Turning Carbon into Opportunity:

Breakthroughs in CO_2 Capture and Electrochemical Conversion



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Climate change is one of the defining challenges of our time. Carbon dioxide (CO_2), the primary greenhouse gas emitted from fossil fuel combustion, accounts for nearly three-quarters of global greenhouse gas emissions. While traditionally viewed as a polluting and unwanted by-product of industrial activity, scientists are increasingly exploring ways to transform CO_2 from a pollutant into a valuable resource.

Prof. Abdelbaki Benamor from the Gas Processing Center and his research team, in collaboration with Prof. Mazen Khaled from the College of Arts and Sciences, are leading an innovative project focused on developing a novel integrated electrochemical system for CO_2 utilization. The system is capable of capturing CO_2 and converting it into valuable products such as syngas, a mixture of hydrogen (H_2) and carbon monoxide (CO) widely used in the chemical and energy industries.

This research represents an important step toward building a circular carbon economy where industrial emissions are reused rather than released into the atmosphere.

From Waste Gas to Valuable Resource

CO_2 is emitted in large quantities from power plants, natural gas processing facilities, and other industrial operations, with estimated global emissions of approximately 44 Gt annually, including about 56 million tons emitted yearly in Qatar. Traditionally, carbon capture technologies absorb CO_2 using chemical solvents (or sorbents) and later release it to the atmosphere through an energy-intensive regeneration process.

The innovative approach developed at Qatar University integrates two traditionally separate processes- CO_2 capture and CO_2 conversion- into a single electrochemical system, as shown in Figure 1. Instead of releasing the captured CO_2 through heating, the system directly converts it into useful chemical products within the same solvent medium.

This integration offers several advantages:

- Reduced energy consumption by eliminating the desorption step.
- Lower operational costs for carbon capture systems.
- Direct production of valuable chemicals from captured carbon.

Such advances could significantly improve the economic feasibility of carbon capture technologies worldwide.

How the Integrated System Works

The research project proposes a system where CO_2 is first absorbed into a chemical solvent, typically an amine-based capture solution, which is widely used in industrial gas treatment processes. Once absorbed, the CO_2 is transported to an electrochemical reactor where specially designed catalysts trigger its transformation into valuable products.

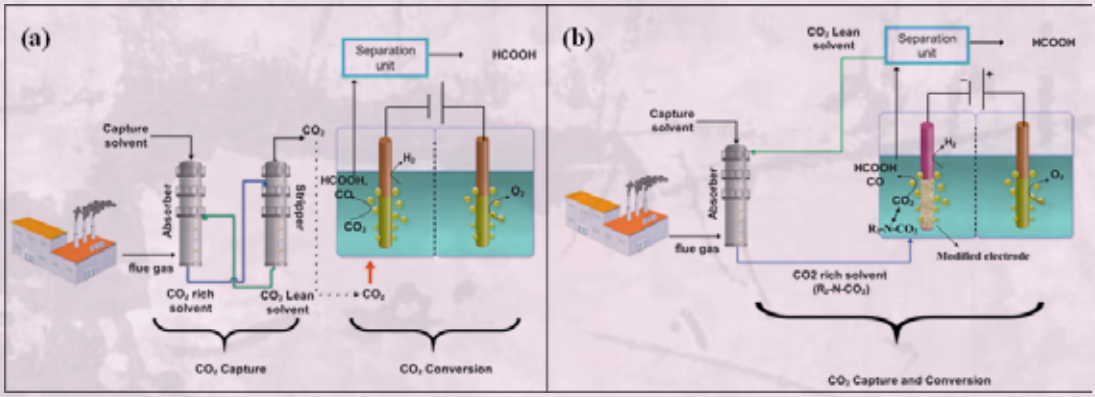


Figure 1: A schematic representation of two different CCU technology approaches: (a) a separate process where CO_2 capture and conversion take place independently, and (b) the proposed integrated approach that merges both steps. In the integrated system, R_2–N–CO_2 signifies CO_2 captured in an amine solution, existing in the form of either bicarbonate or carbamate species.

The process involves three main stages:

1. CO_2 Absorption

CO_2 from industrial sources dissolves in an amine-based solvent, forming intermediate chemical species such as carbamates and bicarbonates.

2. Electrochemical Conversion

Within an electrochemical reactor, catalysts facilitate reactions that convert CO_2 into carbon monoxide (CO) and hydrogen (H_2).

3. Syngas Formation

The mixture of CO and H_2 forms syngas, a key feedstock used to produce fuels, chemicals, and synthetic hydrocarbons.

This integrated process enables continuous CO_2 capture and conversion within the same system.

Research Process for the Integrated CO2 Capture and Conversion System

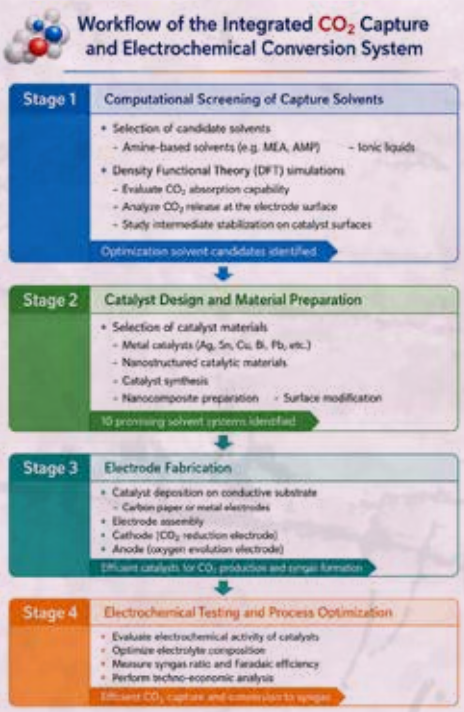


Figure 2: Schematic workflow illustrating the overall research strategy.

The workflow illustrated in Figure 2 presents the research strategy starting with computational solvent screening using density functional theory (DFT), followed by catalyst design, electrode fabrication, and electrochemical testing to optimize CO_2 conversion efficiency and syngas production.

Designing the Catalysts of the Future

At the heart of this technology are advanced electrocatalysts developed by the research team. These materials accelerate chemical reactions while maintaining selectivity toward the desired products.

The research focuses on developing several innovative catalytic materials, including:

- Single-atom nickel catalysts supported on graphene oxide.
- Copper-based metal oxide catalysts with mesoporous structures.
- Hybrid catalysts engineered to improve activity and selectivity.

These materials are designed to achieve:

- High catalytic activity.
- High Faradaic efficiency toward syngas production.
- Long-term operational stability.

Experimental evaluation involves advanced techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), XPS, and electrochemical testing to ensure that the catalysts maintain their performance under real operating conditions.

Combining Experiment with Advanced Simulation

One of the unique strengths of this project lies in the integration of computational modeling and experimental research. Before testing solvents and catalysts in the laboratory, researchers perform quantum-mechanical simulations using Density Functional Theory (DFT) to screen potential materials and electrolytes.

These simulations help identify:

- The most promising CO_2 capture solvents.
- Optimal catalyst–solvent interactions.
- Reaction pathways and energy barriers.

This combined computational and experimental approach accelerates discovery and reduces the time required to develop efficient systems.

Laboratory Experiments and Results

Recent laboratory studies have demonstrated encouraging progress in the electrochemical conversion of CO_2 into valuable chemicals. A dendritic bimetallic electrode, synthesized through controlled electrodeposition, showed excellent performance for converting CO_2 into formate, achieving a Faradaic efficiency of 86.5% and a partial current density of –27.3 mA cm^{-2} at –1.1 V vs. RHE.

This remarkable activity is attributed to its unique dendritic nanostructure and optimized PbSn interface, which enhances electron transfer and stabilizes key reaction intermediates while suppressing the competing hydrogen evolution reaction as shown in Fig. 3a.

In parallel investigations, Ni-doped $SrTiO_3$ catalysts have also demonstrated promising activity for CO production in CO_2-saturated MEA solutions, delivering a current density of approximately –46 mA cm^{-2} at –1.0 V with high Faradaic efficiency and low charge-transfer resistance.

These findings highlight the critical role of advanced catalyst design and electrolyte optimization in improving CO_2 electro-reduction performance, as shown in Fig 3b.

Building on these results, ongoing research aims to further refine catalyst structures and reaction conditions to achieve even higher efficiencies and improved selectivity toward valuable products such as formate and syngas, which are important feedstocks for sustainable fuels and industrial chemicals.

Toward the Next Generation of Carbon Technologies

Beyond laboratory experiments, the research team is also evaluating the economic feasibility of the proposed system. Using process modeling and techno-economic analysis, the researchers aim to determine:

- Capital and operating costs.
- Energy efficiency.
- Scalability for industrial implementation.

These studies will help move the technology toward Technology Readiness Level (TRL-5), bringing it closer to real-world deployment.

Looking Ahead

The work led by Prof. Abdelbaki Benamor represents an exciting step toward transforming CO_2 from an environmental challenge into a valuable resource. By integrating capture and conversion technologies into a single process, the project could open new pathways for sustainable chemical production and carbon management. As global efforts intensify to reduce emissions, innovations like these demonstrate how advanced science and engineering can turn environmental challenges into opportunities for innovation and economic growth.

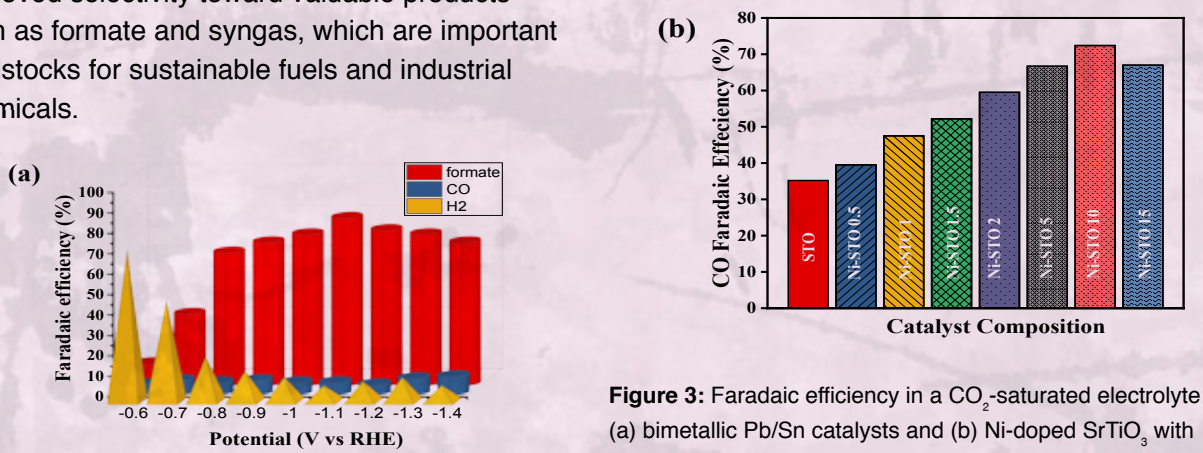


Figure 3: Faradaic efficiency in a CO_2-saturated electrolyte: (a) bimetallic Pb/Sn catalysts and (b) Ni-doped $SrTiO_3$ with varying weight ratios.