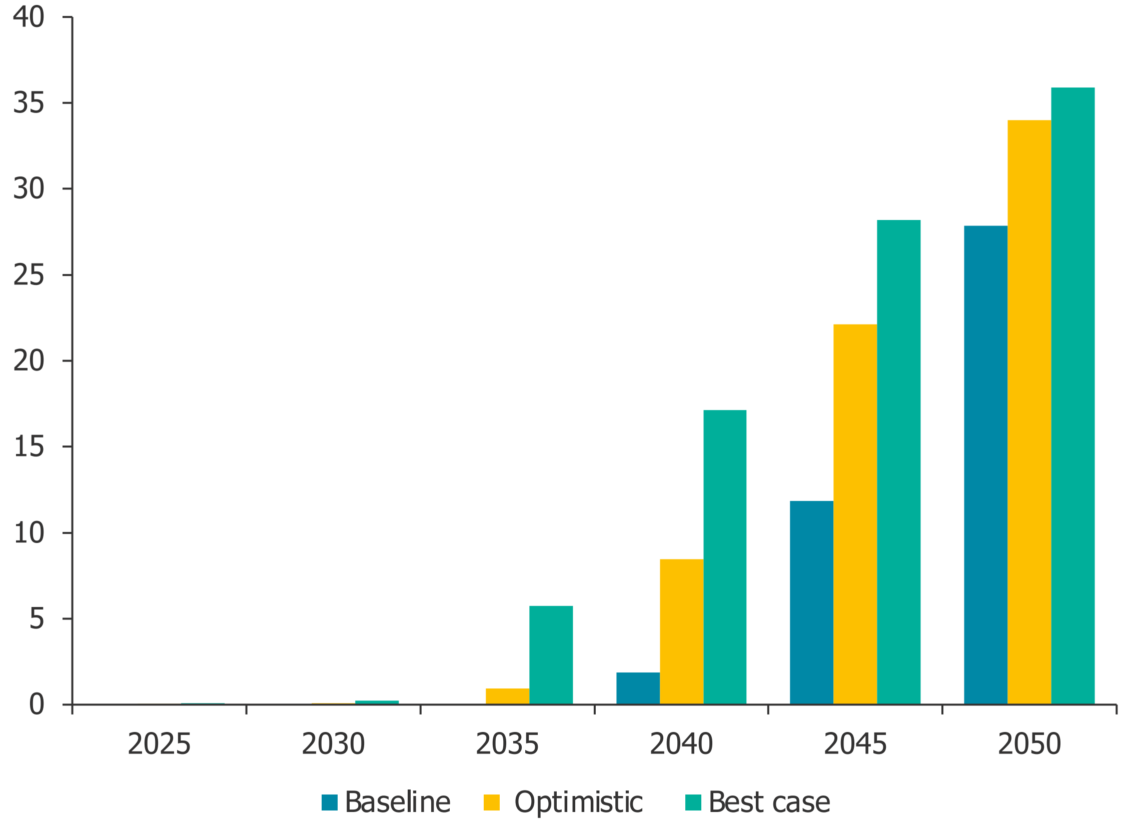
MARKET FORECAST

Lux Research converted the market volume to market value (US$) and CO_2 utilization potential (Gt)

Example: Market Value
US$ billion



Example: CO_2 Utilization Potential
Annual Gt of CO_2



Lux Research estimated a starting market volume in 2020 and projected growth to 2050 to establish the total addressable market

Market	2020 market volume (tonne)	Market growth rate (CAGR %)	2050 market volume (tonne)	Sources and comments
Precast concrete	7 billion tonne	5.2%	32 billion tonne	2020 market volume for cement production is 4.2 billion tonne according to the International Energy Agency; on average cement makes up 18% of concrete with ranges of 7% to 15% reported by Portland Cement Association upwards to 22% reported by Nasution et al. (2015), equating to an approximate market volume of 23 billion tonne; precast concrete is approximately 30% of the global concrete market Market growth rate is based on the triangulation of annual growth rates from leading companies related to precast concrete products from CRH, Forterra, and Holcim as well as projected growth rates from the National Precast Concrete Association
Aggregates	45 billion tonne	3.3%	119 billion tonne	2020 market volume based on a triangulation of reported market volumes from a series of reputable sources; Holcim reports 256 million tonnes with an approximate 2% market share (excluding China); the Chinese Aggregates Association reports consuming 20 billion tonnes in 2019 with China having a 45% market share; due to the wide range of reported numbers, Lux defined 45 billion tonne as the starting market volume in 2020 based on the above Market growth rate based on the triangulation of annual growth rates from leading companies CRH, Holcim, CEMEX, and Vulcan
Carbon black	14 million tonne	5.5%	70 million tonne	2020 market volume based on the value reported by Recovered Carbon Black Market growth rate based on the annual growth rates reported by Recovered Carbon Black
Methanol	100 million tonne	5%	432 million tonne	2020 market volume based on the value reported by the Global Maritime Forum and the Methanol Institute Market growth rate based on values reported by the International Energy Agency and Methanol Institute ranging from 3% to 7% annually; Lux took the average of the two as the 7% growth rate is representative of a recent expansion of methanol production capacity that is unlikely to be sustained in the long-term

Lux Research estimated a starting market volume in 2020 and projected growth to 2050 to establish the total addressable market

Market	2020 market volume (tonne)	Market growth rate (CAGR %)	2050 market volume (tonne)	Sources and comments
Formic acid	780,000 tonne	2%	1.4 million tonne	2020 market volume based on values reported by Perez-Fortes et al. (2016) Growth rate is based on a triangulation of values reported by Perez-Fortes et al. (2016) and Lux Research's interviews with Dioxide Materials and Coval Energy that range between 1% to 3.8%
Animal feed	337 million tonne	6%	1.9 billion tonne	2020 market volume based on reported values by Fraanje et al. (2020) on 90% of soybean production used for animal feed Growth rate based on triangulation of values reported by the Food and Agriculture Organization as it relates to demand in fish and livestock products
Methane	32 billion tonne	3%	79 billion tonne	2020 market volume based on values reported by the International Energy Agency Growth rate based on triangulation of annual growth rate between 2010 to 2019 reported by the International Energy Agency; excludes 2020 due to the impact of COVID-19 on natural gas production
Jet fuel	305 million tonne	8%	3.1 billion tonne	2020 market volume based on values reported by the International Civil Aviation Organization Growth rate based on triangulation of values reported by the International Civil Aviation Organization, the International Air Transport Association, the International Energy Agency, Shell Sky Scenario, and ExxonMobil Outlook for Energy; growth rates range from 5% to 24% through 2050; assumes growth will likely be between the low and medium scenarios of the reported values
Polyurethane	24 million tonne	3%	58 million tonne	2020 market volume based on values reported by Statista Growth rate based on annual increase in demand towards 2025 of 27.9 million tonnes reported by Statista

Lux Research estimated starting product price in 2020 to project the cost tipping point between incumbent and CCU end products

Market	Incumbent 2020 price (US$/tonne)	Incumbent price change (%/year)	CCU end product 2020 price (US$/tonne)	Sources and comments
Precast concrete	US$19	1.1% increase/year	US$26	2020 incumbent product price based on triangulation of reported revenue for precast concrete products from leading producers CRH, Forterra, and Holcim; incumbent price increase based on annual historical price changes reported by the U.S. Bureau of Labor Statistics CCU end product price based on a CO_2 cost of US$100/tonne and the utilization of 0.085 tCO_2 cost for the production of 1 tonne of CO_2-cured concrete
Aggregates	US$10	1.5% increase/year	US$50	2020 incumbent product price based on triangulation of reported revenue for aggregates from leading producers Holcim and CRH along with Chinese Aggregates Association reports of RMB 15/tonne to RMB 115/tonne; due to the wide range, Lux defined US$10/tonne as the starting incumbent product price; incumbent price increase based on annual historical price changes reported by the U.S. Bureau of Labor Statistics CCU end product price based on triangulation of values reported by Hepburn et al. (2019) and Lux Research's personal correspondence with Carbon8 Systems, Carbicrete, and CarbonBuilt
Carbon black	US$1,229	0.4% increase/year	US$4,800	2020 incumbent product price based on triangulation of reported prices from Orion Engineered Carbons and ChemAnalyst; incumbent price increase based on annual historical price changes before 2020 reported by the Federal Reserve Bank of St. Louis CCU end product price based on Lux Research's correspondence with Solid Carbon Products on reported cost of goods sold

Lux Research estimated starting product price in 2020 to project the cost tipping point between incumbent and CCU end products

Market	Incumbent 2020 price (US$/tonne)	Incumbent price change (%/year)	CCU end product 2020 price (US$/tonne)	Sources and comments
Methanol	US$350	1% increase/year	US$1,381	2020 incumbent product price based on triangulation of methanol contract prices reported by Methanex with a heavier weightage towards Asia-Pacific contract prices due to the larger volumes sold in the region; incumbent price increase based on annual historical methanol contract prices changes reported by Methanex, but does not reflect short-term volatility CCU end product price based on Lux Research's power-to-X cost model assuming state-of-the-art electrolysis and CO_2 hydrogenation technologies
Formic acid	US$600	No price increase	US$575	2020 incumbent price based on values reported by CEIC for 85% concentration formic acid; no price increase assumed based on historical price trends, though formic acid prices are volatile in the short-term CCU end product price based on Lux Research's power-to-X cost model assuming state-of-the-art electrolysis and CO_2 hydrogenation technologies
Animal feed	US$1,200	1% increase/year	US$2,400	2020 incumbent price based on values reported by the Federal Reserve Bank of St. Louis; incumbent price increase based on annual historical price changes reported by the Federal Reserve Bank of St. Louis CCU end product price based on Lux Research's correspondence with Novonutrients; estimated price is two-times higher than incumbent price

Lux Research estimated starting product price in 2020 to project the cost tipping point between incumbent and CCU end products

Market	Incumbent 2020 price (US$/tonne)	Incumbent price change (%/year)	CCU end product 2020 price (US$/tonne)	Sources and comments
Methane	US$17	3.5% increase/year	$US170	2020 incumbent price based on triangulation of reported values by The World Bank and the U.S. Energy Information Administration of approximately US$4/mmBTU; incumbent price increase based on projections for Europe and the U.S. based on changes reported by The World Bank CCU end product price based on values reported by Becker et al. (2019)
Jet fuel	US$450	3% increase/year	US$2,250	2020 incumbent price based on January 2021 spot price reported by the International Aviation Transport Authority; incumbent price increase based on annual historical price changes reported by the International Aviation Transport Authority, though jet fuel prices are directly tied to oil prices and long-term forecasts remain challenging CCU end product price based on triangulation of values reported by the International Council on Clean Transportation and corroborated with Lux Research's correspondence with Sunfire, Climeworks, and Infra Technology
Polyurethanes	US$3,200	0.5% increase/year	US$4,160	2020 incumbent price based on triangulation of values reported for TPU resin price by Plastic News and Plastic Price; incumbent price increase assumed at 0.5% increase/year due to the commodity nature, though price remains susceptible to isocyanate availability, but was not considered for the scope of this study CCU end product price based on Lux Research's correspondence with CO_2-derived polyurethane producers citing an average 10% premium over fossil fuel-based polyurethane

Financial incentives project the introduction of increasing carbon pricing from a baseline of US$10/tonne and capped at US$100/tonne

Scenario	Carbon price introduction year	Initial carbon price (US$/$tCO_2$)	Yearly increase (US$/$tCO_2$)	Maximum carbon price (US$/$tCO_2$)	Sources and comments
Baseline	2020	US$10	US$2	US$100	Initial carbon price based on existing carbon prices reported by The World Bank's Carbon Pricing Dashboard showing 75% of existing carbon pricing is less than US$10/tonne Yearly increase in carbon pricing based on the assumption carbon pricing reaches US$/50/tonne by 2040; Lux Research acknowledges increase in carbon pricing will be regionally specific and vary widely
Optimistic	2020	US$10	US$2.5	US$100	Initial carbon price based on existing carbon prices reported by The World Bank's Carbon Pricing Dashboard showing 75% of existing carbon pricing is less than US$10/tonne Yearly increase in carbon pricing based on the assumption of the lower end of the carbon price level range of US$30/tonne to US$100/ton reported by the Carbon Pricing Leadership Coalition required for meeting the ambitions of the Paris Agreement; projection reaches US$35/tonne by 2030 and never reaches US$100/tonne
Best case	2020	US$10	US$4	US$100	Initial carbon price based on existing carbon prices reported by The World Bank's Carbon Pricing Dashboard showing 75% of existing carbon pricing is less than US$10/tonne Yearly increase in carbon pricing based on the assumption of the middle of the carbon price level range of US$30/tonne to US$100/ton reported by the Carbon Pricing Leadership Coalition required for meeting the ambitions of the Paris Agreement; projection reaches US$50/tonne by 2030 and reaches US$100/tonne by 2043

Adoption variables assess the impact of competing technologies and willingness to adopt based on price premiums

Lux Research qualitatively assessed two adoption variables – impact of competing technologies and industrial willingness to adopt – on a scale of 0 to 1. The adoption variables are additional factors designed to capture external factors beyond cost and financial incentives that potentially influence market traction. The below two tables summarize how the two adoption variables are assessed on a scale of 0 to 1.

Impact of competing technologies	Description
0	All other competing technologies are cheaper and have a lower carbon footprint than the CCU end product; the CCU end product is a non-starter for the industry
0.4	Most other technologies are cheaper than CCU end product but have a higher carbon footprint; the CCU end product will witness some adoption in industry but remain a niche technology without addition factors
0.6	All technologies (including CCU end product) have similar price point and carbon footprint; adoption by industry will depend on access to competing technologies
0.8	Most other technologies are more expensive than CCU end product, but some have an equal or lower carbon footprint; CCU end product will be the dominant technology choice in most markets, but other technologies may be adopted as well
1	All other competing technologies are more expensive and have a higher carbon footprint; CCU becomes the clear incumbent technology across the global market

Willingness to pay	Description
0 to 1	What percentage of the industry will adopt the CCU end product even if it is more expensive than the incumbent product? From the perspective of the industry, how important is it to have a sustainable product in the portfolio? Does the CCU end product offer performance advantages to offset the higher price? Is the CCU product a commodity or specialty product?

Conversion to CO_2 utilization (Gt) is based on market volume (tonne) and average CO_2 consumption per tonne of product

Market	tCO_2 utilization per tonne of product	Sources and comments
Precast concrete	0.001 (low), 0.015 (average), 0.05 (high)	Average CO_2 utilization based on a conservative estimated of 1.5% CO_2 by assuming 10% CO_2 uptake and 15% cement content in concrete; low and high CO_2 utilization is based on the range reported by Woodall et al. (2019)
Aggregates	0.087 (low), 0.34 (average), 0.44 (high)	Average CO_2 utilization based on mineralization to calcium carbonate from wollastonite as reported by Zevenhoven et al. (2006); the high CO_2 utilization is the theoretical limit for CaCo3, and the low CO_2 utilization is the lower end reported by Woodall et al. (2019)
Carbon black	3.7 (low), 4 (average), 4.2 (high)	Low CO_2 utilization based on Lux Research's personal correspondence with Solid Carbon Products; the high CO_2 utilization is based on values reported by Solid Carbon Products; assumes CO_2 utilization is applicable to carbon black with it being a paracrystalline carbon
Methanol	1.28 (low), 1.37 (average), 1.5 (high)	Average and low CO_2 utilization for methanol is based on the values reported by Perez-Fortes et al. (2016); high CO_2 consumption is based on Lux Research's personal correspondence with Carbon Recycling International
Formic acid	0.49 (low), 0.668 (average), 0.96 (high)	Average and low CO_2 utilization for formic acid is based on values reported by Perez-Fortes et al. (2016); high CO_2 consumption is based on values reported by Rumayor et al. (2018) with a range from 0.83 to 0.96
Animal feed	0.5 (low), 0.6 (average), 0.7 (high)	CO_2 utilization based on Lux Research's personal correspondence with Deep Branch Biotechnology and Solar Foods; Deep Branch Biotechnology claims 10 kg of CO_2 is required for 7 kg of protein; Solar Foods claims 2 kg of CO_2 is required for 1 kg of protein
Methane	0.8 (low), 0.9 (average), 1 (high)	CO_2 utilization based on values reported by Wai et al. (2020) and Benjaminsson et al. (2013); additional insight on CO_2 utilization obtained through Lux Research's personal correspondence with Electrochaea
Jet fuel	3 (low), 4.5 (average), 6 (high)	CO_2 utilization based on values reported by Yao et al. (2020); assumes CO_2 conversion does not have 100% selectivity for jet fuel and instead results in the production of gasoline to jet fuel range hydrocarbons
Polyurethane	0.05 (low), 0.15 (average), 0.25 (high)	CO_2 utilization based on an assumed 1:1 ratio of CO_2-derived polyols and isocyanates for polyurethane production; the range of CO_2 content in polyols varies between 10% to 50% by weight as reported by Muller et al (2021)

Lux Research

Lux Research is a research and advisory firm, focused on sustainable innovation that is commercially viable. Across all industries, an ever-increasing focus on sustainability is a major driver of change in business as we all strive to meet corporate sustainability goals, government regulations, and consumer expectations.

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