Hydrogen for a Better Planet

One of the most promising alternatives for a sustainable planet for all
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“Hydrogen is the most important constituent of the universe.”
—Gerhard Herzberg, physicist, physical chemist and Nobel Laureate
Introduction

Steady incremental progress towards a hydrogen economy

For centuries, we had no idea it existed. The first hints of it in the lab made scientists call it “flammable air.” It defied common sense by producing water when burned and being lighter than air. Amazing, for hydrogen is the most abundant element in the universe and on our planet.

As a source of energy, hydrogen has no close competitors. One gram of hydrogen fuel yields the same amount of energy as ten million grams of coal when subjected to the pressures inside stars. The average-sized star contains an unimaginable quantity of it: 75% of its mass is comprised of hydrogen atoms—which is plenty to last through the ages.

Every light you see up in the night sky is powered by hydrogen, which produces energy that lasts billions of years and supplies the hydrogen that makes the water you drink. Imagine: just a fraction of the 1-to-10 million hydrogen-to-coal energy ratio could power our society for thousands of years without the need to burn anything.

In stars, hydrogen releases its energy at its most extreme. Yet, the hydrogen in your glass of water is the same element as the one burning in stars. It actually came from there and can be extracted through less violent means to achieve the incredible energy potential of the hydrogen atom.

As a potential source of clean energy, hydrogen also has no close competitors. For starters, its combustion results in water vapor. The caveat, however, is to develop the technology to make it clean on the production side. Currently, only about 5% of the world’s hydrogen fuel is produced using renewables, so there is a way to go before we can call hydrogen a 100% clean fuel. Happily, there has been technology innovation on the production side to make hydrogen clean.

This ebook explores the important role that hydrogen—a fundamental element—has played for humanity over the past five hundred years and how issues like climate change and energy availability for all could be tackled using hydrogen fuel.

We also explore Hydrogen 2.0™ and how this new method could yield the transformational, localized production of hydrogen energy at the point-of-use, safely and with no carbon emissions.
“In its special role as the simplest of all atoms, hydrogen has starred in some great episodes in the history of science.”

—Daniel Kleppner, Lester Wolfe Professor of Physics, Emeritus at MIT
Hydrogen History in Ten Milestones

Hydrogen is fundamental and basic to our understanding of the natural world. The importance of the hydrogen atom to science, and our understanding of the universe, cannot be overestimated. The hydrogen atom has a fascinating story in human “firsts.”

Hydrogen is so simple, so elegant in its internal composition, that initially it was thought to be the basic building block of matter. Yet, although it is the most abundant element in the universe and is present in every molecule of water here on Earth, hydrogen was invisible to us until the 16th century. That is when scientists discovered a mysterious substance they referred to as “flammable air,” which paradoxically, produced water when combusted. The surprises from “the mother of all atoms” were far from over.

This intriguing “new” element proved to be lighter than air, enabling humans to fly well before the advent of the airplane. The study of hydrogen, in its unique position as the simplest of all atoms, literally helped physics uncover the workings of the subatomic world. Hydrogen enabled scientists to understand basic concepts such as the building blocks of matter, energy, and the nature of light, opening the door to the discovery and understanding of quantum mechanics.

As an energy source, hydrogen powers rockets, the Hubble Space Telescope, and holds the potential to become a mainstream clean fuel for all types of applications.

There is a fascinating history behind hydrogen’s crucial role in science, technology, and society, and the men and women whose work with this all-important element enabled humanity’s progress. The universe’s most energetic element has been the inspiration for many of the most important discoveries of the last 500 years.

From hydrogen to anti-hydrogen, here are ten such milestones:

1. 1671: First-time hydrogen gas is produced in a lab
   Before the 16th century, nobody had ever “seen” hydrogen. As abundant as it is, in its pure molecular form it is so light and so prone to mixing with other elements, that it isn’t commonly found on Earth. The first scientist to “see” it was Swiss alchemist Paracelsus in 1536 who unknowingly observed hydrogen when he noted a gaseous byproduct arising from acids attacking metals. It was 135 years later, in 1671, that British scientist Robert Boyle—who’s regarded as the first modern chemist and pioneer of the modern experimental scientific method—replicated this experiment with iron filings and acids. This mix resulted in the production of highly reactive pure hydrogen and is widely recognized as the first-ever hydrogen gas produced in a lab using the scientific method.

2. 1766: Hydrogen recognized as a discrete substance for the first time
   It took nearly one hundred years to realize that Boyle’s gas was more than a by-product of a reaction. In 1766, Henry Cavendish was the first to isolate and characterize hydrogen as a discrete substance, naming the gas from the metal-acid reaction “flammable air.” He speculated that “flammable air” was, in fact, identical to the hypothetical substance called “phlogiston” (a 17th-century theory that tried to explain oxidation by postulating that a fire-like element called phlogiston is contained within combustible bodies and released during combustion). Then in 1781, Cavendish discovered that when his “flammable air” burned, it combined with oxygen to produce water.
After months of speculating, his work on this novel gas led him to realize that he had, in fact, discovered an element, not just a substance. Two years later, French chemist Antoine Lavoisier gave the element the name hydrogen (from the Greek word hydro meaning “water” and genes meaning “creator”).

3. 1783: Hydrogen powers the first human aircraft

A hundred years before the invention of the airplane, humans took flight using hydrogen. It did not take much time after realizing that this “gas” was lighter than air to ideate a way to lift humans into the sky. The first hydrogen-filled balloon was invented by Jacques Charles in 1783. A few decades later, hydrogen became the first reliable form of air travel following the 1852 invention of the first hydrogen-lifted airship by Henri Giffard. This invention inspired German Count Ferdinand von Zeppelin to devise rigid airships lifted by hydrogen that later were called Zeppelins, the first of which made its maiden flight in 1900. Regularly scheduled flights started in 1910 and by 1914, 35,000 passengers had taken to the sky in these airships. Hydrogen also powered the first non-stop transatlantic crossing by air, which was made by the British airship R34 in 1919.

4. 1806: Hydrogen is used to power engines for the first time

Did you know that the hydrogen-powered internal combustion engine preceded the gasoline-powered engine by 50 years? The internal combustion energy was a new technology in the 1800s, and many scientists were experimenting with different ways to power it. Hydrogen’s energetic potential gave French scientist and politician François Isaac de Rivaz the idea to build the first engine powered by hydrogen. This engine came to be known as the de Rivaz engine, an internal combustion engine powered by a mixture of hydrogen and oxygen. This engine had an electric ignition system used to start the reaction between the two elements. Just a year later, Rivaz obtained a French patent for his invention, which was published in 1807.

5. 1913: Hydrogen is used to establish the atomic model of elements

In 1913, Danish physicist Niels Bohr discovered that the hydrogen atom is made up of a positively charged nucleus of very small dimensions and an even smaller electron closely orbiting around it. His work with hydrogen led him to perfect the first theoretical model of the atom by introducing the relationship between the radius of the electron orbits and the energy contained in them. Bohr published his findings in a set of the papers known as the “Bohr Trilogy,” which became seminal for understanding the structure of the atom. Importantly, his measurements with hydrogen allowed him to include in his atomic model the quantum effect to explain how electrons “jumped” orbits and changed their energy state.

6. 1925: The quantum effect is proven by experimenting with hydrogen

In 1925 and 1926, the work of three physicists (all Nobel laureates) on the hydrogen atom enabled science to develop the model and the explanation for quantum mechanics. First, Werner Heisenberg laid the groundwork to establish the theory of quantum mechanics by working on the wave-particle duality of photons and electrons. Specifically, he focused on the frequencies and intensities of spectral transitions in the hydrogen atom. The model was completed when Paul Dirac introduced Einstein’s Theory of Relativity to explain the effect that the elliptical orbits of electrons had on the energy spectra of hydrogen. At the same time, Wolfgang Pauli developed the mathematics around it all. After the work of these three physicists, Quantum Mechanics became widely regarded as one of the most solid physical theories to explain what happens at the subatomic level.
Quantum mechanics has not only consistently been proven through experimentation, but it is also the basis for many widespread technologies we depend on in our everyday lives.

7. 1938: Work on hydrogen results in the Magnetic Resonance Method—the precursor to MRI

In 1938, Isidor Rabi, working at Columbia University, created an experiment to configure the magnetic field for deflecting particles in a molecular beam. The Magnetic Resonance Method he invented enabled scientists to measure the magnetic moment of protons and deuterons; these measurements gave us the first accurate measures of the size of the nucleus of atoms and the ways in which it behaves. A few years later, just after WWII, his method was adopted as a noninvasive medical diagnostic tool to “see” inside the human body—which led to the MRI machines that are widely used throughout the world today.

8. 1960: The atomic clock is invented

It was Isidor Rabi who, once again, first suggested the possibility of atomic clocks in 1945. Based on this idea, Norman Ramsey and his student Daniel Kleppner, invented the high-precision hydrogen maser clock in 1960, which became the first successful atomic clock stable to one second in 300 million years. Applications of their invention came immediately. The first applications were implemented by NASA, who used sets of atomic clocks and receivers to triangulate the actual positions of space probes (by precisely measuring the time the radiations from these probes arrived). This technology evolved out of academia and government to become the basis of modern Global Positioning Systems (GPS), which guides all satellites and enables every single location-based app on our mobile phones today.

9. 1977: First hydrogen battery enables space exploration

Although hydrogen has been powering rockets since the U.S. and the USSR launched the space age in the 1950s, it is the subsequent invention of the hydrogen battery that has enabled us to explore Mars and run the International Space Station (ISS). These batteries are known as nickel hydrogen batteries and were used for the first time in 1977 aboard the U.S. Navy’s Navigation Technology Satellite-2 (NTS-2). Today, the ISS and several NASA planetary probes, such as Mars Odyssey and the Mars Global Surveyor, are equipped with nickel-hydrogen batteries. In the dark part of its orbit (when the Earth blocks the sun), the Hubble Space Telescope is also powered by nickel-hydrogen batteries. The Hubble batteries lasted for more than 19-years after launch before being replaced by new ones.

10. 1996: Antihydrogen becomes the first antimatter particle ever produced in a lab

It is quite fitting to close this list of ten hydrogen “firsts” with something that today still sounds like science fiction. Since the beginning of the scientific discovery of hydrogen, it has defied prevailing common understanding, such as producing water when burned or being lighter than air. So, the last “first” on our list is related to antihydrogen, which is the antimatter counterpart to hydrogen. Antimatter is one of quantum mechanics implications, the first particle of it—a positron—was observed by Carl Anderson at the California Institute of Technology in 1932. It would take more than 60 years before scientists could actually produce an antimatter particle in the lab. This feat was enabled by hydrogen. In 1996, antihydrogen was produced at CERN and to this date, it is the only type of antimatter atom ever to have been produced by physicists.
“The more I look at Earth, and certain parts of Earth, the more I feel [like] an environmentalist, it’s just a blanket of pollution in certain areas.”

—Scott Kelly, NASA Astronaut
Chapter 2

Climate Change
The Urgent and Important Issue to Tackle

“When you can see climate change from space, you can’t help but become an environmentalist,” astronaut Scott Kelly recently proclaimed from the International Space Station (ISS). Civilization’s footprint is so significant that it is now a question of survival to pay attention. A warming planet affects everyone. It is a problem that makes national boundaries not only irrelevant, but invisible.

We all know what painful compromises mean. Until just a few years ago, extracting oil and gas were easy. Find the source, dig a hole, pump it out or carve it off, and ship it. That is the primary reason these energy sources were universally adopted. They were cheap, reliable, and plentiful.

But then, easy-to-mine sources became more difficult to find. Fracking, one of the most Earth-damaging extraction methods ever devised, had to be invented to finesse oil and gas out of rocks and sands. Moreover, the economies of China and India grew so much that pollution levels from coal and oil became unsustainable. Earlier this year, China implemented, for the first time ever, two days of “Red Alert” in its capital—meaning it was too toxic to breathe outdoors without a mask.

Facts and data confirm what astronaut Kelly saw from the International Space Station. Data from the State of Climate Report released by the National Centers for Environmental Information (part of the National Oceanic and Atmospheric Administration) indicates that the February 2016 global temperature set a new record for “highest monthly departure from average.” It goes on to indicate that the December–February 2016 global temperature also set a record for “highest departure from average for any three-month period.” This comes on top of July 2015 being the warmest month ever recorded (since records started in 1880) and 2015 being the warmest year on record.

According to the World Meteorological Organization (WMO), a United Nations body, in their Status of the Global Climate Report, “Levels of greenhouse gasses in the atmosphere reached new highs and in the Northern hemisphere spring 2015, the three-month global average concentration of CO₂ crossed the 400-parts-per-million barrier for the first time.” How many records must be broken before we get serious about reversing the huge impact we have on the Earth’s climate?

The fact that 15 of the top 16 warmest years on record have occurred since 2000, with each successive year becoming the warmest on record, should be enough to spring us into action. Urgent, focused action.

Astronaut Scott Kelly concluded his remarks about the pollution he could see from the ISS with the following statement, “We can fix it if we put our minds to it.” Quite an optimistic note from a man who became familiar with viewing our planet. After all, he orbited the Earth 5,440 times (that’s about 15 times per day).

Climate change is a global problem, a problem that many of us believe can be fixed. However, to do so, the problem must be solved from several fronts. There are three focus areas to ensure we work in a direction that has an impactful and lasting positive effect to tackle a warming planet—and fix it on time. Here are the three pillars we need to work on to effect climate change:
1. Policy
This is probably the most effective collective tool we have at our disposal. Governments around the world have finally made solving the climate problem a priority. Policies that encourage people and industry to actively do their part are sprouting everywhere. For example, the set of policies adopted last December at the Paris Conference (collectively known as “COP21”) are a huge step in the right direction and have definitely focused the minds of our leaders on tackling a problem we can no longer ignore. No matter your nationality, the size of your country, or your ranking on greenhouse emissions, the solution to global warming must be global in scope. Climate change does not recognize national borders.

2. Culture
Good policies serve to set the stage. Lasting change needs the focus of everyone, everywhere. Encouragingly, more and more people around the world are taking actions like biking to work, conserving energy and demanding clean fuel with the objective of doing their part. After all, the pollution and climate impact seen by astronaut Kelly from space are felt every day by people down here.

3. Innovation
The third pillar to tackle climate change must come from sheer human ingenuity. We all know there is a limit to what people and governments will do to reduce global warming, and that “comfort zone” is a reality we cannot ignore. Innovation is crucial to solving our global warming problem.

Thousands of entrepreneurial companies and organizations around the world are working on technology innovations to tackle the greenhouse gasses that result in climate change. From clean energy to clean transportation to clean manufacturing, the collective efforts of industry are starting to make it to market and are making a positive impact. The policies of our governments plus the demands of our customers help technology companies like ours “put our minds to it” as astronaut Kelly suggested.

The WMO Status of the Global Climate Report also indicated that global warming is occurring at an alarming and unprecedented rate. “The future is happening now,” said WMO Secretary-General Petteri Taalas in a statement released alongside the report. “The alarming rate of change we are now witnessing in our climate as a result of greenhouse gas emission is unprecedented in modern records.”

We should all take note. We can see the imagery of this data on the accelerating pace of climate change all around us. Photographs of the Bird’s Nest, the stadium built for the Beijing 2008 Summer Olympics, shrouded in gray smog, or a lone polar bear floating on a small chunk of melting ice remind us every day that climate change is an urgent problem waiting to be solved.

In December 2015, a historic accord was reached by 195 countries in Le Bourget, France. The resulting “Paris Agreement” is the first globally inclusive pact to fight climate change, calling on the world to collectively cut and then eliminate greenhouse gas pollution (GHG). Although it’s not obvious, this change in geopolitical attitude from mere talk to serious, binding action is being fueled by innovation.

The fact that the Paris Agreement happened after previous attempts failed is evidence that technological breakthroughs are enabling countries on all sides, developed and developing, to see viable alternatives to hydrocarbon-based energy sources without long-term, painful compromises. Thus, a commitment to the carbon emission goals required by the treaty was no longer seen as a road to economic catastrophe.

Innovations that made the Paris Agreement possible are here. Solar panel installations are soaring, wind adoption is growing, and innovative entrepreneurs in many industries are closer to making the promise of a clean planet possible. Even on the consumer front, innovation is leading the way to no-compromise everyday living—think Nissan Leaf, Chevy Volt, Toyota Prius and Tesla, for example.
“Climate change has become a pillar of the U.S.-China bilateral relationship.”

Chapter 3

A Better Planet
The Tough Choices and the Brave Governments and Industries Behind Them

On March 31, the U.S. and China issued a joint statement aimed at getting the world on the right track to address global warming. The statement declared, “The United States and China will sign the Paris Agreement on April 22nd and take their respective domestic steps to join the [Paris Climate] Agreement as early as possible this year.”

More than 170 countries signed the agreement in April, which is in itself a record, with the highest number of countries ever signing an international treaty. After years of hesitation, climate change has finally become a central issue for the world’s largest economies, and the rest of the world has responded. The top two world economic powers—and CO2 contributors—don’t dance around the climate change issue anymore.

For a long time, any agreement on climate change between the superpowers seemed to be a zero-sum game. Take the mixed results of the Kyoto Protocol, for instance. For many years, the point of contention to agree on curbing carbon emissions was the huge differential in the development stages between developed and developing economies.

In fact, the United States originally opted out of Kyoto because of the exemptions granted to China, India, and developing countries. For the 12-years that the protocol was in place, the world’s largest polluters—U.S., China, and India—were practically free to keep doing business as usual. The arguments that the U.S. and China made for not following the Kyoto agreement back in 1999 were opposite sides of the same coin.

While the U.S. claimed that Kyoto restrictions would cost jobs and damage their economy, China argued that to agree to curb carbon emissions would slow its economic growth and cause them to fall behind their goal of becoming a superpower. They reasoned, and many economists agreed, that developed economies got there in part by using energy with practically no restrictions. Over the 12-years that this agreement was in effect (from 1999 to 2011), both the U.S. and China actually increased their carbon emissions, while Europe and Russia—who signed the agreement with no exemptions—actually reduced their emissions and grew at the same time.

We seem to be in a completely different economic and political climate today (pun intended). In their March 31 joint statement, President Obama and President Xi Jinping stressed the “need for a swift transition to low-carbon, climate-resilient economies.” Their past “economic impact” positions are completely gone from this statement. The two presidents further stated that their countries will work together “to accelerate clean energy innovation and deployment.”

United Nations Secretary General Ban Ki-moon underscored the significance of the milestone when he indicated, “The historic agreement is only the beginning. We must urgently accelerate our efforts to tackle climate change.” It is refreshing to see the world leaders agree that resilient economies and a responsible attitude to address climate change can, indeed, coexist.
As the largest economy in the world and the second largest greenhouse gas emitter accounting for 12% of total emissions worldwide, the Obama administration is keenly aware that specific actions need to go along with its signature. The world is watching how American government and industry tackle climate change.

For instance, India’s environment minister Prakash Javadekar told BBC News, “What happens in the U.S. will have a definite bearing on how the world takes all these ideas, commitments and pledges into effect. So people are eagerly awaiting what happens in the U.S.” This is significant, coming from an economy that ranks fourth in greenhouse gas emissions.

David Waskow, Director of International Climate Initiative for World Resources Institute said, “The joint statement that the United States and China will sign and join the Paris Agreement as early as possible this year sends an extremely powerful signal.” He further notes that the crucial element of trust required for the goal of working together on energy innovation and deployment, “Cements the role that climate plays in the U.S.-China relationship. It shows the confidence that both countries have in each other’s ability to deliver on their climate commitments.”

In fact, the growth excuses of the past as expressed by the top economies, which are also the top contributors of CO₂, was due more to the fear of moving away from the comfortable status quo of hydrocarbons. This is because coordinated innovation on a global scale—meaning cooperation to get there—was never included in these arguments.

The puzzle pieces necessary for the world to tackle climate change finally seem to be falling into place. For instance, the cooperation to fuel energy innovation is happily backed by the material means to make it happen. The Presidents’ Joint Statement exerts both countries will “Commit to taking concrete steps to implement the commitments they made in their September 2015 Joint Statement to use public resources to finance and encourage the transition toward low-carbon technologies as a priority.”

The other important pieces come from the innovators themselves: entrepreneurs and companies all around the world who believe technology can provide the necessary solutions the world requires to tackle man-made climate change once and for all.
“Hydrogen has secretive as well as exuberant properties.”

—Daniel Kleppner, Lester Wolfe Professor of Physics, Emeritus at MIT
Chapter 4

Hydrogen to the Rescue
How Hydrogen Can Help Us Leap to a Cleaner Planet

When it comes to the Periodic Table, hydrogen is number one. Literally and figuratively. Hydrogen is light, simple, and extremely energetic. Hydrogen’s elemental role in water, life, and fuel make it such a wonder amongst the other 117 elements in the universe. First, hydrogen is water: it is literally the water-forming element. Hydrogen is named after the Greek words hydro for “water” and genes for “forming.” Hydrogen is essential for life in two ways. It is present in all the molecules in living things, including you and me, and it literally acts as the “glue” of the DNA molecule by holding together the bonds between the two helix strands. Finally, hydrogen is fuel: NASA uses hydrogen as a fuel for the rockets that deliver crew, cargo and probes to space. Hydrogen actually fuels every moving thing, as the element plays a key role in the energy contained in hydrocarbons (thus, the “hydro” prefix) and in the creation of the photons that hit solar panels.

The last point—hydrogen as fuel—makes this element a truly transformative agent of change for society with the potential to power everything from cars to cities. Hydrogen embodies three unique characteristics that make it extremely valuable. These characteristics are intrinsic to the element itself and are the foundation that makes it the perfect energy source.

1. Hydrogen is everywhere

The most abundant element in the universe makes up 75% of matter by mass and more than 90% by the sheer number of atoms. It’s the fuel of stars and is present in every molecule of water—the most plentiful substance here on Earth. It is this abundance that makes hydrogen so attractive as a source of energy that could be powering societies everywhere.

2. Hydrogen is clean

Hydrogen is a clean-burning fuel because it produces zero pollutants during its use. There’s no greenhouse gasses, no emissions, no particulates, and no negative environmental impact. The combustion of hydrogen fuel results only in water vapor that nature immediately reincorporates into the environment. Historically, the challenge has been how to make the production and transportation of hydrogen as “clean” as the element itself.

3. Hydrogen is available 24/7

Hydrogen provides reliable 24/7 availability in any weather, at any time of the day or the night, anywhere in the world. Here’s some perspective: According to a Slate Magazine article, “Hawaii needs more electricity at precisely the moment in the day that sun power starts to fade.” Wind suffers from the same environmental conditions: no wind power where the wind does not blow.
Alternative energy sources are problematic in urban areas where wind and sunlight are constrained. 24/7 availability is a huge advantage of hydrogen. Given the amazing potential of hydrogen in so many areas, it is no surprise that we are rapidly approaching a new era that can be powered by hydrogen energy—despite the big challenges in its extraction and handling processes. Decades of research and work on hydrogen are finally paying off.

Just last month for example, a second pan-European hydrogen refueling infrastructure for passenger and commercial fuel cell electric vehicles was deployed. This six-year Hydrogen Mobility Europe 2 (H2ME 2) project brings together 37 partners from across Europe for the deployment and operation of 1,230 fuel cell vehicles and the addition of 20 extra hydrogen refueling stations to the existing hydrogen European network. This initiative marks just the latest milestone in the progress we’ve seen for hydrogen energy in the past several years.

One of the key drivers behind the surge in hydrogen progress is that governments, research institutions, and industry around the world clearly see the potential of hydrogen as an abundant and clean energy source and are working together to unlock its enormous market value.

This progress is underscored in the latest report from the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) which states, “A decade of sustained global research, development and demonstration is now producing the necessary technological breakthroughs for hydrogen and fuel cells to compete in the market.”

We may be quite close to a time where we can finally realize the intrinsic benefits of hydrogen—abundance, sustainability and availability—and make the universe’s most abundant element the power behind humanity’s sustainable progress.
“With a new national commitment, 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 [be] pollution free.”

— President George W. Bush, 2003 State of the Union
Chapter 5

The Economic Challenges of Getting to a Hydrogen Economy

It is not only a matter of achieving a cleaner planet, the latent economic value of producing and using hydrogen energy on favorable market terms could be in the trillions of dollars. In the past, promises of a “hydrogen economy” failed to materialize. False starts for a hydrogen economy have not stopped the efforts to make it happen. It isn’t hard to see why. Hydrogen’s specific energy—or the energy potential per unit-of-mass—is three-times that of gasoline and diesel, nearly five-times that of coal, and almost six-times that of ethanol. The goal is definitely worth pursuing.

A seminal look into the future of energy was explored in the acclaimed book, *The Third Industrial Revolution*, by futurist Jeremy Rifkin. The book treats hydrogen as the third of five pillars for taking civilization to its next transformative leap forward into what he calls the “third industrial revolution.” Rifkin’s thesis of a fully distributed energy system to power everything from mobile devices to cities, positions hydrogen as a vital energy carrier that can move us away from fossil fuels and into renewables.

He cites some progress towards that vision, such as a major public/private initiative by the European Union, called the Joint Technology Initiative, to speed up the production of hydrogen from renewables. What we really need, however, is Rifkin’s vision of hydrogen on steroids so that it can become a source of fuel, and not simply an energy carrier.

Rifkin’s book was written almost eight years ago. His vision at the time held that the third industrial revolution would happen when new energy and new communications technologies converged. He called this the “Internet of Energy,” where distributed communication and energy systems would work together.

Unfortunately, the hydrogen component of Rifkin’s puzzle has not yet materialized. Just a couple of weeks ago, for instance, an article appeared titled, “Whatever Happened to the Hydrogen Economy?” It is a title which has, unfortunately, become all too common.

Our progress toward the goal has been slow. After all, hydrogen gas is a challenging molecule. Producing, storing, and distributing hydrogen using traditional methods is difficult and expensive such that a real ROI is unachievable, even when the avoided social costs of carbon are duly considered. This underscores a concept that makes or breaks the adoption of any new technology: market forces.

There are countless papers and opinions about the need to address the many inefficiencies across the full hydrogen supply and consumption chain before we ever see a bonafide hydrogen economy. For any energy source to “power an economy,” or to be a pillar for an industrial revolution in the sense that Rifkin suggests, the value—including all operational considerations—needs to be self-evident.
Market forces dictate what the prevailing power sources will be. Hydrocarbons prevailed as the energy source of choice during the twentieth century because of simple market forces. Specifically, oil, coal, and gas are highly energetic and have been relatively cost-efficient to extract, store, transport, and consume. In that context, hydrogen math does not work yet. The challenges behind traditional hydrogen across various stages in its path towards market simply make it uncompetitive.

Here are each of these challenges.

**Challenge #1: Producing hydrogen**

Large-scale hydrogen production using traditional methods, such as steam reformation of natural gas, gasification of coal, and electrolysis of water, are cost-prohibitive. Regardless of whether the energy used to produce hydrogen is derived from nuclear, fossil fuels, or renewables, the amount of energy required via these methods to liberate hydrogen from the bonds it forms in water, coal, or gas has historically not justified the relatively small energy that is produced. As a result, hydrogen has been relegated to the role of a mere energy carrier suitable for only specialized applications, rather than being elevated to the mainstream fuel source that we want it to be.

**Challenge #2: Storing hydrogen**

Then there is the serious problem of storage. Diatomic hydrogen (H₂) is a tiny molecule; its volumetric density is very low, lower than that of all of our other combustible gases. Therefore, it is fundamentally hard to get enough combustible gas in one place to be of practical use. Storing hydrogen gas is extremely difficult and requires expensive equipment. It is usually compressed and cooled to extremely low temperatures to reduce its volume (and increase its density) for storage purposes. This results in compressed hydrogen or liquid hydrogen (i.e., maximum compression). Both forms can severely weaken tanks and other storage devices; this process of hydrogen embrittlement further adds to the bottom line costs of taking liquid or gas hydrogen to market.

**Challenge #3: Transporting hydrogen**

The challenges and costs of hydrogen transportation are an extension of the challenges and costs of hydrogen storage. The hydrogen economy vision, as originally conceived back in the 1970s, required a completely new infrastructure to take hydrogen gas to market. The sheer complexity and cost of building and operating the hydrogen infrastructure required to compress, store, and transport sufficient hydrogen mass to address market demand—and the assumption that the huge infrastructure for other fuels would eventually be rendered obsolete—was flawed. The vision ignored the realities of market forces, which heavily favored the incumbent infrastructure.

In the past decade, there have been two major shifts that have improved the relative value of hydrogen. First, the relative economic value of hydrocarbons is eroding. As easy-to-access sources of oil and natural gas deplete, methods such as fracking and deep drilling drive up the cost of these fuels when measured by direct costs, social costs, or both. The social costs of carbon, including those of hydrocarbon extraction, have become much better understood. Importantly, these extraction techniques add to the hidden environmental costs of continuing life as usual—such as the pollution of aquifers by chemical by-products and the global warming caused by emissions after combustion. On both the economic and environmental fronts, traditional energy sources are becoming less attractive.
This brings us to the second shift that improves the relative value of hydrogen: efficiency of use. In the past decade, hydrogen use has seen unprecedented innovation. Take fuel cell technology for example. Positive advances in the productivity of fuel cells have most, if not all, of the major automotive manufacturers set to launch hydrogen fuel cell electric vehicles. Just this summer, Toyota put a stake in the ground for hydrogen power when the Toyota Mirai, the world’s first hydrogen fuel cell car, hit the market in California. Interestingly, hydrogen-powered cells are not just grounded. Last month, discount airline EasyJet announced plans for a hybrid airplane based on hydrogen.

However, for such hydrogen fuel cells to provide lasting value in the market, similar breakthroughs are needed to solve the three market challenges explained above. As bold as Toyota’s move is, the same article indicates that they are “Hoping that there will be enough infrastructure to support its hydrogen-powered car.” Needless to say, “hope” and the reality of market forces need to meet each other halfway. Otherwise, regulations and artificial subsidies will always be required to power these cars and planes, and hydrogen energy will not become mainstream because the market forces are not sufficient to drive adoption.
“If we could have one superpower, it would be to have energy to fuel poverty reduction.”

— Bill and Melinda Gates, 2015 Annual Letter
Chapter 6

Hydrogen 2.0: Designed to Eliminate Friction

Bill and Melinda Gates dedicated their annual letter this year to the availability of clean energy. They note that 1.3 billion people do not need to imagine a life without power—“that is what life is like for them every day.”

Don’t just picture the basics; visualize zero power for things like giving birth at night or keeping food from rotting. In this context, power becomes a fundamental human rights issue for a whopping 18% of the world’s population. The Gates, who have been an amazing force for good in this world, are optimistic about the prospects of this superpower of energy materializing. And for good reason. In their letter, they go on to say, “We’re betting that within 15 years, scientists and engineers will develop big breakthroughs that will put us on a path to zero carbon emissions and make energy more affordable for everyone.”

We actually don’t need to make a bet: clean, affordable and available energy for everyone, everywhere may be much closer than that.

The trillion-dollar value mentioned in the previous chapter could materialize by bringing to market a cost-competitive and clean method of hydrogen production that leverages much of our existing liquid fuel storage and transportation infrastructure. One of the most recent hydrogen breakthroughs is around a completely new approach to hydrogen production that is called Hydrogen 2.0.

This term refers to the highly efficient, localized production of clean hydrogen fuel, on-demand at the point-of-use, safely, affordably and with no carbon emissions. What this means is that, for the first time, we can envision hydrogen going mainstream and opening a new era of commercially viable applications with mass-market potential that could change the way we power our factories, offices, and homes.

Hydrogen 2.0 aims to improve the relative market value of hydrogen on all three fronts: production, storage, and distribution.

To this end, at Joi Scientific, we focus our efforts on making hydrogen available as a source of clean energy at a price point that can compete with traditional and alternative fuels. This requires a method for producing hydrogen efficiently, on-demand, right where it is needed, so as to eliminate or minimize costly infrastructure requirements. By doing all of the above, we believe Hydrogen 2.0 will align first- and second-order market forces, and lower the barriers to widespread adoption.

Hydrogen 2.0 can mark the beginning of a new era where hydrogen is generated from seawater using sustainable technology that does not create carbon emissions that harm the environment. It is an abundant energy source that has no negative impact on nature or people, making it affordable without compromise.

Here are the seven ways Hydrogen 2.0 could transform not only the hydrogen fuel segment, but our entire approach to energy:
Chapter 6

1. **Hydrogen 2.0 is low-cost**
   Economics drives widespread adoption of nearly everything—especially something as pervasive as energy. The process behind Hydrogen 2.0 makes the economics of hydrogen work by the simple fact that it requires no exploration; no mining; no exotic, precious, or rare earth chemicals; and no expensive electrolysis. This process is also affordable for developing economies and provides a level of pricing stability and levelized cost that neither fossil fuels—because of their scarcity or market fluxes, nor renewables—because of fluctuations in their natural availability, can provide.

2. **Hydrogen 2.0 is available on-demand**
   Hydrogen 2.0 is transported and stored as seawater—not as volatile hydrogen gas—and then transitioned into energy on-demand, where and when it is needed as fuel. The Hydrogen 2.0 process converts hydrogen into a gas at the point-of-use, on-site or on-board, for instant consumption. This distributed and on-demand availability further drives down costs, improves operational flexibility, and creates a safe energy source.

3. **Hydrogen 2.0 is lifecycle clean**
   Unlike traditional hydrogen production processes that emit 5 kilograms of greenhouse gases for every 1 kilogram of hydrogen produced, the Hydrogen 2.0 production process produces zero pollutants during its production or use. Hydrogen 2.0 eliminates both the ecologically damaging greenhouse gases and the health damaging particulates emitted by coal, diesel, and other hydrocarbon-based fuels. Its use does not lead to loss of habitat or environmental damage, and the process lacks byproducts that could poison downstream processes (such as carbon monoxide or halides).

4. **Hydrogen 2.0 leverages existing infrastructure**
   Just as the economics of producing a fuel drive its adoption, the economics of taking it to market determine whether society can afford it. Hydrogen 2.0 will leverage the world’s existing liquid fuel distribution channels—standard tanks, pumps, and nozzles. It does not require expensive retrofitting or a completely new infrastructure to get energy where it is needed.

5. **Hydrogen 2.0 is easy to store and transport**
   Hydrogen 2.0 is produced on-demand where and when it is needed, which means that before you need it, it is stored and transported as water. As a result, it can be stored, without pressure, at a wide range of temperatures (0°C to 90°C). There is no need for compression, or even for special tanks and pipes that are sometimes used to deal with the natural corrosiveness of hydrogen when in high concentrations.

6. **Hydrogen 2.0 is safe**
   Hydrogen’s volatility has traditionally made storage and transportation expensive when compared to other forms of energy. Because Hydrogen 2.0 extracts hydrogen from water on-demand at the moment of use, it enables the element to remain in a natural liquid state (in water) at room temperature without pressure until the fuel is required. Needless to say, this water-based feedstock is safe to handle, store, and transport; and it is non-flammable and non-hazardous if spilled.
7. **Hydrogen 2.0 cleans hydrocarbons**

Hydrogen 2.0 makes other fuels cleaner. Specifically, it can be used to manufacture synthetic gasoline or to enrich traditional fuels, boosting the octane and BTU level of hydrocarbons when combined with coal, oil, and natural gas to make them burn completely, burn cleaner, and burn more energetically.

A way to actualize the “energy miracle” that Bill and Melinda Gates refer to in their letter, is to work to expedite the world’s transition to clean and affordable hydrogen energy, and to make it available to people everywhere, in both developed and developing economies.

Like other monumental calls for ingenuity to move humanity forward, this one is being answered from the Kennedy Space Center with Hydrogen 2.0. Their goal of clean and abundant energy for everyone is no longer a noble intention: it is a movement joined by people everywhere—from governments to scientists to companies—to the world’s biggest and smartest philanthropists. This collective work and ingenuity to tackle the urgent need for clean energy that reaches every corner of the planet will soon bear fruit so that the future “energy miracle” becomes a near-term reality that benefits everyone, everywhere.
“It always seems impossible until it’s done.”

—Nelson Mandela
Chapter 7

A World Powered by Hydrogen
The Three Pillars of Hydrogen 2.0

The hydrogen economy has had several false starts. For decades, the fuel promise for the most energetic of elements kept eluding us. But during that same time, hydrogen technology continued to make incremental progress taking us in the right direction. The key areas of production, storage and transportation have all seen innovation. We also have the attention, and the funding that comes with it, of governments and industry everywhere.

The approach we are working on with Hydrogen 2.0 involves the efficient production of hydrogen from water molecules, which will allow us to take it to market without the limitations of expensive infrastructure. Both are equally crucial to realizing the promise of a hydrogen-powered society.

This chapter explores the three pillars of the potentially transformative vision behind Hydrogen 2.0: abundance, affordability and sustainability.

1. Abundance of Energy
Despite being the universe’s most abundant element, hydrogen’s use has been restricted by the challenges of how to harvest its energy. The problem being that traditional hydrogen production is a centralized process that requires a specialized and expensive infrastructure for safe storage and distribution. The infrastructural barriers have constrained hydrogen’s availability, and to this day, hydrogen fuel is only used for specialized applications.

This is where Hydrogen 2.0 could change the game through the localized production of hydrogen energy at the point-of-use. It is based on efficient extraction technology that produces hydrogen gas from water. Thus, the first pillar of Hydrogen 2.0 is the transformational shift in the creation of hydrogen and in the way it is taken to market.

Both are necessary ingredients in order to call any energy “plentiful.” Today, we could not call hydrogen an abundant source of energy because it is, for many practical purposes, unavailable to society as a whole. The costs of producing it and delivering it to market present significant barriers to availability.

Because Hydrogen 2.0 is produced on-demand, where and when it is needed, it can leverage the existing infrastructure for liquid fuel storage and transportation, making it truly available to all. This availability also augments renewables, such as solar and wind, which are not available 24/7, nor in every part of the world. This would make Hydrogen 2.0 energy that everyone can access.
2. Affordable Energy
Affordable energy is the second pillar of Hydrogen 2.0. To compete alongside hydrocarbons and renewables, hydrogen fuel must be made at yields that are cost-competitive to alternatives. It also requires a paradigm shift in the supply chain so that “affordable” also means a source of energy with stable and predictable pricing. For perspective, in the past, the energy required to harvest hydrogen from water made it expensive. This is because of the relatively low yields generated by electrolysis, a traditional process used to separate hydrogen from its oxygen bond in the water molecule.

Regarding stability in pricing, one needs to look beyond traditional hydrogen (since it was a niche fuel). Pricing stability is something hydrocarbons have never provided. Pricing volatility is a dual-edged sword: high oil prices make it unaffordable for developing economies, while low prices offer little incentive for companies and governments to make hydrocarbons available to all.

Hydrogen 2.0 eliminates the need for expensive compromises. It can be produced in abundance on a cost-competitive basis to other energy alternatives without requiring subsidies. Because it is produced from nature’s most abundant substance, water, it is also an energy source with an unprecedented level of predictability in pricing stability.

3. Sustainable Energy
The final pillar of Hydrogen 2.0 is as clear as water. Literally. Zero emissions is Hydrogen 2.0’s answer to the urgent calls for taking action on climate change. In particular, zero emissions results from having a clean process in both the production and the consumption ends.

Here’s why: on the production side, traditional hydrogen fuel processes require high amounts of energy as well as emit an average of 5 kilograms of greenhouse gases for every 1 kilogram of hydrogen produced. In addition to not being very environmentally friendly, this made the cost of traditional hydrogen too high for widespread adoption.

The Hydrogen 2.0 extraction process frees hydrogen from water molecules without chemicals, catalysts or electrolysis, and without any greenhouse gas emissions. This is huge: it finally makes hydrogen fuel cost-competitive and clean.

On the consumption side, things are just as clear. The Hydrogen 2.0 process returns only clean water back into the environment. This is because burning hydrogen as a fuel results in nothing but pure water. In places where purifying water is not an option, the Hydrogen 2.0 process could provide a valuable source of pure drinking water. This is energy everyone can drink.
“With these two gifts, fresh water and electricity, we could enable the people who are left out today because of their lack of resources to join in the global economy and have hope.”

— The late John Sheptor, Joi Scientific COO
Chapter 8

The Developing World
The Imperative Need for Fuel Availability

In this era of ubiquitous WiFi and social media, it is hard to imagine that 20% of the world’s population still live without access to power for education, medicine or infrastructure. That’s zero power for things we take for granted, such as preserving food, responding to emergencies and communicating with the rest of the world.

Dr. Jim Yong Kim, Director of the World Bank, has a bold initiative to end this extreme poverty. His influential international body recognizes the pivotal role energy plays in the daily lives of people everywhere. Specifically, the World Bank is focusing on boosting prosperity for the bottom 40% people of the world. Dr. Kim calls it “shared prosperity.” The genius is they recognize clean and affordable energy as a lever to make this lofty goal happen. The World Bank is working to raise $40 billion to invest in non-carbon energy systems for the 70 poorest nations by 2020 so that they can benefit from COP21, the system of matching grants for clean energy initiatives set up at the Paris Innovation Forum last fall.

This promise is especially relevant when it comes from Dr. Kim. He has a track record of delivering transformative change for those who need it the most. As Director of the World Health Organization’s HIV/AIDS Department (from 2003 to 2005), he led the “3 by 5” initiative: the first-ever global goal for AIDS treatment, which helped to expand its reach in developing countries. The goal of ending extreme poverty could not be in better hands: Dr. Kim received a MacArthur “Genius” Fellowship, was recognized as one of America’s “25 Best Leaders” by U.S. News & World Report, and TIME Magazine named him among its “100 Most Influential People in the World” in 2006.

Dr. Kim’s plan has a solid foundation to make it viable. The funds will include a combination of matching grants and World Bank investment, which make interest-free money available to combat climate change right away and positively impact the lives of the poorest people on Earth. Dr. Kim gave the examples of successful clean energy initiatives in Pakistan and Peru where the costs per kilowatt fell dramatically, especially with distributed power. Finally, the World Bank’s recent shift in strategy makes it more agile and flexible when it comes to investing in crises—especially health and energy crises, which tend to affect the poor the most.

The late John Sheptor, Joi Scientific’s Chief Operating Officer and former deputy director for operations, procurement and logistics for the presidential Emergency Plan for AIDS Relief (PEPFAR) who led the logistics of the PEPFAR Drug Supply Initiative, saw first-hand the negative effect that lack of electricity and fresh water had on entire towns and villages around the world. This, he pointed out, was the main source of the healthcare crisis and eventual social collapse. In his words, “1.3 billion people on this Earth have no access to electricity. This forces them into poverty and all of the challenges of poverty.”
Ending extreme poverty is a challenge that international institutions like The World Bank, governments and innovative energy companies like ours and many others are set to win by working together.

The work we are doing with Hydrogen 2.0 can help international organizations, such as The World Bank, achieve their goal of shared prosperity, which includes using energy to improve the lives of billions of people who have no access to power. To achieve this, governments, international organizations, and industry everywhere need to work together to expedite the world’s transition to clean and affordable hydrogen energy and make it available to all—especially in the developing world.

The system of distributed hydrogen power behind Hydrogen 2.0—the type of system that visionary leaders like Dr. Kim recognize as the most practical way of bringing energy to those who need it the most—could boost progress in this front. This is because the localized production of hydrogen energy at the point-of-use, safely, affordably and with no carbon emissions is pivotal to make energy available everywhere.

Hydrogen 2.0’s efficient extraction technology to produce hydrogen gas from water on-demand, and on-location so that people can have clean hydrogen energy (and water), where and when it is needed, could change the lives of millions in need.

The crucial elements of life quality—access to electricity and clean water—that form the foundation of civilization can be catalysts for change for the one-in-five-people in the world who currently don’t have them. With clean water and electricity, food production and small business ventures will thrive, people will be healthier, and they will be able to focus on enhancing the quality of their lives, not just in struggling to survive.
“The sea is only the embodiment of a supernatural and wonderful existence. It is nothing but love and emotion; it is the Living Infinite.”

— Jules Verne, Twenty Thousand Leagues Under the Sea
Conclusion

The Incremental, Steady Progress in Hydrogen Technology is Reaching a Tipping Point

The energy change that the world needs is still elusive. Taken together, clean sources of energy amount to a significant change, but not the transformative change that the world is seeking to combat climate change and tackle poverty.

We need clean fuel sources that can compete alongside hydrocarbons and represent clear and easy ways to reduce carbon emissions without painful compromises or expensive new infrastructure. The countries who signed the Paris Agreement this past April are counting on these alternative ways to power their economies. It is up to industry, governments and international bodies to collaborate together to realize the vision of a sustainable world economy that grows.

Breaking the century-old monopolistic hold that hydrocarbons have enjoyed can only be done by tapping into one or several sources of energy that collectively are as plentiful and as affordable as oil and gas.

It also needs to be done by leveraging the world’s existing liquid fuels infrastructure. Even so, the way to tackle climate change is not to suddenly replace everything. Rather, it is to offer solutions that complement all other energy sources so that market forces and innovation take us to a sustainable world at a pace everyone can afford.

Hydrogen 2.0 is one of the innovative answers to the urgent and important sustainability challenges the world faces. It can offer a no-compromise energy source for our society. Best of all, Hydrogen 2.0 is designed to co-exist with traditional fuels. Specifically, it is designed to leverage the existing transportation and storage infrastructure. Hydrogen 2.0 can even make existing fuel sources, whatever they may be, burn cleaner and more efficiently.

The time for abundant and clean energy that everyone can afford—especially our planet—is upon us.

At Joi Scientific, we are working to unlock the huge economic, environmental, and social value of hydrogen. This value could materialize by bringing to market a cost-competitive and clean method of hydrogen production that leverages much of our existing liquid fuel storage and transportation infrastructure.

When we achieve this mission, together with the many advocates of hydrogen, we will be helping to usher in a new era, akin to the concept of a Third Industrial Revolution envisioned by acclaimed futurist Jeremy Rifkin a few decades ago.

So, continue to watch this space.