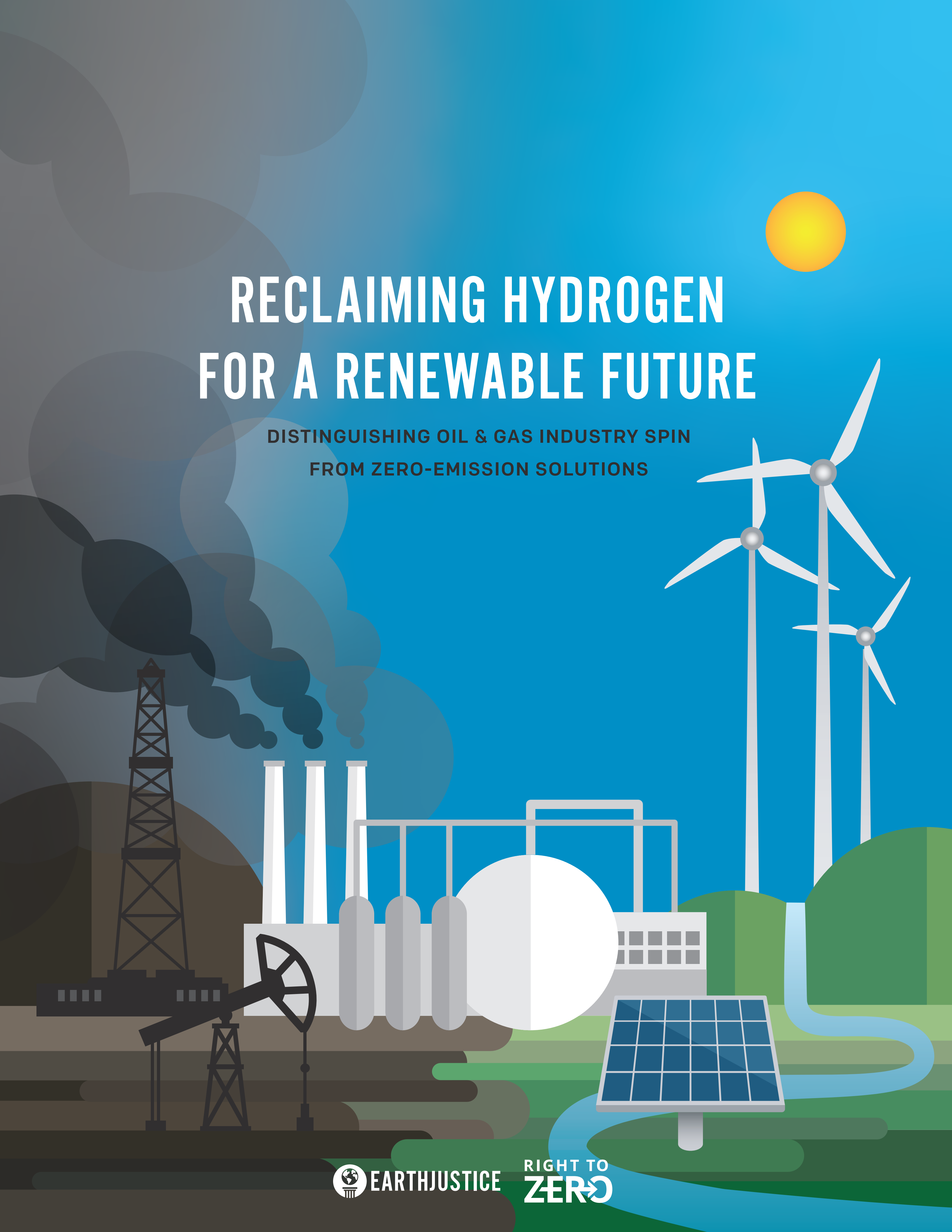
RECLAIMING HYDROGEN FOR A RENEWABLE FUTURE

DISTINGUISHING OIL & GAS INDUSTRY SPIN FROM ZERO-EMISSION SOLUTIONS



EARTHJUSTICE

RIGHT TO ZERO

AUGUST 2021

Sasan Saadat, **Earthjustice's Right to Zero campaign**

Sara Gersen, **Earthjustice's Right to Zero campaign**

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EXECUTIVE SUMMARY

The fossil fuel industry has helped generate enormous interest around hydrogen, making it difficult for policymakers to tell how much they can rely on hydrogen to meet climate goals. Too often, companies that profit from our reliance on fossil fuels invoke the vague promise of "clean," "renewable," or "green" hydrogen to derail action today. To avoid this trap, policymakers must scrutinize claims about hydrogen and think critically about where it can be a meaningful part of real climate solutions. To reclaim hydrogen for a renewable future, policymakers should explore opportunities to produce hydrogen from renewable electricity and use it to decarbonize sectors that cannot directly rely on a renewable electric grid.

First, reclaiming hydrogen for a zero-emission future requires a transition away from producing it with polluting technologies. Currently, oil and gas companies produce nearly all of the United States' annual supply of hydrogen—about 10 million metric tons—from fossil fuels through a process that pollutes neighboring communities with health-harming emissions and the atmosphere with greenhouse gases. Transforming hydrogen from a climate threat to a climate tool requires a transition to green hydrogen. **Green hydrogen is made using 100% renewable electricity to split hydrogen from water molecules**. For now, this is the only established way to produce hydrogen without emitting greenhouse gases or other health-harming pollutants. This whitepaper helps policymakers distinguish green hydrogen from hydrogen produced through polluting processes using inputs like fossil fuels and gas from factory farms. Fueling an industrial facility with green hydrogen would mitigate climate pollution, but not other pollution from its industrial processes, and so deployment of green hydrogen can never justify a buildout of facilities that would increase toxic pollution.

It will always be more efficient to rely first on the direct use of renewable electricity wherever it is possible to do so, rather than convert that electricity into hydrogen before using it as an energy source.

Once policymakers understand what green hydrogen is, they should consider the barriers to its widespread deployment. It will always be more efficient to rely first on the direct use of renewable electricity wherever it is possible to do so, rather than convert that electricity into hydrogen before using it as an energy source. This principle applies to vehicles, household appliances, and any other sector that has clean electric options for decarbonization. Moreover, relying on green hydrogen will require significant investments in storage and transportation infrastructure like dedicated pipelines because it behaves differently than the methane in our existing fossil gas infrastructure. Leakage in this infrastructure could undermine the benefits of green hydrogen because hydrogen is a greenhouse gas that is five times more potent than carbon dioxide. Scaling up the infrastructure to make green hydrogen widely available will take another decade—too long to delay dramatic reductions of climate pollution in the sectors that have other decarbonization options.

With these limitations in mind, policymakers can identify the sectors for which green hydrogen may nevertheless be a promising decarbonization tool, where it is worth careful exploration, and where they should instead deploy other technologies that are available today.

Our best option for deploying green hydrogen is to displace the fossil fuel-derived hydrogen already in use today. However, hydrogen is not an excuse to build or expand polluting industrial facilities. After additional study, policymakers may also find that green hydrogen is an appropriate tool for decarbonizing maritime shipping, aviation, industrial processes that require high temperatures, long-distance trucks or trains, and/or a small portion of our electricity supply. Given the limits on the supply of green hydrogen that are likely to persist for another decade, in the near-term, policymakers should reserve it for sectors that do not have other viable decarbonization options.

The gas industry has used false promises around hydrogen to hinder commonsense climate action, such as the shift to electric appliances like the induction stove top pictured here. *Tom Werner / Getty Images*

For the sectors that have zero-emission solutions available today, policymakers should embrace those solutions and reject any suggestion that climate action can wait for green hydrogen. For instance, the gas industry has used false promises around hydrogen to fight commonsense proposals to transition to clean, electric alternatives to burning gas in residential and commercial appliances. However, green hydrogen cannot make a meaningful dent in the climate pollution from these gas-fired appliances and the leaky pipelines that deliver gas to America's homes and businesses.

Meeting the scale and urgency of the climate crisis will require deployment of renewable resources on an unprecedented scale and a widespread transition to electric models for things like household appliances and cars—uses where electric technologies are readily available and economies of scale will further drive down costs. For instance, in the transportation sector, battery-electric vehicles are the most promising decarbonization strategy for most on-road vehicles. Stabilizing the climate will require aggressive near-term investments in these vehicles and their fueling infrastructure, regardless of whether green hydrogen may prove to be a cost-effective tool for some heavy-duty long-haul vehicles.

Green hydrogen provides an additional reason to deploy renewable energy resources at an unprecedented pace. Not only are massive investments in renewable resources like wind and solar necessary to decarbonize the electric grid, but economies of scale in renewable electricity generation are key to driving down the cost of green hydrogen. Despite industry rhetoric to the contrary, green hydrogen is not an excuse to build, expand or continue operations at gas-fired power plants. Even if future innovations may make it possible to retrofit these combustion turbines to operate solely on green hydrogen, the facilities would continue to pollute the air and burden the water supply. Today's renewable energy and battery technologies can cost-effectively supply 80% of the electricity we need by 2030 and 90% by 2035. Green hydrogen is a potential tool for achieving a fully decarbonized electric grid because it can store renewable energy for long periods and convert it back into electricity with zero-emission fuel cell technologies.

As we continue to electrify everything that can feasibly plug into a clean power grid, we can strategically deploy green hydrogen to displace the fossil-derived hydrogen that industry is using today and to power sectors that are otherwise difficult to electrify. When used as a marketing tool by the fossil fuel industry, hydrogen can be used to hinder necessary climate action. But when reclaimed and deployed as a solution to decarbonize sectors we cannot otherwise electrify, green hydrogen can play an important role in a zero-emission future.

INTRODUCTION

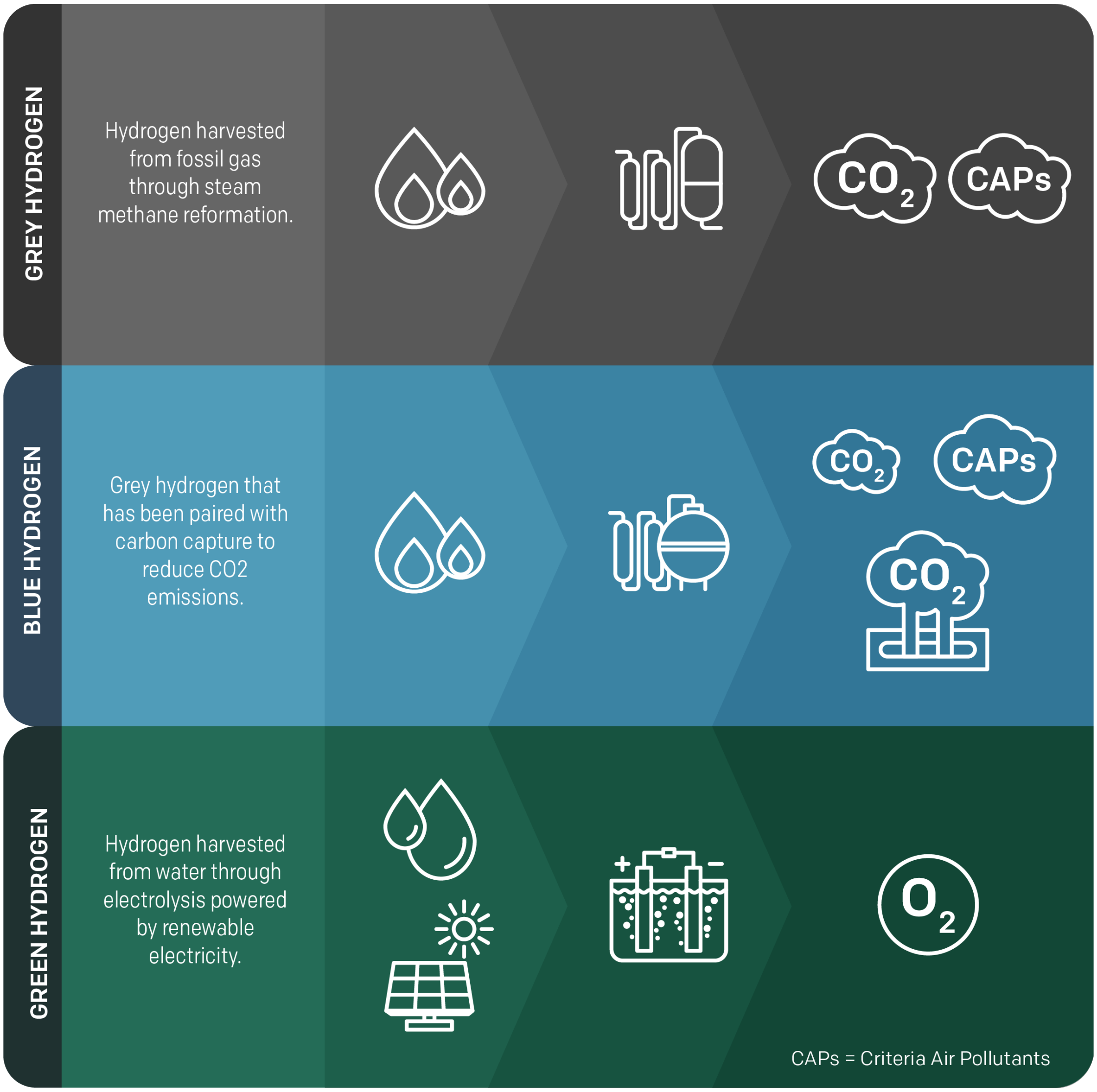
To chart a course toward a safer climate and more habitable planet, we must rapidly reduce emissions of greenhouse gases across our society. The biggest contributor to greenhouse gas emissions is the burning of fossil fuels. Consequently, the clearest path to reducing emissions is to switch from fossil fuels to renewable, zero-emission energy in our transportation, buildings, and power generation (sectors that are collectively responsible for about 75% of United States' greenhouse gas emissions).[1] This transition would make significant strides in eliminating the devastating public health impacts of pollution throughout the life cycle of fossil fuels—pollution that is most severely concentrated in Black, Brown, Indigenous, and poor communities.[2] A just transition will also require careful policy design and meaningful engagement from frontline communities. Renewable energy, energy efficiency, and electrification are zero-emission solutions that eliminate both greenhouse gases and health-harming air pollution. To meet the scale and urgency of the climate crisis will require deployment of renewable resources on an unprecedented scale—ultimately achieving 100% clean power generation—and a complete transition to efficient, electric models for things like household appliances and cars.

As we electrify everything that can feasibly plug into a clean power grid, "green hydrogen" is a promising tool for transitioning to renewable energy in sectors that lack a viable route to direct electrification. Green hydrogen is hydrogen produced by using 100% renewable electricity to split water molecules.

To understand the potential role of green hydrogen, consider the challenges of cutting climate pollution from one hard-to-electrify sector: maritime shipping. Maritime travel is difficult to decarbonize because battery-powered ocean-going vessels will not be able to handle long-haul voyages across the ocean, at least for the foreseeable future. The hope for green hydrogen is that it may store energy from clean electric resources like wind and solar in a fuel that could be used to propel large, long-haul ships. This vision is at least a decade away from reality, if it overcomes the challenges to cost-effective production and efficient on-vessel storage. Still, it offers a path to displacing the highly polluting bunker fuel currently relied on to move much of the world's goods across oceans.

Section I describes the status quo in industrial hydrogen production. Despite hydrogen's potential to become a climate solution in the future, today's reality is that global hydrogen production—more than 99.8 % of which is not green—is responsible for an enormous amount of climate pollution, more than the entire nation of Germany.[3] Oil and gas companies produce almost all of the United States' hydrogen supply from fossil gas, through a pollution-intensive process called steam methane reformation. Communities near oil refineries bear the brunt of this pollution because hydrogen production most often takes place at refineries, which are the main hydrogen consumers.

Figure 1. Three Types of Hydrogen Production



Globally, less than 1 percent of hydrogen is produced through electrolysis and less than 0.02% is green hydrogen (i.e., produced from electrolysis powered purely by renewable electricity).[4] **Using hydrogen will not break our dependence on fossil fuels unless we quit relying on fossil fuels to produce hydrogen**.

Section II discusses the fossil fuel industry's recent public relations blitz supporting increased reliance on hydrogen. The fossil fuel industry has created a wave of hype around investments in hydrogen, which often conflates green hydrogen with the polluting hydrogen that the industry produces from fossil gas. One of the industry's main strategies is to fund trade associations that advocate for policies that would increase hydrogen production from renewables and fossil fuels alike. Companies are also using hydrogen to greenwash new investments in fossil fuels, as they attempt to justify infrastructure projects with the vague and unsupported notion that the fossil fuel infrastructure might one day be repurposed for hydrogen. Policymakers must carefully scrutinize claims about hydrogen becoming a climate solution because the fossil fuel industry is aggressively promoting investments in hydrogen that would benefit their shareholders, but are not wise climate solutions.

Section III discusses the definition of green hydrogen and the challenges to its widespread deployment. To help policymakers avoid unsustainable or costly decisions, this report offers criteria to help decide where it might be appropriate to deploy green hydrogen. Widely deployed green hydrogen is still at least a decade away and will always be less efficient than directly using renewable electricity wherever feasible. Still, green hydrogen could be a good climate solution for specific applications in a sector if:

CRITERIA FOR DEPLOYING GREEN HYDROGEN

1. There are no low-cost decarbonization strategies available;
2. There are no electric technologies being developed that could take advantage of zero-emission electricity directly;
3. The logistics and costs of infrastructure for hydrogen transportation and storage can be contained;
4. Technologies for using hydrogen fuel in the sector are or will be available; and
5. Transitioning to green hydrogen could reduce air pollution.

Section IV discusses the potential for green hydrogen as a decarbonization tool in different sectors. Based on the considerations presented in Section III, the highest priority and best use for green hydrogen is to displace the massive amounts of fossil-derived hydrogen that are currently being used in industrial processes. For the next few years, volumes of green hydrogen will be small and costs will be high. Policymakers need to direct this precious resource to displace existing, pollution-intensive hydrogen, rather than create new pots of hydrogen demand.

STEAM METHANE REFORMATION

Methane is made up of 1 carbon and 4 hydrogen atoms. To obtain hydrogen, high-temperature steam (water vapor at 700-1000 °C) reacts with the methane under pressure. The reaction of methane (CH_4) and water vapor (H_2O) produces hydrogen gas (H_2) and carbon monoxide (CO). A second reaction (pressure swing adsorbtion) is performed with additional steam (H_2O) to purify the CO and CH_4 mixture, leaving more Hydrogen and carbon dioxide (CO_2).

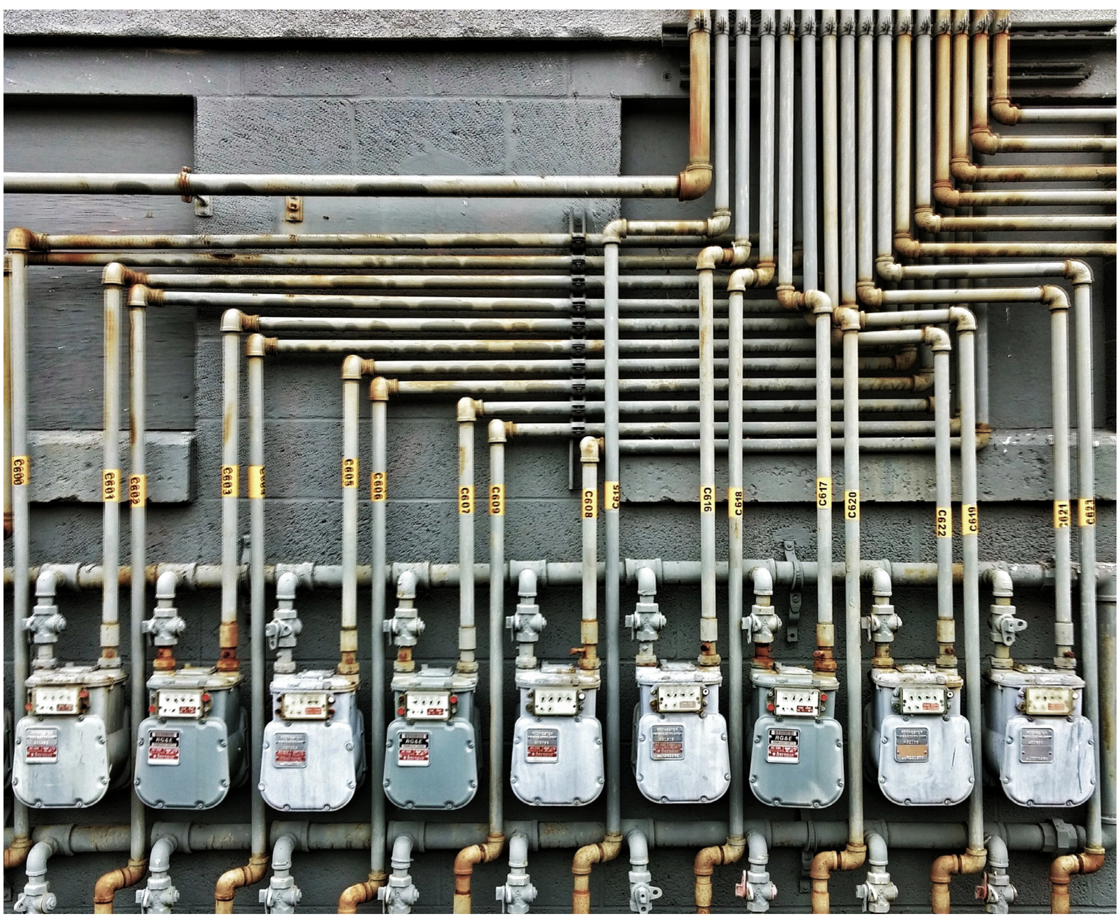
$CH_4 + H_2O \text{ (steam)} \rightarrow CO + 3H_2$
$CO + H_2O \text{ (steam)} \rightarrow CO_2 + H_2$

In the 2030s, green hydrogen's role could expand to address hard-to-electrify sectors or provide a small portion of our electric power supply by storing surplus renewable energy. Maritime shipping, aviation, high-heat industrial processes, and long-haul trucking are all potential applications for green hydrogen that policymakers should explore with caution. **In the meantime, the declining cost of renewables and batteries is widening the range of things that can easily be electrified, potentially narrowing the applications for which hydrogen should be considered.**

There are some sectors for which hydrogen is a dead end. The chief subject of misleading industry hype is the gas distribution network. The pipeline system that delivers methane to gas-fired appliances in homes and businesses cannot carry a significant amount of hydrogen—researchers estimate that hydrogen can only comprise about 7% of its energy content before hydrogen creates safety hazards. Nonetheless, gas companies tout hydrogen as a means of continuing their business model, while fighting against a climate solution that is available today: a full transition to electric appliances.

The very real risk is that these fossil fuel industry initiatives use the idea of green hydrogen to drive climate investments toward fossil fuel assets while siphoning them away from established, zero-emission solutions. The most urgent, near-term priority for climate action is accelerating deployment of the solutions that are already available and managing the transition from the fossil fuel economy. In addition to these aggressive near-term actions, policymakers can explore the potential for green hydrogen to decarbonize hard-to-electrify sectors.

These gas distribution lines cannot be used to deliver pure hydrogen. Injecting appreciable volumes of hydrogen in gas lines to burn in gas appliances poses health and safety risks. *Kevin Lucas, EyeEm / Getty Images*



I TODAY, HYDROGEN PRODUCTION RELIES ON FOSSIL FUELS AND THREATENS OUR CLIMATE AND PUBLIC HEALTH

The recent hype around hydrogen can mask the fact that the fossil fuel industry already produces hydrogen on a massive scale, with devastating consequences for the climate and communities. Gas companies and oil refineries are responsible for producing nearly all of the United States' annual supply of hydrogen—about 10 million metric tons[5]—through an energy-intensive industrial process called steam methane reformation (SMR) of fossil gas.[6,7] Coal gasification is also a significant source of hydrogen production in other parts of the world, accounting for 2% of global coal demand.[8] Globally, hydrogen production's toll on the climate is so great that hydrogen production is responsible for more greenhouse gas emissions than the entire country of Germany.[9]

In addition to emitting greenhouse gases, SMR emits pollution that harms public health in neighboring communities, including nitrogen oxides, fine particulate matter, carbon monoxide, and volatile organic compounds.[10] While SMR plants contribute to warming the climate globally, their local impacts are concentrated in the same communities on the frontlines of oil refineries. Oil refining company Phillips 66 for example, recently entered an agreement with industrial gas company Linde, to **build what will be the largest hydrogen production unit in the United States**.[11] The SMR project is being constructed in St. James Parish, Louisiana[12]—a predominately African-American community in the heart of a region of the U.S. Gulf Coast known as "Cancer Alley," so-named because the concentration of petrochemical plants and refineries cause high rates of cancer in local residents.[13]

The fossil fuel industry is not just the primary producer of hydrogen—it is also the primary consumer of hydrogen. Roughly 60% of domestic hydrogen demand comes from crude oil refineries,[14] where it is used to lower the sulfur content of diesel.[15] Demand for hydrogen from refineries continues to rise alongside

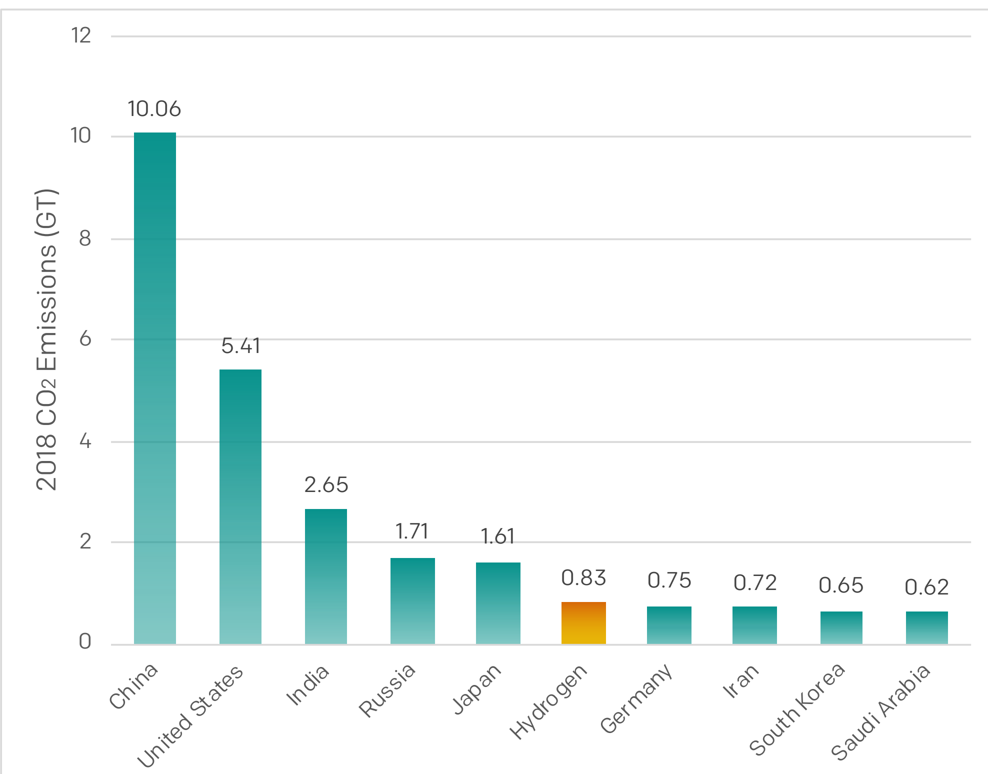


Figure 2. Top 10 Carbon Dioxide Emitters - 2018[21]

increasing global demand for diesel fuel. Global hydrogen demand has grown 28% over the last decade,[16] which means that pollution from producing hydrogen from fossil fuels is also increasing.[17] After the petroleum industry, the second largest consumer of hydrogen (about 30%) is industrial agribusiness, which uses hydrogen as a feedstock for chemical fertilizers.[18] The remainder (~10%) is used for other chemical and industrial processes like methanol production.[19]

The fossil fuel industry has multiple incentives for promoting hydrogen. First, the industry's vision for hydrogen calls for continued reliance on fossil gas to produce hydrogen, expanding existing revenue streams.[20] In contrast, a transition to a zero-emission economy means rejecting hydrogen from fossil fuels and *only* using green hydrogen, which is derived from 100% renewable electricity. Second, industry sometimes uses rhetoric about green hydrogen to justify new infrastructure for fossil gas. Gas utility companies boost their profits when they build more pipelines to deliver fossil gas to homes and businesses, with the monopolies' captive customers footing the bill. Some gas companies are fighting to expand their fossil gas infrastructure by spreading misleading claims about the potential for hydrogen to decarbonize their gas. Similarly, companies that profit from building gas-fired power plants are beginning to rely on the promise that they might one day retrofit these facilities to burn green hydrogen to justify investments in new gas-fired electricity generators.

The bulk of hydrogen demand in the United States today is for use in crude oil refineries. The fossil fuel industry is the country's primary producer and consumer of hydrogen. *Thomas Northcut / Getty Images*

II THE FOSSIL FUEL INDUSTRY IS CAMPAIGNING TO INCREASE RELIANCE ON HYDROGEN FROM FOSSIL FUELS

Policymakers must carefully scrutinize claims about hydrogen's role in reducing climate pollution because much of the hype around hydrogen comes from the fossil fuel industry, whose foremost interest in protecting shareholder profits may not align with sensible climate strategies. As public demand for climate action continues to rise, hydrogen has taken on a central role in the oil and gas sector's long-term planning.[22] In March 2021, several oil majors, gas companies, and fossil fuel-intensive utilities launched the "Clean Hydrogen Future Coalition," which urged the Biden administration to increase policy support for a wide range of hydrogen production methods and uses.[23] Oil and gas companies have joined with other industries —primarily chemical and car companies—to form at least six trade associations to advocate for more hydrogen production in the United States.[24] As a recent article in *Nature Climate Change* observed, "the gas industry is turning to hydrogen for a new lease of life."[25]

U.S. fossil fuel companies are following a playbook that oil and gas companies have already played in Europe and Australia.[26] In the United Kingdom, a group called "the Hydrogen Taskforce," backed by BP, Shell, and a slew of gas companies, launched to advance the mission of securing hydrogen's role in the energy transition through increasing government investment. The Taskforce's focus is on increasing support for hydrogen injection into the gas grid, with goals such as achieving 100% hydrogen for home heating[27] (a goal the UK's climate chief properly called "unwieldy and impractical").[28] In the European Union, a report by watchdogs revealed that the hydrogen lobby there—mainly comprised of the gas industry—spent nearly 60 million euros successfully convincing the European Commission to pursue a "Hydrogen Backbone." This vision calls for blending small amounts of hydrogen in the existing gas system with the aspiration of eventually expanding and repurposing that system.[29] The report also highlights how a major global lobbying group, the Hydrogen Council, was launched in 2017 by FTI Consulting, a public relations firm exposed for setting up fake "grassroots groups" in the United States to oppose climate action.[30] The Australia Hydrogen Council, which similarly draws most of its members from the gas industry, as well as the oil and auto industries, is focused on advancing a vision of hydrogen-powered transportation, and calls for "incentives or government policies created to drive scalability [to] initially be hydrogen technology agnostic."[31] In California, a coalition of oil, gas, hydrogen, and auto companies wrote to Governor Gavin Newsom asking him to invest half of the $1 billion dedicated to zero-emission transportation toward "hydrogen fuel infrastructure to serve the light-duty, transit and heavy-duty vehicle markets."[32] Similarly, the Clean Hydrogen Future Coalition, which includes large gas trade associations and companies, as well as oil majors BP and Chevron, sent a recent letter to President Biden calling for additional funding and tax incentives for "clean" hydrogen "from a variety of energy resources" for the power and transportation sectors.[33]

There are common themes that emerge across these efforts: the largest backers of hydrogen efforts are oil and gas companies; their marketing materials lead with the benefits of green hydrogen, but explicitly advocate for "all-of-the-above" hydrogen production, which is currently dominated by fossil fuel-derived hydrogen; and they primarily focus on the benefits of using hydrogen for injection in the gas grid or as a vehicle transportation fuel (where the transition to direct electrification is already underway).

III HYDROGEN CAN BECOME A DECARBONIZATION TOOL IN THE FUTURE IF POLICYMAKERS SEPARATE THE PROMISING OPPORTUNITIES FROM FOSSIL FUEL INDUSTRY HYPE

This section provides information to help policymakers understand the potential for using green hydrogen to reduce emissions and to identify instances where industries are making misleading claims about hydrogen to fight climate solutions that are available and cost-effective today. First, we explain what it means for hydrogen to be "green," which is a critical concept to understand in light of the many industry claims of "clean," "renewable," and "green" hydrogen that include highly polluting production pathways. Next, we explain the challenges to deploying green hydrogen. Policymakers should consider these limitations to determine where green hydrogen could be a useful decarbonization strategy.

1. FOR NOW, THE ONLY ESTABLISHED WAY TO MAKE HYDROGEN WITHOUT GREENHOUSE GAS EMISSIONS IS BY USING RENEWABLE ENERGY TO FUEL ELECTROLYSIS.

The first step in understanding whether a hydrogen project is a practical climate solution is to ask how the hydrogen is made. As discussed above, the predominant method for producing hydrogen today is a highly polluting process called steam methane reformation of fossil gas. Creating hydrogen that is suitable for a sustainable and equitable energy transition requires a total transformation in how it is produced. Today, the only established method of producing hydrogen without emitting greenhouse gases or other pollution is using renewable electricity to power electrolysis: a process that splits hydrogen from water molecules. We use the more specific term "green hydrogen" in this report to refer to this kind of hydrogen, consistent with the International Energy Agency's definition of "green hydrogen": hydrogen produced "using electricity generated from renewable energy sources."[34] While other nascent production pathways are being explored for producing hydrogen without pollution,[35] it would be premature to include other technologies in a definition of green hydrogen before they prove their ability to produce hydrogen without emissions.

To rely on electrolytic hydrogen as a climate strategy, it is essential to use 100% renewable energy to produce the hydrogen. Because electrolysis is so energy-intensive, hydrogen made with grid-average electricity is *even more carbon intensive than hydrogen made from SMR of fossil gas*. This is true even in California, which has a cleaner electric grid than most of the country.[36]

To deliver meaningful environmental benefits, green hydrogen production must be paired with the build-out of new renewable resources and/or use surplus renewable energy. If hydrogen producers were to buy power from existing hydropower, solar, or wind facilities, the customers who have historically purchased that renewable energy are liable to shift to grid-average electricity or contract with a fossil fueled generator. When power plants burn more fossil fuels to serve these customers, it defeats the purported environmental benefits of the "green" hydrogen producers using renewable energy. This phenomenon is known as "resource shuffling."

To deliver meaningful environmental benefits, green hydrogen production must be paired with the build-out of new renewable resources and/or use surplus renewable energy.

Policymakers should exercise caution with other forms of hydrogen that industry touts as "clean," "renewable," or even "green." For instance, the California Air Resources Board allows California hydrogen producers to call hydrogen derived from fossil fuels "renewable" when the companies match their fossil gas with the "environmental attributes" of biomethane from landfills in Mississippi and dairies in Indiana.[37] These companies market their hydrogen as "renewable" even though it is made from fossil gas, using the polluting steam methane process we describe above. Policies will not

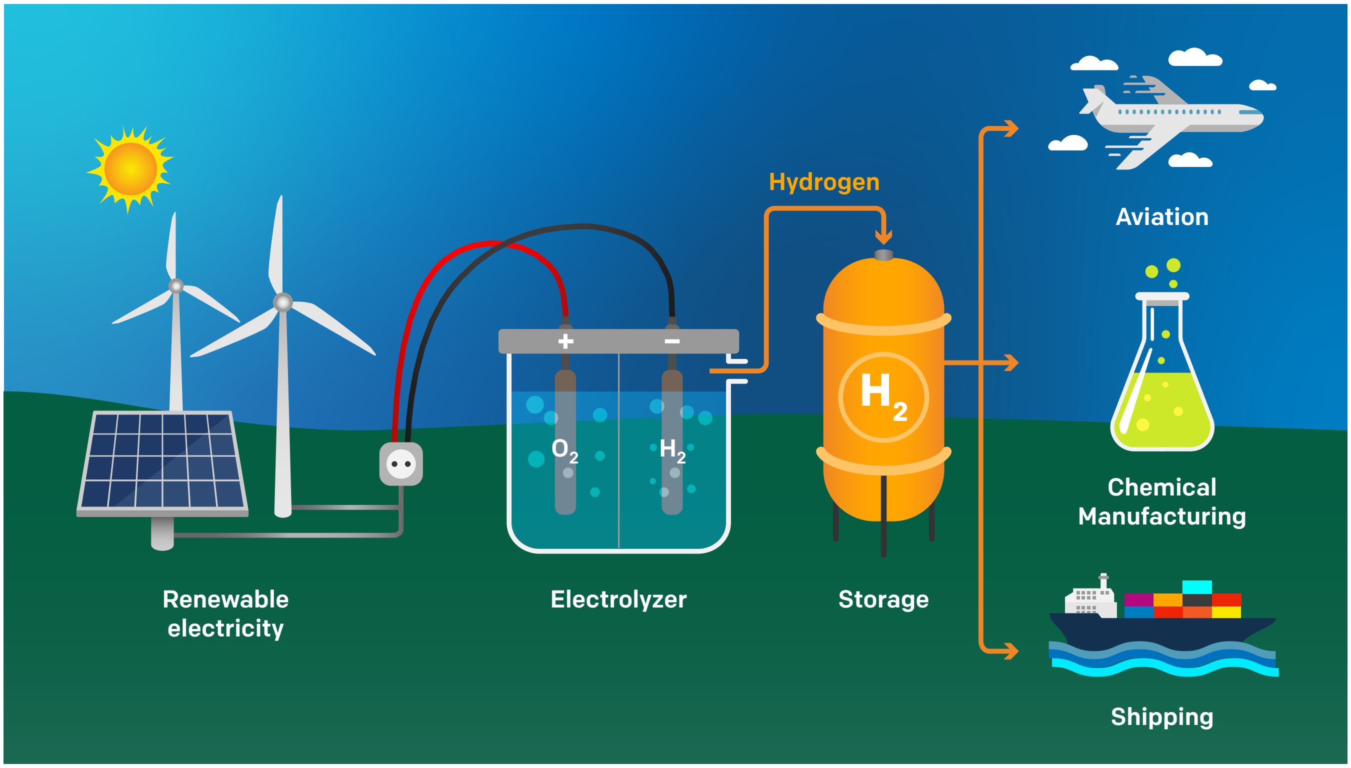


Figure 3. Green hydrogen production and use

catalyze the deployment of innovative technologies if their definition of "clean," "renewable," or "green" hydrogen includes the industry's business-as-usual practices paired with biomethane credits.[38]

The hydrogen industry's preferred definition of "green" hydrogen includes any hydrogen made from biomethane or biomass,[39] regardless of its climate and public health harms. For instance, this definition of "green hydrogen" would include hydrogen made from crops grown for the specific purpose of becoming an energy source. Although biomass conversion is sometimes touted as an opportunity to harness materials that would otherwise go to waste, the economic reality is that the cost-effective and logistically manageable sources of biomass are not dispersed waste streams, but energy crops. Data on the climate impacts of the U.S. EPA's Renewable Fuel Standard shows why it is essential to exclude purpose-grown energy crops as a feedstock for hydrogen. The Renewable Fuel Standard provides an incentive to increase biofuel production even though the EPA's review showed the program had led to

EUROPEANS LEADING THE WAY ON DEPLOYING THE TECHNOLOGY TO PRODUCE GREEN HYDROGEN

In 2020, the European Commission set a target to deploy 6 GW of renewable hydrogen electrolyzers by 2024 and 40 GW by 2030.* Meeting this goal will require a massive scale up of manufacturing capacity, which the European Commission predicts could cut the costs of electrolyzers in half by 2030. Wider deployment of electrolyzers can reduce the cost of production by both allowing manufacturers to achieve economies of scale and by spurring competition between suppliers. The United States should also develop a strategy for scaling up its electrolyzer manufacturing capacity or risk being left behind.

*Neil Ford, *Europe must double green hydrogen projects to hit target* (Aug. 26, 2020), https://www.reutersevents.com/renewables/wind/europe-must-double-green-hydrogen-projects-hit-target.

the conversion of up to 8 million acres of land—nullifying and overwhelming any climate benefit the program might have had.[40]

Timber is another example of a biomass feedstock that could contribute significant greenhouse gas emissions. Policymakers must not assume that biomass from forests is a carbon-neutral source of energy, especially when there is no guarantee that logged forests will have a chance to regrow. Even when trees can regrow, it will take many decades or more than a century to recapture the carbon that enters the atmosphere when forests are logged for energy.[41]

In addition to the unproven climate benefits of biomethane- and biomass-based hydrogen, the public health and environmental harms of many biogenic feedstocks make it misleading to call this hydrogen "green." As the Federal Trade Commission has explained, consumers can interpret claims that a product has a general environmental benefit to mean that the product has no negative environmental impact.[42] Consumers' expectations for the environmental integrity of a "green" product are directly at odds with the production methods for many biogenic feedstocks, such as biomethane from cow manure lagoons. Policies that create a market for biomethane inadvertently increase pollution from industrial agriculture facilities, whose air and water pollution cause significant harm to neighboring communities that are disproportionately low-income and communities of color.[43]

Producing hydrogen from fossil fuels with carbon capture to reduce emissions (what is often referred to as "blue hydrogen") is also not compatible with a zero-emission future. Even after an industrial facility installs expensive carbon capture technologies, it will continue polluting because that equipment is expected to capture 85% to 95% of a facility's climate pollution at best.[44] The process of capturing, compressing, transporting, and storing carbon is energy intensive.[45] With a power plant, for example, carbon capture can consume 30-50% of the plant's energy output.[46] Even if it were powered by renewable energy, the environmental benefit of this added energy and cost can be undermined by leakage of stored carbon.[47] Capturing carbon also does not reduce emissions of most health-harming air pollutants, such as particulate matter and nitrogen oxide, and some researchers estimate that it will lead to lifecycle *increases* of these pollutants in line with the additional fuel needed as a result of efficiency losses and increased energy use.[48]

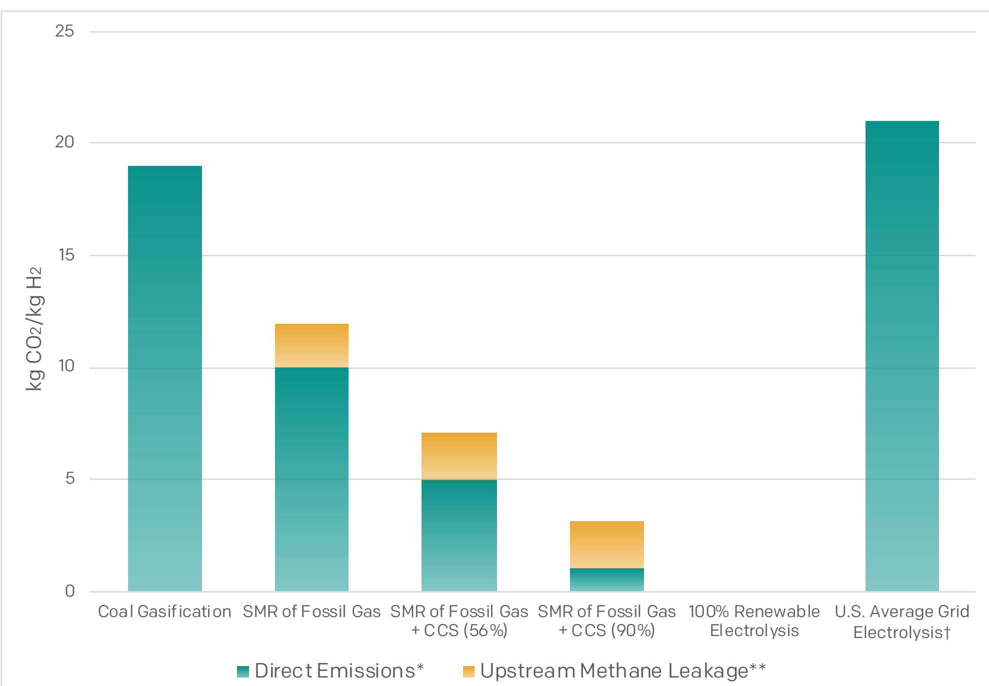


Figure 4: Carbon Intensities of Hydrogen Production

*Source: Bartlett and Krupnick 2020; IEA 2019

**Source: NRDC 2021

† 2017 Data, does not include upstream emissions

Moreover, carbon capture does not address the significant upstream emissions from extracting and then transporting gas across a leaky pipeline network. In the past few years, a growing number of studies have revised upward the scale of unaccounted-for leaks of methane from gas production, processing, transmission, and storage.[49] **Based on an analysis by the Natural Resources Defense Council, accounting for current upstream leakage at average rates reported in the United States would add another 2.1 kg CO_2/kgH_2 to the carbon intensity of blue hydrogen—roughly double the onsite emissions for SMR with 90% carbon capture.**[50] Even the vice president of Norwegian oil company Equinor (which is aiming to be a global leader in blue hydrogen production) acknowledged that 100% carbon capture from methane reforming is not physically possible, and admits that upstream emissions risk "killing the concept of blue hydrogen."[51]

Carbon capture does not address the significant upstream emissions from extracting and transporting fossil gas.

A recent United Nations report warns that the world must immediately slash methane emissions to stall near-term warming and avoid crossing irreversibly damaging climatic tipping points while we pursue rapid decarbonization. Extending and expanding reliance on methane-leaking infrastructure ignores this message.[52] Capturing carbon from fossil-fueled hydrogen production leaves these significant emissions unabated, yet comes at substantial added cost—so far, the cost of captured carbon has only been economically feasible when the carbon is used for enhanced oil recovery, which instigates further fossil fuel production and the related emissions.[53] Consequently, industry analysts and environmental groups alike warn that this strategy is likely an unwise and distracting investment.[54]

2. LIMITATIONS OF GREEN HYDROGEN

Green hydrogen cannot deliver near-term emissions reductions at scale because of several constraints: the significant amount of renewable energy that is lost through conversion into green hydrogen, high costs, difficulty of storage and transport, and environmental challenges such as water demand from its production. In sectors where industry might retrofit equipment that burns fossil gas to burn hydrogen, there is the additional risk that a transition to green hydrogen could increase air pollution. These constraints limit both the supply of green hydrogen and our ability to use it. Moreover, because dramatic reductions in greenhouse gas emissions must begin this decade to avert climate catastrophe, we must immediately decarbonize sectors that have solutions available today and cannot wait for the widespread availability of green hydrogen.

Therefore, proposals to use green hydrogen must be vetted on a case-by-case basis to assess whether and how they manage these constraints, and whether doing so is more cost-effective than directly using renewable electricity. Because of its scarcity, competition for green hydrogen among sectors could drive up the cost. Conversely, limiting green hydrogen demand to only essential sectors under scenarios with high renewable penetration could allow its use at negligible extra cost.[55] In the short term, the only plausible economical option will be using renewable-driven electrolysis systems for niche applications in hard-to-abate sectors where infrastructure buildouts can be contained.[56]

Energy inefficiency

Using renewable electricity to power electrolysis results in substantial energy losses—anywhere between 20 and 40% of the energy is lost.[57] **Because of this inherent inefficiency, green hydrogen will always be a considerably more expensive fuel than renewable electricity**.[58] Not only is energy lost in the process of making green hydrogen, but equipment that uses green hydrogen is often less efficient than its competitors. A comparison of space heating technologies in buildings provides a good example of the efficiency advantages of using renewable energy directly as electricity instead of converting it to hydrogen. Hydrogen-based, low-temperature heating systems consume 500 to 600% more renewable energy than heat pumps.[59] Heat pumps can use renewable electricity on the power grid directly and efficiently. Analysts describe heat pumps

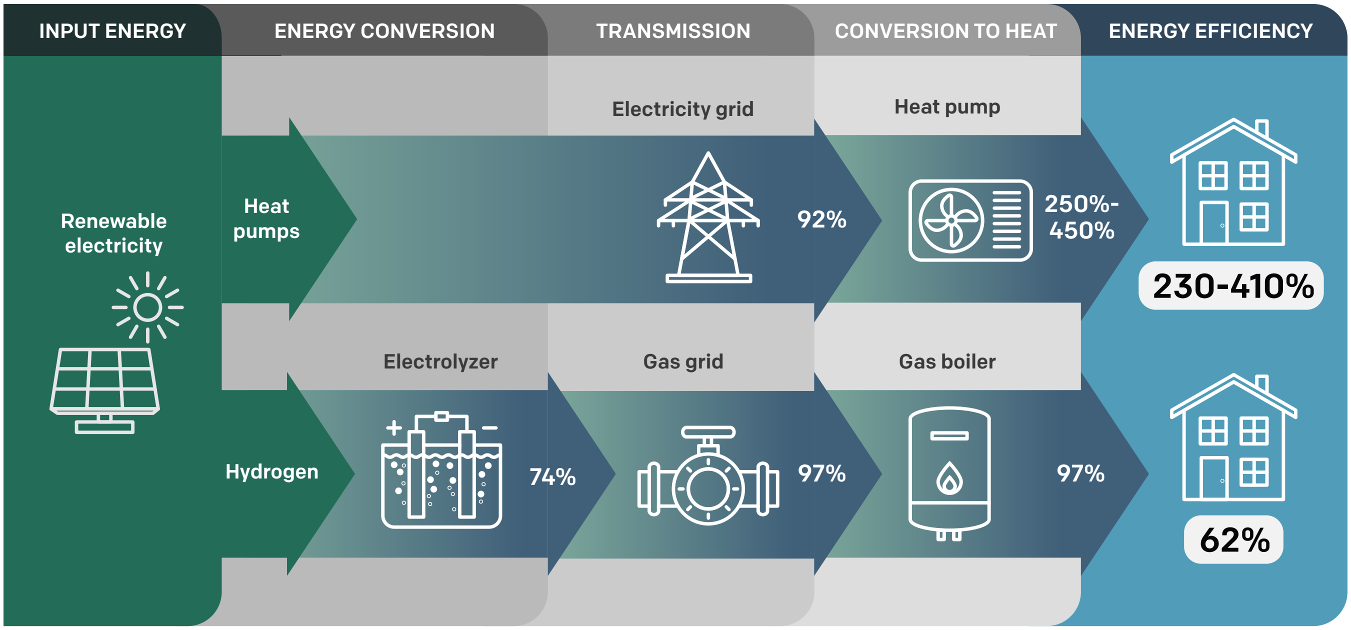


Figure 5: Comparison of efficiencies for hydrogen and heat pumps in homes

Data source: Ed Reed, *Hybrid hydrogen heating hopes*, Cornwall Insight Ireland (Nov. 29, 2018), https://www.cornwall-insight.com/uploads/CoTW%20Hydrogen_MH.pdf.

as having efficiencies greater than 100% because they transfer ambient heat, rather than combusting fuel to create it. Ultimately, heat pumps deliver warm air and hot water 3 to 5 times more efficiently than conventional furnaces and water heaters. As a result of their superior efficiency, heat pumps are cheaper to operate than equipment that burns fossil gas or equipment that burns green hydrogen, and even provide upfront capital cost *savings* when replacing the combination of a gas furnace and air conditioner (since heat pumps can provide both functions).[60]

Because electrolysis is so energy intensive, achieving substantial volumes of green hydrogen for any major economic sector would require enormous amounts of renewable electricity. Just deploying enough clean energy to eliminate emissions from the electricity sector by 2035 will be a titanic effort, requiring a six-fold increase over historic rates of renewable energy deployment, even if demand for electricity were static.[61] Transitioning to electric vehicles and ditching gas appliances for efficient electric technologies will dramatically increase demand for electricity and the need for new renewable resources.[62] Meeting the global demand for green hydrogen that one industry group predicts in 2050 could require the build out of solar resources that cover more than 81,250 square miles.[63] This is a land area larger than the state of Minnesota. Using green hydrogen in segments that can use direct electricity would exacerbate the challenge of deploying sufficient renewable resources by wasting renewable capacity on energy-intensive electrolysis.[64]

Costs

Currently, conventional fossil hydrogen costs between $1.25/kilogram and $2/kilogram in the United States,[65] while green hydrogen costs between $2.50/kilogram and $4.50/kilogram.[66] Three sets of analysts — BloombergNEF, Wood Mackenzie, and McKinsey — have recently found that green hydrogen could become cost-competitive by 2030 as economies of scale drive down the cost of electrolyzers and the price of wind and solar power continues to fall.[67] The Biden administration has announced a goal of reducing the cost of green hydrogen by 80% by 2030, indicating that federal policy might help achieve price reductions even greater than what analysts have predicted by the end of the decade.[68] The biggest influence on the cost of renewable hydrogen is the cost of the clean electricity that powers its production. Low-cost green hydrogen requires abundant, low-cost, renewable energy.[69] Increasing total deployment of renewable energy is therefore a precondition for economically producing appreciable amounts of green hydrogen.

It is important for policymakers to consider long-term cost forecasts for green hydrogen when considering permits for new gas-fired facilities if developers claim the new fossil fueled infrastructure could be retrofitted to run on green hydrogen. For example, a company that recently proposed a new gas plant in Newburgh, NY estimated that hydrogen in 2040 will cost $45/MMBtu in nominal dollars.[70] In contrast, the most recent Energy Information Administration 2020 Annual Energy Outlook projects natural gas to cost well below $4/MMBtu in 2040 (in 2019$) in its Reference Case.

To have hydrogen replace the energy supply of fossil gas in the global economy would require building 3 to 4 times more storage and pipeline infrastructure.

Fuel costs would be even greater for blends of green hydrogen and zero-carbon methane, as the production of "synthetic methane" involves first making green hydrogen and then using the hydrogen as an input into another chemical process. Yet, some industry members and policymakers have contemplated using blends of green hydrogen and synthetic methane in residential and commercial appliances, which were designed to burn methane and cannot safely burn pure hydrogen.[71] A report prepared for the California Energy Commission finds that "[e]ven under optimistic cost assumptions, the blended cost of hydrogen and synthetic natural gas is 8 to 17 times more expensive than the expected price trajectory of natural gas."[72] The high costs of these gases make it difficult for gas-burning appliances to compete against electric options in a zero-carbon future. The inefficiency of converting clean electricity into hydrogen (let alone synthetic methane) before using its energy will always make it more costly than plugging directly into the electric grid.

Pollution from combustion

Burning hydrogen creates health-harming pollution. Proponents of hydrogen will often note that hydrogen fuel cells only emit water vapor, but many potential applications for hydrogen involve combustion rather than fuel cells. Hydrogen combustion's most significant public health threat is oxides of nitrogen (NOx), a pollutant that damages heart and respiratory function, impairs lung growth in children, and leads to higher rates of emergency room visits and even premature death.[73] NOx is a precursor to both ambient ozone and fine particulate matter pollution,[74] and also contributes to climate change.[75] One group of researchers predicted that **burning pure hydrogen would emit more than six times as much NOx as burning methane**, the main component in fossil gas.[76] NOx emissions could be reduced through advances in pollution control technology or by lowering flame temperatures, but this requires either lower volumes of hydrogen in the combustor (and consequently, increased reliance on fossil fuels) or de-rating the engine which results in efficiency losses and power decreases.[77] Industry should not be allowed to increase hydrogen combustion without first demonstrating control technologies that will avoid increases in NOx emissions. In 2018, air pollution from fossil fuel combustion was linked to roughly 355,000 premature deaths in the United States—pollution that African Americans were exposed to at a rate 1.54 times that of the overall population.[78] As long as combustion continues, proposals to reduce greenhouse gases by displacing some or all of the fossil fuels with hydrogen will not alleviate the uneven burdens of air pollution, and may even worsen them.

Safe transport and storage

Today, the majority (around 90%) of hydrogen in the United States is produced at or adjacent to where it is used (either onsite by petroleum refineries that use it themselves, or by nearby gas companies that deliver it by pipeline).[79] Transporting hydrogen is expensive due to its low energy density, which means that large amounts of space are required to hold a relatively modest amount of hydrogen energy. By way of comparison, to have hydrogen replace the energy supply of fossil gas in the global economy would require building 3 to 4 times more storage and pipeline infrastructure.[80]

Safely transporting, storing, and handling hydrogen can add significant costs. For instance, it only costs a few dollars per kilogram to produce hydrogen from fossil gas, which is how most hydrogen is produced today in California and across the United States. Yet the average retail price of hydrogen at fueling stations in California is about $16.50 per kilogram—the equivalent of about $6.40 per gallon of gasoline.[81]

Precautions against leaks are also necessary at each stage of handling hydrogen. Containing hydrogen is more challenging than containing other gases because hydrogen is the smallest and lightest molecule in the universe; 50,000 molecules of hydrogen gas can fit in the width of a human hair.[82] It is also extremely flammable, making it susceptible to combust even in small concentrations.[83] Deliberate steps are necessary to detect leaks because hydrogen is a colorless and odorless gas.[84] Leakage could diminish the climate benefits of a transition to green hydrogen because hydrogen itself is a greenhouse gas that is more than five times more potent than CO_2.[85]

The three main ways of transporting hydrogen are by pipelines, trucks or rail, and ships, each of which would require massive investments in new infrastructure to transport hydrogen at scale:

(1) **Pipelines:** Pipelines are the most cost-effective means of transport. Hydrogen pipelines today are very limited; there are only about 1,600 miles of dedicated hydrogen pipelines in the United States—mostly clustered in Southern California and along the Gulf Coast in Texas and Louisiana near refineries and chemical plants. Building a hydrogen pipeline can cost up to 68% more per mile than a conventional fossil gas pipeline.[86] **It is important not to confuse hydrogen pipelines with the United States' vast network of gas pipelines that were designed to deliver methane because these fossil gas pipelines cannot carry meaningful volumes of hydrogen. Hydrogen's size and energy density make it incompatible with generic pipeline materials and compressor designs**.[87] Hydrogen can cause "embrittlement" in pipes and its higher flammability and leakage rates create safety risks.[88] Conventional gas pipelines do not have systems for detecting leaks of hydrogen.[89] Thus, the lowest cost manner of transporting pure hydrogen would require massive investments in dedicated pipeline networks.

(2) **Trucks and rail:** Hydrogen can also be transported in high-pressure tube trailers on trucks or rail cars. Compression in tube trailers is expensive, however, and is only suitable for small volumes over short distances of 200 miles or less.[90] Unless the trucks used to

CAN WE RETROFIT EXISTING PIPELINES TO CARRY PURE HYDROGEN?

The first question to ask if the fossil fuel industry claims it can use existing gas infrastructure to deliver hydrogen is whether they are talking about pipelines that deliver gas to homes and commercial businesses. These "distribution" pipelines *cannot* be retrofitted to deliver pure hydrogen. The gas-burning appliances in homes and commercial buildings cannot burn hydrogen without an unacceptable risk of explosion. For insights into industry arguments for blending small amounts of hydrogen into distribution pipelines, see Section IV.

In contrast, the "transmission" pipelines that carry fossil gas from production centers to storage facilities and industrial users could conceivably be retrofitted to carry pure hydrogen. This retrofit would require significant costs, including replacing all of the pipeline's compressors.

transport the hydrogen are themselves zero-emission, then this comes with significant air pollution and greenhouse gas impacts of diesel combustion.

(3) **Ships:** For longer, intercontinental transport, hydrogen could be liquefied and transported by ship. Ships could transport relatively large volumes of liquid hydrogen, but liquefaction is expensive, and requires energy-intensive (and costly) chilling of hydrogen (to -252°C). Alternatively, ships can carry ammonia (they already do) as an energy carrier (ammonia is NH_3—meaning it carries three hydrogen molecules for each molecule of nitrogen). But if hydrogen is ultimately the desired commodity at its destination, this requires costly and energy-intensive re-conversion at the point of use.

The low energy density of hydrogen presents similar challenges for hydrogen's storage. Kept in a gaseous state, hydrogen storage requires large amounts of space. The cheapest solution is geologic salt caverns, which could store weeks' or months' worth of hydrogen, but these are geographically limited.[91] Pressurized containers could in theory be built anywhere, but their footprint and cost would limit them to small (days' worth) volumes.[92] To shrink hydrogen's footprint, it can be cooled and compressed to a liquid state, or converted to ammonia, but these present the same temperature and energy conversion loss challenges as shipping, mentioned above.[93] All storage options present risks, which planners should evaluate on a case-by-case basis.[94]

Water use

Electrolysis uses freshwater as a feedstock and is thus a significant source of freshwater demand. Producing one kilogram of green hydrogen requires between 9 and 11 liters of water as a feedstock.[95] Because additional water is also required for system cooling, total water demand can be between 15 and 20 liters of water for each kilogram of green hydrogen.[96] On a global basis, the water demand for electrolysis is far less than the water requirements for extraction and processing of fossil fuels. Still, climate change will constrain global freshwater resources in significant ways—e.g., by increasing evaporation and droughts, altering precipitation patterns, melting freshwater stored in glaciers, and contaminating aquifers with saltwater from rising sea levels.[97] These impacts will mean water-stress will both expand and intensify. Regions with the potential to produce low-cost, abundant green hydrogen may intersect with areas of water-stress, presenting localized resource challenges. For example, many of the most-often discussed "solar-hydrogen superpowers" are in regions with high insolation like North Africa, the Middle East, and the U.S. Southwest—all regions with extreme drought risk.[98] Some researchers are exploring ways to use low-grade and saline water for electrolysis, which could open more opportunities for green hydrogen production in regions facing water scarcity.[99]

Time

Today, less than 1 percent of hydrogen is produced through electrolysis and less than 0.02% is entirely produced from renewable electricity (i.e., green hydrogen).[100] **Dramatic reductions in climate pollution cannot wait until the 2030s, when we expect to see significant cost declines and increased availability for green hydrogen**. Maintaining a reasonable chance of limiting warming to 1.5° C requires more than half of global emissions reductions to happen before 2030—a commitment the Biden administration made in its latest submission of the United States' Nationally Determined Contributions under the Paris Agreement.[101] In reality, for wealthy nations like the United States, which is also the largest historical emitter of greenhouse gases, even steeper and earlier reductions must be made, since poorer nations will require more time and carbon budget to develop.[102] To reduce emissions as rapidly as possible, mitigation must take full advantage of solutions that *already* exist and can be quickly deployed starting today.

The urgent need for near-term reductions means we cannot afford to wait for the commercial availability of green hydrogen to decarbonize sectors that already have decarbonization tools.

IV IDENTIFYING THE PROMISING APPLICATIONS FOR GREEN HYDROGEN

This section explores the potential for various sectors to use green hydrogen as a cost-effective decarbonization tool. Below, we have sorted different applications in terms of their suitability for decarbonization with green hydrogen, using basic questions that policymakers can apply to any sector or potential hydrogen project. As a general principle, policymakers should never delay deployment of cost-effective decarbonization tools that are available today based on the hope that green hydrogen might become available in the future.

1. LEAST-REGRETS USES FOR GREEN HYDROGEN

Displace fossil hydrogen in current uses as an industrial feedstock

As discussed in Section I, industry currently produces so much hydrogen from fossil fuels that hydrogen production is a significant climate threat. Green hydrogen could avoid these emissions without requiring new technologies for hydrogen use. Industrial clusters that have hydrogen customers grouped in a small geographic footprint would allow for supply to be delivered by dedicated pipeline (the cheapest mode of delivery), and leverage existing storage infrastructure.

As the energy transition proceeds, demand for oil refining and chemical fertilizer production should decrease: sustainable and zero-emission transportation would reduce reliance on petroleum, and sustainable practices would reduce reliance on chemical agriculture inputs. In the next decade, while oil refining is required to meet increasingly stringent fuel specification standards, hydrogen demand may grow in the refining sector, and it would be a win for both the climate and public health if these inputs are instead supplied by green, zero-emission hydrogen. However, the potential for green hydrogen to displace fossil hydrogen cannot be a justification for expansion of refineries or chemical fertilizer plants. It should only be considered as a clean feedstock for existing, polluting systems that must rapidly wind down to meet climate and environmental justice objectives.

2. SECTORS TO EXPLORE WITH CAUTION

Maritime shipping

Global maritime transport accounts for roughly 3% of global greenhouse gas emissions, and is responsible for roughly 15% of global emissions of sulfur oxides and nitrogen oxides—pollution that disproportionately harms public health in port-adjacent communities.[103]

Inland vessels, ferries, and other smaller ships sailing shorter distances can already be powered using batteries and operate with zero-emissions.[104] The unexpected pace of technological progress in batteries has even led companies to begin building and piloting battery-powered zero-emission tankers and container vessels.[105] Given challenges to recharging batteries that need to cross thousands of miles of ocean, however, reliance on liquid fuels in international voyages is unavoidable for the foreseeable future.

Recent reports identify green hydrogen and green hydrogen-derived ammonia as a promising path to decarbonizing ships with longer voyages.[106] Green ammonia (derived from green hydrogen plus nitrogen in the atmosphere) is viewed as slightly more promising because it is easier to store and requires less space than pure green hydrogen for a given energy content.[107] If used in internal combustion propulsion systems, ships burning green hydrogen or ammonia will still emit air pollutants such as NOx (and unburned ammonia—a pollutant that is toxic to both humans and aquatic life).[108] To reduce air pollution, green ammonia or hydrogen should be used in fuel cells, a solution that is less established than combustion engines but is being piloted for some long-voyage vessels.[109]

		Are there currently technologies for using hydrogen in this sector?	Would use of green hydrogen require significant investments in hydrogen transportation and storage?	Are lower-cost decarbonization strategies available for this sector today?	Is green hydrogen likely to be necessary to decarbonize this sector?	Air pollution impacts of transition to green hydrogen
LEAST-REGRETS USES FOR GREEN HYDROGEN	Displace fossil hydrogen currently used as an industrial feedstock	Yes	Not if green hydrogen is produced on-site.	No	Yes	A transition to green hydrogen would avoid air pollution from current hydrogen-production practices.
EXPLORE WITH CAUTION	Maritime shipping	No	Yes	No	Yes	A transition to green hydrogen or green ammonia would reduce emissions from vessels, especially if they used fuel cells.
	Aviation	No	Yes	No	Yes	Potential for emissions reductions if planes use green hydrogen in fuel cells, rather than burning hydrogen.
	Industrial processes that require heat above 400°C (such as steel production)	Requires case-specific analysis	Yes	Partially	Maybe	Depends on what fuel the green hydrogen would displace. If a facility is currently burning fossil gas, a transition to green hydrogen combustion will not reduce (and may increase) NOx emissions.
	Long-term storage of renewable electricity paired with fuel cells	Yes, fuel cells that can deliver stationary power exist and are in operation around the world today.	Yes	No. Current technologies enable us to cost-effectively achieve 90% clean energy on the electric grid by 2035, but do not offer solutions for long-term storage of renewable energy.	Maybe. It is unclear what technology will emerge as the most cost-effective tool for long-term storage of renewable electricity.	Green hydrogen using fuel cells can eliminate on-site air pollution.
	Long-haul trucks and trains	Fuel cells are commercially available, but are still being piloted and tested for long-haul trucking in the United States (>200 miles a day) and line haul locomotives (cross country).	Yes	Partially	Maybe. Battery-electric and overhead catenary systems are the two primary alternatives for zero-emission long-haul transportation. Hydrogen fuel cells may be able to outcompete the demand for batteries and high-capacity charging for long, heavy-duty hauls, and the infrastructure costs of overhead lines.	A transition to green hydrogen fuel cells would avoid health-harming tailpipe emissions.
REJECT THE HYDROGEN HYPE	Combusting hydrogen in new, existing, or expanded fossil gas power plants	Current turbines can handle small amounts of blended hydrogen, but running on pure hydrogen requires yet to be demonstrated modifications.	Yes	N/A. However, unsubsidized solar and wind, even when paired with batteries, are much cheaper than gas plants running on even modest blends of hydrogen, which would have minimal greenhouse gas reduction benefits.	No, gas plants are best decarbonized by being decommissioned.	Hydrogen blends running in gas turbines are likely to increase NOx pollution.
	Industrial processes that require heat below 400°C (e.g., food and beverage processing, packaging, textile, and some chemicals processing)	No	Depends on facility	Yes	No	Burning hydrogen would cause more air pollution than electric alternatives.
	Gas-burning appliances in homes and commercial buildings	Gas-burning appliances can tolerate some blending of hydrogen into the gas mixture, but it is unclear how much.	Yes	Yes	No	Indoor air pollution would continue and may worsen.
	Cars, buses, and short- haul trucks	Yes	Yes	Yes	No	Like battery-electric vehicles, fuel cell vehicles have no tailpipe pollution.

Figure 6: Evaluating potential applications for green hydrogen

These paths are preferred to both biofuels, which a World Bank report dismisses as "highly unlikely to be available at sufficient scale and to be sufficiently cost-competitive" and synthetic carbon fuels, which they conclude "involves multiple energy-intensive steps which leads to poor energy efficiency."[110]

Aviation

Aviation emits more than 2% of global CO_2 emissions and is expected to rapidly rise.[111] Like maritime shipping, the aviation sector may not be able to rely on widespread electrification to eliminate emissions, given the limitations of batteries and charging for long-haul routes. Independent experts have identified using renewable electricity to produce hydrogen or kerosene (derived from green hydrogen) as a potential path to decarbonizing aviation, with some companies already piloting its potential for short-haul flights under 500 miles.[112] Some startups are investigating the potential for hydrogen-powered aviation, with some developing hydrogen "capsules" that would be interchangeable, and will be piloted in aircrafts powered by fuel cells capable of regional flights up to 700 miles, with a goal for actual flights by 2025.[113]

High-heat industrial processes

Green hydrogen may play an important role in decarbonizing high-temperature industrial processes, such as steel production, that do not have electric decarbonization options. Steel production is an industry for which green hydrogen is an especially attractive decarbonization strategy because green hydrogen could provide both high-temperature heat and replace coking coal in the iron-ore reduction process. Meanwhile, many industrial processes use temperatures well within the range of lower-cost alternatives. Electric heat pumps will probably be the most cost-effective option for decarbonizing industrial processes that require heat up to 400°C.

Currently, about 40% of gas used for industrial heat is for temperatures less than 100°C—like for food, beverage, and textile processing, packaging, and some chemicals processing.[114] Even for higher temperature heating demands, other electricity based options are commercially established (e.g., electric arc furnaces, resistance, microwave and plasma heating). Electric arc furnaces are now used in some steel production and can reach temperatures up to 3500°C.[115]

Long-haul trucks and trains

Hydrogen fuel cells are already in use in the transportation sector, but they are significantly more expensive, and would require significantly more renewable electricity, than battery-electric vehicles.[116] These constraints limit their potential to segments of the surface transportation sector where, like shipping and aviation, batteries are not soon expected to achieve necessary energy density or refueling needs for long, heavy-duty hauls. Locomotives that carry heavy freight across the country, for example, need so much energy that an entire rail car of batteries might be required where catenary or other electrified rail infrastructure is not feasible,[117] and some worry that battery weights could penalize the payload of long-haul trucks (though jurisdictions like California and Europe have passed additional zero-emissions vehicle weight allowances).[118] While some analyses show that the current and rapidly advancing state of battery cost and performance will overcome these concerns, the need for high energy density and fast refueling times makes hydrogen fuel cells a potential solution for these surface transportation segments.[119] A few truck manufacturers continue to explore hydrogen fuel cells for long-haul trucks,[120] and hydrogen fuel cells are being used to displace diesel engines in some locomotives.[121]

Long-term storage of renewable electricity paired with fuel cells

The near-term focus for decarbonizing the electric grid should be dramatically increasing deployments of renewable resources and batteries—the mature technologies that can cost-effectively supply 80% of the United States' electricity by 2030 and 90% of electricity by 2035.[122] Achieving a zero-carbon grid will require a variety of energy storage technologies that can store renewable energy over different time scales. Green hydrogen's advantage is that it could economically store renewable energy for long periods of time with minimal energy loss.[123] It is unclear whether green hydrogen will be able to compete against other long-term energy storage technologies, such as compressed air and electrochemical storage.[124]

Importantly, fuel cells do not present the substantial air pollution concerns that come with combustion turbines, because fuel cells only emit water vapor.

Fuel cells would be the appropriate technology for re-converting green hydrogen into electricity. Most importantly, fuel cells do not present the substantial air pollution concerns that come with combustion turbines because fuel cells only emit water vapor.[125] Further, fuel cells can operate at higher efficiencies (up to 60%) than combustion power plants (about 40%).[126] Fuel cells can be sited in urban settings near the customers who rely on them because they are quiet and do not emit air pollution, helping to reduce expensive investments in the transmission system and the risk of power outages when transmission lines fail.[127] Fuel cells are an established and commercially available technology, unlike burning pure hydrogen in power plant turbines. And because fuel cells rely on the same principal processes as electrolyzers (they are essentially electrolyzers that work in reverse) they are likely to benefit from the expected cost declines that will come from increased investment in green hydrogen.

The main drawback of fuel cells is that they tend to have smaller energy capacity compared to combustion turbines and have initially been limited to meeting smaller energy demands. But this is changing—fuel cells can provide power for systems as large as utility power stations, and groups of modular fuel cell systems have been joined to create small power plants up to 63 MW in size.[128] While the larger deployments of solar and wind necessary to generate surplus renewable energy continue to be scaled, higher capacity fuel cell technology and costs are likely to improve. In the meantime, it is important that policymakers and energy system planners seek ways to prioritize their deployment in place of alternatives that would rely on combustion and its corresponding air pollution.

3. SECTORS WHERE HYDROGEN IS NOT A SOLUTION

In these sectors, there are unique and likely insurmountable challenges to cost-effectively deploying green hydrogen, in addition to the cross-cutting challenges described in Section II. Please see page 18 for information about the infrastructure needed to safely transport and store hydrogen and page 17 for information about the deployments of wind and solar resources that will be necessary to drive down the cost of green hydrogen.

Combusting in fossil gas power plants

Several entities have supported proposals for investments in gas-fired power plants with claims that their new fossil fuel infrastructure could one day transition to burning green hydrogen.[129] These proposals often lack meaningful consideration of the substantial barriers to retrofit a gas plant to wholly or even partially run on green hydrogen. The project proponents' vague claims about hydrogen are likely a tactic for dismissing climate and public health concerns about expanded fossil fuel reliance.

There are no commercially available power plant turbines now that can burn pure hydrogen. Without this technology, even power plants that have access to green hydrogen will continue to burn a mixture of hydrogen and fossil gas. Even burning a gas blend with 50% green hydrogen and 50% methane would require industry to overcome significant obstacles. Hydrogen's energy density (one-third of fossil gas), molecular size (the smallest of all molecules), flammability, and flame speed (an order of magnitude faster than fossil gas)[130] all pose challenges to retrofitting gas plants to run on green hydrogen, which scale with increasing concentrations of hydrogen in the power plant's fuel blend. Beyond the turbine itself, running a gas turbine on pure hydrogen requires different fuel delivery piping and components; different gas turbine controls, ventilation systems, and enclosures; and different selective catalytic reduction systems for

THE INTERMOUNTAIN POWER PROJECT

The project with the most advanced plans for transitioning to green hydrogen is the Intermountain Power Project in Utah. This facility has access to underground salt caverns for storing hydrogen, which do not exist in most parts of the country, and abundant renewable generating capacity as well as existing transmission lines. This intersection of low-cost storage, delivery, and energy capacity conditions is likely to be extremely limited across the United States.

NOx removal.[131] Many of these are also needed for high blends of hydrogen mixed with traditional gas.[132]

Even if logistical challenges can be overcome to allow gas-fired power plants to burn a gas blend with even 30 to 50% green hydrogen, this feat will have a modest effect on greenhouse gas emissions. For example, a 30% hydrogen blend would only achieve a 12% CO_2 reduction. This is because of hydrogen's low energy density, which means that large volumes of hydrogen deliver less energy than the methane in fossil gas.

The air quality impacts of combustion turbines will not only persist if they transition to hydrogen, but will worsen absent satisfactory advances in emission control technology. Indeed, it is unclear if and when industry will develop turbines that can burn hydrogen without violating air quality standards. Transitioning to hydrogen-burning turbines threatens to increase air pollution because hydrogen burns at a higher temperature than methane. A study conducted by General Electric on its combustion turbines found that a 50/50 mixture of hydrogen and fossil gas (by volume) increased concentrations of NOx in gas exhaust by 35 percent.[133] A recent report by a gas turbine industry association warned that these higher flame temperatures will produce more health-harming NOx emissions "if no additional measures are undertaken."[134] The industry association recommended that "[s]ome flexibility might be needed on NOx limits," noting that complying with pollution standards will be even more challenging if governments adopt the stronger NOx limits it foresees in the future.[135] For these reasons, regulators should not allow any increases in hydrogen blending without

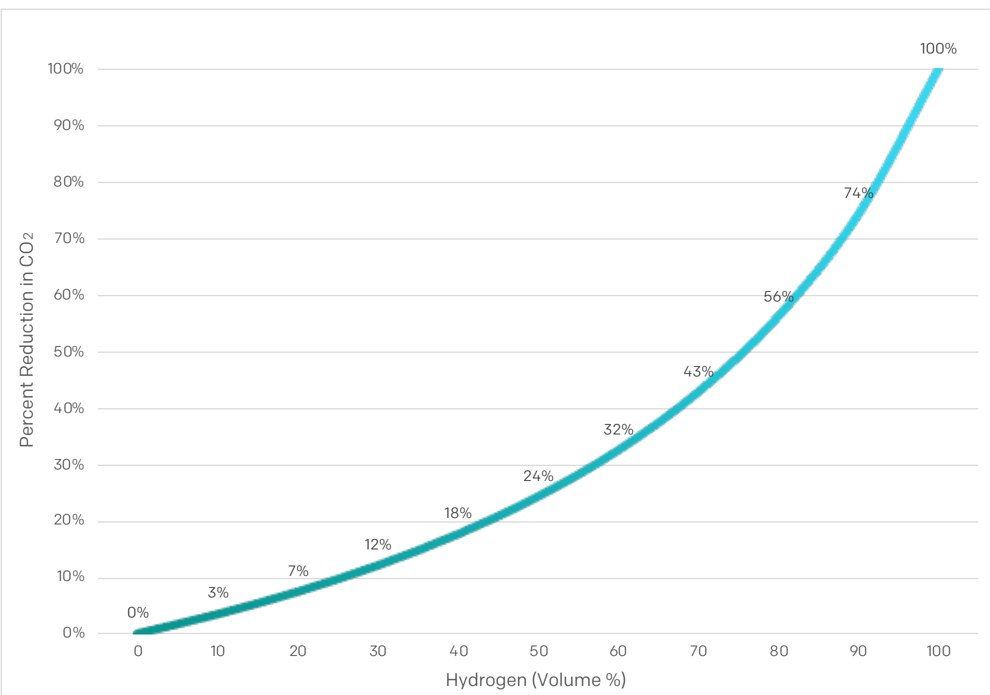


Figure 7: Relationship between CO_2 emissions from combustion and hydrogen/methane fuel blends (volume %)

GREENWASHING SPOTLIGHT

Danskammer Energy LLC is proposing to build a new 636 MW fossil gas combined cycle plant in the Town of Newburgh, New York. Under the Climate Leadership and Community Protection Act ("CLCPA"), New York has committed to achieving ambitious greenhouse gas reductions by 2030 and 2050, 70% renewable electricity by 2030, and a zero-emission electricity sector by 2040. Danskammer maintains that its proposed fossil gas plant will comply with state law because the proposed plant could theoretically someday convert to operation on hydrogen or another zero-carbon fuel and has floated the possibility of a hydrogen pilot study post-construction. However, the Company does not explain—and does not appear to know—how operating the proposed plant on hydrogen would actually work, including where the hydrogen might come from and how it would be transported to and stored on-site. When asked for additional details, Danskammer conceded that it is not proposing to operate on green hydrogen as part of the project under review, basic details on the potential hydrogen pilot project are not available at this time, and further approvals would be necessary in connection with any proposal to operate on hydrogen. Unsurprisingly then, Danskammer does not commit to a hydrogen transition and does not even plan to develop a scope for any pilot study until sometime after its proposed plant is approved to run on fossil gas. Moreover, after reviewing Danskammer's application for a facility air permit, the Commissioner of the New York State Department of Environmental Conservation tweeted that the application does not justify the project or show compliance with the CLCPA.

Source: Basil Seggos, https://twitter.com/basilseggos/status/1410334434595946496.

reviewing the adequacy of a facility's emission controls and establishing an emissions monitoring program. Regulators should set specific limits on a facility's NOx emissions during startup periods; gas turbine NOx emissions often spike before their pollution controls warm up and a transition to hydrogen could exacerbate these spikes of uncontrolled emissions. This is a public health concern for residents living near such a facility and especially in non-attainment areas, which may potentially increase the disparate impact many fence-line communities already bear in this country. Without sufficiently improved pollution control technology, another alternative would be to lower the flame temperature by "derating" the turbine, which means that the unit would not operate at its full nameplate capacity.[136] This strategy could increase the risk of power outages if grid planners had assumed these plants will be able to perform at capacity when needed.

Water use is another environmental burden that will persist regardless of whether combustion turbines transition to green hydrogen. Fossil-fueled power plants are the nation's top user of fresh water and demand tremendous amounts of water for cooling. As the climate changes, there will be less fresh water available to cool these power plants—putting their continued operation at risk.[137]

Finally, policymakers should not permit the buildout of new gas-fired power plants under the assumption that it will be economical to operate these facilities with green hydrogen. As mentioned above, a company that recently proposed a new gas plant in Newburgh, New York estimated that hydrogen in 2040 will cost $45/MMBtu in nominal dollars.[138] In contrast, the most recent Energy Information Administration 2020 Annual Energy Outlook projects natural gas to cost well below $4/MMBtu in 2040 (in 2019$) in its Reference Case.[139]

Gas-burning appliances in homes and commercial buildings

Burning fossil fuels to keep us warm in the winter, heat our water, and power other appliances collectively contributes about 10% of the nation's greenhouse gas emissions.[140] Climate policy poses an existential threat to America's gas companies because the most cost-effective way to tackle these emissions is by transitioning from appliances that burn fuel to electric appliances that run on a decarbonized power grid.[141] In the face of this threat, hydrogen has emerged as a new tool for the gas industry to sow confusion and combat measures that would help homes and businesses transition to electric appliances.

Multiple independent studies show that there is a weak economic case for deploying green hydrogen in buildings through the gas distribution grid.[142] The main reason is the superior efficiency of heat pumps, which use small amounts of renewable electricity to move ambient heat to where it is needed. One recent Pacific Gas & Electric Company-funded study found that California could save $20 billion by choosing a high electrification pathway instead of relying on renewable gases like hydrogen and synthetic methane in buildings.[143] Heat pumps for space and water heating are not only the cheapest of all zero-carbon options—in many instances, their superior efficiency means they will yield cost savings relative to conventional gas-based heating systems.[144]

There are several reasons why green hydrogen is a bad fit for addressing the pollution from gas-burning appliances:

(1) **Injecting green hydrogen into the gas system could require significant investments into a system that was not designed for hydrogen**. In California, the regulated gas utilities have proposed a pilot project to study how much hydrogen they might safely inject into the gas distribution system, and under what conditions. The utilities identified numerous potential safety and reliability risks they intend to study. For example, the elastomers and rubbers that seal many pipeline components can swell or develop voids after exposure to pure hydrogen; hydrogen can cause embrittlement of steel pipes; and the utilities do not know how much hydrogen they can

BEWARE THE HYPE AROUND HYDROGEN BLENDS

Southern California Gas Company and San Diego Gas & Electric Company brag in press releases about proposing "groundbreaking" research that could allow them to deliver gas with an "industry-leading" 20% hydrogen blend, calling it a "key milestone in our efforts to decarbonize our energy system."* If these companies find a way to safely deliver a gas mixture that is 20% green hydrogen and 80% fossil gas, their gas will still be a major climate threat. Because of hydrogen's low energy density, burning a gas blend with 20% green hydrogen will only reduce carbon dioxide emissions by about 7%. This is close to the ceiling for how much hydrogen the gas companies could deliver to homes and businesses before creating an explosion risk in gas-fired residential appliances, which is around 25% hydrogen.**

* Southern California Gas Company & San Diego Gas & Electric Company, *SoCalGas and SDG&E Announce Groundbreaking Hydrogen Blending Demonstration Program to Help Reduce Carbon Emissions* (Nov. 23, 2020), https://www.prnewswire.com/news-releases/socalgas-and-sdge-announce-groundbreaking-hydrogen-blending-demonstration-program-to-help-reduce-carbon-emissions-301178982.html.

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safely store in the underground formations that they rely on for gas storage. Because hydrogen molecules are much smaller than methane molecules, utilities may also need to upgrade their infrastructure to prevent it from leaking into the atmosphere. When a pipeline carries a blend of hydrogen and methane, hydrogen can leak at three times the rate of methane.[145] Regulators should not let gas utilities force their captive customers to bear the costs of modifying pipeline infrastructure to carry hydrogen safely and with minimal leakage. It is unreasonable for resources to go toward hardening a gas system that has no role in a zero-emission future, rather than reserving resources for building electrification.

(2) **Even after blending in green hydrogen, the gas system hits a dead end as a decarbonization tool**. Regardless of whether retrofits could theoretically enable the gas system to deliver pure hydrogen to homes and businesses, local gas utilities could not do so. At most, gas utilities can blend limited amounts of hydrogen with methane because appliances that were designed for methane gas cannot safely burn pure hydrogen.[146] The most optimistic scenarios estimate that the gas system that serves homes and most businesses could only handle up to 20% hydrogen by volume—representing just 7% of the energy in the gas pipeline system because hydrogen is less energy dense than methane.[147] In that case, fully decarbonizing the gas system would require the gas utilities to procure enough renewable methane to supply the remaining 93% of energy need on the system. There is no feasible way to displace 93% of the country's fossil gas demand with non-fossil sources of methane. Even under the gas industry's "high resource potential" scenario, methane from landfills, animal manure, food waste, and water treatment facilities could displace less than 9% of the fossil gas this country currently uses each year.[148] The same report identifies various methods of creating additional methane that could displace up to 19.5% of America's gas consumption in its most aggressive scenario.[149] The gas industry's claims about the potential for supposedly "renewable natural gas" may be overly optimistic. A report by the Union of Concerned Scientists found that there is only enough potential biomethane supply to displace about 3% of California's fossil gas use.[150] Other sources of "renewable natural gas" are being studied, but are decades

BIOMETHANE

Biomethane—sometimes referred to as "biogas," "renewable natural gas," or "RNG"—is methane generated through the decomposition or gasification of organic matter. The most common sources of biomethane are landfills, animal manure from factory farms, wastewater treatment plants, forest and agricultural waste products, or crops grown for the specific purpose of converting into energy.

While gas utilities—often in partnership with industrial agribusiness—have promoted biomethane as a drop-in alternative to fracked gas, the actual supply of non-fossil gases is extremely limited. And despite the industry's branding of this gas as "renewable," much of it comes from sources that are highly polluting, and can perversely increase greenhouse gas emissions. The small fraction of biomethane that is genuinely sustainable to produce cannot justify anything close to the current gas distribution system, and is best allocated to niche, hard-to-electrify end uses.

For a more detailed look at the industry's misleading claims about biomethane, see Earthjustice's report with Sierra Club: *Rhetoric vs. Reality: the Myth of "Renewable Natural Gas" for Building Decarbonization*. Sasan Saadat et al., *Rhetoric vs. Reality: the Myth of "Renewable Natural Gas" for Building Decarbonization* (July 2020), https://earthjustice.org/report/building-decarbonization.

away from commercialization.[151] Even if a gas company could buy a blend of zero-carbon gas, the cost would be exorbitant—potentially 8 to 17 times the cost of natural gas.[152] Thus, the current and potential future supplies of non-fossil gases do not alter the imperative to quickly and dramatically reduce gas throughput.

(3) **Injecting hydrogen into the gas system does not eliminate—and may increase—the indoor air pollution from gas-burning stoves, furnaces, and other appliances**. Unlike electric appliances, all gas-burning appliances emit nitrogen oxides, pollution that contributes to respiratory and heart diseases.[153] Under the status quo, gas combustion for heating and cooking results in significant NOx pollution and other combustion byproducts that would be considered illegal if measured outdoors. Recent studies show that children growing up in homes with gas stoves have a 42% increased risk of developing asthma symptoms.[154] In their joint application to the California Public Utilities Commission to research the compatibility of hydrogen blends with their infrastructure, the California gas utilities acknowledged that blends of hydrogen and methane "may yield higher NOx emissions than natural gas because hydrogen burns faster than natural gas, which increases combustion temperatures and reduces ignition lag. . . . therefore, additional emissions testing should be completed with natural gas end-use equipment operating with hydrogen blends."[155] Regulators should not allow gas companies to inject hydrogen into their

GREENWASHING SPOTLIGHT

Across California, local governments have adopted policies that encourage new buildings to use all-electric appliances as a cost-effective strategy to reduce greenhouse gases. The nation's largest gas utility, Southern California Gas Company (SoCalGas), has repeatedly fought these commonsense measures by urging policymakers to instead consider the possibility that gas companies' infrastructure could deliver hydrogen and other so-called "renewable" gases. For instance, the company made the following argument in its attempts stop Ventura County from blocking the build-out of fossil gas infrastructure to new homes:*

> SoCalGas urges the County to consider other GHG emission-reduction strategies that are scalable and easier to implement, more resilient and more affordable. Specifically, the use of renewable gasses such as hydrogen and renewable natural gas (RNG), are low carbon to negative fuels that can dramatically reduce county greenhouse gas emissions and provide optionality and flexibility for the energy system.

This is self-serving hype from the gas company. Despite its vague claim that green hydrogen is "more affordable" and "easier to implement" than using all-electric appliances in new homes, SoCalGas has never revealed the potential cost of procuring green hydrogen and upgrading its infrastructure to handle hydrogen blends. Promoting the interests of its shareholders, SoCalGas is invoking the future potential of hydrogen to stop policymakers from choosing climate solutions that are cost-effective today.

* SoCalGas, Comment letter RE: County of Ventura – Draft 2040 General Plan Update EIR (Feb. 28, 2020) at 12.

distribution systems unless independent researchers find that doing so will not further degrade indoor air quality.

Cars, buses, and regional trucks

Green hydrogen is not an attractive technology for decarbonizing most vehicles on the road because battery-electric vehicle technology provides a straightforward path for cars, buses, and trucks. In the market segments where battery-electric and hydrogen options are available, the battery-electric options are cheaper to purchase and operate than their hydrogen competitors, even when the hydrogen vehicles run on less expensive hydrogen from fossil fuels.[156] By the mid-2020s, researchers expect many battery-electric vehicles to have an even lower cost of ownership than vehicles with internal combustion engines.[157] Battery-electric light-duty vehicles will likely reach upfront price parity with combustion engines between 2022 and 2024, at which point they will produce operational savings relative to conventional vehicles at no added cost.[158] Though manufacturers of fuel cell vehicles could reduce upfront purchase prices by scaling up production, the economics of fueling a battery-electric vehicle with renewable energy have inherent advantages over fueling a fuel cell vehicle with green hydrogen. Hydrogen cars require more than 2 to 3 times as much renewable energy as battery-electric cars because so much energy is lost in the process of compressing and transporting hydrogen and converting it into electricity in fuel cells.[159]

Some efficiency improvements are possible. Nonetheless, a recent study found that to meet climate goals, "in comparison to electric vehicles, hydrogen-based propulsion technologies will reach market readiness too late."[160]

Given the economic advantages of renewable electricity over green hydrogen as a vehicle fuel, fuel cell vehicles will likely only be viable in the shrinking market segments that lack battery-electric options. Even for long-haul trucking, where hydrogen was once thought to be necessary for decarbonization, battery-electric vehicles are emerging as a cost-effective and low-risk mitigation pathway thanks to rapidly improving battery technology.[161] Recent studies find that these dramatic improvements can render long-haul battery-electric trucks with 500-mile range both technically feasible and economically compelling.[162] About 80% of trucks travel less than 500 miles,[163] making battery-electric technologies the best option for the vast majority of trucks.

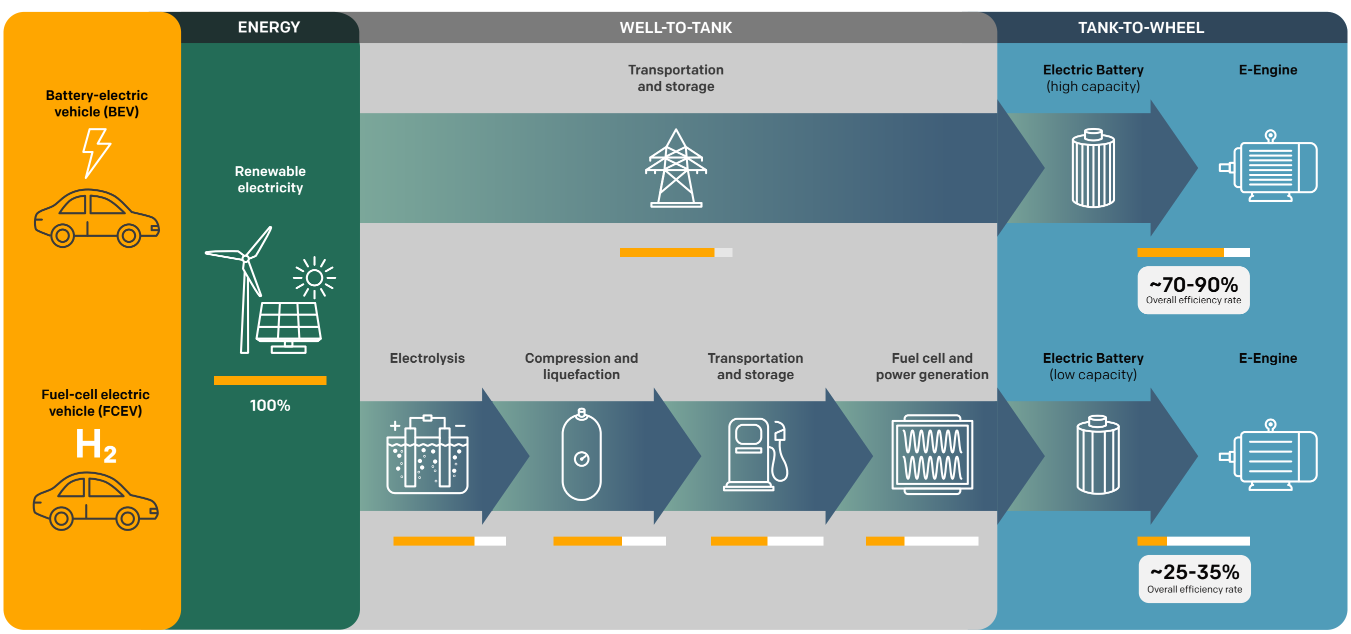

Figure 8: Comparing the efficiency of renewable energy in battery and fuel cell vehicles

Data source: Volkswagen (2020)

Recognizing the challenges for fuel cell vehicles, industry is rethinking investments in hydrogen. Scania, one of the world's largest truck and bus manufacturers, decided to end its fuel cell vehicle program because "three times as much renewable electricity is needed to power a hydrogen truck compared to a battery electric truck" and maintenance is more challenging for hydrogen vehicles than their battery-electric competitors.[164]

Volkswagen is also focusing on electric vehicles, with its chief executive officer declaring that "You won't see any hydrogen usage in cars. . . . Not even in 10 years, because the physics behind it are so unreasonable."[165] Likewise, Mercedes-Benz is ending its hydrogen car program because it could not scale up sales and production enough to make hydrogen cars cost-competitive.[166]

GREENWASHING SPOTLIGHT

Toyota is advertising its hydrogen fuel cell car, the Mirai, with the misleading claim that "[t]he more you drive, the more you clean air." The idea behind this claim is that the car's air intake has a filter that captures particulate matter and other impurities in the air before sending oxygen to its fuel cell. However, Toyota's ads ignore the emissions from producing hydrogen, even though almost all of the hydrogen in the United States is produced from fossil fuels through a process that releases significant health-harming pollution. Ultimately, these ads are likely to give consumers the false impression that they can help improve air quality by driving more often.

Source: TOYOTA MIRAI, Air Purification System (last visited July 30, 2021), https://www.youtube.com/watch?v=VX8p0mG7pLY.

CONCLUSION

Recently, hydrogen has captured the attention of the press and policymakers, partly because green hydrogen may become a climate solution for sectors that have long seemed out of reach for renewable energy. However, hydrogen hype is also flowing from industry trade associations that represent the oil and gas industry, which produce the vast majority of hydrogen in use today from fossil fuels. For the oil and gas industry and for other incumbents of the fossil energy system—like certain manufacturers of combustion vehicles, turbines, and boilers and companies that profit from building gas pipelines—hydrogen may offer a path to continued relevance and investment under potential climate policies.

While hydrogen can—and likely must—complement traditional renewables and electrification, policymakers should only promote hydrogen that is genuinely compatible with a zero-emission future. Today, more than 99% of the hydrogen that industry produces in the United States is made from fossil fuels through a process that emits massive amounts of health-harming pollution into neighboring communities. Appropriate investments in green hydrogen, which is made from renewable electricity, are no excuse for expanding or continuing hydrogen production that threatens the climate and public health.

Further, policymakers should understand the limits of green hydrogen's economic potential. Green hydrogen is not a useful tool for sectors that can decarbonize by transitioning to electric technologies and relying on a renewable power grid. It will always be more cost-effective to use renewable energy directly from the grid than to use green hydrogen; due to the inefficiency of converting renewable energy into hydrogen, powering equipment with green hydrogen requires several times as much renewable energy than doing the same job with clean electricity. Therefore, policymakers should focus on supporting green hydrogen in sectors that lack feasible electric options, such as maritime shipping.

Currently, industry trade associations are advocating for the use of a broad range of hydrogen sources and seeking public support for using hydrogen in sectors that have more cost-effective strategies for transitioning to renewable energy. Policymakers must carefully scrutinize these requests. The window to rapidly transition to a just, zero-emission energy system is narrowing. There is no time to waste with distractions or missteps. To chart a clear course, we must distinguish green hydrogen's true potential from fossil fuel industry spin, and reclaim it for a renewable future.

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