"The world's overloaded power grids are on the cusp of a megabattery boom."
—BLOOMBERG

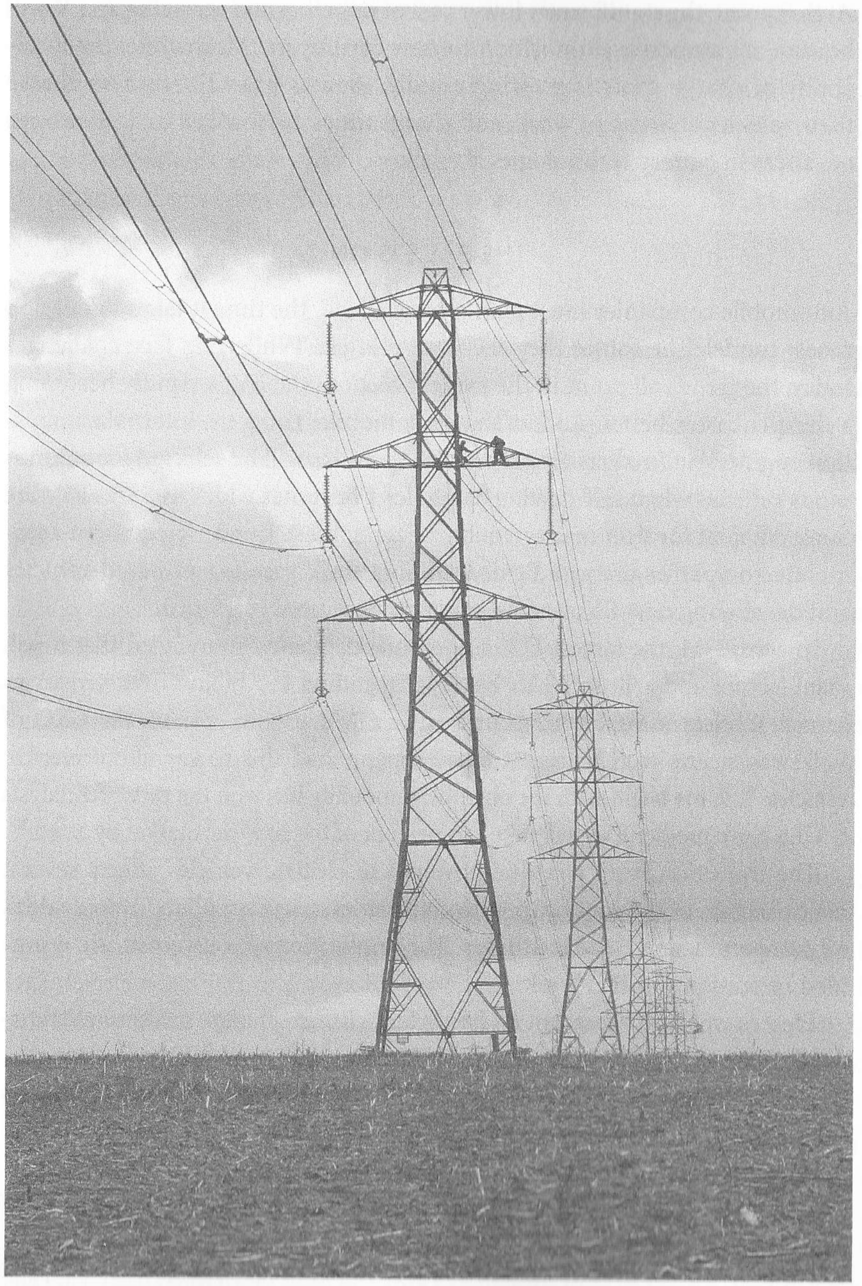

FIGURE 6.1. Power transmission lines. (Source: Wikimedia Commons)

Chapter Six

ENERGY STORAGE

Renewable wind and solar power are cheap, abundant, and produce zero-emissions electricity. But they have one significant drawback: intermittency. Wind turbines cannot generate power on calm days, and solar panels cannot generate power at night or on cloudy days. Given the intermittency inherent in solar and wind generation, there is a growing need for energy storage to balance the demand and the supply of power. Understanding energy storage first requires an explanation of how electricity is managed on the grid.

THE LOAD PROFILE

Electricity is consumed in varying amounts throughout the day, described by a *load profile*, a graph of demand for electricity in a 24-hour day.[1] Electricity demand is typically lowest during the night, when most people are sleeping and businesses are closed. During the day, the load profile increases, especially in warmer regions with air conditioning. The load profile typically reaches a peak, referred to as *peak load*, in the late afternoon or early evening, when air temperatures reach a daily high and workers return home to switch on air conditioning, lights, appliances, and other electrical devices.

Managing the load profile is an essential task of a modern electrical grid, as consumers and businesses expect electricity to be continually available. Fluctuating demand for electricity requires the grid operator to supply

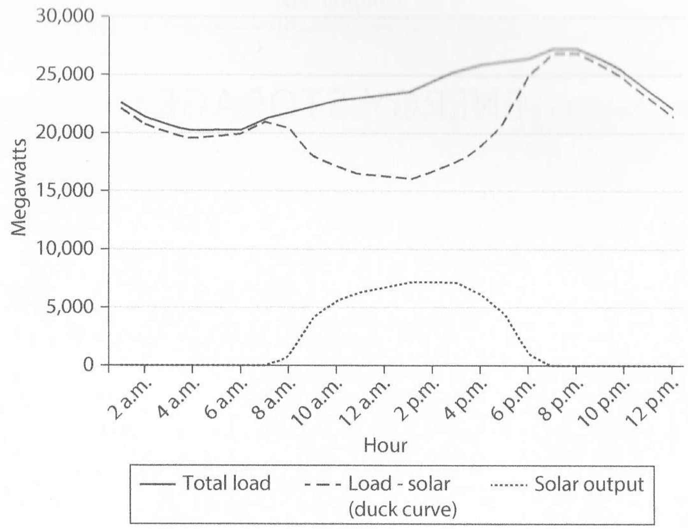

FIGURE 6.2. California's load curve (*Source*: Wikimedia Commons)

enough electricity to meet peak load without oversupplying electricity when demand falls. Managing the grid becomes harder when the generation of electricity is from intermittent sources such as wind and solar power.

The challenge posed by the intermittency of wind and solar power is already evident in California, where generation of electricity by renewables has affected the entire state's load profile for electricity. Figure 6.2 is the load profile for California.[2] Demand for electricity, as shown by the line labeled Total Load, hits a low at about 5:00 A.M., then slowly increases throughout the day, peaking at about 7:00 P.M. The problem that has emerged is that generation of electricity from solar power, as shown by the Solar Output line, peaks around 2:00 p.m. This distorts the net demand curve—the difference between overall demand and solar power output—to the line labeled Load – Solar. This distorted load profile vaguely has the profile of a duck, hence it is referred to in the utility industry as the "duck curve."

The grid operator must ensure that the supply of electricity precisely meets the demand curve throughout every 24-hour day, a challenge made increasingly difficult by the growing supply of electricity from wind turbines and solar panels. The duck curve in California is worsening every year with

the addition of renewables. California is a leader in renewable energy, but other states are rapidly catching up and experiencing the same challenge balancing the load profile.

Solutions to the duck curve include demand response, peaker plants, and energy storage.

Demand Response

Utilities encourage customers to reduce demand for electricity during peak load periods, a tactic called *demand response*. Utilities do this by offering a financial incentive to customers, for example by reducing the utility bill of customers who install sensors that automatically increase the temperature setting on air conditioning during especially hot summer days. Demand response can assist utilities in balancing the load profile, but it cannot solve the problem of intermittent wind and solar power at scale.

Peaker Plants

Across the United States there are approximately 1,000 peaker plants that use natural gas to supply electricity on an as-needed basis.[3] Peaker plants have the advantage of being "dispatchable," meaning they can be rapidly turned on and off. But they are costly. Investment bank Lazard calculates the average natural gas peaker plant levelized cost of electricity (LCOE) at $175/MWh, five times the cost of power from renewables.[4] Costly peaker plants solve the challenge of balancing the load profile, but at great cost.

Energy Storage

More than 96 percent of global grid-scale storage capacity is in the form of pumped hydro storage, a technology developed more than 100 years ago.[5] Pumped hydro storage uses electricity to pump water from a lower-elevation reservoir to a higher one. When electricity is needed, the process is reversed, and stored water from the higher reservoir is released through turbines, which generates electricity. Pumped storage hydro is a reliable, dispatchable system for producing electricity on demand, with a round-trip efficiency that converts 70–75 percent of the electricity used to pump water back to the grid when needed.[6]

Unfortunately, pumped hydro is a poor solution to the energy storage challenge resulting from the rapid growth in solar and wind power generation. Pumped hydro storage is only feasible where the geology provides for two large water reservoirs conveniently separated by significant elevation, which is present in very few locations. Even more prohibitive, pumped hydro storage is costly to construct, and costs are not forecast to decline given the extensive engineering and construction required to build pumped hydro storage sites.[7]

Many other technologies exist for storing electricity on the grid, including compressed air, multiple battery technologies, and even flywheels. Among these technologies, lithium-ion batteries have the advantage of being extremely efficient, exhibiting round-trip efficiency of 92–93 percent. Conveniently, manufacturing costs of lithium-ion batteries are rapidly declining, driven by demand in an entirely different sector.

MEANWHILE IN THE AUTOMOBILE MARKET . . .

Tesla became the first American automobile company since the Second World War to successfully enter the mass market and the first to offer exclusively electric vehicles (EVs). But the success of the Model S created a problem for Elon Musk and his team. Tesla had taken advantage of the declining cost of lithium-ion batteries for laptops and mobile phones, following growth in those sectors to lower costs. However, Tesla's demand for lithium-ion batteries to build vehicles outstripped demand from laptops and mobile phones. It was estimated that production of the Tesla Model S in 2014 accounted for 40 percent of all lithium-ion batteries manufactured globally.[8] This prompted Musk to try another innovation, the Gigafactory, with the objective of reducing the manufacturing costs of lithium-ion batteries.

BIRTH OF THE GIGAFACTORY

In 2014, Tesla broke ground in Sparks, Nevada, on what it calls the Gigafactory, the world's biggest lithium-ion battery factory. It is difficult to overstate its size. When fully complete, it will be the largest building in the world,[9] designed to take advantage of manufacturing scale to lower the price of Tesla's battery packs by 30 percent.[10] Jessika Trancik, a professor at MIT, found that "lithium-ion battery technologies have improved in terms of their

costs at rates that are comparable to solar energy technology," estimating that costs decline 20–31 percent for every doubling in market size.[11]

This creates a virtuous circle for Tesla. Lower battery prices make Tesla's cars more cost-competitive, increasing demand for them, increasing the production of batteries, decreasing the cost of manufacturing, and thus again driving up demand. Tesla's relentless focus on batteries drove costs down to \$142/kWh in 2021,[12] less than half the cost when the Model S was launched. Elon Musk predicts a further 56 percent decline over the coming three years.[13] This is good news for Tesla. And great news for renewable wind and solar power.

DECAPITATING THE DUCK

Taking advantage of the rapidly declining cost of lithium-ion batteries, battery energy storage systems (BESSs) are replacing natural gas peaker plants to balance the load profile of the electrical grid. This solution is referred to as "decapitating the duck," as lithium-ion batteries store excess electricity generated from wind and solar and feed it back to the grid in the evening and at other peak times of the day, eliminating the bulge in the load profile curve. Not only are BESSs less costly than peaker plants, but lithium-ion batteries also have faster response times and can be instantly ramped up and down to balance the load on the electrical grid.

Vistra, a leading American utility, built the world's largest BESS in a retired natural gas power station in California. The Moss Landing project has 300 MW of power for 4 hours, providing 1,200 MWh of storage capacity, enough power for 225,000 homes.[14] The project can be expanded by a factor of 5 to 1,500 MW at a future date.[15] Vistra is not alone with this strategy. The U.S. Department of Energy forecasts 27 percent compound annual growth in grid storage through 2030.[16]

The extraordinary importance of lithium-ion batteries was recognized in 2019 when the Nobel Committee awarded the Nobel Prize in Chemistry to three scientists, announcing: "This lightweight, rechargeable and powerful battery is now used in everything from mobile phones to laptops and electric vehicles. It can also store significant amounts of energy from solar and wind power, making possible a fossil fuel-free society."[17]

Ever cheaper lithium-ion batteries will solve the short-term energy storage problem associated with the daily load profile. Unfortunately, batteries are ineffective at providing long-term energy storage to handle multi-day periods of low wind and sun. Addressing the intermittency challenge of renewables will include two additional solutions.

BACKUP ENERGY: V2G

In February 2021, winter storms pummeled Texas and knocked out power generation in much of the state, leaving 3 million homeowners in the dark. Electric vehicles can, in the future, prevent those blackouts.

Electric vehicles have the capability to send electricity back to the grid when they are not being used, a process called vehicle-to-grid (V2G) or bidirectional charging. In this way, electric vehicles are positioned to provide backup energy when the grid becomes overloaded. Ford's F-150 Lightning pick-up truck is the first electric vehicle in the United States to offer V2G capability.[18] V2G can provide significant backup energy; for example, Ford's F-150 has batteries capable of powering the average American home for up to 10 days.

Tesla sells a home battery system called the Powerwall, which uses the same lithium-ion batteries found in its automobiles. Like V2G, home battery systems can reduce grid instability. In California, homeowners with a Tesla Powerwall battery are participating in an experimental "virtual power plant" to send electricity back to the grid during periods of high demand, helping to reduce power outages and potentially generating additional revenue for Powerwall owners.[19]

V2G and home battery systems are a viable solution for backup energy storage, solving the problem of blackouts during periods of severe weather or other dislocations on the electrical grid. But they cannot provide long-term energy storage capable of maintaining reserve capacity for many days or weeks, a challenge requiring a different climate solution.

LONG-TERM STORAGE AND THE ENERGY TRANSITION

The global energy transition to wind and solar power will create a growing need for long-term storage to ensure electrical grid stability. A report by the University of California, Berkeley, estimates that a U.S. grid using 90 percent renewable energy would require 150 GW of storage capacity rated for 4 hours (i.e., 600 GWh),[20] a more than 100-fold increase on current capacity.[21] BESS projects using batteries will meet some of that demand, but batteries are a poor solution for multi-day energy storage.

Venture capital investors are financing engineers who are developing a wide range of multi-day energy storage products, including new battery designs, capacitors, flywheels, pumped air, and gravity systems. These technologies hold promise, but all face considerable technical and commercial hurdles. Fortunately, there exists an entirely different climate solution that can provide long-term, scalable energy storage: green hydrogen.

"Hydrogen will become, 30 years from now, like oil is today."

—SEIFI GHASEMI, CEO, AIR PRODUCTS & CHEMICALS, INC.

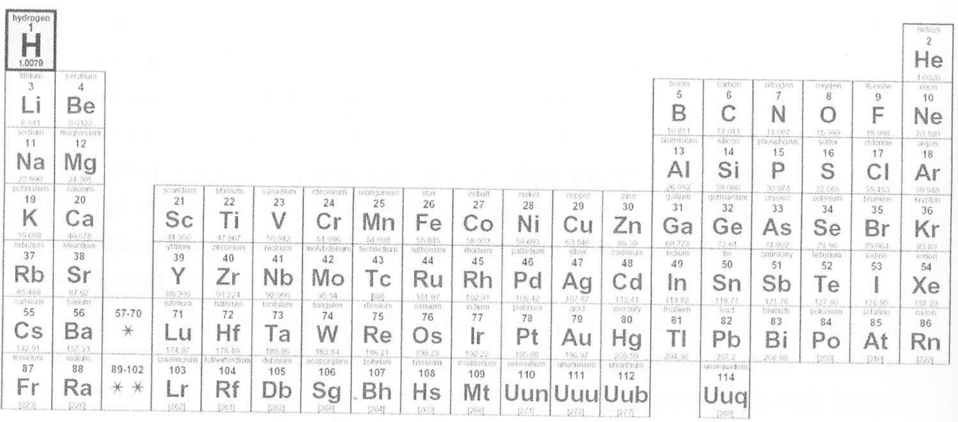

FIGURE 7.1. The periodic table, with hydrogen emphasized (Source: Wikimedia Commons)

Chapter Seven

GREEN HYDROGEN

Renewable solar and wind power are the fastest-growing sources of new power generation on the planet, and declining costs will continue to accelerate the energy transition from fossil fuels to renewables. Simultaneously, the declining cost of batteries is solving the challenge of solar and wind power intermittency, providing short-term energy storage to balance the grid's load profile. But there are several sectors of the economy that are poorly suited to electrification. Air travel, long-distance ocean freight, heavy trucks, fertilizer, and industrial processes such as production of steel cannot easily be converted to electricity. And long-term energy storage for the electrical grid still relies on fossil fuel–powered peaker plants. Hydrogen, specifically "green hydrogen," is an attractive alternative, a potentially unlimited source of energy that does not emit greenhouse gases.

Hydrogen has long been used as a source of energy. Early in the twentieth century, hydrogen blimps provided the first transatlantic air travel, and hydrogen is used today in a range of industrial applications, from oil refining to fertilizers. Hydrogen is an appealing fuel because it is the lightest element (figure 7.1), providing twice as much energy per unit mass as oil or natural gas. Unfortunately, hydrogen is a challenging fuel to use as it is highly combustible and needs dedicated infrastructure for distribution. Because hydrogen is so light, the energy density per unit volume is very low, requiring high-pressure systems to liquify hydrogen for transport. But the greatest challenge to hydrogen is cost.

Hydrogen is the most abundant element in the universe yet occurs naturally on Earth only in compound form with other elements—hydrogen combined with oxygen is water, and hydrogen combined with carbon forms the hydrocarbons found in fossil fuels. To use hydrogen as a fuel, it must first be separated from other compounds. Steam methane reforming is the most common method for production of hydrogen, in which natural gas is used as the source of methane in the process. This is commonly referred to as "gray hydrogen." Unfortunately, production of hydrogen using steam methane reforming does not mitigate climate change, as the natural gas used in the process emits CO_2.

Hydrogen can also be produced using technologies to capture and store CO_2 emissions, a climate mitigation technique described in the next chapter. Production of hydrogen in this way avoids emissions of greenhouse gases and is referred to as "blue hydrogen"; however, it is significantly more costly than gray hydrogen because of the expense of capturing and storing CO_2. From a climate change perspective, blue hydrogen is better than gray hydrogen, but from an investor perspective it is uneconomical without large government subsidies or other incentives. Fortunately, there is another process for production of hydrogen that has the potential for both low cost and low emissions.

GREEN HYDROGEN

Hydrogen can be produced by splitting water into its respective elements, oxygen and hydrogen. The technology to do this, an electrolyzer, uses an electrical current to separate water molecules. Electrolyzers require significant energy to operate, which is both costly and polluting if the power is generated from the burning of fossil fuels. Fortunately, the rapid growth in renewable solar and wind power creates an opportunity to produce hydrogen using zero-emissions electricity, and to do so at low cost. Schematically, production of "green hydrogen" is relatively simple, as shown in figure 7.2:

Green hydrogen is currently more costly to produce than gray or blue hydrogen, as electrolyzers are expensive to manufacture and require large inputs of electricity to operate. But that is rapidly changing.

The cost of electrolyzers is following a learning curve as demand and production expand, estimated at 9–13 percent.[1] This means the cost of electrolyzers is forecast to fall by approximately 11 percent for every doubling

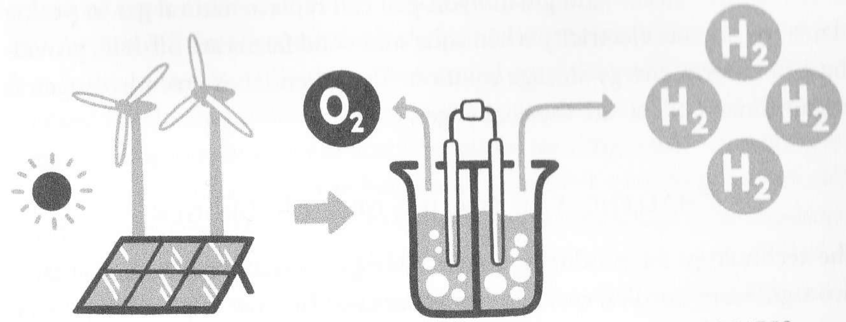

FIGURE 7.2. The production process for green hydrogen (Figure by the author)

in existing units produced. Demand for electrolyzers is forecast to grow rapidly, so even a modest learning curve will result in significantly better economics. Along with lower electrolyzer costs, the price of electricity, the primary input to creating green hydrogen, is also forecast to drop significantly because of the declining cost of power from wind and solar. Given forecasts for inexpensive electrolyzers and cheap renewable electricity, Goldman Sachs predicts a more than 500-fold increase in hydrogen production facilities by 2050.[2]

SO MANY APPLICATIONS

Dr. Julio Friedman of Columbia University foresees a broad range of applications for green hydrogen, calling it the "Swiss Army knife of deep decarbonization."[3] Hydrogen can be used in an extraordinary number of ways.

In transportation, fuel cells convert hydrogen to electricity, which is then used to power vehicles. Hydrogen-fueled buses are already in use, and hydrogen can be used to power long-distance trucking and shipping. Even aircraft. Airbus has announced plans to develop a commercially viable hydrogen airplane that could enter service by 2035.[4]

In agriculture, hydrogen is a feedstock to ammonia, and green hydrogen can be used to produce inexpensive, emissions-free fertilizer.[5] In industry, hydrogen can be used in the production of steel in lieu of coal, enticing investors to finance a $3 billion green hydrogen plant in Sweden to produce emissions-free steel.[6] And green hydrogen can replace natural gas in peaker plants to generate electricity when solar and wind farms are off-line, providing a long-term energy storage solution. The potential of green hydrogen is extraordinary, but so are the challenges.

CHALLENGES TO SCALING GREEN HYDROGEN

The technology for producing green hydrogen already exists, but it faces two significant hurdles: cost and infrastructure. The cost of producing green hydrogen, $3 to $8 per kilogram, is uncompetitive with gray hydrogen and other fuel sources and will remain so until costs decline to $1/kg.

Forecasts for green hydrogen production costs vary widely. Morgan Stanley predicts green hydrogen sited next to wind farms in the American Midwest could be competitive in 2022,[7] while Bloomberg New Energy Finance predicts it will take until 2050 for green hydrogen to decline in price to $1/kg.[8] There is little doubt that the cost of producing green hydrogen will decline markedly with cheaper electrolyzers and ever-cheaper wind and solar power. But then low-cost hydrogen will face a second challenge: transporting it from where it is produced to where it will be used.

Hydrogen is challenging to ship and store, requiring pressurization at low temperature. Existing natural gas and oil pipelines cannot be repurposed, as pure hydrogen creates brittleness in steel pipes and valves. Building new hydrogen infrastructure creates a Catch-22—should companies invest in hydrogen transportation infrastructure before the cost of green hydrogen becomes competitive or should they wait, in which case costs may never decline? Overcoming the infrastructure challenges facing green hydrogen requires innovative solutions by businesses and investors. One American company, Air Products & Chemicals, is betting it has found a way forward.

COMMERCIAL INNOVATION

Air Products, a global leader in industrial gases, has established a $5 billion joint venture with a Saudi renewable energy company to build the world's largest green hydrogen project. Located in the desert of northwestern Saudi Arabia,[9] the project is in an ideal spot for generating extremely low-cost solar power during the day and wind power at night. It also has a port.

Air Products is using an innovative strategy to address the infrastructure challenge of transporting hydrogen from Saudi Arabia to markets where it can be used. Instead of compressing and shipping hydrogen by pipeline, this facility will first convert the hydrogen to ammonia, which is denser and less costly to transport by ship. The shipped ammonia will be unloaded and trucked to refueling stations, where it will be disassociated to yield hydrogen, thus avoiding construction of costly pipelines on either end.[10] Refueling stations will provide hydrogen to buses and automobiles running on fuel cells. Air Products expects this single facility to produce enough green hydrogen to run 20,000 hydrogen-fueled buses.[11] Simon Moore, a vice president at Air Products, had this to say about his company's plan: "No kidding, this can be done."[12]

THE GREEN HYDROGEN FUTURE

Hydrogen could meet up to 24 percent of the world's energy needs by 2050.[13] For this to happen, massive amounts of additional renewables will need to be constructed to power electrolyzers, and new shipping, pipeline, and refueling infrastructure will need to be built, all of which will require investment capital. McKinsey & Company forecasts global investment in green hydrogen will reach $300 billion annually by 2030.[14] Investment bank Evercore estimates $2 trillion in spending on hydrogen from 2030 to 2050.[15]

Green hydrogen holds the potential to decarbonize the gaps remaining after the transition from fossil fuels to renewable wind and solar, and after the transition from the internal combustion engine to electric vehicles. Long-distance trucking, shipping, air travel, heavy industry, and agriculture can all reduce greenhouse emissions with green hydrogen. Most important, hydrogen can provide long-term energy storage to allow for 100 percent penetration of intermittent renewable power on the electrical grid.

The climate solutions described in section 2 of this book, including green hydrogen, can reduce global greenhouse gas emissions by a remarkable 75 percent by 2050.[16] Which is an extraordinary reversal after 250 years of emissions growth. But it is not enough to take emissions to *zero*, the target that scientists forecast is needed to avoid catastrophic climate change. That will require one more climate solution: carbon removal.