

Editorial

Can CO₂ become a fuel?

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For decades, carbon dioxide (CO₂) has been treated as the ultimate waste product of modern civilization—an unavoidable by-product of energy generation, industrial growth, and economic progress. Today, that perception is undergoing a fundamental shift. Advances in carbon conversion science are redefining CO₂ not as an end point, but as a starting material for a new class of carbon-neutral fuels and chemicals [1,2]. This transformation represents one of the most promising intersections of physical science, energy technology, and climate mitigation.

At the heart of this shift lies rapid progress in catalysis and electrochemical systems capable of converting CO₂ directly into useful products such as carbon monoxide, formate, methanol, and synthetic hydrocarbons [3-5]. These molecules are not laboratory curiosities—they are industrial feedstocks and energy carriers that already underpin global supply chains. The ability to produce them from captured CO₂ closes the carbon loop and offers a pathway to sustain energy-intensive industries without net emissions. Recent breakthroughs in catalyst design have been especially significant. Researchers are moving beyond noble-metal systems toward earth-abundant materials, nanostructured catalysts, and single-atom active sites that deliver higher selectivity, lower overpotentials, and improved stability [6-8]. Atomic-scale control of surface chemistry has enabled unprecedented steering of reaction pathways, allowing selective formation of CO, formate, or multi carbon products - an achievement that was unattainable only a decade ago.

Equally important is the integration of carbon conversion with realistic exhaust and flue-gas streams. Rather than relying on purified CO₂, emerging systems increasingly operate under industrially relevant conditions, reducing energy penalties and system complexity [9]. This transition from idealized laboratory experiments to deployable reactor architectures marks a critical step toward commercialization. Climate implications are profound. Carbon-neutral fuels derived from CO₂ offer solutions for sectors that are difficult to electrify, including aviation, maritime transport, steelmaking, and long-duration energy storage [10]. In these contexts, chemical fuels remain indispensable, and carbon conversion provides a bridge between intermittent renewable electricity and continuous industrial demand. Nevertheless, carbon conversion is not a singular solution. Persistent challenges include catalyst degradation, energy efficiency limitations, infrastructure costs, and the necessity of

powering conversion systems with low-carbon electricity to ensure genuine climate benefit [11]. Addressing these challenges requires physics-based modelling, reactor engineering, and rigorous lifecycle assessment, elevating carbon conversion from a materials problem to a systems-level scientific endeavour.

What makes this field particularly compelling is its deeply interdisciplinary nature. Progress depends on advances in surface physics, electrochemistry, fluid dynamics, materials science, and computational modelling - often guided by machine learning and high-throughput experimentation [12]. Fundamental physical insights are translating directly into technologies with global climate relevance. By reimagining CO₂ as a resource rather than a residue, advanced carbon conversion challenges one of the central assumptions of the fossil-fuel era. As climate pressures intensify and global energy demand continues to rise, turning carbon from a liability into an asset may define one of the most consequential chapters in applied physical science.

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