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Making CO_2 a Valuable Resource

A Techno-Economic Sprint Before Climate Reality Becomes Our Doom?

WHITE PAPER

CO_2 – Waste or Feedstock

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Executive Summary

Carbon dioxide (CO_2) is widely acknowledged as the primary anthropogenic contributor to climate change. While traditional mitigation strategies such as emissions reduction and geological sequestration remain essential, this white paper explores how CO_2, if treated as a resource rather than a waste product, could offer a complementary path to industrial decarbonization. The question is no longer *if* we can capture CO_2, but whether we can scale its utilization fast enough to make a meaningful dent in emissions.

Based on historical analogues, techno-economic modeling, and global market dynamics, this document outlines a dual-lever strategy: penalizing fossil-based emissions while incentivizing CO_2-derived industrial products. The roadmap presented offers near-term, medium-term, and long-term strategies across sectors such as fuels, materials, and chemicals.

The key message: **Every year gained is one future generations can still act upon.**

Problem Definition: The CO_2 Paradox

Despite massive investment in CO_2 capture technologies, only 0.7% of global emissions are currently utilized. The rest is vented, flared, or buried. Industrial demand exists but remains fragmented and under-incentivized. Without a shift from treating CO_2 solely as a pollutant to also recognizing its resource value, even the most ambitious capture strategies will underdeliver.

This paper tackles the gap between what is technically possible and what is economically deployed and proposes how to bridge it.

1. Introduction: From Emission to Industrial Feedstock

The debate around carbon dioxide (CO_2) is long-standing and often polarized: reduction versus sequestration, capture versus compensation, growth versus environment. Yet in between these binary approaches lies a potent third path utilization.

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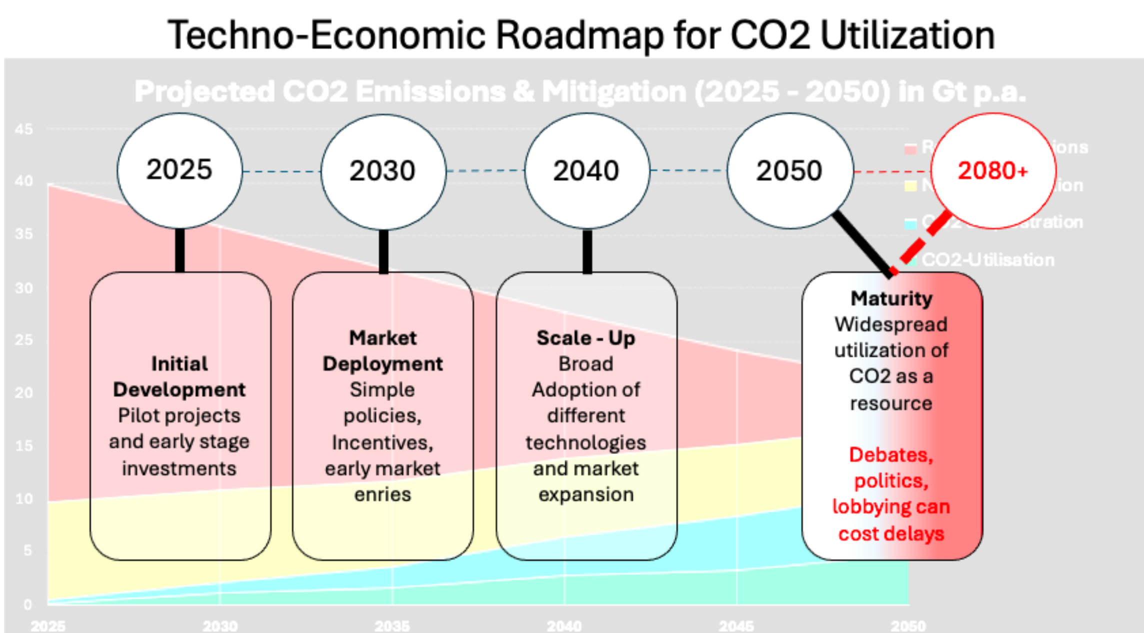
CO_2, long framed exclusively as a climate liability, holds untapped value as an industrial feedstock. This white paper does not challenge the need for emissions reduction or geological storage. Rather, it asks: *How much more could we do*if we recognized CO_2 as a resource in its own right?

Drawing on four decades of industrial experience, this paper frames CO_2 utilization not as a panacea, but as an essential part of the solution mix. The insights are built on technical realism, market viability, and an understanding that innovation and scale and not just good intentions will determine outcomes.

What follows is a roadmap designed to catalyze action. Each section builds on the conviction that with the right incentives and technologies, carbon can be looped—not just captured.



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2. Techno-Economic Case for CO_2 Utilization

2.1 Historical Analogues: Innovation Overcomes Cost

Technological history demonstrates that early cost barriers are often eclipsed by scale effects:

- **Solar PV** saw a price drop from over $1,000/W in the 1950s to under $0.25/W today.
- **Electric vehicles** once ridiculed for range and cost are now part of revolutinized mainstream.
- **Ammonia synthesis** via the Haber-Bosch process reshaped agriculture despite initial inefficiencies.
- **Aviation** experienced exponential cost reduction as captured by Wright's Law [1]. These trajectories confirm that early criticism of cost, efficiencies or scalability, as currently levied at CO_2 utilization technologies, historically fails to anticipate long-term transformation.

2.2 The Real Costs: Delay, Not Innovation

Failure to act imposes greater cost than technological risk. According to data compiled by reinsurance firms such as Munich Re and Swiss Re, the annual global cost of climate-related natural disasters has averaged more than $300 billion in recent years. Fossil fuels seem cheap only because externalities such as disaster recovery, health impacts, and environmental degradation are not priced into their market value. Every year without scaling utilization widens the future carbon removal gap, increasing both technical and political burden.

2.3 Dual Economic Lever: Fossil Fees vs. Clean Incentives

We advocate a two-part economic model:

- Levy a climate impact fee on fossil-based fuels and materials.
- Reinvest revenues to subsidize and de-risk CO_2-derived products. A $50/ton CO_2 fee on jet fuel could finance e-kerosene initiatives. This self-balancing mechanism reflects how solar and wind benefited from feed-in tariffs and carbon taxes [2]. To address concerns that such a fee could raise costs for end users, policies should be designed with revenue recycling measures such as targeted rebates, investment in public infrastructure, or lowering other taxes that neutralize net consumer cost. In some cases, tiered pricing or exemptions for vulnerable sectors can also maintain affordability while supporting the transition.

3. Market Overview: Utilization Today and Tomorrow

3.1 Current Utilization (230 Mt/year) [3]

The industrial use of CO_2 is real but currently small:

- 130 Mt in **urea fertilizer production**.
- 70 - 80 Mt in **enhanced oil recovery**.
- ~25 Mt across **food, beverage, dry ice, and welding gas sectors**.

3.2 The Addressable Market (Up to 7 - 9 Gt/year by 2050)

Initial estimates placed the industrial CO_2 utilization potential between 3 and 5 gigatonnes annually by 2050. With the inclusion of recent technological advancements and emerging industrial pathways, we now revise the **total addressable market to approximately 7–9 Gt/year by 2050**. This projection reflects innovation scaling, integration across industrial sectors, and the convergence of conventional and frontier CO_2 applications.

Scalable applications include:

Concrete mineralization could account for up to 1 Gt/year of CO_2 by 2050. This process involves injecting CO_2 into wet concrete during curing, where it reacts with calcium compounds to form stable calcium carbonates. Not only does this sequester CO_2 permanently, but it also strengthens the concrete making it economically attractive for construction firms and ready for integration with green building codes.

Examples:

CarbonCure Technologies (Canada)

CarbonCure injects captured CO_2 into concrete during mixing, where it mineralizes into calcium carbonate, enhancing the concrete's strength and durability. This process reduces the carbon footprint of concrete by approximately 5–7%. With installations at over 700 concrete plants globally, CarbonCure has helped avoid over 100,000 tonnes of CO_2 emissions annually. Notable clients include Deloitte and Shopify, who have integrated CarbonCure's technology into their sustainability strategies.

Solidia Technologies (USA)

Solidia has developed a CO_2-curing process for concrete that reduces emissions by up to 70% compared to traditional methods. Their technology involves curing concrete with CO_2 instead of water, resulting in stronger, more durable products while permanently sequestering CO_2. Solidia's approach has surpassed four million kilograms of carbon impact in cement and concrete production.

E-fuels for aviation and shipping, such as synthetic kerosene and e-methanol, may absorb up to 2 Gt/year of CO_2. These fuels are synthesized by combining green hydrogen with captured CO_2, offering a net-zero alternative to fossil-based transport fuels. As international aviation and maritime sectors face increasing decarbonization pressure, demand for scalable, drop-in fuels is set to expand dramatically.

Polymers and CO_2-based chemicals could absorb up to 500 Mt/year of CO_2. Chemical companies are already developing technologies to convert CO_2 into monomers, polyurethanes, and intermediates for detergents and solvents. This market is driven by both regulatory compliance and consumer demand for carbon-conscious products.

Carbon materials via pyrolysis hold potential for up to 1 Gt/year of CO_2. In this pathway, CO_2 is split into solid carbon and oxygen via high-temperature processes like plasma pyrolysis. The solid carbon can be used in advanced materials, batteries, or even construction additives, while the oxygen can be captured for industrial reuse creating a circular value loop.
Accelerated Enhanced Weathering: Spreading of alkaline minerals (e.g., olivine, basalt) on land or ocean to sequester atmospheric CO_2 via natural reactions. Estimated market between 1.0-1.5 Gt/year. On land, this technique not only sequesters CO_2 but can also improve soil fertility and crop yields. In marine applications, it helps mitigate ocean acidification and promotes long-term carbon storage.

Artificial Photosynthesis: CO_2 converted into fuels using solar energy via catalytic systems or synthetic leaves. Evonik and Siemens Energy have initiated a pilot plant in Marl, Germany, employing artificial photosynthesis to produce chemicals from CO_2 and water through electrolysis, utilizing bacteria to facilitate the process
Estimated market: 0.5–1.0 Gt/year

Nanomaterials, Aromatics, Solvents, and Battery Integration: Includes carbon nanotubes (CNTs), CO_2-derived aromatics (BTX), green solvents, and lithium–CO_2 batteries. SkyNano utilizes electrochemical processes to transform CO_2 from power plant flue gas into carbon nanotubes (CNTs), which are used in batteries,

electronics, and composite materials. This approach not only sequesters CO_2 but also produces high-value materials, contributing to both emission's reduction and economic value creation.
Estimated market: ~0.2–0.3 Gt/year

Aromatics Production via CO_2 Conversion Aromatic hydrocarbons such as benzene, toluene, and xylene can be synthesized from CO_2 using advanced catalytic processes. A common route involves the Fischer-Tropsch synthesis to convert CO_2 into C2+ hydrocarbons, followed by transformation into aromatics using zeolite catalysts. Alternatively, a methanol-mediated pathway can be employed: CO_2 is first converted to methanol, then into olefins, and finally upgraded to aromatics. These chemicals are critical feedstocks in the petrochemical industry.
Estimated market : ~0.15 – 0.3 Gt / year by 2040 (IEA)

Steel Slag Carbonation
Steel slag, a byproduct of iron and steel production, is rich in alkaline oxides like MgO and CaO. These compounds react with CO_2 to form stable carbonates. The resulting materials can be used in cement, paper, and plastic industries, offering a dual benefit of CO_2 sequestration and waste valorisation from heavy industry.
Estimated market: ~0.25 – 0.5 Gt/year , assuming 60-70% yield in partial carbonisation (World Steel Association, Journal of cleaner production (2021)

Supercritical CO_2 ($scCO_2$) as a Green Solvent
Supercritical CO_2 held above its critical temperature and pressure—serves as an environmentally friendly solvent and reaction medium. It is particularly valuable in bioresource conversion, where it can be used to extract essential oils, antioxidants, and other valuable compounds. Additionally, it enhances various thermochemical reactions and separation processes due to its unique fluid properties.
Estimated market:~10-30 Mt/year (NREL)

Lithium–CO_2 Batteries
Lithium–CO_2 (Li–CO_2) batteries represent a promising class of next-generation energy storage systems. These batteries utilize CO_2 during the discharge cycle, converting it into lithium carbonate and carbon while generating electricity. With high theoretical energy density and inherent CO_2 capture, they are especially suited for closed-loop systems, remote operations, or even space applications.
Estimated market: 1-2 Mt/year 2040 to 2050 (ACS Energy Letters and Fraunhofer market models)

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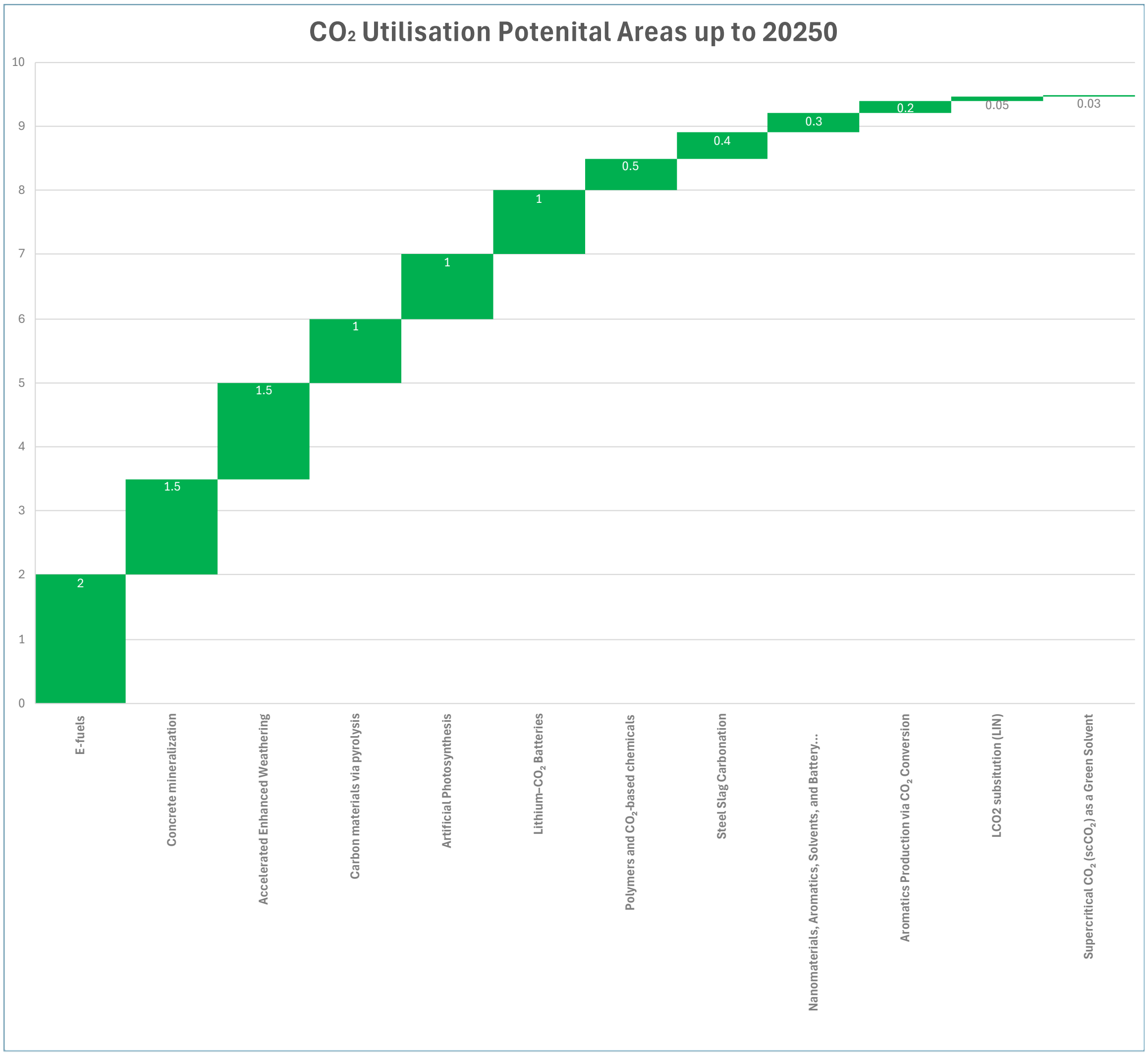

4. Tech Pathways: What's Scalable and When

4.1 Short-Term (2025 - 2030)

LCO_2 substitution for LIN in cryogenics offers an immediate opportunity, particularly in industries using liquid nitrogen for cooling and inerting. In certain food processing, metal treatment, and cryogenic logistics applications, liquefied CO_2 can provide a functionally equivalent alternative. Substituting LIN with LCO_2 where technically viable could unlock an additional 50 Mt/year of CO_2 utilization, while simultaneously easing pressure on nitrogen supply chains and reducing reliance on energy-intensive air separation units [8].

CO_2-enhanced concrete curing is another near-term solution, already demonstrated at commercial scale. By injecting CO_2 during the curing phase of precast concrete, manufacturers not only sequester carbon but also achieve measurable strength improvements and faster setting times. Current technology can support up to 100–250 Mt/year of utilization, especially in regions undergoing rapid urbanization or infrastructure renewal [4].

E-methanol production at ports and refineries utilizes captured CO_2 in combination with green hydrogen to produce synthetic methanol. This fuel can be used directly in shipping or serve as a chemical feedstock. Locating such production close to high-volume CO_2 sources, like refineries or industrial hubs, minimizes transport and increases efficiency. Early pilots suggest a near-term utilization potential of ~100 Mt/year [5].

4.2 Medium-Term (2030 - 2040)

Biofixation using algae and engineered microbes represents a promising pathway for scalable CO_2 conversion into proteins, bioplastics, and specialty chemicals. Algae systems have a high photosynthetic efficiency and can be cultivated in photobioreactors on non-arable land, using industrial flue gases as a carbon source. Engineered strains of microbes, like cyanobacteria, can also be optimized for CO_2 uptake and specific product outputs. Estimated potential: 100 Mt/year [9].

Electrochemical synthesis of formic acid and methanol involves converting CO_2 using renewable electricity and advanced catalysts. These reactions are increasingly efficient and modular, allowing decentralized implementation near CO_2 point sources. Products like formic acid serve in agriculture and manufacturing, while methanol can be used in transportation and chemical production. Estimated potential utilization: up to 300 Mt/year [6].

Polymers and CO_2-based chemicals, including polyols, urea derivatives, and intermediates for cleaning agents and surfactants, could collectively utilize ~500 Mt/year of CO_2 by 2040.

Steel slag carbonation, using alkaline oxides from steel production to bind CO_2 into carbonates, could achieve **250–500 Mt/year**, based on current and projected global slag output.

4.3 Long-Term (2040 +)

Artificial photosynthesis mimics natural plant functions by using sunlight to convert CO_2 and water into fuels such as syngas or methanol. Efforts led by institutions like the University of Cambridge have demonstrated prototype "artificial leaves" that perform this conversion without releasing additional CO_2. While still in pilot stages, this technology offers a self-powered, distributed approach to carbon-neutral fuel production and could reach industrial relevance post-2040 [10].

Plasma-based CO_2 pyrolysis splits CO_2 into solid carbon and oxygen using high-temperature plasma or catalytic reactors. The resulting carbon can be used in applications ranging from battery anodes to construction materials, while the oxygen can offset industrial O_2 demand. This approach is highly promising for hard-to-decarbonize sectors with abundant point-source CO_2. If fully deployed, it could account for up to 500 Mt/year in utilization [7].

Accelerated enhanced weathering, via spreading of olivine or basalt on land or in coastal waters, facilitates CO_2 mineralization. Estimates suggest 1.0–1.5 Gt/year of CO_2 can be absorbed sustainably by 2050.

Aromatics production from CO_2, through methanol-to-olefin-to-aromatics conversion, supports circular petrochemicals and could utilize 150–300 Mt/year.

Supercritical CO_2 as a green solvent, while lower volume (~10–30 Mt/year), contributes high-value utilization in pharma, extraction, and materials processing.

Lithium–CO_2 batteries, still in development, may support 1–2 Mt/year in niche or off-grid energy systems, particularly in space, military, or sealed industrial environments.

5. Infrastructure: Local vs. Distributed Hubs

Scalable CO_2 use is tightly linked to the spatial dynamics of emissions sources and utilization demand. High-concentration, stationary CO_2 emitters such as cement plants, refineries, and steel mills can serve as ideal anchor points for localized CO_2 hubs. In these regions, CO_2 pipelines can efficiently transport captured gas to nearby utilization or storage sites. Such networks are already operating in regions like Texas and the Netherlands, where industrial clusters justify dedicated pipeline investments.
However, not all emitters are co-located with viable offtake opportunities. In these cases, **distributed, modular utilization units** such as containerized conversion systems or mobile CO_2 liquefaction units can be deployed directly at remote or medium-sized emitters. These technologies lower the barrier to entry by avoiding the need for extensive infrastructure and can flexibly adapt to site-specific conditions. Moreover, modular systems are ideal for integrating with intermittent renewable energy sources, allowing utilization even in regions with limited grid stability.

Ultimately, a hybrid infrastructure model will be required: centralized pipeline hubs for dense industrial regions and distributed modular platforms for geographically dispersed emitters. This dual approach increases resilience, minimizes transport emissions, and accelerates the geographic spread of CO_2 utilization [11].

6. Policy Framework for Adoption

Implement a fossil-derived CO_2 fee system.
This involves levying a carbon impact fee on fossil-based fuels, chemicals, and materials based on their life-cycle CO_2 emissions. Such a fee would internalize environmental externalities and create a predictable economic signal to drive investment into carbon-neutral and carbon-negative alternatives.

Redirect revenue to technology incentives and capital support.
The funds raised through CO_2 fees should be allocated to de-risk and scale carbon utilization technologies. This includes direct grants, feed-in tariffs, tax credits, and innovation challenges that lower the upfront capital costs of CO_2 capture and conversion plants.

Set minimum mandates: e.g., 5% synthetic kerosene blending in aviation.
To accelerate adoption in hard-to-abate sectors like aviation, policymakers can impose blending mandates requiring a defined share of synthetic fuels in jet fuel consumption. The 5% synthetic kerosene blending target is aligned with the European Union's "ReFuelEU Aviation" proposal, which mandates increasing levels of Sustainable Aviation

Fuel (SAF) blending starting in 2025, aiming for 6% by 2030 and higher targets beyond. This mandate ensures offtake certainty and justifies early capital investment in CO_2-to-fuel plants.

Reward durable carbon locking in construction.
Public procurement standards and green building regulations can include credits or performance-based incentives for materials that incorporate mineralized or otherwise sequestered CO_2. This stimulates demand for CO_2-enriched concrete, carbonated aggregates, and emerging materials like carbon-infused polymers, anchoring long-lived CO_2 storage in the built environment.

7. A Forecast Beyond 2050: The Residual Delta and the Question of Reversibility

The chart below illustrates how projected mitigation via CO_2 utilization, sequestration, and natural sinks might reduce global emissions from 40 Gt/year in 2025 to 25 Gt/year by 2050.

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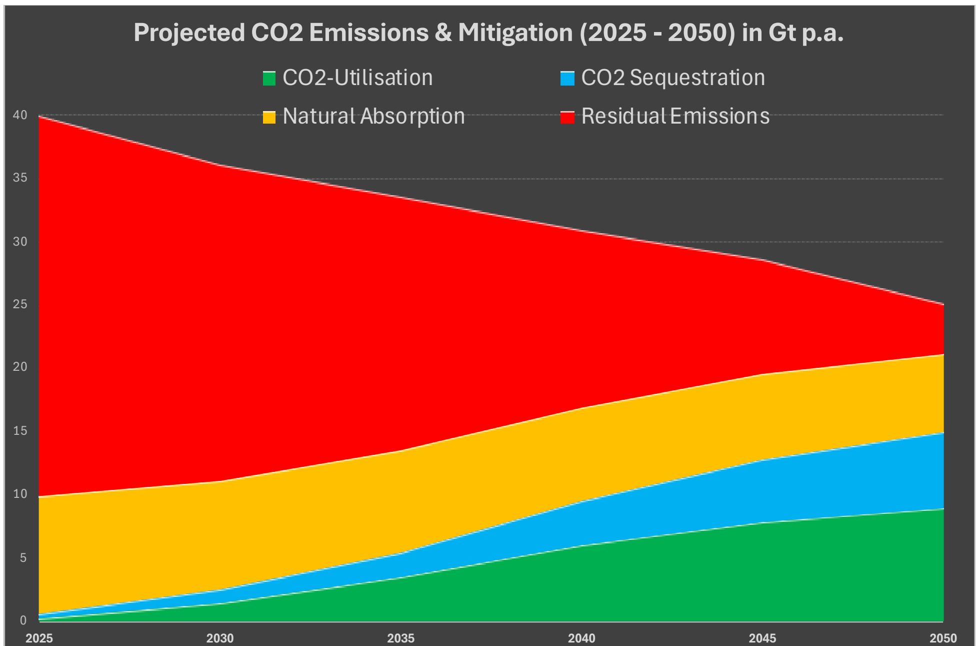

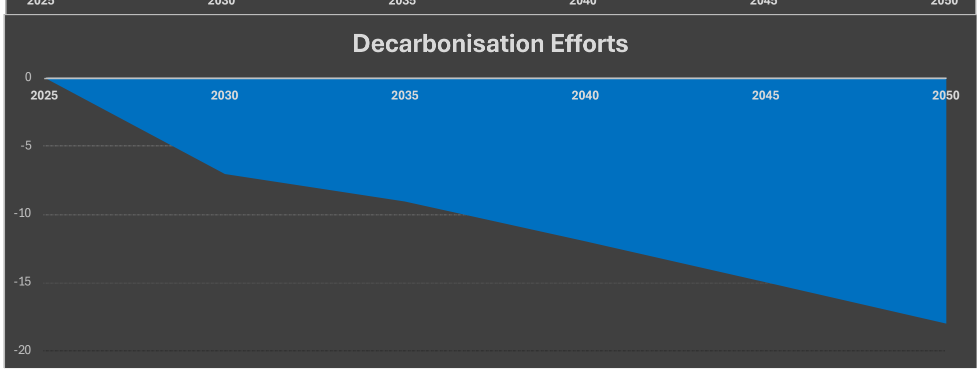

Note: The declining total emissions trajectory reflects external decarbonization efforts assumed under global policy commitments (e.g., IEA Net Zero 2050), while this paper focuses on the mitigation potential of CO_2 utilization within that context

Even with optimistic assumptions, the residual emissions remain significant approaching 5 - 10 Gt/year in 2050. This residual delta presents an existential dilemma: Will we reach zero, or simply reduce the damage curve?

From my own industrial experience, no large-scale transformation follows projections precisely. Technologies slip, political commitments waver, and debates especially around carbon pricing stretch timelines into the 2080s. Yet forecasts are essential, not because they are accurate, but because they create direction.

7.1The Role of Natural Sinks in CO_2 Balance

While this paper focuses on industrial utilization, it is essential to acknowledge that **natural carbon sinks** such as forests, oceans, and soils currently absorb approximately 12 to 13 gigatons (Gt) of CO_2 per year, according to IPCC and NOAA [12] estimates. These systems function as Earth's original carbon economy. However, their **absorption capacity is both finite and vulnerable**: forest degradation, ocean acidification, and land-use changes are already reducing their effectiveness. Moreover, as climate feedback loops accelerate like permafrost thaw or wildfire carbon release, these sinks may become less reliable. Therefore, CO_2 utilization technologies must supplement, not substitute, nature-based solutions. Only by combining both approaches biological and industrial can we realistically close the emissions gap and navigate the path toward climate stability.

Our strategic goal, then, must not only be to reduce emissions. We must industrialize carbon circularity to absorb, transform, and valorize CO_2 with the same seriousness once reserved for fossil extraction and at the same time we have to preserve nature's own CO_2 rebalancing system.

8. Conclusion

The chart in paragraph 7 illustrates how projected mitigation via CO_2 sequestration, CO_2 utilization are not a silver bullet, but they are indispensable tools. Economic logic, historical precedent, and engineering practice all point to its viability if the correct policies, infrastructures, and incentives are put in place. Biggest economical question mark is behind sequestration, but we have to ask ourselves what is our atmosphere worth if we only applied economical logic? Every tonne of CO_2 transformed into product or material is a tonne that no longer accelerates the climate crisis.

To frame this effort around time-bound action, a phased roadmap emerges:

- **2025–2030:** Prioritize substitution technologies (e.g., LCO_2 for LIN), CO_2-enhanced concrete curing, and initial e-methanol pilots near large point sources. Set minimum mandates and CO_2 fees with built-in recycling mechanisms.
- **2030–2040:** Scale biofixation systems and electrochemical conversion technologies. Expand modular infrastructure and cross-sector purchasing agreements to de-risk private investment.
- **2040+ and beyond 2050:** Integrate emerging breakthroughs like artificial photosynthesis and CO_2 pyrolysis into mainstream industry. Combine high-capacity utilization with residual sequestration to close the emissions gap.

Forecasts will always be uncertain and numbers might be “wrong”, but it provides direction and focus. Aligned and decisive action within this timeline gives the next generation the best possible chance to bend the climate curve.
And the greatest cost risk is not that we try too early. The greatest cost risk is that we wait too long.

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10. Glossary Table

Term	Definition
CO_2 Utilization	The industrial process of converting captured carbon dioxide into fuels, chemicals, or building materials.
Photobioreactor	A closed, light-exposed system used to grow algae or microbes for CO_2 conversion—suitable for non-arable land.
E-fuels (Electrofuels)	Synthetic fuels made by reacting green hydrogen with CO_2, offering net-zero alternatives to fossil fuels.
CO_2 Mineralization	A chemical process in which CO_2 reacts with minerals (e.g., in concrete) to form stable solid carbonates.
Plasma CO_2 Pyrolysis	A high-temperature method that splits CO_2 into solid carbon and oxygen using plasma energy.
Artificial Photosynthesis	A technology mimicking plant photosynthesis to convert sunlight, CO_2, and water into chemical fuels.
Climate Cost Rebalancing	A dual-policy framework combining CO_2 impact fees on fossil products with incentives for low-carbon technologies.
Carbon Impact Fee	A fee on fossil-based fuels or products proportional to their CO_2 emissions, used to fund clean alternatives.
Distributed Utilization Units	Modular, often containerized systems for CO_2 capture and conversion deployed at emission sites.
Natural Carbon Sinks	Ecosystems (e.g., forests, oceans, soils) that naturally absorb atmospheric CO_2.
Residual Delta	The remaining CO_2 emissions after accounting for all mitigation and absorption—critical to track for net-zero.
Techno-Economic Modeling	A methodology combining technical performance and economic analysis to assess technology viability.
Wright's Law	A principle stating that costs decrease predictably with every doubling of cumulative production.
Feed-in Tariff	A policy guaranteeing favorable pricing for renewable or low-carbon products to accelerate adoption.
Green Hydrogen	Hydrogen produced via electrolysis powered by renewable electricity, with near-zero carbon footprint.
Sustainable Aviation Fuel (SAF)	Low-carbon fuels for aviation, including biofuels and synthetic kerosene made from CO_2 and hydrogen.

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11. Call to Action: What Should Happen Next

1. **Policymakers** must begin embedding utilization targets into national climate strategies, backed by carbon fee-and-dividend systems that fund circular CO_2 projects.

2. **DPGS consults Industrial Leaders** in off-take agreement establishment, plan, design, and build pilot & industrial sized plants, and advise co-location of CO_2 conversion technologies.

3. **DPGS can support Investors** viewing CO_2 as an emerging asset class with risk mitigation, green branding, and as a project realisation with executable value through our FlexGate lens

4. **Research Institutions** must prioritize breakthrough pathways like artificial photosynthesis and scalable pyrolysis.

This isn't just a mitigation strategy, it's an industrial opportunity. The time for scaled, market-driven CO_2 utilization is now.

Acknowledgments

This paper draws on decades of experience in industrial gas technologies including manufacturing, purification, liquefaction, compression, storage, distribution and collaborative insights from peers and institutions committed to energy transformation.

About the Authors

Jurgen Orczech is Director and co-owner of DesignPro Global Solutions with more than 35 years in industrial gas production and application, CO2 recovery, process, liquefaction, compression and hydrogen economy. With hands-on leadership in pioneering gas projects worldwide in 9 countries over 4 continents, he now advises companies and governments on innovation, decarbonization, energy efficiency and practical transition with project execution capabilities through DPGS & Alliance Patners.

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