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INTRODUCTION

In his January 2003 State of the Union address, George W. Bush announced a major initiative laying out his vision of a hydrogen economy: "Tonight, I'm proposing $1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles. A single chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car—producing only water, not exhaust fumes. 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 pollution-free."

That speech was the reason I wrote the first edition of this book—which was published in 2004—to answer the question of whether such a high-tech Eden was hype that was too good to be true or whether it would happen in your lifetime.

But although I supported increasing the budget for hydrogen in the 1990s when I helped oversee the program at the Department of Energy, I slowly changed my mind after talking to dozens of experts, reading dozens of studies, and doing my own analysis for that book. Hydrogen simply had too many fatal limitations.

So, two decades ago, I predicted that this Eden was a myth and that hydrogen vehicles could not compete with plug-in vehicles. And indeed, today, electric vehicles outsell hydrogen ones 1,000-to-1.

The dream of a hydrogen economy has gone nowhere, particularly when you compare it with the electrification economy, which is widely understood to be the most efficient, affordable, and scalable set of solutions to climate change. Today, as the International Energy Agency (IEA) explained in 2023, "Hydrogen is mainly used in the refining and chemical sectors and produced using fossil fuels such as coal and natural gas, and thus responsible for significant annual CO_2 emissions."[1] While hydrogen demand keeps growing, it "remains concentrated in traditional applications." The traditional application of hydrogen is as a chemical feedstock. For instance, hydrogen is needed to make ammonia fertilizer because ammonia is NH_3, one nitrogen atom and three hydrogen atoms.

But the dream of a hydrogen economy is not built around using pollution-free hydrogen as a feedstock, which would reduce global greenhouse gas (GHG) emissions by no more than 2%. It's built on hydrogen as an energy carrier, much as electricity is an energy carrier, in the hopes of having ten times that impact (or more) on GHG emissions. In the energy delivery system, energy carriers lie between primary sources such as coal or wind and end-use applications such as vehicles, power plants, and home heating. They are "transmitters of energy." Like electricity, hydrogen is not a readily accessible energy source like coal or wind. Hydrogen is bound up tightly in molecules such as water (H_2O) and natural gas, which is mostly methane (CH_4), so it is expensive and energy-intensive to extract and purify.

Australian electrochemist John Bockris, who is credited with originating the phrase "hydrogen economy" in the early 1970s, wrote in 2002, "Boiled down to its minimalist description, the 'Hydrogen Economy' means that hydrogen would be used to transport energy from renewables (at nuclear or solar sources) over large distances; and to store it (for supply to cities) in large amounts."[2] Our cars, homes, and industries would be powered not by pollution-generating fossil fuels but by hydrogen from pollution-free sources.

In recent years, climate experts have focused on the goal of "green" hydrogen, or hydrogen made by electrolyzing water with renewable power. This became the key goal because, for hydrogen to be of any value in the fight against climate change, it must be made in a way that releases little, if any, GHGs, of which carbon dioxide is the most important.

Unfortunately, the cost of producing green hydrogen is still high, even though the idea seems obvious and tidy: Use electricity from a wind turbine to run current through water, "electrolyzing" it to split off the hydrogen molecules. But nothing involving hydrogen turns out to be easy. So predictions have blown up.

Electrolyzer prices jumped 50% between 2022 and 2023, according to S&P Global Commodities, because "electrolyzer projects tend to be highly complex, bespoke, and are proving far harder to construct than initially anticipated."[3] A 2023 Boston Consulting Group analysis noted electrolyzers used to make green hydrogen production "have a cost-overrun potential exceeding 500%."[4]

A September 2024 BloombergNEF study forecast electrolysis system capital costs falling by only "about one half from today to 2050 in China, Europe and the US assuming continued government support and free trade." The market research firm explains that this forecast "is about three times as high as what we anticipated in our 2022 analysis."[5]

Claims that carbon-free hydrogen energy will soon be a marketplace winner assume that costs of key equipment must steadily drop over time—and will do so faster than the competition. But even though the price of renewables has dropped sharply in the last two decades, the process of making hydrogen from renewables, storing it, and transporting it over large distances remains expensive and inefficient. That's why 98% of hydrogen today is still produced from fossil fuels—hydrocarbons—in processes that generate large quantities of CO_2.

After decades of effort and billions in spending by governments, car companies, and others, "the uptake of hydrogen in new applications in heavy industry, transport, the production of hydrogen-based fuels or electricity generation and storage . . . remains minimal, accounting for less than 0.1% of global demand," as the IEA reported in September 2023.[6] All the major novel applications of hydrogen—where it's used as an energy carrier—have failed in the market because hydrogen is a lousy energy carrier. If it had been a good energy carrier, we probably would have started using it as one a long time ago.

The central focus of this book is to explain why hydrogen is such a poor energy carrier—especially compared with electricity—and, therefore, why its role as a climate solution will be limited before 2050, if ever.

Indeed, for the foreseeable future, hydrogen should be considered a climate problem, not a climate solution. The world has not even started to address the CO_2 emissions from hydrogen's traditional use as a chemical feedstock for petrochemicals and fertilizers. That 100 million tons a year of hydrogen is responsible for about 2% of global CO_2 emissions. Simply replacing that dirty feedstock hydrogen with green hydrogen would require generating as much renewable electricity as the United States produces each year from all sources, renewable and nonrenewable. Achieving that goal by 2050—without significantly increasing hydrogen emissions—is implausible. The chances we would simultaneously be able to turn hydrogen into a successful energy carrier are vanishingly low.

The environmental paradise of a clean hydrogen economy rests not only on green hydrogen itself but also on a fuel cell for converting it into useful energy without generating pollution. A fuel cell is a small, modular electrochemical device, similar to a battery, but which can be continuously fueled. For most purposes, think of a fuel cell as a black box that takes in hydrogen and oxygen and puts out water plus electricity and heat but no pollution.

But just as hydrogen has not become a competitive energy carrier, fuel cells have not become a competitive conversion device even though they were invented nearly two centuries ago. In 1839 London, William Grove was experimenting with electrolysis, decomposing water into oxygen and hydrogen by using electricity. He figured out how to reverse the process to generate electricity by combining oxygen and hydrogen. Grove then quickly built the first fuel cell, which he called a "gaseous voltaic battery," or gas battery.

Yet here is the astonishing thing, as reported by Canary Media in June 2023: "Since the invention of the fuel cell in 1839, no company has been able to earn a profit from this energy-generating technology. Until the historic moment in which we now find ourselves."[7] In 2022, the article explains, a German manufacturer of methanol-powered fuel cells announced $1.8 million in profit.

But that company had *lost* a combined $22 million in the previous six years, and it was focused on niche applications: portable and remote use. We may have a long wait before a company making a fuel cell that could actually enable a broader hydrogen economy no longer has total losses that exceed total profits. The other four publicly traded fuel cell companies have combined cumulative losses of about $10 billion. And each of them saw their highest losses ever in 2022.

So, 180 years after fuel cells were invented, the industry has failed to live up to its promises. After decades of effort by scientists and entrepreneurs and billions in subsidies, hydrogen is not a successful energy carrier, and fuel cells are not a successful energy conversion device for hydrogen. At this point, we have no reason to believe they will be even a modest climate solution by 2050.

With so many obstacles remaining, major government policy should not be based on any claim of inevitability for green hydrogen as a major energy carrier. Government investments can and should be limited and slow. We must minimize both the cost of misallocating vast amounts of renewables and money and the likelihood of massive, stranded assets built for a hydrogen economy that never materializes.

You wouldn't use hydrogen to decarbonize either a sector or a niche application unless every other plausible solution had failed. And if you can do something with electricity, hydrogen will never be able to compete seriously. That was clear two decades ago, as I spelled out in the 2005 paperback edition of this book.

Hydrogen and fuel cells don't merely have to overcome their many limitations to succeed in the marketplace. They must also surpass and defeat their main competition—electricity and electrification technologies—which have been improving in cost and performance much faster for decades. Even though the world is diverting tens of billions of dollars—and potentially hundreds of billions—to hydrogen and enabling technologies, its fatal flaws today are the same as in the early 2000s.

First and foremost, hydrogen vehicles are an incredibly inefficient way to use carbon-free energy. Converting renewable energy to green hydrogen with an electrolyzer—then transporting, storing, and pumping it into a vehicle's onboard fuel cell just to regenerate electricity to turn an electric motor—means throwing away as much as 80% of the original renewables. And it relies on expensive electrolyzers and fuel cells.

That complex process can't compete with simply using the original renewable electricity to charge the battery on an electric vehicle and then running the electric motor off the battery, which loses less than 20% of the renewables. So you can go four times farther on the same renewable power with an electric vehicle than a hydrogen car—at a far lower cost.

The hydrogen scheme is as if you wanted someone to ship you bottled water—but to do that, they used the water to make champagne, shipped the champagne to your destination under expensive, carefully controlled conditions, and then distilled it back into water before delivering it to you.

For the same reason, hydrogen is a lousy way to try to store solar or wind power for use when the sun isn't shining or the wind isn't blowing. Converting renewables to hydrogen and then back to electricity is so costly and inefficient that many other strategies are already more cost-effective, as studies have shown.[8] Also, more efficient long-duration energy storage technologies are now emerging.

The same analysis applies to other key sectors when electricity goes head to head with hydrogen. One European expert reviewed thirty-two independent studies on hydrogen heating from the European Union, the United Kingdom, Brazil, and California. "You need five to six times more electricity to generate the same amount of heat with hydrogen than with an efficient heat pump," he explained. "That's the Achilles' heel for hydrogen. It's basic thermodynamics."[9]

Other highly inefficient uses of renewable electricity, according to a 2023 analysis, are making green hydrogen to directly displace natural gas power generation and "blending hydrogen into the gas grid."[10] Worse, although running hydrogen through a fuel cell produces no pollution, burning it in a retrofitted gas turbine is not clean power. It will generate nitrogen oxides, which form tiny particulates that can penetrate deep into the lungs, leading to serious diseases. And blending safe amounts of hydrogen into the gas grid is an almost complete waste of renewables because it involves a large misallocation of resources while barely reducing GHG emissions.

This "opportunity cost" issue is crucial yet too often absent from media and policy discussions about hydrogen. If we misallocate all those renewables, we lose the opportunity to achieve far more reductions for far less money by using them to directly replace fossil fuels. At the rate the nation and the world are cutting emissions—not fast enough and not at all, respectively—green hydrogen won't make sense until after

2050. Opportunity cost matters, especially because we have only one opportunity to avert catastrophic climate change over the next decade and don't have time, money, and resources to waste.

Second, no one will make a big investment in a hydrogen delivery infrastructure until it's clear that a hydrogen-using technology (like fuel cell cars) is a winning product. But no one will scale up making such hydrogen tech without a vast infrastructure already in place to move hydrogen around cheaply and efficiently. This "chicken and egg" problem of who goes first and risks losing billions has never been solved.

Third, hydrogen is a hazardous fuel to use, and in industrial settings, a great deal of money and training are spent to avoid serious accidents. As a 2021 "Review on Hydrogen Safety Issues" noted, "It is difficult to maintain safety in production, storage, transportation, and utilization because of the inherent characteristics of hydrogen."[11] Hydrogen has many combustion regimes, as a major 2011 report explained.[12] For hydrogen concentrations above 10%, acceleration of the combustion wave up to sound velocity (about 1,000 feet per second) "has been found in many experiments." But scenarios with higher concentrations can create a "detonation," which is "a combustion wave that travels at supersonic speeds relative to the unburnt gas in front of it." That speed can be over 6,000 feet per second.

Fourth, there is still no practical and affordable way to store hydrogen, which makes transporting it over long distances expensive and energy intensive. Many companies want to liquefy and supercool hydrogen to –423°F (–253°C) for transport, even though that process can consume as much as 40% of the hydrogen's energy. Keeping the temperature that low in a tanker truck is challenging, especially as the liquid hydrogen sloshes back and forth, so it starts to "boil off," dangerously increasing the pressure in the tank. The excess hydrogen is typically vented into the air.

That brings us to one of the biggest challenges hydrogen faces: Even though it is perhaps the leakiest gas, we now know that leaking or releasing hydrogen into the air makes the planet warm much faster—especially in the near term—than scientists realized.

Hydrogen as a Climate Solution

Our energy choices are inextricably tied to the fate of our global climate. The burning of fossil fuels emits CO_2 into the atmosphere, where it builds up, blankets the planet, and traps heat, accelerating global warming. Earth's atmosphere now contains more CO_2 than at any time in the past few million years, leading to rising global temperatures, more extreme weather events (including floods and droughts), devastating wildfires, ocean acidification, sea level rise, and many more threats to humanity.

Failure to rapidly reverse that trend will lead to ever-worsening and ultimately catastrophic climate impacts that will be irreversible for generations. In the past two decades, the science has grown stronger that to avoid such impacts, the world needs to hold total warming to "well below 2°C above pre-industrial levels" while "pursuing efforts to limit the temperature increase to 1.5°C," as the nations of the world agreed unanimously in the 2015 Paris Agreement and reaffirmed in Glasgow in 2021.

The world's top climate experts of the Intergovernmental Panel on Climate Change explained in their 2018 *Special Report on Global Warming of 1.5°C* that meeting the 1.5°C (2.7°F) limit requires net zero global emissions by 2050, whereby whatever emissions the world can't mitigate would be offset by negative emission technologies that currently aren't commercial.[13] Keeping warming below 2°C (3.6°F) still requires net zero global emissions just a decade or two later.

Yet since 2000, annual global emissions have risen to the equivalent of 50 billion tons of CO_2. In fact, we are currently headed to as much as 6°F (3.3°C) warming by 2100 based on policies in place globally.[14]

However, our urgent need to rapidly reduce the rate of warming is at odds with the rapid expansion of hydrogen use because the latest science reveals hydrogen is a major indirect GHG. Hydrogen is not a GHG that directly traps heat, as carbon dioxide and methane do, "but its chemical reactions change the abundances of the greenhouse gases methane, ozone, and stratospheric water vapor, as well as aerosols," explains a 2023 journal article.[15]

The result is that hydrogen has thirty to forty times the global warming potential of CO_2 over a twenty-year period (GWP20), a critical period for reaching the goals of the Paris Agreement. Unfortunately, recent studies tend to overhype the climate benefit of hydrogen: Not only do they use the much lower hundred-year GWP of hydrogen (GWP100), but they also use outdated estimates. That approach can make hydrogen strategies that actually increase net CO_2 emissions look as if they offer some climate benefit because the new GWP20 of hydrogen is about seven times bigger than the old GWP100.[16]

The authors of the 2023 article note that "By reducing short-lived climate forcers, such as hydrogen, there is potential to slow down global warming in the next 20–25 years." Unfortunately, we will be doing the exact opposite. The study urges, "It will be important to keep hydrogen leakages at a minimum to accomplish the benefits of switching to a hydrogen economy." Yet hydrogen is the most leak-prone gas because it is the tiniest and lightest of molecules. Many current proposals imagine vastly more hydrogen production, transportation, and use, all but guaranteeing a massive surge in hydrogen leaks and venting of boil-offs from liquid hydrogen storage.

Significantly, hydrogen leaks are very hard to detect, and undetected hydrogen leaks cause 22%–40% of hydrogen accidents.[17] Until and unless we can drive hydrogen leaks and boil-offs down to near zero, it will make no sense to divert renewable energy to its production.

If the world had started cutting emissions when we started having annual meetings to address the problem—three decades ago—things would be much easier. But during the time we have had nearly thirty global climate meetings, GHG emissions have risen 50%. Also, we now know that to avert the worst impacts, we must reduce emissions as close to zero by midcentury as we can, which means we need to have solutions that can get very big, very fast.

Analysis by Massachusetts Institute of Technology researchers working with the nonprofit Climate Interactive has found that technologies such as fusion, which still need at least one breakthrough to become commercial, are unlikely to contribute to lowering global temperatures in 2100 by more than 0.1°C. And it's entirely possible that fusion—the most unique and challenging use of hydrogen-based energy—doesn't even achieve that.

Long-term research and development of strategies such as hydrogen as an energy carrier or direct air capture (DAC) and storage of CO_2 remain worthwhile. But both need major breakthroughs before significant money should be devoted to scaling them up. That's especially true because DAC has the same major flaw as hydrogen: Its overall efficiency is low (5%–10%) but the price is high.

So both hydrogen and DAC consume vast amounts of renewables that could achieve far more CO_2 emission reductions for far less money if used to directly replace fossil fuels. Also, it's entirely possible, if not likely, that there will be better and cheaper ways of doing what they can do. Hyping them as major pre-2050 climate solutions is counterproductive, and subsidizing significant deployment of either means greatly misallocating renewable energy and money—a big opportunity cost.

Because the goal of hydrogen is replacing fossil fuels, "the electricity you use to make it would have to be ridiculously cheap. And if you have that, why use it to make hydrogen?" as inventor and electrification expert Saul Griffith told the *New York Times* in 2023.[18] In 2022, Griffith explained, "I developed hydrogen tanks that I sold to a consortium of the world's auto companies," and so "I will do very well if hydrogen is a winner."[19] It's his expertise with hydrogen that fuels his skepticism.

Our decades of dawdling mean we must focus the overwhelming majority of our money on rapidly deploying technologies that are already successful, such as solar power, wind power, batteries for storage, electric vehicles instead of gasoline ones, and electric heat pumps instead of natural gas boilers. In every sector, we must pour more money into all electrification technologies than we do into hydrogen energy technologies because, again, the hydrogen solution to a climate problem is exceedingly unlikely to compete with the electric one.

International Energy Agency energy analyst Dr. Simon Bennett, who coauthored their 200-page *Future of Hydrogen* report in 2019, told me in 2024, "Many of the technologies that have generated the most excitement in the past decade were ones that had the effect of outcompeting hydrogen or CCS [carbon capture and storage] in an application where we used to think hydrogen was the best approach."

The (New) Hype About Hydrogen

Unfortunately, the fossil fuel industry—which generates hundreds of billions of dollars annually in revenues from promoting the fuels destroying our livable climate—sees an opportunity to make tens of billions from hydrogen while continuing to produce polluting fossil fuels. So it has spent millions promoting the idea. As Canary Media explained in October 2023, fossil fuel companies "form the core membership of the biggest hydrogen lobbying groups."[20] They are one of the few industries that use hydrogen directly—and the only one that produces the fossil fuels responsible for making virtually all hydrogen today.

The industry believes that the challenges of making hydrogen with renewables (or nuclear power) mean it will inevitably be made by reforming natural gas and then capturing and storing the resulting CO_2, so-called blue hydrogen. But as one 2023 analysis concluded, "Blue hydrogen is not clean or low-carbon and never will be."[21] Also, as Bloomberg warned in a 2021 article, it has inherent economic limitations.[22]

The fossil fuel industry isn't the only one overhyping hydrogen and other similarly sexy strategies that are implausible or even counterproductive as near-term solutions. The Department of Energy promotes all energy technologies and seldom criticizes any of them, no matter how dubious or implausible. The US Inflation Reduction Act alone could lead to a half trillion dollars or more in tax credits for hydrogen that either achieve very expensive GHG reductions or actually increase net emissions.

The venture capital community also oversells its investments, pouring billions of dollars into every conceivable technology without distinguishing between those with high and low potential for impact. The companies themselves are on an endless quest to raise money and convince venture capitalists they can deliver on their promises of large, rapid, and affordable emission reductions, no matter how implausible.

Major media outlets, from *The Economist* to the Associated Press to the *New York Times*, write credulously about products that still need at least one breakthrough to be affordable and scalable—and thus are unlikely to be major contributors to the emission reductions we need by 2050. Throughout the book, I'll document some of this hype because it has become so deceptively pervasive.

Much of the bad policy and overhype driving this resurgence of interest in hydrogen stems from a broad lack of understanding about the intractable nature of hydrogen as an energy carrier, the inherent inefficiency of carbon-free hydrogen, and its inability to compete with electricity, especially given rapid advances in electrification technologies. These challenges are the major focus of this book.

Chapter 1 focuses on the history of hyping hydrogen as an energy carrier from the 1990s through today. Chapter 2 looks at the much longer history of hydrogen itself and what might be called the original hype about hydrogen: fusion energy, which is sometimes described as "the future of energy, and it always will be."

In Chapters 3 through 5, I'll dive into hydrogen production. Chapter 3 provides an overview of how hydrogen is produced today and how it might be produced with little or no carbon emissions in the future. It explains why green hydrogen is by far the most important type of hydrogen in our rapidly warming world but is hard to make affordably. It also examines why geologic hydrogen is not likely to be practical, plentiful, or pollution-free.

In Chapter 4, we'll see why nuclear power is far too expensive and impractical to scale up hydrogen production and dig into the safety concerns with hydrogen generation near nuclear reactors. We'll also examine why "economics killed small nuclear power plants in the past—and probably will keep doing so," as the *IEEE Spectrum* presciently warned in 2015.[23]

Chapter 5 examines the hydrogen production method favored by fossil fuel companies: adding CCS to a traditional system for reforming natural gas into hydrogen. It explains why this approach leads to high GHG emissions and why, if we ever develop a practical and affordable CCS system, we should just use it directly on a fossil fuel power plant.

Chapters 6 and 7 explore some of the major applications for hydrogen currently being funded. In Chapter 6, we'll look at the overhyped, complex, expensive, and inefficient technology of direct air capture of CO_2, which many seek to combine with hydrogen to make synthetic liquid hydrocarbon "e-fuels." Although e-fuels are often touted as solutions for air travel and shipping—and even ground transport—we'll look at their many fatal limitations, including their huge opportunity costs.

Chapter 7 details another proposed application—hydrogen cars—and why electric cars have crushed hydrogen ones over the past two decades. We'll see how hydrogen's immutable limitations undercut the business case for it as an energy carrier in virtually all applications.

In the Conclusion, I'll review the book's central arguments and examine how we can accelerate real climate and energy solutions while avoiding the huge opportunity cost of the many false promises.

The Future of Hydrogen

Two decades ago, I ended the Introduction to this book as follows: "This book makes the case that hydrogen vehicles are unlikely to achieve even a 5% market penetration by 2030. And this in turn leads to the book's major conclusion for all readers, from policymakers to corporate executives to investors to anyone who cares about the future of the planet: *Neither government policy nor business investment should be based on the belief that hydrogen cars will have meaningful commercial success in the near- or medium-term*."

The prediction was accurate. Indeed, it's exceedingly unlikely hydrogen vehicles will achieve even a 1% market penetration by 2030. In fact, 1% by 2050 would be an achievement at this point given the remarkable and ongoing progress of both electric vehicles and batteries.

The original prediction can now be broadened, and perhaps surprisingly, it's not pessimistic—it is merely realistic. Making enough green hydrogen to replace the 100 million tons of hydrogen used directly as a chemical feedstock today (primarily in the fertilizer and petrochemical industries) would be a worthy and meaningful focus of our hydrogen effort. That could save up to 2% of global emissions—if it is truly green. Beyond that, hydrogen energy technologies are unlikely to contribute even 1% of overall net GHG emission reductions in 2050.

That's especially true when we factor in the warming impact of hydrogen leaking and venting. Also, scaling up green hydrogen before most fossil fuel emissions have been eliminated would be counterproductive because of the huge opportunity cost. It would misallocate enormous amounts of renewables that could achieve far greater emission reductions at far lower costs elsewhere in the economy.

For instance, one of the most highly touted applications for hydrogen is a part of the steelmaking process responsible for about 2% of global emissions. But achieving that in the next quarter century would require a massive and expensive industry retooling—"many hundreds of billions of dollars," according to one industry expert.[24] The cost per ton of CO_2 saved would probably be much higher than fully electrifying sectors such as ground transportation and heat for buildings and industry. So while it's worth pursuing the technology's development and demonstration, it shouldn't be a priority for near-term rapid deployment. The best near-term strategy for steel is to focus on increasing the recycling rate of scrap steel, which can be converted to "secondary" steel in an electrified process with an electric arc furnace. At the same time, we should increase funding for development and demonstration of emerging technologies that make primary steel directly with electricity. Beyond steel, most other plausible applications are niche areas with lots of competition, as we'll see.

That reality, in turn, leads to this book's major conclusion for all readers, from policymakers to corporate executives to investors to anyone who cares about the future of the planet: *Neither government policy nor business investment should be based on the belief that hydrogen energy technologies will inevitably be even a small contributor to decarbonizing the energy system by 2050.*

In other words, hydrogen investments do not deserve a privileged position among the list of potential climate solutions. Quite the reverse. Nothing about hydrogen justifies hundreds of billions of dollars in tax incentives or subsidies over the next fifteen years in the United States or worldwide.

Hydrogen is far more likely to be a major boondoggle than anything else, but most people in government, business, venture capital, and the media apparently do not understand that reality. Therefore, it's important to understand how hydrogen works, what its risks and opportunities are, why it has utterly failed to live up to its promise as an energy carrier and climate solution despite considerable effort and money—and the growing number of reasons it remains a bad bet to do so for decades to come.

Finally, while the outcome of the 2024 US Presidential election does not change any of the analysis here, it does strengthen the conclusions. The winner has repeatedly called climate action a hoax, has spread misinformation about core climate solutions like wind power and batteries, and is an avowed opponent of domestic and international climate action. This means it will be much harder for the nation and the world to achieve the Paris climate targets—which another decade of dawdling has already put in grave jeopardy—and avoid catastrophic climate change.

The Trump Administration is likely not only to slow or even terminate domestic policies aimed at reducing GHG emissions but also to actively promote policies that will increase them. So it will become even more important for the rest of us—including states, companies, investors, nonprofits, other countries, and all those who care about maintaining a livable climate—to achieve the highest possible emissions reductions with our actions and money. We must redouble our focus on the real electrification solutions. We simply cannot afford the wasted time and opportunity cost of the many false promises I have discussed here as the window to keeping warming below 3.6°F (2°C) starts to shut even faster.

CHAPTER 1

Hydrogen Hype—Then and Now

From William Grove's first hydrogen fuel cell to today, billions and billions of dollars have been spent attempting to refine and scale hydrogen technology. Throughout this book, we'll see why efforts to make hydrogen a dominant energy carrier have largely failed—and why they're even less likely to succeed now than two decades ago, when I wrote the first edition of this book.

Yet we are now in a frantic rush to spend tens, if not hundreds, of billions of dollars on hydrogen. Trying once again to advance hydrogen as a significant energy solution to the climate problem at the expense of real solutions is probably one of our biggest climate policy blunders, in the United States and worldwide.

To understand what hydrogen's limitations are and how we are just repeating past errors, we need to look back at modern attempts to develop it. My hydrogen journey started in the early 1990s, coinciding with a resurgence of interest in hydrogen as a possible energy carrier or car fuel.

The 1990s: A Hydrogen Fuel Cell Breakthrough?

I first came to the US Department of Energy (DOE) in 1993 to help oversee research and development (R&D) in clean energy. At that time, hydrogen R&D did not even have its own separate budget line but instead was nestled inside the renewable energy budget. For the previous decade, hydrogen research funding had languished in the $1–$2 million per year range, one-hundredth of 1% of the overall departmental budget—a penny out of every $100. Also, annual DOE funding for the fuel cells needed for vehicles—proton-exchange membrane (PEM) fuel cells—was less than $10 million.

Within days of my arrival, I was briefed on recent work by one of the national laboratories that DOE oversaw. They'd had a breakthrough with the potential to dramatically reduce the cost of PEM fuel cells.

Fuel cells are one of the Holy Grails of energy technology. They are pollution-free electric "engines" that run on hydrogen. Unlike virtually all other engines, fuel cells do not rely on combustion or fossil fuels. Therefore, they produce no combustion byproducts, such as oxides of nitrogen, sulfur dioxide, or particulates, the air pollutants that cause smog and acid rain and that have been most clearly documented as harmful to human health.

Fuel cells have reliably provided electricity to spacecraft since the 1960s, including the Gemini and Apollo missions and the space shuttle. But finding a fuel cell with the right combination of features for powering a car or truck proved much more difficult. Why? To begin with, you need a fuel cell that is lightweight and compact enough to fit under the hood of a car but that can still deliver the power and acceleration drivers have come to expect. The fuel cell must also be able to reach full power in a matter of seconds after startup, which rules out a variety of fuel cells that operate at very high temperatures and thus take a long time to warm up. Fuel cells must also be similar in price and reliability to the gasoline-powered internal combustion engine, an exceedingly mature technology that is the product of more than a hundred years of development and real-world testing in hundreds of millions of vehicles.

Furthermore, these hardware hurdles are all quite separate from how the fuel for fuel cells—hydrogen—would be produced and delivered to the vehicle. Hydrogen, first and foremost, is not a primary fuel, like natural gas or coal or wood, which we can drill or dig for or chop down and then use at once. Hydrogen is the most abundant element in the universe, true enough. But on Earth, it is bound up tightly in molecules of water, coal, natural gas, and so on. To unbind it, a great deal of energy must be used. We'll dig much deeper into the implications of these properties of hydrogen later in the book.

For all these reasons—plus the sharp drop in government funding for alternative energy under president Ronald Reagan—hydrogen fuel cell vehicles (FCVs) received little attention through most of the 1980s. Still, a few government and industry laboratories (along with a small and ardent group of hydrogen advocates and state energy experts) kept plugging away, particularly on PEM fuel cells.

Fuel cells require catalysts to speed up the electrochemical reaction, and PEM fuel cells use platinum, a very expensive metal. An early 1981 analysis for the DOE presciently argued that PEM fuel cells would be ideal for transportation if the amount of platinum could be sharply reduced. By the early 1990s, Los Alamos National Laboratory (and others) had succeeded in cutting the amount of platinum by almost a factor of ten, a remarkable improvement. This still did not make PEM fuel cells close to cost-competitive with gasoline engines, but it did dramatically reinvigorate interest in hydrogen-powered vehicles. PEMs were exactly the kind of low-temperature fuel cell that could be used in a car.

After I was briefed on the Los Alamos work at DOE, I began urging increases in funding for PEM fuel cells and for the development of a transportation fuel cell strategy. At the time, it was far from clear that electric vehicles (EVs) could satisfy all the criteria for a successful alternative fuel vehicle (AFV) to replace liquid fossil fuels. Hydrogen FCVs were the only plausible AFV that could be CO_2-free and scalable.

The Clinton administration's entire team supported R&D for fuel-efficient technologies. So funding for hybrid vehicles, including fuel cells, increased significantly. So, too, did funding for hydrogen production, because even if we succeeded in commercializing fuel cells, we would still need to find affordable, pollution-free sources for hydrogen. Even today, over 95% of hydrogen is made from fossil fuels—coal, oil, and especially methane (CH_4), which releases vast quantities of CO_2, the primary human-caused greenhouse gas.

In mid-1995, I moved to the DOE's billion-dollar Office of Energy Efficiency and Renewable Energy, where I was in charge of all budget and technology analysis. Ultimately, I ran the entire office for much of 1997 as acting assistant secretary. I was able to work with other fuel cell advocates in and out of the administration, especially my DOE colleagues Brian Castelli and Christine Ervin, to keep the PEM fuel cell budget creeping upward even as the entire budget for the office was cut 20% by a 1995 Congress that was extremely skeptical of all energy R&D.

By 1998, when I left DOE, the hydrogen budget was ten times larger than in 1993, and the proposed PEM fuel cell budget was more than three times larger. This funding did help drive down the cost of fuel cells (PEM and others) steadily while performance increased. Harry Pearce, vice chairman of the General Motors Corporation, said at the North American International Auto Show in January 2000, "It was the Department of Energy that took fuel cells from the aerospace industry to the automotive industry, and they should receive a lot of credit for bringing it to us."[1]

The 2000s: Hyping Hydrogen

In the 2000s, hydrogen budgets were ballooning everywhere in a race for patents and products. Hydrogen hype was also ballooning. William Clay Ford Jr., chairman of the Ford Motor Company, said in October 2000, "I believe fuel cells will finally end the 100-year reign of the internal combustion engine," a poignant statement from the great-grandson of the man whose manufacturing innovations had begun that reign a century earlier with the Model T. But he was wrong.

This was the era of President Bush's 2003 State of the Union, in which he called for a historic $1.2 billion in research "so that America can lead the world in developing clean, hydrogen-powered automobiles." Yet as I began researching and writing the first edition of *The Hype About Hydrogen*, it became clear that more hype and more funding wouldn't be enough to overcome hydrogen's many obstacles.

Toyota had just come out with its game-changing second-generation Prius. It was far more fuel efficient than traditional internal combustion engine cars, and its tailpipe had so little pollution that California classified it as a partial zero-emission vehicle. In the first edition of this book, published in 2003, I noted that "hybrid gasoline–electric vehicles *today*, such as the Toyota Prius, are already much more efficient than traditional internal combustion vehicles, and nearly as efficient as *projected* fuel cell vehicles (assuming fuel cells achieved the performance targets)." So, I concluded, "it is possible, we may never see a durable, affordable, fuel cell vehicle, with an efficiency, range, and annual fuel bill that matches the best hybrid vehicle." That is still true.

But even if they ever could beat the best hybrids, hydrogen cars would still have one unfixable problem: the competition from EVs. It was clear two decades ago that if we could build a practical EV that could be charged directly with carbon-free electricity, it would travel four times farther on the same amount of carbon-free electricity than a hydrogen fuel cell car and thus would not only conserve the use of such clean power but also make the electric car much cheaper to run.

So I predicted that "hydrogen vehicles are unlikely to make a significant dent in US greenhouse gas emissions in the first half of this century." Even in the 2000s, it was increasingly clear that hydrogen would make sense as a climate solution only if that sector could not be electrified. We'll look more closely at the competition between electric and fuel cell cars in Chapter 7.

Around when the first edition of this book was published, a National Academy of Sciences panel released a major report with a variety of important technical conclusions suggesting the challenges ahead for hydrogen cars. For instance, the panel said, "The Department of Energy should halt efforts on high-pressure tanks and cryogenic liquid storage. . . . They have little promise of long-term practicality for light-duty vehicles."[2]

The next month, March 2004, a study by the American Physical Society concluded that "a new material must be discovered"[3] to solve the storage problem. No such material has been found, and the two types of onboard hydrogen storage that the academy rejected are still today the only ones being seriously considered.

Bill Reinert, US manager of Toyota's advanced technologies group, was asked in January 2005 when fuel cells cars would replace gasoline-powered cars. He replied, "If I told you 'never,' would you be upset?"[4]

The 2010s: Return to Reality

By the 2010s, the hype about hydrogen seemed to have given way to reality. Even by September 2008, *The Economist* had written that "the promise of hydrogen-powered personal transport seems as elusive as ever," in an article titled, "The Car of the Perpetual Future."[5] The article continued, "The non-emergence of hydrogen cars over the past decade is particularly notable since hydrogen power has been a darling of governments worldwide, which have spent billions of dollars in subsidies and incentives to make hydrogen cars a reality."

In 2013, the independent research and advisory firm Lux Research released "The Great Compression: The Future of the Hydrogen Economy." Their study concluded that despite billions in R&D spent in the previous decade, "the dream of a hydrogen economy envisioned for decades by politicians, economists, and environmentalists is *no nearer*."[6]

Ford Motor Company aggressively pursued FCVs in the first decade of the twenty-first century. By 2009, their thirty Ford Focus FCVs had, combined, over a million miles on them. Yet after all this work, Ford's *Sustainability Report 2013/14* explained, "extensive DOE analysis has not yet revealed an automotive fuel cell technology that meets the DOE's targets for real-world commercialization, or that maintains proper performance throughout the targeted lifetime while staying within the targeted cost."[7]

The onboard storage problem was never solved. Ford concluded in its 2013/2014 report that because of the "still significant challenges related to the cost and availability of hydrogen fuel and onboard hydrogen storage technology," we need "further scientific breakthroughs and continued engineering refinements" to "make fuel cell vehicle technology commercially viable."

Other companies faced similar problems but decided to start marketing vehicles anyway. Toyota's Mirai FCV started selling in Japan in December 2014—and in the US in August 2015—for about $57,000 before incentives. But Pat Cox, former European Parliament president, said in a November 2014 talk on hydrogen cars that Toyota was probably losing between $66,000 and $133,000 on each car.[8]

During this lost decade for FCVs, their major competitor, plug-in electrics, surged into the marketplace thanks to a once-obscure 2006 startup called Tesla Motors. By 2014, Tesla had become California's largest auto industry employer, according to the US Department of Energy.[9] Its market capitalization (the total value of all its stock) then was more than half that of General Motors.

Indeed, battery technology had improved so much during that decade that Tesla was selling a fully electric vehicle with no gas engine. By the end of 2010, Chevy had released the Volt plug-in hybrid in the United States. At the same time, Nissan released the LEAF, which by the end of 2016 had become the world's top-selling all-electric car, with total sales of over 250,000. Tesla's Model S had sales of more than 150,000.

The 2020s: The Hype Strikes Back

In the past ten years, there have been no major breakthroughs in hydrogen technology that would address the key problems of inefficient and expensive production, inadequate storage technologies, and the lack of infrastructure for transporting and fueling hydrogen.

"The math still doesn't add up," the head of European Union lending and advisory operations at the European Investment Bank told Bloomberg in May 2024.[10] "At the moment, there is no case that we can see for a model based on green hydrogen independently produced and distributed as an energy commodity."

In its *Sustainability Report 2013/14*, Ford devoted two full pages to "Hydrogen Fuel Cell Vehicles (FCVs)," used the term "FCV" thirty times, and featured the Ford Focus FCV. By the time of its *2024 Integrated Sustainability and Financial Report*,[11] Ford devoted only two paragraphs to the subject and never used the term "FCV," and the Ford Focus FCV was replaced by the "fully electric Focus electric vehicle (EV)." Yet Ford hasn't completely given up on FCVs. Today, they have moved on to a partnership with the DOE aimed at developing and demonstrating medium- and heavy-duty fuel cell trucks. But even if such trucks ever

(continued...)