Addressing Materials Challenges for Fuel Cells and Electrolyzer Technologies: Membrane and Catalyst Innovations

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The transition to sustainable hydrogen economies faces fundamental materials limitations across the polymer electrolyte membrane (PEM) electrolyzer and fuel cell value chain. Despite enabling carbon-free power generation through fuel cells, green hydrogen production via electrolysis and its conversion in fuel cells remain constrained by performance limitations, efficiency losses, and durability challenges. Other key challenges include reliance on perfluorosulfonic acid membranes with high cost, and hydration-dependent performance; gas crossover phenomena compromising efficiency and safety; catalyst systems dominated by platinum-group metals (PGMs), notably Pt cathodes for oxygen reduction reaction (ORR) in fuel cells and Ir anodes for oxygen evolution reaction (OER) in acidic electrolyzers in which scarcity and high cost.

To address membrane limitations, our group focuses on alternative and cost-effective solutions [1,2]. We develop ion-conducting membranes via radiation-*induced graft polymerization* of vinyl monomers onto various base polymers. These radiation-grafted membranes offer distinct advantages including utilization of commercial base polymers, precise control, spatially resolved functionalization and intrinsic avoidance of solution-processing steps. Our group utilizes *electrospinning* as well to fabricate composite and hybrid membranes. These approaches enable membranes with tunable ion exchange capacity, water uptake and ionic conductivity. We achieved the development of new generation asymmetric membranes and bipolar membranes as well. Moreover, for PEM electrolyzers, we embedded recombination catalysts within thin membranes mitigate hydrogen crossover, eliminating auxiliary layers while maintaining efficiency.

Our complementary catalyst innovations target PGM reduction and activity enhancement to reduce cost and enhance performance [3-6]. For ORR in fuel cells, Pt nanoparticles (2–3 nm) on functionalized graphene supports (nanoplatelets, rGO, hybrids) reduce Pt consumption while enhancing activity. These catalysts are synthesized by impregnation-reduction, microwave-assisted deposition, photocatalytic deposition, and electrophoretic deposition.

Moreover, we develop transition metal-doped iridium oxide catalysts (Mn, Ni, Ti) for acidic OER in PEM electrolyzers. Our work engineers Mn-, Ni-, and Co doped IrO_2 systems via sol-gel synthesis, where dopant integration induces significant electronic modulation that optimizes reaction energetics. This reduces OER activation barriers, enhances exothermic behavior, and improves catalytic efficiency. Specifically, Mn-doped variants achieve substantial reductions in noble metal loading while delivering significantly lower overpotentials compared to pure IrO_2, attributed to Mn redox cycling facilitating lattice-oxygen-mediated pathways. To further boost stability, we leverage anodized TiO_2 nanotube arrays on titanium mesh substrates, providing high-surface-area supports that enhance catalyst anchoring and mitigate dissolution through synergistic charge transfer. These advances enable high-performance, durable electrodes with reduced precious metal reliance, and advancing scalable hydrogen technologies toward commercial viability.

In this presentation, we contextualize these material innovations within global efforts to overcome fuel cell and electrolyzer limitations. We highlight key projects including *Graphene Flagship*, *HYSouthMarmara Hydrogen Shore* (Turkiye's first hydrogen valley initiative) and other projects.

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