Electrofuels

One way to store excess renewable electricity is to convert it to **hydrogen, methane, or ammonia**.

By F. Todd Davidson, Kazunori Nagasawa, and Michael E. Webber

In a 1961 speech to Congress, President John F. Kennedy famously dedicated the United States to putting a man on the moon within the decade. In a somewhat less famous address to Congress, President George W. Bush proposed dedicating the nation to perfecting a new fueling paradigm for American automobiles. "With a new national commitment," Bush declared, "our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen, and pollution-free."

That child, born in January 2003, is 14 ½ years old and will soon be taking drivers ed. Unless she has access to one of the rare fuel-cell powered vehicles, her first car definitely will not be fueled by hydrogen.

While the idea of a hydrogen-based economy got a lot of attention during the first years of the George W. Bush administration, some important details were left out. For one, even though hydrogen is the simplest and most common element, very little of it is found in nature in the form of hydrogen gas. Instead, hydrogen gas must be extracted from other molecules like water or produced through processes that convert energy from a different form to hydrogen fuel and these have associated losses.

At the same time, while hydrogen was touted as a clean fuel, since water vapor is its only combustion product, critics and energy analysts complained that its production processes were not clean. Almost all the hydrogen produced at that time was made from fossil fuel, either directly as a result of the combination of methane and steam, or indirectly via electrolysis using electricity from natural gas or coal-fired power plants to split water into oxygen and hydrogen. Add to that the difficulty of storing hydrogen gas, and the enthusiasm for the hydrogen economy began to wane.

That doesn't mean that hydrogen can't be the means to a cleaner economy, one based on renewable energy. Hydrogen can be produced through electrolysis using electricity from wind turbines, solar cells, geothermal, or hydroelectricity, eliminating carbon emissions entirely at the point of production. The hydrogen can be reacted with other elements to produce synthetic fuels that can be more easily transported and stored. Because these fuels are, in essence, a way of storing the energy content of electricity from renewable sources, they are called *electrofuels*.

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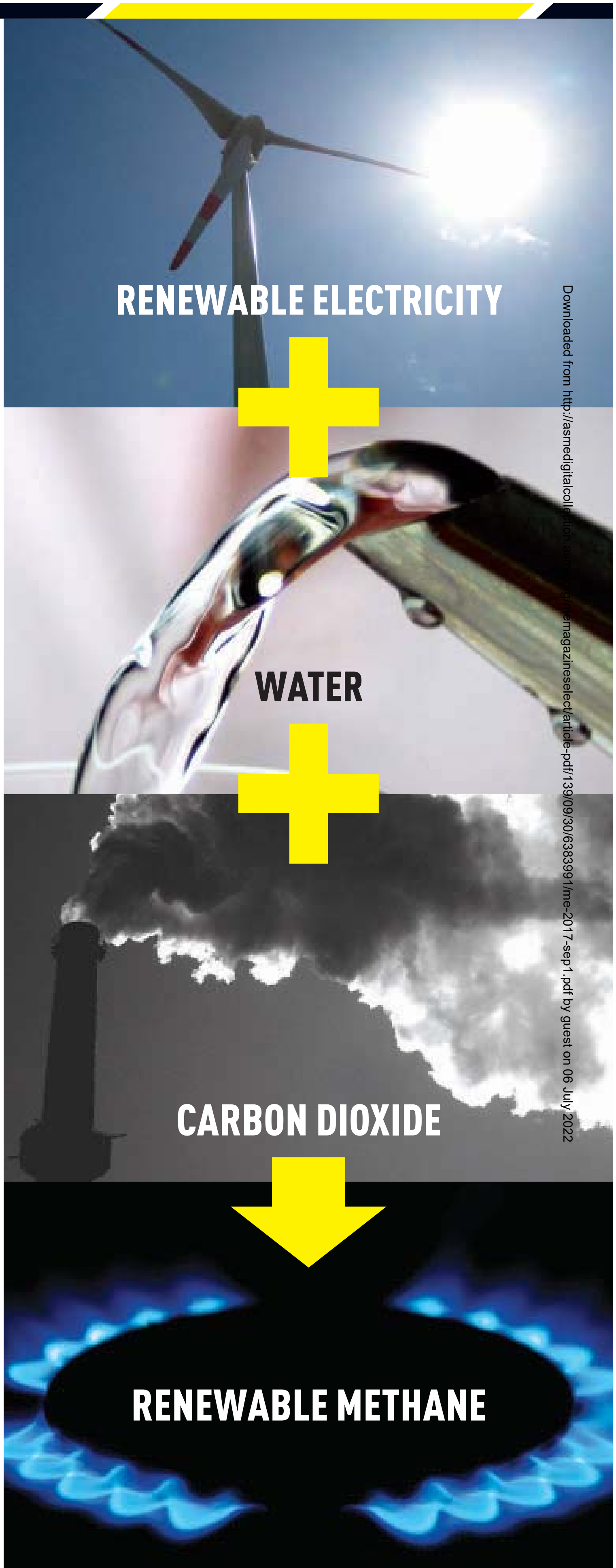
These fuels have the potential to reshape the national energy landscape. We have enough renewable power to produce electrofuels at significant volumes, which would displace conventional carbon-emitting fuels from finite sources such as gasoline and diesel. What's more, making low-carbon, energy-dense fuels from electricity can be done in a way that helps address the problem of intermittency that confronts efforts to increase the amount of renewable power on the electric grid.

When it comes to powering vehicles, the energy density of the fuel or battery is a critical consideration. The perfect energy storage medium would have high volumetric energy density (require little storage space), high gravimetric energy density (would not weigh much), and produce no carbon dioxide when used. By some measures, hydrogen is fantastic: it produces no CO_2 when burned, and its gravimetric energy density, 120 MJ/kg, is the highest of any liquid or gaseous fuel. Unfortunately, hydrogen remains a gas under all but the most extreme conditions, which means it requires a lot of volume to store the fuel. Compressing hydrogen to 69 MPa (10,000 psi) or liquefying it at -253 °C (-424 °F) can improve its volumetric energy density, but at the cost of complicating the handling of the fuel.

To improve volumetric energy density under standard conditions, we need to look to heavier chemical structures that have the advantage of being liquid at standard room temperatures and pressures. Gasoline's chemical structure, for instance, can be approximated with seven carbon atoms and seventeen hydrogen atoms (C_7H_{17}), yielding an energy-dense liquid. A popular car like the Toyota Corolla can travel almost 400 miles on a single tank of gas; the gasoline in that 13-gallon tank weighs only 82 pounds. That is why gasoline and diesel are so



attractive for transportation—and why they are hard to replace with electricity or alternative fuels such as ethanol. For the electric-powered Chevy Bolt to travel the same distance as a fully fueled Corolla, it would need a fully charged battery pack weighing nearly 2,000 pounds and occupying the space of 150 gallons.

Unfortunately, as more and more carbon atoms are included in a chemical chain, the fuel gets heavier and fewer hydrogen atoms are available to combust with oxygen per unit mass of fuel. Instead, the oxygen combines with the carbon atoms, which not only releases much less energy than burning hydrogen, but also produces carbon dioxide. This dynamic can be observed by comparing the volumetric and gravimetric energy density, and the subsequent carbon dioxide emissions of combusting different hydrocarbon fuels. (See chart on page 35.) Methane—with one carbon atom and four hydrogen atoms—has the highest gravimetric energy density and the lowest carbon dioxide emissions per unit of energy released during combustion, but it also has the lowest volumetric energy density due to its gaseous nature at standard conditions. As more carbon atoms are attached to a hydrocarbon chain the volumetric energy density rises but the gravimetric energy density begins to decline and the carbon dioxide emissions begin to rise.

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While no perfect fuel exists, electrofuels made from renewable electricity are a good compromise. They have the lowest emissions of the gaseous and liquid options, and have reasonable energy density.

The simplest electrofuel—hydrogen made from renewable electricity—is based on an old idea. The production of hydrogen from electricity was first posited to a general audience by Jules Verne in his 1874 novel, *Mysterious Island*. Renewable hydrogen suffers from the same volumetric energy density and handling disadvantages as hydrogen made from fossil fuels. However, hydrogen can be mixed directly into existing natural gas pipelines up to a concentration of 10 percent, enabling renewable hydrogen to utilize existing infrastructure for transmission and distribution.

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Even more conveniently, it can also be used as a precursor for manufacturing other fuels. Hydrogen and carbon dioxide can be fed into a reaction chamber where, through the Sabatier process, a catalyst such as nickel can yield water and methane gas fuel. The source of carbon dioxide could either be from the ambient air or from a concentrated source such as carbon capture at the facility where the methane is eventually burned. Either way, this electrofuel—essentially renewable natural gas—produces virtually no net carbon emissions, while being able to tap into the existing natural gas infrastructure. This concept is being piloted at industrial scale in Europe through a scheme marketed as "Power-to-Gas."

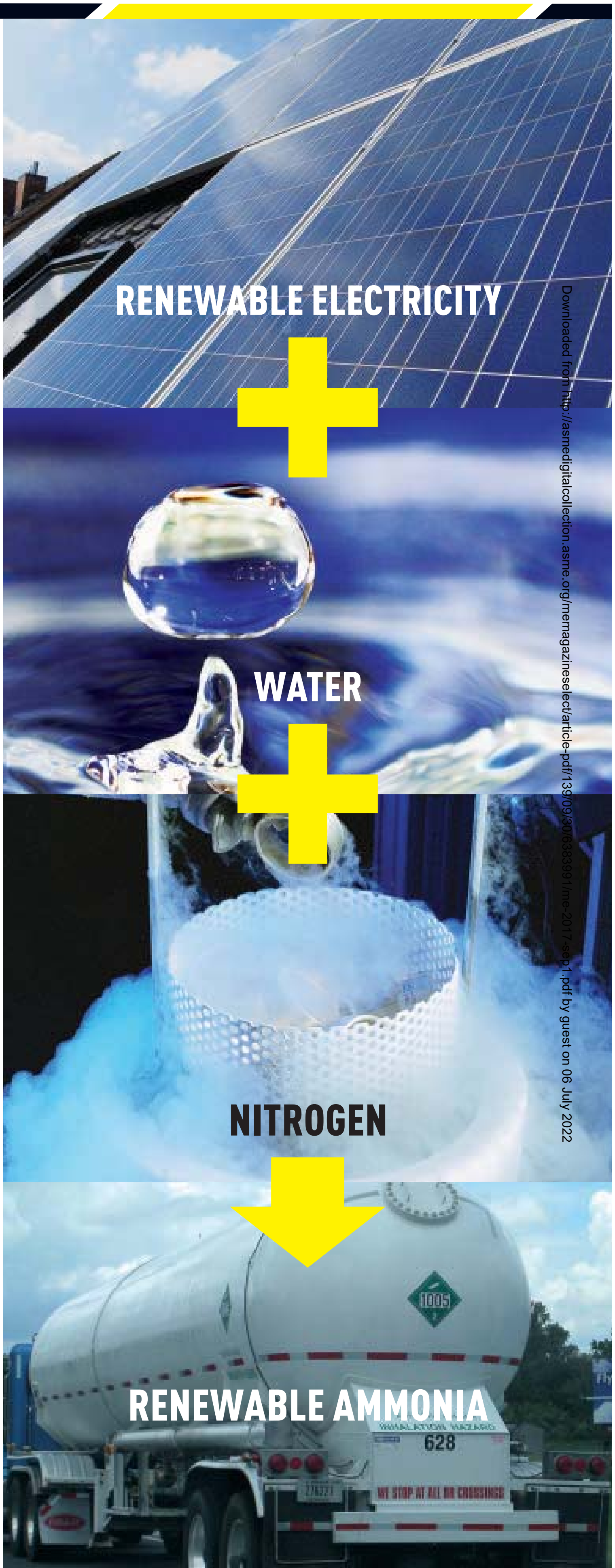
Another potential electrofuel is ammonia produced using the Haber-Bosch process, an exothermic reaction of hydrogen and atmospheric nitrogen using a metallic catalyst. The Haber-Bosch process is already widely used in industrial production of nitrogen-based fertilizers, but typically reforms methane with steam to produce sufficient hydrogen for the ammonia reaction. To make ammonia an electrofuel, the hydrogen required for the reaction could be produced via solar- or wind-powered electrolysis, and the rest of the process could be powered by renewable energy sources, avoiding the need to extract fossil reserves of methane. The production of renewable ammonia provides an effective energy carrier for transporting hydrogen—ammonia can be liquefied at a temperature of -33 °C (-28 °F), significantly warmer and easier to achieve compared to the -253 °C (-423 °F) required to liquefy hydrogen.

These simple chemical pathways allow us to start with renewable, carbon-free electricity from wind and solar installations and produce an array of liquid and gaseous fuels that can be used for future power generation, transportation needs, or industrial processes.

To engineers, it's not enough for a process to work. We must know that it can work at scale. How much electrofuel—renewable hydrogen, renewable methane, and renewable ammonia—could the United States produce in a year?

According to the U.S. Energy Information Administration, the United States produced 609 billion kWh of renewable electricity in 2016. If instead of feeding that electricity to the grid, it was directed to the production of renewable fuels using electrolyzers performing with 75 percent efficiency, then it could produce 12 billion kg of hydrogen. That renewable hydrogen could in turn produce either 19 billion kg of methane or 52 billion kg of ammonia. To put those amounts in perspective, the United States produced approximately 9 billion kg of hydrogen, 600 billion kg of natural gas, and 9 billion kg of ammonia in 2016.

On the basis of energy, the production of 12 billion kg of hydrogen would be the equivalent of 11.5 billion gallons of gasoline, approximately 8 percent of annual gasoline consumption in the United States, a nontrivial amount. As



COMPARISON OF FUEL CHEMICAL REACTION

Fuel	Chemical reaction to form electrofuels	Energy required to form the fuels [kJ of energy per mole of fuel]
RENEWABLE HYDROGEN	$2H_2O + e- \rightarrow 2H_2 + O_2$	285.8
RENEWABLE METHANE	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ + *heat*	-164.0
RENEWABLE AMMONIA	$N_2 + 3H_2 \rightarrow 2NH_3$ + *heat*	-45.8

Hydrogen can be produced using renewable electricity (denoted as *e-*) as an input. Hydrogen is both a fuel and an input for the exothermic, catalyst-induced reactions to make methane and ammonia, hence all three are rightly called electrofuels.

renewable power sources continue to grow, the technical potential for production of renewable fuels will continue to rise.

Challenges do exist for utilizing renewable electrofuels. Electrolysis on this scale would require a sustainable supply of purified water. This challenge can be technically overcome with desalination, but the resulting integrated desalination and electrolysis system will require additional capital and supply of renewable energy.

Ammonia also faces challenges with safely storing, transporting, and handling the fuel due to its corrosive and hazardous nature. If the challenges of ammonia are too significant, alternative synthetic fuels could be considered that provide similar hydrogen carrier capability.

Storing excess energy in chemical bonds in the form of hydrogen, methane, or ammonia is an effective way to achieve long-term, grid-scale storage.

While the potential to displace conventional, nonrenewable, carbon-emitting fuels is appealing, the production of electrofuels could also help us manage the grid in the face of more variability. That gives us one more reason to consider them a solution to several problems simultaneously.

The rise of wind and solar has helped reduce emissions and wholesale electricity costs from the power sector. But, because wind and sunshine change according to a mix of climatic, meteorological, and astronomical factors, they introduce a lot of variable supply into the grid. This variability is different than the conventional mindset of dispatchable power plants such as those fueled by nuclear, coal, and natural gas, and is a technical challenge for grid managers. As additional renewable electricity is installed in coming years, countries might face increasing hurdles with integrating these intermittent energy supplies with the grid.

One way to solve the variability challenge is through grid-scale energy storage. Despite significant effort, electrochemical batteries still face technical and economic challenges to achieve grid-scale storage. Pumped hydro storage and compressed air energy storage can provide long duration, large capacity storage but deployment of those systems are dependent on finding the right geography or geology.

Storing excess energy in chemical bonds in the form of hydrogen, methane, or ammonia is an effective way to achieve long-term, grid-scale storage. Instead of storing a surplus of electricity in batteries to be used later, we can convert that electricity into energy-dense liquids and gases. Doing so has the potential to be simpler and cheaper while also helping to decarbonize the transportation sector. And that means fabricators of the electrofuels can get paid twice: once for stabilizing the electric grid, and again when they sell the fuels.

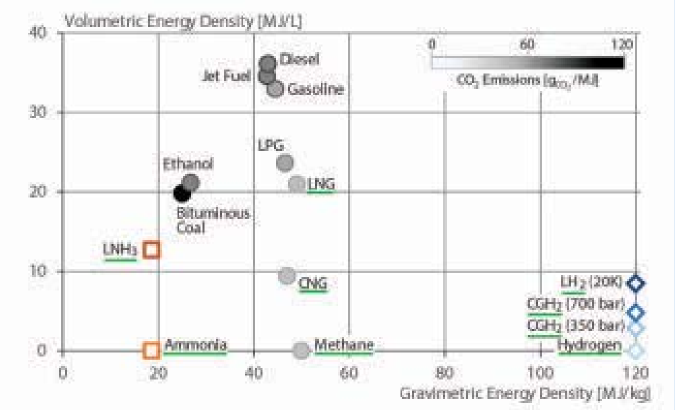
The production of synthetic fuels is an opportunity to make our energy system cleaner and more reliable. This process would solve several problems at once: stabilizing intermittent electricity supply while creating renewable fuels for use in power generation, transportation, and industry.

The large-scale introduction of wind and solar power now makes the production of renewable fuels at least technically feasible. Policymakers should start to give electrofuels the attention they deserve. There are many tax credits or subsidies for renewable or low-carbon sources of electricity such as wind, solar, geothermal, and nuclear, but electrofuels are not yet prominent in the discussion. And, while states like California have mandates for energy storage, stakeholders often ignore the option of electrofuels despite the potential for them to be a more useful and affordable competitor to batteries.

It may be some time before it becomes common for drivers to get behind the wheel of a hydrogen-powered car, as President Bush called for. But electrofuels may provide a unique solution to a number of challenges. And it's time our markets and policies recognize that possibility. **ME**

COMPARISON OF VOLUMETRIC AND GRAVIMETRIC ENERGY DENSITY OF FUELS

A comparison of the volumetric and gravimetric energy density of various fuels (using lower heating value). Hydrocarbon fuels are shown in gray tones corresponding to their carbon emissions from combustion. Candidate electrofuels are underlined. Compressed gases and liquefied fuels are denoted with a prefix of C and L; for instance, compressed gaseous hydrogen is CGH_2 and liquefied ammonia is LNH_3.



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