

Fuel Cells: A Quiet Revolution Powering a Sustainable Future

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Introduction: From Combustion to Conversion

Human progress has long been fuelled by combustion, but that very dependence has brought us to the edge of a planetary crisis. The continuous burning of fossil fuels has released immense quantities of carbon dioxide and other greenhouse gases, accelerating global warming. The Swedish chemist Svante Arrhenius¹ was among the first to describe this phenomenon in the late 19th century, yet it has taken over a century for the urgency of his insight to shape global energy policy. Today, as nations rally around net-zero commitments, the need for cleaner and more sustainable energy sources has never been greater.

Among the emerging technologies capable of answering this call, hydrogen fuel cells have emerged as one of the most promising. Hydrogen, long recognized as a crucial element in the transition to a sustainable energy future, offers the potential to provide abundant, clean, and secure energy.² When combined with fuel cell systems, hydrogen enables electricity generation without combustion, a process that emits only water vapor as its by-product. This elegant chemistry not only eliminates local pollutants such as nitrogen oxides and particulates but also provides exceptional energy efficiency, converting chemical energy directly into electrical energy at efficiencies reaching nearly eighty percent in certain systems.

Evolution and Principles of Fuel Cells

The journey of fuel cell technology began in 1838, when the German chemist Friedrich Schönbein first demonstrated the electrochemical reaction between hydrogen and oxygen. Several decades later, Sir Thomas Francis Bacon built upon this foundation to create the first practical hydrogen-oxygen fuel cell using nickel electrodes.³ Although initially expensive and limited to laboratory research, Bacon's design established the principles that continue to guide fuel cell innovation today.

Modern research has since expanded fuel cell

technology into several distinct types, each designed for specific operating conditions and applications. These include proton exchange membrane fuel cells, direct methanol fuel cells, alkaline fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, and solid oxide fuel cells, while more recent developments, such as microbial fuel cells, use biological catalysts to generate electricity from organic substrates. Of these, the proton exchange membrane fuel cell, often abbreviated PEMFC, has gained particular prominence due to its compact design, rapid start-up, and adaptability to mobile and stationary power uses.⁴

A PEM fuel cell works by converting hydrogen and oxygen into electricity through two complementary reactions: hydrogen oxidation at the anode and oxygen reduction at the cathode. Protons migrate through a polymer electrolyte membrane while electrons travel through an external circuit, creating a continuous flow of current.^{5, 6} The overall reaction produces electricity, heat, and pure water, demonstrating the harmony between scientific ingenuity and environmental stewardship.

At the heart of the cell lies a sophisticated combination of materials. The electrodes are typically made from carbon-supported platinum catalysts blended with a proton-conducting polymer such as Nafion. The membrane allows protons to pass while keeping the gases separated, maintaining both chemical integrity and electrical isolation. Surrounding these components are gas diffusion layers made of porous carbon fibers treated with Teflon, which distribute the reactant gases, manage moisture, and collect current.^{7, 8}

Despite decades of refinement, challenges remain. Only a fraction of the platinum catalyst surface area actively contributes to the reaction because of uneven ionomer distribution and restricted gas diffusion within the electrode. These microscopic inefficiencies, especially at the cathode where oxygen reduction is sluggish, reduce the overall cell efficiency.^{7, 9} Researchers are addressing these limitations through innovative

catalyst nanostructures, improved ionomer interfaces, and alternative materials that promise to lower cost and enhance durability.

Applications Across Sectors

Fuel cells are remarkable for their versatility, capable of powering everything from handheld devices to megawatt-scale power plants. Their applications can be broadly grouped into portable, stationary, and transportation domains, each with distinct technological and economic potential.

In the portable sector, fuel cells provide power for devices that traditionally rely on batteries, such as laptops, communication equipment, and small appliances. They are also used in outdoor and emergency power generation for activities like camping, disaster relief, and remote monitoring. These systems, which range from a few watts to several hundred watts, offer far higher energy density than rechargeable batteries and can operate for extended periods without recharging. While their commercial success is limited by cost and component lifespan, the growing demand for clean, mobile power continues to drive innovation in this area.

Stationary fuel cells represent the most mature and widespread application. Used for residential, commercial, and industrial power generation, they provide both stand-alone and grid-connected electricity. Their modular design, quiet operation, and ability to deliver combined heat and power make them ideal for decentralized energy systems. In particular, polymer electrolyte and direct methanol fuel cells have gained traction in telecommunications and emergency backup installations, replacing traditional diesel generators. Because they can operate under harsh conditions and require minimal maintenance, stationary fuel cells are now viewed as key enablers of distributed generation and microgrids, providing resilient power to communities and industries alike.

Perhaps the most transformative potential of fuel cells lies within the transportation sector. This industry accounts for a substantial share of global greenhouse gas emissions and decarbonizing it is central to achieving climate goals. Fuel cell electric vehicles, often referred to as FCEVs, offer a compelling alternative to internal combustion engines. They provide the range

and refueling convenience of conventional cars while eliminating tailpipe emissions. Leading manufacturers such as Toyota, Hyundai, and Honda have introduced commercial models powered by hydrogen fuel cells, demonstrating that this technology is no longer confined to the laboratory. Beyond passenger vehicles, fuel cell systems are being developed for buses, trucks, trains, ships, and even aircraft, signaling a gradual but determined shift toward a cleaner transportation ecosystem.

Scientific and Engineering Challenges

Although fuel cells embody the ideals of sustainable chemistry, several scientific and engineering barriers still limit their widespread adoption. One of the most significant challenges is the dependence on platinum, a rare and costly metal, as the catalyst for both the hydrogen oxidation and oxygen reduction reactions.⁴ Considerable global research effort is now devoted to developing platinum-alloy catalysts, core-shell nanostructures, and non-precious metal alternatives that maintain stability and activity while reducing cost.^{10, 11}

Another critical issue concerns the longevity of the polymer membrane, which must withstand mechanical stress, high temperature, and chemical attack during continuous operation. Degradation of the membrane can lead to fuel crossover and reduced performance, so developing more resilient polymers remains a major research focus. Equally important is water and heat management: excess water can flood the electrode pores, while insufficient hydration increases electrical resistance. Innovative micro-porous layers, controlled humidity systems, and advanced flow-field designs are being engineered to manage these dynamics effectively.¹²

Finally, the success of fuel cells depends on a reliable hydrogen infrastructure. Sustainably producing hydrogen, ideally through electrolysis powered by renewable energy, remains a formidable logistical and economic challenge. Advances in storage materials, distribution networks, and safety protocols are vital to ensure that hydrogen can be delivered efficiently and safely at scale.¹³

The Future and Prospects of Fuel Cell Technology

The prospects for fuel cell technology are as dynamic as the field itself. Research is steadily moving toward systems that are not only efficient and durable but also economically competitive with conventional energy sources. The development of green hydrogen, produced through electrolysis powered by renewable energy, offers a pathway to close the carbon loop entirely. As renewable energy generation expands globally, coupling it with large-scale hydrogen production can ensure a continuous and flexible power supply that complements intermittent sources like solar and wind.

Advancements in materials science, particularly in the design of nanostructured catalysts and high-performance composite membranes, are expected to reduce costs while improving performance. Artificial intelligence and data-driven modeling now aid the design of optimized fuel cell components, accelerating discovery and commercialization. Furthermore, the integration of fuel cells into hybrid systems that combine batteries or supercapacitors is opening new frontiers in smart grid management, electric mobility, and off-grid electrification.

In the coming years, decentralized power systems supported by compact fuel cell units could become essential for energy access in remote areas and disaster recovery operations. As international collaboration strengthens and regulatory frameworks evolve, fuel cells are poised to transition from niche applications to a mainstream energy solution. Their quiet operation, clean by-products, and scalable design embody a technology perfectly aligned with the goals of sustainable development and circular energy systems.

Fuel cells demonstrate how chemistry and engineering together can redefine the way humanity generates and uses energy. From the pioneering experiments of the 19th century to the sophisticated systems of today, this technology has traveled a remarkable path. As materials improve, costs decline, and infrastructure expands, fuel cells will continue to transform sectors ranging from transportation to power generation. They represent not only a scientific achievement but a moral imperative, a cleaner, quieter, and more sustainable answer to the energy challenges of our age.

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Guest Articles

Electrospinning: A versatile approach of making innovative materials

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Electrospinning is a method extensively used for producing nanomaterials, particularly nanofibers. It is a technique where, a high voltage electric field is used to produce electrically charged jets from a polymer solution which then upon evaporation make nanofibers of the polymer. Electrospinning is a technique of fabricating man-made fibers using electrostatic forces. Polymers that are commonly used for electrospinning include polyvinylidene fluoride polysulfone, polyacrylonitrile (PAN), polyvinyl alcohol, cellulose acetate, and polyurethane.

This technique, known earlier as "electrostatic spinning," was discovered long ago. J.F. Cooley and W.D. Morton initially patented electrospinning in 1902 and gave details of the apparatus for electrically dispersing fluids. Generally, any electrospinning apparatus consists of three major components namely, a high voltage supply, a spinneret (metallic needle) and a collector (Figure 1). Usually, the polymer solutions are fed using a syringe pump, which is connected to the high voltage power supply, at a controlled rate. The highly charged polymer suspension in the syringe needle, directs fibers towards the oppositely charged collector, which can be a flat surface or a rotating drum, to collect the fibers. In conventional spinning techniques, the fiber is subjected to a group of forces

such as tensile, gravitational, aerodynamic, rheological, and inertial, whereas in electrospinning, the spinning of fibers is achieved primarily by the tensile forces created in the axial direction of the flow of the polymer by the induced charges in the presence of an electric field.

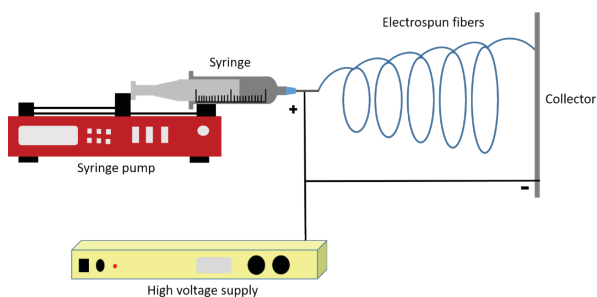


Figure 1. Schematic diagram of electrospinning apparatus

Further, by modifying simple electrospinning, a further step has moved forward to make coaxial electrospinning, in which by introducing multiple feed solutions to simultaneously electrospin two or more polymer solutions from coaxial capillaries. The spinnerets are sharing an axis, allowing for the injection of one solution into the other at the needle tip with the core fluid getting drawn within the outer one to produce continuous coated or hollow nanofibers. Moreover, coaxial spinning is highly effective in encapsulating