



## Electrocatalysis for energy conversion reactions

Cite this: *RSC Sustainability*, 2025, 3, 5406Zhenyu Sun<sup>ab</sup>

DOI: 10.1039/d5su90061a

rsc.li/rscsus

The continued consumption of fossil fuels and growing global energy demand are driving significant climate change and environmental degradation. Addressing these challenges urgently requires the advancement of clean and efficient energy technologies. One promising approach to achieving this goal lies in electrocatalysis, which facilitates chemical conversion by lowering the activation barriers of reactions and accelerating reaction kinetics (De Luna *et al.*<sup>1</sup>). Electrocatalytic reactions can use renewably generated electricity, enabling carbon mitigation and energy sustainability. Direct transformation *via* electrocatalysis can overcome the Carnot limit linked to traditional thermal processes that use heat. For these reasons, extensive efforts have been devoted to developing electrocatalysis for various emerging energy conversion processes, such as water splitting, fuel cell reactions, and carbon/nitrogen upgrading. The design and synthesis of high-performance electrocatalysts, catalyst evaluation, investigation of electrocatalytic mechanisms, and engineering of electrode/electrolyte interfaces, are the

focus of much current research. These endeavours are expected to facilitate the development of electrocatalysts integrated with related industries toward a sustainable future. This themed collection on “Electrocatalysis for energy conversion reactions” aims to provide alternative ways to defossilize the energy industry and transform chemical energy into more usable forms. The following summarizes the findings of the publications in this themed issue.

To reduce anthropogenic carbon emissions and mitigate continued global warming, intensive work has been directed to capture CO<sub>2</sub> and convert the sustainable C<sub>1</sub> molecule into valuable chemicals and fuels. Direct electrochemical CO<sub>2</sub> reduction (ECR) provides an appealing route, due to operating at ambient conditions, harnessing renewable energy resources, and using water as a source of hydrogen without the need for H<sub>2</sub>, favouring a net-zero-emission carbon economy (Sun<sup>2</sup>). ECR was first demonstrated by Hori *et al.* in the 1950s and has stimulated increasing research interest over the past decade owing to the rapidly decreasing cost of renewable electricity. A variety of metallic and metal-free electrocatalysts have been developed to improve conversion rate, energy efficiency, product selectivity, and electrolysis durability. Wijewardena and her colleagues (<https://doi.org/10.1039/D5SU00174A>) summarized recent

advances in graphene-based materials as catalysts for ECR. Their work focused on strategies including heteroatom doping and metal-graphene hybridization to optimize catalytic performance. They discussed both conventional graphene-based materials and emerging graphene analogs for ECR.

Single atom catalysts (SACs) feature ultrahigh-atom utilization and a tailorable coordination structure, affording unique and high catalytic activity for many reactions. Al-Mahayni and coworkers (<https://doi.org/10.1039/D4SU00747F>) performed density functional theory (DFT) analysis to investigate four Ti- and Mo-based MXenes (Ti<sub>2</sub>C, Ti<sub>3</sub>C<sub>2</sub>, Mo<sub>2</sub>C, and Mo<sub>3</sub>C<sub>2</sub>) and ten supported single metal atoms (Ag, Au, Co, Cu, Fe, Ni, Ru, Pd, Pt, and Zn) for ECR to C<sub>1</sub> products (CO, HCOOH, CH<sub>3</sub>OH, and CH<sub>4</sub>). By calculating the formation energy of MXenes, binding energy of SACs, activity (H adsorption energy, reaction energy of the thermodynamic limiting step of CO<sub>2</sub> reduction reaction), and selectivity (the adsorption of CO<sub>2</sub> against the adsorption of H), five catalysts were screened to display good performance following the order Ni@Ti<sub>3</sub> > Ru@Mo<sub>2</sub> > Fe@Mo<sub>2</sub> > Co@Mo<sub>2</sub> > Pd@Ti<sub>3</sub>. Among these SACs, MXene supported Ni was shown to possess the lowest overall reaction energy barrier at 0.27 eV followed by Fe (with an overall reaction energy barrier of 0.4 eV),

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warranting their further synthesis and experimental testing for ECR.

The electro-cycloaddition of CO<sub>2</sub> to generate cyclic carbonates is intriguing because cyclic carbonates can be used as monomers for polycarbonates, electrolytes, and aprotic solvents, among others. Honores *et al.* (<https://doi.org/10.1039/D5SU00100E>) investigated the electrochemical cycloaddition of CO<sub>2</sub> to epoxides utilizing Ni(cyclam)Cl<sub>2</sub> and Co(cyclam)Cl<sub>2</sub>Cl as electrocatalysts in 1-butyl-3-methylimidazolium-based ionic liquids (ILs) without addition of any other organic solvents. ILs were shown to facilitate epoxide ring opening and stabilize the reaction species. 1-Butyl-3-methylimidazolium bromide provided high yields while 1-butyl-3-methylimidazolium tetrafluoroborate and 1-butyl-3-methylimidazolium bis-(trifluoromethylsulfonyl)imide only gave low conversion. Spectroelectrochemical measurements indicated that the halide anions in ILs enhanced carbonate formation. DFT calculations confirmed the important role of the *trans*-I isomer of [Ni(cyclam)]<sup>+</sup> in facilitating CO<sub>2</sub> coordination and activation. This work highlights the potential of tetraazamacrocyclic metal complexes for promoting electrochemical carbon capture and transformation in ILs.

Achieving industrially viable and efficient electrocatalysis necessitates the design and development of robust electrolyzers. Soni *et al.* (<https://doi.org/10.1039/D4SU00826J>) demonstrated the integration of thermoelectric generators with reactive carbon electrolyzers to

convert captured CO<sub>2</sub> into CO. The thermoelectric generators harnessed waste heat to drive the ECR electrolyzers, thus negating any reliance on external sources of heat. Liquid bicarbonate was used to provide high concentrations of captured CO<sub>2</sub>, which improves CO<sub>2</sub> utilization efficiency and contaminant tolerance, addressing the drawbacks of gaseous CO<sub>2</sub> electrolysis. This study shows that by coupling carbon capture and conversion technologies together a viable route to tackle the dual challenges of energy sustainability and decarbonization can be found.

The anodic electrocatalytic oxygen evolution reaction (OER) plays a role for sustainable production of H<sub>2</sub> and other value-added chemicals (Zhang *et al.*<sup>3</sup>). However, the large overpotential and the oxidizing environment at the anode lead to energy loss and stability issues. Coupling DFT calculations and microkinetic modelling provides a way to determine key intermediates, rate-limiting steps (RLS), and reaction pathways, yielding benefits in the screening and rational design of improved OER electrocatalysts. Tripathi *et al.* (<https://doi.org/10.1039/d5su00080g>) showed that the formation of OOH\* *via* an Eley-Rideal (ER) mechanism is likely the RLS, consistent with experimental Tafel slope analyses if the interfacial field response of O\* and OH\* is considered. The desorption of O<sub>2</sub>\* is unlikely to be rate-limiting.

Iridium oxides (IrO<sub>2</sub>/IrO<sub>x</sub>) are state-of-the-art electrocatalysts for the OER. There

is a growing demand for this rare metal. However, Ir has a low natural abundance (only 0.02 ng g<sup>-1</sup>) and limited supply (with an annual production <10 tons). This necessitates the development of efficient Ir recycling processes from end-of-life materials (Clapp *et al.*<sup>4</sup>). Turnbull and co-workers (<https://doi.org/10.1039/d5su00038f>) demonstrated a microwave-assisted Ir leaching method from IrO<sub>x</sub>. An Ir recovery of up to 83 ± 10% in the form of IrCl<sub>6</sub><sup>2-</sup> was attained with an extraction condition of low acid concentration ([H<sup>+</sup>] = 0.5 M) and moderate temperature (139 °C).

## References

- 1 P. De Luna, C. Hahn, D. Higgins, S. A. Jaffer, T. F. Jaramillo and E. H. Sargen, What would it take for renewably powered electrosynthesis to displace petrochemical processes?, *Science*, 2019, **364**, 350.
- 2 Z. Sun, Renewably powered electrochemical CO<sub>2</sub> reduction toward a sustainable carbon economy, *RSC Sustainability*, 2023, **1**, 1908.
- 3 M. Zhang, W. An, Q. Liu, Y. Jiang, X. Zhao, H. Chen, Y. Zou, X. Liang and X. Zou, Tunnel-structured IrO<sub>x</sub> unlocks catalytic efficiency in proton exchange membrane water electrolyzers, *Nat. Commun.*, 2025, **16**, 7608.
- 4 M. Clapp, C. M. Zalitis and M. Ryan, Perspectives on current and future iridium demand and iridium oxide catalysts for PEM water electrolysis, *Catal. Today*, 2023, **420**, 114140.

