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Can Shifting from Temporary Mitigation to Permanent Removal Accelerate the Urgency of Negative Carbon Goals?

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True carbon dioxide negative emissions represent not merely an extension of emission reductions, but a systemic carbon transition centered on long-term removals consistent with limiting global warming to 1.5 °C by 2100. Only when carbon utilization evolves from short-term emission cuts into a long-term carbon management system deeply integrated with carbon dioxide removal (CDR) will humanity gain the genuine capacity to reverse atmospheric carbon accumulation.

Achieving true negative carbon emissions hinges not on mere reduction efforts, but on transforming carbon dioxide removal from a temporary mitigation measure into a core strategy for addressing the climate crisis. Carbon dioxide removal (CDR) employ a range of techniques and methods to remove carbon dioxide from the atmosphere and store it permanently as a means to address climate change. Carbon dioxide removal (CDR) should no longer be viewed as a last resort but rather deeply integrated with Carbon Capture and Utilization (CCU) systems to establish a long-term, effective carbon management framework. Existing carbon dioxide utilization technologies contribute to emissions reduction. Certain enhanced oil recovery (EOR), coalbed methane recovery, and natural gas recovery technologies can utilize CO_2 while enabling relatively long-term geological storage, thereby offering more durable mitigation benefits. However, despite these advantages, their primary role remains the temporary sequestration of carbon, as they do not fundamentally address the challenge of long-term carbon accumulation. Fundamentally reducing atmospheric CO_2 concentrations to meet the 1.5 °C global warming limit by 2100 therefore requires the deployment of carbon dioxide removal (CDR) technologies.[1]

The synergistic interaction between CDR and CU redefines the role of carbon utilization, transforming it from an end-of-pipe solution into a frontline tool for atmospheric emissions reduction. However, carbon neutrality cannot rely solely on carbon cycling; it also requires achieving permanent removal from the atmosphere. While converting carbon dioxide into fuels or chemicals reduces short-term emissions, its primary function is to delay re-emission rather than prevent it. Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU) primarily focus on reducing emissions by preventing fossil carbon from entering the atmosphere, while Carbon dioxide removal (CDR) targets reducing historical atmospheric loads. Integrating CDR and CCU yields different outcomes depending on the product lifecycle: Direct Air Capture to Fuel (DAC-to-Fuel) builds a circular carbon economy to achieve carbon neutrality, while Direct Air Capture or calcified materials enable permanent sequestration to achieve carbon negative emissions. These pathways address distinct but complementary roles within a broader mitigation portfolio required to move beyond a projected 3°C warming trajectory and toward alignment with the 1.5°C goal, in conjunction with aggressive emission reductions. Consequently, policy frameworks must differentiate incentives to support two distinct pathways: fuel applications that replace fossil energy sources, and material/storage applications that achieve net negative carbon targets. Consequently, the current growth in carbon utilization investments has not yet translated into a substantial reduction in atmospheric CO_2 concentrations.

In the pursuit of global emission reduction targets, the effective utilization and gradual release of carbon sources have become critical issues. The energy sector is the largest contributor to global greenhouse gas emissions, accounting for approximately 73% of total emissions. Carbon capture technology transfers carbon sources into more stable forms by capturing carbon dioxide from industrial facilities and energy production processes and converting it into valuable products. However, different carbon utilization methods exhibit varying characteristics regarding CO_2 release during their application. Short-term utilization forms, such as the combustion of synthetic fuels, lead to the re-release of CO_2, thus limiting their emission reduction effects to the fuel substitution process itself.[2] It is essential to distinguish between carbon utilization methods and their duration to determine whether they genuinely reduce atmospheric CO_2 concentrations over the long term or merely serve as temporary measures to mitigate atmospheric carbon levels.

HOW CAN INDUSTRIAL SYSTEMS TRULY ACHIEVE CARBON TRANSFORMATION?

Transportation, industry, and agriculture collectively constitute the primary sources of global carbon emissions. Transportation directly drives the rise in fossil fuel consumption and the growth in transport fuel demand, while industry primarily manifests as emissions from energy-intensive production processes. Agriculture provides significant natural carbon sinks through agroforestry and soil carbon sequestration, delivering synergistic benefits for ecosystems and climate adaptation. These three sectors collectively determine the trajectory of carbon emissions in the short, medium, and long term. From perspectives of feasibility and synergistic effects, focusing on these areas addresses the primary sources of global emissions while integrating short-, medium-, and long-term strategies. This approach points to critical pathways for achieving carbon-negative transformations in these sectors and realizing global net-zero goals.

In the transportation sector, achieving low carbon and negative carbon outcomes requires moving beyond simple electrification or technological

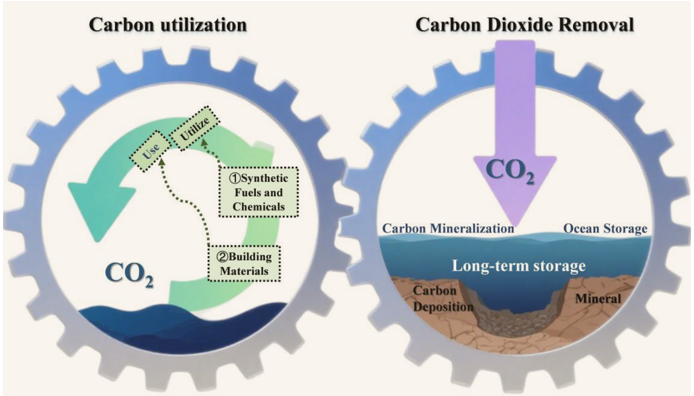

Figure 1. Synergistic carbon utilization and removal achieve net negative carbon targets through carbon capture and conversion technologies and permanent sequestration pathways.

substitution. The 2024 Global Carbon Emissions Report indicates that the transportation sector accounts for 23.4% of total emissions.[3] It demands the integration of carbon removal and utilization within systems that prioritize health, social equity, and urban spatial governance. Although the expansion of electric vehicles and public transit systems can reduce transportation emissions, electrification alone cannot fully address the intertwined carbon and health challenges associated with heavy duty transport, long haul logistics, and rapid urbanization. The International Energy Agency projects that large scale adoption of electric vehicles could reduce global carbon dioxide emissions by approximately 450 million tons by 2050. However, shipping, aviation, and heavy freight transport remain difficult to decarbonize. For these sectors, using carbon dioxide captured from the atmosphere to produce synthetic fuels or integrating direct air capture technology provides a pathway toward true negative carbon emissions.

In the industrial sector, integrating carbon utilization with carbon removal technologies is crucial for achieving long-term structural emissions reductions. Industrial production processes, particularly steel, cement, and fertilizer manufacturing, account for approximately 20% of global carbon dioxide emissions. Deep decarbonization targets cannot be met solely through energy efficiency improvements or fuel switching. Traditional Carbon Capture and Utilization (CCU) pathways mitigate emissions in the short term by converting captured CO_2 into synthetic chemicals or fuels. However, the carbon element is typically re-released during product use, limiting their contribution to long-term decarbonization. In contrast, integrating carbon capture with carbon dioxide removal pathways delivers enduring climate benefits. Mineral carbonation technology, in particular, provides a permanent storage form by mimicking natural rock weathering processes to convert CO_2 into stable carbonate minerals. This process utilizes industrial byproducts like steel slag and cement kiln dust as reactants, reducing the need for virgin ore mining and lowering environmental footprints.

In agriculture and land use, some carbon utilization methods, such as growing conventional crops under solar panels or expanding agricultural production, can improve soil fertility and crop yields but still generate emissions during management, functioning mainly as mitigation rather than removal. Biochar technology, however, converts agricultural residues into stable carbon forms that sequester carbon for centuries while improving soil quality and productivity.[4] Global deployment of biochar is projected to sequester around 300 million tons of carbon dioxide annually by 2050, and forest restoration could sequester approximately 1 billion tons per year.[5] Integrating agricultural photovoltaics, crop production, and carbon removal technologies such as biochar and forest restoration can therefore achieve genuine negative carbon outcomes while maintaining agricultural productivity.

THE TRANSITION FROM CARBON REDUCTION TO CARBON NEGATIVITY

Action is urgent. The transition from carbon reduction to carbon negative emissions hinges on the synergistic integration of carbon utilization and permanent carbon removal. Specifically, in the transportation sector, integrated pathways such as biofuel systems based on BECCS and DACCS-derived e-fuels can achieve true negative emissions: biomass energy does not introduce new fossil carbon, but without permanent storage, net negative emissions cannot be achieved. When biomass-derived CO_2 or air-captured CO_2 is subsequently sequestered via CCS technology, the system prevents its re-entry into the atmosphere, achieving permanent carbon removal. Simultaneously, CO_2 removal can be achieved without integrating CCU and CCS within the same pathway. Methods such as enhanced rock weathering, biochar application, and ocean carbon sequestration directly remove CO_2 from the atmosphere, soil, or ocean systems while delivering co-benefits like improved soil health or enhanced ocean alkalinity. These nature-based and geochemical processes serve as complementary carbon removal solutions that capture environmental carbon without generating additional CO_2 and contribute to long-term carbon storage enhancement in terrestrial and marine environments. This requires not only technological innovation but also governments must clearly distinguish between Carbon Capture and Utilization (CCU) and Carbon Dioxide Removal (CDR), incentivize Carbon Removal Shares (CRS) mechanisms, and implement transparent life-cycle accounting systems to track carbon from capture to final sequestration.

To accelerate this transformation, cross-sector collaboration and cross-subsidization are essential. All policies, investments, and innovations must serve the core objective of permanently reducing atmospheric carbon dioxide concentrations to keep global warming under control. This is not merely a climate agenda, but a civilizational mission to restore the Earth's climate system and secure a sustainable future.

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DECLARATION OF INTERESTS

The authors declare no competing interests.