EXECUTIVE SUMMARY

CO2 CAPTURE & UTILIZATION

The Emergence of a Carbon Economy

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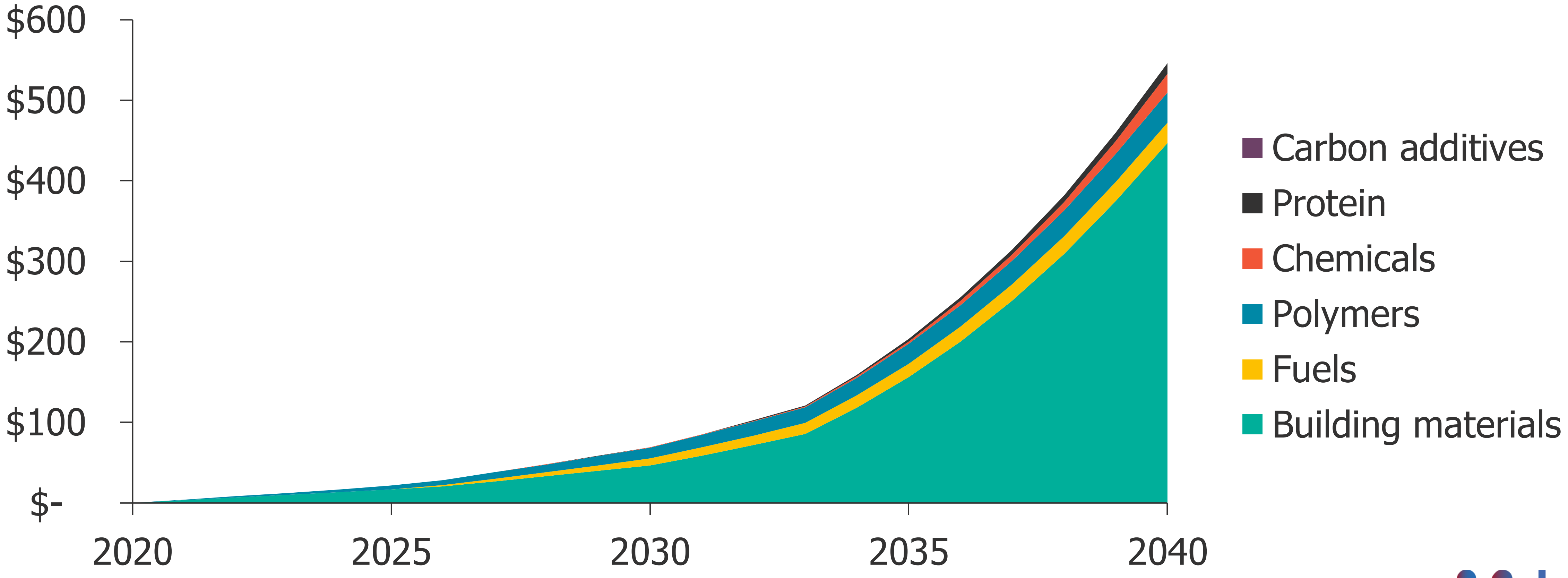
EXECUTIVE SUMMARY

CO_2 utilization will be a $550 billion dollar market by 2040, driven by the building materials sector

GLOBAL CO_2 UTILIZATION MARKET

Market size (billion dollars, USD)



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EXECUTIVE SUMMARY

CO_2 utilization will be a $550 billion dollar market by 2040, driven by the building materials sector

The global market size for CO_2 utilization is set to reach a market value of $70 billion by 2030, which will then increase to $550 billion by 2040.

- **Building materials** will become the largest sector for CO_2 utilization, capturing 86% of the total market value by 2040. Technologies for CO_2 utilization in the building industry have low technical barriers – adoption will only be impeded by regulatory constraints, which will likely ease up post-2030.
- The **polymers** and **protein** sectors will remain niche applications of CO_2 utilization despite the expected success of CO_2 utilization technologies in these sectors. CO_2 utilization for polymer production is commercially proven and successfully deployed at scale but the market size for polycarbonates will remain small. As for proteins, CO_2 utilization technology is still at the development stage, but adoption will be driven by rising demand for alternative proteins.
- **Fuels, chemicals** and **carbon additives** provide vast potential for CO_2 utilization, but it will not be reached without extensive innovation and/or regulatory support for widespread adoption. CO_2 utilization adoption in fuels will be driven by production of synthetic jet fuel from CO_2 – the technology has high production costs, but synthetic fuels are essential for the aviation sector to decarbonize. Despite having the most vibrant start-up landscape for CO_2 utilization, CO_2-based chemicals will be outmatched by bio-based chemicals and recycling due to high costs of production. As for carbon additives, the sector is also unlikely to become a major market for CO_2 utilization due to high costs of production, long timelines for performance validation, and lack of valuable applications.

Global CO_2 emissions witnessed steady growth in the 21st century despite unprecedent action against climate change

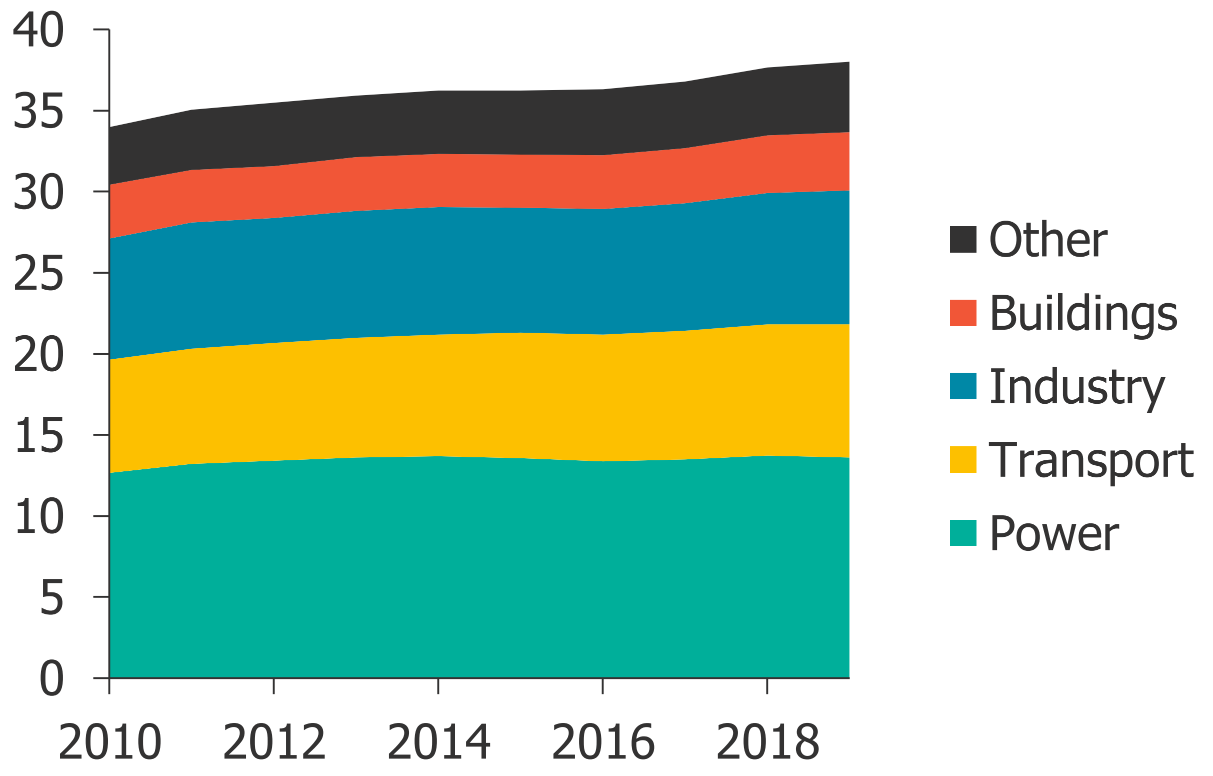
Global CO_2 emissions have steadily increased in the 21st century, spurred by economic growth across the world. While emissions growth stalled between 2014 and 2016, increased industrial activity across developing nations reversed the trend and 2019 witnessed a record 38 GT of CO_2 emitted globally.

China is the world's largest emitter, contributing 30% of global CO_2 emissions. In a distant second is the U.S. (13%), followed by the EU (8%), and India (6%). Over the past year, Vietnam was the fasting growing nation for year-on-year emissions.

The power generation sector remains the most flagrant emitter, contributing 36% of the world's CO_2 emissions, followed by industry (22%) and transportation (21%).

Global CO_2 emissions

CO_2 emitted (gigatons, GT)

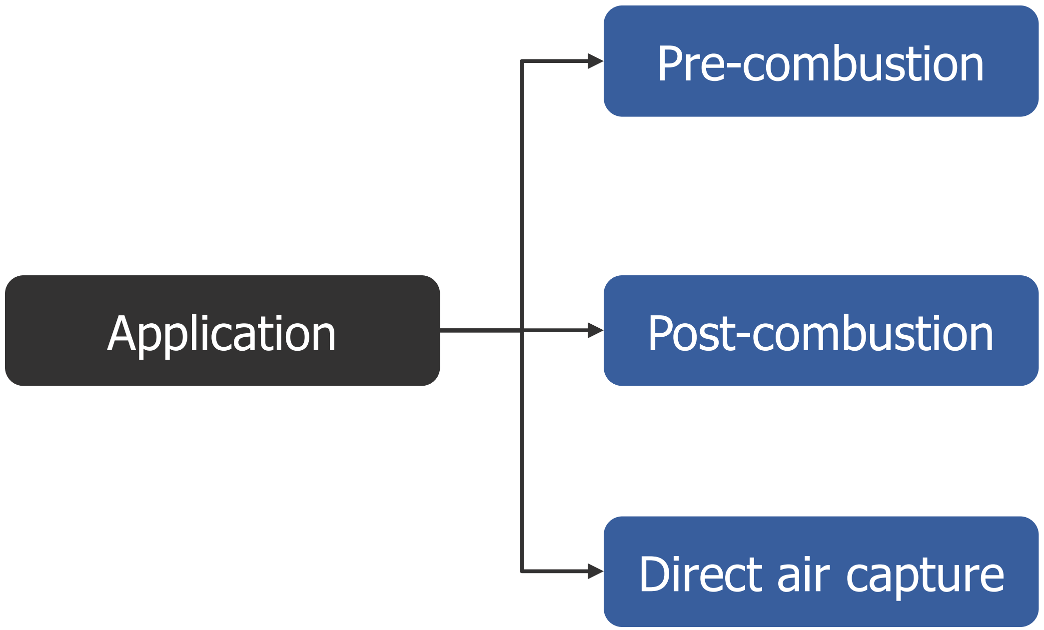


Source: Fossil CO2 emissions of all world countries (2020) – EU Joint Research Center

CO2 CAPTURE

CO_2 capture is the separation of CO_2 from a mixture of gases

CO_2 capture can be sub-divided into applications with varying concentration of CO_2 in the gas mixture:



Pre-combustion – Refers to the separation of CO_2 from non-combustion gases, for example natural gas or process gas from ethanol/ammonia plant.
Concentration of CO_2: 50% - 90%

Post-combustion – Refers to the separation of CO_2 from combustion flue gas.
Concentration of CO_2: 5% - 30%

Direct air capture – Refers to the separation of CO_2 from ambient air.
Concentration of CO_2: 0.04%

Pre-combustion dominates the CO_2 capture industry with post-combustion gaining commercial traction post-2020

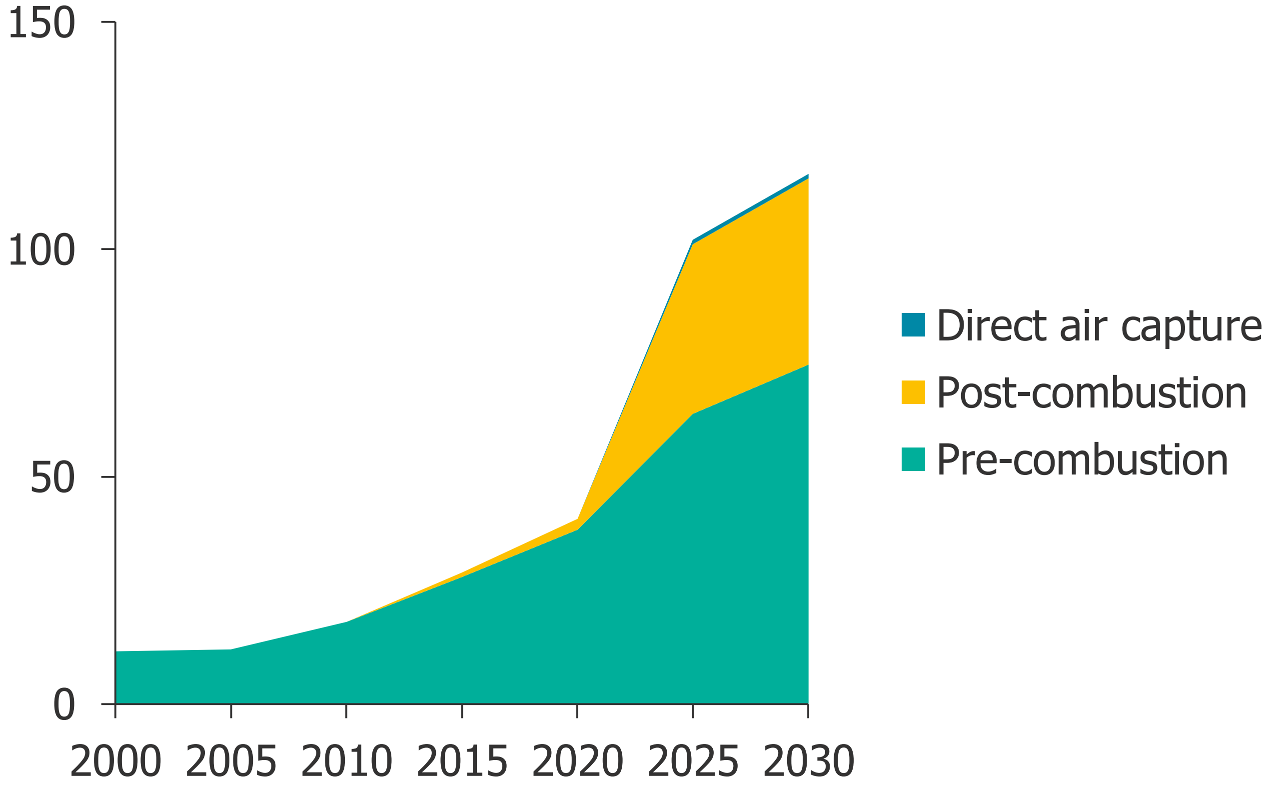
Commercial-scale CO_2 capture and storage projects today are mostly for industrial gas separations in natural gas processing and fertilizer production. To-date, there were only two post combustion capture projects built at the commercial scale – **Boundary Dam CCS** in Canada and **Petra Nova CCS** in the U.S.

So far, over 36 MTPA of post-combustion CO_2 capacity was announced to come online in the 2020s – these facilities will be in the U.S., Norway, and UK, among others, with the captured CO_2 used in enhanced oil recovery (EOR) applications or sequestered in dedicated geological resources.

Direct air capture will remain niche, with over 1.4 MTPA of capacity set to come online by 2030 – this will increase as technology developers are likely to announce more projects as they scale.

CO_2 Capture & Storage Capacity

Capacity (million tons per annum, MTPA)



Source: Global Status of CCS (2020) – Global CCS Institute

CO_2 Capture

POST-COMBUSTION

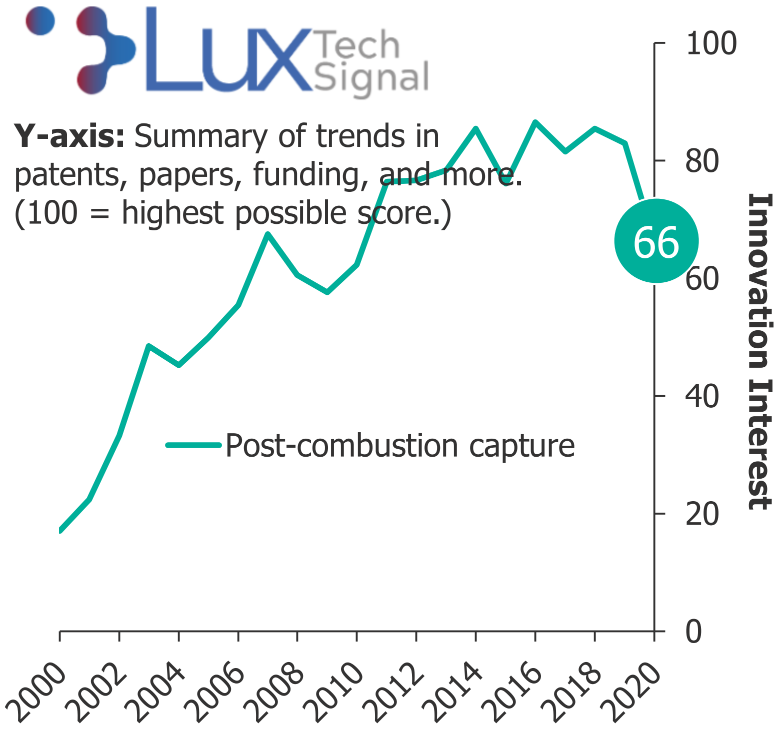
CO_2 is separated from post-combustion flue gases for sequestration or utilization

LUX TAKE

CO_2 capture is an important solution for emitters with no near-term & economical alternatives for reducing emissions. Novel technologies are targeting capture costs of sub-$80/metric ton of CO_2 but have yet to validate such claims at scale. Near-term deployment will therefore rely on aggressive carbon pricing and financial incentives to drive momentum.

Holly Havel

What you should do: CO_2 capture remains essential for a carbon-neutral energy system. Assess the current landscape of CO_2 capture players and consider engaging with promising developers in anticipation of stronger penalties that will likely be implemented this decade in countries aiming for carbon-neutrality.



DATA HIGHLIGHTS

$1 billion

Cost of Petra Nova CCS, the world's largest post-combustion CO_2 capture facility, that was deployed at a coal plant in the U.S.

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CO_2 Capture

DIRECT AIR CAPTURE

Direct air capture technology extracts CO_2 from ambient air through CO_2-selective solvents or solid sorbents

LUX TAKE

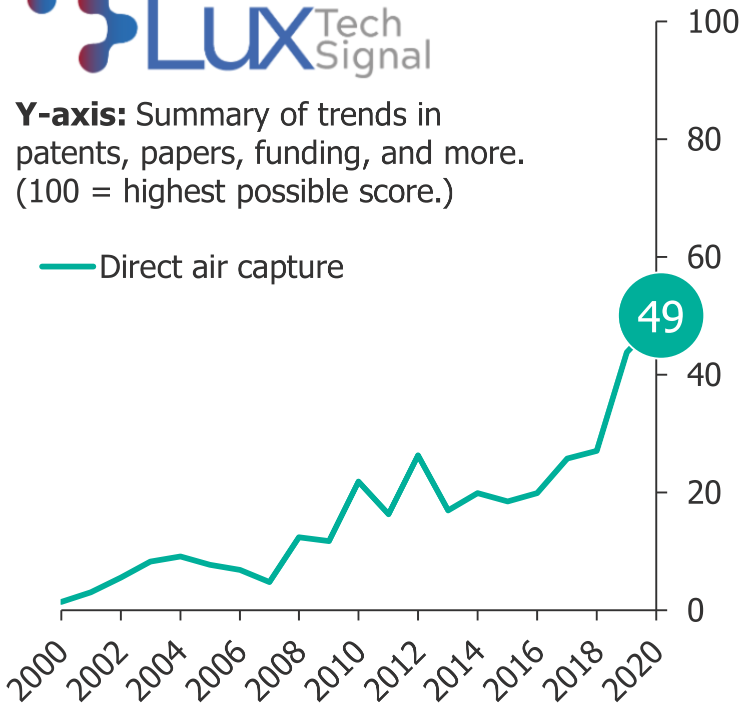
Due to the inherent limitation of low CO_2 concentration in ambient air, DAC will continue to remain expensive. However, it can be a valuable offset tool for emissions that are challenging to eliminate, for e.g., Scope 3 emissions. Innovations will drive down costs but promised costs of sub-\$100/metric ton of CO_2 should be treated with strong skepticism.

Holly Havel

What you should do: Assess your emission profile and identify the ceiling of your emission abatement capabilities with existing low-carbon technologies – Scope 1 and 2 emissions should be abated through nearer-term technologies while DAC is only necessary to offset emissions that cannot be realistically eliminated otherwise.

Lux Tech Signal

Y-axis: Summary of trends in patents, papers, funding, and more. (100 = highest possible score.)



DATA HIGHLIGHTS

$280 million

Total amount of publicly disclosed funding raised by direct air capture companies over the past five years.

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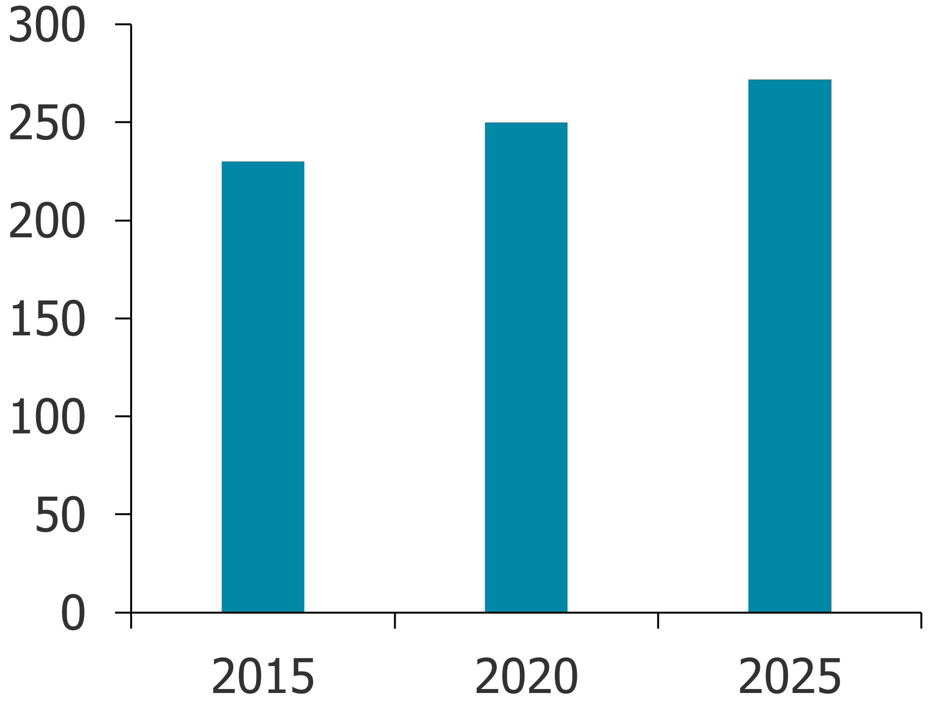
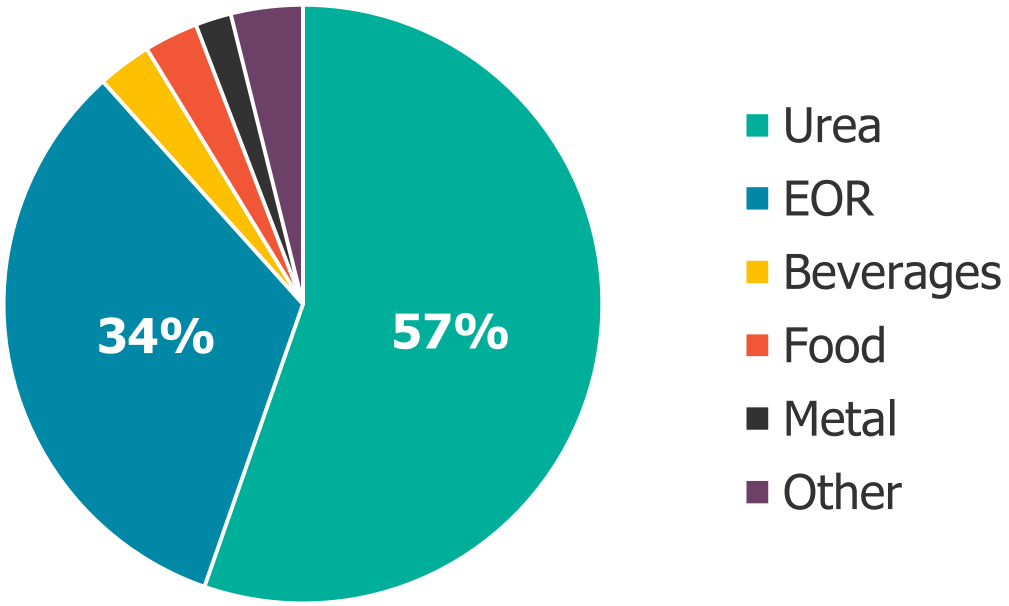
Global CO_2 consumption is projected to grow to 272 million tons per year driven by urea production & EOR application

Global CO_2 Consumption
CO_2 (million metric tons/year)

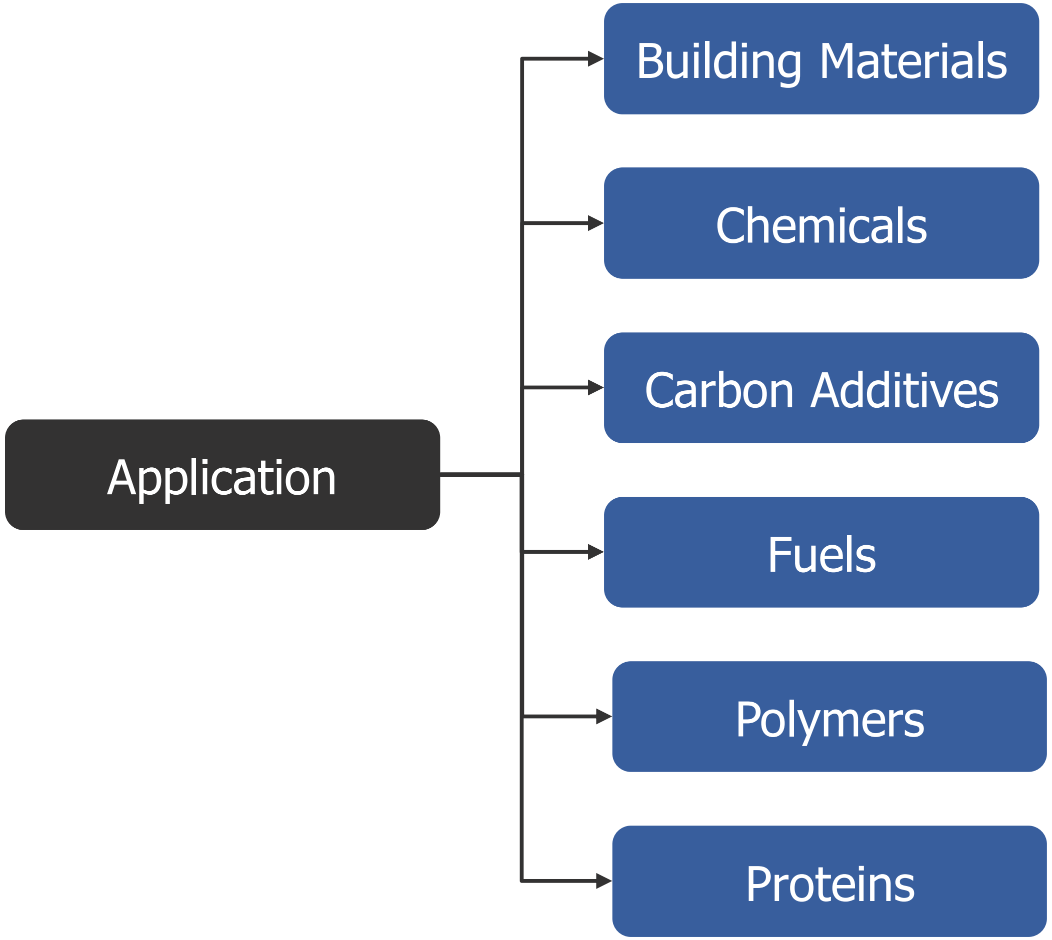


CO_2 Consumption by Industry



Source: Putting CO2 to Use. IEA (2019)

CO_2 can be converted into six types of products



Building Materials – CO_2 is used to produce aggregates or in curing wet concrete mix

Chemicals – CO_2 is used to produce C1 chemicals such as methanol and formic acid

Carbon additives – CO_2 is used to produce carbon materials such as carbon nanotubes and graphene

Fuels – CO_2 is used to produce hydrocarbon fuels such as diesel and methane

Polymers – CO_2 is used to produce polymers such as polycarbonates or polyhydroxyalkanoate

Proteins – CO_2 is used to produce single-cell proteins for feed applications

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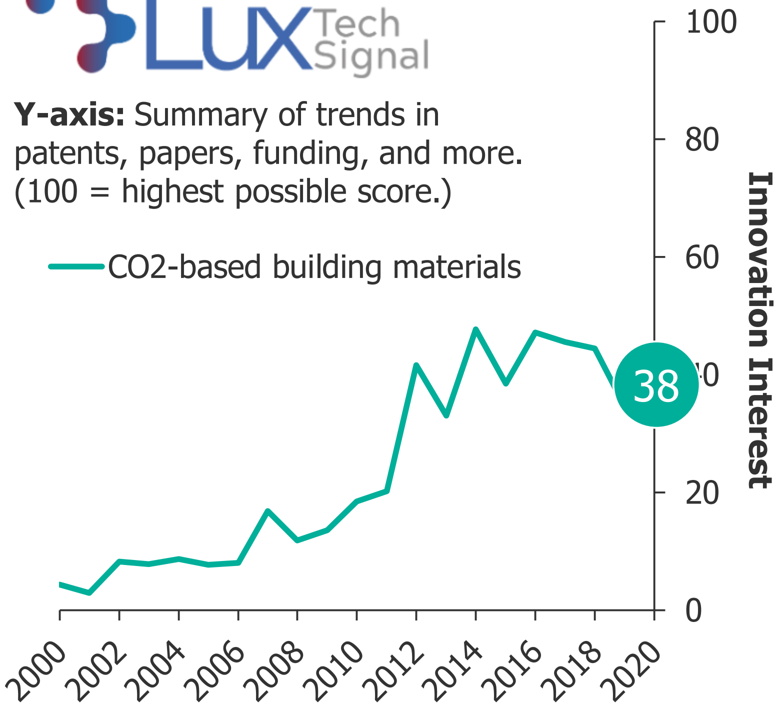
CO_2 Utilization

BUILDING MATERIALS

CO_2 can be used to produce aggregates to mix with cement, or injected directly into wet concrete for curing

Lux Tech Signal

Y-axis: Summary of trends in patents, papers, funding, and more. (100 = highest possible score.)



LUX TAKE

CO_2 emissions are unavoidable in the concrete industry due to the use of limestone. CO_2 utilization provides an avenue for the industry to close its carbon loop – on top of sustainability benefits, performance advantages can also be gained. There is low commercial activity today, but rapid commercialization is expected due to low technology barriers.

Drishti Masand

What you should do: The technology is a near-term opportunity in CO_2 utilization. While it can decarbonize the concrete industry, it also provides a sizeable carbon sink for other industries looking to store their CO_2 emissions. Engage with technology developers in CO_2-based concrete and focus on those that offer performance advantages.

DATA HIGHLIGHTS

500

Number of patent publications in the field of CO_2-based materials, including over 40 patents filed in 2020.

CO_2 Utilization

CHEMICALS

CO_2 is used for producing chemical intermediates such as carbon monoxide, methanol, and formic acid

LUX TAKE

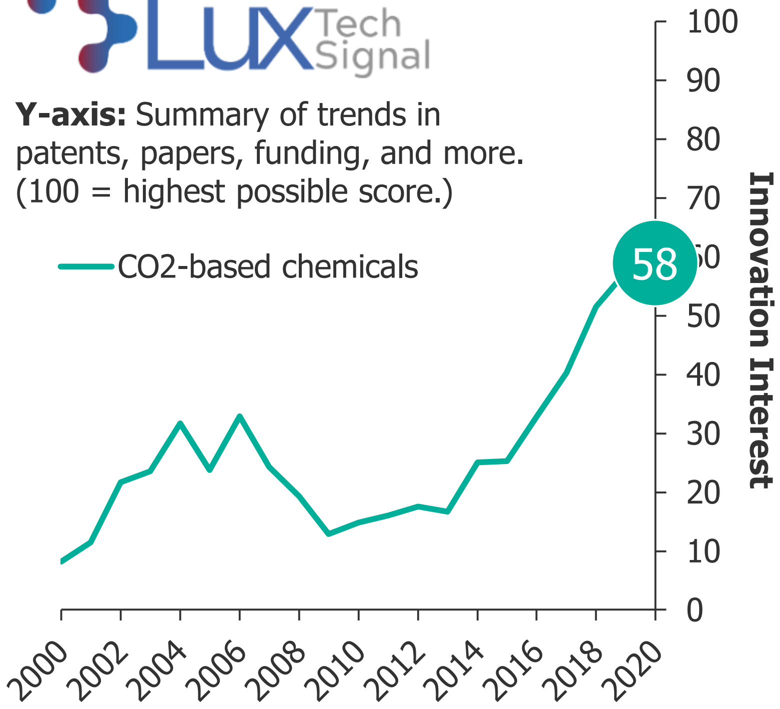
CO_2 utilization can provide the chemical industry with a fresh source of essential carbon feedstock in the transition from fossil resources. Despite its potential, CO_2 utilization for chemicals is at an early stage of development and highly energy-intensive – commercial viability requires securing cheap renewable energy.

Runeel Daliah

What you should do: Given its high costs, CO_2 utilization should not be a priority option for the decarbonization of the chemicals industry. Explore and identify the limits of more advanced technologies such as recycling & bio-based feedstocks first to determine the need for CO_2-to-chemicals in your operations.

LuxTech Signal

Y-axis: Summary of trends in patents, papers, funding, and more. (100 = highest possible score.)



DATA HIGHLIGHTS

6,700

Number of academic publications in the field of CO_2-based chemicals, including over 1,200 published in 2020.

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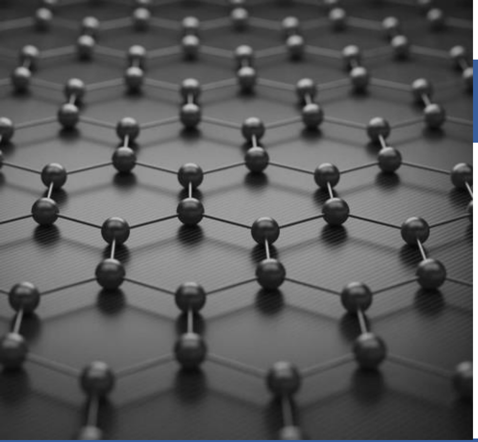


CO_2 Utilization

CARBON ADDITIVES

CO_2 is used for producing carbon nanomaterials like carbon nanotubes (CNTs), graphene, or other allotropes

LUX TAKE

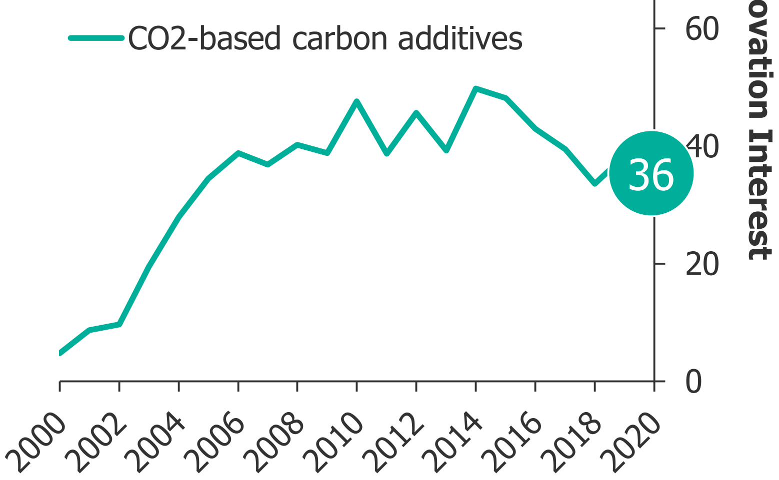
Producing carbon additives is appealing as these new technologies can consume high amounts of CO_2. However, activity in this space is low and CO_2-based additives will face the same challenges as conventional materials. Success will hinge on strong application development, solid cost reduction, and supply quality.

Cecilia Gee

What you should do: CO_2-based carbon additives will not move the needle for decarbonization given the lack of technological validation at scale and low market penetration expected. Without many viable short- to medium-term opportunities, seek other solutions that offer higher traction with lower barriers to adoption.

LuxTech Signal

Y-axis: Summary of trends in patents, papers, funding, and more. (100 = highest possible score.)



DATA HIGHLIGHTS

4 metric tons

Estimated amount of CO_2 needed to produce one metric ton of carbon additives.

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CO_2 Utilization

SYNTHETIC FUELS

CO_2 is used for producing both liquid and gaseous hydrocarbon fuels such as jet fuel and methane

LUX TAKE

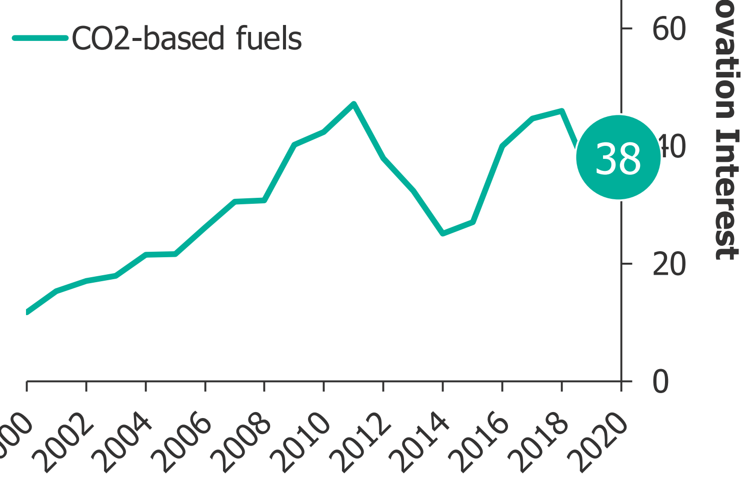
The fuels sector represents one of the largest potential markets for CO_2 utilization, but adoption is – and will remain – severely limited due to a lack of regulatory support coupled with the capital-intensive nature of the technology. Success in the sector hinges on the aviation sector taking unprecedent action to support the adoption of low-carbon fuels in its operations.

Yuan-Sheng Yu

What you should do: Synthetic fuels are not a near-term opportunity in CO_2 utilization and projects will not be economically feasible without drastic regulatory support. Explore the technology for demonstration projects but look towards more advanced platforms in both CO_2 utilization and low-carbon fuels for commercial operations.

Lux Tech Signal

Y-axis: Summary of trends in patents, papers, funding, and more. (100 = highest possible score.)



DATA HIGHLIGHTS

110 million

Total amount of synthetic fuel production capacity (in liters) announced to come online in the next five years.

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CO_2 Utilization

POLYMERS

CO_2 can directly or indirectly be used to make a wide range of polymers including novel PCs, PURs, and PHAs

LUX TAKE

CO_2 is an emerging option for substituting or complementing non-renewable feedstock in polymer production. Most CO_2-to-polymer activity, however, involves the production of novel polymers requiring further market development. Given that the addressable market is limited, polymers from CO_2 will likely have minimal impact on carbon abatement.

Kristin Marshall

What you should do: CO_2 utilization is a low-priority option for the decarbonization of polymers given its limited scope. Those targeting novel polymers should prioritize performance and keep in mind competing bio-based technologies. There is also room to participate in other areas along the value chain (for e.g., catalyst development).

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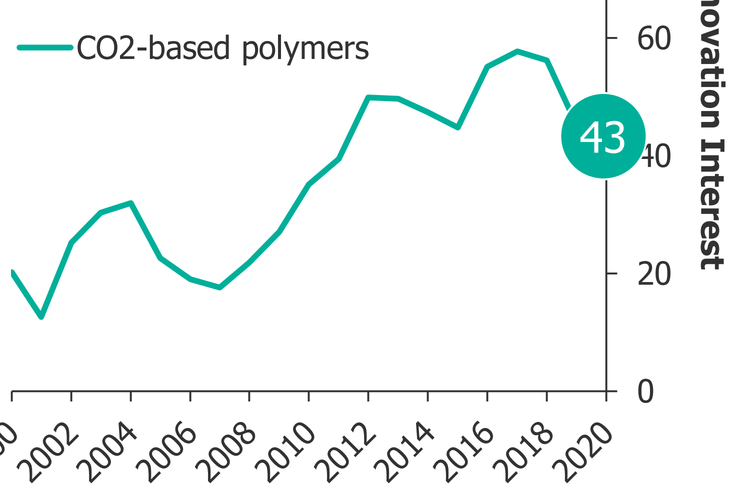
Y-axis: Summary of trends in patents, papers, funding, and more. (100 = highest possible score.)



DATA HIGHLIGHTS

5,000

Production capacity (in metric tons) of Covestro's CO_2-polyol commercial facility in Germany.

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CO_2 Utilization

SINGLE-CELL PROTEIN

CO_2 is used as a feedstock to produce proteins for feed or food applications

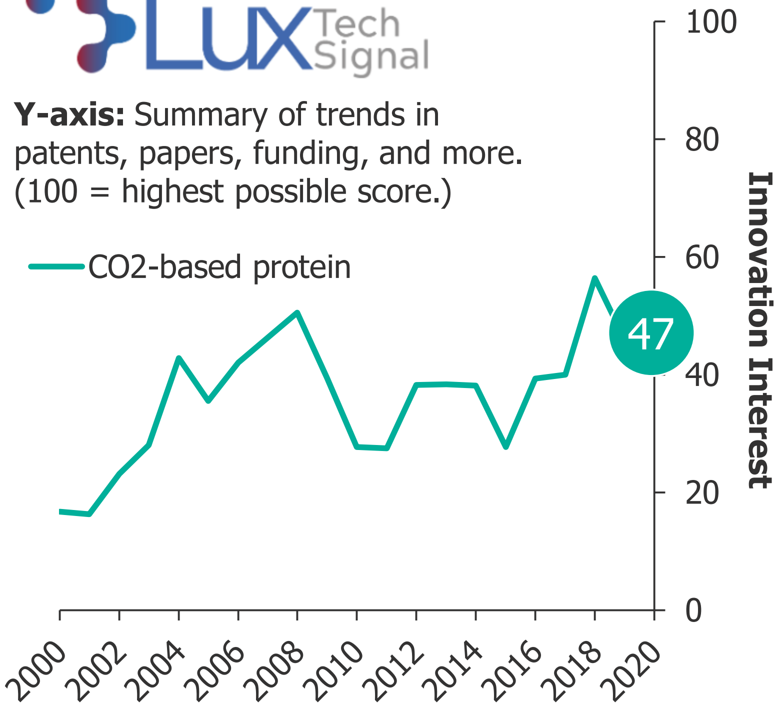
LUX TAKE

Single-cell protein production has potential to produce large protein quantities with less resources (e.g., land and water) in less time compared to conventional protein sources. Scaled production requires significant investment and technical challenges abound. Despite this, CO_2-based proteins are set to capture a large share of the market for alternative proteins.

Laura Krishfield

What you should do: Single-celled protein is at an early stage of development. Those with available CO_2 waste streams should carefully consider capitalizing on the opportunity. Keep tabs on the players advancing pilot scale production as they are backed by the greatest amount of technical and financial support.

Y-axis: Summary of trends in patents, papers, funding, and more. (100 = highest possible score.)



DATA HIGHLIGHTS

1,700

Number of patent publications in the field of CO_2-based proteins, including over 100 patents filed in 2020.

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Outlook & recommendations

REGULATORY SUPPORT & INCENTIVES

Low-carbon technologies require strong regulatory support for adoption – this is especially applicable to CO_2 utilization which is at an early-stage with expensive costs & strong competition from alternate technologies. **A more structural approach is needed to help guide decisions in policy making & funding allocation for CO_2 utilization – a first step would be to create generally accepted standards for techno-economic assessments (TEA) and life cycle analysis (LCA).**

MARKET DRIVERS

The vast majority of CO_2 capture and utilization technologies will be held back from widespread adoption due to economic unfeasibility. While regulatory support is needed to offset high productions costs, a lack of financial incentives does not necessarily mean the technology will fail. **The high cost of CCU will remain a major barrier to its adoption but opportunities may arise from broader trends in the fuel, chemicals, materials, and food sector.**

ECONOMIC FEASIBILITY

If regulatory incentives remains lacking and there are no market drivers for the adoption of CCU, then it will have to compete with its incumbent purely on a cost basis. This puts CCU at a significant disadvantage. **While technology innovations will increase efficiency, securing a cheap source of renewable energy will go much further than efficiency improvements in bridging the price premium.**

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