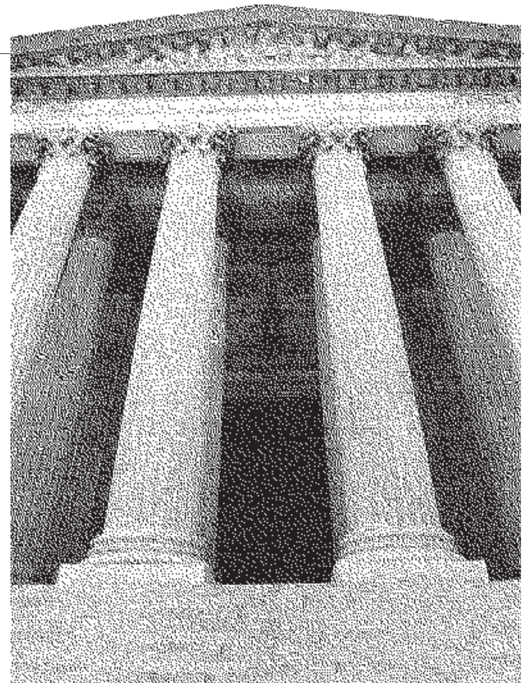

THE DEBATE

Renewable Energy Boon—or Environmental Boondoggle?

Green hydrogen, produced using wind, solar, and other renewable electricity to split water molecules, is either lauded as an indispensable clean energy source to fight climate change, or criticized as an overhyped promise.

Politically, at the Appalachian Regional Clean Hydrogen Hub ribbon-cutting last year, Senate environment committee chair Shelley Moore Capito (R-WV) lauded the Energy Department's $30 million award to the project and vowed she'd continue advocating policies needed to "help the hydrogen economy thrive."

Supporters envision a "green hydrogen economy" built on zero-carbon fuels that cut air pollution and create new jobs, while building on existing electric and gas infrastructure. But critics describe the green hydrogen economy as a pipedream and an expensive energy boondoggle. Currently comprising less than 1 percent of global hydrogen production, clean hydrogen investments will reach a 31 percent annual compound growth rate by 2032, fuel cell company Plug Power, Inc., projects.

But what are the green hydrogen economy's real prospects? What factors will boost green hydrogen demand? Could costs—including for pipelines and storage—turn the promise into a pipedream? Could the Trump administration's pro-fossil fuel policies pose an insurmountable barrier or, conversely, motivate a countervailing boon as concerned advocates seek to advance clean energy in today's environment? Do any major technical challenges or breakthroughs change the prospects?

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Senior Associate, Energy & Power
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"Green hydrogen will require its own delivery system. An entirely new pipeline system would have to be built"

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"Scaling up hydrogen would seriously undermine effective efforts to avoid catastrophic climate change"

Joseph Romm
Senior Research Fellow
Penn Center for Science, Sustainability, and the Media

Reports of Its Death Are Greatly Exaggerated

By Selene Law and Diana Rasner

Green hydrogen was all energy-policy people talked about until recently. Indeed, just two years ago the Inflation Reduction Act promised healthy subsidies for green hydrogen production. But this support has now fallen to the wayside. Even before the new administration took office, the green hydrogen story had started to sour. The abundant clean energy required to produce it never quite materialized, with renewable power prices in Europe remaining stubbornly high. End users have been unwilling to swallow such a high green premium.

Now the pendulum may be swinging in the opposite direction, High power prices and electrolyzer costs are not uniformly seen in every geography. China, for example, has been building out green hydrogen production capacity. China now produces nearly 60 percent of global electrolyzer manufacturing capacity, with the cost of green hydrogen around $2-3 per kilogram in provinces with abundant renewable power. For reference, the target price of U.S. hydrogen production under the IRA was $2 by 2025 and $1 by 2030.

China currently has an estimated 3.6 gigawatts of electrolyzer capacity operational, with at least another 9 gigawatts in the post-final investment-decision stage. China is using renewable hydrogen in every major hard-to-abate sector: refining and petrochemicals, fertilizer production, steel smelting, mobility, and power storage. For example, Sinopec's 260 megawatt electrolyzer plant in Xinjiang will replace grey hydrogen production. Meanwhile, Baowu Zhanjiang's hydrogen-ready direct-reduced-iron-shaft furnace produced the first hot metal in 2024.

Despite China's dominance in this space, as in almost every other space in clean tech, there are other signs of green hydrogen's utility. Gigawatt-scale hydrogen projects in Europe and the United States have been delayed and cancelled, but pockets of demand still exist, such as e-fuels or distributed ammonia production. Perhaps a better way of looking at green hydrogen is not comparing it with the envisioned versatile energy Swiss Army knife, but specialized like a chef's blade—not one-size-fits-all but for a specific and important purpose.

In the European Union and other geographies too, policy and mandates are likely to translate into at least some degree of green hydrogen demand growth. Every EU member state must ensure that at least 42 percent of the hydrogen used in industry is a renewable fuel of non-biological origin by 2030 and 60 percent by 2035—effectively forcing refineries, fertilizer plants, and future green steel projects to secure low-carbon molecules or pay carbon penalties.

Mandates in aviation and maritime regulation are also likely to encourage hydrogen demand. ReFuelEU Aviation obliges fuel suppliers to blend 1 percent synthetic "e-kerosene" by 2030, which is likely to create real, binding demand for green hydrogen as the essential feedstock in synthetic aviation fuel production. FuelEU Maritime similarly mandates ships over 5,000 gross tons calling at European ports to reduce their greenhouse gas intensity of fuel by 6 percent by 2030. Together these hard quotas translate into at least some degree of mandatory replacement of existing power sources.

Furthermore, Europe adds additional levies on imported grey hydrogen under the Carbon Border Adjustment Mechanism, while the region's internal carbon price is adding additional costs on grey hydrogen produced locally. Meanwhile, the European hydrogen bank offers subsidies to projects bridging the gap between renewable hydrogen production costs and the offtake prices. Admittedly, projects would have to show credible offtake for around 60 percent of the project's production—a tough criterion to fulfill. Other countries, such as Japan and China, also have supportive policies in place for ramping up green hydrogen.

While it is getting harder to plan gigawatt-scale projects, demand could come from smaller distributed-use cases. Most distributed hydrogen projects are still in early stages but show promise. Distributed green hydrogen cases cut out the need for transportation, which alongside production cost, is a major sticking point for developers and consumers.

U.S. company Talus AG uses solar-powered electrolyzers that convert water to green hydrogen, then synthesizes ammonia in containerized, modular systems deployed on-site at farms and co-ops. Boston-based start-up ReMo builds small- to mid-scale modular ammonia plants that use local renewable electricity to drive electrolysis, generating green hydrogen for ammonia on-site. They produce local ammonia and reduce any supply chain disruptions that could bring real benefits to remote and island agricultural sites.

Finally, the meteoric growth of data centers could also bring new use cases for hydrogen. U.S. start-up ECL Data Centers is building the world's first fully off-grid, modular data center powered primarily by green hydrogen fuel cells in California. Hydrogen fuel cells could become an option to help data centers to leverage on-site renewable energy alongside batteries.

Selene Law is senior associate, energy & power, Cleantech Group. Diana Rasner is group lead, materials & chemicals and waste & recycling.

Green Hydrogen Is a Resource Fool's Errand

By Jonathan Lesser

As a power resource, so-called "green" hydrogen has been aptly described as a "thermodynamic obscenity" because it takes far more energy to produce it than it provides when used. That's an immutable consequence of the second law of thermodynamics. By the time one includes the energy required to transmit electricity to the necessary electrolysis plants, operate those plants, and compress the resulting hydrogen for transport and storage, the total energy expended will be twice the amount of useful energy the hydrogen contains.

The resulting *energy return on investment* will thus be one-half, or 0.5 with 1.0 as an even score. By contrast, the EROI for nuclear plants is around 75, meaning the electricity they generate is 75 times greater than the amount of energy input required. Just as no one would agree to spend $100 on an investment with a negative return, it is foolish for society to invest in any energy resource that inherently requires more energy to produce than it can provide.

The dismal green hydrogen EROI excludes the additional energy required to transport it where it will be used, either in electric generating plants that burn pure hydrogen (which do not, as yet, exist) or to other storage facilities where it can be used in vehicles.

The current cost to produce hydrogen with electrolysis is between $6-10 per kilogram. In 2021, the Department of Energy launched its Hydrogen Shot program, with a goal of reducing the cost to just $1 per kilogram. But even under the best circumstances, and assuming significant technological advances in electrolysis, the costs will never fall that low when the costs of production, storage, transport, and generation are tallied. Already, numerous green hydrogen projects in Europe have been cancelled.

Proponents claim that vast quantities of green hydrogen can be produced using surplus wind and solar generation. However, that claim presupposes there will be sufficient surplus wind and solar capacity, along with battery storage, to provide a steady stream of surplus power. But the surplus electricity won't be free; wind and solar developers still have to recover their costs and make a profit. Moreover, the distribution and transmission lines required to deliver the surplus electricity will be costly.

There's also a practical problem: how does one run an electrolysis facility that depends on intermittent delivery of wind and solar power? Do the plant managers require the employees to be on-call on windy and sunny days? No manufacturing facility operates that way. The only way to overcome this is to ensure that surplus electricity can be stored. But battery storage is costly. The most recent estimate published by the National Renewable Energy Laboratory put the cost of a typical 60 megawatt facility at over $470 per kilowatt-hour of electricity provided.

Next, consider that green hydrogen would be used either for generating electricity or in vehicles. In either case, it will require its own delivery system. Existing natural gas pipelines are primarily steel; older pipes are cast iron. Exposing them to hydrogen results in embrittlement, leakage, and potentially catastrophic explosions. Hence, an entirely new pipeline system would have to be built.

Even if that challenge could be overcome, the hydrogen must be stored where it is to be used, such as for refueling vehicles. Only about 1,200 hydrogen-powered vehicles are in operation in the entire United States, virtually all of them in California.

Green energy advocates also assume that dispatchable *emissions-free generating resources* will be developed to overcome the inherent intermittency of wind and solar power, and that these will be fueled by hydrogen. New York State power planners, for example, assume that, by 2040, 15,000 megawatts of DEFR capacity will be available. Although some existing natural-gas-fired generating plants can burn small quantities of hydrogen, the technology to burn pure hydrogen in a generator does not exist.

Under the Inflation Reduction Act, green hydrogen is eligible for a subsidy of up to $3 per kilogram. One kilogram of hydrogen contains just over 33 kilowatt-hours of electric energy (before conversion losses). That subsidy is equivalent to about 8.8 cents per kilowatt-hour. Burn the hydrogen in a conventional power plant (if one existed with that capability) having a heat rate of 7,000 BTUs per kilowatt-hour, and the subsidy increases to 20 cents. That's five times higher than the average wholesale price of electricity in the country. The costs also far exceed estimates of the social cost of carbon.

Even if green hydrogen is touted as a way to reduce greenhouse gas emissions, its impact on the climate won't be measurable. The Biden administration set a goal of manufacturing 10 million metric tons of green hydrogen per year by 2030. Even if that replaced an equivalent amount of gasoline, the impact on U.S. GHG emissions would be negligible, a few days' worth of annual emissions.

Jonathan Lesser is a senior fellow with the National Center for Energy Analytics. In December 2023, the Manhattan Institute published his report "Green Hydrogen: A Multbillion-Dollar Boondoggle."

It Is a False Solution to the Climate Crisis

By Nile Malloy

The hydrogen rush currently sweeping California risks repeating long-standing patterns of environmental racism and classism that frontline communities have resisted for decades. Backed by over $41 million in federal oil and gas lobbying in 2023 alone, the drive for "green hydrogen" threatens to deplete already scarce water resources and expand fossil fuel infrastructure in frontline neighborhoods already burdened by pollution. The California Environmental Justice Alliance is a coalition of 10 organizations representing frontline communities across the state, and we refuse to let hydrogen become another burden imposed on low-income neighborhoods and communities of color that already bear the brunt of pollution.

Despite frameworks like CEJA's Equity Principles for Green Hydrogen, most hydrogen planning lacks meaningful community engagement, enforceable safeguards, or transparent accountability. Nearly all of California's hydrogen today is produced from fossil fuels, while truly green hydrogen makes up only a tiny fraction of overall output. Our communities assert that green hydrogen means hydrogen produced via electrolysis with surplus water and additional renewable energy, delivered to the grid on the principles of additionality, deliverability, and one-hour matching. Unfortunately, a lack of legislative consensus on a strong standard leaves the door wide open for greenwashing. Community concerns are treated as obstacles to circumvent rather than fundamental project criteria—which has long been the industry standard. While fossil fuel giants secure billions in public funding through the hydrogen hub program, frontline communities are left with vague promises and non-disclosure agreements to stifle their concerns.

Fossil fuel companies are lobbying heavily to ride the hydrogen wave, promoting green hydrogen as a clean add-on, while building pipelines, storage hubs, and hydrogen-natural gas blending facilities in communities already burdened by decades of environmental degradation. Many "clean" hydrogen projects are simply cover for expanding fossil fuel infrastructure.

The deeply unpopular Scattergood Generating Station in Los Angeles is one example. Despite warnings from environmental justice research and law that hydrogen combustion emits nitrous oxides, worsening smog and health risks, the city plans to convert SGS into a hydrogen-ready plant. The project retains fossil infrastructure while sidelining cleaner alternatives like battery storage. Critics also cite concerns over cost, cumulative health impacts, water use in drought-prone areas, and the uncertain supply of truly green hydrogen.

It takes over 9,000 liters of purified water to produce just one ton of green hydrogen. California is a drought-prone state in which population growth, intensive agriculture, and climate change heighten water scarcity. Proposed facilities are concentrated in regions like the Central Valley, where hundreds of communities already face water shutoffs and agro-industrial contamination. In Tulare County alone, dozens of water systems serving predominantly Latine and farmworker communities have failed contamination standards for years. Programs that incentivize diverting scarce water to produce hydrogen are both shortsighted and unjust.

Green hydrogen requires massive investment, costing up to six times more than fossil-based hydrogen due to its heavy reliance on renewable energy, plus the additional costs of building and maintaining methods of hydrogen transportation infrastructure—pipelines or trucking. Rather than right-sizing this technology to limited hard-to-electrify applications, it is propped up with public subsidies that could be better applied toward funding genuinely affordable, safe, and efficient clean energy solutions.

Perhaps the most frustrating case against green hydrogen is that it diverts focus from climate solutions we already know work. These same public dollars could accelerate wind and solar, battery storage, building electrification, public transit, and community microgrids—proven, scalable solutions rooted in meeting people's needs.

We cannot trade one system of harm for another. Green hydrogen, as currently conceived, is not the clean energy breakthrough it's marketed to be. A fuel system that relies on fracked gas, water-intensive processes, or high-pollution combustion—regardless of what color hydrogen label is slapped onto it—is not clean. It's simply old harm rebranded as something new. Without strict regulation and enforcement—consistently lacking in frontline communities—hydrogen development is likely to repeat old patterns of environmental harm while claiming to be clean.

We can build energy systems that center real democracy, where clean technologies create local jobs and wealth, and climate action strengthens rather than threatens frontline neighborhoods. This future centers on distributed renewable energy and community ownership, ensuring enough energy for everyone while building the equitable, healthy world we all deserve.

Nile Malloy is the climate justice director at the California Environmental Justice Alliance, a statewide coalition advancing the voices and leadership of frontline communities of color.

The Trillion-Dollar Green Hydrogen Scam

By Joseph Romm

New analysis confirms that trying to turn hydrogen into a large-scale energy and climate solution would be a disastrous dead end. It would cost trillions of dollars and undermine genuine climate action by misallocating vast quantities of renewables that could achieve far deeper reductions, and far more cheaply, by directly replacing coal, oil, and gas.

We know what the practical, affordable, and scalable climate solutions are—but are on track to misallocate over $1 trillion by 2050 trying to prematurely scale up various costly, deeply flawed technologies, including hydrogen, direct air capture, and small nuclear reactors. But hydrogen is the most flawed, especially since this leakiest of gases drives near-term warming with 35 times the climate impact of CO_2 over a 20-year period.

In the early 1990s, I helped the deputy secretary of energy oversee every solution we were pursuing—including renewables and hydrogen. I ultimately ran the billion-dollar Office of Energy Efficiency and Renewable Energy, which supported many of the winning and emerging solutions we have today, including solar, wind, and geothermal power as well as advanced batteries, heat pumps, and electric vehicles. My new book *The Hype About Hydrogen: False Promises and Real Solutions in the Race to Save the Climate* sorts out the real, scalable solutions from the magical thinking.

Right now, hydrogen is mainly used as a chemical feedstock for petrochemicals and fertilizers. More than 98 percent is made from fossil fuels (hydrocarbons) and causes 2 percent of global greenhouse gas emissions. Just replacing that dirty hydrogen with green hydrogen would require as much renewable electricity as the U.S. produces yearly from all sources—renewable and nonrenewable—to power the electrolyzers that extract hydrogen from water molecules.

That staggering inefficiency gives green hydrogen from renewables—the only practical way to make carbon-free hydrogen—a huge opportunity cost. Because if we misallocate vast amounts of renewables to make hydrogen, we lose the opportunity to achieve over four times as much CO_2 reduction for less money simply by using those renewables to directly replace fossil fuels in power plants, vehicles, and other sectors we can electrify, such as heating and air conditioning.

So, after decades of effort and billions in spending by governments and companies, the use of hydrogen for "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 percent of global demand," as the International Energy Agency reported in 2023. Hydrogen is a lousy energy carrier, especially compared to using electricity directly.

Significantly, while virtually everyone had predicted electrolyzers and green hydrogen would come down steadily in price this decade—as much as 80 percent—the cost of producing both are still high. In fact, electrolyzer prices jumped 50 percent in recent years, 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." A 2023 Boston Consulting Group analysis noted electrolyzers used to make green hydrogen "have a cost-overrun potential exceeding 500 percent."

As a result, *BloombergNEF* now forecasts their price will only drop in half by 2050, "assuming continued government support and free trade." The market research firm notes this forecast "is about three times as high as what we anticipated in our 2022 analysis." So, as JP Morgan explained in March, "just 1 percent of all projected green hydrogen production has a binding offtake agreement."

In June, the modelers at Climate Interactive completed a detailed hydrogen analysis. Absent any new climate policies and actions, their En-ROADS model—which they created with MIT—projects total warming of 3.3°C by 2100 even with baseline renewable use more than quadrupling.

Yet, a big push to have 5.5 percent of final energy demand provided by green hydrogen by 2050 would lower that temperature by just one tenth of a degree. But even assuming hydrogen's massive technological and practical challenges can be overcome, that path would have a cumulative cost of over $25 trillion by 2050, and it would average over $3.5 trillion more each year after that through 2100. It's a tiny effect for the money spent.

But the opportunity cost is huge, because that path requires adding enough renewables from 2025 through 2100 to double the baseline growth. Yet the analysis found that with a little over half the added renewables we could have twice the temperature impact for a fraction of the cost of the hydrogen path—by using those renewables to directly replace fossil fuels.

At best, green hydrogen could be a niche climate solution post-2050—with a couple of technology breakthroughs. But any effort to scale up hydrogen before the entire economy has cut energy-related CO_2 emissions by 90 percent would seriously undermine efforts to avoid catastrophic climate change.

Joseph Romm is a former acting assistant secretary of energy, and now a senior research fellow at the Penn Center for Science, Sustainability, and the Media.