Global Roadmap for Implementing CO_2 Utilization

November, 2016

CO_2 SCIENCES | THE GLOBAL CO_2 INITIATIVE

ICEF Innovation for Cool Earth Forum

Acknowledgements

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Executive Summary

Background: Confronting an urgent challenge

This study presents a roadmap for commercialization potential of carbon dioxide utilization (CO_2U) technologies through 2030.

A significant reduction of carbon emissions is crucial to avoiding enormous economic and environmental damages. Renewable power generation and other low- and zero-carbon technologies are an important part of the solution. Carbon negative technologies (those that reduce atmospheric CO_2 concentrations) are also needed to achieve the agreed global goal of keeping temperature increases well below a 2^{o}C increase over pre-industrial levels. CO_2U technologies can play an important role, but have not yet received much attention nor have their potential been explored in a comprehensive fashion.

A detailed market assessment study that was completed earlier in 2016 by GCI found that CO_2U has the potential to reduce carbon emissions over 10% by 2030 (GCI's website provides more details). One goal of this work is to create greater awareness concerning the potential for developing and deploying profitable, emissions-negative CO_2U technologies on a mass scale.

The study: Identifying and forecasting market opportunity

This study analyzes the current state of CO_2U technology, assessing almost 180 global technology developers on the basis of their technology feasibility, readiness, markets and momentum.

Research revealed that significant progress in CO_2U has been made in the past five years (2011-16), with many technologies shown to be scalable. Momentum is favorable for four major markets – **building materials, chemical intermediates, fuels** and **polymers.**

Within those markets, the study further identifies eight product categories to pursue, based on the maturity of their technology, market promise, and potential impact on the mitigation of carbon emissions. Those categories are:

- **Building materials**
  - Concrete
  - Carbonate aggregates
- **Chemical Intermediates**
  - Methanol
  - Formic acid
  - Syngas
- **Fuels**
  - Liquid fuels
  - Methane and
- **Polymers** (polyols and polycarbonates)

Funding and incentives are necessary for most of these products to accelerate development and achieve full-scale commercial roll out capability. This study presents a commercialization roadmap for each of the eight categories.

The roadmap was developed with three dimensions in mind: policy, technology and market. Those three dimensions greatly impact the path and speed to commercialization. The results are presented by considering the business as usual case (status quo), which is also the worst case scenario. The best case represents likely outcomes if swift strategic actions are taken to remove barriers and mitigate risks.

Strategic actions to accelerate CO_2U commercialization

Best-case scenarios in the forecast would support and hasten commercialization of CO_2U-derived products across the eight identified product categories. These optimal scenarios will be driven by the implementation of strategic actions recommended in this study. They are:

Technology

- Research to improve catalysis for CO_2 reduction must be funded. The needed substantial increase in funding should come from government, corporations and private institutions.
- Research in improving electrolysis to produce hydrogen must be funded.
- Government funding is critical for exploring early stage technologies and creating future options for CO_2U technologies.

Market

- Collaborations among research institutes, start-ups, governments and corporations for process integration of CO_2 conversion, hydrogen generation, and carbon capture must be funded.
- A CO_2 pipeline infrastructure is critical for the deployment of CO_2U technologies at scale. This opportunity creates new business options/models and creates a new value chain critically needed to scale CO_2U technologies.

Policy

- Substantial increase in government funding for R&D
- Carbon pricing, either through emissions trading or tax mechanisms.
- Tax and other incentives
- Mandates
- Government procurement
- Government support for certification and life cycle assessments.

Life cycle analysis (LCA)

The climate benefit of a CO_2U product depends not only on how much CO_2 the product contains. The amount of CO_2 emitted in making the product also matters. So does the amount of CO_2 emitted in making any competitive products that may be displaced. To the extent that climate benefits are a goal of those promoting CO_2U products, LCA is essential. Considerable work is needed to standardize LCA methodologies for CO_2U. The Global CO_2 Initiative is planning a major project in 2017 to bring together stakeholders to address this issue.

CO_2U's potential: Profitable markets and mitigated CO_2 emissions

At full scale, 5 CO_2U products (see below) could create a market over US $800 billion by 2030. CO_2U has the potential of utilizing 7 billion metric tons of CO_2 per year by 2030 – the equivalent of approximately 15 percent of current annual global CO_2 emissions. CO_2U can create new business opportunity and simultaneously contribute to CO_2 reduction. Both conclusions are consistent with an earlier market study that the GCI commissioned concluding that CO_2U can remove over 10% of the emitted CO_2 and represents an annual market opportunity of $0.8-1.1 Trillion.

Roadmap to 2030: Market size and mitigation impact

Market size and CO_2 reduction potential can be significantly impacted by taking action now. Below are examples from five markets. For example, the market for CO_2-based fuels can be quadrupled by 2025 (from $50b to $200b), increasing the CO_2 reduction by 15 fold (from 0.03b tons to 0.5b tons). Similarly, decisive and timely action can have a major impact on both the market size and potential to mitigate CO_2 emissions for other CO_2-based products.

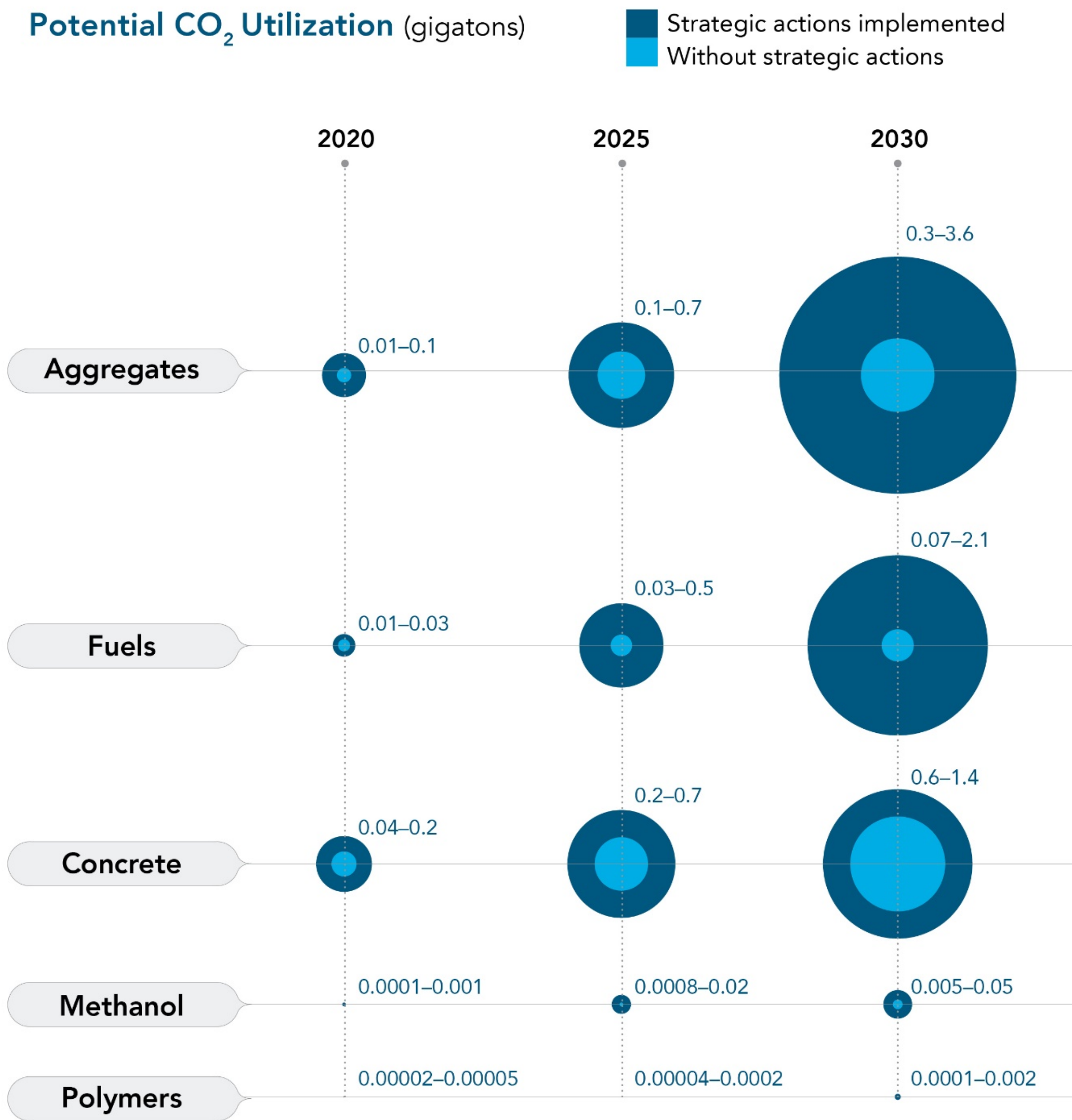


Figure 0.1: Potential CO_2 reduction due to implementing strategic actions

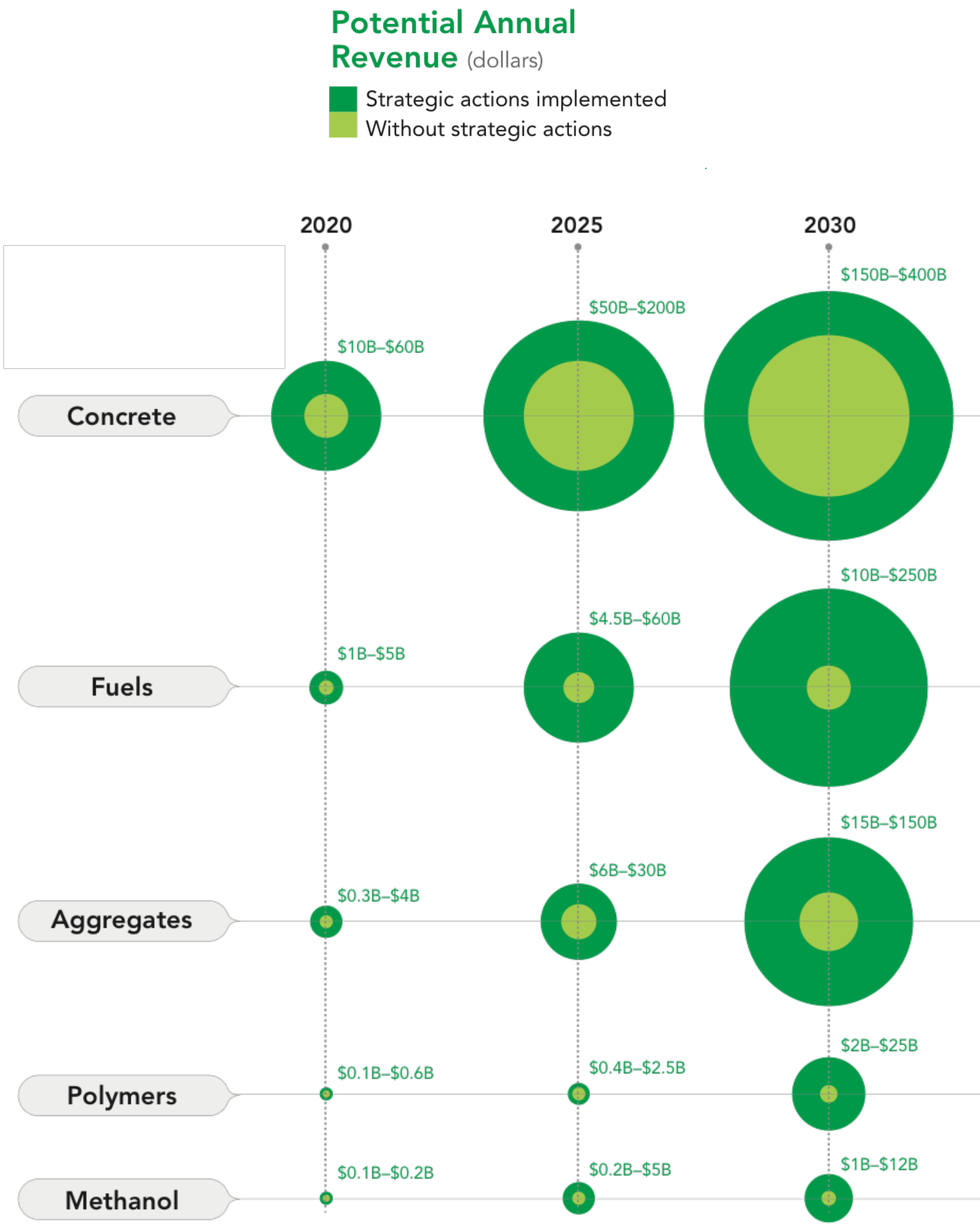


Figure 0.2: Potential increase in market size due to implementation of strategic actions

I. Background and goals of the study

The Grand Challenge of the Planet: Reducing carbon emissions

Over 35 GT of CO_2 are emitted into the atmosphere every year, altering the Earth's climate system and threatening catastrophic damages in the years ahead. The implications of climate change are massive:

- Economic and political instability
- Food and clean water scarcity
- Health or survival risks for all animal species
- More volatile and extreme weather
- Loss of landmass

The United Nations' December 2015 Paris COP21 conference – in which 195 sovereign nations, in both the developed and developing world, agreed on a framework that committed each to taking action against climate change – was judged historic on several levels.

After Paris: A new impetus for zero-carbon research

Among other covenants, the signers of the Paris accord agreed to:

- Limit global temperatures to "well below" 2^o C (3.6 F) above pre-industrial levels and "endeavor to limit" them even more, to 1.5^o C, between 2015 and 2030.
- Restrict the amount of greenhouse gases emitted by human activity to the levels that trees, soil and oceans can naturally absorb, beginning at some point between 2050 and 2100.
- Review each country's contribution to cutting emissions every five years, enabling them to address the urgency of the challenge.

Similar conclusions have been voiced by the IEA and IPCC experts about the critical need for carbon-negative technologies. Figure 1.1 shows that continuing to deploy energy efficiency and renewable power generation will limit the increase in temperature rise but we may end up with a 4^oC increase. We need to have CO_2 absorbing solutions. Of course, plants are nature's great weapon, however, they are slow and we need solutions that can absorb CO_2 at a much faster rate. Figure 1.2 presents the two other options: Carbon Capture and Sequestration (CCS) and Carbon Capture and Utilization (CCU).

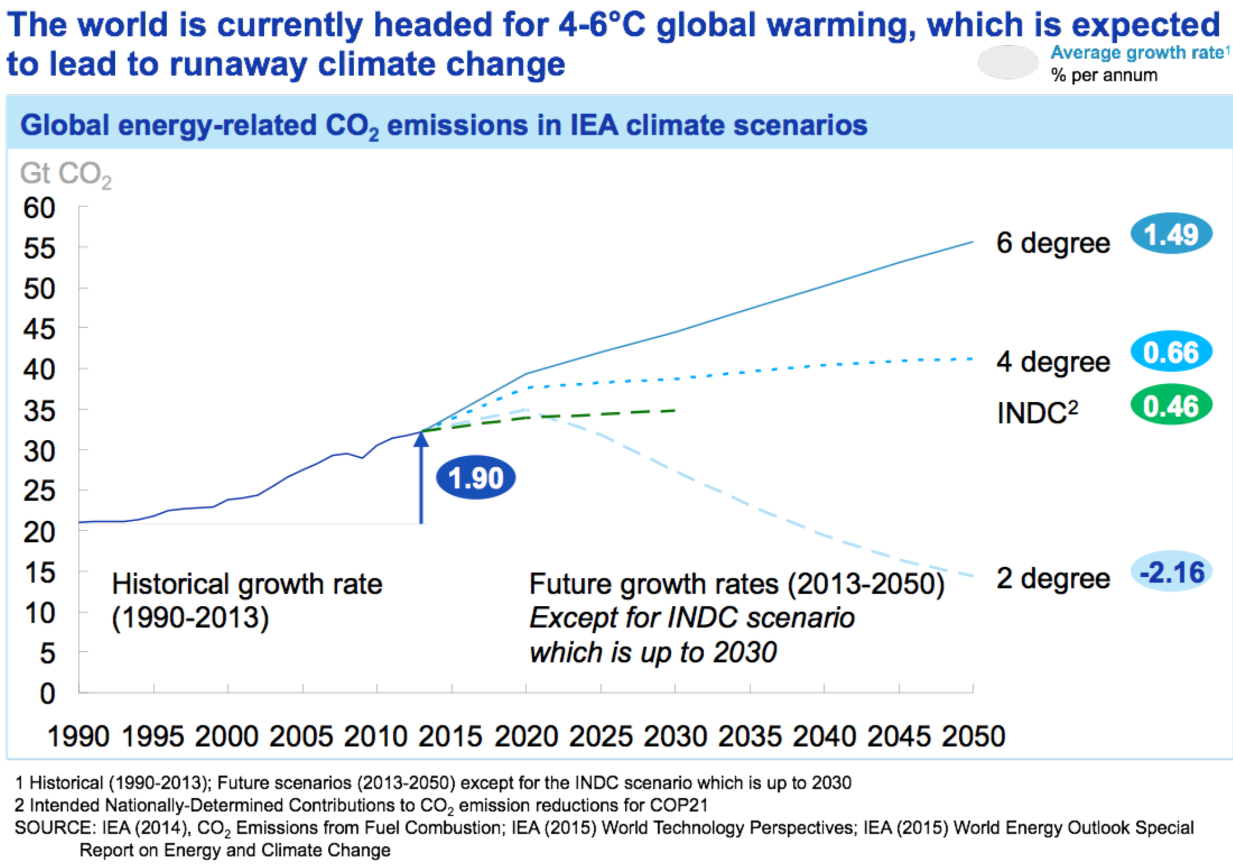


Figure 1.1: The need for carbon-negative technologies to limit temperature increase

Figure 1.2: Examples of carbon-negative technologies

Carbon dioxide utilization (CO_2U)

CO_2U differs from prevalent carbon capture and storage (CCS) solutions in one basic way. CCS captures CO_2 emissions exclusively for storage, usually reinjecting them into geological formations; the goal of CO_2U is to convert CO_2 into end products that in turn are emissions-neutral or negative.

The development of CO_2U technologies is being promoted for three key reasons:

- It can be used for mitigation to meet internal or external standards for CO_2 emissions for carbon dioxide producers.
- It would allow for carbon dioxide to be used as an alternative to fossil-fuel-derived feedstocks.
- It can contribute to achieving national or global aims for decreasing carbon emissions.

As this report and other studies show, CO_2U has been the focus of a myriad of research tracks investigating multiple conversion processes and potential markets and end products in recent years. However, the Paris agreement and recent private and public initiatives have added new urgency and momentum to fundamental R&D efforts that will lead to more rapid commercialization of products that use CO_2 conversion to reduce carbon emissions.

These initiatives include the Carbon XPRIZE, a US $20 million global competition designed to "incentivize and accelerate" CO_2U solutions development, and the SCOT (Smart CO_2 Technology) project, a public-private-academic collaboration community based in the European Union and the Global CO_2 Initiative.

This study: Presenting a global CO_2U commercialization roadmap through 2030

This is a roadmap of the global commercialization potential of carbon dioxide utilization technologies through 2030. CO_2U technologies use CO_2 (pure or as emitted) either unchanged (e.g., enhanced oil recovery/EOR, carbonated drinks, supercritical CO_2 solvents) or by converting it into a value-added end product like a fuel or a chemical.

This study focuses on products **derived by conversion of CO_2**. Identifying the most mature, economically promising and impact-mitigating applications for CO_2 conversion is critical to driving further investment and innovation in catalytic fashion. That investment will accelerate time-to-market for solutions that capture and reduce global CO_2 emissions, and offer sustainable climatological benefits.

Conversion challenges have historically created a bottleneck in the rapid development, production scaling, and commercialization of CO_2U-based products. Fundamental challenges have included:

- CO_2 has been more difficult and expensive to obtain than the petroleum, coal and natural gas sources of raw material for most chemical manufacturing. This concern has been amplified in 2015-16 by the fall in global petroleum prices.
- Converting a stable CO_2 molecule to a useful chemical has generally required lots of energy, typically generated from fossil-fuel sources – thus potentially causing a net *increase* in CO_2 emissions.

- It has been costly to provide the hydrogen feedstock necessary to create the desired end products.
- It's therefore been difficult to assess the true potential (and by when) of CO_2 mitigation, and tie that to policy and funding decisions.

However, greatly increased attention to CO_2 conversion by both developers and policy-makers has produced new research, initiatives and collaborations that have the potential to address these challenges. These advances include, but aren't limited to:

- **The development of catalysts** that enable new technology pathways and make conversion processes more efficient.
- Consideration of renewable energy sources (solar or wind energy) to power CO_2 conversion. The reduction in the cost of renewable power generation technologies is a major parameter that is making CO_2U more feasible than it was 5 years ago.
- **Advances in mineralization** technologies to produce building materials.
- **Advances in photocatalytic reduction** of CO_2, which uses light directly in conversion.

This study identifies:

- **Product categories and sub-categories** with the most realistic deployment prospects based on policy considerations, analysis of technology and forecasts of market potential.
- **Current barriers** to development and potential means of overcoming them. Criteria include an assessment of conversion technology pathways and their relative impact on CO_2 reduction, potential market demand and geographical/geopolitical impacts on development and commercialization.
- **Centers of activity** in CO_2U research and development.
- Projected timelines for deployment.

This ten-to-fifteen-year roadmap will enable decision makers and key stakeholders to make appropriate and informed funding/investment decisions regarding technology development and commercialization of CO_2U technologies. Its ultimate focus is on clearly prioritized market entry. The study will also show how policy/market/technology levers can be used to accelerate market penetration.

II. Overview of findings

Six major markets identified

We have identified and analyzed 180 global developers who are actively engaged in CO_2U and, ultimately, the development of end products.

A database of CO_2U developers was compiled from multiple sources: conference proceedings, the SCOT Project and PitchBook databases, patent searches, consortium websites, and in-house knowledge. These entities include start-ups, mid-sized companies, corporations, consortia and research institutes.

The study defined six markets or product clusters by number of active developers, conversion technology pathways, and targeted end products:

- **Algae** (processed separately to create biofuels or food additives)
- **Building materials** (for conversion to carbonates or infusion of CO_2 into materials)
- **Chemical intermediates** (such as methanol, syngas, formic acid and malic acid)
- **Fuels** (mainly for methane and alcohol)
- **Novel materials** (such as carbon fiber)
- **Polymers** (e.g., polycarbonates, polyurethane and PHA)

Concentration of active developers

We found that the number of developers was especially concentrated in three of these segments:

- Chemical intermediates
- Fuels
- Building materials

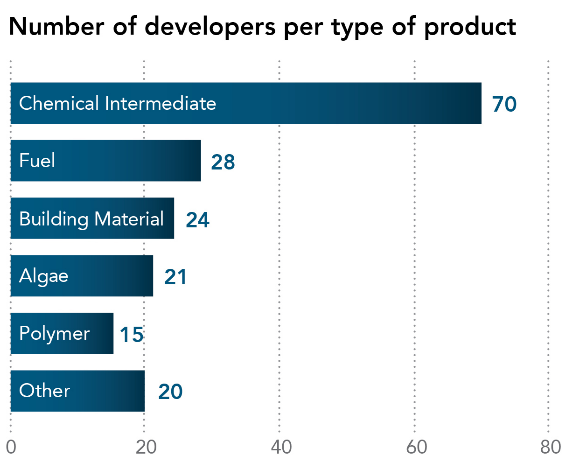


Figure 2.1: Number of active developers by end-product market cluster.

The study also identified and analyzed a wide range of technology pathways. Catalytic conversion, mineralization and electrochemical conversion are the most widely studied pathways based on number of developers (see Figure 2.2). Time-to-commercialization depends heavily on this concentration of research efforts.

Catalyst development is critical in the drive to make conversion processes more efficient; research in this field builds upon decades of work in catalysis in general. Other processes – photocatalytic, photosynthesis and algae production – focus directly on using sunlight as a low-cost energy source for conversion.

The study concurrently identified and analyzed the strengths and weaknesses of six technology pathways that are being used, or are being considered for use, in the conversion of CO_2 to commercial products: **catalytic, electrochemical, fermentation, mineralization, photocatalytic** and **photosynthetic.**

Mineralization, catalytic conversion, and electrochemical processes have the highest number of developers and researchers, which will help propel these technologies forward.

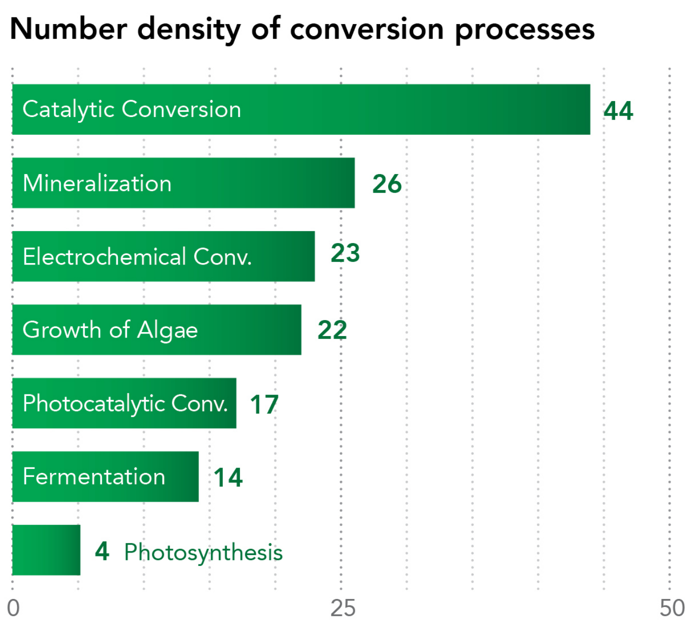


Figure 2.2: Number of developers by CO_2U technology pathway.
(Some developers serve more than one market.)

Catalytic conversion and mineralization are the most well developed pathways. Mineralization of CO_2 is the only conversion technology pathway currently being used for building materials. Catalytic conversion is widely used for production of chemical intermediates, fuels, and polymers.

Fermentation is less established as a process for CO_2 conversion. Two companies at scale, LanzaTech and Newlight Technologies, respectively, use carbon monoxide and methane as the main carbon sources for their processes, respectively. At this time, photocatalytic and electrochemical conversion technologies require more development and evidence of scalability.

Consortia and collaborations have been founded, notably in Europe, to fully utilize the impact of CO_2U technology on CO_2 mitigation. In addition, the study found a significant increase in the number of new publications on conversion of CO_2 via catalytic reduction. More than 600 papers on this topic were published by academic and government entities on this topic in 2015, compared to about 350 two years earlier.

Maturity and momentum of each market

Armed with direct interviews with over a dozen developers as well as secondary research, the study applied a technology readiness level (TRL) scale of 1 (least) to 9 (most) to determine the relative stage of development and create a framework for expected time-to-market.

The TRL applied in this study ranges from basic and applied research, proof of concept and laboratory testing (stages 1-5), to prototyping, piloting and final development (stages 6-8), to full-scale deployment/market introduction (9).

We also applied standardized rubrics to better quantify the mitigation potential and technology fit of each market.

Four markets recommended for funding and investment

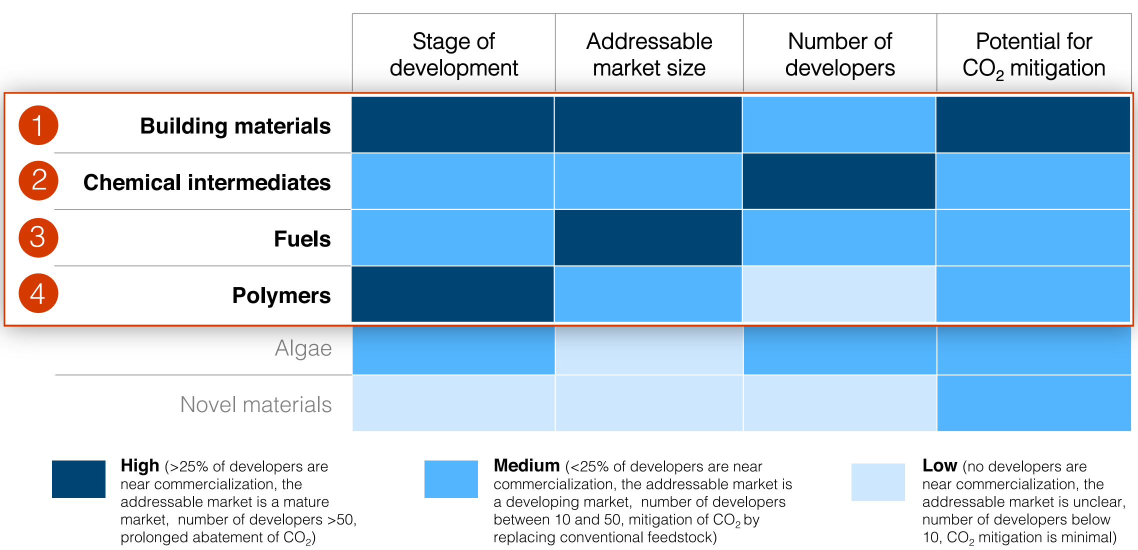


Figure 2.3. The study has identified four markets that offer the best opportunities for support and investment. The assessment is based on an analysis of active developers, first-person interviews, in-house expertise and scientific momentum.

Another important consideration that was factored in our analysis is "permanence". Permanence refers to the period during which CO_2 is stored in a product. Products such as cement can fix CO_2 in solid form for centuries if not longer. Products such as polymers may decompose in years or decades, returning CO_2 to the atmosphere and minimizing the benefits of using the CO_2 in those products.

A related concept is displacement. If CO_2 is used as a feedstock for liquid fuels, that can displace the extraction of petroleum that would otherwise be used to produce those liquid fuels. (This will depend on market conditions, but in many circumstances today that is the most likely result of using CO_2 as a liquid fuel feedstock.) To the extent CO_2 in product creation displaces the extraction of petroleum, there is a very high CO_2 benefit because that petroleum remains underground and is not combusted.

This study recommends further investment in four clusters or markets – **building materials, chemical intermediates, fuels** and **polymers** – based on the following summary of findings:

- **Building materials**
  - It's thermodynamically favorable to make carbonates and requires less energy input to achieve. This makes this market attractive for developers because the technology is more readily scalable today.
  - The two main CO_2U technologies used in building materials are mineralization for carbonate aggregates and the use of CO_2 to cure concrete. Key innovators include Carbon8, Solidia Technologies and CarbonCure. Aggregates are coarse particles used in construction and can be gravel or crushed stones or other similar materials.
- **Chemical intermediates**
  - There are many research projects underway to make conversions more efficient; for example, by developing more effective catalysts which could offer breakthroughs in conversion efficiencies.
  - Niche markets have been commercialized; one example is the production in Iceland of methanol using geothermal energy. Methanol, syngas and formic acid are the most widely developed. (Please note that some developers categorize these chemicals under *fuels*.)
- **Fuels**
  - Production of fuels from CO_2 fits within the macro trend toward low carbon fuels. CO_2 competes with petroleum-derived feedstock, as well as bio-based feedstocks such as sugar cane.
  - Fuels represent one of the largest potential markets for CO_2U technology given the many global mandates for greener alternatives.
- **Polymers**
  - Several production routes, such as polyhydroxyalkanoates and polycarbonates, have already been commercialized for high-value products in niche markets.
  - Key developers include Covestro, Novomer and Asahi Kasei.

Two markets eliminated from further consideration

The study also eliminated two markets, **algae** and **novel materials**, from further consideration.

- **Algae** is not yet cost-effective due to high downstream processing costs. Although algae biofuel projects received over US $1 billion in funding in 2009-2010, largely for development and pilot-scale testing, investment began to dry up in 2011. The category has been hampered by intrinsic limitations in algae production and a weak (to date) business case for production at scale. Some projects remain active and some new entrants have been identified. However, a majority of players from 2011 have exited the market through bankruptcies (such as Abengoa, Independence Bio Products and A2BE Carbon Capture) or strategic pivots, while others are idle.

- **Novel materials** have to this point received very limited developer focus. While we strongly believe that such products can have significant impact on CO_2 reduction, there is a great uncertainty in time to market and scale. The case for CO_2 to carbon fiber is a prime example. The study identified one research effort (George Washington University) for CO_2 conversion to **carbon fiber**, and it is at a very early-stage of development. If the new process can make fibers at lower cost, then emissions reductions can occur in three ways:

    - Use of a low-carbon-footprint carbon fiber product (assumes no change in market penetration).
    - Greater use of carbon fibers in additional markets (assumes increase in market penetration rates).
    - Replacement of steel by carbon fiber. This will have a significant impact on overall emissions since steel contributes 6.7% to global emissions; there would be associated benefits from reducing fuel use in transportation and freight sectors due to light-weighting.

However, we recognize that there are a number of technological barriers that need to be overcome to attain such potential and for the purpose of this study market estimates are not included. We strongly believe that funding of this area is critically important given the game-changing nature of this technology option.

III. Momentum within recommended markets

Eight sub-categories identified

We further segmented each recommended market to identify sub-sectors: end-product categories with the earliest and highest likelihood of commercialization and success. Differentiation was based on three major considerations:

- **Concentration of developers:** The study considered both the number of developers in a segment and how far along they were on the path to commercialization those developers were. Success of commercialization was linked to:
    - Relatively low energy requirements for conversion technology pathway.
    - Simplicity of reaction mechanisms or processes.
    - Size of potential markets.
- **Market Dynamics:** The study also assessed the progress of individual developers towards commercialization in the 2011 to 2016 timeframe.
    - It considered how many development efforts were at an early stage in 2011 and then progressed, stalled or were disbanded.
    - It also considered the growth or decrease in the number of developers over this time frame.
- **Outlook:** It forecast how long it would take to bring technologies in each segment to scaled production, while being cost competitive with incumbent solutions.

Based on these criteria, the study identified eight promising product categories within the four markets:

- **Building materials**
  1) Concrete
  2) Carbonate aggregates
- **Chemical intermediates**
  3) Methanol
  4) Formic acid
  5) Syngas
- **Fuels**
  6) Liquid fuels
  7) Methane
- **Polymers**
  8) Polyols and polycarbonates

Visualizing CO_2U innovation momentum, 2011-16

To gain a greater understanding of the dynamic progress among CO_2U development organizations during the past five years, we plotted their progress in technology and commercial innovation and CO_2 mitigation potential using a standard weighting system.

- The **technology score** (vertical or Y-axis) is weighted based on (in descending order) technology value, competitive landscape, IP strength and regulatory factors.

- The **commercial development score** (horizontal or X-axis) is weighted based on (in descending order) TRL (technology readiness level), developer base and commercial maturity.

- The **mitigation potential** (bubbles) is weighted based on (in descending order) market size, ease of set-up and extent to which CO_2 is used as feedstock.

We then compared the status of developer organizations in 2011 vis-à-vis 2016. Those followed from 2011 were color-coded based on their 2016 status.

- **Green** = Active
- **Yellow** = Strategic pivot
- **Red** = Discontinued
- **Gray** = Idle or unknown

Building materials: Significant progress, immediate opportunity

The study found that the use of CO_2U in concrete curing represents an immediate opportunity. Moreover, with additional allocated resources, building materials can have a significant mitigation impact on CO_2 emissions. The study found:

- **Concentration of developers:** A relative high density of developers, with many near commercialization and a relatively low number in early stage. Two significant factors drive the success of commercialization:
  - Relatively little energy is required for carbonation.
  - Concrete made by curing with CO_2 has better performance characteristics than traditional curing methods.

- **Market Dynamics:** Developers were able to move from pilot to commercialization in both the concrete and carbonate aggregates segments. Overall:
  - Several early-stage entities disappeared because they were not able to develop a product beyond pilot stage.
  - Several new developers focusing on carbonation to produce aggregates have entered the market in the last five years

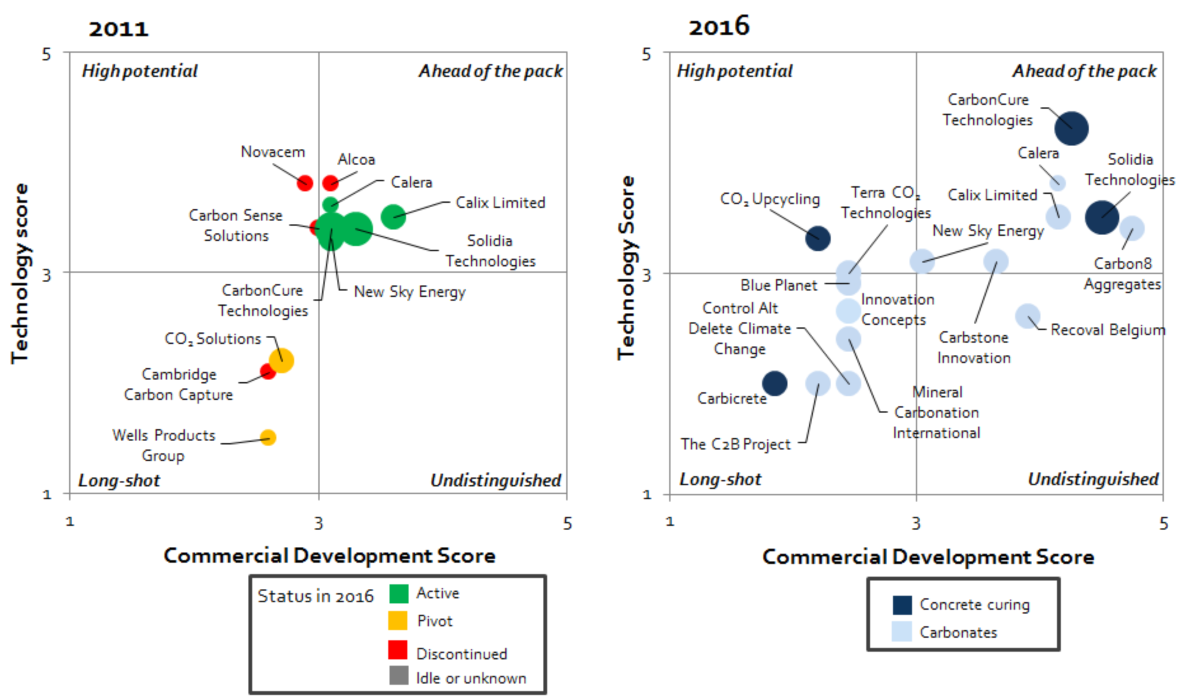


Figure 3.1: A visualization of the CO_2U building materials market, 2011 and 2016.

Chemical intermediates: Long-term opportunities; those with fuel applications are closest to commercialization

In general, the study found limited progress in the chemical intermediates market over the past five years due to lack of incentives and concerns about economic feasibility. Those products that can also be used as fuels or in fuel production – methanol, formic acid and syngas – offer the best opportunity. The study found:

- **Concentration of developers:** A low number are near commercialization, with many in early stages. The most widely developed products are CO (syngas), methanol and formic acid, for three major reasons:
  - Their reduction reactions are less complicated than those for other potential end products within the chemical intermediates market.
  - They can be used as chemical intermediates and as fuels or precursors to fuels.
  - Governments have incentivized fuel production from CO_2 to lower carbon emissions, but this policy has not been the case for the production of chemicals.

- **Market Dynamics:** Very few developers moved from pilot to commercialization stage for all market segments. The number of start-ups investigating solutions for energy-efficient conversion of CO_2 has increased dramatically, with most start-ups tending to focus on catalysis and conversions by reduction.

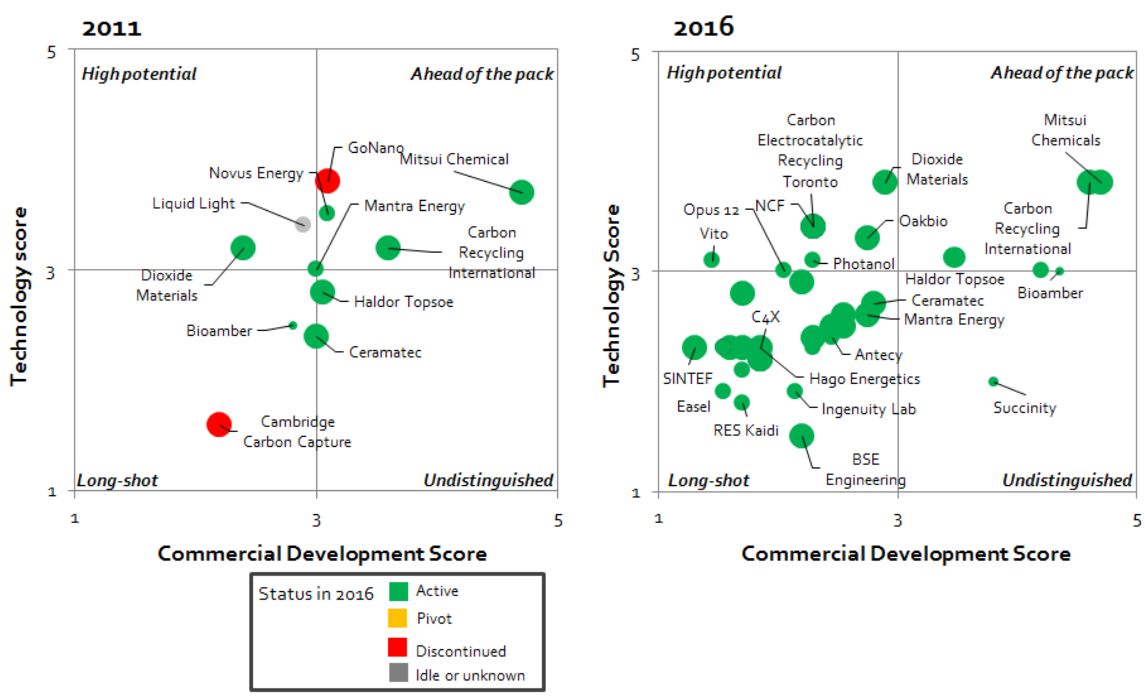


Figure 3.2: A visualization of the CO_2U chemical intermediates market, 2011 and 2016.

Drilling deeper, a further analysis of the methanol, formic acid and syngas product categories reveals:

- **Concentration of developers:** There are currently very few methanol developers, but two companies (Mitsui Chemical and Carbon Recycling International) have been identified with commercialized technology; in syngas and formic acid, the study identified multiple early-stage efforts focusing on conversion by catalysis.

- **Market Dynamics:** Across all market segments, very few developers moved from pilot to commercialization stage.
    - Several startups have been formed for the three markets, indicating potential growth. Many are developing technologies for chemical production.
    - The focus of most developers of syngas from CO_2 is on using excess energy (e.g., from chemical or steel plants) to produce syngas that can be converted to a different product by another process.

Fuels: Two sub-categories are at – or near – commercialization

Liquid fuels: Ready to produce at scale

Significant progress within the liquid fuels sub-category during the last five years shows that the technology is primed for production at scale. The study found:

- **Concentration of developers:** Four developers are near commercialization or have already commercialized CO_2U; LanzaTech is able to produce in scale.
  - LanzaTech converts carbon monoxide into ethanol, hence the low impact shown on the CO_2 mitigation score.
  - Methanol from CO_2 is closest to production in scale.

- **Market Dynamics:** Development has progressed relatively quickly for liquid fuels due to available government funding for projects and mandates for renewable fuels.
  - Stage of development went from pilot testing in the lab in 2011 to pilot testing at commercial scale in 2016.
  - The focus of developments has been on integrating CO_2 capture, renewable energy supply, hydrogen generation and CO_2 conversion in the case of methanol and on efficient (multi-step) conversion of CO_2 into fuels in the case of other liquid fuels.
  - Europe is leading because it has set targets to create a low-carbon-emission mobility economy.

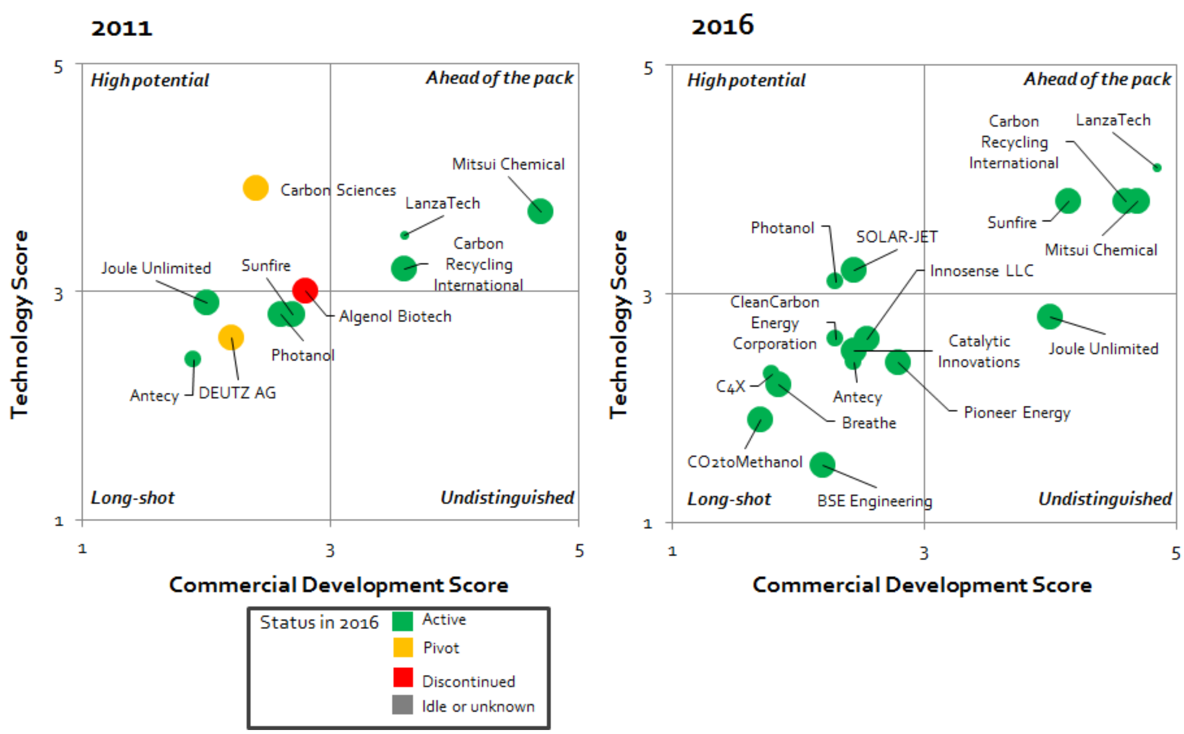


Figure 3.3: A visualization of the CO_2U liquid fuels market, 2011 and 2016.

Methane: Significant technological progress

Progress has been especially pronounced in Europe because of funding support. However, the low price of natural gas poses a significant competitive challenge. Additionally needing to add 4 Hydrogen molecules while eliminating 2 Oxygen molecules makes such development extremely energy intensive.

- **Concentration of developers:** Three CO_2U methane developers were found to be near commercialization.
  - Although the processes have been shown to be at scale, it remains to be seen if they will be cost-effective without subsidized funds.

- **Market Dynamics:** Development has been relatively fast for the methane sub-category compared to the others due to funding and collaborations in Europe.
  - Stage of development went from pilot testing in the lab in 2011 to pilot testing at commercial scale in 2016.
  - Focus of collaborations is on integrating CO_2 capture, renewable energy supply, hydrogen generation and CO_2 conversion into gaseous or liquid fuels.
  - Europe is leading because it has set targets to create a low carbon-emission mobility economy.
  - Projects often focus on the use of overcapacity of electricity or excess heat from industrial plants.

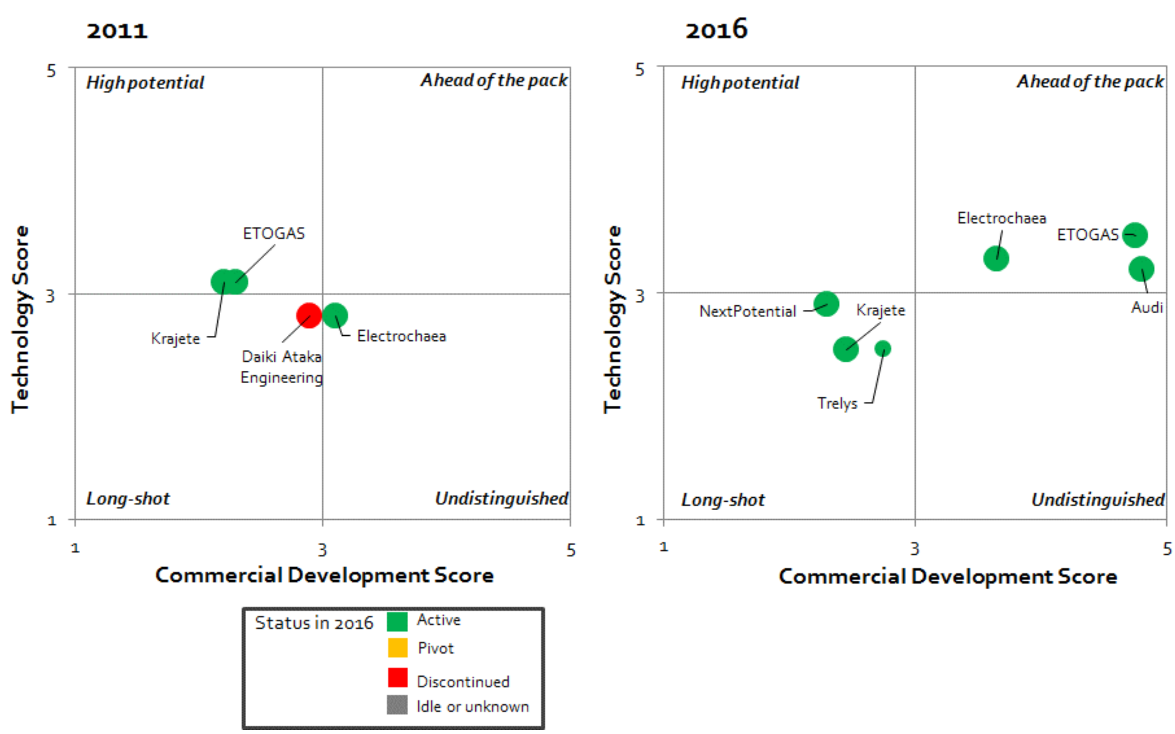


Figure 3.4: A visualization of the CO_2U methane market, 2011 and 2016

Polymers: A dearth of incentives, and startups

The creation of polymers through CO_2U is possible, but not yet economical. A limited number of developers are investing in it, but lack of incentives is inhibiting the entry of startups. The study found:

- **Concentration of developers:** Several are near commercialization, but there are very few early-stage developers.
  - Several companies have shown that polymers from CO_2 can be produced at scale.
  - Most companies have focused on polycarbonates and polyols (used to produce polyurethane). These companies were able to build on years of expertise in catalysis to commercialize their CO_2U technology. This allows developers to replace technology that uses dangerous phosgene gas.
  - Some developers are corporations (e.g., Covestro and Asahi Kasei) that have used their know-how in catalysis to develop commercial pilot plants for producing polymers from CO_2.
  - Production capacity remains a fraction (less than one percent) of the current capacity available to develop polymers from conventional feedstocks.

- **Market Dynamics:** Developers have successfully moved from lab and pilot to commercialization stage. However, the lack of new initiatives indicates that follow-up projects from those developers and competing companies will be rare – most likely due to the current relatively high cost of polymers made from CO_2.

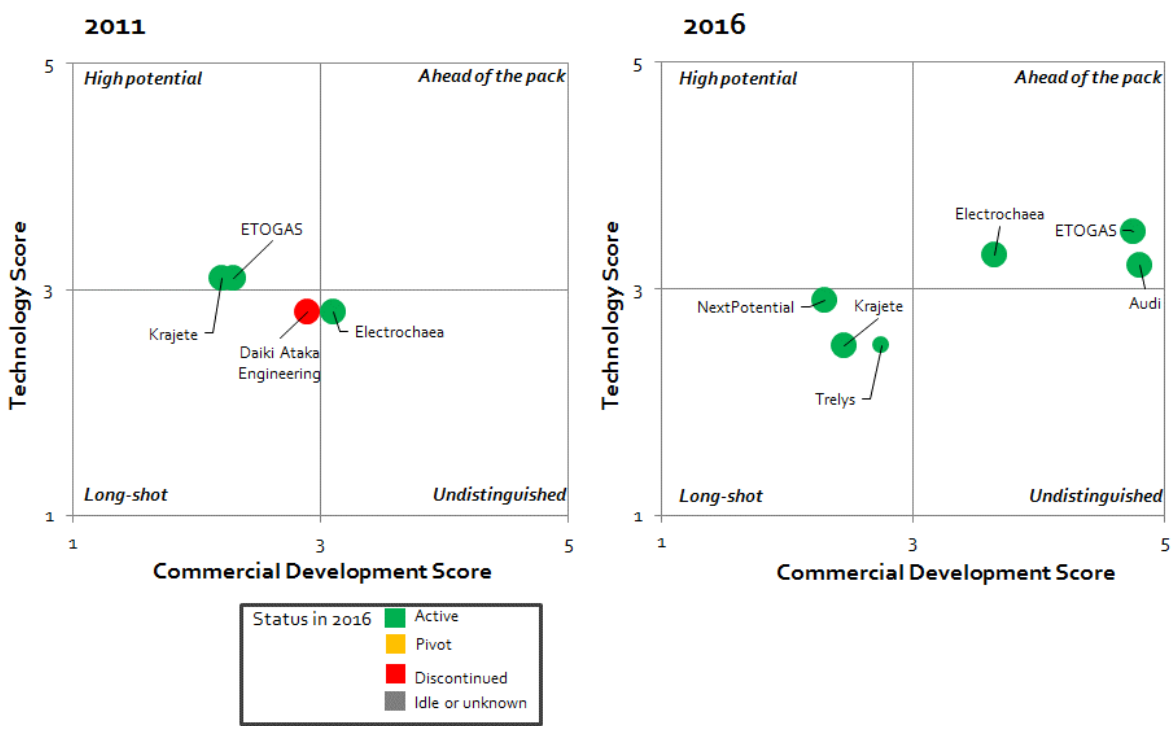
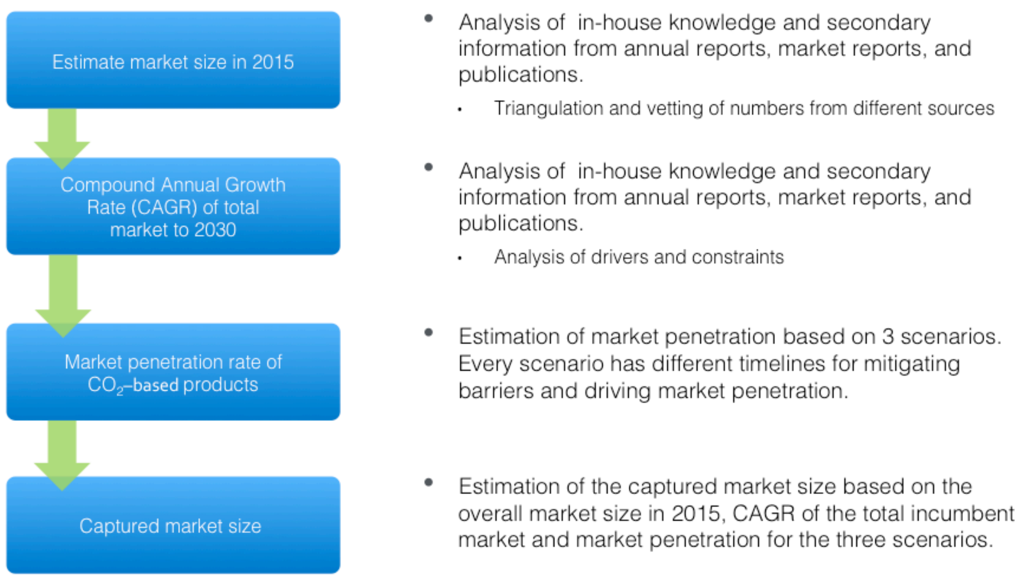


Figure 3.5: A visualization of the CO_2U polymers market, 2011 and 2016.

IV. CO_2U market sub-category projections through 2030

Market sizing

The study estimated the 2015 market size and estimated compounded annual growth rates (CAGR) of each of the eight categories within the four markets. The findings were based on existing proprietary research and secondary information from annual reports, published market studies and industry publications. The below diagram shows the methodology used in assessing addressable markets.



We have used **several references** (see table below) to estimate: market size, market growth, use of CO_2, penetration rate, etc.

Market	Market size 2015	Sources	Comments
Concrete	20-30 B metric tons	1, 2, 3	Based off market size for cement assuming 12.5% of concrete is cement.
Aggregates	25-35 B metric tons	1, 2, 4	Triangulated with concrete (70-80 wt% aggregates) and asphalt/construction fill (~90 wt% aggregates) market size. We assumed ~50% of incumbent aggregates to be suitable to be replaced.
Methanol	60-70 M metric tons	5, 6 , 7, 8	None
Formic acid	0.5-1.0 M metric tons	9, 10	None
Syngas	130-150 GW thermal	11, 12, 13	Difficult to estimate as syngas is used as an intermediate at the same plant as production, as such producers of syngas do not report output
Polymers	8-10 M metric tons	14, 15	Market size is for polyols and polycarbonates only. Percentage polyols for PU is assumed to be 35%, based on Covestro split.
Methane	3,000-4,000 B m^3	16	None
Liquid fuels	800-1,000 B gallons	17, 18	Conversion factor of 31.5 from barrels to gallons

The study then projected each cluster's market penetration rate based on three scenarios:

- **Best case**: Strategic actions are taken that remove barriers at earliest possible opportunity.
- **Optimistic**: Strategic actions are taken to mitigate barriers.
- **Pessimistic**: Status quo is maintained.

Each category and scenario has different timelines for mitigating technology, policy and business barriers and driving market penetration. The study then estimated addressable market size by five-year milestones (2020, 2025 and 2030).

In order to go from market projections to corresponding levels of CO_2 consumed by different products, we used the following table:

Product	Mt of CO_2 used / Mt of product	Assumptions	Source
Aggregates	0.34	Based on CO_2 mineralized to calcium carbonate from wollastonite	19
Concrete	0.085	We assumed the conversion factor is the average of the 3 values found from the sources given	20
Fuels	3	We assumed that gasoline consists of C_8H_{18} on average. We assumed the conversion factor to be 3 on average based on the stoichiometry of the reaction of CO_2 to C_8H_{18}	21
Methanol	1.37	We assumed the conversion factor to be 1.37 on average based on the stoichiometry of the reaction of CO_2 to CH_3OH	22
Polymers	0.3	We assume the conversion factor to be 0.3 on average based on the sources given	23, 24

We now can estimate the amount of CO_2 used for the different scenarios cited above.

Building materials: concrete and carbonate aggregates

Concrete

Concrete curing using CO_2 offers immediate investment opportunities, with a potential for high ROI, while also delivering on CO_2 abatement. We expect the market to grow under existing conditions, but additional incentives could accelerate that growth by as much as five years.

- **Estimated total market size in 2015**: 20-30 billion metric tons. The study estimates that the total concrete market is expected to grow to approximately 40 billion metric tons by 2030, with a CAGR between 3 and 4 percent.
- **Technology pathway**: Curing of concrete by CO_2 injection is an add-on to current processes (heat and steam), driven by performance and cost.
- **CO_2U forecast and considerations:** By 2030, the CO_2U concrete curing market is forecast to grow to between 6.5 billion (pessimistic), 10.5 billion (optimistic) and 16.5 billion (best case) metric tons.
  - Concrete curing using CO_2 is partially driven by the need to increase performance and reduce cost.
  - No changes in codes and standards are necessary.
  - Concrete production is a source of high CO_2 emissions. Incentives to reduce carbon emissions are few.
  - Funding was available for developers in the past, especially in the US and Canada. Several companies are in the commercialization stage.
  - Concrete offers a solution for permanent CO_2 storage.
  - CO_2 curing would reduce water usage.

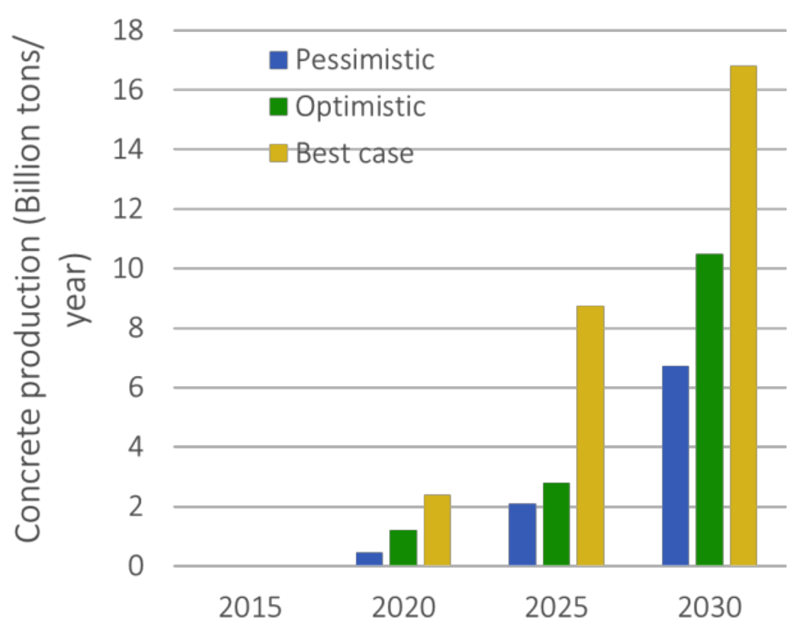


Figure 4.1: Estimated growth of CO_2U concrete curing market through 2030.

Concrete: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of successful mitigation by 2030
Availability of CO_2 for curing	Capture of CO_2 during production of cement; development of a supply infrastructure.	High. If demand is proven, a comprehensive supply chain will follow.
Lack of incentive for concrete manufacturers to adopt process	Concrete manufacturers could be incentivized to reduce carbon emissions by governments.	High. Concerns about global warming will drive governments to seek solutions with an immediate impact.
Lack of developers	Increase funding for "green" concrete.	High. Technology has proven to be viable.

Carbonate aggregates

Carbonate aggregates from CO_2U have high potential to abate CO_2 emissions, but they need to become cost-competitive. The category offers an attractive long-term opportunity, if investments are made in CO_2 infrastructure and the scaling up of technology.

Carbonate aggregates produced from CO_2U can be used in concrete, asphalt, and construction fill.

Conversion of CO_2 into carbonates offers the potential to convert low-value materials (such as solid wastes containing calcium oxide) into useful products. However, materials from municipal waste sites or steel plants must be transported from their point of generation to the carbonate production site, increasing the price of CO_2-derived products.

- **Estimated total market size 2015**: 25-35 billion metric tons. The total aggregate market is expected to grow to approximately 50 billion metric tons by 2030 with a CAGR between 3 and 4 percent.
- **Technology pathways**: Direct carbonation; indirect carbonation.
- **CO_2U forecast and considerations**: By 2030, the CO_2U carbonate aggregates market is forecast to grow to between 1 billion (pessimistic), 3.5 billion (optimistic) and 10.5 billion (best case) metric tons. Drivers:
  - Concrete production is a source of high CO_2 emissions. Currently, concrete production via CO_2U is not incentivized. If enacted, incentives would accelerate growth.
  - As noted above, concrete production is a source of high CO_2 emissions. Incentives to reduce carbon emissions are low.
  - Funding was available for developers in the past, especially in the US and Canada. Several companies are in the commercialization stage.
  - Concrete offers a solution for permanent CO_2 storage.

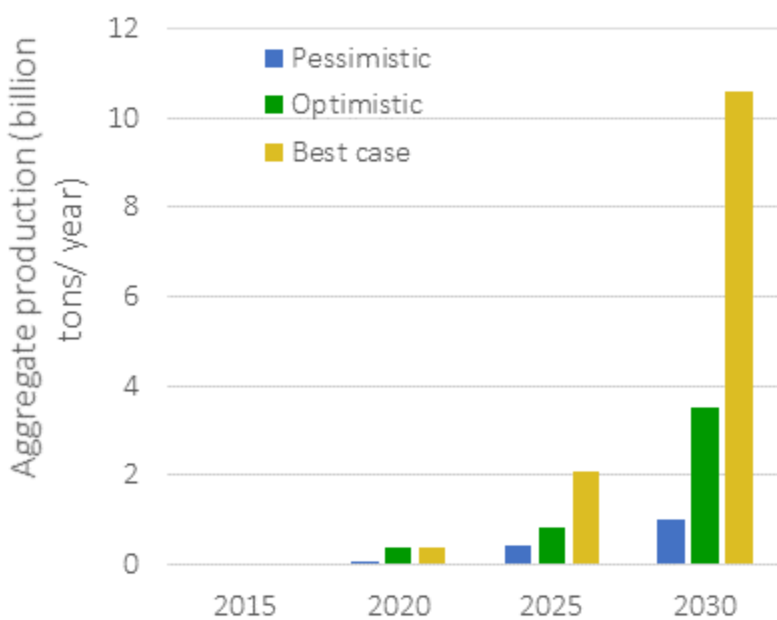


Figure 4.2: Estimated growth of CO_2U carbonate aggregates market through 2030.

Carbonate aggregates: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of success mitigation by 2030
Demonstration at large scale at low-cost	Process integration of conversion to carbonates and local supply of solid waste and CO_2	High, infrastructures can be set up to be cost competitive with traditional aggregates.
Lack of incentives for aggregate producers; Payback periods could be too long	Subsidize early developers of CO_2 conversion to carbonates or tax carbon emissions at cement factories	High, programs and regulations connected to COP21 will take time to be implemented. Europe is most likely the early adopter.
Product will have to be qualified by existing regulations	Expedite standardization and regulations to lower time to less than 5 years	High, regulations and standards will have been resolved by 2030.

Other barriers include access to CO_2, lack of funding to move the technology past low capacity production, and lack of cost competitiveness due to transportation costs involved with waste material to be used as feedstock.

Carbon8 is currently producing 180,000 metric tons of carbonate aggregates per year, but scalability of the technology remains to be determined.

Chemical intermediates: methanol, formic acid and syngas

Methanol

Today, methanol is largely used in chemical production as an intermediate in the production of formaldehyde, methyl tert-butyl ether, acetic acid and dimethyl ether; olefins is an emerging sector.

However, its emerging application – as a fuel blend – is potentially highly significant. The market for conversion of CO_2 to methanol is driven by the demand for fuels from renewable sources. CO_2U-derived methanol offers great promise as this demand continues to grow, but investments are necessary to drive this market to its full potential.

- **Estimated total market size in 2015**: 60-70 million metric tons. The total methanol market is expected to grow to approximately 190 million metric tons by 2030, with a CAGR between 7 and 9 percent. The estimate assumes that the bio feed stock market share for methanol used as a fuel is 50 percent by 2030, and the overall market share of methanol used a fuel increases from 12 percent in 2015 to 30 percent in 2030.
- **Technology pathways**: Catalytic hydrogenation; photocatalytic; electrochemical.
- **CO_2U forecast and considerations:**
    - By 2030, the **CO_2U methanol market for fuels** is forecast to grow to between 4 million (pessimistic), 23 million (optimistic) and 34 million (best case) metric tons.
    - CO_2U methanol for use as a chemical intermediate lacks clear incentives for CO_2 mitigation; no projects targeting the chemical production market currently exist. By 2030, the **CO_2U methanol market for chemical intermediates** is forecast to grow to between 1.3 million (optimistic) and 9.3 million (best case) metric tons.
    - Methanol from CO_2 is currently only cost competitive in special scenarios.
        - Funding for “renewable” methanol is tied to production of energy from renewable sources.
        - Major hurdles for methanol via CO_2U are current high production costs and low production volumes.
        - Methanol from CO_2 conversion, usually produced by the electrolysis of water, requires cheap hydrogen and demands inexpensive/renewable sources of electricity (e.g., hydrothermal in Iceland or wind in Germany).
        - Policies and regulations for CO_2 mitigation driven by the Paris COP21 agreement could help reduce costs.

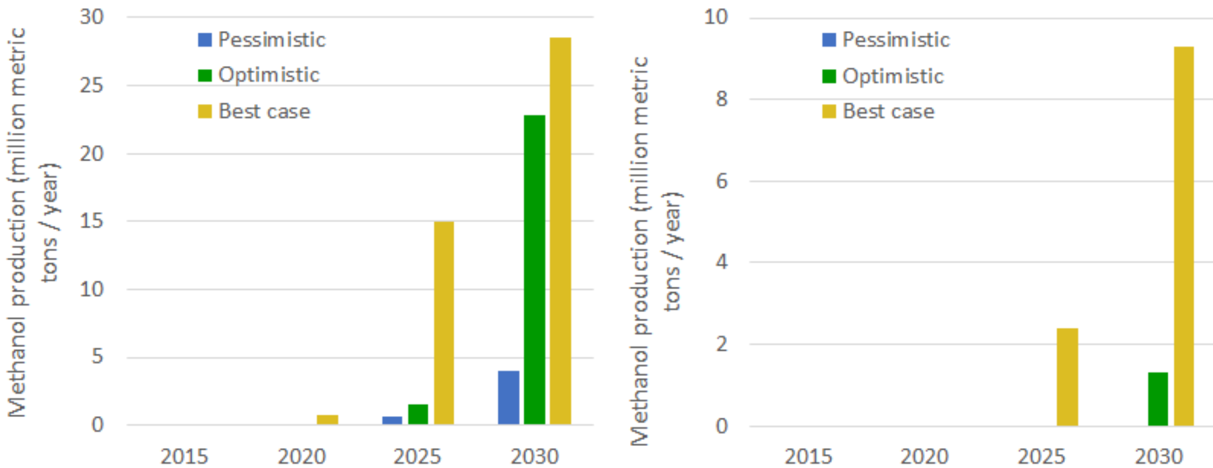


Figure 4.3: Estimated growth of CO_2U methanol (fuel) and CO_2U methanol (chemical intermediate) markets through 2030.

Methanol from CO_2: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of success mitigation by 2030
Access to low-cost H_2	Development of electrolysis and access to low-cost renewable energy, i.e. process integration of renewable energy or excess energy, carbon capture and conversion to syngas	High, pilot programs are in place
Reduction of compounds besides CO_2, especially H_2O and catalyst efficiency	Catalysts promoting CO_2 production and inhibitors of side reactions; Further catalyst R&D	High, catalyst improvements are expected
Current mandates for fuels from renewable sources can be met by biofuels from bio-based feedstocks	Increase mandates, implement carbon tax or replace bio-based feedstocks	High: Mandates are likely to become more strict by 2030

Other barriers include access to a clean energy supply, relatively low energy density of methanol as compared to gasoline, creation of a CO_2 capture and/or methanol infrastructure, and uncertainty about funding. Some of these concerns are also valid for other markets for fuels, polymers or chemicals.

Formic acid

Currently, formic acid is used as a chemical intermediate in adhesives, preservatives, dimethylformamide (DMF), and other products. Because it's more reactive than methanol, formic acid is more suitable as a chemical intermediate. Research in the reduction of CO_2 to formic acid (CH_2OH) is still early-stage. Formic acid also has been proposed as a fuel source for fuel cells. This application is still in a proof-of-concept phase.

Funding and incentives drive formic acid; potential is small as compared to other market segments. CO_2 conversion to produce formic acid has high potential in theory because formic acid is suitable as a chemical intermediate. However, demand will remain low unless specific applications are more developed.

- **Estimated total market size in 2015**: 500,000 to 700,000 metric tons. The total formic acid market is expected to grow to approximately 1.0 million metric tons by 2030 with a CAGR between 3 and 4 percent.
- **Technology pathways**: Catalytic hydrogenation; electrochemical.
- **CO_2U forecast and considerations**: By 2030, the CO_2U formic acid market is forecast to grow to between 10k (pessimistic), 50k (optimistic) and 475k (best case) metric tons annually.
  - Applications need to be developed; current demand is relatively low.
  - The driver for using CO_2 conversion to produce formic acid is weak, because governments are not incentivizing creation of chemical intermediates from renewable sources.
  - Use as a fuel for fuel cells would allow for carbon-neutral transportation, if formic acid were made from renewable sources.

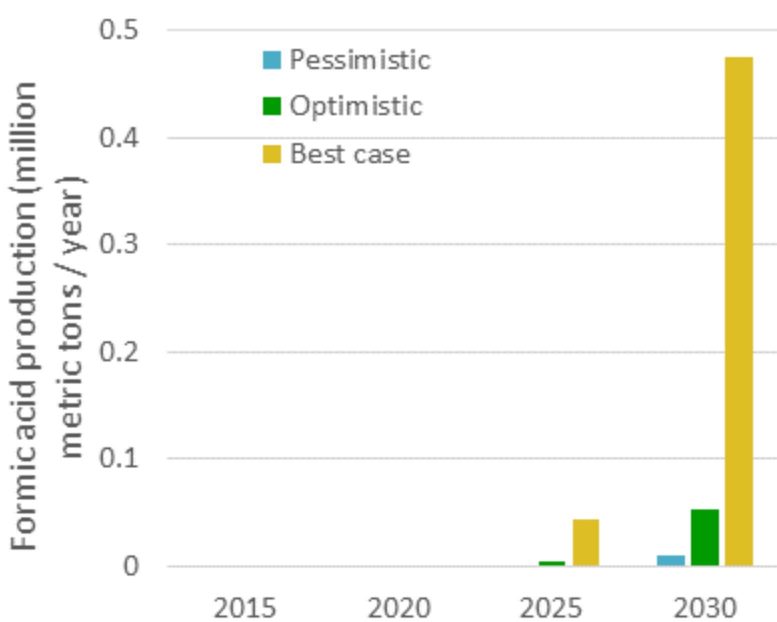


Figure 4.4: Estimated growth of CO_2U formic acid market through 2030.

Formic acid from CO_2: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of success mitigation by 2030
More efficient conversion	Research into improving catalyst selectivity and increasing catalyst life. This includes catalysts that would allow for contaminated CO_2.	High, development will take 10-15 years
Lack of funding for programs to focus on formic acid from CO_2	Set up government or private programs, especially in APAC and the US. Incentivize collaboration between renewable energy suppliers and converters.	High, funding is available in Europe. US and APAC will follow suit if programs are successful
Lack of current demand for formic acid	Formic acid could be developed as an alternative `green' chemical intermediate or a fuel to fuel cells	Low, demand in these fields is unlikely to be high unless there is a breakthrough in fuel cells

Formic acid from CO_2 cannot compete for another 10 years, perhaps 15. CO_2U formic acid is more early stage than methanol and syngas.

Other barriers include access to a clean energy supply, creation of a CO_2 capture infrastructure, insufficient incentive for formic acid producers to reduce carbon emissions, and lack of access to plants for scale-up projects. These concerns may also be valid for other markets for fuels, polymers or chemicals.

Syngas

Syngas (synthesis gas) is a versatile chemical intermediate; it is more reactive. Its uses include making liquid fuels (by Fischer-Tropsch reaction) as well as methanol itself. Syngas is also used in power generation, but this application is not considered a CO_2U end product because other methods are more efficient and lower in cost. Although it's currently relatively small, the syngas market derived from carbon monoxide and hydrogen is growing at a healthy CAGR (8 percent).

Syngas from CO_2 has significant potential as it can be used as an intermediate in the production of many chemicals and materials. Many developers are investigating CO_2 conversion to syngas. However, efforts must be incentivized to be able to compete with more conventional production methods by 2030.

- **Estimated total market size in 2015**: The development of syngas for power generation makes the total market size difficult to quantify because syngas is normally converted to other chemicals or used for power generation; this study estimates the current market to be 130-150 gigawatts annually. The total syngas total market is forecast to grow to approximately 500 gigawatts annually by 2030 with a CAGR of between 8 and 10 percent.
- **Technology pathways**: Electrochemical; catalytic hydrocarbon reformation.
- **CO_2U forecast and considerations**: The CO_2U syngas market is forecast to grow to between 15 (pessimistic), 110 (optimistic) and 265 (best case) gigawatts by 2030.
  - Syngas from CO_2 conversion can be used to produce a range of chemicals and fuels.
  - Because it enables developers to produce fuels or chemical intermediates downstream, CO_2U syngas production can be added on to an existing manufacturing plant. For example, the technology can be added on by steel plants to decrease carbon emissions and generate an additional revenue stream.
  - There are currently no direct incentives for companies to use renewable sources to produce syngas; renewable alternatives include generation of syngas from biomass.

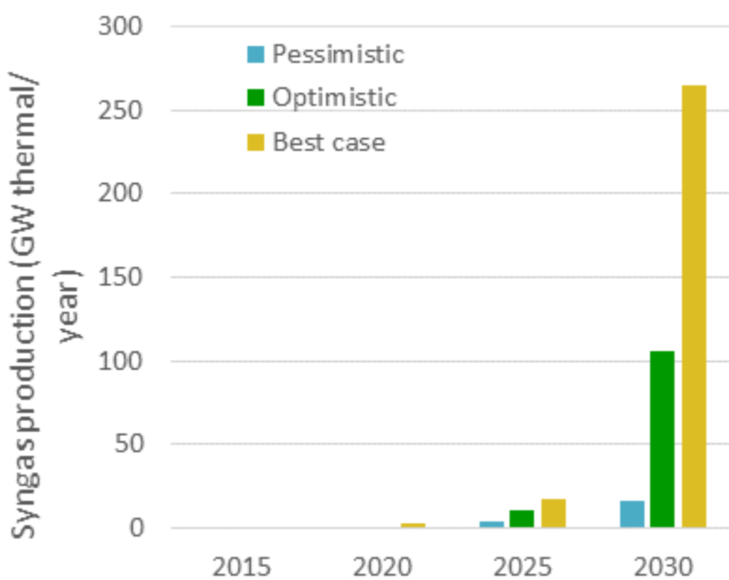


Figure 4.5: Estimated growth of CO_2U syngas market through 2030.

Syngas from CO_2: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of success mitigation by 2030
Access to low-cost hydrogen and access to a clean energy supply	Development of electrolysis and access to low-cost renewable energy, i.e. process integration of renewable energy or excess energy, carbon capture and conversion to syngas	High if excess energy of plants or renewable sources can be utilized
Lack of demonstration facilities	Increase funding for pilot programs and for scaling up production of syngas	High, Funding in Europe has focused on pilot programs
Lack of incentives to reduce carbon emissions	Tax on carbon emissions or mandate reduction of carbon emissions	Low, although Europe could be an early adopter

Other barriers include competition with syngas generated from biomass, creation of a CO_2 capture and/or syngas infrastructure, and competition with alternatives to reduce carbon emissions at plants. Some of these are also valid for other markets for fuels, polymers or chemicals.

Fuels: liquid fuels and methane

Liquid fuels

Liquid fuels include gasoline, diesel and kerosene, and additives such as methanol and formic acid. Biofuels from renewable sources such as sugar cane have been growing through funding and incentives, but fuels from CO_2 conversion have a negligible market share at present.

Yet liquid fuels from CO_2U have the potential to replace polluting alternatives. CO_2 conversion to liquid fuel production demands an integrated approach to developing the technology, incentivizing renewable fuels by policy, and creating an infrastructure for low-cost CO_2.

- **Estimated total market size in 2015**: 800 billion to one trillion US gallons annually. The overall liquid fuels market is expected to exceed one trillion US gallons annually by 2030 with a CAGR of 1-2 percent.
- **Technology pathways**: Photocatalytic; biocatalysis; catalytic hydrogenation.
- **CO_2U forecast and considerations**: By 2030, the CO_2U liquid fuels market is expected to grow to between 7 billion (pessimistic), 45 billion (optimistic) and 165 billion (best case) US gallons annually.
  - Europe leads in funding to lower carbon emissions.
  - Europe has a mandate to derive 10 percent of liquid fuels from renewable sources by 2021. Sources of energy for conversion must also be to be renewable.
  - European consortia have been established comprising members of the value chain (universities, energy suppliers, CO_2 suppliers, converters and users).
  - Fuels from CO_2 conversion target the same market as fuels from bio-based feedstocks.

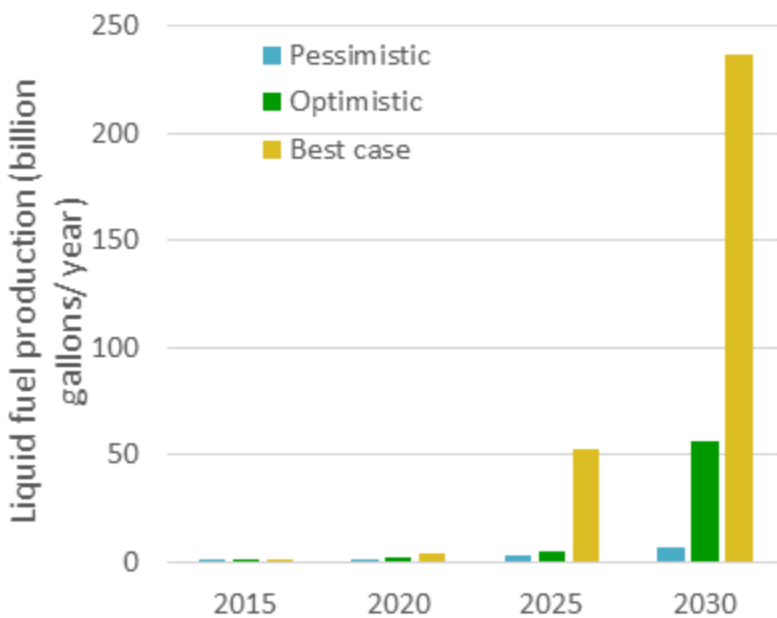


Figure 4.8: Estimated growth of CO_2U liquid fuels market by 2030.

Liquid fuels from CO_2: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of success mitigation by 2030
Current mandates for fuels from renewable sources can be met by biofuels from bio-based feedstocks	Increase mandates or replace bio-based feedstocks	High: Mandates are likely to become more strict by 2030
Access to renewable energy at a low price	Increase availability from energy from solar, wind and other renewable sources	High: in areas of oversupply of solar and wind energy
Efficient conversion of CO_2	Technological advances in conversion of CO_2 are necessary to allow for different quality feedstocks to be used and to increase the yield of the conversion	High: Advances in catalysis and photocatalysis should allow for more efficient conversion

Other barriers include lack of access to a low-cost hydrogen and clean energy supply and creation of a CO_2 capture infrastructure. Note that some of these are also valid for other markets for fuels, polymers or chemicals.

Methane

Methane is produced from resources such as shale gas, tight gas and coal beds. According to the Energy Information Administration, shale accounts today for one-half of US natural gas production, with its share expected to approach 70 percent by 2040.

Producing methane from CO_2 is possible, but it remains to be seen if it can be profitable. It can only be cost-competitive if alternatives are made more expensive through carbon taxes or by mandating methane production from renewable sources. Developers are investigating bio-methane from renewable sources to reduce CO_2 emissions, and methane from CO_2 conversion will compete with these renewable sources. European consortia have been established comprising members of the value chain (universities, energy suppliers, CO_2 suppliers, converters and users).

- **Estimated total market size in 2015**: 3-4 trillion cubic meters annually. The overall methane market is expected to grow to 4-5 trillion cubic meters by 2030 with a CAGR between 1 and 2 percent.
- **Conversion technologies**: Fermentation; catalytic hydrogenation; photocatalytic.
- **CO_2U forecast and considerations:** By 2030, the CO_2U methane market is expected to grow to between 4 billion (pessimistic), 13 billion (optimistic) and 65 billion (best case) cubic meters annually.
- Funding in Europe for the co-electrolysis of CO_2 and water is ongoing, with several countries possessing significant alternative energy sources, such as hydroelectric and wind power.
- Shale-gas-fired technology is replacing coal-burning plants in the US, thereby reducing carbon emissions and reducing the drive in the US to reduce CO_2 emissions.

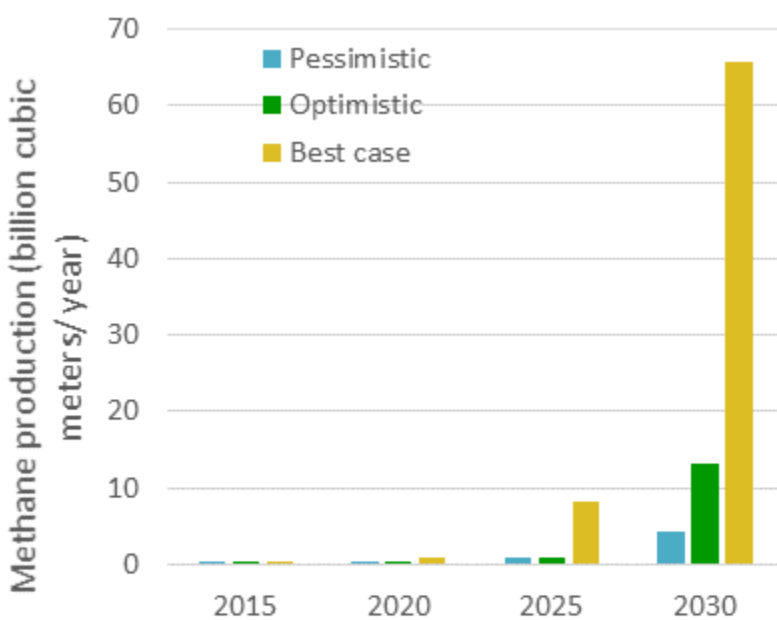


Figure 4.7: Estimated growth of the CO_2U methane market through 2030.

Methane from CO_2: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of success mitigation by 2030
Requirement of process integration	Development of conversion technology and access to low-cost renewable energy, i.e. process integration of renewable energy or excess energy, carbon capture and conversion	High, pilot programs are in place
No incentive to change; gas is seen as an improvement over oil and coal in countries such as the US	Change in policy to mandate more strict requirements for CO_2 emissions or implement carbon taxes	Low, the US is meeting its current standards
Low-cost and effective catalysts	Funding into development of more durable and selective catalysts; Development of fermentation technology	High: catalyst improvements are expected

Other barriers include low gas price of fossil derived methane, lack of access to a low-cost hydrogen and clean energy supply and creation of a CO_2 capture infrastructure. Note that some of these are also valid for other markets for fuels, polymers or chemicals.

Polymers

Polyols and polycarbonates

While there are a smaller number of developers compared to the building materials, chemical intermediates and fuels categories identified in this study, several large companies with access to technical knowledge and production facilities are focusing on the production of polycarbonates and polyols from CO_2. Research into other types of polymers is more fragmented.

Polyols and polycarbonates from CO_2 have been commercialized, but it remains to be seen if the technology can compete. Reduction of the cost of CO_2 and/or greater incentives to reduce carbon emissions must be implemented to be able for CO_2U polymers compete with those from conventional feedstock.

- **Estimated total market size in 2015**: 8-10 million metric tons for polyols and polycarbonates. The total market for these two polymers is forecast to grow to 17 million metric tons by 2030, with an estimated CAGR of 3-5 percent. Other polymers, such as polyhydroxyalkanoates (PHA), are far from commercialization.
- **Technology pathways**: Epoxide copolymerization; fermentation.
- **CO_2U forecast and considerations**: By 2030, the CO_2U polymers (polyols and polycarbonates) market is forecast to grow to between 0.4 million (pessimistic), 1.7 million (optimistic) and 6.8 million (best case) metric tons annually.
    - The major contemporary driver for the development of CO_2U polymers is to reduce CO_2 emissions from chemicals and materials manufacturing processes and facilities.
    - Funding is available in Europe to companies exploring using CO_2 as a feedstock.
    - The thermo-catalytic conversion process is not currently cost competitive.

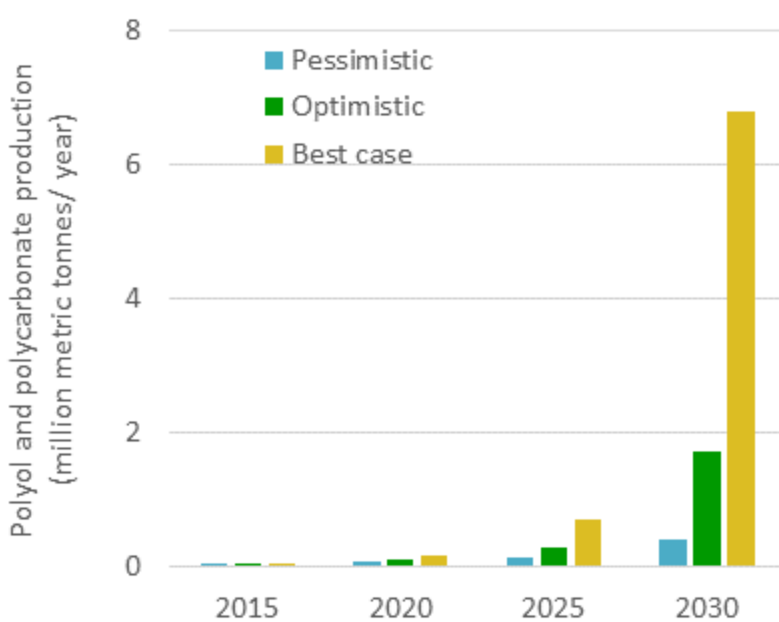


Figure 4.6: Estimated growth of the CO_2U polymers (polyols and polycarbonates) market through 2030.

Polymers from CO_2: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of success mitigation by 2030
No incentive for reduction of CO_2 emissions for polymers and chemicals at plants	Set up mandates and regulations. Incentivize collaboration between renewable energy suppliers and converters.	Low, although Europe could be an early adopter
Not cost competitive	Improve conversion efficiency, reduce cost of feedstock and/or energy, implement carbon tax	Low, a global carbon tax is unlikely
Access to low priced CO_2	Development of capture of CO_2 and creation of a supply chain infrastructure	High, supply chain will be developed based on progress in other markets

Other barriers include time for qualification of polymers by customers, access to a low-cost clean energy supply, and uncertainty about funding. Note that some of these are also valid for other markets for fuels, polymers or chemicals.

Overall drivers, barriers and constraints

While there are different market forces that influence near term and long term potential of the different market segments, we summarize the overall drivers, barriers and constraints in terms of three dimensions: policy, technology and market.

Policy

- **The Paris agreement sets global goals for reducing CO_2 emissions and establishes a system to support national governments in doing so.** The agreement entered into force in early November 2016.
- **The drive toward a carbon-neutral economy and less dependence on oil,**
- **In general CO_2U is not a priority in government R&D strategies.**
- In recent years CCS has received more attention than CO_2U. That has helped drive down costs of carbon capture, which are essential for both approaches, but the funding for utilization technologies has been limited. However CO_2U is now receiving greater attention around the world. CO_2U is often called "CO_2 transformation," "CO_2 usage" or "CO_2 re-use" by European policy makers and developers.

Technology

- Lack of coherent funding strategies from governments to support CO_2U technologies.
- Another barrier is **the lack of access to facilities** to scale up CO_2U technologies.
- **Lack of access to feedstocks** – for hydrogen, CO_2, and renewable energy – is an additional barrier.

Recently, we began to see activities clustering in research centers. We believe this will critical mass to accelerate the development of early stage technologies. Appendix 1 shows examples of such activity centers.

Market

- A barrier is **the lack of access to facilities** to scale up CO_2U technologies.
- **Cost: CO_2U must compete** with conventional feedstock and bio-based feedstocks, which are often lower in cost.
- Access to a national CO_2 infrastructure.
- Lack of process integration of renewable energy and conversion processes (no robust value chain)

The above barriers and constraints affect the different market segments in different ways. In some cases, technology may be the biggest barrier while in others it may be the policy. Fig.4.7 attempts to show how the relative influence of the three dimensions: policy, technology and market on the development of different products. We have scored (1 through 5) the four market segments as shown below.

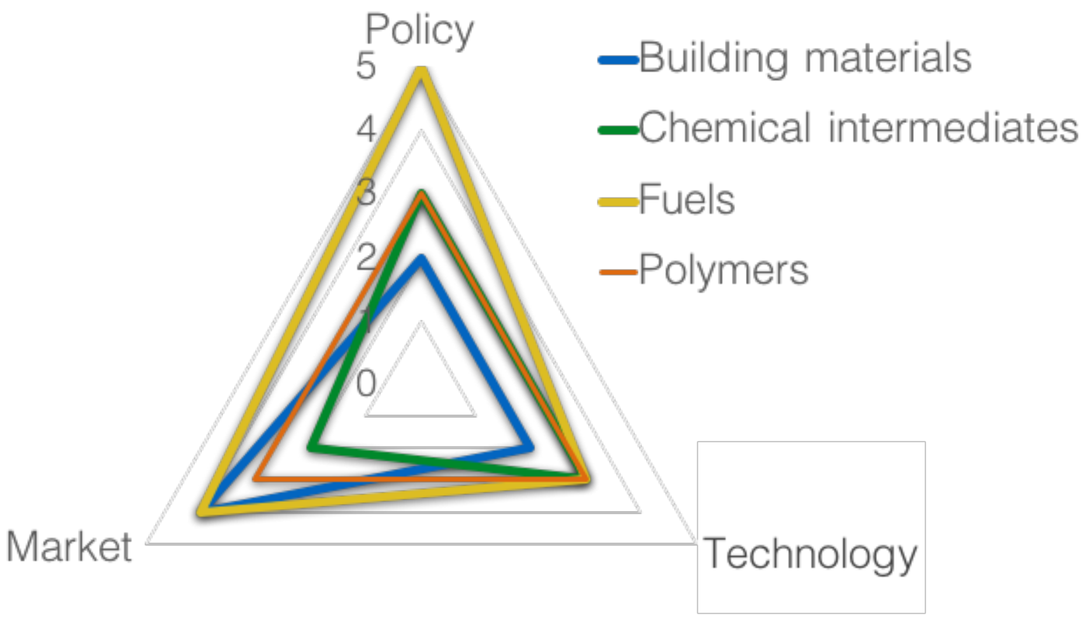


Fig. 4.7 Relative influence of the dimensions on different CO_2- based products

For example, Policy has a greater impact on the development and market penetration of fuels versus polymers. Another example is the smaller influence that technology will play on the market deployment of building materials versus polymers.

V. Life cycle assessment

The climate benefit of a CO_2U product depends not just on how much CO_2 the product contains. The amount of CO_2 emitted in making the product also matters. So does the amount of CO_2 emitted in making any competitive products displaced. To the extent that climate benefits are a goal of those promoting CO_2U products, life cycle analysis is essential.

Understanding the full life cycle emissions impacts of CO_2U technologies is especially important for validating policy support and for guiding research. At first glance, technologies that divert one ton of CO_2 into an economically valuable product would seem to reduce emissions by one ton of CO_2, but this is not the case, for several reasons.[i] As shown in Figure 5.1, a true understanding of the emissions impacts of CO_2U technologies must be based on rigorous life-cycle assessment (LCA), which takes several other factors into account:

- The CO_2 capture process, including any energy penalty that must be offset through additional power generation;
- Compressing and transporting CO_2 to the location of the CO_2U process;
- The energy consumed in the CO_2U process itself;
- The production of additional feedstocks, catalysts and other materials used in the CO_2U process; and
- The emissions resulting from end-of-life treatment for the CO_2-based product.

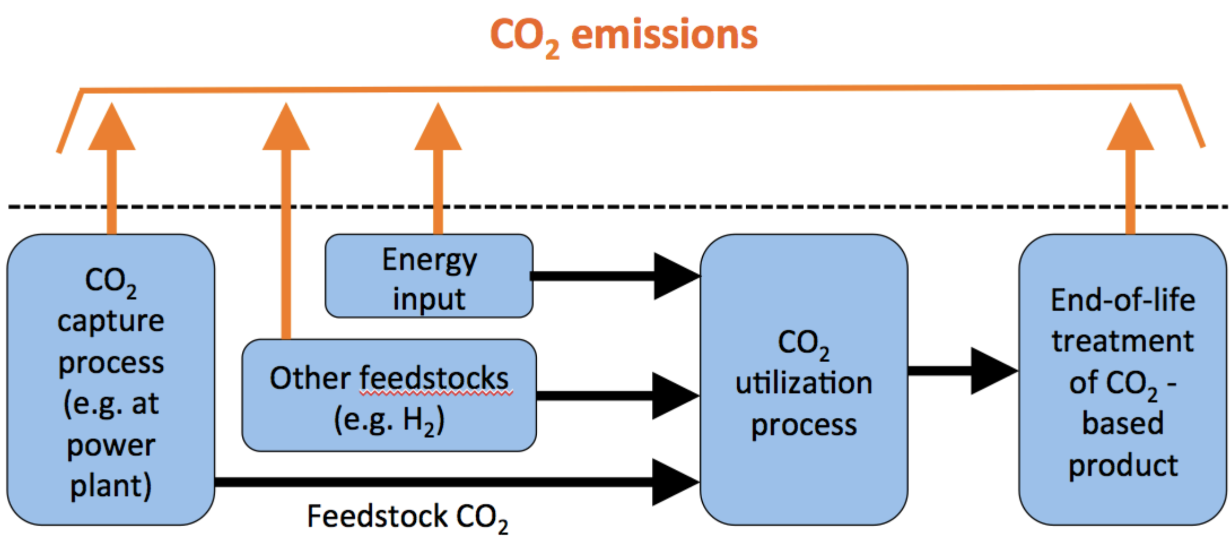


Figure 5.1: Emissions sources for CO_2U technologies. Adapted from von der Assen, 2015.

The ISO 14000 series establishes a standard framework and general procedure for performing LCA calculations, and is widely accepted.[ii] However, even when using this framework, there are many other complications that occur in practice.

The first complication comes from the impact of using different CO_2 sources as feedstock for a CO_2U process. Electric power generation is the largest source of emissions, but many others exist, such as natural gas processing and fertilizer production.[iii] These sources have different energy requirements for capture (largely based on their purity) so a LCA must take this into account. It is possible to define an “environmental merit order” that ranks CO_2 sources by the environmental impacts of using them as feedstock[iv]. This is fine in principle, but CO_2U processes in the market will probably decide which sources to use based on capture costs[v] or pipeline infrastructure[vi] instead of environmental benefits.

A second complication is to correctly specify what comparison the LCA will be used to make. For example, comparing the emissions impacts of different possible end-uses for a specific amount of captured CO_2 (such as storage, EOR, mineralization or chemical intermediate production) is different from comparing the emissions impacts of switching from a conventional process for producing a specific product (such as aggregates or methanol) to one based on captured CO_2.

Third, in all cases other than air capture[vii], the production of CO_2 for use as feedstock in CO_2U technologies is accompanied by co-products such as electricity, steel, cement, ammonia, etc., and the overall emissions of these processes cannot be entirely assigned to the CO_2-based product(s). The preferred method for handling this is known as “system expansion”, in which the scope of the analysis is increased to include all other relevant products.[viii] Unfortunately, this can get extremely unwieldy for processes that involve lots of products, and it also means that the LCA does not result in a clear emissions impact from a single CO_2-based product.

The alternative method, known as “proportional allocation”, parcels out the total emissions among the various co-products, usually based on mass. However, this method sometimes leaves room for ambiguity, and different approaches to allocation have been shown to lead to significantly different LCA conclusions.[ix]

A fourth complication is the lack of data on some of the non-CO_2 reactants, catalysts and other parts of the full CO_2U system. Tracking the emissions footprints of these items is a significant supply-chain information challenge, and it is often impossible in practice to use complete information for a LCA study. Therefore there is a need for standard approximations or estimates to compare LCAs for multiple products on an equal basis.

Finally, it’s important to note that while the primary focus of climate policy is on CO_2 emissions, there are other environmental impacts from CO_2U technologies that should be considered, such as the acidification potential, ozone layer depletion potential, etc.

Because of these complications, LCA experts can come to very different conclusions about the overall emissions impact of the same or similar CO_2U technologies. For example, a review of 16 individual studies of CO_2U technologies including mineral carbonation (mineralization), chemical production, biofuels production, and EOR found a wide range of results, whose variation is so big that it is difficult to draw conclusions about their relative emissions impact, or give guidance to policymakers.[x]

Unfortunately, because of limited research funding, the CO_2U LCA research community is small, and there are very few additional studies. Some additional studies have looked at the production of plasticizers[xi], synthetic hydrocarbon fuels[xii], polyols for polyurethane production[xiii], dimethyl carbonate[xiv], and dry reforming of methane for dimethyl ether production[xv], but there are large gaps in the literature. These LCA studies are relatively low-cost, and should receive more funding.

As governments and industry consider increasing policy support for CO_2U, ideally, they will need to compare and harmonize their approach to LCA as it applies to policy decisions. Governments and industry should increase their focus on this topic and ensure that LCA is included in all CO_2U research coordination efforts. However, given the increasing interest in CO_2U, other stakeholders may need to act sooner. The Global CO_2 Initiative is planning to convene a global expert panel in an attempt to 'standardize' LCA analysis for CO_2U technologies. Additionally, the X Prize Foundation is pursuing rigorous LCA for all entries in its Carbon X Prize, and will gather detailed process data, putting it in a position to contribute to standardizing LCA approaches for CO_2U.

Policy and industry support for CO_2U may also need to consider other key factors beyond the environmental impacts as analyzed by LCA, such as whether the revenue from CO_2U technologies can cover the costs of feedstock CO_2, and the scalability of the technology.[xvi] A related challenge is the perceived trade-off between CO_2U business models that maximize profit through producing small volumes of high-value products, and those that maximize emissions reductions by producing large volumes of lower-value products.[xvii]

Of course, the challenges faced in applying LCA to CO_2U technologies are not entirely new, as LCA has been a key part of environmental analysis and policymaking for many years, most notably relating to biofuels and bioenergy.[xviii] Increasing funding for CO_2U LCA could draw the attention of experts currently focused only on biofuels/bioenergy issues and bring their expertise to bear on CO_2U issues.

VI. Recommendations for strategic actions

CO_2U will only help meet climate goals if CO2 products are widely deployed. The prospects for that are good in some market segments, although in others high costs, well-established alternatives and entrenched incumbents create barriers to market entry. Sound market strategies, targeted technological development and supportive policies all have a role in accelerating deployment and supporting CO_2U technologies in the market.

Technology

Decrease the cost of CO_2 utilization

Fund research to improve catalysis for CO_2 reduction and to improve electrolysis to produce hydrogen.

Conversion of CO_2 into CO_2U products requires more energy than conversion from conventional feedstocks because of the thermodynamic stability of carbon dioxide. Research and development is focusing on catalysis and other conversion processes to reduce the amount of required energy.

Thermo-catalytic conversion of CO_2 has been commercialized for several applications. In general, yields, half-life, and selectivity of catalysts need to be further increased. In addition, operating temperatures should be reduced to lower operating costs. Funding should go into applied research in catalysis.

A hydrogen feed is needed in many processes. Generation of H_2 by electrolysis using renewable energy at a low cost is necessary to make CO_2U cost-competitive. Funding also should go into applied research in electrolysis.

Funding also should be applied to research on alternative processes to thermo-catalytic conversion: fermentation, electrochemical, and photocatalytic means. These processes typically demand less energy usage. And additionally, funding support is needed for research that enables CO_2 feeds with contaminants to be used in CO_2U technology, which currently requires relatively high-purity CO_2 to optimize catalyst life.

Maximize high-potential long shots

Fund applied research on long-shot technologies and applications that have the highest CO_2 abatement potential.

In addition to the four markets analyzed in this work, there are early-stage CO_2U technologies and applications that could offer solutions beyond 2030. It's essential to fund fundamental and applied research into these technologies to further maximize the potential of CO_2U for CO_2 mitigation. We propose that the focus for these long shots be CO_2U technology that allows for sustained capture of CO_2, rather than making CO_2-neutral products. One of the highest-potential technical areas in this regard is the production of carbon fiber.

Figure 6.1 depicts a potential timeline for implementing the technology levers.

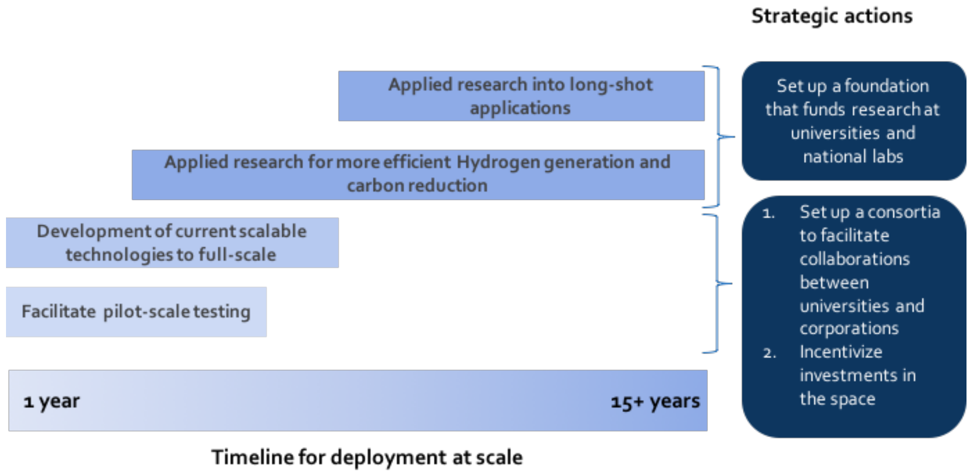


Figure 6.1: Potential timeline for implementing Technology levers

Market

Scale up production

Make funding available to establish collaborations among research institutes, start-ups, governments and corporations for process integration of CO_2 conversion, hydrogen generation and carbon capture.

Consortia should be established to enable the CO_2U value chain, integrating carbon capture; the supply of affordable hydrogen from sources such as a chemical plant or a technology like electrolysis; access to low-cost renewable energy (such as over-capacity electricity); and physical plants for CO_2 conversion and CO_2U product manufacturing.

One example that currently exists in the US is the DOE-supported Joint Center for Artificial Photosynthesis (JCAP). China has also created a research cluster around CO_2U technologies at SARI (Shanghai Advanced Research Institute).

Access to Capital

Various institutions are not aware of the value proposition of CO_2U technologies.

Articulating the value proposition of CO_2U solutions will drive more capital, especially impact capital, that has social and financial returns in mind.

Such capital enables a faster adoption and faster market deployment of CO_2-based products.

Figure 6.2 Depicts a potential timeline for implementing the market levers.

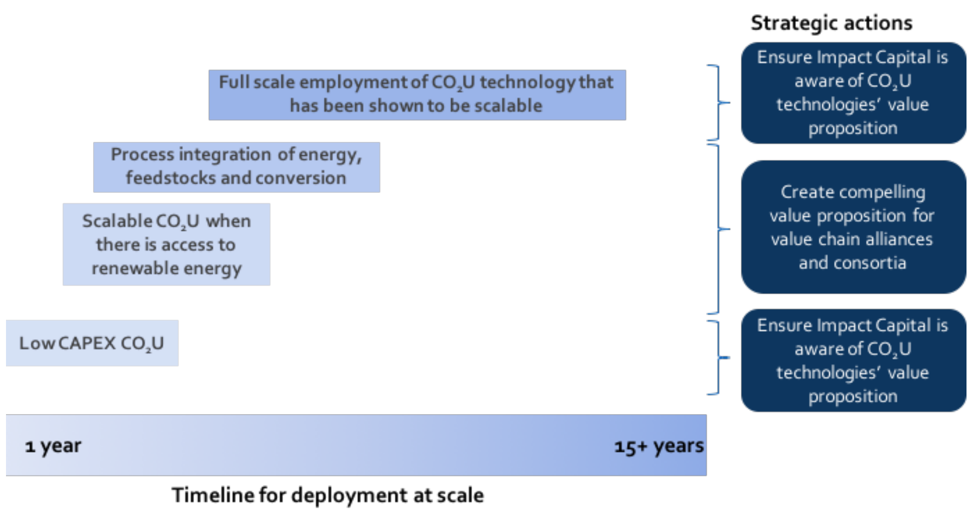


Figure 6.2: Potential timeline for implementing market levers

Policy

Supportive policies can help start and build markets for CO_2U products. Different policies may be appropriate in different jurisdictions, depending on local circumstances. In this section we catalogue policies that can play an important role in promoting CO_2U products.

Government support for R&D

Governments spend billions of dollars every year on research and development for clean energy technologies. Yet support for R&D on carbon dioxide utilization is modest. A significant increase in funding in this area could speed deployment of CO_2U technologies and yield important dividends.

In December 2015, heads of state from more than 20 countries announced Mission Innovation, a pledge to double R&D on clean energy within five years. Governments participating in Mission Innovation include the United States, China, Japan, the European Union and Saudi Arabia. The increase in R&D budgets from these countries in the next few years offers an important opportunity to scale up government R&D funding for CO_2 utilization. This could be part of the R&D portfolio of all Mission Innovation governments (as well as many industries).

Carbon Price

A price on carbon dioxide emissions, whether through an emissions trading program or tax mechanism, provides emitters with an important incentive to cut emissions. There are many strategies for doing so. In the power sector, for example, emitters could respond to a carbon price by (i) improving efficiencies, (ii) switching to lower carbon fuels, (iii) capturing carbon dioxide and sequestering it underground, (iv) capturing carbon dioxide and using it in products, or (v) some combination of the foregoing. In cases in which capturing carbon dioxide and using it in products is cheaper than the alternatives, a carbon price will provide an important incentive for CO_2 utilization. Even when capturing and using CO_2 in products is not the cheapest alternative in the short-term, a carbon price may help incentivize investments into CO_2 utilization technologies if market participants expect the price to endure for the medium or long-term.

Tax Incentives

Governments could offer tax credits for the use of CO_2 in products to help spur development of the industry. This type of focused, direct incentive can have a significant impact. However to the extent the objective of the tax credit is to cut CO_2 emissions, it would be important to establish eligibility criteria that took into account (i) the permanence of the removal of CO_2 from the atmosphere due to the product, and (ii) the life cycle emissions associated with the product. These create significant methodological challenges and are an important area for future research.

Mandates

Governments could mandate the use of CO_2 in certain products as a tool for spurring the market. Broader mandates, such as those requiring the use of renewable fuels in liquid fuel supplies, could also provide incentives for CO_2 use, if costs of CO_2 use are competitive with other compliance strategies.

Pipeline and other infrastructure development

CO_2 must either be used at the point of capture or transported by pipeline. Considerable investment in CO_2 pipeline networks will be needed for CO_2 utilization to flourish. Governments have an important role in helping establish these pipeline networks, both by facilitating regulatory approvals for pipeline construction and potentially by assisting with financing.

Government procurement

Government (including military) procurement can provide early market demand for emerging technologies, such as the US Navy's procurement of biofuels.[xix] This form of market stimulation also helps establish standard technical specifications for new products, which can help catalyze efficient supply chains. Several CO_2U technologies may be good targets for government procurements, such as CO_2-cured cement and CO_2-based aggregates, which could be included in government procurement guidelines for construction projects.[xx]

Product labeling

Providing consumers with easy-to-understand labels on products indicating their environmental qualities can increase demand for those products. Some of the most prominent examples of this strategy are the US Energy Star and Energy Guide programs, the Japanese Energy Efficiency Label program, and the EU Energy Labeling Directive. Consumer products based on captured CO_2 could be incorporated into these or similar labeling programs. The most appropriate CO_2U technologies for this may be CASE (coatings/adhesives/sealants/elastomers) and related plastics products.

Credits under regulatory and voluntary programs

Governments could offer additional credits under existing regulatory programs tied to the use of CO_2U products. For example, vehicle emissions regulations and appliance energy efficiency regulations could include additional credit for vehicles or appliances that are manufactured using CO_2U products such as foam insulation. Governments could also work with voluntary labeling programs such as LEED to include credit for buildings that use CO_2U -based construction materials.

Support for certification and testing

Governments could fund the certification and testing of CO_2U -based products by organizations such as UL, ASHRAE, ASME and others. These accreditation processes can accelerate the adoption of new technologies into existing supply chains, but do require funding in order to conduct the necessary testing and certification steps.

Support for expanded Lifecycle Assessment studies

Governments could increase funding support for LCA research, with a focus on specific CO_2U technologies that are industrially relevant. If so, this should be pursued in coordination with private-sector efforts to improve and standardize CO_2U LCA, such as the efforts by GCI and X Prize. Governments could also work to improve data availability throughout the supply chains relevant to CO_2U technologies.

Market-focused recommendations

Market-focused recommendations may also be useful as we believe there are current market opportunities that can proceed without policy initiatives. Combining major technology and market recommendations for specific product categories leads to the following recommendations:

Building materials

CO_2 curing of cements offers a superior product and superior price and should be able to move quickly if the following strategic actions are taken:

- Ensure financing for conversions of precast concrete facilities.
- Focus on converting the practices of incumbents rather than creating competitive companies.
- Identify the most cost effective places to capture CO_2 for this purpose.
- Build an infrastructure to deliver CO_2 – pipelines ultimately, but probably rail, ship or truck initially.
- Conduct detailed market surveys to determine optimum places to begin deployment on a country-by-country basis.

Carbonate based aggregates offer a very large volume sink for carbon dioxide but face more entrenched competitors and a price sensitive market. The following strategic actions are recommended:

- Conduct detailed market surveys to determine optimum places to begin deployment on a country-by-country basis starting with core material sources.
- Research needs to ensure that core material that may be hazardous is properly contained by the carbonate and the intended use
- Ensure that appropriate certifications are obtained for the material produced to be used in concrete.
- CO_2 sources and delivery systems need to be identified to support the locations identified
- Obtain financing for facilities based on the above, taking advantage of green bank and development bank options in less developed countries.

Fuels, chemical feedstock and plastics

Practically all of these applications are in direct competition with fossil fuel enabled value chains for the same product. To date these uses of CO_2 have been strongly affected in the market by the price of petroleum. Four classes of strategic action need to be taken:

- R&D to lower the cost of the CO_2 based product such as:
    - Improved catalysts for the generation of hydrogen and to drive the conversion process.
    - Emphasis on products that can use existing parts of the production and distribution infrastructure.
- Ensure low cost capture of carbon dioxide and to the extent possible sources that are not fossil fuel derived.
    - Infrastructure for delivery as noted above will be critical.

- Work with incumbents to ensure faster access to market and smooth transition to non-fossil based products.

High potential early stage technologies

There are a number of technologies that have high potential impact but are in an early stage of development. The acceleration of the products to market and application is essential. The following strategic actions are recommended:

- Provide "end in mind" funding for research and development that does the following:
    - ARPA-e like supervision of development
    - Early engagement with market partners
    - Rapid identification and handling of regulatory issues.

The implantation of the above cited levers will lead to significant increase in CO_2 reduction (Figure 6.3) and will create significant business opportunities (Figure 6.4)

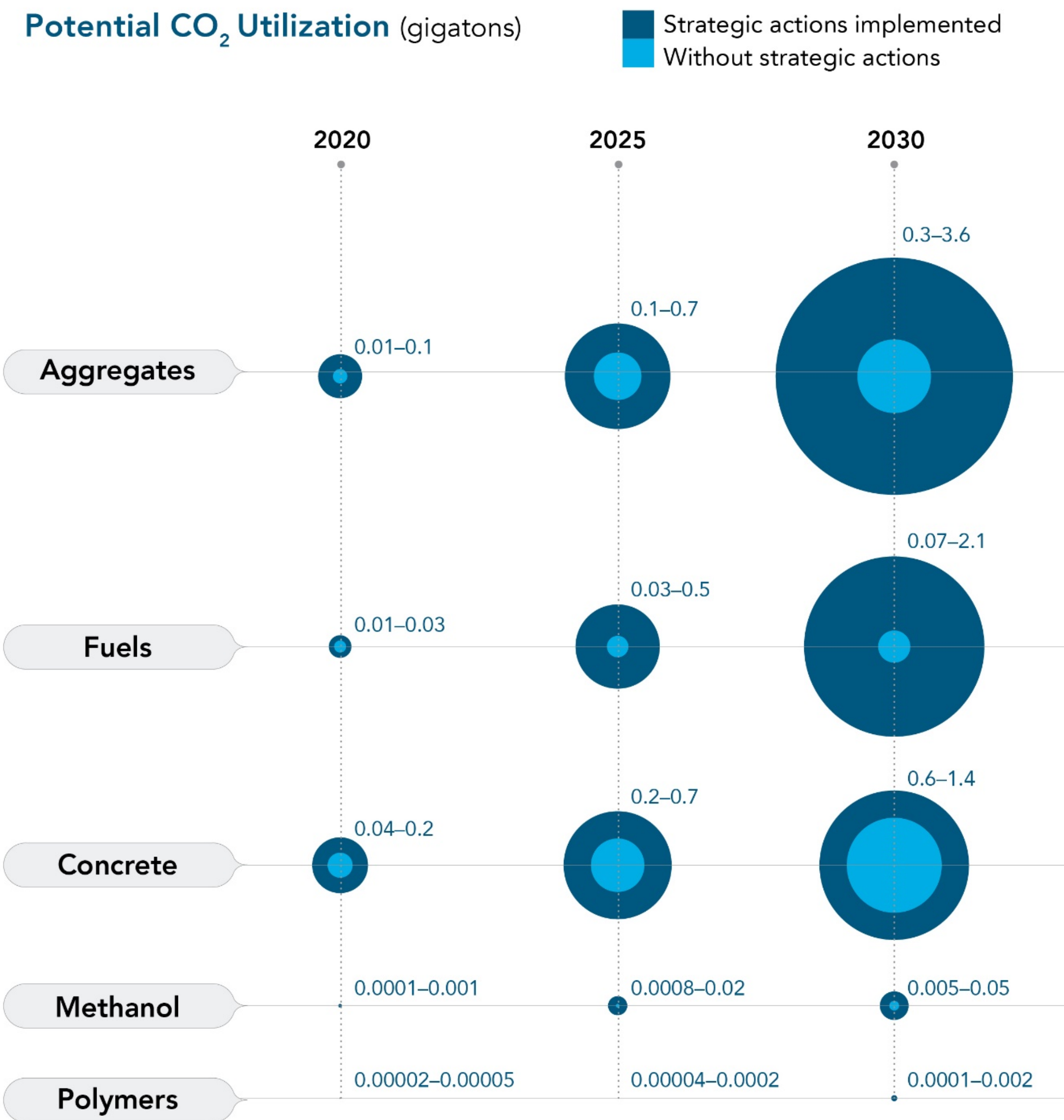


Figure 6.3: Potential in CO_2 reduction due to implementing strategic actions

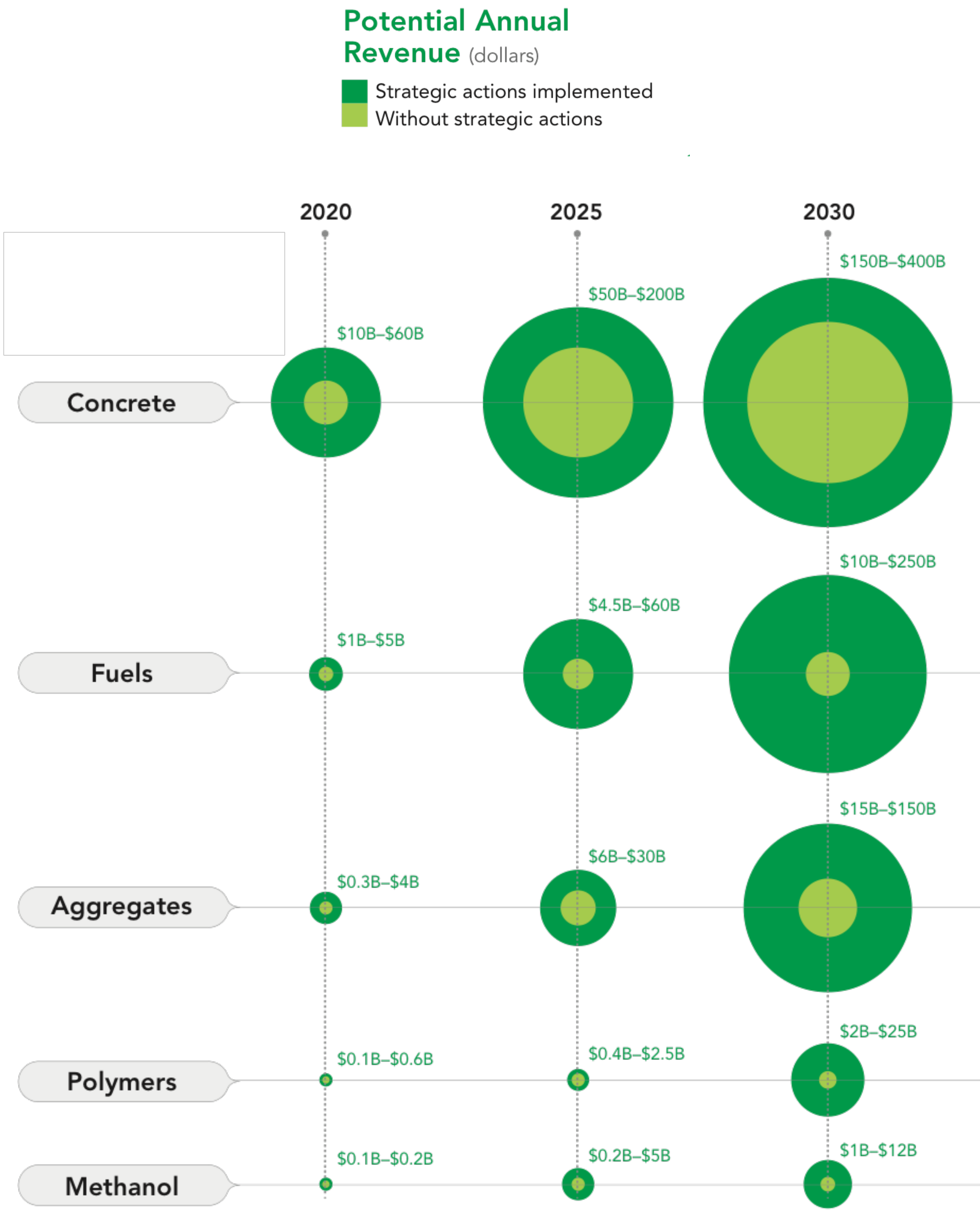


Figure 6.4: potential increase in financial returns due to implantation of strategic actions

VII. Conclusions

- **The commercialization of products derived from carbon dioxide utilization (CO_2U) offers opportunities to mitigate CO_2 emissions at a profit.**

- CO_2 mitigation and CO_2U are critical to decreasing the risks associated with climate change. CO_2U utilizes CO_2 to produce materials, fuels, or chemicals, whereas mitigation strategies like carbon capture and storage remain an added cost.

- Significant progress has been made CO_2U during the last five years, with many technologies proving to be scalable and visible momentum in four major markets:

    - Building materials
    - Chemical intermediates
    - Fuels
    - Polymers

- Funding, incentives and prompt strategic actions are necessary to move CO_2U toward full-scale capabilities. At full scale, CO_2U could open markets reaching or exceeding US $800 billion by 2030.

- CO_2U has the potential to utilize 7 billion metric tons of CO_2 per year by 2030 – the equivalent of approximately 15 percent of global CO_2 emissions today.

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About The Global CO_2 Initiative and ICEF

The Global CO_2 Initiative (GCI) and CO_2 Sciences, Inc.

The Global CO_2 Initiative (GCI) was announced at the January 2016 World Economic Forum in Davos. The Initiative is focused on funding the R&D and commercialization of CO_2-based products that will reduce carbon dioxide emissions by up to ten percent annually.

The GCI established CO_2 Sciences, Inc., a non-profit organization that funds innovative R&D in CO_2U to create CO_2-based products. CO_2 Sciences is structured to aggressively catalyze innovative research funding in carbon capture and use by granting up to $400 million in the next ten years to qualified research applicants throughout the world.

By harnessing market demand for products that capture and reuse CO_2 – and through "impact investing" – GCI aims to catalyze substantial economically driven change in the form of markets and products that reuse increased amounts of CO_2.

Innovation for Cool Earth Forum

The Innovation for Cool Earth Forum (ICEF) is aimed at addressing climate change through innovation. ICEF investigates via discussion what innovative measures should be developed, how innovation should be promoted and how cooperation should be enhanced among stakeholders in fighting climate change.

ICEF is held every year in Tokyo. The ICEF Steering Committee helps make decisions regarding the agenda and program to reflect the wide range of views of the international community. Policymakers, businesspeople and researchers from around the globe participate. The ICEF Roadmap Project helps to promote the development and deployment of clean energy technologies with roadmaps released each year.