# Electrons to Molecules: Electricity-Driven Processes for Future Generation of Renewable Hydrogen, Net-Zero Fuels, Chemicals, and Materials

**Interconverting electrical and chemical energy efficiently and cost-effectively provides a massive opportunity to generate renewable hydrogen, create net-zero fuels and chemicals, capture and convert carbon dioxide ($CO_2$), and create innovative sustainable industrial processes.**

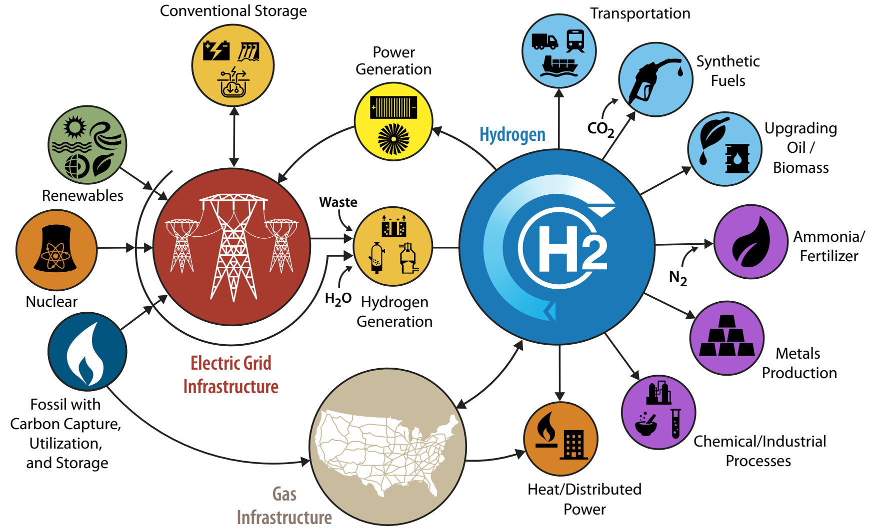
NREL is exploring the use of renewable, affordable electricity as the driving force for the conversion of low-energy molecules—such as water and carbon dioxide—to generate higher-value, higher-energy chemicals, materials, and fuels as end-use products or as a means toward energy storage. This combination of producing goods and materials more sustainably with end-of-useful-life circularity in mind will drive a more sustainable future economy capable of meeting the world's needs in a manner that leaves the environment and the planet healthy for generations to come.

## Renewable Hydrogen

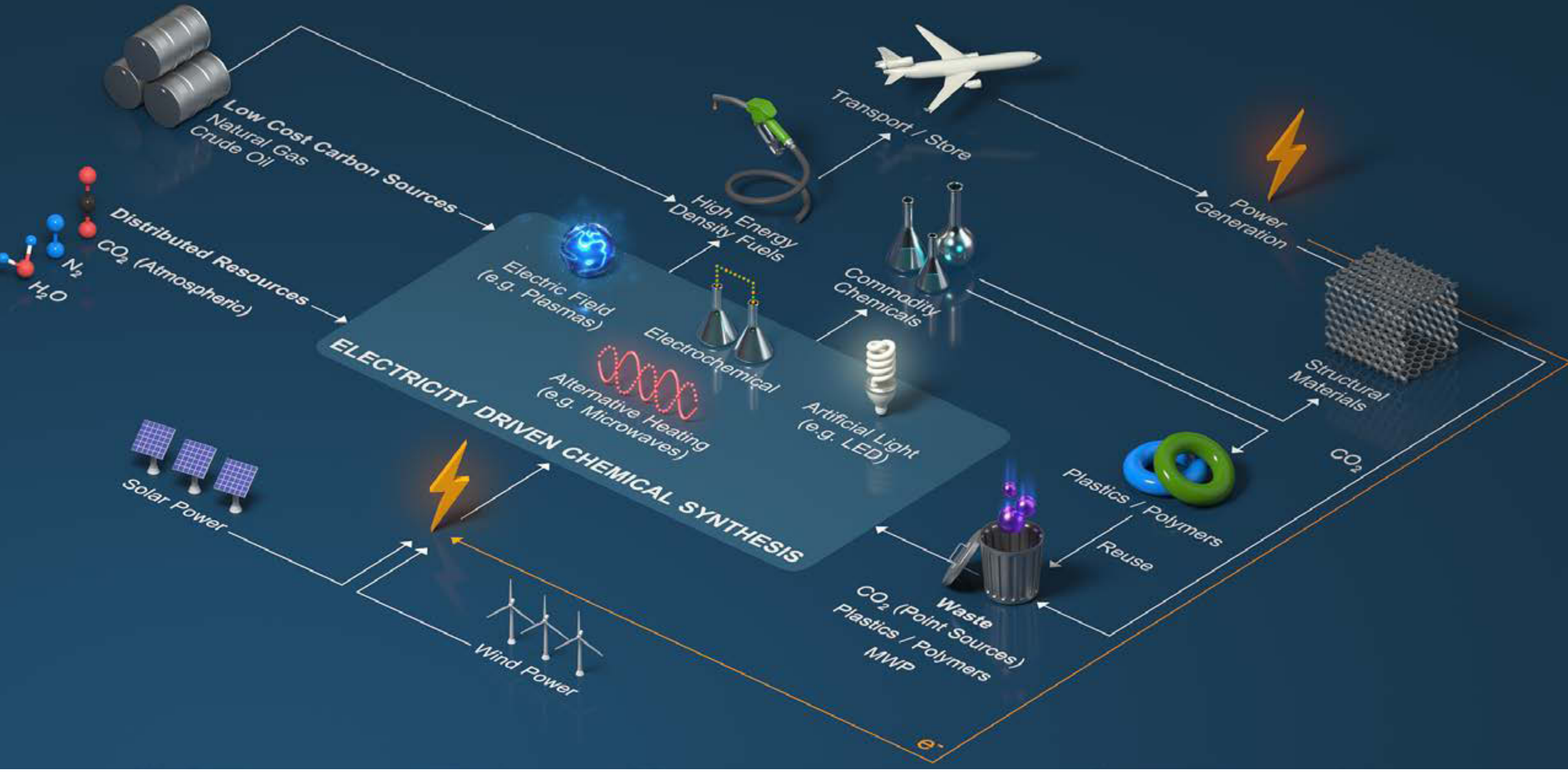
Renewable hydrogen will be a key component for the generation of net-zero fuels and chemicals, reactive capture and conversion of $CO_2$, and decarbonization of industrial processes. As shown in the figure, renewable hydrogen can be generated from carbon-free renewable electricity. When combined with fuel cell technology, hydrogen can be used for short-term storage as fuel for transportation, or long-term energy storage for the utility industry. Importantly, hydrogen can provide reducing equivalence and be used to upgrade $CO_2$ to chemicals and/or fuels using either biological processes (e.g., bio-methanation) or thermochemical processes (e.g., methanol synthesis). When used to upgrade either biomass-derived or carbon-based waste feedstocks, renewable hydrogen allows the generation of net-zero fuels or chemicals. Renewable hydrogen can be used within the Haber-Bosch process to generate green ammonia, which can be used as fertilizer helping to decarbonize farming. The marine sector is interested in using green ammonia to decarbonize shipping.

## Reactive Capture and Conversion of $CO_2$

Industrial interest in reactive capture and conversion of $CO_2$ is growing; and when combined with low-cost, abundant, renewable electricity, it will provide new low-carbon, low-cost routes to the chemicals, materials, and fuel (e-fuels) that we use today. Reactive capture technologies would involve reacting $CO_2$ within a given capture media using either direct electrochemical reduction, chemical reduction using a universal energy carrier such as hydrogen, and/or biological reduction. NREL has demonstrated such reactive capture technology using gas fermentation bio-methanation technology to generate methane from $CO_2$.




**H2@Scale: Generation and Utilization of Renewable Hydrogen**



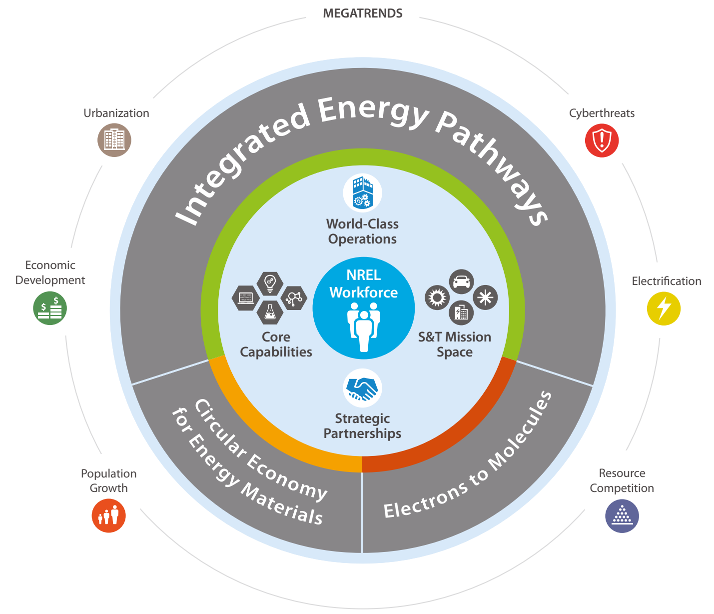

Electrons to Molecules: Electricity-Driven Process

## Generation of Net Zero-Carbon Fuels with Electrons to Molecules

Electricity-driven processes can directly or in combination with either chemical or biological processes reduce feedstocks such as $CO_2$ and biomass (biomass cheaply captures $CO_2$) to net-zero fuels or chemicals. Net-zero products are products that have no net greenhouse gas emissions or carbon footprint. For example, at NREL, readily available compounds such as carbon dioxide and water are being transformed via electro-catalysis into reactive intermediates and coupled with biological or catalytic processes to generate compounds that we use today to make chemicals, plastics, and fibers. These routes include mature industrial technologies and promising alternative approaches that require significant early-stage research to address technical and commercialization barriers. Research is needed across the full spectrum of electrochemical, bio-electrochemical, and hybrid electro-chemical/biochemical pathways.

## Decarbonizing Industry

The innovation and implementation of electricity-driven processes will drive the decarbonization of industry processes and the production of goods and materials in an economic and sustainable manner. This transition will involve simple solutions such as replacement of fossil-fuel driven furnaces with electricity-driven furnaces; but even higher efficiencies could be realized through innovative electricity-driven processes. These processes would be based on the direct use of electricity such as electrochemical or electric field-driven processes (e.g., non-thermal plasmas) and/or indirect use of electricity such as electricity-driven light-emitting diode (LED) systems for artificial photochemical or photo-biochemical reactor systems, as well as microwave-driven processes.




NREL's 10-Year Plan: A Vision for the Future

These new solutions may require hybrid approaches for end-to-end processing of a given feedstock to a given product that combines an electricity-driven reaction step with biological or catalytic conversion and/or separation steps. Besides the conversion of $CO_2$ and water, the use of electricity-driven processes can be developed to convert other feedstocks such as nitrogen to ammonia, transform carbon-based feedstocks such as crude oil, natural gas, and biomass into chemicals and materials; deconstruct plastics for recycling and reuse; and refine ores to generate metals.

NREL
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