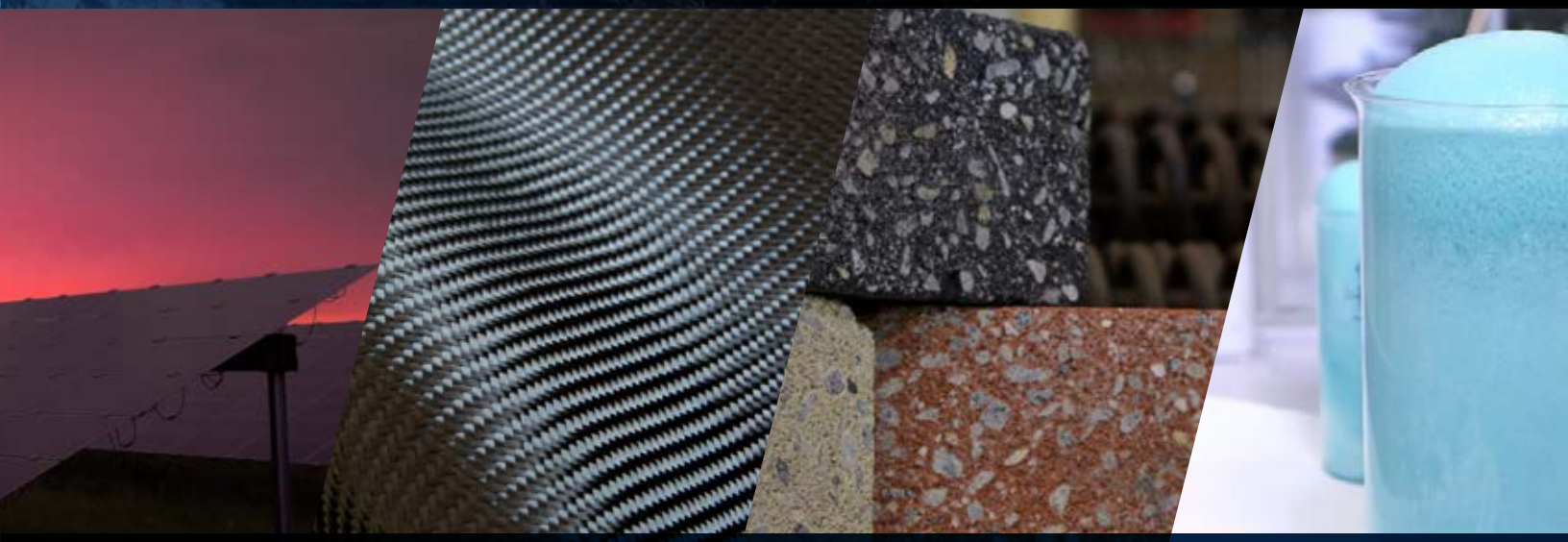
EXECUTIVE SUMMARY

A Roadmap for the Global Implementation of Carbon Utilization Technologies

Transforming CO2 from a liability to an asset at significant market scale

November, 2016

CO_2 SCIENCES | THE GLOBAL CO_2 INITIATIVE



ACKNOWLEDGEMENT

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Executive Summary

The Global CO_2 Initiative (GCI) and CO_2 Sciences

The Global CO_2 Initiative (GCI) focuses on funding research, development and commercialization of products that reuse CO_2. These products have the potential to reduce global annual carbon dioxide emissions by as much as ten percent.

The GCI, announced in January 2016 at the World Economic Forum in Davos, aims to drive substantial economically based change by developing and harnessing market demand for products that capture and reuse CO_2. CO_2 Sciences, Inc., GCI's non-profit, is structured to aggressively catalyze innovative research in carbon capture and use through grants to qualified applicants worldwide totaling $400 million over the next ten years.

To carry out its mission, CO_2 Sciences is developing a "toolkit" of capabilities and expertise (Figure 1) to assess market opportunities in the carbon-based products industry (CBPI), evaluate time horizons for short and long term opportunities, and identify a roadmap for implementation.

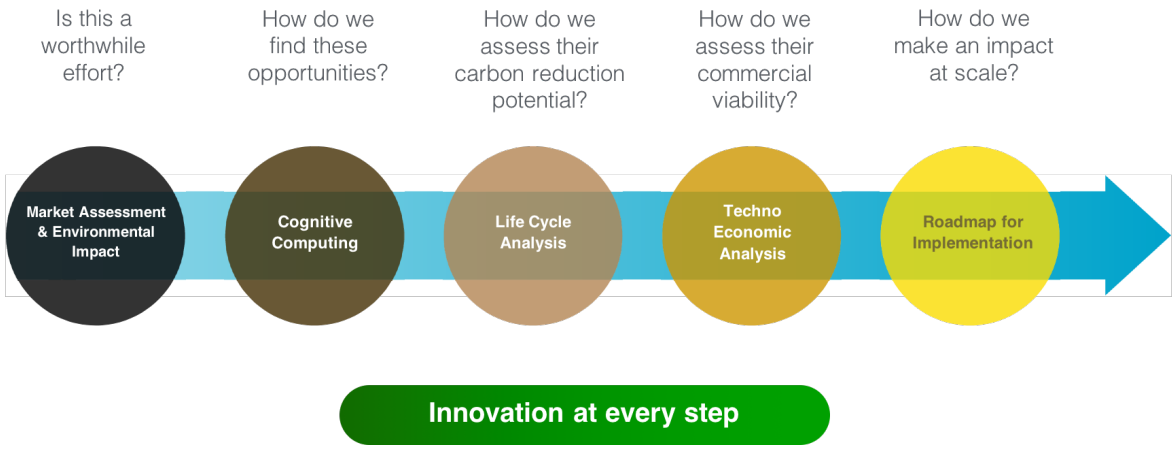


Figure1: CO_2 Sciences Toolkit: Developing capabilities to advance CBPI

To date, we have completed a Market Assessment and Roadmap for Global Technology Implementation. This document provides a summary of the results of our market assessment study (released earlier this year) and, in greater detail, the results of work to develop a roadmap for global implementation of CBPI. We conclude with recommendations for strategic actions.

Market Assessment - A briefing

CO_2 Sciences commissioned an independent study to conduct a detailed assessment of the global market opportunity for CO_2-based products. The study identified a large number of potential products and used the following criteria to focus on 25 of them:

1. **Environmental Impact**
    a. CO_2 potential: total amount of CO_2 that can be captured
    b. Permanence: length of time before the captured CO_2 is released

2. **Economic Impact**

a. Willingness to pay: maximum price of CO_2 that can be paid while keeping a given product competitive
b. Ease of Implementation: capital requirements, regulatory and market channel barriers

The 25 products shown in Figure 2 span seven categories:

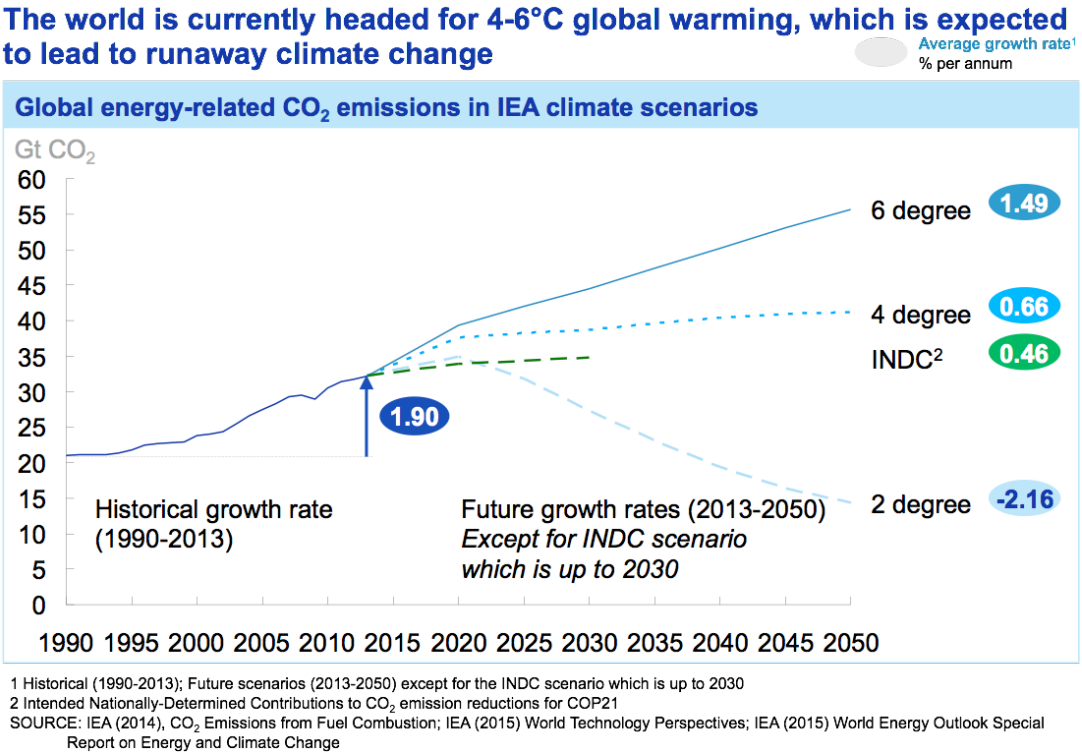
Figure 2: Examples of products that can be made from CO_2

The assessment included a bottom-up analysis for each of these seven categories and concluded that:

> CBPI can significantly contribute to reducing carbon emissions. Our initial estimate is that over 10% of annual CO_2 emissions can be captured in these products.
>
> These products represent an annual revenue opportunity of $800 billion to $1.1 trillion.

Background: Confronting an urgent challenge

The significant reduction of carbon emissions into the environment is crucial to averting a global climatological, economic, environmental and political catastrophe. While renewable power generation and a number of adaptation options can help with CO_2 reduction, experts agree that carbon negative technologies are needed to keep temperature increases below 2ºC (Figure 3).



1 Historical (1990-2013); Future scenarios (2013-2050) except for the INDC scenario which is up to 2030
2 Intended Nationally-Determined Contributions to CO_2 emission reductions for COP21
SOURCE: IEA (2014), CO_2 Emissions from Fuel Combustion; IEA (2015) World Technology Perspectives; IEA (2015) World Energy Outlook Special Report on Energy and Climate Change

Figure 3: Negative carbon emission rates are needed to limit temperature increase to 2^0C.

CBPI represents a major carbon reduction technology that, prior to the GCI, has not received attention nor been explored in any comprehensive fashion. As shown in Figure 4, CBPI can cover 15-20% of the projected gap between the 2ºC goal and use of all currently identified solutions.

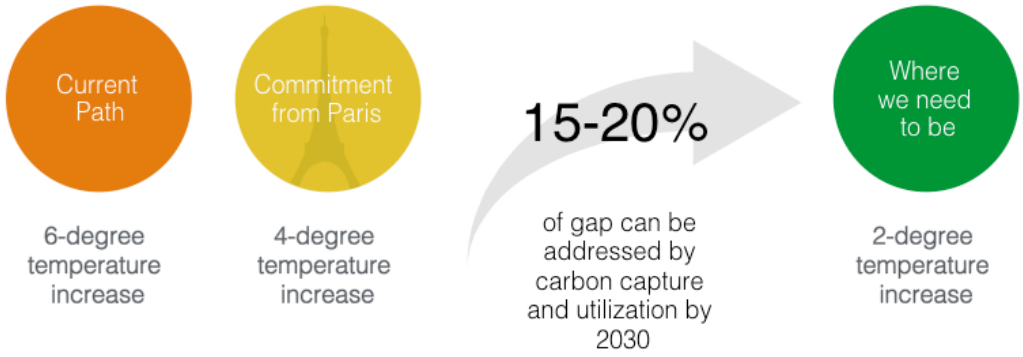


Figure 4: CBPI can play a significant role in addressing gap to achieve a 2^0 future

Identifying and forecasting market opportunity

Technology pathways assessment

We have identified and analyzed 180 developers who, worldwide, are actively engaged in CBPI and, ultimately, in the development of CO_2-based products. A database of CBPI developers was compiled from multiple sources. These entities include start-ups, mid-sized companies, corporations, consortia and research institutes.

Following in depth technology assessment, we defined six markets or product clusters (Figure 5) based on the number of active developers, conversion technology pathways and targeted end products:

1. **Chemical intermediates** (such as Methanol, Syngas and Formic acid)
2. **Fuels** (such as Methane and Liquid fuels)
3. **Building materials** (such as Concrete and Aggregates)
4. **Algae** (processed separately to create biofuels or food additives)
5. **Polymers** (such as polycarbonates, polyurethane and PHA)
6. **Novel materials** (such as carbon fiber)

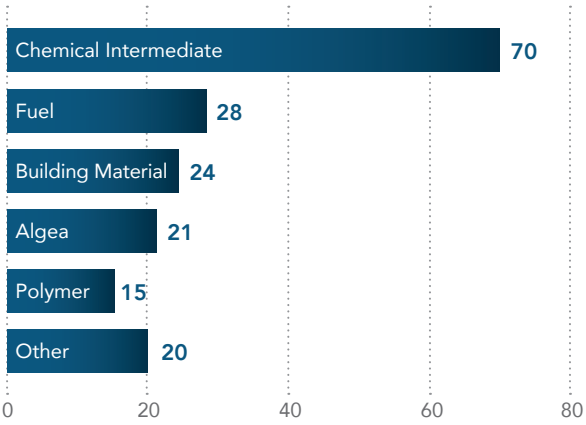


Figure 5: Number of active developers by end-product market cluster

Four markets are recommended for funding and investment

For each product or product category, we applied a Technology Readiness Level (TRL) of 1 (least) to 9 (most) to determine the relative stage of development and create a framework for expected time-to-market. We also used standardized rubrics to better quantify the mitigation potential and technology fit of each market. As a result, four markets were recommended for further analysis as shown in Figure 6. Algae and novel materials will not be part of the roadmap development as they will not significantly impact markets before 2030.

The roadmap analysis focused on eight categories within these four markets:

1. Chemical Intermediates: Methanol
2. Chemical Intermediates: Syngas
3. Chemical Intermediates: Formic acid
4. Fuels: Methane
5. Fuels: Liquid fuels
6. Building materials: Concrete
7. Building materials: Aggregates
8. Polymers

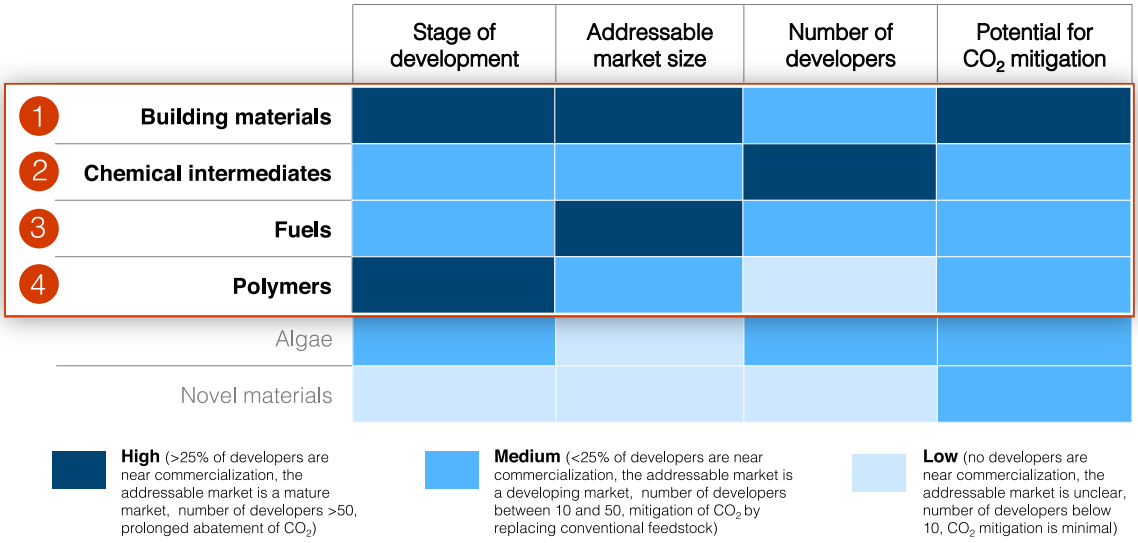


Figure 6. Markets that offer the best opportunities for support and investment

Market sizing

The study estimated the 2015 market size and compound annual growth rates (CAGR) for 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. Figure 7 indicates the methodology used in assessing markets.

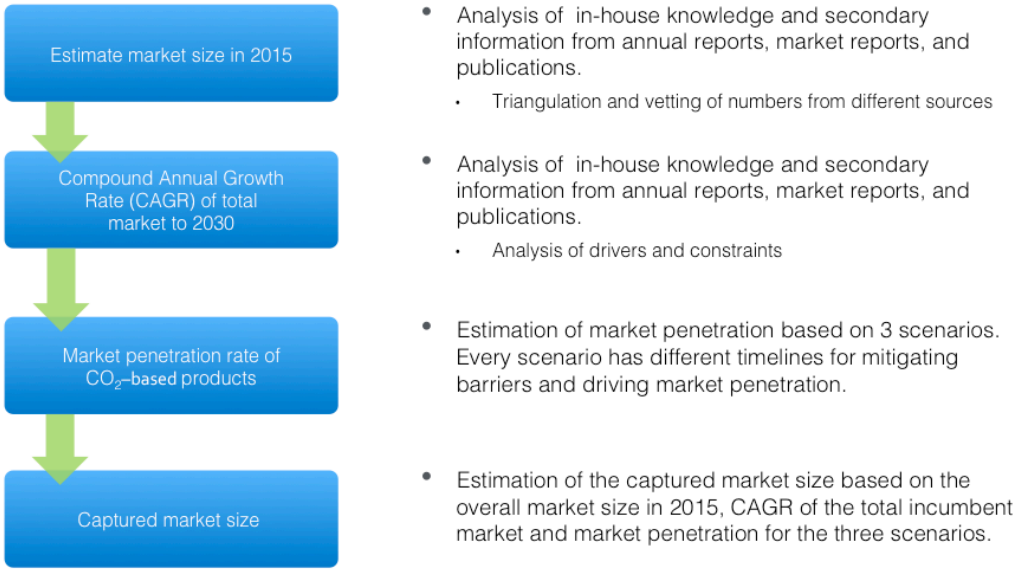


Figure 7. The methodology we used in assessing CBPI markets

We then projected each product'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 of the eight categories has a timeline 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). Figure 8 presents an example of that analysis showing the potential for one building material market segment (concrete curing) to absorb CO_2 over the next 15 years. Similar analysis was conducted for the remaining seven categories.

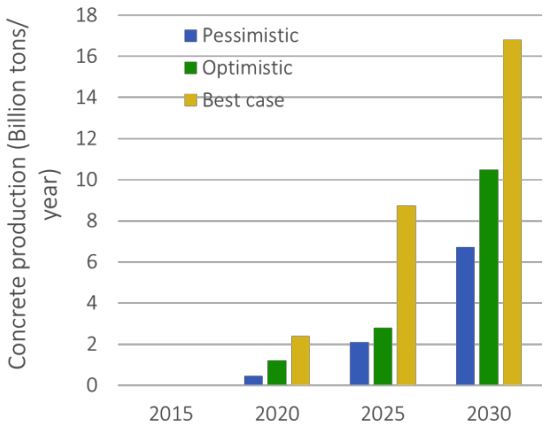


Figure 8: Estimated growth of CBPI concrete curing market through 2030

Drivers and barriers

Different market forces influence near term and long term potential of the different market segments. Market **drivers** include:

- The Paris agreement sets global goals for reducing CO_2 emissions and establishes a system to support national governments in doing so. These agreements entered into force in early November 2016.
- The drive toward a carbon-neutral economy and less dependence on oil.

Working against these drivers are **barriers** including:

- **Lack of coherent government funding strategies to support CBPI technologies.**
- **Lack of access to facilities** to scale-up CBPI technologies.
- **Lack of access to feedstocks** – for hydrogen, CO_2 and renewable energy.
- **Cost: CBPI must compete** with conventional feedstock and bio-based feedstocks, which are often lower in cost.

In general, these drivers and barriers can be examined by considering the respective roles of **Technology, Market and Policy**.

In some cases, technology may be the largest barrier while, in others, the largest barrier may be policy. Figure 9 illustrates the relative influence (1 low to 5 high) of policy, technology and market on the development of different products. For example, policy has a greater impact on the development and market penetration of fuels than on polymers.

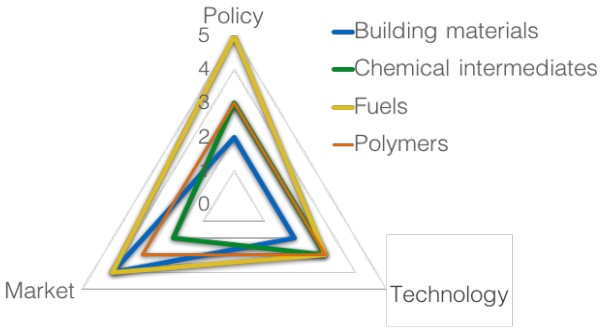


Fig. 9 Relative influence of the dimensions on different CO_2- based products

Recommendations for Strategic Actions

Consideration of the drivers and barriers enables us to develop the following recommendations to leverage the drivers and diminish the barriers.

Technology:

1. **Decrease the cost of CO_2 utilization: Fund research to improve catalysis for CO_2 reduction and electrolysis to produce hydrogen.**

   Research is needed to reduce the energy requirements of CO_2 catalysis and other conversion processes. A hydrogen feed is needed in the production of many CO_2-based products. To make CBPI more cost-competitive, applied research is needed in generating low cost H2 by electrolysis using renewable energy.

2. **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 CBPI technologies and applications that could offer solutions beyond 2020. One of the highest-potential technical areas in this regard is the production of carbon fiber. Figure 10 depicts a potential timeline for implementing the technology levers.

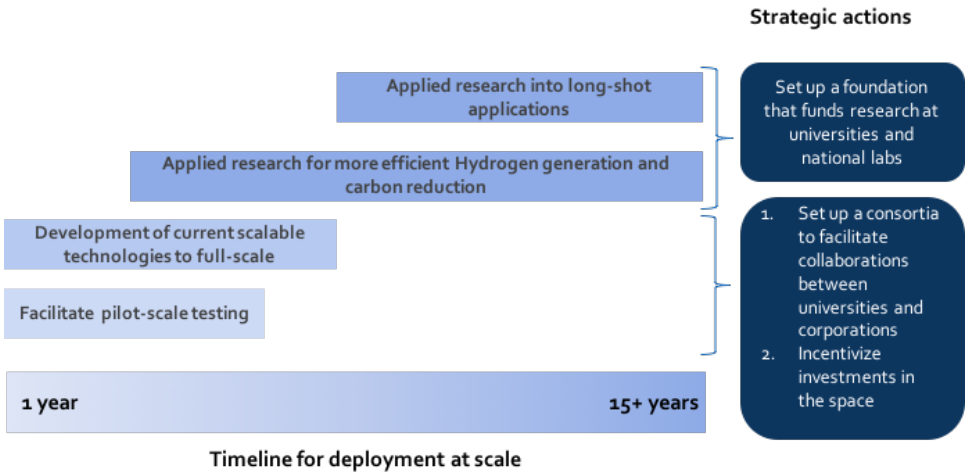


Figure 10: Potential timeline for implementing Technology levers

Market

1. **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 develop CBPI value chains, 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 CBPI product manufacturing.

2. **Access to Capital: Articulate and communicate the value proposition for CBPI technologies.**

As the market potential for CBPI solutions has only recently been identified by the CO_2 Sciences market assessment and global implementation roadmap, the value proposition is generally unknown by investors. Articulating and communicating the value proposition will increase the availability of capital and particularly impact investments that consider both social and financial returns. We are not implying inferior financial returns but emphasizing the double bottom line returns nature of investing in CO_2-based products. This capital will enable faster adoption and market deployment of CO_2-based products. Figure 11 depicts a potential timeline for implementing the market levers.

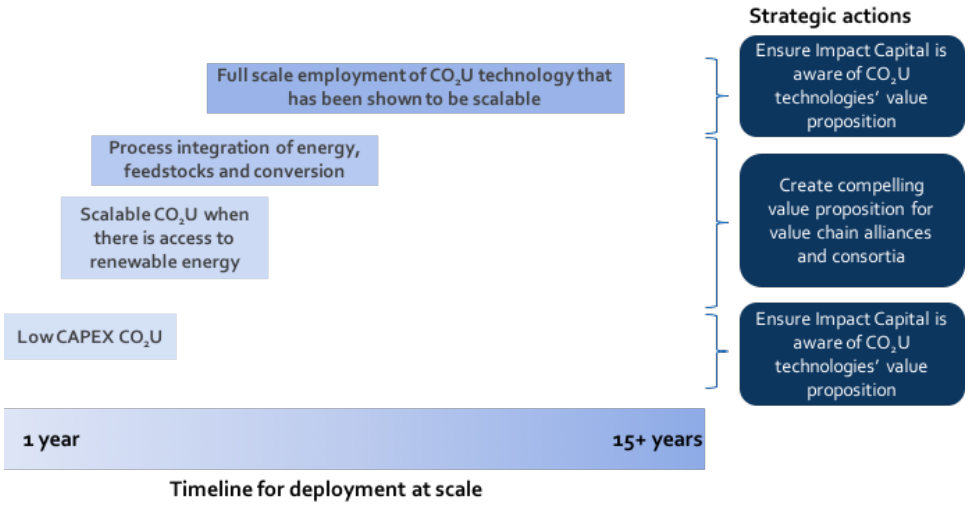


Figure 11: Potential timeline for implementing market levers

Policy

Supportive policies can help start and build markets for CBPI products. Different policies may be appropriate in different jurisdictions, depending on local circumstances. The following are policies that can play an important role in promoting CBPI products.

1. **Government and Industry support for R&D:** Support for R&D on carbon dioxide utilization is currently modest. A significant increase in funding in this area could speed deployment of CBPI 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. The increase in government R&D budgets offers an important opportunity to scale up R&D funding for CO_2 utilization. Support from corporations and other private funders (e.g. philanthropists) for R&D can also serve to accelerate progress on new technology creation.

2. **Carbon Price:** A price on carbon dioxide emissions, whether through an emissions trading program or tax mechanism, would provide emitters with an important incentive to cut emissions.

3. **Mandates:** Governments could mandate the use of CO_2 in certain products as a means to spur the market.

4. **Government procurement:** Government (including military) procurement can provide early market demand for emerging technologies, such as the US Navy's procurement of biofuels.

5. **Credits under regulatory and voluntary programs:** Governments could offer additional credits under existing regulatory programs tied to the use of CBPI products.

The implementation of the above cited levers will lead to significant increase in CO_2 reduction (Figure 12) and will create significant business opportunities (Figure 13).

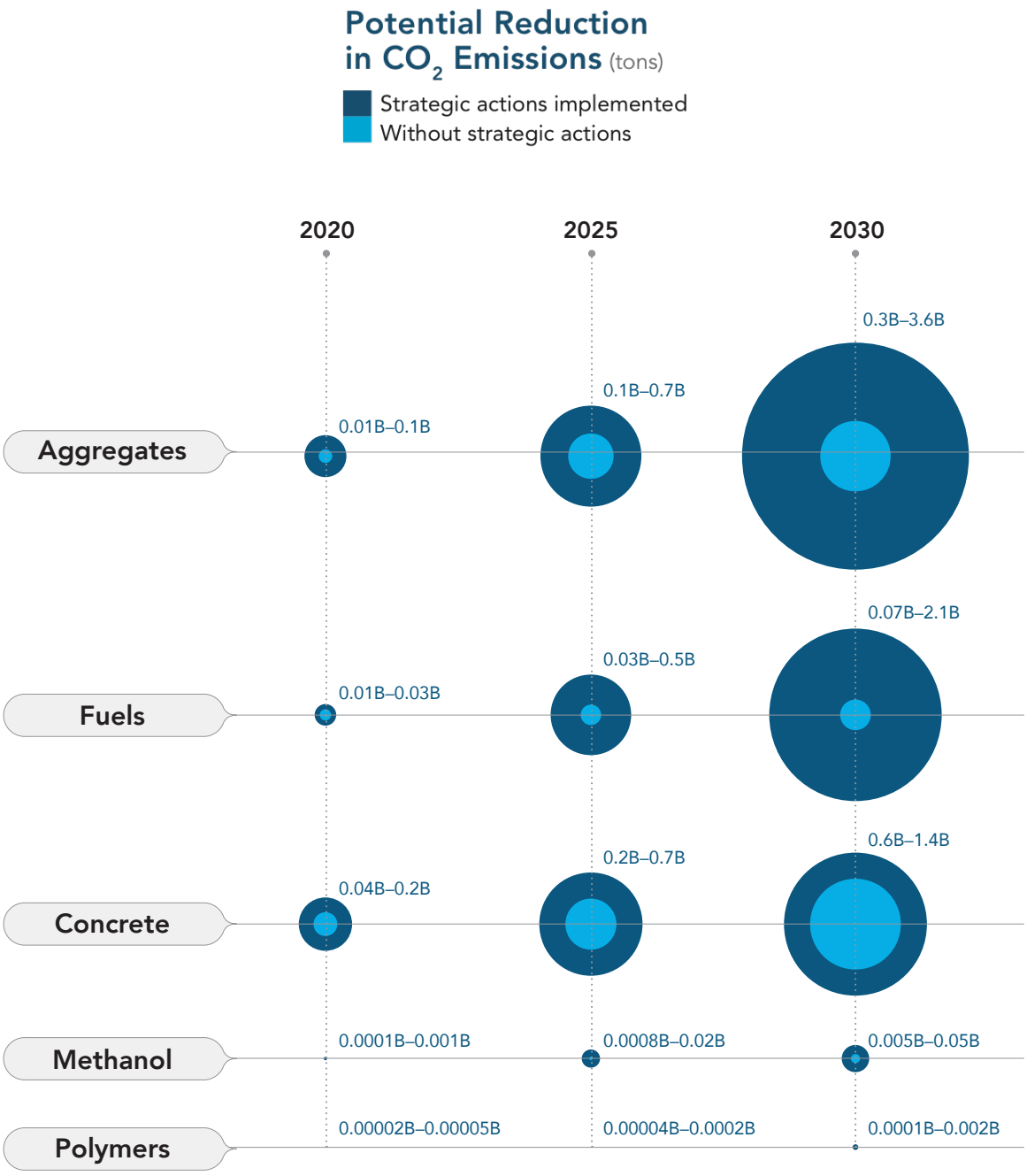


Figure 12: Potential CO_2 reduction due to implementing strategic actions

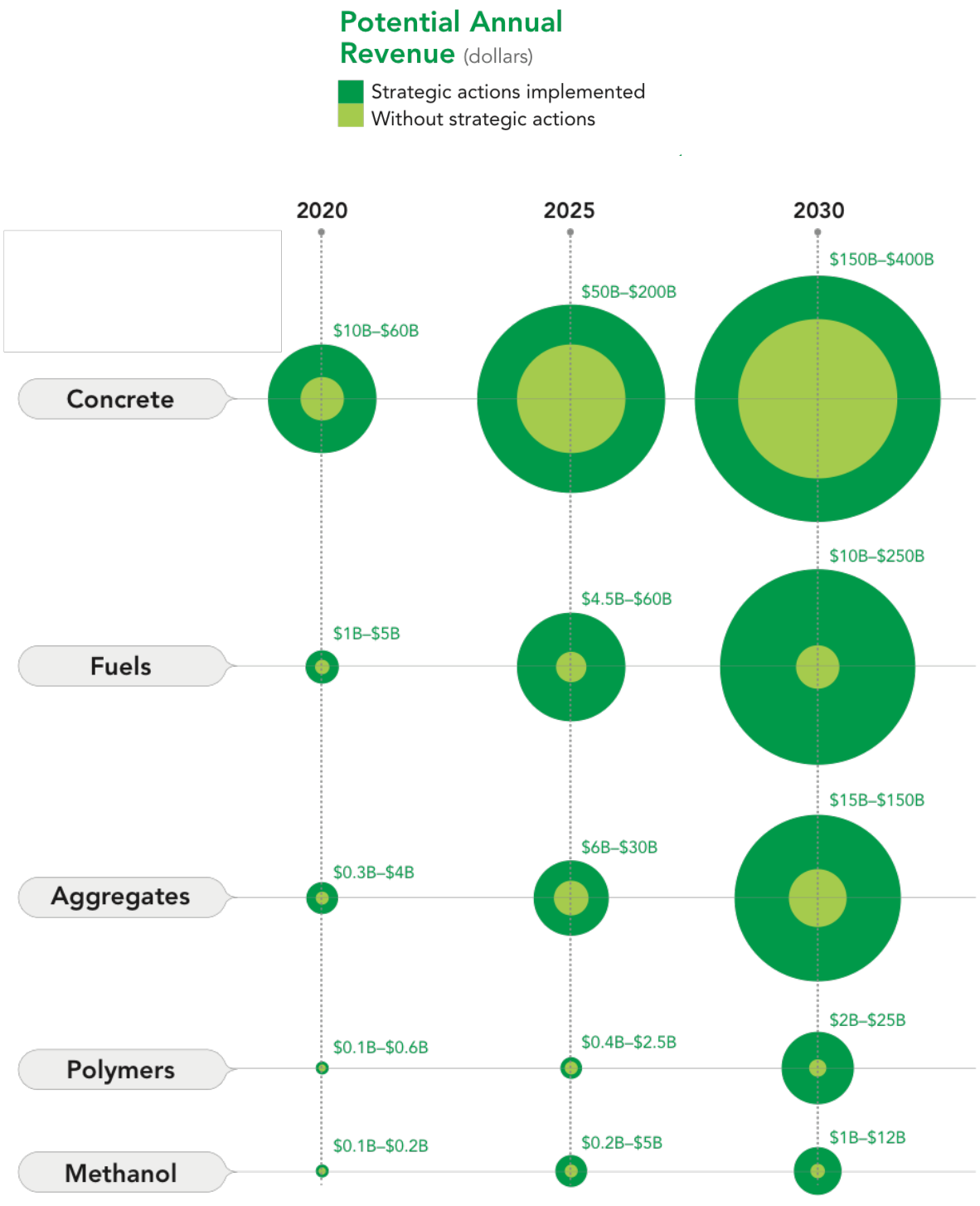


Figure 13: Potential increase in financial returns due to implementation of strategic actions

Conclusions

- **The Carbon Based Products Industry (CBPI), created through broad scale commercialization of products derived from CO_2, offers a huge opportunity to mitigate CO_2 emissions driven by market returns.**

- CO_2 mitigation and CBPI are critical to decrease the risks associated with climate change. CBPI utilizes CO_2 to produce valuable materials, fuels or chemicals, whereas mitigation strategies like carbon capture and storage represent only an economic cost to society.

- Over the past five years, significant progress has been made on research and development of CO_2-based products. Many technologies are proving to be scalable. There is visible momentum in four major markets: building materials, chemical intermediaries, fuels and polymers.

- Funding, incentives and prompt strategic action are necessary to move the CBPI to its full potential. At its full potential scale, our most recent global roadmap shows that the **CBPI could reach or exceed US $800 billion by 2030 and, critically, the Carbon Based Products Industry has the potential to utilize seven billion metric tons of CO_2 per year by 2030 – the equivalent of approximately 15 percent of current annual global CO_2 emissions.** The path to a 2^o future depends on it.